Cape Peninsula University of Technology

DESIGN OF NONLINEAR NETWORKED CONTROL FOR WASTEWATER DISTRIBUTED SYSTEMS

by

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DECLARATION

I, Olugbenga Kayode Ogidan, declare that the contents of this dissertation/thesis represent my own unaided work, and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed **Date**

ABSTRACT

This thesis focuses on the design, development and real-time simulation of a robust nonlinear networked control for the dissolved oxygen concentration as part of the wastewater distributed systems. This concept differs from previous methods of wastewater control in the sense that the controller and the wastewater treatment plants are separated by a wide geographical distance and exchange data through a communication medium. The communication network introduced between the controller and the DO process creates imperfections during its operation, as time delays which are an object of investigation in the thesis. Due to the communication network imperfections, new control strategies that take cognisance of the network imperfections in the process of the controller design are needed to provide adequate robustness for the DO process control system.

This thesis first investigates the effects of constant and random network induced time delays and the effects of controller parameters on the DO process behaviour with a view to using the obtained information to design an appropriate controller for the networked closed loop system. On the basis of the above information, a Smith predictor delay compensation controller is developed in the thesis to eliminate the deadtime, provide robustness and improve the performance of the DO process.

Two approaches are adopted in the design of the Smith predictor compensation scheme. The first is the transfer function approach that allows a linearized model of the DO process to be described in the frequency domain. The second one is the nonlinear linearising approach in the time domain. Simulation results reveal that the developed Smith predictor controllers out-performed the nonlinear linearising controller designed for the DO process without time delays by compensating for the network imperfections and maintaining the DO concentration within a desired acceptable level. The transfer function approach of designing the Smith predictor is found to perform better under small time delays but the performance deteriorates under large time delays and disturbances. It is also found to respond faster than the nonlinear approach. The nonlinear feedback linearisig approach is slower in response time but out-performs the transfer function approach in providing robustness and performance for the DO process under large time delays and disturbances. The developed Smith predictor compensation schemes were later simulated in a real-time platform using LabVIEW.

The Smith predictor controllers developed in this thesis can be applied to other process control plants apart from the wastewater plants, where distributed control is required. It can also be applied in the nuclear reactor plants where remote control is required in hazardous conditions. The developed LabVIEW real-time simulation environment would be a valuable tool for researchers and students in the field of control system engineering.

Lastly, this thesis would form the basis for further research in the field of distributed wastewater control.

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DEDICATION

This work is dedicated to my wife – Grace Oluwakemisola Ogidan for going through the "thick and thin" with me. I feel so grateful unto God for giving you to me as wife.

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GLOSSARY

Terms/Acronyms/Abbreviations	Definition/Explanation
APHA	American Public Health Association
ARMA	Auto Regressive Moving Average
ARPANET	Advanced Research Projects Agency Network
ASM1	Activated Sludge Model 1
ASP	Activated Sludge Process
ATM	Automatic Teller Machine
BOD	Internal Model Control
IMC	Biological Oxygen Demand
EPRI	Electric Power Research Institute Networked Wastewater Distributed Systems
CAN	Controller Area Network
CDM	Coefficient Diagram Method
CI	Clegg Integrator
COD	Chemical Oxygen Demand
COST	Co-operation in the Field of Scientific and Technical Research
CPG	Control Prediction Generator
CPUT	Cape Peninsula University of Technology
CSAEMS	Centre for Substation Automation and Energy Management
DBA	Dynamic Bandwidths Allocation
DC	Input/output
DDE	Delay Differential equation
DE	Differential Equation
DHCP	Dynamic Host Configuration Protocol
DNS	Domain Name Server
DO	Dissolved Oxygen
DCS	Distributed Control Systems
DTC	Dead Time Compensator
FARIMA	Fractional Auto Regressive Moving Average
FSP	Filtered Smith Predictor
FTC	Fault Tolerant Control
FTP	File transfer Protocol
GPI	Generalised Proportional Integral
GPS	Global Positioning System
HTTP	Hyper Text Transfer Protocol
IAWPRC	International Association on Water Pollution Research and Control
IAWQ	International Association on Water Quality
INTRERNET	International Network
LabVIEW	Laboratory Virtual Instrument Engineering Workshop
LAN	Local Area Network
LMI	Linear Matrix Inequality

LPV	Linear Parameter Varying
LQR	Linear Quadratic Regulator
LRD	Long Range Dependent
LSM	Least Squares Method
MADB	Maximum Allowable Delay Bound
MATI	Maximum Allowable Time Interval
MATLAB	Matrix Laboratory
MMF	Maximum Minimum Fair
NCS	Network Control Systems
NDC	Network Delay Compensator
NEPSAC	Nonlinear Extended Prediction Self-Adapting Control
NMPC	Nonlinear Model Predictive Control
NN	Neural Network
NPC	Network Predictive Control
NPID	Nonlinear Proportional Integral Derivative
ODE	Ordinary Differential Equation
OUR	Oxygen Uptake Rate
PC	Personal Computer
PI	Proportional Integral
PID	Proportional Integral Derivative
PROFIBUS	Process Field Bus
PROFINET	Process Field Network
QoS	Quality of Service
RMS	Rate Monotonic Scheduling
RTDS	Real-Time Distributed Systems
RVTD	Random Variable Time Delay
SCADA	Supervisory Control and Data Acquisition
SIMULINK	Simulation and Link
SRD	Short Range Dependent
TCP	Transfer Control Protocol
THRIP	Technology and Human Resources for Industry Programme
UDP	User Datagarm Protocol
VoIP	Voice Over Internet Protocol
WLAN	Wireless Local Area Network
WWT	Wastewater Treatment
WWTP	Wastewater Treatment Plants

MATHEMATICAL NOTATION

Symbols/Letters	Definition/Explanation
Q_r	Return flow rate of aerobic tank
Q_o	Input flow rate
Q_a	Internal recycle flow rate
Q_e	Effluent flow rate
Q_w	Wasting sludge flow rate
$Q_{n,n=1,5}$	Output flow rates for corresponding tanks of the structure
O_3	Ozone
O_2	Oxygen
NH_4^+	Ammonium
NO_3^-	Nitrate
NO_2^-	Nitrite
H_2O	Water
S_o	DO concentration in the aerobic tank
$S_{oin,n}$	DO concentration in the nth tank
K_{La}	Oxygen transmission coefficient
$S_{o,sat}$	DO concentration at a saturation point
$r_{so,n}$	Oxygen uptake rate
V_n	Tank volume
n	Current number of aerobic tanks
u	Air flow rate
k_1 , k_2	Constant calculated from = 240 metre cubed per day
S_o^d	DO concentration of desired linear system
S_o^{sp}	DO c ncentration set-point
K_p	Pr portional gain
T_i	Integral gain
τ_{ca}	Controller to actuator delays
τ_{sc}	Sensor to controller delays
τ_{tot}	Total delay
τ_c	Critical delay
τ_{COD}	Delay due to COD analysis
τ_{sc}^{η}	Network sensor to controller delay
τ^w	Waiting time
τ^f	Frame time
τ^p	Propagation time
k	Time index
T	Sampling period
$G_p(s)$	Transfer function the closed loop DO process
$G_p^m(s)$	Model of the linearised DO process used for controller design
$C(s)$	PI controller for the linear DO process

$R(s)$	Reference signal
S_{ALK}	Alkalinity
μ_{mH}	Maximum heterotrophic growth rate
S_1	Soluble Inert organic matter
Y_A	Parameter description
Y_H	Autotrophic yield
f_p	Heterotrophic yield
X_{Bi}	Fraction of biomass to particulate products
X_{Pi}	Fraction nitrogen in biomass
K_s	Half-saturation (hetero.growth)
K_{OH}	Half-saturation (hetero.oxygen)
K_{ON}	Hal -saturation (nitrate)
b_H	Heterotrophic decay rate
η_g	Anoxic growth rate correction factor
η_h	Anoxic hydrolysis rate correction factor
κ_h	Maximum specific hydrolysis rate
K_X	Half-saturation (hydrolysis)
μ_{mA}	Maximum autotrophic growth rate
K_{NH}	Half-saturation (auto.growth)
b_A	Autotrophic decay rate
K_{OA}	Half-saturation (auto-oxygen)
K_O	Ammonification rate

CHAPTER ONE

PROBLEM STATEMENT, OBJECTIVES, HYPOTHESIS AND ASSUMPTIONS

1.1 Introduction

The term Networked Control Systems (NCS) refers to feedback control loops that closed through a real-time network.(Nilsson, 1998; Yang, 2006). In NSC, plants, actuators, sensors, and controllers some of the components found and these components do exchange data in real-time. The data transfer in the form of feedback signals are done through a communication network. In order to safe the cost and achieve flexibility of control, easy maintenance, more attention is now being given to the use of data networks in control system loops.

Even though the use of communication network in control systems has a lot of merits, it is still faced with a lot of challenges. These challenges make NCS analysis rigorous such that the traditional control strategies are inadequate to be used in NCS. Some of the challenges which have become research focuses in NCS include time delay, insufficient bandwidth, and packet drop to mention a few. This research will focus on the investigation of the effects of network induced time delays the control of distributed wastewater treatment plants. Appropriate control strategies would also be developed to mitigate the degrading effects of these network imperfections on the closed loop control of dissolved oxygen process of the wastewater treatment plants. In an attempt to select the appropriate control strategies, MATLAB/Simulink and LabVIEW simulations would be performed. These would be done in order to investigate and to validate the control strategies developed in this thesis. The results obtained in the thesis would be useful for future studies on distributed control of wastewater treatment facilities and Networked Control Systems.

Section 1.2 is the awareness of the research problem, while the aim and objectives of the research are given in section 1.3. The hypothesis, delimitation and assumption under which the research is conducted are outlined in sections 1.4, 1.5 and 1.6 respectively. Section 1.7 discusses the deliverables of the thesis, the Chapter breakdown is discussed in section 1.8 and the Chapter concludes in section 1.9.

1.2 Problem awareness

For a very long time, control systems have been made us of in many applications. The application areas include airplanes, refineries, and process industries to mention a few. Feedback control is an important concept in the field of control system. This means that in feedback control systems, the output of the system is normally passed through the feedback loop and compared with the desired set-point. This is done so that an error signal is generated. This error signal is then used by the controller to produce the appropriate control action for the plant under consideration. This is illustrated in Figure 1.1 where $y(t)$ is the output signal, $r(t)$ is the error signal $u(t)$ is the control action used to control the plant. When a communication networks is introduced to a traditional feedback control system, then the result is networked control systems as illustrated in Figure 1.2.

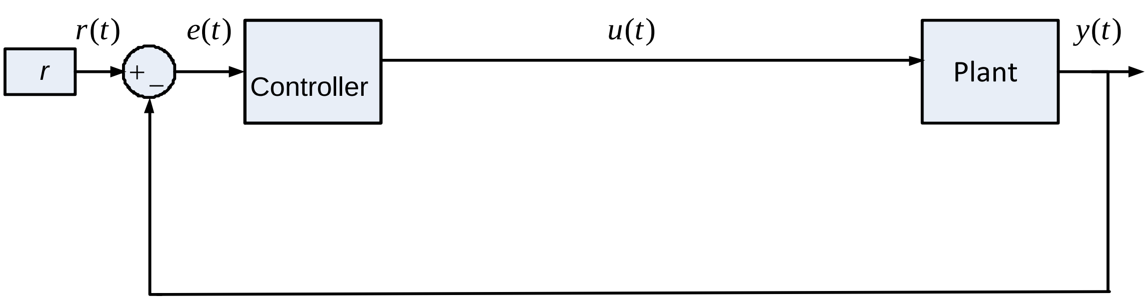

Figure 1.1: The traditional control system

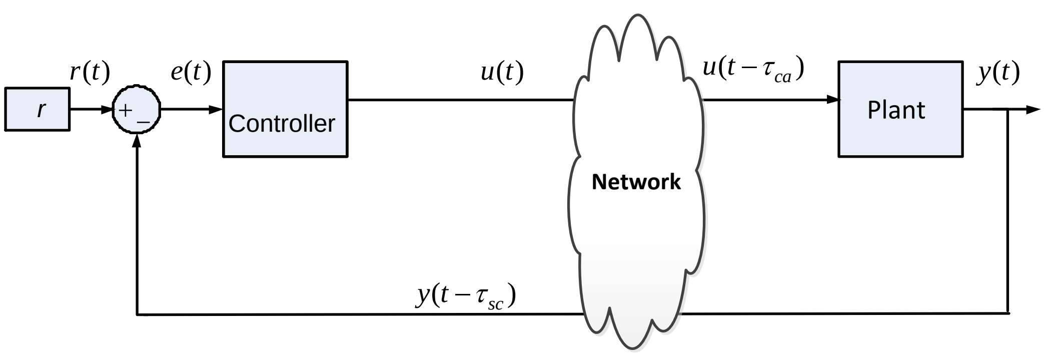

Figure 1.2: The Networked Control Systems

Networked Control Systems is a field that basically merges control systems and information systems. In information system, networks are approached from the computer science point of view and as such consideration is not given to the time of sending and reception of the information sent as well as an acknowledgement from the recipient about the arrival of information. In feedback control systems, confirmation of information arrival, arrival times as well as the acknowledgment of information received are all very important for proper performance of the control system. So in Networked Control Systems, it is not only important that the information arrives, if it does not arrive at the right time, this can lead to a breakdown of the control system.

In real-time distributed networks control systems, sensors, actuators, controllers and plants to be controlled are all connected in a real-time distributed network (Baillieul and Antsaklis, 2007). Delays and packed losses are the main issues in the operation of networked control systems that lead to instability and network degradation. To achieve a stable system that performs according to the set specifications, good control design and implementations are required to ensure effectiveness in the communication network by reducing or eliminating (compensating) the network drawbacks.

1.2.1 Statement of the problem

The design of a robust nonlinear networked control for wastewater distributed systems in order to overcome network imperfections that results in degradation of the wastewater distributed control system. This entails the design of controller that will provide robust control of the Dissolved Oxygen (DO) concentration in the wastewater by controlling the valve of the wastewater plant while minimizing the effect of communication drawbacks on the closed loop DO process control system. If a controller designed is able to work well under different sets of assumptions such as network imperfections, then it is said to be robust.

The focus of this research will be mainly on the controller design and real-time simulation while giving due consideration to the communication channel drawbacks. This is done to make sure that the plant under consideration is appropriately controlled by the control strategies developed in this thesis. To achieve the above, the problem is addressed at under the following sub-problems.

1.2.2 Design sub-problems

Design sub-problem 1: Overview of the existing methods of time delay compensation in NCS in order to ascertain the most appropriate strategy for the wastewater treatment plant (WWTP) control. This is done through literature review.

Design sub-problem 2: Overview of the WWTP models in order to select the appropriate model for the investigations carried out in this thesis. This review also assists to familiarize with the WWTP dynamics with a view to finding appropriate methods of control for the WWTP.

Design sub-problem 3: Analysis and design of a nonlinear control strategy for the wastewater treatment plant in the absence of network induced time delays.

Design sub-problem 4: Analysis of closed loop DO process behaviour in the presence of network induced time delays

Design sub-problem 5: Determination of the maximum value of time delays that will result in instability for the DO process under different conditions through simulation

Design sub-problem 6: Development of the Smith predictor compensation scheme for the DO process under the influence of time delays using the transfer function approach

Design sub-problem 7: Development of the Smith predictor compensation scheme for the DO process under the influence of time delays using nonlinear feedback linearising approach in state space

1.2.3 Real-time simulation sub-problem

Real-time simulation of the developed NCS using PC based models of the DO process (WWTP) and artificial delays as communication network in the MATLAB/Simulink and LabVIEW environment.

1.3 Aim and objectives of the thesis

The aim of the research project is to develop and implement methods, algorithms, and software for the design of robust nonlinear networked control of wastewater plants under communication channel imperfections.

The objectives are as follows:

a) To review the control design strategies that takes cognizance of time delays in their design.

b) To review and investigate the appropriate models of the wastewater plants

c) To develop a control strategies for the nonlinear DO process without network delays

d) To investigate the DO process closed loop behaviour under constant and random time delays by simulation.

e) To investigate the effects of PI controller parameters on the DO process behaviour under random time delays by simulation

f) To design robust networked control strategies for the DO process that takes into cognisance network imperfections and incorporates it as part of the closed loop control system.

g) To make use of the LabVIEW real-time environment in simulating and validating the developed control design strategies.

1.4 Hypothesis

The previous research has proven that network delays and packet losses results in performance degradation and instability of the closed loop control systems. The work in this thesis proves that the performance of networked control systems can be improved based on the control strategies developed in this thesis

1.5 Delimitation of the research

In order to solve NCS problems, two main approaches are usually adopted namely: the communication and networking approach and the control design approach. The proposed research concentrates mostly on the control design approach. The Smith predictor control strategies are developed for the DO process of wastewater treatment. The proposed Smith predictor control strategies take into consideration communication imperfection in their designs. This is done in order to ensure the DO concentration desired trajectory is maintained despite the presence of network drawbacks. Communication network is based on the Ethernet and artificial delays in the form of transport delays are used to represent the time delays on the Ethernet network. The time delays considered in this research include the controller to actuator delays (τ_{ca}), the sensor to controller delays (τ_{sc}), and process delays (τ_{COD}), due to time taken to analyse the Chemical Oxygen Demand (COD) by COD analysers. The process delays due to COD analyser (τ_{COD}), are considered as part of the sensor to controller delays.

The developed control strategies are simulated using the MATLAB/Simulink packages and the real-time simulation is done in the LabVIEW environments.

1.6 Assumptions

In order to achieve the aim and objectives of the research, the following assumptions are made.

1. The nonlinear control strategies are more suitable for the control of nonlinear systems. (Galvez et al., 2007; Slotine and Li, 1991).
2. The simulation environments MATLAB/Simulink is able to produce results that are comparable to the real-time implementations (Copp, 2001).
3. Network transmissions are free of quantization error and packet drops (Tipsuwan and Chow, 2003)
4. Personal computer that is used to host the model of the WWTP and the developed controller can adequately represent a lab-scale WWTP (Nketoane, 2009).
5. No model uncertainty or model mismatch is experienced between the model of the DO process representing the actual DO process and the DO process model used for the Smith predictor

1.7 Deliverables of the project

- Literature review of the NCS with a focus on the Smith predictor compensation scheme
- MATLAB/Simulink and the LabVIEW packages are used for modeling of the WWTP
- nonlinear feedback linearising controller is designed for the DO process without time delays
- The degrading effects of the constant and random time delays on the closed loop DO process is Investigation
- The degrading effects of the PI controller parameters (K_p and T_i) on the closed loop DO process control system is investigated
- A robust strategy for designing of a Smith predictor based compensation scheme for the DO process in the frequency domain using transfer function is derived
- A robust strategy for designing of a Smith predictor-based compensation scheme for the DO process in the time domain using nonlinear linearising feedback linearisation is derived

- Real-time simulation of the developed closed loop DO process control system is perform in the LabVIEW environment

1.8 Chapter Breakdown

There are eight Chapters in this thesis. They are: the problem statement, problem analysis and introduction to the model of the DO process of the WWTP, investigation of the influence of time delays on the DO process under different conditions, development of Smith predictor based compensation scheme for the DO process using the transfer function and nonlinear linearising approach approaches, real-time implementation of the developed methods and conclusion.

Chapter 1: In chapter one, the reasons for the research are outlined starting with the problem statement, the aims and objectives of the research, research motivation, hypothesis, and assumptions.

Chapter 2: In this chapter, previous studies on NCS are reviewed with a view to finding the most appropriate approach for the research. These include NCS Communication Protocols such as the TCP and UDP protocols, network induced time delays, their causes and effects on NCS, network control methodologies as well as the Smith predictor compensation scheme for eliminating time delays (deadtime) in the process control systems.

Chapter 3: The Chapter three introduces the COST Benchmark structure of the ASP known as the Activated Sludge Model 1 (ASM1). The background of the WWTP with emphasis on the Activated Sludge Process ASP) is discussed. The ASM1 model as well as the usefulness of the Dissolved Oxygen (DO) concentration in the ASP are enumerated. The reason for using this internationally accepted model is that it allows for comparison of results with that of other researchers in terms of controller design. The chapter ends by proposing the networked control of the DO process in a networked wastewater treatment facility.

Chapter 4 starts by outlining the types of time delays that could affect system performance in the ASP. The process delays such as the delay due to Chemical Oxygen Demand (COD) analysis (τ_{COD}) as well as the network induced time delays

$(\tau_{ca}, \tau_{sc}, \tau_{tot})$ were recognised. It also presents the investigations of network induced time delays on the DO process control system. The effects of constant delays, random delays and the choice of controller parameters (K_p and T_i) are investigated and the results discussed. The purpose of these investigations is to know the threshold delay value that makes the DO process become unstable under the various conditions described above. This information helps in the design of a robust networked control that compensates for communication imperfections and as such would is able to stabilise the DO process control system in a networked environment.

Chapter 5 presents a transfer function approach for the design of a Smith predictor-based DO process compensation scheme in order to mitigate the effects of time delays on the DO process. In this chapter, the positioning of the time delays is such that the PI controller is placed far away from the linearing controller and the nonlinear DO process. This type of arrangement makes the nonlinear DO process to behave like a linear (linearised) one. As a result, the transfer function approach is used to derive the Smith predictor compensation scheme to eliminate time delays from the DO process control system. The chapter contains the derivation of the Smith predictor scheme, simulation of the DO process under constant and random time delays and the Smith predictor. Results of the simulations are analysed and discussed.

Chapter 6 proposes another approach for the design of the Smith predictor –based DO process compensation. This is known as the nonlinear feedback linearising approach. The arrangement of the closed loop DO process control system in this chapter is such that the PI controller and the nonlinear linearising controller are placed close to each other, far from the nonlinear DO process. The derivation of the Smith predictor compensation scheme in state space using the nonlinear linearising approach is presented. Simulation of the DO process under constant and random time delays and the Smith predictor are performed and the results presented.

Chapter 7 presents the real-time implementation of the developed Smith predictor-based DO process compensation schemes. The aim of this Chapter is to show how the methods designed in this thesis are implemented in real-time to stabilise the DO process in the presence of network imperfections. The transfer function approach developed in Chapter five and the nonlinear linearising approach developed in Chapter six are implemented in the real-time environment using the NI-LabVIEW software

Chapter 8 is the conclusion of the thesis and the deliverables of the thesis. It outlines the application of the thesis results, possible future works as well as the publications from the thesis.

1.9 Conclusion

In this Chapter, the NCS is introduced and the awareness of the problem of under consideration in this thesis is given. The methods to be used to solve the problem are clearly stated as well as the delimitation of the research work to be undertaken. The research hypothesis is also stated while the Chapter concludes with an outline of what is to be done in each Chapter of the thesis. Chapter two will be literature review of the Networked Control Systems.

CHAPTER TWO

LITERATURE REVIEW ON NETWORKED CONTROL SYSTEMS

2.1 Introduction

In the traditional control systems, there is exchange of information between sensors, controllers and actuators. This is a type of point-to-point arrangement where these components (sensors, controllers and actuators) are close to each other as shown in Figure 2.1a. As a result, time delays do not constitute any problem. Even when they exist, they are so negligible and are ignored. In the case of Networked Control Systems (NCSs), the sensors, controllers and actuators are not close to each other but are arranged in a remote or distributed form (Gupta and Chow, 2010). As such, a communication medium is used to exchange information between them. In other words, the major difference between the traditional closed loop control systems and NCS is that in case of NCS, the communication network is considered as part of the closed loop control system as shown in Figure 2.1b. According to Sun et al. (2011), control systems whose control loops are connected with real-time networks to exchange information and control signals are labelled as Networked Control Systems. (Wang and Liu, 2008; Nilsson, 1998; Jianyong et al., 2004; Yang, 2006). The communication channel may be shared with other nodes outside the control system and it might not be shared (Hong, 1998).

The inclusion of communication network in the traditional control system introduces network imperfections that adversely affect the exchange of information between the distributed sensors, controllers and actuators. The network imperfections adversely affect the performance and stability of the closed loop control system. This chapter examines the studies on NCS. The chapter is arranged as follows: Section 2.1 is the introduction; section 2.2 examines the history of NCS. NCS overview in terms of configuration, structure, time-sensitivity, research foci and components is considered in section 2.3. Sections 2.4 and 2.5 investigate network delays/packet drop and the network control methodologies respectively. The chapter 2.6 discusses the Smith predictor compensation scheme while the chapter concludes in section 2.7. The publications cited in the thesis and the publication years are shown in Figure 2.2.

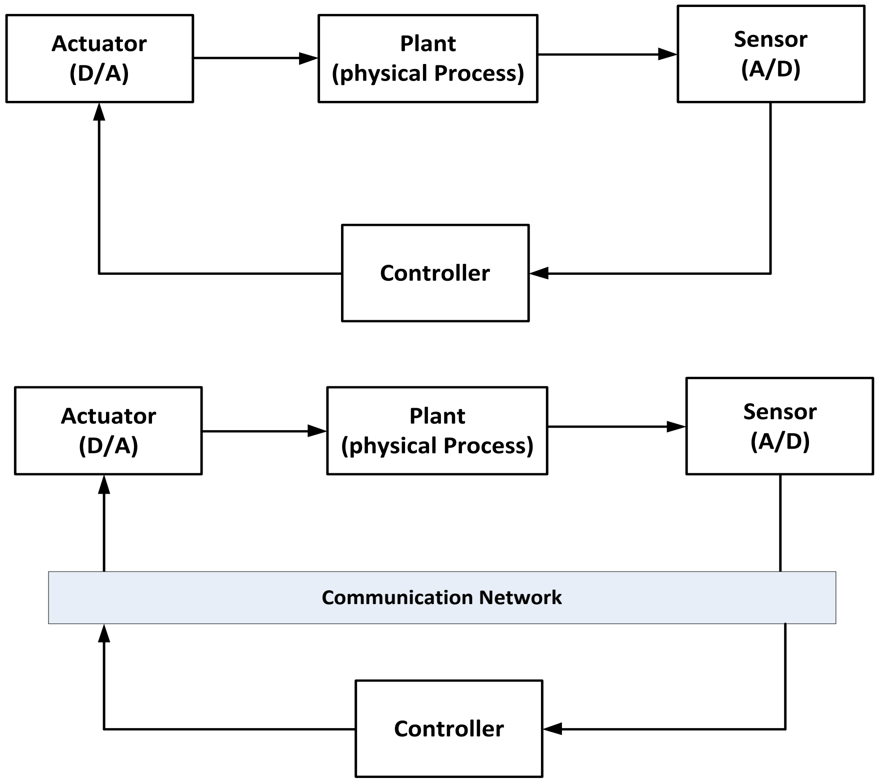

Figure 2.1: A comparison between the traditional control system and NCS structure a) Traditional Control system, b) Networked Control System

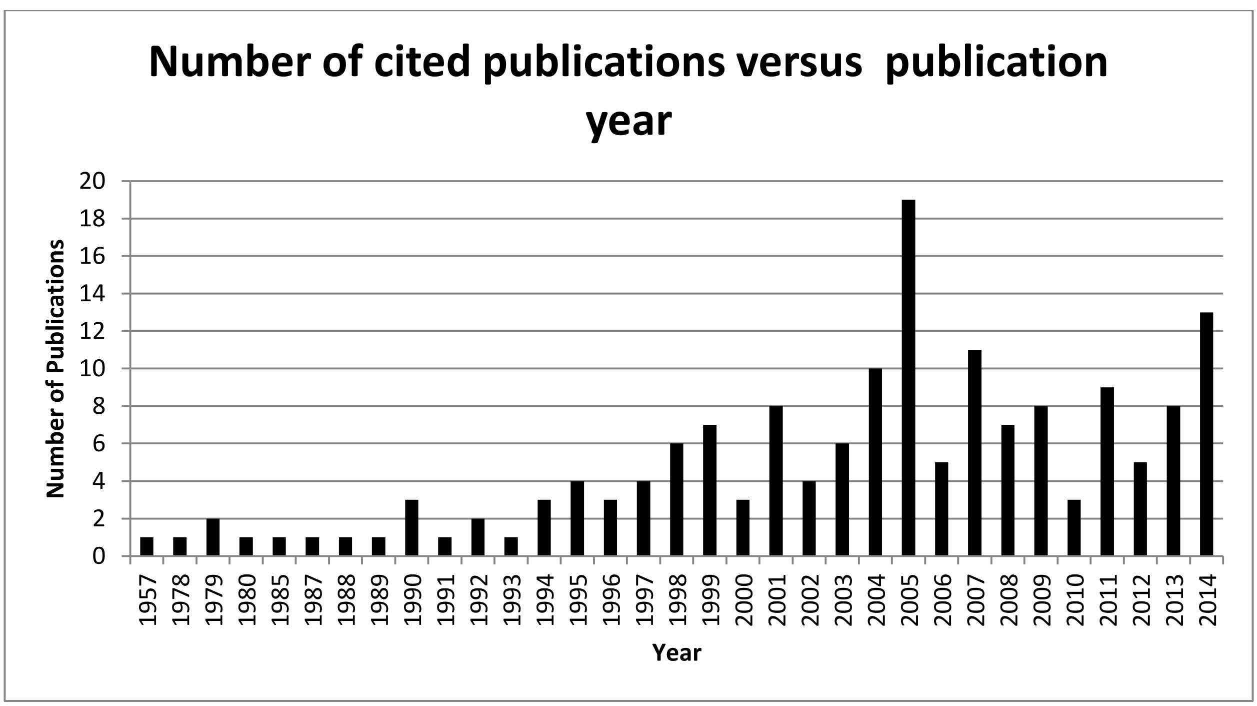

Figure 2.2: Publications cited in the thesis in relation to the year of publication

2.2 History of Networked Control Systems

Control systems dates back to 1868 when J.C Maxwell conducted the dynamic analysis of centrifugal governor (Maxwell, 1967). In 1903, the Wright brothers made their first successful test flight (Crouch, 2002). The fly by wire flight control system was later designed to replace the mechanical circuit of hydro-mechanical flight control system.

With the introduction of microprocessors, digital computers became prominent and were used in control systems with the microprocessors bringing in new features. The first digital fly by wire aircraft was introduced in 1972. In 1975, there was the evolution of Distributed Computer Systems (DCSs) (Gupta and Chow, 2010). As the industrial control needs expand and there were needs to control plants in hazardous environments, for example nuclear reactor power plants, space projects to mention a few, the research in tele-operation became prominent (Gupta and Chow, 2010).

With the advent of networking technologies, there had been tremendous improvement in the field of NCS. This is as a result of the low cost and easy access to the Internet (Gupta and Chow, 2010). NCS is now moving towards distributed NCS – a network integrating distributed sensors, distributed actuators and distributed control algorithms over a network in real-time (Chow and Tipsuwan, 2001; Huo et al., 2005).

NCS has many advantages which include: reduced cost of cabling, reduced weight, it offers modularity, flexibility, simple installation and maintenance and high reliability in system design (Tipsuwan and Chow, 2003; Zampieri, 2008).

Applications of NCSs include control of industries especially in hazardous environment such as nuclear reactor power plants, space projects, flight control, nursing homes, and military applications (Chow and Tipsuwan, 2001). Other potential applications include terrestrial exploration, factory automation, space exploration, remote diagnosis and troubleshooting especially in dangerous or environments with hazards, tele-robotics, tele-operations to mention a few (Hsieh, 2004; Leung, 2005).

Despite the advantages and potentials of NCS, it is still faced with a lot of challenges like network induced time delays and packet drop that tend to degrade the network performance resulting in system failure (Nilsson, 1998). Others include jitter, inadequate bandwidth, network protocol (TCP, UDP, CAN or Wi-Fi) influence, timing and synchronization of network devices including computers, sensors, embedded hardware that are nodes in the network and so on (Gupta and Chow, 2010). Some of these shall be considered in detail later. In traditional control systems, only the sensor and actuator are considered as part of the closed loop while the controller and plant are placed closed to each other. In contrast, NCS introduces a situation in which the controller and plant are separated from each other such that a communication medium is required between them which give rise to the challenges outlined above.

2.3 Overview of Networked Control Systems

This section reviews the Networked Control System on the basis of its characteristics as configuration, time-sensitivity, structure and components as shown in Figure 2.3.

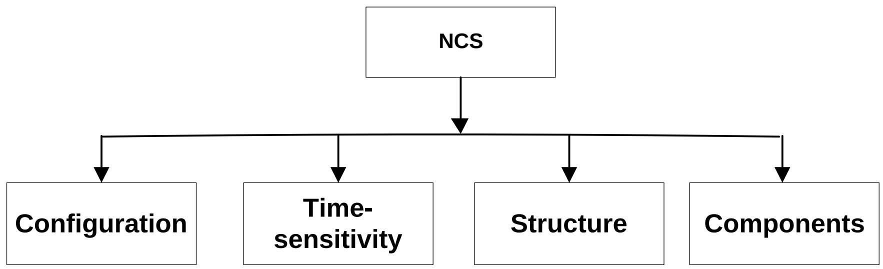

Figure 2.3: Diagram showing an overview of the NCS

2.3.1 NCS Configuration

By broad examination, the configuration of the NCS mostly depends on its application areas:

(i) Control of complex systems

(ii) Control of remote systems. (Tipsuwan & Chow, 2001)

2.3.1.1 Control of complex systems

Complex control systems are large-scale systems containing several sub-systems. The components of these subsystems are sensors, actuators and controllers. Complex systems usually result in complicated circuit systems because of several sensors and actuators that have to be connected. As a result, NCS is applied to reduce the complexity of wiring components and to bring about flexibility in the installation, maintenance and troubleshooting (Ozguner et al., 1992; Boustany et al., 1992).

2.3.1.2 Control of remote systems

This is often referred to as tele-operation control. This is a case where a central controller is installed in a local site while the plant is located in a remote site. In other words, the local site can be several kilometres away from the remote site. This is the class of remote data acquisition systems and remote monitoring (Wang and Liu, 2008). In remote control scenario, there could be a dedicated communication link between a controller and the object being controlled. Example is the radio-controlled airplane. In this case, other airplanes cannot share the frequency of communication. This type of system is usually very costly in terms of maintenance, installation and upgrade. A more cost effective way to achieve remote control is to make use of shared network. An example is the Internet which is readily available, large and cheap. Figure 2.4 (Gupta and Chow, 2008) illustrates a shared network.

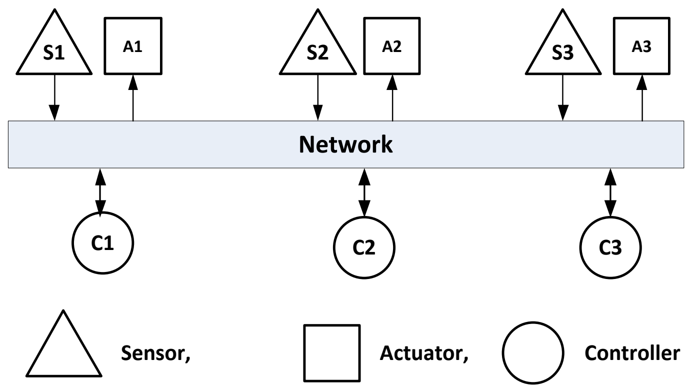

Figure 2.4: A shared-network (Gupta and Chow, 2008)

2.3.2 Direct structure and hierarchical (indirect) structure

In Networked Control Systems, there are two general design approaches namely: direct structure and hierarchical (indirect) structure (Gupta and Chow, 2008). According to Gupta and Chow (2008), the NCS in the direct structure is composed of a controller and a remote system containing a physical plant, sensors and actuators. This is shown in Figure 2.5 (Gupta and Chow, 2008). The controller and the plant are physically located at different places and are directly linked by a data network in order to perform remote closed-loop control. The controller computes the control signal and the control signal is sent as packet through the network to the plant. The plant then returns the system output to the controller by putting the sensor measurements into a packet as well. NCS examples utilizing the direct structure include a distance learning lab (Overstreet and Tzes, 1999) and a direct current motor speed control system (Chow and Tipsuwan, 2001).

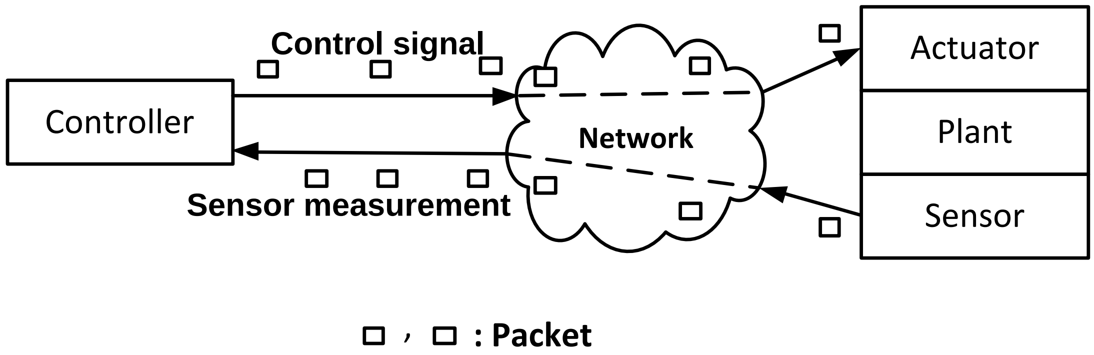

Figure 2.5: NCS in the direct structure (Gupta and Chow, 2008)

The hierarchical structure on the other hand consists of two controllers which are the main controllers and a remote closed-loop system with its controller. The main controller computes and sends the reference signal in a packet via a network to the remote system. The remote system then processes the reference signal to perform local closed-loop control and returns the sensor measurements to the main controller for networked closed-loop control. The networked control loop usually has a longer sampling period than the local control loop since the remote controller is supposed to satisfy the reference signal before processing the newly arrived reference signal (Gupta and Chow, 2008). In other words, data are exchanged between components directly in case of the direct structure compared to the hierarchical structure in which a central controller has to wait for set-point satisfaction before measurements as well as alarm signals and status signals are completed (Chow and Tipsuwan, 2001). This arrangement is illustrated in Figure 2.6 (Gupta and Chow, 2008). Applications utilizing the hierarchical (indirect) structure type include mobile robots (Tipsuwan and Chow, 2002), and tele-operation.

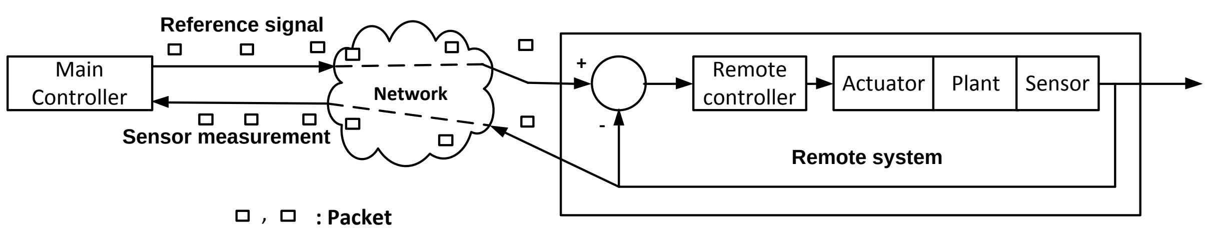

Figure 2.6: NCS in the hierarchical structure (Gupta and Chow, 2008)

Some NCSs combine these two structures thereby forming a hybrid structure. Examples are the remote teaching lab (Chow and Tipsuwan, 2005).

The requirements of an application under study and the designer's choice are major factors in determining between either the direct structure or the hierarchical structure. For example, the direct structure may be preferred in a case where the aim is to achieve a faster control response of a DC motor speed over the network (Tipsuwan & Chow, 2001). On the other hand, a robotic manipulator that usually requires several motors at the joints of the robot to simultaneously and smoothly rotate together might require the hierarchical structure to develop a more robust control system (Tipsuwan & Chow, 2003). This thesis makes use of the direct structure.

2.3.3 Time sensitive and time-insensitive applications

Considering time as a factor, NCS can be grouped under two main headings namely:

(i) Time-critical/time-sensitive applications

(ii) Time-delay-insensitive applications.

Time sensitive/critical applications are such that if the process does not complete at a defined time, failure is inevitable. This can be in form of undesirable or inferior output, system damage and so on. Examples of such time-critical systems include tele-operation through networks, automated highway driving, undersea operations, fire-fighting operations or even military operation. In the case of time-delay-insensitive applications, even though they operate in real-time, they can still complete beyond the specified time without great consequence, that is they are not time critical. Examples are electronic-mail, File Transfer Protocol (ftp), Domain Network Server (DNS), and Hypertext Text Transfer Protocol (HTTP).

In tele-operated systems, the level of human interference also varies from application to application (Wang and Liu, 2008). Considering the human interference, three groups can be discovered. They are:

(i) Tele-operated with human intervention

(ii) Tele-operated without human intervention

(iii) Hybrid tele-operated systems

2.3.4 NCS Components

In NCS study, it does not matter whatever hardware or software are employed to achieve NCS, there are four important functions that must be considered. They are information acquisition (sensors), commands (controllers), communication and control implementation (actuators). Each of them will be considered briefly.

2.3.4.1 Data Acquisition (Sensors)

NCS requires the collection of relevant data using distributed sensors in the network to study the system under control. Sensor data can be in any form for example temperature, pressure, weight, images, arrays, videos streams and so on. Sensor occupies a very important place in NCS because there cannot be an effective control if the sensor is not sensitive enough to effectively present the actual state of the plant being studied. As a result, a lot of researches about sensor are ongoing including sensor fusion and sensor networks (Vieira, 2003), development of middleware and operating systems for sensor nodes (Park et al., 2006), information assurance (Olariu and Xu, 2005), energy efficient sensor nodes (Yamasaki and Ohtsuki, 2005) and sensitivity of the data. Image data is used for surveillance applications (Chang et al., 2005), robot navigation (Mariottini et al., 2005), target tracking (Saeed and Afzulpurkar, 2005) and tele-operation to mention a few. Ground and aerial vehicles (Rathinam et al., 2006) are controlled through visual and other local sensing schemes algorithms.

2.3.4.2 Commands (Controllers)

This is the control law that ensures the control system follows a particular desired trajectory. Researchers have applied different strategies for instance from classical control theory, starting from PID control, optimal control, adaptive control, robust control, intelligent control and many other advanced forms of these control algorithms. Due to network induced delay and data drop out, applying all these control strategies over a network is a very challenging task. In the course of this study, this would be considered in detail.

2.3.4.3 Control implementation (Actuators)

Just as there exists distributed sensors in NCS at different locations, it is also possible have actuators connected to one or more controllers through the network. This helps to achieve scalability in NCS.

2.3.4.4 Communication

The importance of communication in NCS cannot be over-emphasised. Today, there are various communication means that can be used in NCS including telephone lines, cell phone networks, satellite networks, CAN, INTERNET, LAN, WLAN, GPS. Internet is the most widely used due to the fact that it is inexpensive and able to cover a wide geographical location. GPS systems can be used to localize vehicles all over the planet. Military applications, surgical and other emergency medical applications, however, can use dedicated optical networks to ensure fast speed and reliable data communication (Wang and Liu, 2008). In all these, the choice of the network mostly depends on the application requirement but it is good to bear in mind ease of use, reliability, availability and security (Gupta and Chow, 2010).

The world first packet switching network is the ARPANET which stands for Advanced Research Projects Agency Networks. It was developed by the United States defence department in 1969 (Gupta and Chow, 2010). Later the field bus came with its different variations such as the Profibus (Process Field Bus) in 1989 mostly used for automation technology and Controller Area Network (CAN). Others include Device-Net and PROFINET. Although these early networks such as Profibus and CAN provide a reliable real-time communication for industrial distributed systems, they are proprietary and not commercially available off-the shelf and also expensive to maintain. The Ethernet has today become the most widely implemented physical and data link protocol. This is as a result of the fact that it is cheap and has backward compatibility with existing Ethernet infrastructure. There are now fast Ethernet (10-100 Mb/s) and gigabyte Ethernet (1000Mb/s) as well as the switch Ethernet which is very prominent for industrial applications (Lee et al., 2005, Gupta and Chow, 2010). Ethernet is the network of choice in this thesis.

2.3.4.5 The Open Standard Interface model

Considering the Open Standard Interface (OSI) model, communication protocols can be found in the Data Link, Network and Transport layers (Soundtraining, 2014). This is shown in Table 2.1 (Cisco, 2014).

Table 2.1: The OSI Model (Simoneau, 2006)

Layer Number	OSI Model	Protocol
7	Application Layer	FTP,HTTP, Telnet, SMTP
6	Presentation Layer	MPEG, ASCII, SSL
5	Session Layer	NetBIOS, SAP
4	Transport Layer	TCP, UDP
3	Network Layer	IPv4, IPv6
2	Data Link Layer	Ethernet
1	Physical Layer	RS232, 10BaseT, 100BaseT

From the OSI model, it could be observed that Ethernet protocol belongs to the Data Link layer which is the layer 2 of the OSI model while the Internet Protocol (IP) and the TCP/UDP protocol belong to the network layer and transport layers respectively. Ethernet on layer 2 is seen to run on the layer 3 which is the Internet protocol (IP). However with the IP, it is a nondeterministic protocol and so it is connectionless (Tipsuwan and chow, 2003). In other words, it does not acknowledge the packets sent through and so there is no guarantee that what is transmitted is received at the destination. TCP in the contrast exhibits hand-shaking and performs acknowledgement on the data transferred. As a result, TCP protocol delivers a more reliable data but the time it takes for acknowledgement constitutes a source of overhead in the network and so compromises performance (Antoniou, 2007). In a situation where time delay has negative impact on the system such as the case of NCS, TCP is not a recommended protocol. UDP also in the transport layer 4 is a connectionless protocol. Though unreliable in terms of data accuracy, it does not add unnecessary overhead to the system.

In summary, the primary difference between UDP and TCP is the level of assurance that the data sent actually arrives at the given address. While TCP is optimized for accurate delivery due to its ability to acknowledge received data, it experiences a lot of latency due to overhead within the network. UDP gives higher throughput and shorter latency especially with real-time applications. Table 2.2 shows the varying characteristic of the TCP and UDP protocols.

Table 2.2: UDP and TCP characteristics

UDP	TCP
Unreliable	Reliable
Connectionless	Connection-oriented
No acknowledgement	Acknowledges segments
No sequencing	Allows segment sequencing
No re-transmission or windowing	Allows for segment re-transmission and flow control by windowing

2.3.4.6 Network Configuration

Before being recognised on the network, every host must understand the network configuration. The network configuration includes IP addresses for Domain Name System (DNS) and the Dynamic Host Configuration Protocol (DHCP) Servers, the default gateway, and the subnet host addresses. Through knowing the local subnet and network resource IP addresses, the host can interact with other hosts and use network resources to accomplish tasks. A predefined start up sequence is used to ensure all devices receive and confirm network configuration correctly. This process gives network connection a plug and play feel. A network can either be statically or dynamically defined.

2.3.4.7 Static and Dynamic Host Configuration Protocol (DHCP)

In a small unchanging network, it might make sense to have all host and resource IP addresses unchangeable, or static. This creates a very predictable environment with little configuration effort. Using Static addressing, the host PC wakes up with a predefined understanding of its IP address and network resource locations. Unlike the Dynamic Host Configuration Protocol (DHCP) which is used for larger and complicated networks (Fnal, 2014), this predefined and unchanging environment (static) makes management of small networks more straight forward. In other words, Static IP address requires a small amount of configuration and management up front for a small network but allows the reliable configuration of game and application servers.

2.3.5 NCS Research Foci

Despite the advantages and potentials of NCS, it is still faced with a lot of challenges like time delay and packet dropout that tend to degrade the network performance leading to system failure. Others include jitter, inadequate bandwidth etc. In an attempt to solve these problems, different research foci have emerged. Some of these challenges include (Gupta and Chow, 2010):

- Bandwidth allocation and scheduling
- Network security
- Fault Tolerant Control
- Component Integration
- Data quantization
- Network delay and packet drop, to mention a few (Gupta and Chow, 2010).

2.3.5.1 Research Trends in NCS

NCS study is usually approached from two different perspectives as shown in Figure 2.7 namely:

(i) Control of Network

(ii) Control over Network

Control of Network involves improving the communication network through congestion reduction, routing control, networking protocol, efficient data communication and the likes to improve quality of network and quality of service. For example, various congestion control and avoidance algorithms have been proposed (Altman et al., 1999; Mascolo, 1999) to gain better performance when the network traffic is above the limit that the network can handle.

Control over network on the other hand concentrates on designing of control systems and control strategies to achieve improved performance of the NCS. The control over network is the approach of choice in this research. Figure 2.7 shows the emerging research in NCSs theory and implementation (Gupta and Chow, 2010).

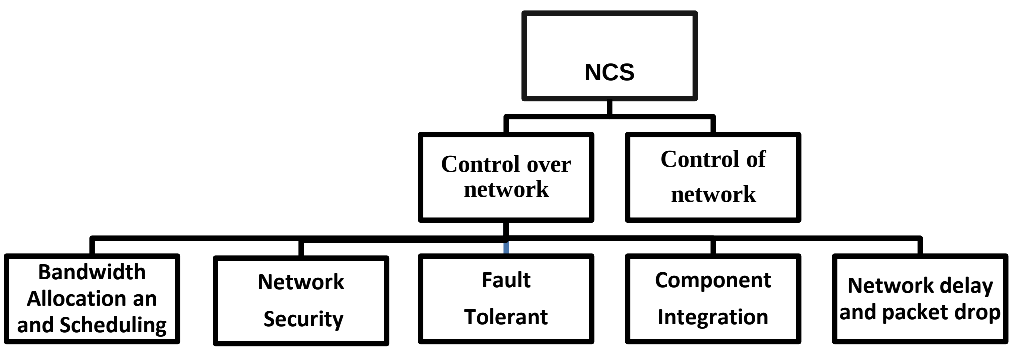

Figure 2.7: **Research foci in NCS (Gupta and Chow, 2010)**

2.3.5.2 Bandwidth allocation and scheduling

Since NCS takes place on communication channels such as the Ethernet, DeviceNet, CAN to mention a few, there could be a case of competition between multiple nodes accessing the network. This phenomenon occurs when multiple nodes are trying to access the network at the same time leading to congestion in the network (Zhang et al., 2013). There is therefore the need for an optimal use of the available bandwidth to guarantee efficient service delivery in the face of competing demands. To achieve this, several approaches are being used including Maximum-Minimum Fair (MMF) principle which helps to find reasonable bandwidth allocation scheme for competing demands (Gupta and Chow, 2010) and the Maximum Allowable Time Interval (MATI). Studies in this respect include: Scheduling MATI (Nesic and Teel, 2004a; Nesic and Teel, 2004b; Carnevale et al., 2007; Tabbara et al., 2007; Dacic and Nesic, 2007). In order to guarantee NCS stability, the Maximum Allowable Delay Bound (MADB) could also be found while the network scheduling approach to be used should have a sampling time within this MADB. This is done by using NCS scheduling approaches and the dynamic bandwidth allocation strategy. Studies that adopt the NCS scheduling approach include the Rate Monotonic Scheduling (RMS) and deadline monotonic scheduling algorithm employed by embedded systems researchers for parallel processing and multithreading. Brainky et al. (2003) improved on this and proposed that to guarantee stability of the NCS, it was better to drop certain percentage of the data packet of a fast sampling NCS if a set of NCSs could not be scheduled with a given time constraint within which every packet is guaranteed to be delivered. Others include the simple queue method, try-one-discard, Petri-net modeling to mention a few (Gupta and Chow, 2010).

For the case of Dynamic Bandwidth Allocation (DBA), this approach is used for networks supporting multimedia applications. Examples include VoIP, video traffic, and ATM networks. IP over optical network performance can be improved with DBA, depending on the reallocation paradigm and the network topology (Gannet et al., 2005). Another study in this regard is the distributed parameter estimation in wireless sensor networks (Li and AlRegib, 2007). Zhang et al. (2013) conducted a review on the NCS. The study revealed that due to scheduling of the packet transmissions as a result of multiple sensor nodes, it is difficult to ensure constant sampling in NCS. As a result, the time between two successive transmission/sampling could be said to be very uncertain and significantly large. According to the authors, this situation goes a long way to affect system stability (Wittenmark et al., 1995; Fridman et al., 2004).

Generally speaking, time-varying sampling instants can either be fixed or not fixed (Tipsuwan and Chow, 2003). For the not fixed cases, they might vary with respect to time, system state or controlled by supervisor which is external.

2.3.5.3 Network security

Any network is susceptible to interception. For the fact that NCS is used in hazardous environments such as nuclear reactor plants, space projects, nursing homes, military applications, it is expedient that adequate security is guaranteed. Dzung et al. (2005)

conducted a study based on an open communication system, The authors also provided an overview of Information Technology (IT) security in Industrial automation as well as possible counter measures. Today, Intrusion Detection Systems (IDS) are employed to aid security of Networks (Tsang and Kwong, 2005; Creery and Byres, 2005). The authors in (Xu et al., 2005) developed core architecture to address the collaborative control issues of distributed device networks under open and dynamic environments. Gupta and Chow (2008) developed a characterization of the WNCS application on the basis of security effect on NCS performance to show this trade-off for an NCS path-tracking application. In some cases, the problem of NCS could be approached from an Information Technology (IT) perspective in which the matter of security is approached from the Information Technology (IT) point of view.

2.3.5.4 Fault Tolerant Control

As a result of built in redundancy, failure rates increase. In order to prevent failure of the system, Fault Tolerant Control (FTC) implementation becomes necessary. Literatures reveal several studies that have been done to achieve FTC. Patankar, (2004) presented a model for fault tolerance in NCS using time-triggered protocol communication, Huo et al., (2005) studied scheduling and control co-design for robust FTC of NCS based on robust $H\infty$ FTC idea.

2.3.5.5 Component Integration

For the fact that NCS incorporates different independent modules, there is the need to find a method of integrating (coordinating) all these independent modules to form one distributed system. This means that apart from improving each independent module, the interface must be made efficient enough to achieve the goal of the NCS. Garcia et al. (2004) developed a highly integrated control and programming platform being used for integrated control of large production plant in energy and power management industries. Gupta et al. (2010) worked on a multi-sensory networked controlled integrated navigation system for multi-robots by examining the practical aspects of design and building of an NCS using the Internet as a communication medium.

2.3.5.6 Data quantization

Researchers vary in their view about quantization. In digital control, quantization is as a result of finite word length and quantization error (Astrom and Wittenmark, 1994). That is the truncation of some words caused by calculation in certain control algorithm as analog signals are being converted to digital format. Since in NCS, digital control is inevitable, the presence of quantization affects stability of the NCS. While some studies believe quantization is inevitable and should be ignored, others confirm its negative effects in NCS (Tipsuwan and Chow, 2003). Studies that have been done regarding quantization include: quantization with network delay (Fridman and Dambrine, 2009), quantization with packet losses (Tsumura et al., 2009; Ishido et al., 2011) quantization with packet loses and delay (Tian et al., 2008).

2.4 Network Delay and packet drop

There are two main drawbacks in networked control systems, namely network delays and packet losses. The packet drop in networked control system also leads to system performance degradation. Packet drop can be constant, time-varying, or random and they occur due to network unreliability. There are two main types of packet losses, network induced packet dropout and active packet dropout.

2.4.1 Network-induced packet dropouts and active packet dropouts

Network-induced packet dropouts occur due to unavoidable errors or losses in the transmission of packet because of network sharing and the presence of the uncertainties and noises in the communication channel (Li et al., 2007). Active packet drop arises when a set of NCSs is unschedulable, therefore packets are purposely dropped in order to stay within an allocated transmission rate, for the purpose of congestion control to ensure that the set of NCS is schedulable and the overall NCS stability is guaranteed (Zhang et al., 2001).

Zhang et al. (2001) grouped packet drop based on the online/offline information. In order words, the control algorithms were designed based on whether the packet loss was counted online or offline. Studies in which the offline framework was implemented include (Zhang et al., 2001; Yue et al., 2004; Gao and Chen, 2008; Wang et al., 2007; Elia and Eisenbeis, 2011). Studies that make use of the online approach include (Xiao et al., 2000; Lin and Antsaklis, 2005; Quevedo and Nesic, 2011). In this thesis, network time delays is investigated in detail using the offline approach with the aim of providing solution to the drawbacks associated with it during the real-time control implementation.

2.4.2 Time Delays

Time delayed systems are also referred to as systems with dead time or systems with after-effect. This phenomenon occurs when plant, controller and sensors are connected through a shared network (Cooper, 2014). Dead time in control systems is the time lag between the moment when a controller sends out a control signal and the moment when the measured process variable first begins to respond. (Cooper, 2014). It could also be the time lag between when the sensor sends its measured value to the controller for computation and the moment the sent value is used by the controller for computation. Leo (1994) considered a detection system that records discrete events and defined dead time as the time after each event during which the system is not able to record another event. Dead time in control systems can be larger or smaller than the sampling time. They pose great challenge on the performance of control systems especially when they are larger than the sampling time (Gupta and Chow, 2010).

2.4.3 Causes of deadtime in control systems

Time delays in the system appear due to sampling (measurement lag), sensor/actuator non-collocation (communication lag), and transportation lag (Tasdelen, and Ozbay, 2013; Poorani and Anand, 2013). Some of these causes are discussed below:

(i) Sample and hold – The presence of sample and hold loop in many control systems result in additional delay factor of one sampling time into each loop. The overall dead time (time delay) experienced by the system is increased (Cooper, 2014; Poorani and Anand, 2013)

(ii) At other times, there are control systems in which the plant and the controller are separated by wide geographical distance and as such, the control have to be performed remotely. The time it takes the controller to send control signals to the plant located several kilometres away might constitute dead-time in the control system (Cooper, 2014). In some cases, switching to a faster measuring device or even locating the sensor and control action closer to each other would be sufficient to eliminate dead-time. At other times, the dead time seems to be inherent in the control system and the only way to eliminate it is designing control strategies in form of a dead-time compensator such as the Smith predictor for the control system (Cooper, 2014).

(iii) In some process control schemes, the yielding time of measurement in sensor and analyser could lead to time delay that affect the performance of the system. In order to cope with extreme weather condition in harsh environment, a thermocouple might be shielded. If care is not taken, the shield around the thermocouple might make it less sensitive to the environmental temperature thereby creating delay in the detection of temperature changes in the fluid being measured (Cooper, 2014). Also the travel time that is the time it takes for materials to travel from one point to another in a control system can constitute time delay. For instance if the temperature of a fluid flowing in a pipe changes and the sensor is located at a distance, the new temperature would not be detected until the fluid reaches the sensor location. The time it takes to sense the new temperature is a form of dead-time (Cooper, 2014).

For Networked Control Systems, depending on the type of network used, the network can induce some delays which may be constant, time-varying or random depending on the network protocols used. In NCS there are three major delay types which contribute to the total delays in the closed loop system. They are the Sensor-to-controller delay (τ_{sc}) ,controller –to-actuator delay (τ_{ca}) and controller computational delay (τ_{cp}) (Lian et al., 2001).

Fundamental delays that occur on a Local Area Network (LAN) have several sources (Lian et al., 2001). These sources includes the waiting time delay τ^{w} which is a delay in which the main controller have to wait for queuing and network availability before sending the packet out. Frame time delay τ^{f} which is the time the controller takes to place a packet on the network, and the Propagation delay τ^{p} which is the time the packet takes to travel through the medium and it depends on the speed of signal transmission and the distance between the source and destination (Lian et al., 2001; Tipsuwan and Chow, 2003). This is illustrated in Figure 2.9 (Tipsuwan and Chow, 2003).

2.4.4 Network delays in the forward and feedback loop

Figure 2.8 shows network delays in the control loop, where r is the reference signal, u is the control signal, $u(KT-\tau_{ca})$ is the delayed controlled signal due to the network induced time delay in the forward path known as the controller to actuator delay (τ_{ca}), y is the output signal, $y(KT-\tau_{sc})$ is the delayed output signal as a result of the network induced time delay in the feedback path known sensor to controller delay (τ_{sc}), k is the time index and T is the sampling period. The timing diagram describing the system is shown in Figure 2.9.

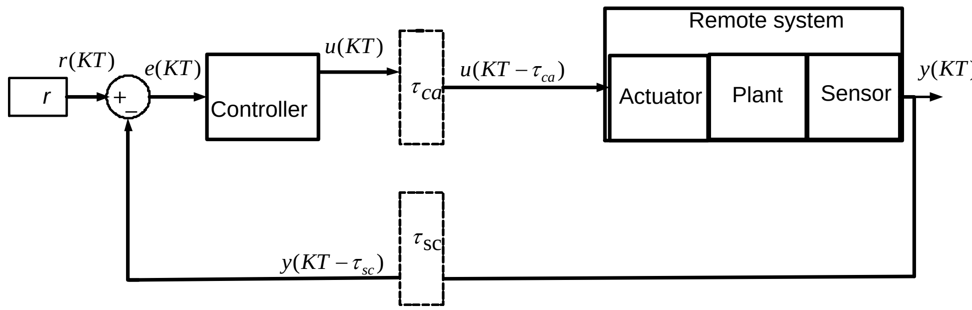

Figure 2.8: Networked delays in control loop of NCS (Tipsuwan and Chow, 2003)

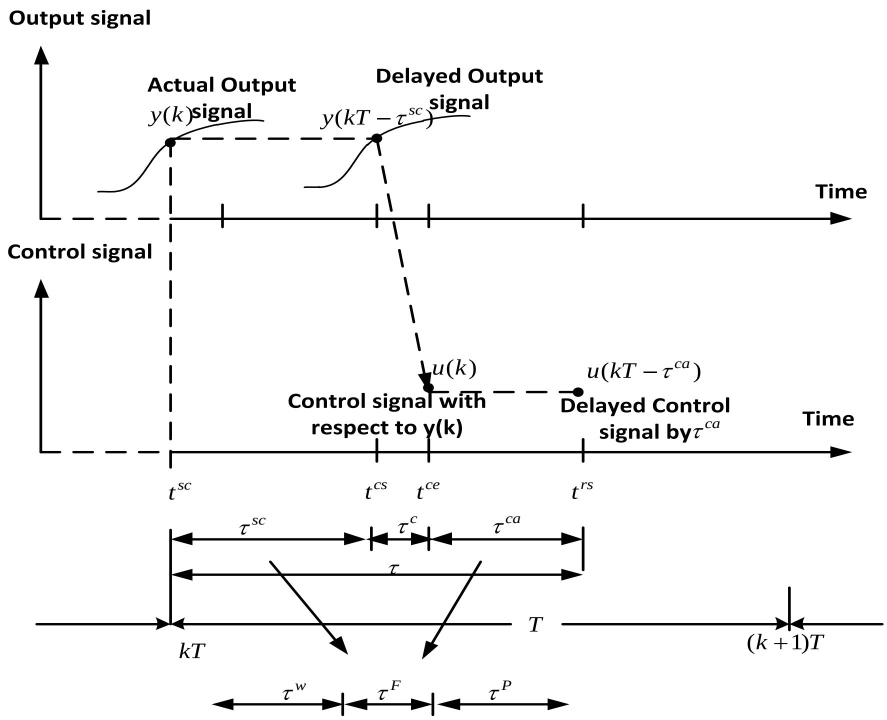

Figure 2.9: Network delay propagations Timing diagram in discrete time form (Tipsuwan and Chow, 2003)

2.4.5 Effects of network induced time delay

The effects of networked induced time delay in NCS can be grouped into two:

(i) Poor System response

(ii) Reduction in stability region

2.4.6 Poor system response

This is noticed in the longer settling time and higher overshoot experienced by the control systems in response to transient signals due to networked induced time delays in Figure 2.10 where the plant is $G_p(s)$ and $G_c(s)$ is the controller. τ_{ca} and τ_{sc} are the network induced time delays in the forward and feedback paths respectively. As the network delays increase from 0.0005 to 0.3135 seconds, rise in the system overshoot and longer settling time is experienced by the control system as seen in Figure 2.11 (Singh, 2012).

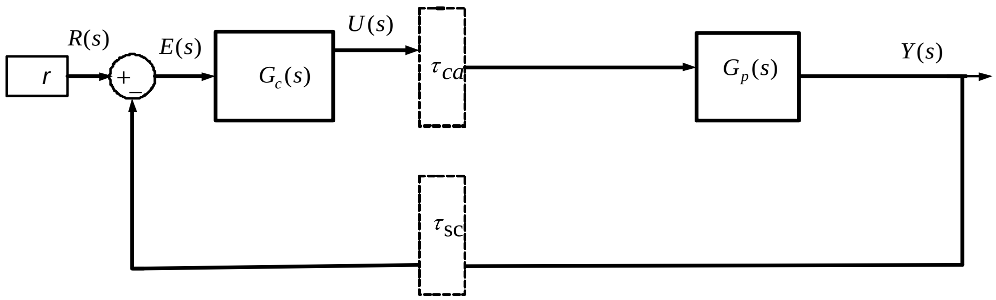

Figure 2.10: Closed loop system under network delays τ_{ca} and τ_{sc} (Singh, 2012)

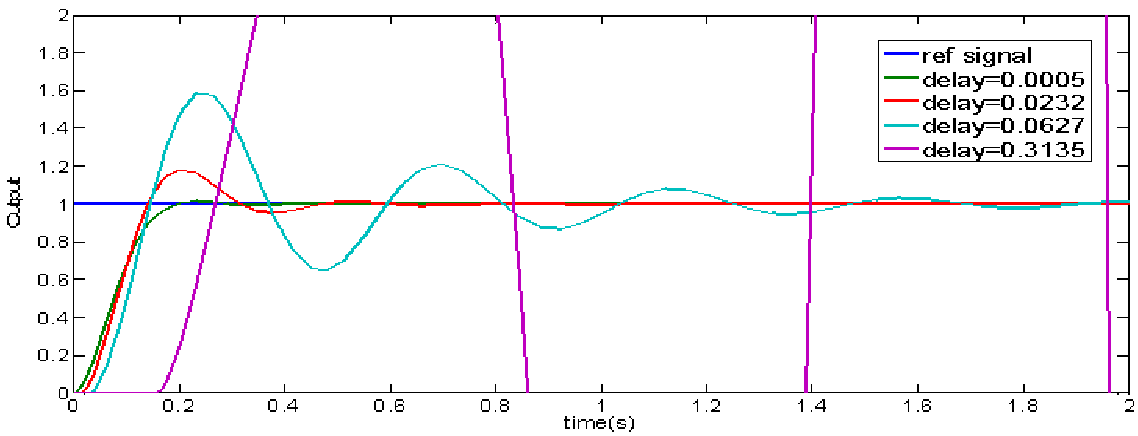

Figure 2.11: System step response due to the influence of network delays τ_{ca} and τ_{sc} (Singh, 2012)

2.4.7 Decreased stability margin

A reduction in the system stability margin or stability region is another effect of the network induced time delay. This can make the system unstable. The stability region or stability margin of a system may not be possibly determined by analytical method. In such cases, simulation is employed (Zhang et al., 2001). This is done by increasing the delay and testing the closed loop system matrix (Zhang et al., 2001).

2.4.8 Modelling of time delays

In order to minimize the effects of time delays on the performance of NCS, the time delays must be recognized, accurately modeled and then compensation methods must be applied (Gupta and Chow, 2010). Network induced time delays modeling was reported by Gupta and Chow (2010), as being measured by as Markov chain (Liu et al., 2012), Auto-Regressive Moving Average (ARMA) model (Li and Mills, 2001), Fractional Auto-Regressive Moving Average (FARIMA) model and so on. The Short-Range Dependent (SRD) and Long-Range Dependent (LRD) characteristics of Fractional Auto-Regressive Moving Average (FARIMA) model has made it to be preferred when high level of accuracy is required. Another is the fluid model (Filipiak, 1988). (Nilsson, 1998) modeled the delays as independent random delays with underlying Markov chain and used empirical approach to obtain the network induced time delays using a CAN as the protocol. Another approach used in literature is to model the TCP protocol using differential equation. (Lin and Chen, 2005) adopted this approach by developing a TCP model using fluid-flow and stochastic differential.

2.5 Control Design Methodologies in NCS

Generally speaking, control design methodologies can be divided into two broad groups depending on how recent it is namely:

(i) Conventional control - developed up to 1950

(ii) Modern control - concepts and techniques developed from 1950 to today

Conventional control relies on developing control system models using differential equations (DEs), however the system equation can be expressed in the frequency domain by Laplace transforms where it can be manipulated algebraically. On the realization that control system equations could be structured in a way that computers may understand and efficiently compute them, modern control methods emerged. It has been shown that any nth order differential equation describing a control system can be reduced to n first order differential equations. The set of first order equations can therefore be arranged in the form of matrix equations, this is known as the state variable method.

Due to network drawbacks, the control methodologies for networked control systems have to maintain controlling and maintaining system parameters as well as system stability as much as possible (Tipsuwan and Chow, 2003). Different methodologies are introduced to suite different network behaviours. Studies of networked control methodologies have highlighted existing methodologies suitable for designing controllers and they are as follows:

(i) Queuing methodology
(ii) Augmented deterministic discrete-time model methodology
(iii) Optimal stochastic control methodology
(iv) Perturbation methodology
(v) Sampling time scheduling methodology
(vi) Robust control methodology
(vii) Fuzzy-logic modulation methodology
(viii) End-user control adaptation methodology
(ix) Event-based methodology
(x) Networked Predictive Control

Each of them shall be considered briefly.

The recent control design methodologies for networked control are reviewed. Despite the methodology chosen, the objective is to control the NCS so that stability is guaranteed while providing good performance for the closed-loop control system. The basic concepts of the control algorithms are presented here.

The main purpose of any methodology in NCS is to maintain system performance while also stabilizing the system. To apply these methodologies, there are some assumptions that are made. They include:

(i) There exist an error-free network transmission
(ii) Overloading of network traffic is not possible
(iii) Difference between the sensor and controller sampling time called the skew time is constant
(iv) Computational delay τ^c is smaller and much smaller than sampling period T
(v) Every dimension of output measurement or control signal can be packed into one single frame or data message (Tipsuwan and Chow, 2003).

2.5.1 The augmented deterministic discrete-time model methodology

This is based on discrete-time state space models. The controller uses past measurement to calculate the control signal at time k. The network delays are handled by augmenting the delays into the full system state model, and the stability for periodic delays is proven based on the eigenvalues of the augmented system state transition matrix (Halevi and Ray, 1988), (Raju, 2009).

2.5.2 Queuing methodology

The queuing methodology uses observers and predictors to compensate for the time delays and hence make the NCS time-invariant (Luck and Ray, 1990a,1994b). The observer is to estimate the plant states and the predictor is to compute the predictive control based on past output measurements. Using this method, random (non-deterministic) network delays can be converted to deterministic delays. Since both the observer and the predictor are model-based, the performance of the system highly depends on model accuracy.

2.5.3 Optimal stochastic control methodology

Nilsson (1998) proposed an optimal stochastic control methodology for NCS (Nilsson, 1998). The basic idea of this approach is to formulate the NCS problem as a LQG problem. The system dynamics are given in state-space and the optimal controller gain is solved from the formulated LQG problem using dynamic programming. Solving the problem requires past delay and full state information of the control system, and for the latter, the Kaman filter may be applied. In his work, the time delay was assumed to be random, but less than one sample interval. Later, delays that are longer than one sample interval were considered using the optimal control methodology.

2.5.4 Perturbation methodology

In perturbation methodology, the difference between the current plant output values and the most recently transmitted plant output values are considered as perturbation to the system (Walsh et al., 1999). The main focus is to find a model that eliminates the system error. The stability is proven using the Lyapunov approach on the dynamics of the error with several assumptions for instance error free communications, fast sampling and noiseless observations (Raju, 2009).

2.5.5 Sampling time scheduling methodology

The Sampling time scheduling methodology can be used for determining the sensor sample times of NCS based on the delay sensitivity of each control loop in the network (Hong, 1995). The first procedure is to analyse sensitivity of the delay using general frequency domain analysis on the worst-case delay bound. Under certain conditions, this methodology leads to optimal network utilization. (Kim, Kwon, and Park 1996, 1998) improved on this methodology by developing a new algorithm for multidimensional NCS.

2.5.6 Robust control methodology

Robust control methodology is a situation in which the network-induced time delays are treated as perturbations to the nominal system, after which control design is performed in the frequency domain using robust control theory (Goktas, 2000; Tipsuwan and Chow, 2003). Both the sensor to controller delay (τ_{ca}) and the controller to actuator delay (τ_{sc}) are assumed to be bounded and able to be approximated by different models such as the fluidflow model (Filipiak, 1988), Markov chain (Liu and Yao, 2005), Auto-Regressive Moving Average (ARMA) model (Li and Mills, 2001) to mention a few.

2.5.7 Fuzzy-logic modulation methodology

The Fuzzy-logic modulation methodology (Almutairi et al., 2001) takes an advantage of fuzzy- logic to update the controller gains based on the error signal between the reference and the actual output of the system and the output of the controller. The fuzzy-logic modulation methodology includes online and offline membership function design by optimization (Raju, 2009).

2.5.8 End-user control adaptation methodology

In the End-user control adaptation methodology (Tipsuwan and Chow, 2001), the controller parameters are adapted to measure the traffic conditions of the network. The controller parameters are adjusted to aim for the best possible system performance and to obtain the desired Quality of Service (QoS) requirements of the system.

2.5.9 Event-based methodology

In event-based methodology (Tarn and Xi, 1998), the system motion is used as the reference of the system instead of time. In other words, the time space is mapped into event space such that system stability no longer depends on time. In this way, the network-induced time delays will not destabilise the system.

2.5.10 Network Predictive Control

The Networked Predictive Control (NPC) consists of two main parts: the control prediction generator (CPG) and the Network Delay Compensator (NDC). The former is designed to generate a set of future control predictions. The latter is used to compensate for the unknown random network delays. In this way, it is able to compensate for networked time delays that make the NCS unstable and degrade the system performance (Liu *et al*., 2004, 2005).

The authors in Munoz de la Pena, and Christofides (2007), developed a Lyapunov-based Model Predictive Controller (LMPC) in order to regulate the state of a nonlinear system towards the equilibrium. The LMPC differs from previous model predictive controller in that it takes into account data loses in the formulation of the optimization problem and the implementation of the controller. The LMPC was first investigated with the closed loop applied in a sample and hold fashion in the absence of data loses. Afterwards, the LMPC was also investigation in the presence of data loses. When data loses occur, the LMPC updates the input based on the prediction obtained using the model. This was tested with the worst case scenario and it was found that the system trajectory was guaranteed to remain within the stability region, which means that any delay less that this worst case delay will be stable. In Munoz de la Pena, and Christofides (2008), the authors improved on the study by carrying out an explicit characterisation of the stability region. This study guarantees that the stability region is an invariant set for the closed loop system under data loses. This study was meant to benefit wireless network control systems and the nonlinear systems control under asynchronous measurement sampling. A chemical process example was carried out to validate the effectiveness of the proposed scheme.

In Liu et al. (2010), two-tier control architecture was proposed for nonlinear systems. This is a hybrid system comprising of an upper-tier with a wired link (point-to-point) and a lower-tier with a wireless communication meant to perform multiple measurements such as temperature and concentration in chemical processes. In an attempt to mitigate the data loses in the upper-tier due to wireless communication, a Lyapunov-based Model Predictive Control was proposed. The system therefore benefits from the point-to-point connection of the lower-tier which ensures system stability and the upper-tier improves the closed loop performance of the system. A theoretical result with a chemical process reveals faster system response with lower operational cost.

In summary, the augmented deterministic discrete-time model methodology is used to apply to a linear plant with a periodic network time delay (Halevi and Ray, 1988). The queuing method uses queuing mechanisms to convert a time-varying (random) network delay to time-invariant (deterministic) delay by reshaping random network delays using queuing mechanism (Luck and Ray, 1990;1994). The optimal stochastic theory treats random delay effects in NCS as a Linear Quadratic Gaussian (LQG) problem (Nilsson, 1998).

The sampling time scheduling method (Hong, 1995) is able to guarantee the stability and performance of NCS by appropriate selection of the sampling period. The robust control method, uses robust control theory (Goktas, 2000) to designed a networked controller in the frequency domain and such that *a* prior information about the probability distribution of network delays is not required. Perturbation methodology (Walsh et al., 1999) uses the difference between the current plant output values and the most recently transmitted plant output values to acts as a perturbation to the system and searches for limits to this error.

The fuzzy logic methodology uses a PI controller to compensate networked induced delay by taking advantage of fuzzy logic to update the controller gains based on the error signal between the reference and the actual output of the system, and the output of the controller. The end-user control adaptation methodology (Tipsuwan and Cho, 2001), seeks the ability to measure the traffic conditions or quality of service of the network, and the controller parameters for example controller gains are adapted accordingly. Event-based methodology (Tarn and Xi, 1998) uses motion as the reference of the system instead of time.

2.5.11 Discussion of control methodologies in NCS

According to Tipsuwan and Chow (2003), for the control methodologies described above, not all control methodologies can be applied to all situations because of their different capabilities in handling communication drawbacks. For example, when it comes to linear systems, all the methodologies described above work well but for nonlinear systems, perturbation methodology, robust methodology and event based methodology have been successful.

It could be observed that the work of (Tipsuwan and Chow, 2003) covered the NCS control methodologies up to 2003. Hesphanha et al. (2007) reported the advancement in NCS between 2003 and 2007. The authors improved on the networked Control methodologies by using the Delayed Differential Equations (DDEs) to model NCS. Two Marchov chain modeling approaches were also used by Zhang et al. (2005) and Yang (2006) to model the forward and feedback paths of the NCS.

Zhang et al. (2013) in their study grouped the control methodologies employed in addressing the problem of time delays in NCS into the robust framework and the adaptive frame work. These two frameworks are further discussed as follows:

(i) The robust framework

Robust framework is simple in design but conservative because it does not utilise the time delay information such as time delay size as well as other special features of NCS to control the system. These NCS features include time-stamp, data transmitted in packets and the actuator capability of making intelligent selection.

(ii) Adaptive Framework

The adaptive framework makes use of these special features of NCS to take intelligent decisions such as the time-stamp techniques, data transmitted in packets and the size of delay information. Under the adaptive framework, there are two approaches. The first involves modelling the NCS as a nondeterministic or stochastic system. Then using the size of time delay, the system is able to choose suitable control algorithms. The second approach is the predictive approach. In this case, the system sends a finite number of future control commands to the actuator. The actuator then makes an intelligent selection of the appropriate one depending on the size of time delay (Zhang et al., 2013).

Another approach that is used in literature to handle time delays especially in process control is the Smith predictor compensation scheme (Smith, 1957). It has been used to provide robustness for systems with constant delays (Tasdelen and Ozbay, 2013) as well as time-varying delays (Velagic, 2008, Dang et al., 2012) with appreciable success. In order to eliminate time delays in this study, all the possible delays in the system ($\tau_{ca}, \tau_{sc}, \tau_{tot}$) are considered in designing the controller such that the designed controller is robust over time-varying delays.

2.6 The Smith predictor

The Smith predictor is a control strategy designed by O.J.M. Smith in 1957 (Smith, 1957). It is a form of predictive control to mitigate the challenges of dead-time in a control system. It is found to be the best and most implemented dead-time compensator scheme (Smith, 1957, Smith, 1985, Kuzu and Songuler, 2012) employed to stabilise control systems. Dead time in control systems is the time lag between the moment when a controller sends out a control signal and the moment when the measured process variable first begins to respond (Cooper, 2014). Cconsidering a detection systems that records discrete events, deadtime could be defined as the time after each event during which the system is not able to record another event. Dead time in control systems can be larger or smaller than the sampling time. They pose great challenges to the performance of control systems especially when they are larger than the sampling time (Gupta and Chow, 2010).

As mentioned in section 2.4.1, time delays in the system appear due to sampling (measurement lag), sensor/actuator non-collocation (communication lag), and transportation lag (Tasdelen, and Ozbay, 2013, Poorani and Anand, 2013). Smith predictor compensation scheme had been applied in different areas including telecommunication (Lee et al., 2004; Mascolo, 1999), biological systems, and flexible-link robot manipulator (Chen et al., 1997).

2.6.1 Types of Smith predictors

Sourdille and O'Dwyer (2003) reported three types of modified Smith predictor structures that may be identified for stable processes. They are:

(i) Disturbance rejection improvement structures,
(ii) Two degrees of freedom structures and
(iii) Other structures

2.6.2 Disturbance rejection improvement structures

In this group, the purpose is to eliminate dead time using a fast disturbance rejection structure. For instance in the work of Hang and Wong (1979), the dead time was eliminated from the closed loop control because the authors interchanged the model dead time and the process model. This disturbance rejection strategy is achieved in different ways. They include the use of dynamic compensator in the feedback loop (Watanabe et al.,1983) and the use of filter to obtain pole-zero cancellation, (Romagnoli *et al.,*1988). Ramirez-Neria et al, (2013) modelled the nonlinearity in the system as a disturbance function and used a Generalised Proportional Integral (GPI) observer that estimated the lumped disturbance in the system and a truncated Taylors series to reduce the control to simple linear control. Another example of disturbance rejection improvement structure is (Huang et *al,.* 1990) which included a compensator between the main feedback loop and the minor feedback loop.

2.6.3 The two degrees of freedom

This structure decouples the plant and regulator such that separate designs are done for each response. Examples include the double controller structure (Tian and Gao, 1998a, 1998b, 1999a. In Kuzu and Songuler (2012), the Astrom's Smith predictor decouples the disturbance response from the set point response and hence can be independently optimized. With this structure, the designer is freer to choose the transfer function.

2.6.4 Other structures

In this group, the Smith predictors objectives are not clearly defined or they might be used for other functions. As a result, it is difficult to classify then into either of the first two classifications. An example is Kantor and Andres (1980).

2.6.5 Merits of the Smith predictor

The advantages of the Smith predictor include the fact that it can be easily extended from a single input-single output system to a multiple-input multiple-output system (Sourdille and O'Dwyer, 2003). Another advantage is that Smith predictor removes the dead time from the dynamics of the loop, making possible to operate the loop at higher gains (Smith, 1957). This is done by eliminating the dead time from the characteristic equation of the closed-loop system (Moreno et al., 2012, Kuzu and Songuler, 2012).

2.6.6 Demerits of the Smith predictor

Despite the merits listed above, the Smith predictor disadvantage is due to the fact that it is a model based scheme and as such the precise model of the plant is required at each instant to give best performance. At other times, we have non-modelled dynamics of the system or other forms of disturbances in the control system. So the traditional Smith predictor is said to have poor disturbance rejection capability especially in the presence of time varying disturbances. As a result, external disturbance and internal unknown dynamics have to be compensated for in order to obtain a satisfactory performance (Kuzu and Songuler, 2012, Tasdelen and Ozbay, 2013).

2.6.7 Review of the Smith predictor compensation scheme

Over the years, Smith predictor had undergone series of improvements since when it was first introduced. This brought about different types of modified Smith predictors. Some of these improvements are outlined in Table 2.3.

Table 2.3: An Overview of the Smith Predictor research trends

Paper	Description	Model type	Delay type	Delay measurement method	Uniqueness of method	Demerit of method	Hardware/ Software	Real-life/Lab. Implementation
(Sourdille and O'Dwyer, 2003)	Generalised Smith predictor was formed from combination of two different modified Smith predictors. Better results were obtained when compared to original Smith predictor	Linear	Constant	None	Excellent servo response resulted from the first modified Smith predictor while the second modified Smith predictor show excellent regulator response	None	Software: MATLAB /Simulink	None
(Rao and Chidambaram, 2005)	In this study three controllers were used in order to control processes with time delay. The first and second were incorporated for the servo plant and regulator respective while the third was for better disturbance rejection. For better robustness, a first order filter was also added	Linear	Constant	None	Enhanced Smith predictor using three controllers and a filter.	None	Software: MATLAB /Simulink	None
(Velagic, 2008)	To deal with random delay, a predictive networked controller with adaptation loop is designed and developed. Adaptation loop is to reduce time delay effect on the control system. For better robustness, a filter is also included.	Linear	Random	None	Adaptation loop reduces the effect of time delay on the system while filter is for robustness	None	Software: MATLAB /Simulink	None
(Galvez et al., 2007)	A Smith predictor is added to the Nonlinear Extended Prediction Self-Adapting Control (NEPSAC) - a form of NMPC to control a Solar Power plant	Nonlinear	Random	None	DTC is added to NMPC to produce a Smith predictor based NEPSAC. Random delays and nonlinear dynamics were successfully controlled	None	Software: MATLAB /Simulink	Implementation on the
(Du Feng and Zhi, 2009)	To eliminate random delay in NCS, Smith predictor is combined with nonlinear PID . Simulations carried out on CAN show the effectiveness of the control scheme.	Nonlinear	Random	True-Time on CAN	Online identification or estimation of time delay is not needed because the predictor models of the network delays are hid into real network data transmission processes. Mathematical model of the plant is not necessary for control.	None	Software: True-Time	None

Paper	Description	Model type	Delay type	Delay measurement method	Uniqueness of method	Demerit of method	Hardware/ Software	Real-life/Lab. Implementation
(Du and Du, 2009)	To eliminate random delay in NCS, new Smith predictor is combined with adaptive PID . Simulations carried out on CAN show the effectiveness of the control scheme.	Linear	Random	True-Time on Ethernet	Online identification or estimation of time delay is not needed because the predictor models of the network delays are hid into real network data transmission processes. Mathematical model of the plant is not necessary for control.	None	Software: True-Time	None
(Puawade et al., 2010)	Temperature control of an oven was done using Smith predictor is developed by Coefficient Diagram Method Simulations. The robustness and stability the scheme are shown	Linear	constant	None	This method represents the system in form of polynomials. The poles of the closed loop transfer function are arranged to obtain desired response in time domain.	None	Software: MATLAB /Simulink	Yes
(Hwang, 2011)	In order to control a decentralized nonlinear interconnected discrete dynamic systems with large delay using fuzzy mixed H_2/H_∞ optimization, a discrete Smith predictor was developed. Results show large nominal time	Nonlinear	Random	None	In this paper, a two degree-of freedom (H_2/H_∞) optimization technique with discrete Smith predictor was employed to control each PTFDS.	None	Software: MATLAB /Simulink	Yes
(Dang et al., 2012)	Random Variable Time Delay (RVTD) is compensated in NCS. The new scheme combining NN estimation with Smith predictor is adaptable, stable and has fast response.	Linear	Random	True-Time2.0 Beta based on CSMA/AMP	NN online- estimation is combined with Smith predictor for time delay compensation in NCS	None	Software: True-Time 2.0 Beta	None
(Bolea et al., 2014)	A gain scheduled Smith PID controller was proposed for open flow canal control. This was meant to deal with large variations in operating conditions of the canal	Nonlinear	None	None	Combining $H\infty$ and pole placement methods, LPV (linear parameter varying) PID controller was designed using LMI regions for the open-flow canal control	None	Software: MATLAB /Simulink	Yes
(Poorani and Anand, 2013)	Heat exchanger is to be maintained at a desired temperature. PID controller failed to control the plant due to time delay so a Smith predictor compensation is used. Simulation result shows that Smith predictor has better performance over PID	Nonlinear Linearisation is not mentioned	None	None	Does not involve much computation Smith predictor performs better than PID controller	Smith predictor is a model based controllerand sensitive to modelling errors.	Software: MATLAB/Simulink	Yes

Paper	Description	Model type	Delay type	Delay measurement method	Uniqueness of method	Demerit of method	Hardware/ Software	Real-life/Lab. Implementation
(Ding and Fang, 2013)	The problem of pure time delay in the feedback path which couldn't be solved using the traditional Smith predictor was considered. Smith predictor has improved by optimizing the inner structure of the scheme to solve the problem of pure time delay in the feedback path		None	None	To model the control system, tests were performed on the equipment and data was obtained. LSM and Ziger-Nicolas were used to fit the data in order to model the plant and controller design respectively	None	Software: MATLAB/Simulink	None
(Ben Atia and Ltaief, 2013)	Varying parameters and time delay makes the adaptive Smith predictor inefficient. Multimodel approach was proposed as a solution to surmount this problem and provide satisfactory results.	Not mentioned	None	None	Online estimation of plant and time delay were carried out using RLS and variable regression respectively. Local controllers based on Smith Predictors were used to generate control laws for corresponding operating zones. These were in turn fussed to provide effective control.	None	Software: MATLAB/Simulink	None
(Veeramachaneni et al., 2013)	The robustness of a PID controller with Smith predictor was investigated in the presence of model uncertainty. Smith predictor based controller was found to increase the stability region of the system.	Not mentioned	None	None	A design method was proposed for finding all robustly stable PID controllers when a Smith predictor is used. Regions of stability were shown in frequency and time domain	None	Software: MATLAB/Simulink	None
(Ramirez-Neira et al., 2013)	A class of disturbed nonlinear system with time delay was considered. Generalised PI (GPI) observer is used to estimate the lumped disturbance in the system. An approximation of predictive disturbance was then carried out using a truncated Taylor series to reduce the control task to a simple linear control. Then a Smith predictor could then be applied.	Nonlinear	None	None	Disturbance and nonlinearity in the plant was modelled into a disturbance function. Time delay in the system was compensated by using a GPI observer with truncated Taylors series expansion. This was to estimate the lumped disturbance prediction. The system was then linear and then a Smith predictor could be applied.	None	Software: MATLAB/Simulink	None

Paper	Description	Model type	Delay type	Delay measurement method	Uniqueness of method	Demerit of method	Hardware/ Software	Real-life/Lab. Implementation
(Moreno et al., 2012)	The Filtered Smith Predictor (FSP) was improved to handle nonlinear situations using Clegg Integrator (CI). A nonlinear PI controller PI+CI was added FSP to introduce nonlinear behaviour. A combined PI+CI+FSP produced satisfactory result	Nonlinear	None	None	PI+CI provide nonlinearity while FSP provides robustness	FSP is only limited to linear systems	Software: MATLAB /Simulink	None
(Teng and yamashita, 2011)	To handle random delay, Smith predictors for linear time-variant systems in the state space is developed	Nonlinear	Random	None	Ordinary differential equation (ODE) was used to obtain the predicted future state to make the closed loop nonlinear system stable.	None	Software: MATLAB /Simulink	None
(Tanaka et al., 2013)	In order to improve the control performance of power generation in a low-cost fly wheel, Smith predictor based compensation scheme was used	Linear	Constant	None	Power fluctuation was reduced by 84.6% when Smith predictor was used to eliminate dead time in the control system	None	Software: MATLAB /Simulink	None
(Tasdelen and Ozbay, 2013)	A new Smith predictor based controller was proposed for systems with integral action and flexible modes under input output time-delay	Linear	Constant	None	Disturbance attenuation property was improved, with respect to periodic disturbances at a known frequency	None	Software: MATLAB /Simulink	None
(Kuku and Songuler, 2012)	Grey predictor and fuzzy PI controller were combined to form a modified Smith predictor. This was proposed for processes with short delay. Simulation reveal that the proposed scheme reduces disturbance	Linear	Constant	None	Fuzzy structure helps to reduce uncertainties caused by predictor such that disturbance frequencies do not have to be estimated	None	Software: MATLAB /Simulink	None
(De Cicco et al., 2014)	In order to solve congestion control problem over the Internet, a congestion control algorithm is developed using the geometric approach. This method is used to quantify the trade-off between disturbance rejection and robustness	Not mentioned	Random	None	The trade-off between robustness and disturbance rejection is quantified in respect of uncertain delay in the modified Smith predictor is determined using the Geometric approach.	None	Software: MATLAB /Simulink	None
(krejci et al., 2014)	Three approaches of mechatronic control were considered namely: Classic cascade control scheme, Smith predictor and the communication disturbance observer scheme. A state space novel structure is proposed	Linear	Not mentioned	None	State space novel method out-performed the other methods in compensation of input disturbance of systems in response time		Software: MATLAB /Simulink	None

Paper	Description	Model type	Delay type	Delay measurement method	Uniqueness of method	Demerit of method	Hardware/ Software	Real-life/Lab. Implementation
(Veeramachaneni and Watkins, 2014)	A graphical method of determining all the stability PID controllers that stabilise the closed loop system and satisfy a robust performance constraint is developed	Linear	Not mentioned	none	A graphical approach of determining stability is developed	None	Software: MATLAB /Simulink	None
(Goto et al., 2014)	The problem of undesirable rotation of isolated table in the control of Anti-Vibration Apparatus (AVA), a two degrees of freedom Smith predictor is developed	Linear	Random	none	Angular over-shoot is reduced by this method	None	Software: MATLAB /Simulink	Real-life implementation pneumatic AVA
(Gurban and Andreescu, 2014)	Two approaches namely: 1) Modified Smith Predictor 2) PID controller tuned by Genetic Algorithm (GA) The latter is found to be a useful tool for PID tuning with suboptimal result.	Nonlinear	Not mentioned	none	Feedback-feed forward approach was used	None	Software: MATLAB /Simulink	None
(Roca et al., 2009)	Feedback linearization +GPC) +FSP are used to control a nonlinear plant	Nonlinear	Random	none	Feedback linearization +GPC) are used to achieve robustness	None	Software: MATLAB /Simulink	Real-life implementation solar plant
(Roca et al., 2014)	Feedback linearization +GPC) +FSP are used to control a nonlinear plant	Nonlinear	Random	none	Instead of the linear nominal model of the plant, nonlinear plant model is used to design the Smith predictor	None	Software: MATLAB /Simulink	Real-life implementation solar plant

2.6.8 Analysis and discussions on the findings of the literature review

The traditional Smith predictor structure is designed to handle delays in the forward path but inadequate when it comes to delay in the feedback path. Over time, there had been several improvements. Smith predictor had been successfully used to eliminate dead time in linear and nonlinear systems, it has also been used successfully in the case of deterministic and nondeterministic systems. Some of these include:

2.6.9 Smith predictor compensation scheme with linear control systems

The work of Puawade et al. (2010) is concerned with a temperature control system during which a Coefficient Diagram Method (CDM) was used to design a Smith predictor. In this method, the system was represented by polynomials where a closed loop transfer function was arranged to obtain the desired system response. Dang et al. (2012) added a Smith predictor to a neural network to achieve adaptable, stable and fast response. Neural network here was used for online estimation of Randomly Varying Time Delay (RVTD) while Smith predictor was used to eliminate dead time in the control system. The problem of pure time delay in the feedback which is not addressed by the traditional Smith predictor (Smith, 1957) was addressed by Ding and Fang (2013). To solve this problem, the inner structure of the Smith predictor was optimised. Tests were performed on the system and the data obtained were fitted using the Least Square Method (LSM) and Ziger-Nicholas in order to model the plant. Predictive networked controller with adaptation loop was designed in (Velagic, 2008). The work of the adaptation loop in this study was to reduce the effect of random delays on the NCS. Simulation results showed the effectiveness of this method in handling random time delays. An improvement of the adaptation approach is the multimode approach. The Smith predictor with adaptation is not able to cope in the presence of high variation of time delays. In an effort to solve this problem, a multimode approach was proposed by Ben Atia and Ltaief (2013). In this approach, local controllers were used to generate corresponding operating laws for different zones which were later fused together for effective performance of the scheme. This approach involved online plant estimation of time delay.

In some cases, existing Smith predictor was combined to achieve better control performance. For instance, a generalized form of the Smith predictor was formed from existing modified Smith predictors (Sourdille and O'Dwyer, 2003) while three controllers and a filter were combined to form an enhanced Smith predictor by Rao and Chidambaram (2005). The work of the first controller was used to control the servo plant, the second controller was used for regulation while the third controller was added for disturbance rejection. The filter was to improve robustness of the control system.

The problem of periodic disturbance rejection was considered in the work of Kuzu and Songuler (2012) where a novel Smith predictor hybrid scheme was developed. In this scheme, in order to handle short time delays, the Smith predictor was combined with a disturbance rejection scheme. This rejection scheme was a combination of fuzzy PI controller and grey predictor. In this scheme, there was no need to estimate the frequency of disturbance while the fuzzy structure assisted in reducing uncertainties. Drawback of this approach was the modelling errors which can be eliminated by adding a Filtered Smith Predictor (FSP) to remove oscillations and to obtain robustness. In an attempt to overcome the poor disturbance rejection in Smith predictor, the following have been proposed in literature:

(i) Modified Smith predictors (Watanabe and Ito, 1981, Astrom et al.,1994, Matausek and Micic, 1999).

(ii) The Internal Model Control (IMC) (Stojic et al., 2001, Tasdelen and Ozbay , 2013)

The IMC representation of a Smith predictor configuration is a means of achieving rejection for a constant disturbance. The effectiveness of the Smith Predictor depends on the precise knowledge of the system plant, then, in some cases, the response may not be acceptable when non-modelled dynamics or disturbances are arisen. Thus, to achieve a good tracking result in presence of such effects, an additional problem of compensating external disturbance and internal unknown dynamics for complex systems must be incorporated in the control task, which for this class of systems is still a challenging control problem. Tasdelen and Ozbay (2013) solved the problem by developing a controller with an observer based output feedback having the following features:

(i) A linear Extended Luenberger-Like Observer which was to produce a lumped disturbance function by estimating the nonlinearities, nonmodeled dynamics, external disturbance inputs and state dependent perturbations.

(ii) A linear observer-based state feedback controller to stabilise the plant and achieve proper trajectory tracking.

(iii) A classical Smith Predictor control scheme. The plant being simple and now linear, the Smith predictor control scheme could then be applied. This was because the original nonlinear delayed plant had been reduced to a simple linear delayed plant by the use of disturbance observer that had the ability to predict lumped disturbances. A Smith predictor scheme could now be applied (Ramirez-Neria, et al., 2013).

To solve the input disturbance problem, three approaches of mechatronic control were considered by krejci et al. (2014) which is the classic cascade control scheme, Smith predictor and the communication disturbance observer scheme. The authors developed a state space novel method which was found to out-performed the other methods in compensation of input disturbance of systems in response time. In the study by Siva et al. (2014), a graphical method of determining all stability PID controllers that stabilise the closed loop system and satisfy a robust performance constraint was developed. A two degree of freedom Smith predictor was developed to correct the unwanted rotation of isolated table in the anti-vibration apparatus control (Goto et al., 2014). The reduction in angular over-shoot reveals the effectiveness of this approach in overcoming random delays. Many of the linear controls are performed using the transfer function method for desiging the Smith predictor (Ding and Fang, 2013; Tanaka et al., 2013).

2.6.10 Smith predictor with Nonlinear systems

Nonlinear systems are more difficult to control than the linear systems. Several methods have been applied in literature to solve the problem of time delays in nonlinear systems by applying the Smith predictor compensation scheme. In some cases, the nonlinear system is converted to a linear form (linearized) after which the Smith predictor is applied to eliminate dead time in the control system. In some other cases, a nonlinear controller for instance a nonlinear PID controller is designed for the nonlinear system after which a Smith predictor is then applied to eliminate the dead time in the nonlinear system.

In the study conducted by Galvez et al. (2007), a nonlinear solar plant under random time delays was to be controlled; the authors first designed a Nonlinear Model Predictive Controller (NMPC) for the solar plant to which a dead time compensation in the form of a Smith predictor was added. This arrangement was regarded as the Nonlinear Extended Prediction Self-Adapting Control (NEPSAC). The NMPC was used to handle the nonlinearity of the system under random time delays influence while the Smith predictor helped to eliminate the dead time in the control system.

In another study, the influence of random time delays on NCS was solved by adding a Smith predictor to a nonlinear PID (NPID) controller (Du Feng and Zhi, 2009). NPID was to address the effect of nonlinearity on the nonlinear system while Smith predictor removes the network time delays. Here, the predictor models of network time delays were hidden in the real network data transmission process. There was therefore no need to have a mathematical model of the plant for the purpose of controller design. A two degree-of-freedom optimization technique was implemented by Hwang (2011) using H_2/H_∞ optimization added to a discrete Smith predictor. This was employed to control nonlinear interconnected discrete dynamic system under the influence of random time delay.

Bolea et al. (2014) attempted to control an open flow canal. In this study a Smith Linear Parameter Varying (LPV) PID controller was proposed to deal with large time delays in the system. This was a form of gain scheduling control for the open flow canal which was a nonlinear system. The design of the PID was done using the pole placement and H_∞ methods.

The authors in Poorani and Anand (2013) failed in their attempt to control a nonlinear heat exchanger by using a PID controller due to influence of time delay. The nonlinear heat exchanger control was successfully achieved using the Smith predictor compensation scheme. Simulation results revealed the superiority of the Smith predictor over PID control.

A nonlinear system with disturbance was converted to a simple linear system to which a Smith predictor was applied to remove time delays in the work of Ramirez-Neria et al. (2013). Disturbance and nonlinearity in the system were modelled as a disturbance function. This was done using a Generalised Proportional Integral (GPI) observer that estimated the lumped disturbance in the system. A truncated Taylors series in used to reduce the control to a simple linear control.

The Filtered Smith Predictor (FSP) was improved to handle nonlinear cases using a Clegg Integrator (CI) (Moreno et al., 2012). In this study, a Proportional Integral (PI) controller added to a Clegg Integrator was used to introduce a nonlinear behaviour into the control system while the presence of FSP was to improve robustness. This nonlinear behaviour had to be introduced because the FSP in its linear form was only suitable for linear systems. These linear systems however might not be able to cope with fast rise times and small overshoots when both are required at the same time. Therefore, PI+CI+FSP was successfully used to control the nonlinear system with dead time.

Teng and Yamashita (2010) used Ordinary Differential Equation (ODE) to generate a set of future control predictions in order to achieve the desired control performance in a closed loop system. This was successfully used to control nonlinear system under random time delays. Gurban and Andreescu, (2014) compared the modified Smith Predictor and the PID controller tuned by Genetic Algorithm (GA) .The generic algorithm tuned PID controller is found to produce suboptimal result. In this approach the nonlinearity of the plant was addressed using a feedback-feed forward method.

In other to control a solar collector field which is a constrained nonlinear plant, a feedback linearisation scheme was developed (Roca et al., 2009). Feedback linearization combined with Generalised Predictive Control (GPC) and the Filltered Smith Predictor (FSP) were used in the design. Feedback linearization helps to simplify the dynamics of the nonlinear system to that of a linear one through algebraic transformation; GPC is to provide control stability while the FSP is meant to provide robustness in the presence of deadtime in the system. Roca et al. (2014) improved on the work of (Roca et al., 2009) such that iinstead of the linear nominal model of the plant, nonlinear plant model is used to design the Smith predictor. Both studies were implemented in with the solar plant and the simulation results reveal the effectiveness of the GPC with Smith predictor over the one without Smith predictor in mitigating time delays.

It could be observed in the above that Smith predictor compensation scheme could be used successfully in linear and nonlinear situations. In the case of nonlinear systems, the controller was designed such that it was able to deal with the nonlinearity of the system while the Smith predictor helped to eliminate dead time in the system. The challenge of nonlinearity in the above control systems were dealt with in various ways. These include converting the system to a simple linear system (Ramirez-Neria et al., 2013; Roca et al., 2009, Roca et al., 2014), designing a nonlinear controller for the nonlinear system (Galvez et al., 2007; Du Feng and Zhi, 2009) or introducing a nonlinear behaviour into the linear controller design (Moreno et al., 2012). Others include gain scheduling (Bolea, 2014) and the two degree of freedom optimization (Hwang, 2011) among others.

2.6.11 Smith predictor with constant and random time delay

One could also see from Table 2.3 that constant and random network induced time delays were successfully compensated by using the Smith predictor compensation scheme. Examples of studies involving constant delay compensations include (Sourdille and O'Dwyer, 2003; Rao and Chidambaram, 2005; Puawade et al., 2010; Tasdelen and Ozbay, 2013). While the studies involving the compensation of random time delays include (Velagic, 2008; Galvez et al., 2007; Du Feng and Zhi, 2009; Du and Du, 2009; Hwang, 2011; Dang et al., 2012).

In most of the cases reviewed, the schemes were implemented in the MATLAB/Simulink environment (Ben Atia and Ltaief, 2013, Veeramachaneni et al., 2013,Velagic, 2008, Ramirez-Neria et al., 2013, Kuzu and Songuler, 2012), however, there were some that were implemented using the TrueTime platform (Du Feng and

Zhi, 2009, Du and Du, 2009, Dang et al., 2012) and the LabVIEW environment (Puwade et al., 2010).

Some of the problems that have been identified with the Smith predictor include modelling mismatch or errors and this is because the Smith predictor is a model-based scheme and require an exact model of the plant. Another challenge is the inability of the Smith predictor to reject internal and external disturbances in the system. This is being addressed in literature by using disturbance rejection schemes (Kuku and Songular, 2012, Tasdelen and Ozbay, 2013). Most of these disturbance schemes are complex and they involve the use of many observers like Linear Extended Luenberger-Like observer, linear observers (Tasdelen and Ozbay, 2013). To achieve robust control, complex algorithms are also being used like the multimode approach (Ben Atia and Ltaief, 2013). This research seeks to use simpler algorithms to apply the Smith predictor compensation scheme in the new field of networked wastewater distributed control systems.

For the purpose of this thesis, the method of Velagic (2008) is improved. In case of Velagic (2008), the mean of delay was used as a means of predicting the random time delays. In this approach, the sum of the time delays in the forward path and feedback path are used as a means forming the Smith predictor scheme to compensate for the deadtime in the closed loop Dissolved Oxygen (DO) process. The challenge of nonlinearity, internal and external system disturbances (network induced time delays and the delay due to the Chemical Oxygen Demand analysis in the DO process) are considered as a robust control problem using simple algorithm to achieve robust control of the system. The Input output linearization is used to obtain the linearised model of the plant. The Smith predictor is combined with nonlinear linearising controller and a PI controller to remove deadtime in the linearised plant. The computation and simulation are carried out in the MATLAB/Simulink environment and the NI LabVIEW for a real-time implementation of the developed methods.

2.7 Conclusion

This chapter reviews existing literatures in Networked Control Systems. The reviewed papers were grouped under the history of NCS giving consideration to NCS configuration, structure, research trends and NCS components. Much focus was dedicated to network induced time delays and their effect on the stability of a traditional control system. It could be observed that the network induced time delays could be constant or random and that the random delays are more difficult to handle than constant delays. To be able to compensate for the network time delays, the delays would have to be modelled and appropriate compensation scheme designed for them in order to reduce or eliminate their adverse effect on the stability of the system. The communication channel was also reviewed. The TCP and UDP protocols were investigated and discovered that each of them have their advantages and disadvantages. While TCP guarantees accurate delivery of data but has a higher overhead leading to late delivery, UPD on the other hand delivers data faster but does not guarantee accuracy of data.

Different control methodologies employed in NCS were also reviewed, such as Queuing methodology, Augmented deterministic discrete-time model methodology, Optimal stochastic control, Perturbation methodology, Sampling time scheduling, Robust control methodology to mention a few. It could also be observed that these methodologies have varying capabilities in mitigating time delays. While all the methodologies mentioned earlier were suitable for linear systems, only perturbation methodology, robust methodology and event-based methodology could work for nonlinear systems (Tipsuwan and Chow, 2003). In a later study, Zhang et al. (2013) investigated the robust and adaptive frameworks of network control methodologies. While the robust framework does not depend on the information about the size of delay, time stamp or other special features of NCS to provide stability and performance for the control system, the adaptive framework does make use of these special features. The Smith predictor compensation scheme was reviewed outlining its research trends. In order to mitigate time-varying network induced time delays in this thesis, the following is considered:

- Ethernet network is the network of choice
- NCS problems are limited to network time delays

- Delays are considered to be between the sensor and controller, between the controller and actuator, and a combination of the two delays
- MATLAB/Simulink is used for modeling of network induced time delays
- Simulations are carried out for constant and random delays
- The Smith predictor compensation scheme is employed to provide delay compensation, stability and robustness for the control system.

The development in this thesis is done for the Dissolved Oxygen (DO) process of the Activated Sludge Process (ASP) of wastewater treatment. The description of the Wastewater Treatment Plant (WWTP) and the ASP is considered in chapter three.

CHAPTER THREE

THE WASTEWATER TREATMENT PLANT

3.1 Introduction

Wastewater Treatment Plants (WWTPs) are a range of technologies used to convert raw waste streams into environmentally-safe fluids after which they are discharged into the environment (Veoliawaters, 2014a). The Activated Sludge Process (ASP) is one of the methods mostly used in biological treatment of wastewater (Yang et al., 2013 ; Mei-jin and Fei, 2014) during which microorganisms in the aerobic tank are used as a means of breaking down organic substances in the wastewater (Samsudin et al., 2013). The microorganisms make use of oxygen which is released into the wastewater for their metabolic processes. Thus, by manoeuvring the aeration airflow, the Dissolved Oxygen (DO) concentration in the aeration basin of the ASP is controlled and through it the activity of microorganisms is controlled (Carp et al., 2013).

The needs for a wastewater treatment are outlined in section 3.2, sections 3.3 discusses the various stages involved in a typical wastewater treatment process and section 3.4 explains the Activated Sludge Process. Models of the WWTP, simulation of the Benchmark model (Copp, 2001) of the DO process in Simulink environment, measure of water quality and energy usage in the Activated Sludge Process are considered in sections 3.5, 3.6, 3.7, 3.8 and 3.9 respectively. The networked wastewater distributed systems is proposed in section 3.10 while the Chapter concludes in section 3.11.

3.2 The need for the wastewater treatment

Water is very important for life of plants and animals. While plants cannot grow successfully without adequate water supply, animals on the other hand need water for their metabolic activities. Clean water however is becoming very scarce around the world as a result of pollution from industrial, municipal or agricultural sources. However, human being cannot do without clean and safe water which is expected to be colourless, odourless and tasteless. Apart from this, there is the need to protect our environment from substances which would be injurious thereby complying with the strict environmental health and safety regulations (Caraman et al, 2007; Brien et al., 2011). The reasons highlighted above therefore make the treatment of wastewater very significant.

3.3 Wastewater treatment processes

Wastewaters are often from two main sources which are municipal and industrial sources. Wastewater treatment is the process of removing a major part of the contaminants in the wastewater in order to produce an effluent which is environmental friendly. In other words, the effluent quality from such a treatment would be in consonance with the environmental health and safety regulations such that it would not be injurious to plants, animals or the environment. However, this wastewater treatment should be achieved at minimum cost. The processes involved in wastewater treatment include: mechanical, biological, chemical and sludge treatments as shown in Figure 3.1 (Humoreanu and Nascu, 2013).

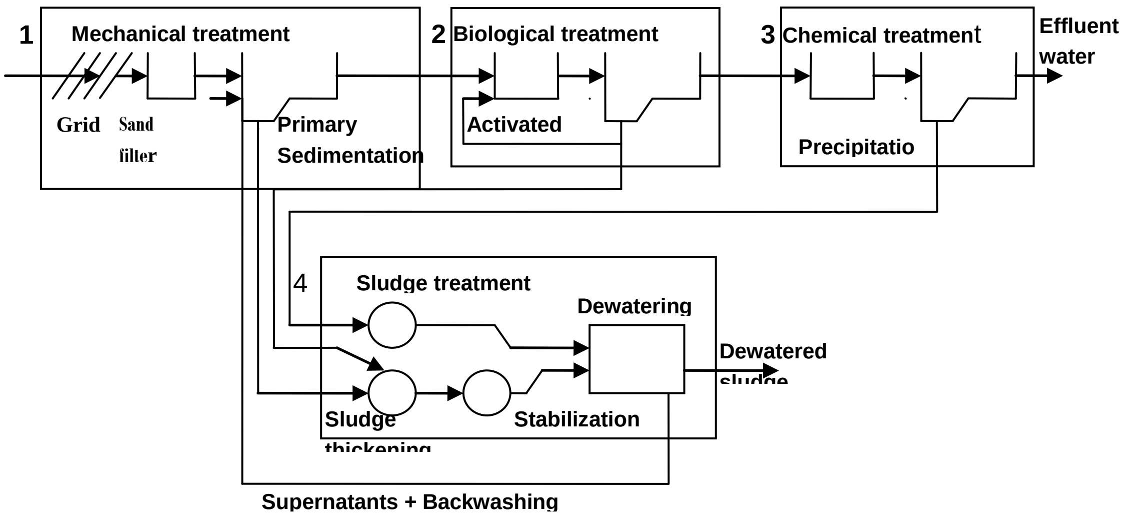

Figure 3.1: Layout of a wastewater treatment plant (Nketone, 2009)

3.3.1 Mechanical treatment

The mechanical treatment can also be referred to as the primary treatment stage and it involves screening, settlement, floatation and grease treatment (Veolia, 2014a). It is the first treatment given to wastewater. It involves the removal of heavy and large objects from the raw wastewater. Raw wastewater flowing into the filtering chamber is made to flow through a bar screen where rocks, sticks, rags, cloth, kitchen refuse and so on are removed. The filtering process helps to provide protection for the downstream equipment such as pipes and channels in the WWTP. This is done by removing objects and materials that are capable of damaging the downstream equipment

After this, primary sedimentation is carried out that involves an aerated sand filter which is responsible for the removal of sand and a primary sedimentation. This stage of filtering helps to reduce the amount of suspended solids in the wastewater through sedimentation. By doing this, the need for aeration is greatly reduced in the later process since large amount of organic matters in particulate form would have been removed in the process. (Nketoane, 2009). Floatation is also performed on the wastewater. This involves a solid-liquid or liquid-liquid procedure applied to particles whose density is lower than the liquid they are so as to make them float and be removable. Grease treatment is also carried out by removing fat, oil and grease from the water. This is necessary to prevent clogging on the downstream process (Veolia, 2014b).

3.3.2 Biological treatment

The biological treatment is the secondary treatment stage of wastewater treatment and the aim of this stage is to employ aerobic and anaerobic bacteria to break down organic matter in the wastewater to a state that it can be easily removed (Veolia, 2014b). In this stage of the wastewater treatment, micro-organisms are used to degrade organic matter and in some configurations, nutrients are also removed (Samsudin et al., 2013; Macnab, 2014). That is microorganisms convert non settle-able solids to settle-able solids. Sedimentation is then carried out to allow the settle-able solids to settle out.

The Activated Sludge Process (ASP) is one of the biological treatment methods used in larger wastewater treatment plants. In the ASP, organic substances are converted to oxidized products and settle-able flocks which is latter removed from the wastewater.

It's basic configuration involves an aerated tank and a settler. Microorganisms grow slowly in the aerated tank, sludge from the settler is re-circulated back to the aerated tank in order to maintain the population sizes of biomass. Excess sludge is removed in order to avoid sludge in the effluent water and to maintain a reasonable suspended solids concentration (Nketoane, 2009).

3.3.3 Chemical treatment

The chemical treatment is also referred to as the tertiary treatment. The aim of this stage is to disinfect the wastewater. Here, chlorine is added to the wastewater to disinfect it due to pathogens which may be injurious to human and animal health by causing diseases. In some cases, ozone (O_3) or ultra violet light is used to disinfect the wastewater. It has been discovered that ozone is safer than chlorine due to the fact that unlike ozone, chlorine is poisonous in the case of accidental release and yet it has to be stored on site (Humoreanu and Nascu, 2013).

Phosphorus is also one of the substances removed during the chemical treatment. As a result, it is common to have precipitation occurring. In order to transfer phosphate into soluble fractions and create flocks, a precipitation chemical is added to the wastewater. Insoluble phosphate together with organically bounded phosphate are then absorbed. Sedimentation or floatation is later used to separate the floc. Instead of using chemicals, enhanced phosphorus removal can be applied by the activated sludge process.

3.3.4 Sludge treatment

Sludge treatment can be seen as an extension of the tertiary treatment. Here, more filtration and clarification is performed on the wastewater. Reverse osmosis treatment could also be involved for the purpose of eliminating final suspended and dissolved solids from the water (Veoli, 2014b).

The treatment of sludge involves organic materials which have to be stabilised to reduce the pathogenic content and avoid odour. Primary and secondary sludge can be continuously aerated for a long period simultaneously in the activated sludge plant and this is known as aerobic stabilization. In the aerobic digestion, the microorganisms extend into a respiration phase where materials previously stored by the cell are oxidized, resulting in a reduction of the biologically degradable organic matter. Bio-gas, methane and carbon dioxide are produced during digestion. Sludge is dewatered by means of mechanical actions, centrifuging or filtering before it is transported away. The water content is removed in order to reduce the transportation cost due to the fact that sludge contains 95% water. After treatment, sludge may be dumped or used as fertilizer. In some cases, the sludge is used for soil conditioning (Nketoane, 2009).

3.4 The Activated Sludge Process

The Activated Sludge Process (ASP) is an aerobic, biological treatment procedure utilising metabolic reactions of microorganisms in order to produce acceptable effluent quality by removing substances that have an oxygen demand. The ASP mainly helps to remove organics and ammonium from the wastewater (Arceivala and Asolekar, 2007; Macnab, 2014; Gaya et al., 2013; Richard, 1989; Jeppson, 1993).

3.4.1 Biological Nitrogen Removal (BNR)

Nitrogen can be presented in different forms, for instance, as ammonia NH_3 ammonium NH_4^+, nitrate NO_3^-, nitrite NO_2^- and as organic compounds. In the raw wastewater, nitrogen is mostly represented as ammonium NH_4^+ and organic nitrogen (Lindberg, 1997). Nitrogen is one of the main components in living organisms and it forms an integral nutrient for biological growth. Nevertheless, when nitrogen is present in effluent wastewater, problems may arise (Lindberg, 1997): For instance, there is a high chlorine requirement if ammonia is present in drinking water supply. In the case of infants, nitrate is toxic while for aquatic animals such as fish, invertebrates, plants and so on, ammonia is toxic. When ammonium is oxidized to nitrate, the result is a high depletion of dissolved oxygen (DO) concentration because of significant oxygen demand which might arise in the receiving water body. For aquatic animals such as fish, invertebrates, plants and so on ammonia is toxic. Since nitrogen exists in form of ammonia and ammonium, the ammonium can be reduced in two steps namely: nitrification and de-nitrification. During nitrification, ammonia is converted to nitrate under aerobic condition. Equations (3.1) and (3.2) describe the nitrification process (Lindberg, 1997);

$$NH_4^+ + 1.5O_2 \rightarrow NO_2^- + H_2O + 2H^+ \quad (3.1)$$

$$NO_2^- + 0.5O_2 \rightarrow NO_3^- \quad (3.2)$$

In the case of denitrification, nitrate is converted to nitrogen gas and the process takes place in anoxic environment. Hence the formula describing the chemical reaction is shown in equation (3.3) (Lindberg, 1997).

$$2NO_3^- + 2H^+ \rightarrow N_2 + H_2O + 2.5O_2 \quad (3.3)$$

3.4.2 The role of dissolved oxygen in the Activated Sludge Process

Dissolved Oxygen (DO) concentration is one of the main control parameters in the activated sludge process (Lindberg and Carlsson, 1996; Hong-tao et al., 2013). This is due to the fact that oxygen plays an integral part in activated sludge process (Vanrolleghem and Lee, 2003). The control of the dissolved oxygen concentration in an activated sludge process is of considerable importance because of economic reasons and process efficiency. Low DO concentration implies inadequate oxygen for microorganisms in the biololgical reactor and results in inhibition of the effectiveness of wastewater treatment and possibly promotes filament growth. On the other hand, high DO concentration can result in energy wastage, high turbulence which can break up the biological flocks as well as hinder the process of denitrification by preventing the conversion of nitrite to nitrogen gas (Lindberg and Carlson, 1996). Dissolved oxygen analysis measures the amount of gaseous oxygen O_2 dissolved in an aqueous solution.

3.5 Models of the Wastewater Treatment Plant (WWTP)

In an attempt to describe the biological reaction occurring in the ASP, many models have been developed by researchers. The purpose of the models is to act as a tool for the study of the complex interactions between varying microbiological communities in the ASP. Some of these include: ASM No. 1, ASM No. 2, ASM No. 2d and ASM No. 3 (Henze et al, 1987, 1995, Samsudin et al., 2013, Yang et al., 2013).

In 1983, a task group was appointed by the International Association on Water Quality (IAWQ) [formerly the International Association on Water Pollution Research and Control (IAWPRC)] to review and produce a model that is capable of depicting the wastewater treatment performance. This group later submitted a report to IAWQ that describes the features of the Activated Sludge Model (ASM) No. 1. (Henze et al., 1987 Activated Sludge Model No.1. IAWPRC Scientific and Technical Reports, No. 1, 1987).

3.5.1 The Activated Sludge Model (ASM No. 1)

The Activated Sludge Model No. 1 (Henze et al., 1987, Samsudin et al., 2013) can be referred to as the COST Benchmark model of the WWTP. It is a reference model of the WWTP published by the International Association on Water Quality (IAWQ). It is a model that is internationally accepted by both research community and the industry for the study of WWTP. It could be regarded as the most popular mathematical description of the biochemical processes occurring within the reactor for nitrogen and chemical oxygen demand removal. The ASM1 can also be amended in order to describe the process of nitrification and denitrification. There are eight processes and thirteen state variables described by this model. The state variables with their definition and appropriate notations are given in Table 3.1 model (Henze et al., 1987; Yang et al., 2013).

Table 3.1: State Variables as defined by the ASM1 model (Henze et al., 1987; Yang et al., 2013)

Definitions	Notations
Soluble Inert organic matter	S_1
Readily biodegradable substrate	S_s
Particulate inert organic matter	X_1
Slowly biodegradable substrate	X_s
Active heterotrophic biomass	$X_{B,H}$
Active autotrophic biomass	$X_{B,A}$

Particulate products arising from biomass decay	X_P
Oxygen	S_o
Nitrate and nitrarte nitrogen	S_{NO}
NH4 + NH3 nitrogen	S_{NH}
Soluble biodegradable organic nitrogen	S_{ND}
Particulate biodegradable organic nitrogen	X_{ND}
Alkalinity	S_{ALK}
Soluble Inert organic matter	S_1

In order to describe the biological behaviour of the system, the eight basic processes are outlined model (Henze et al., 1987; Yang et al., 2013):

1. Aerobic growth of heterotrophs; this process is concerned with the conversion of readily biodegradable substrate, dissolved oxygen and ammonium into heterotrophic biomass.
2. Anoxic growth of heterotrophs; this converts readily biodegradable substrate, nitrate and ammonium into heterotrophic biomass
3. Heterotrophic decay; during this process, heterotrophic biomass is decomposed into slowly degradable substrate and other particulates
4. Aerobic growth of autotrophs; the process is responsible for the conversion of dissolved oxygen and ammonium into autotrophic biomass and nitrate.
5. Autotrophic biomass decay; during this process, autotrophic biomass is decomposed into slowly degradable substrate and other particulates.
6. Hydrolysis of X_S to S_S ; here, slowly biodegradable substrate is converted into readily biodegradable substrate.
7. Hydrolysis of X_{ND} to S_{ND} ; particulate biodegradable organic nitrogen is converted into biodegradable organic nitrogen.
8. Ammonification of S_{ND} to S_{NH} ; Biodegradable organic nitrogen is transformed into ammonium

The equations describing the overall process rates for the process variables are formed using Petersen’s matrix (Petersen et al., 2001). In compliance with the principle of conservation of energy, the DO process taking place within the biological reactor of the ASP can be represented with a mass balance equation.

Two factors that affect the dynamics of the DO are the oxygen uptake rate or respiration r_{so} and the oxygen transfer function K_{La}. In other words, DO concentration in the wastewater is reduced by the aerobic growth of heterotrophic and autotrophic biomas as shown by the equation in (3.4) (Yang et al., 2013; Muga, 2009) and by the oxygen transfer function K_{La} which is determined by the flow rate of the air sent to the wastewater tank.

$$r_{So}(t) = -\hat{\mu}_H \left(\frac{1-Y_H}{Y_H}\right)\left(\frac{s_{S,n}(t)}{K_S + s_{S,n}(t)}\right)\left(\frac{s_{O,n}(t)}{K_{OH} + s_{O,n}(t)}\right) x_{BH}(t) - $$
$$-\hat{\mu}_A \left(\frac{4.57-Y_A}{Y_A}\right)\left(\frac{s_{NH,n}(t)}{K_{NH} + s_{NH,n}(t)}\right)\left(\frac{s_{O,n}(t)}{K_{OA} + s_{O,n}(t)}\right) x_{BA}(t) \quad (3.4)$$

The meaning and the values of the stoichiometric and kinetic simulation benchmark parameters for the ASM1 at a temperature of 15 degrees Celsius (COST 624) are used in this thesis (Copp, 2001).

Table 3.2: Stoichiometric parameter values for ASM1 in the benchmark model

Description of parameters	Symbol	Value
Description of Parameter	Y_A	0.24
Autotrophic yield	Y_H	0.67
Heterotrophic yield	f_p	0.08
Fraction of biomass to particulate products	X_{Bi}	0.08
Fraction nitrogen in biomass	X_{Pi}	0.06

Table 3.3: Parameter values for ASM1 in the simulation benchmark (Copp, 2001).

Description of parameters	Symbol	Value	Units
Maximum heterotrophic growth rate	μ_{mH}	4.0	day^{-1}
Half-saturation (hetero.Growth)	K_S	10.0	$gCODm^{-3}$
Half-saturation (hetero.oxygen)	K_{OH}	0.2	gO_2m^{-3}
Half-saturation (nitrate)	K_{ON}	0.5	$gNO_3\text{-}Nm^{-3}$
Heterotrophic decay rate	b_H	0.3	day^{-1}
Anoxic growth rate correction factor	η_g	0.8	Dimensionless
Anoxic hydrolysis rate correction factor	η_h	0.8	Dimensionless
Maximum specific hydrolysis rate	K_h	3.0	$g\ X_s(gX_{BH}COD\ day)^{-1}$
Half-saturation (hydrolysis)	K_x	0.1	$g\ X_s(gX_{BH}COD)^{-1}$

Maximum autotrophic growth rate	μ_{mA}	0.5	day^{-1}
Half-saturation (auto.growth)	K_{NH}	1.0	$gNH_3\text{-}Nm^{-3}$
Autotrophic decay rate	b_A	0.05	day^{-1}
Half-saturation (auto-oxygen)	K_{OA}	0.4	gO_2m^{-3}
Ammonification rate	K_O	0.05	$m^{-3}(gCOD\ day)^{-1}$

The WWTP considered in this thesis is the benchmark model of the Activated Sludge Process with two anoxic tanks (tank 1 and tank 2) and three aerobic tanks (tank 3, tank 4 and tank 5) (Copp, 2001). This is shown in Figure 3.2 where $Q_O(t), Q_r(t), Q_a(t), Q_e(t)$ and $Q_w(t)$ in (Ml/day) are the input flow rate, return flow rate, internal recycle flow rate, the effluent flow rate, and wasting sludge flow rate respectively, $Q_n(t)$ (Ml/day), $n=\overline{1,5}$ are the output flow rates for the corresponding tanks of the structure.

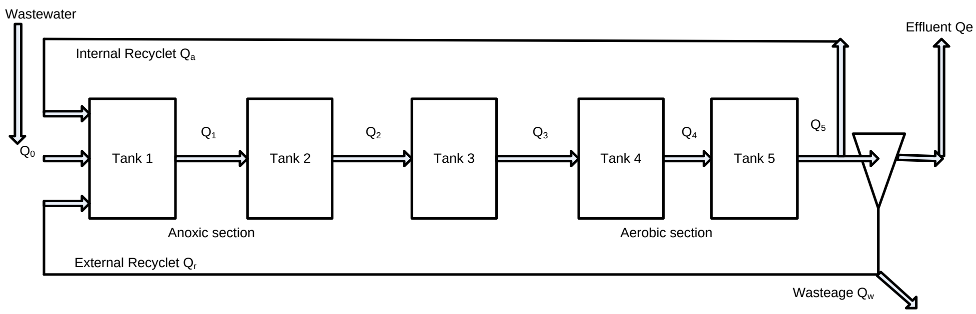

Figure 3.2: The COST Benchmark structure of the ASP (ASM1 plant) (Copp, 2001)

The Benchmark ASM1 model with its two anoxic and three aerobic tanks and a secondary settler combines the process of nitrification and denitrification in a way that is commonly used for achieving biological nitrogen removal effectively.

The oxygen mass transfer coefficient rate is set at 240 day^{-1} while K_{La} in the last tank is controlled so as to maintain DO concentration at 2mg/l.

3.6 Mass balance model of dissolved oxygen concentration for the Benchmark plant

The variables and the rates of reaction in the ASM1 plant associated with dissolved oxygen concentration can be presented by a set of differential equations that describe them. In order to do this, we have to consider both the mass balance of the substrate and the microorganism. This is illustrated in Figure 3.3, where u is the air flow rate, $S_{o,in}$ is the influent flow K_{La} is the oxygen transfer function, $S_{o,d}$ is the dissolved oxygen and S_o is the dissolved oxygen concentration.

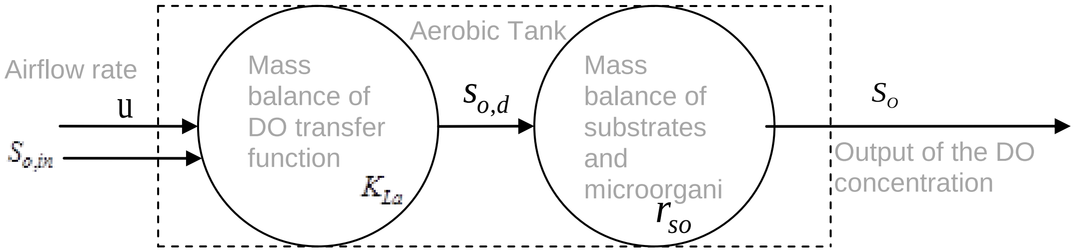

Figure 3.3: Common model of the DO process with airflow rate as the manipulated variable (Nketoane, 2009)

The mass balance of dissolved oxygen concentration into wastewater can be represented as:

Accumulation rate equals to input rate minus output rate plus rate of production by reaction minus rate of reduction by death or consumption

The mass balance equation relates the biomass activity with the air supply and the input organic load. It is in the form:

$$\frac{dS_{o,n}(t)}{dt} = \frac{1}{V_n} Q_n(t)\left(S_{oin,n-1}(t) - S_{o,n}(t)\right) + K_{La,n}(t)(S_{o,sat} - S_{o,n}(t)) + r_{S_{o,n}}(t) \tag{3.5}$$

where:

$S_{o,n}(t)$ is the DO concentration in the *nth* tank

$S_{oin,n}(t)$ (mg/l) is the DO concentration in the *nth* tank

$K_{La}(t)$ is the oxygen transmission coefficient

$S_{o,sat}$ (mg/l) is the DO concentration at a saturation point

$r_{so,n}(t)$ (mg/ld) is the oxygen uptake rate

V_n (m^3) (is the current number of the aerobic tank $(n = 3,4,5)$

Generally, it is assumed that $S_{o,n}(t)$, $S_{oin,n}(t)$, $u(t)$ and $Q_n(t)$ are measured while $S_{o,sat}$ and V_n (m^3) are known constants. Equation (3.5) describes the rate of change in the DO concentration. First term on the right is influent-effluent oxygen times dilution rate

$\frac{Q}{V}\left(S_{oin,n}-S_{o,n}\right)$ followed by $K_{La,n}(t)(S_{o,sat}-S_{o,n}(t))$ as a result of aeration and the last term $r_{SO}(t)$ is the oxygen uptake rate or respiration. The expression for $r_{SO}(t)$ is the equation is as shown in equation (3.4) while its stoichiometric and kinetic benchmark model parameters for the ASM1 are also outlined in section 3.5.1

The oxygen transmission coefficient depends on the flow rate of the air sent to the aerobic tank. This variable is used to control the concentration of the DO into the wastewater. There are different mathematical expressions of the dependences $K_{La,n}(t)\left[u(t)\right]$, but the most used one is by an exponential function shown in equation (3.6). The reason for this choice is that it gives a curve that decays with time which is similar to a natural case dissolving of air in water (Lindberg, 1997).

$$K_{La}(t)=k_1\left[1-e^{-k_2u(t)}\right] \tag{3.6}$$

where the coefficients k_1 and k_2 are determined for $K_{La}(t)=240d^{-1}, u(t)$ (m^3/d) represents the air flow rate and it is the control action. A typical curve of the $K_{La}u(t)$ functions is given on Figure 3.5 (Lindberg and Carlsson, 1996). The oxygen uptake rate is represented as a nonlinear function of the air flow rate.

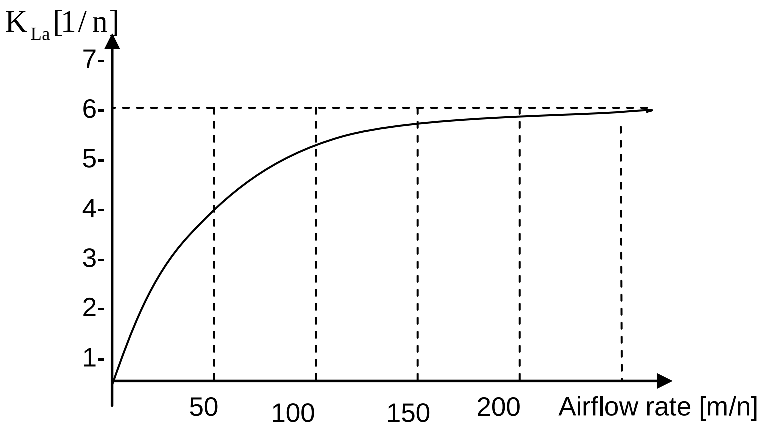

Figure 3.5: Exponential model curve of K_{La} (Lindberg and Carlsson, 1996)

The designs of nonlinear controllers in the thesis are based on the exponential model of the oxygen transfer rate. When K_{La} expression (3.6) is substituted into (3.5), the DO process model used for the controller design in the process model is obtained.

$$\dot{s}_O(t)=\frac{1}{V}Q(s_{O,in}(t)-s_O(t))+r_{SO}+k_1(1-e^{-k_2u(t)})(s_{O,Sat}-s_O(t)) \tag{3.7}$$

3.7 Simulation of the DO model in Simulink

In order to describe or investigate the dynamics of the DO process in the WWTP, the COST benchmark structure of the ASP (Olsson and Andrews, 1998, Tzoneva, 2007) is used in this thesis. The use of this model enables us compare the results obtained for the designed new controller with the results of other researchers.

The differential equation (3.5) is developed into block diagram in the MATLAB/Simulink environment shown in Figure 3.6. Tables 3.4 and 3.5 show the values of the ASM1 Benchmark plant that are simulated within the Simulink model to obtain an open loop response of the DO process as a response to a unit step input. This result of the simulation is shown in Figure 3.7. The MATLAB program (experiment1.m) with the used parameters of the model is given in Appendix (A1).

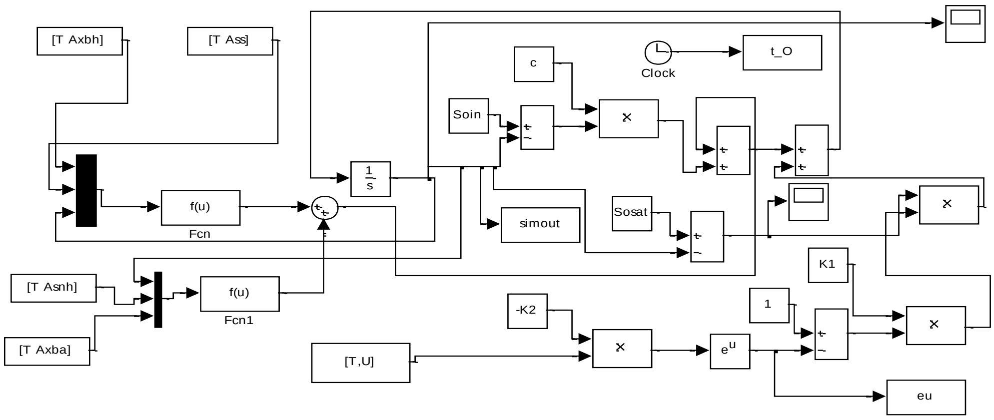

Figure 3.6: Developed Simulink model of the DO process.

Table 3.4 The COST Benchmark structure process parameters (Copp, 2001)

Parameters	$S_{o,sat}$	k_1	k_2	S_o	S_o	S_o	$S_{o,in}$	t	Q_a	X_{BHS}	S_{NHS}
Values	8	240	1.0961e-004	0.491	0.4	1333	0.01	0:0.1	55338	2559.3	1.733

Table 3.5: The COST Benchmark structure process parameters (Copp, 2001)

Parameters	Q_r	Q_O	$\mu_m H$	$\mu_m A$	Y_H	Y_A	K_{OH}	K_S	K_{NH}	X_{BAS}	$S_{S,SS}$
Values	18446	18446	4	0.5	0.67	0.24	0.20	10	1.0	149.78	0.889

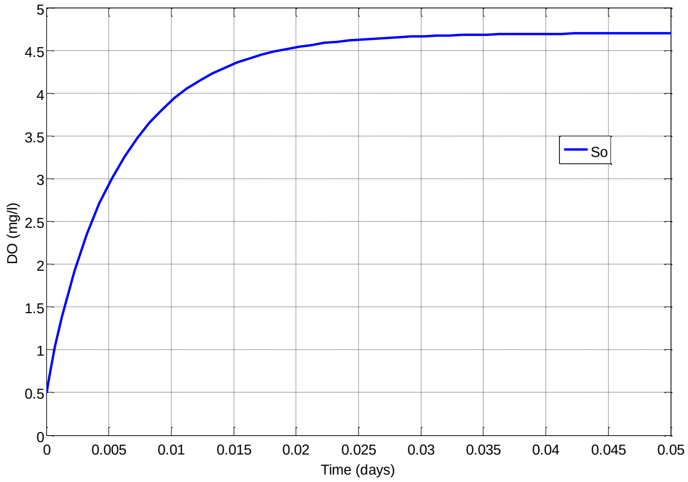

Figure 3.7: Open loop response of the DO process.

It could be noticed the DO process according to Figure 3.7 reached steady state at about 4.7 mg/l. Since the purpose of control is to maintain a set-point for the DO concentration that is close to 2 mg/l (Copp, 2001) as much as possible, there is then the need to design a controller that would improve the performance of the control system. This is done in Chapter four.

3.8 Networked wastewater distributed systems

Several control strategies have been proposed in literature for controlling the DO concentration in the ASP. They include PID controllers, model predictive controllers, etc. In order to overcome the manual tuning of PID, intelligent controllers such as fuzzy logic and neural network controllers have been used (Vlad et al., 2011; Chotkowski et al., 2005; Sanchez and Katebi, 2003; Tzoneva, 2007; Muga, 2009). All these cases cited consider a situation in which both the controller and the WWTP are placed side by side.

Today, field bus and industrial Ethernet are being used in many process controls including the wastewater treatment plants. Many of them are implemented within a particular wastewater treatment facility to connect sensory devices to the main SCADA system. During this process, variable information including water level, temperature, pH, Chemical Oxygen Demand (COD) are transmitted from several devices at one part of the WWTP to the central Supervisory Control And Data Acquisition (SCADA) system (control room) for analysis in an integrated manner and further processing (Moxa, 2014a). The communication medium used here is industrial Ethernet. In another case, the city of Carmel WWTP wanted to expand as well as upgrade their SCADA system. Industrial Ethernet and fibre optics cable where appropriately used to connect existing equipment to the new ones while giving consideration to possible future expansion (Moxa, 2014a).

This thesis considers a new approach of wastewater control with a focus on the DO process in the ASP in which the controller and the WWTP are not in the same location. They are separated by a wide geographical distance such that a communication medium is required between the controller and the WWTP. This communication medium will exist between the controller and the actuator and between the sensor and the controller. This is a Networked Control System (NCS) involving WWTPs and could be referred to as Networked Wastewater Distributed Systems (NWDS). The proposed design would be advantageous to the wastewater industries. For example, it would provide flexibility since it would be possible to perform WWTP control from a remote site located several kilometres away. It would enhance modularity that would aid ease of maintenance. This design would not only afford remote control, it would make it possible to remotely control two or more WWTP at the same time thus a lot of cost could be reduced when this is compared to a situation where each WWTP must have its controller by its side. Another advantage is scalability which means that new WWTP can easily be incorporated into the existing network for the purpose of future expansion of the WWTPs (Tipsuwan and Chow, 2003), (Zampieri, 2008). Despite the merits outlined above, the communication drawbacks do have some influence on the performance of the system (Nilsson, 1998). These communication challenges would be addressed in the course of this study.

3.11 Conclusion

This chapter starts with the need for wastewater treatment and it was found that apart from the need to alleviate water scarcity in some settings, the need for a good quality effluent in compliance with environmental health and safety regulations is paramount. It also outlines the stages involved in a typical wastewater treatment process. The

Activated sludge Process which takes place within the biological reactor of WWTP was considered. It was realized that DO concentration is a major factor that influence the performance of the ASP. Too low DO concentration though ensures very low electrical energy is consumed in the ASP it also means that there would not be enough oxygen available for microorganisms meant to clean up the wastewater. This can result in poor effluent quality. On the other hand too high DO concentration could lead to excessive electrical energy and this also hinders the process of de-nitrification. As a result the DO concentration must be properly maintained at the desired set-point.

In this chapter, the networked wastewater distributed systems was also proposed and its advantages outlined. The possible challenges due to communication drawbacks were also mentioned. In Chapter four, the investigation of the effects of communication drawbacks on the traditional DO process behaviour is performed. This would assist in developing the appropriate controller to mitigate the communication challenges and to provide stability and good performance for the networked DO process.

CHAPTER FOUR

INVESTIGATION OF THE NETWORK INDUCED TIME DELAYS INFLUENCE ON THE CLOSED LOOP DO PROCESS

4.1 Introduction

Chapter three focuses on the dynamics of the WWTP and in particular the Activated Sludge Process and the need to maintain the DO concentration at a desired set point value. The networked wastewater control approach was also proposed. In this chapter, the effects of communication drawbacks on the DO process in a networked wastewater treatment plant is investigated. This makes it possible to obtain the necessary conditions for process performance and other information that would aid the design of a robust networked control for the wastewater treatment plant.

The Chapter's sections are arranged as follows. Section 4.2 outlines the time delays that occur in the networked control systems and whose influence is investigated in this thesis. These include the network induced time delays (τ_{ca}, τ_{sc} and τ_{tot}) and process time delays which might be inherent in the DO process but which could also have adverse effects on the control system stability. Section 4.3 considers the closed loop DO process behaviour in the absence of network time delays. In section 4.4, constant and random time delays were introduced into the DO process and simulations were performed to determine the behaviour of the DO process. In section 4.5 the investigation of the effects of constant and random delays on the closed loop DO process performance is discussed. Section 4.6 considers the investigation of the DO process behaviour under varying PI controller (K_p and T_i) .The results of these investigations were presented in section 4.7. In section 4.8, the saturation limits are introduced as a form of disturbance in the closed loop DO and discussed. The chapter concludes with section 4.7.

4.2. Network delays in the networked wastewater control.

The time delays being considered in this study include the controller to actuator delay (τ_{ca}) which is in the forward path of the closed loop DO process control system, the sensor to controller delay (τ_{sc}) which is in the feedback loop of the closed loop DO process control system and a combination of the two delays ($\tau_{tot} = \tau_{ca} + \tau_{sc}$). It must be noted however that for the ASP, there could exist other type of process delays. Apart from time delays due to the communication network, another source of dead time (time delay) in the ASP is the time it takes the sensor and analysers to perform their measurements or analyses and generate results. For instance, the Chemical Oxygen Demand (COD) is one of the parameters needed to be measured in order to calculate the oxygen uptake rate $r_{so}(t)$ in the ASP. This COD measurement could constitute some amount of time delay. For instance, in the Phoenix-1010 analyser, analysis lag time between the samples that are entering the intake of the analyser and the time it takes the analysed data to be out is usually between 3 to 15 minutes for a measurement that ranges between 10 to 1500 mg/litre COD (Environmental-expert, 2014). As a result, this assumption is made.

Assumption:

The sensor to controller delays (   ) considered in this research is assumed to be made up of both the network induced sensor to controller delay (   ) and the process induced delay due to COD analysis. This is shown in equations (4.2) to (4.3).

$$\tau_{tot} = \tau_{ca} + \tau_{sc} \tag{4.1}$$

$$\tau_{sc} = \tau_{sc}^{\eta} + \tau_{COD} \tag{4.2}$$

$$\tau_{tot} = \tau_{ca} + (\tau_{sc}^{\eta} + \tau_{COD}) \tag{4.3}$$

τ_{tot} = total delay in the forward and feedback path

τ_{ca} = controller to actuator delay

τ_{sc} = sensor to controller delay

τ_{COD} = process delay due to chemical oxygen demand analysis

τ_{sc}^{η} = network sensor to controller delay

4.3. Closed loop DO process in the absence of time delays

Investigations in the paper are done for the closed loop control system of the DO process proposed in (Nketoane, 2009) and shown in Figure 4.1. The closed loop has two components.

- Input/output linearising nonlinear control $u(t)$ leading the nonlinear DO process closed loop behaviour to be equivalent to a stable one with desired behaviour of a linear system

$\dot{S}(t) = aS_O(t) + bv$, where a and b are the state and control coefficients of the desired model of the linearized system and $v(t)$ is the linear control input to the linearised closed loop system.

- Linear control $v(t)$ leading the linearised closed loop behaviour of the DO process to follow some desired trajectory (set point).

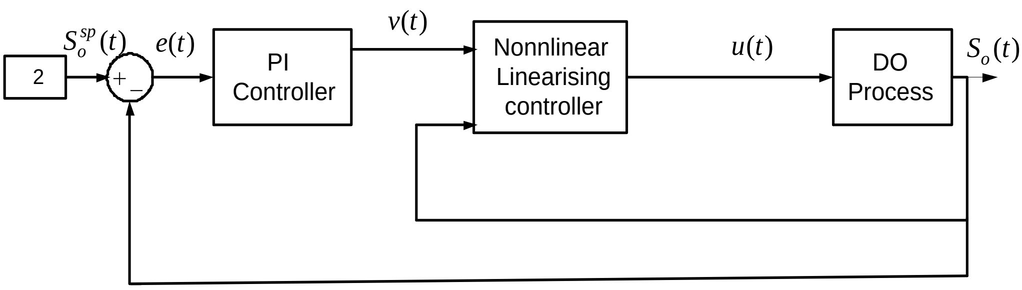

Figure 4.1: Nonlinear linearising closed loop control of DO process without network time delays

The linear control is selected to be Proportional Integral (PI) one, described by the equation (4.4) where the coefficients and are designed for the desired linear system using the pole placement method and is the error between the set point and the closed loop DO process output.

$$V(t) = K_p \left[e(t) + \frac{1}{T_1} \int e(t)dt \right] \qquad (4.4)$$

The nonlinear controller including the linear one for the nth tank where n is omitted is designed to be:

$$u(t) = -\frac{1}{k_2} \ln \left\{ \frac{\left(a + \frac{Q}{V} - k_1 \right) s_O(t) + bK_p \left[e(t) + \frac{1}{T_i} \int e(t)dt \right] + k_1 s_{O,sat} - \frac{Q}{V} s_{O,in}(t) - r_{SO}(t)}{-k_1 (s_{O,sat} - s_O(t))} \right\}$$

(4.5)

Figure 4.2 is the MATLAB/Simulink model of the closed loop DO process with the nonlinear linearising controller and the linear control while 4.3 shows the Simulink diagram of the nonlinear linearising controller.

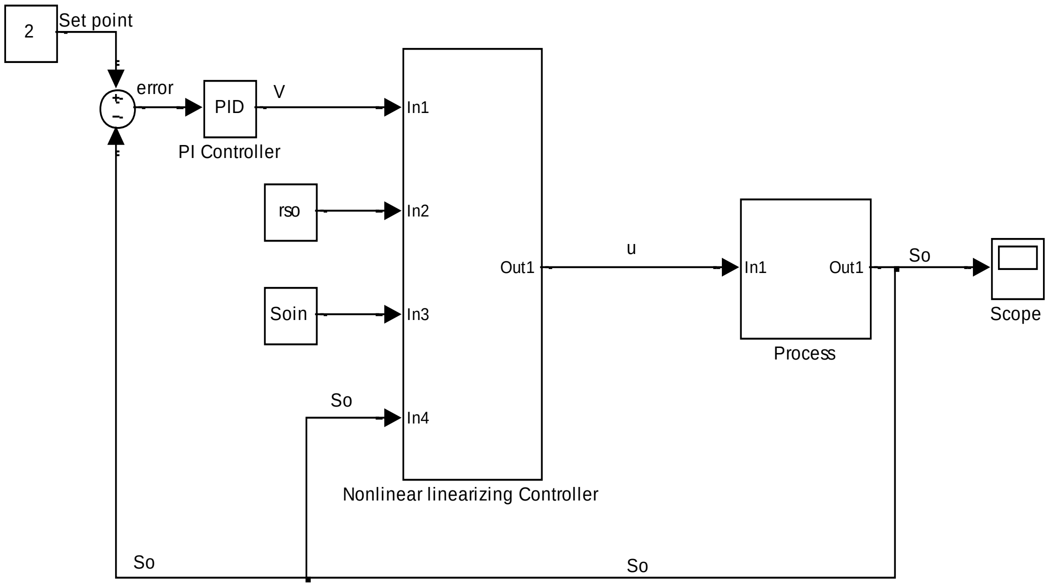

Figure 4.2: Simulink block of the closed loop DO process control ssystem, based on the linear and and nonlinear linearising controllers (Adapted from Nketoane, 2009)

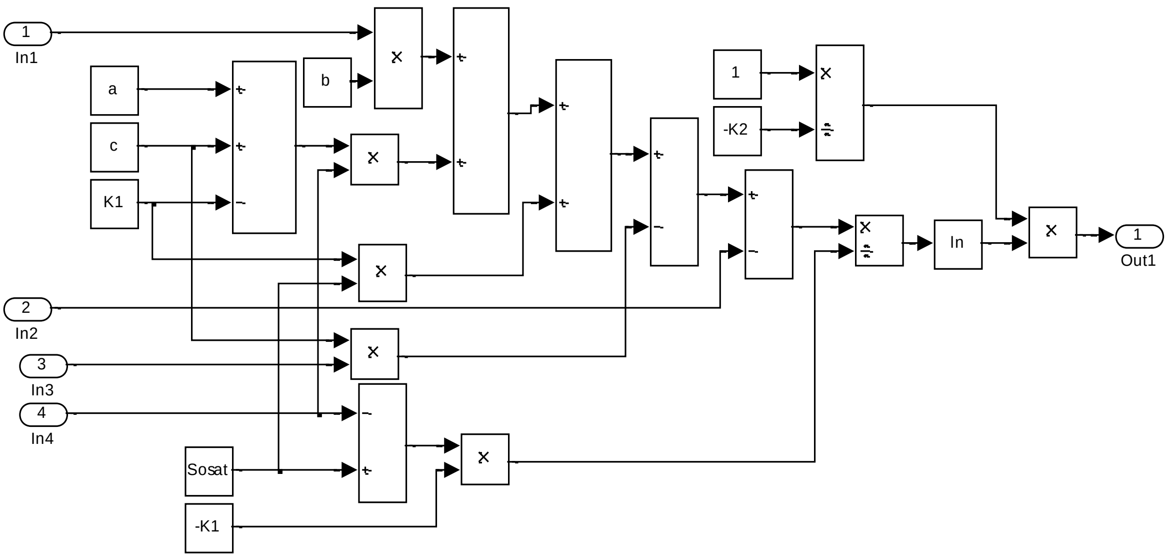

Figure 4.3: Simulink diagram of the nonlinear linearizing controller (Adapted from Nketoane, 2009)

MATLAB/Simulink model of the closed loop system using the linear control and the nonlinear linearising as shown in Figure 4.2 and presented by equation (4.5) is used in this thesis as a basis for investigations of the impact of the network induced time delays. The closed loop response of the DO process according to the structure in

Figure 4.1 simulated using the Simulink block in Figure 4.2 is given in Figure 4.4, for $S_o^{sp}(t)$ = 2mg/l, where $S_o^{sp}(t)$ is the set point for the DO process output. The MATLAB program (experiment2.m) with the values of the model and the controller parameters is given in Appendix (B4.1).

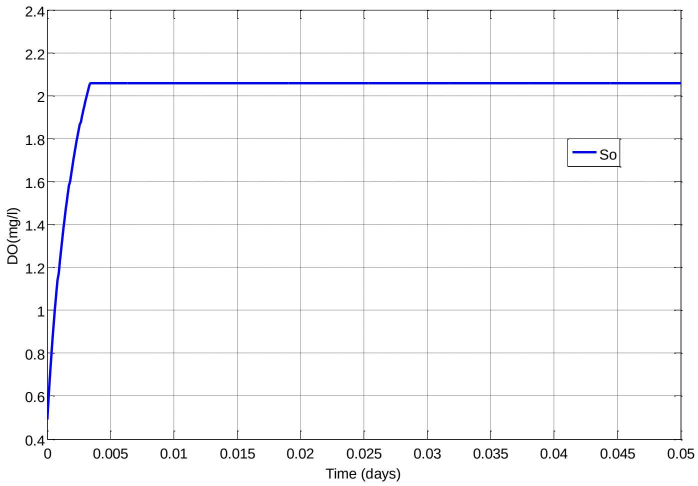

Figure 4.4: Closed loop response of the DO process without network induced time delays

4.4. Closed loop DO process control in the presence of time delays

The remote control of the DO process would bring about communication drawbacks into the traditional DO concentration closed loop control system. Communication delays between the controller and actuator and between the sensor and controller are considered as shown in Figure 4.5

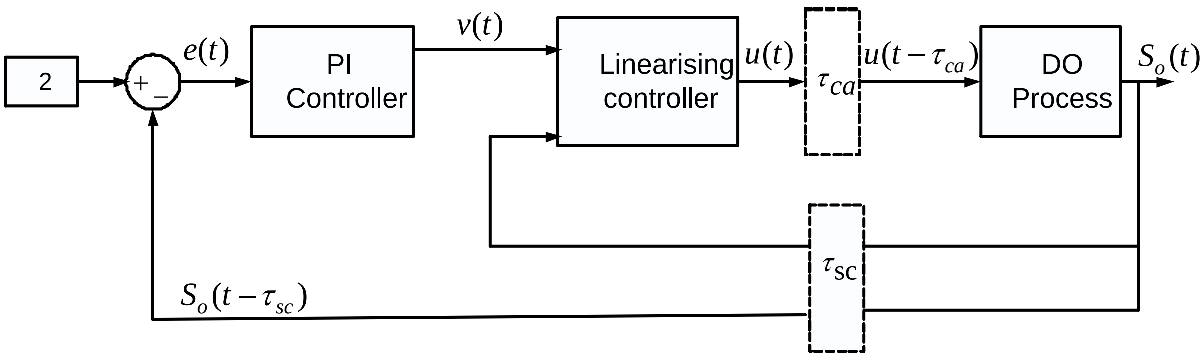

Figure 4.5: Nonlinear linearising closed loop control of DO process including network time delays

The induced time delays lead to a situation where at moment the actuator will receive a control signal from the moment $t-\tau_{ca}$ and the sensor data received by the controller will be from the moment $t-\tau_{sc}$. Time delays can be constant or random but for the purpose of the analysis in this thesis, both constant and random time delays are investigated.

The investigation of the influence of the network induced time delays on the DO process control system could be done in different ways depending on where the delay is placed in the control system. Figure 4.6 shows two different arrangements (Kravaris and Wright, 1989). Case 1 is the linearized DO process approach in which the nonlinear linearising controller and the nonlinear DO process are placed close to each other and far from the PI controller. The combination of the linearising controller and the DO process results in a linearized model of the DO process control system. The network induced time delay is placed between the linearized model of the DO process and the PI controller. Case 2 arrangement is such that the PI controller and the nonlinear linearising controller are placed close to each other and far away from the nonlinear model of the DO process. The network delays are placed between the controllers (PI + linearising controller) and the nonlinear DO process as shown in Figure 4.6a In this thesis, this arrangement is referred to as the nonlinear DO process approach. Figure 4.6b shows the simulation result that compares these two approaches when the DO process is induced with a constant network time delay of 0.000245 days The MATLAB program (experiment_compare.m) with the values of the model parameters is given in Appendix (B4.1b). It could be seen that in both case 1 and case 2, the DO process experiences oscillations resulting in system overshoot due to network imperfections but the approaches differ in terms of delayed system response. In case 1 which is the linearized approach, the linearized model of the DO process under network induced delays did not experience delayed system response. However, a noticeable delayed response is seen in the case 2 which is the nonlinear DO process approach. Possible reasons for this might be that the nonlinear linearising controller placed close to the DO process in case 1 could have performed some delay compensation and cancel out the system delayed response. The two arrangements described (case 1 and case 2) are used in the thesis for the design of the Smith predictor compensation schemes for the DO process in Chapters five and six respectively. For the purpose of investigating the network induced time delays in this Chapter, the nonlinear DO process approach (case 2) is used.

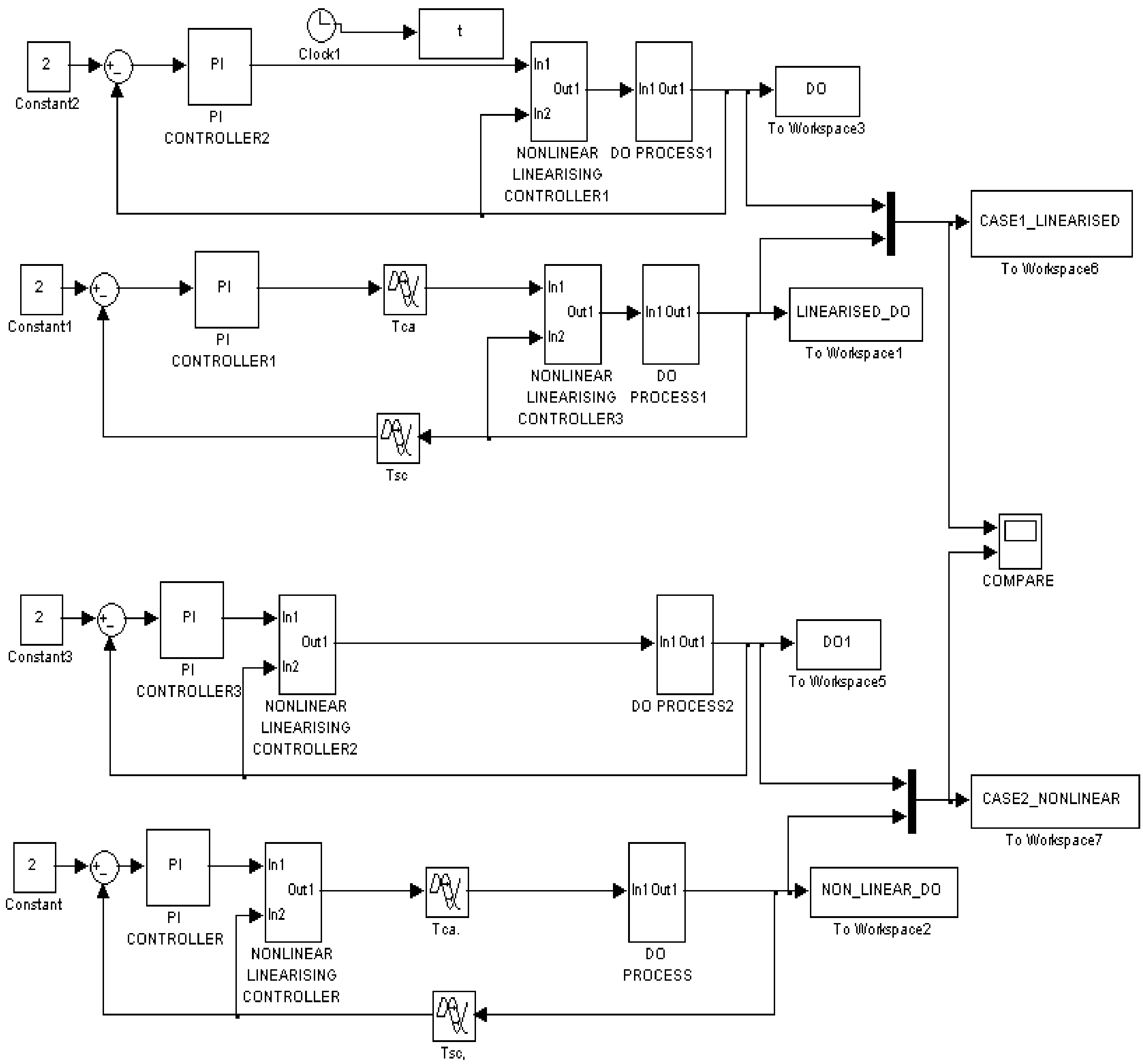

Figure 4.6: Comparison between the linearised DO process approach and the nonlinear DO process approach

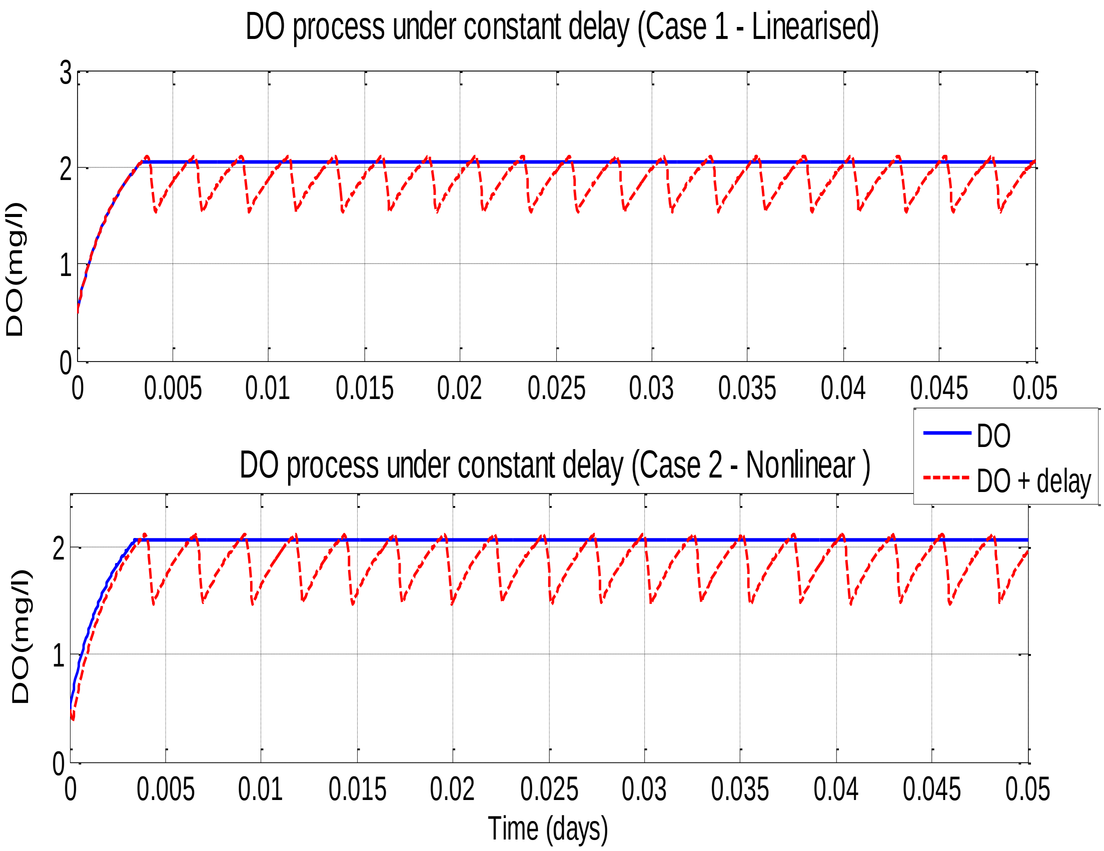

Figure 4.7: Simulation results of the DO process under constant delays comparing the linearised DO process approach and the nonlinear DO process approach. a) Case 1 – Linearised DO process, b) Nonlinear DO process, τ_{tot} = 0.000245 days

4.5 Investigation of the effects of constant and random delays on the closed loop DO process performance

In order to investigate the effects of the network induced time delays on the closed loop DO process behaviour, simulations were carried out using transport delay functions in the MATLAB/Simulink environment. The closed loop DO process was simulated first with only controller to actuator delay (τ_{ca}). This was placed in the forward path of the closed loop system. After this, simulation was done only with the sensor to controller delay (τ_{sc}), placed in the feedback path. The DO process closed loop behaviour was then simulated with a combined delay (τ_{tot} which is the sum of τ_{ca} and τ_{sc}). The values of the delays used for the simulation were chosen from one given minimum value and increased until a sustained oscillation was achieved (critical delay) and even beyond the critical value. This was done to observe the DO process behaviour in the cases of:

- less than the critical delay
- equal to the critical delay
- greater than the critical delay

The same was performed for both constant and random delays. The Simulink block in Figure 4.8 shows this arrangement for constant time delays and Figure 4.14 for random time delays. The MATLAB program (experiment3.m) with the values of the model and the controller parameters is given in Appendix (B4.2). Figures 4.9 to 4.12 show the comparison of the simulation results of the closed loop DO process under the influence of the constant delays and Figures. 4.15 to 4.17 show similar results under the random delays (τ_{ca} only), (τ_{sc} only) and a combined delay (τ_{tot}).

4.5.1 Investigation of the DO process control system under constant time delays

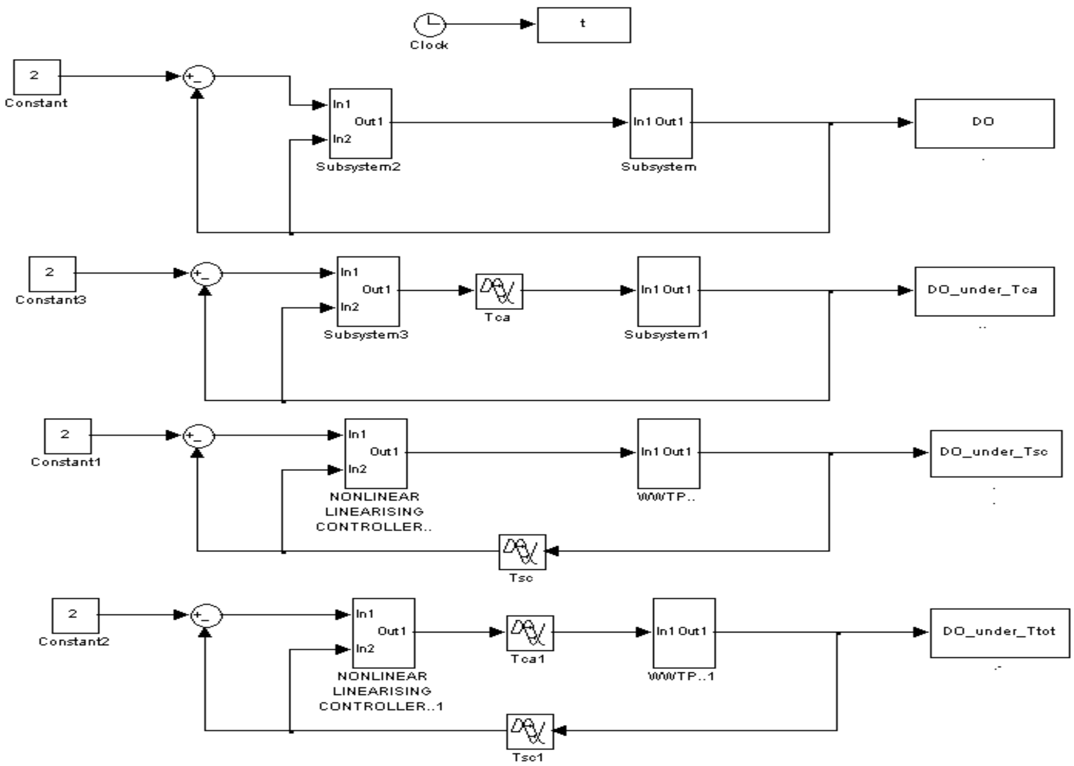

Figure 4.8: Simulink block showing the closed loop DO process with various network induced constant time delays

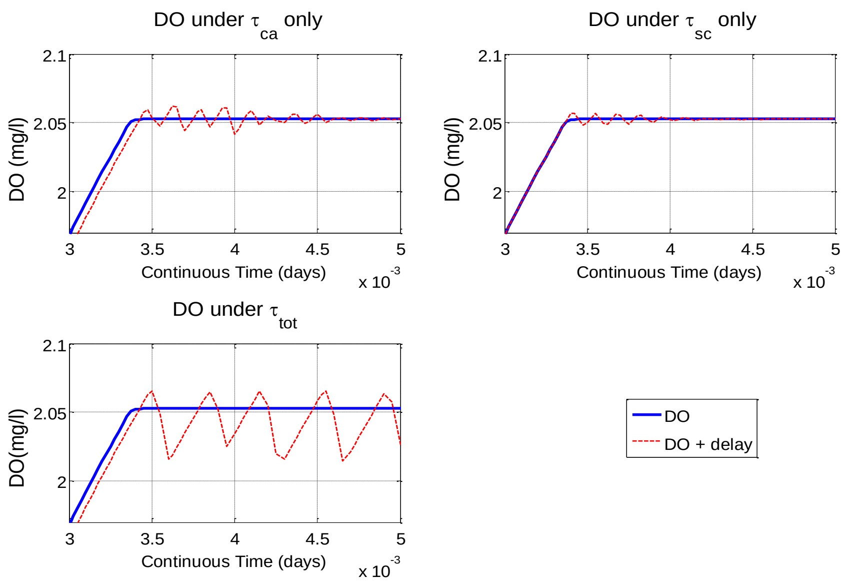

Figure 4.9: Simulation of the DO process closed loop behaviour under network constant delays when τ_{ca} = τ_{sc} = 0.000033 days and τ_{tot} = 0.00066 days

Note: Simulation time is altered to enlarge it for the purpose of clarity

It could be observed that as the value of the network induced constant time delays increase, there is an overshoot in the system response. This is shown in Figures. 4.9 to 4.11. At this stage, the closed loop DO process was able to regain its stability and return to the steady state despite the presence of the network induced time delays. In Figure. 4.9, the system experienced a sustained oscillation when a total delay (τ_{tot}) of 0.000614 days was induced.

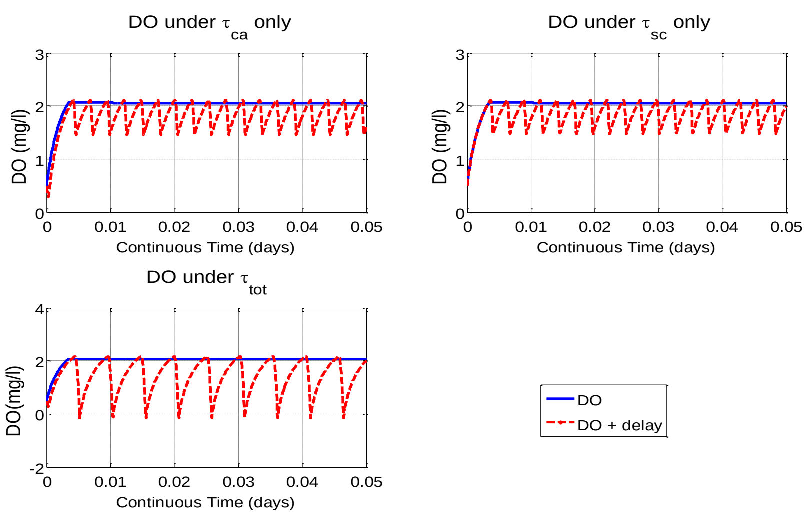

Figure 4.10: Simulation of the DO process closed loop behaviour under network constant delays when τ_{ca} = τ_{sc} = 0.000307 days, τ_{tot} = 0.000614 days

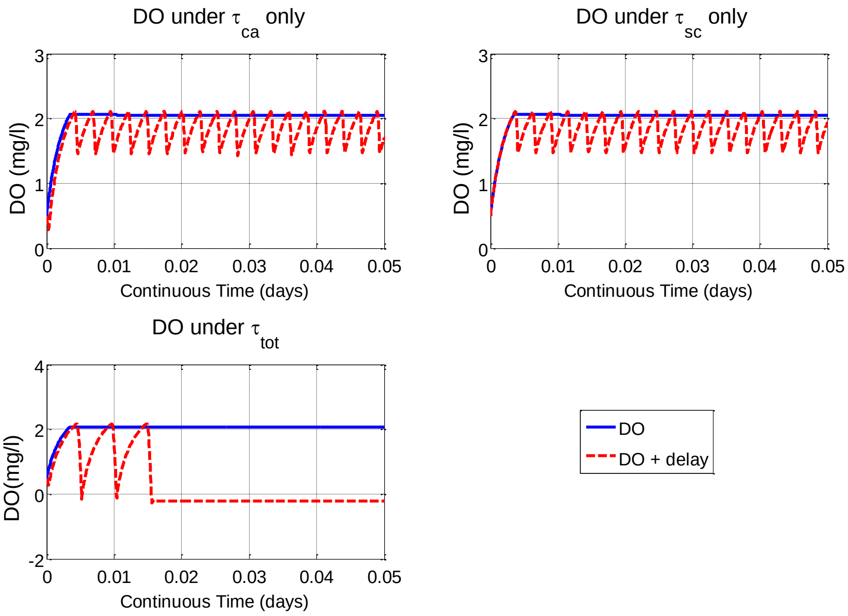

Figure 4.11: Simulation of the DO process closed loop behaviour under network constant delays when τ_{ca} = 0.000308, τ_{sc} = 0.000307 days, τ_{tot} = 0.000615days

This could be referred to as the critical delay. From this point any additional delay would make the system unstable. Figure 4.11 shows the unstable DO process when a total delay (τ_{tot}) of 0.000615 days was induced in the system. The performance indices for the different types and values of the considered above delays are shown in Table 4.1.

Table 4.1: Performance indices of the closed loop DO process under constant time delays

Measurement Conditions	Time delay Values (days)	Kp	Ti	Rise Time (days)	Settling Time (days)	Percentage Overshoot (%)	Steady State Error (mg/l)	Oscillation Amplitude (mg/l) Min; max.	Delay in Response (days)
τ_{ca} only									
$\tau_{ca} = 0$	0	3.2	8000	0.002000	0.003050	1.50	-0.030000	2.030	0
$\tau_{ca} < \tau_c$	0.000033	3.2	8000	0.002033	0.004083	3.20	-0.054000	2.044, 2.064	0.000033
$\tau_{ca} = \tau_c$	0.000307	3.2	8000	0.002308	0.004357	6.00	0.021000	1.460, 2.120	0.000307
$\tau_{ca} > \tau_c$	0.000308	3.2	8000	0.002308	0.004357	6.00	0.024000	1.420, 2.100	0.000308
			τ_{sc} only						
$\tau_{sc} = 0$	0	3.2	8000	0.002000	0.003050	1.50	-0.030000	2.030	0
$\tau_{sc} < \tau_c$	0.000033	3.2	8000	0.002000	0.004017	2.90	-0.054000	2.050, 2.058	0
$\tau_{sc} = \tau_c$	0.000307	3.2	8000	0.002000	0.004017	5.50	0.200000	1.490, 2.110	0
$\tau_{sc} > \tau_c$	0.000307	3.2	8000	0.002000	0.004017	5.00	0.205000	1.490, 2.100	0
τ_{tot}									
$\tau_{tot} = 0$	0	3.2	8000	0.002000	0.003050	1.50	-0.030000	2.030	0
$\tau_{tot} < \tau_c$	0.00066	3.2	8000	0.002033	0.008133	3.20	-0.040000	2.016, 2.064	0.000033
$\tau_{tot} = \tau_c$	0.000614	3.2	8000	0.002307	0.008407	8.00	0.985000	-0.130, 2.16	0.000307
$\tau_{tot} > \tau_c$	0.000615	3.2	8000	0.002308	0.008408	9.00	1.010000	-0.20, 2.180	0.000308

4.5.2 Investigation of the DO process control system under random delays

Communication time delays (τ_{ca} and τ_{sc}) in this case are assumed to be random variables which are uniformly distributed. The DO process is sampled at a sampling period of T = 0.0001days (0.864sec.) using the Zero Order Hold (ZOH) technique. A uniform random number is introduced into the system to generate random delays with the signal to noise ratio of 90% (Velagic, 2008, Searchnetworking, 2014). Figure 4.12 shows the Simulink block of how the uniform random delays used for simulation are generated while Figure 4.13 shows the probability distribution of the random delays generated at a time delay of 0.000027 days. The MATLAB program (experiment_rand.m) with the values of the model parameters is given in Appendix (B4.3.1). The MATLAB program (experiment4.m) with the values of the model parameters and the controller parameters is given in Appendix (B4.3), the Simulink block is as shown in Figure 4.14 while the simulation results are found in Figures 4.15 to 4.17. Table 4.2 shows the performance indices of the closed loop DO process under random time delays.

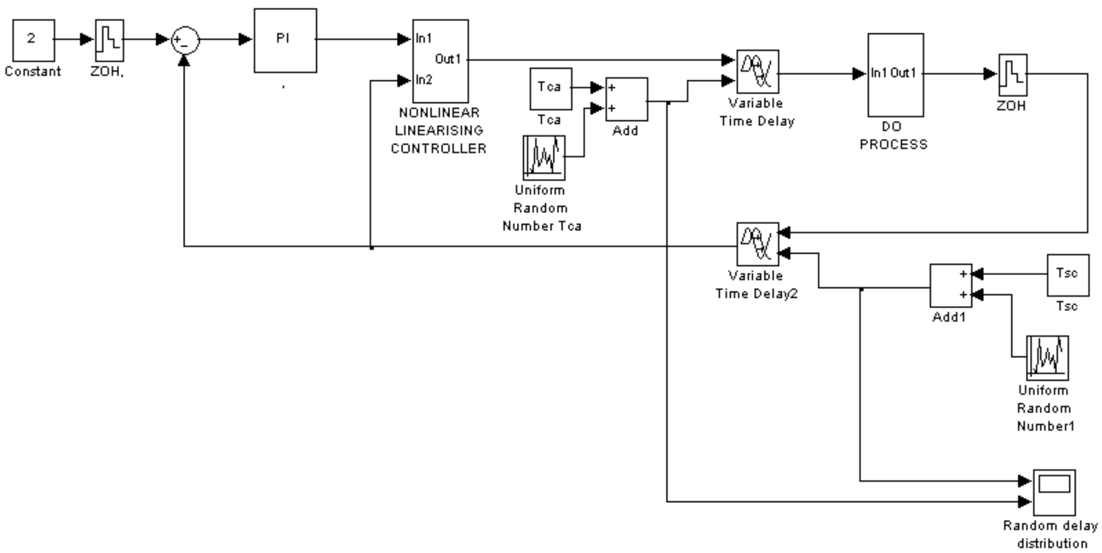

Figure 4.12: Simulink block diagram showing generation of uniform random delays

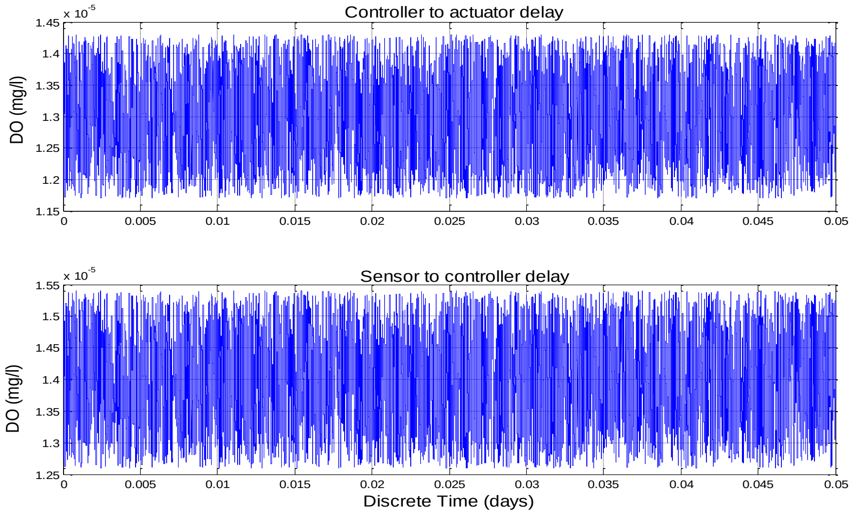

Figure 4.13: Time distribution of random delays ($\tau_{ca} + \tau_{sc} = \tau_{tot}$) = 0.000027 days, a.) controller to actuator delay τ_{ca} = 0.000014 days under interval (-0.0000014 days, 0.0000014 days), b.) sensor to controller delay τ_{sc} = 0.000013 days under interval (-0.0000013 days, 0.0000013 days)

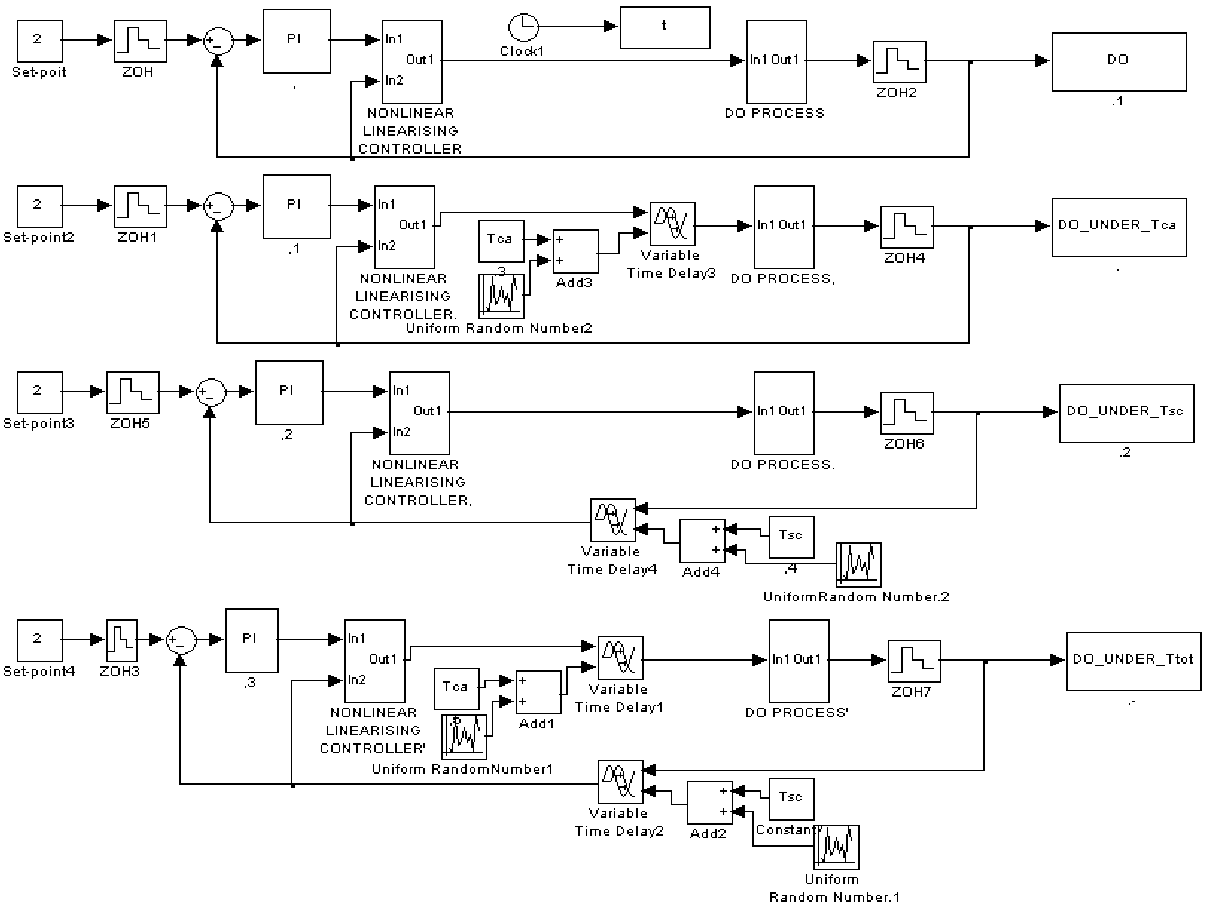

Figure 4.14: Simulink block of the closed loop control of the DO process considering random time network

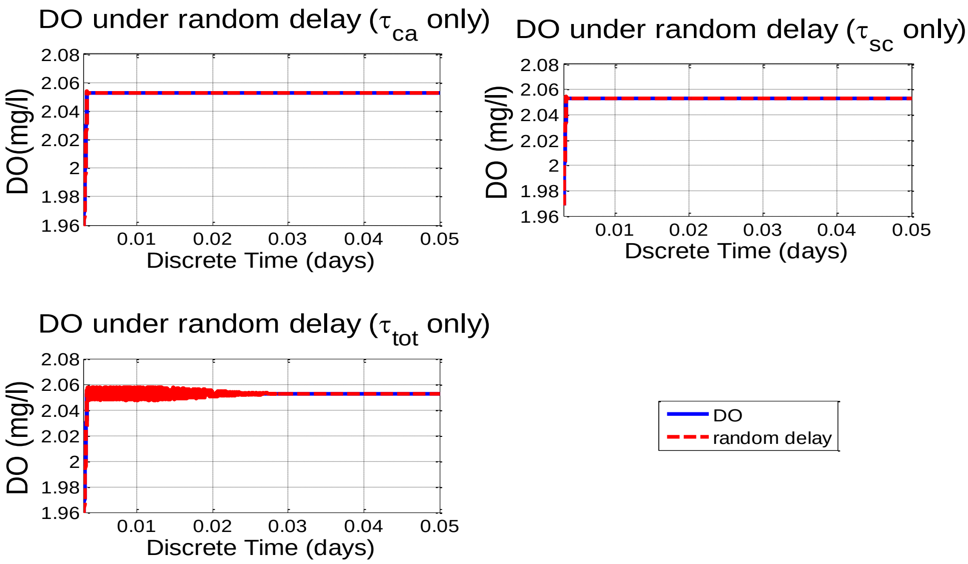

Figure 4.15: Simulation of the DO process closed loop behaviour under random delays when τ_{ca} = 0.000013 days, τ_{sc} = 0.000013 days, τ_{tot} = 0.000026 days

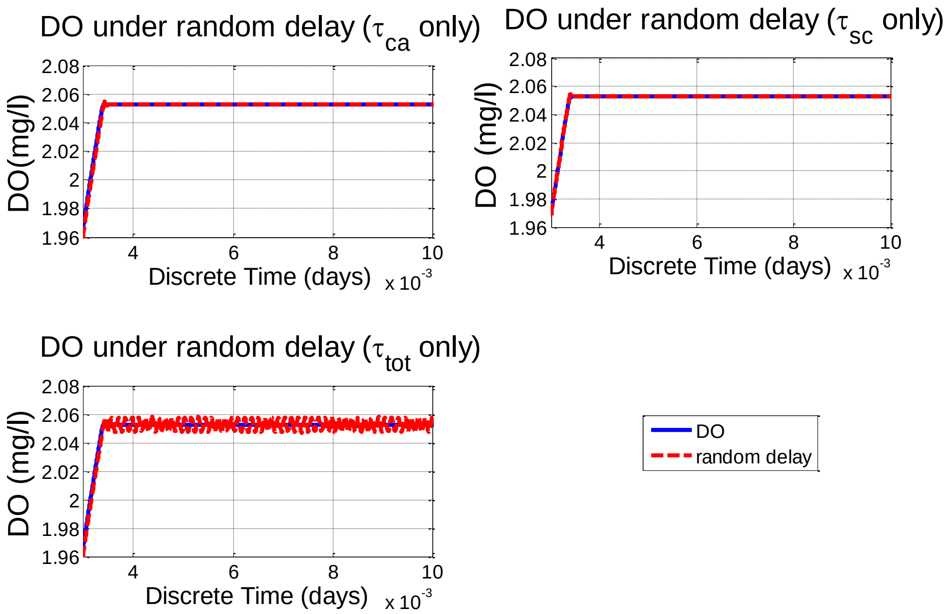

Figure 4.16: Simulation of the DO process closed loop behaviour under random delays when τ_{ca} =0.000014 days, τ_{sc} = 0.000013 days, τ_{tot} = 0.000027 days

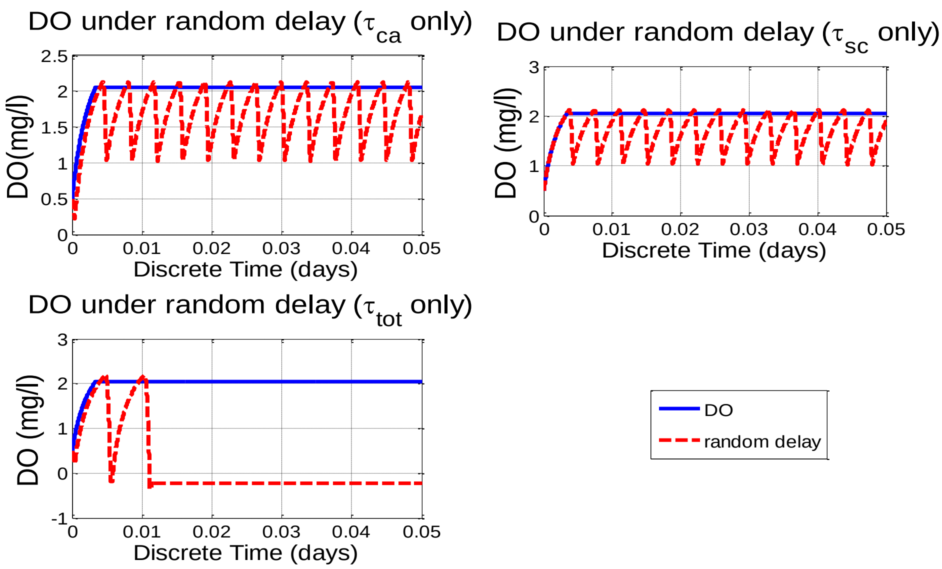

Figure 4.17: Simulation of the DO process closed loop behaviour under random delays when τ_{ca} =0.0004 days, τ_{sc} = 0.0004 days, τ_{tot} = 0.0008 days

4.5.3 Analysis of the results of random time delays influence on the DO process control system

Communication (constant or random) in the control system affect the stability of the DO process and the ASP. In both investigations, the DO process is seen to exhibit similar behaviour under constant and random delays. For example the higher the value of time delays, the more the rise time, percentage overshoot and steady state error. This is shown in Tables 4.1 and 4.2. The network induced time delays (τ_{ca}, τ_{sc} and τ_{tot}) have varying influences on the control system depending on which of the time delays is in operation at a particular time. The DO process is delayed by the value of τ_{ca} when is under the influence of τ_{ca} and τ_{tot} while no delay is experienced in the system response when it is under τ_{sc} only. It could also be observed from both cases of constant and random delays that the DO process under τ_{ca} performed poorer than under τ_{sc} in terms of percentage overshoot but when it is under τ_{ca} it results in better steady state error than τ_{sc}. It could be said that τ_{ca} seems to have greater influence on the system than τ_{sc} which could be due to the fact that τ_{ca} is in the forward path of the control loop and τ_{sc} is in the feedback loop. However the main feature of the investigation with random time delays as compared to this with the constant delays is that with the random time delays, it could be observed that the DO process attained sustained oscillation (critical delay) in 0.000027 days (2.3328 secs.) which is earlier when compared to the case of the constant delays in 0.000614 days (53.0496 secs.). This is shown in Figures 4.10 and 4.16. It could also be noticed that the bigger the probability distribution, the more instability is experienced by the DO process. This is due to the fact that the probability distribution depicts the amount of noise in the communication medium which constitutes a disturbance in the control system. For the purpose of this investigation, a $\pm 10\%$ of τ_{tot} (90% signal to noise ratio) is assumed and used for simulation. In other words, the DO process under random delays becomes more sensitive to disturbances (noise) than under constant delay and so could become unstable (oscillate) with any little change in system dynamics. This confirms why the random time delays are more difficult to handle compared to the constant delays.

Table 4.2: Performance indices of the closed loop DO process under random time delays

Measurement Conditions	Time delay Values (days)	Kp	Ti	Rise Time (days)	Settling Time (days)	Percentage Overshoot (%)	Steady State Error (mg/l)	Oscillation Amplitude (mg/l) Min; max.	Delay in Response (days)
τ_{ca} only									
$\tau_{ca} = 0$	0	3.2	8000	0.002000	0.003050	2.63	-0.052600	2.0526	0
$\tau_{ca} < \tau_c$	0.000013	3.2	8000	0.002013	0.003400	2.73	-0.05460	2.0520, 2.0546	0.000013
$\tau_{ca} = \tau_c$	0.000014	3.2	8000	0.002014	0.003400	2.73	-0.05460	2.0518, 2.0546	0.000014
$\tau_{ca} > \tau_c$	0.000400	3.2	8000	0.002400	0.003400	6.55	0.42200	1.025, 2.131	0.000400
τ_{sc} only									
$\tau_{sc} = 0$	0	3.2	8000	0.002000	0.003050	2.63	-0.052600	2.0526	0
$\tau_{sc} < \tau_c$	0.000013	3.2	8000	0.002000	0.003400	2.73	-0.05460	2.0520, 2.0546	0
$\tau_{sc} = \tau_c$	0.000013	3.2	8000	0.002000	0.003400	2.73	-0.05460	2.0520, 2.0546	0
$\tau_{sc} > \tau_c$	0.000400	3.2	8000	0.002000	0.003400	6.40	0.42100	1.030, 2.1280	0
τ_{tot}									
$\tau_{tot} = 0$	0	3.2	8000	0.002000	0.003050	2.63	-0.052600	2.0526	0
$\tau_{tot} < \tau_c$	0.000026	3.2	8000	0.002013	0.003413	2.87	-0.052600	2.0477, 2.0575	0.000013
$\tau_{tot} = \tau_c$	0.000027	3.2	8000	0.002014	0.003414	2.90	-0.05250	2.047, 2.058	0.000014
$\tau_{tot} > \tau_c$	0.000800	3.2	8000	0.002400	0.003400	9.70	1.08500	-0.364, 2.194	0.000400

4.6. Investigation of the DO Process under random delays with varying controller parameters (K_p and T_i)

The results obtained with the closed loop DO process control system in Tables 4.1 and 4.2 are based on fixed values of the controller parameters(K_p and T_i). In order to obtain more information to aid process performance, an investigation with varying values of K_p and T_i is performed. The purpose is to investigate the effects of the linear controller parameters (K_p and T_i) on the value of the process performance characteristics and the critical delay obtained under the random delays investigations shown in Table 4.2. The fixed values of K_p = 3.2 and T_i = 8000 used for the investigation in Tables 4.1 and 4.2 are considered as reference. Three cases are considered:

Case 1: K_p is varied from 2.2 to 5.2 while T_i is kept constant at 8000.

Case 2: K_p is constant at 3.2 while T_i varies from 2000 to 14000.

Case 3: Both K_p and T_i are increased from a minimum value to maximum (from 2.2 to 5.2 for K_p and from 2000 to 14000 for T_i).

For each case, the performance indices are analysed as shown in Table 4.3. Figures 4.18 to 4.22, Figures 4.23 to 4.27, and Figures 4.28 to 4.32 show the simulation results. . The MATLAB program (experiment5.m) with the values of the model and the controller parameters is given in Appendix (B4.4). For all examinations, the value of the critical delay is kept constant, τ_{tot} = 0.000027 days.

4.6.1 Simulation results of case 1: K_p is varied from 2.2 to 5.2 while T_i is kept constant at 8000.

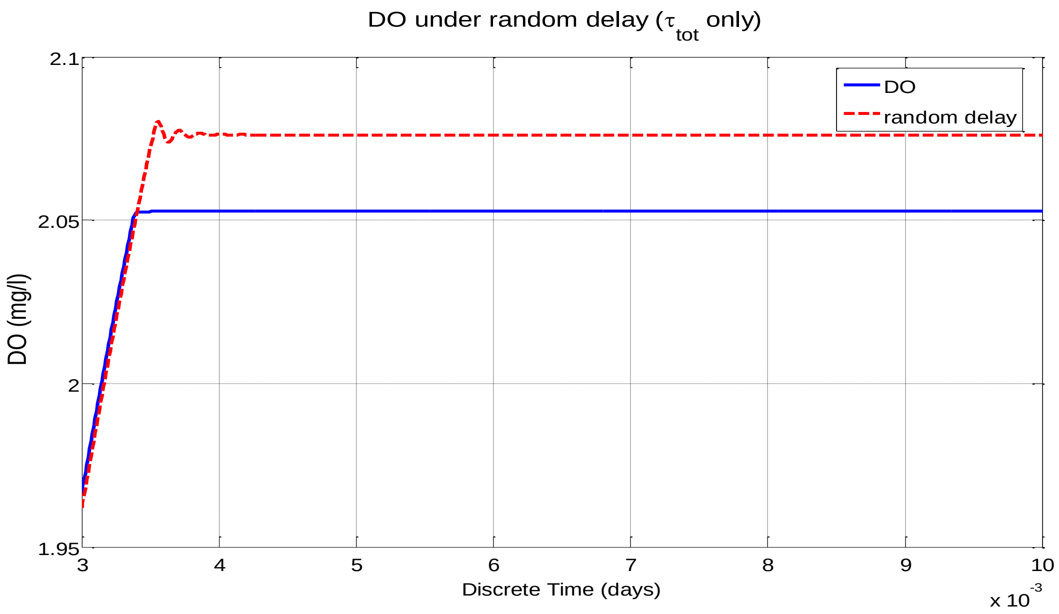

Figure 4.18: Case 1, τ_{ca} = 0.000014 days, τ_{sc} = 0.000013 days, τ_{tot} = 0.000027 days, T_i = 8000, K_p = 2.2

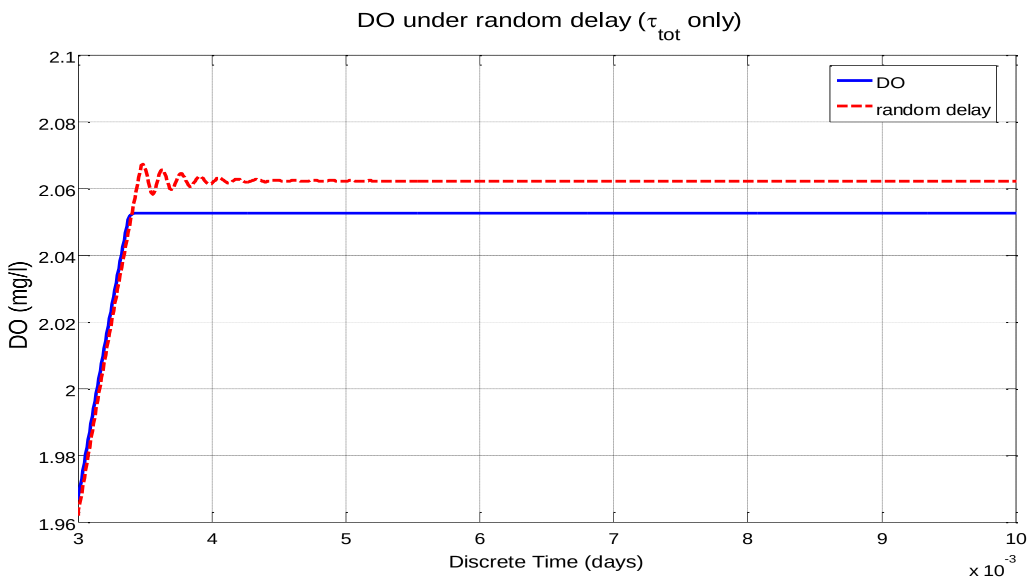

Figure 4.19: Case 1, τ_{ca} = 0.000014 days, τ_{sc} = 0.000013 days, τ_{tot} = 0.000027 days, T_i = 8000, K_p = 2.7

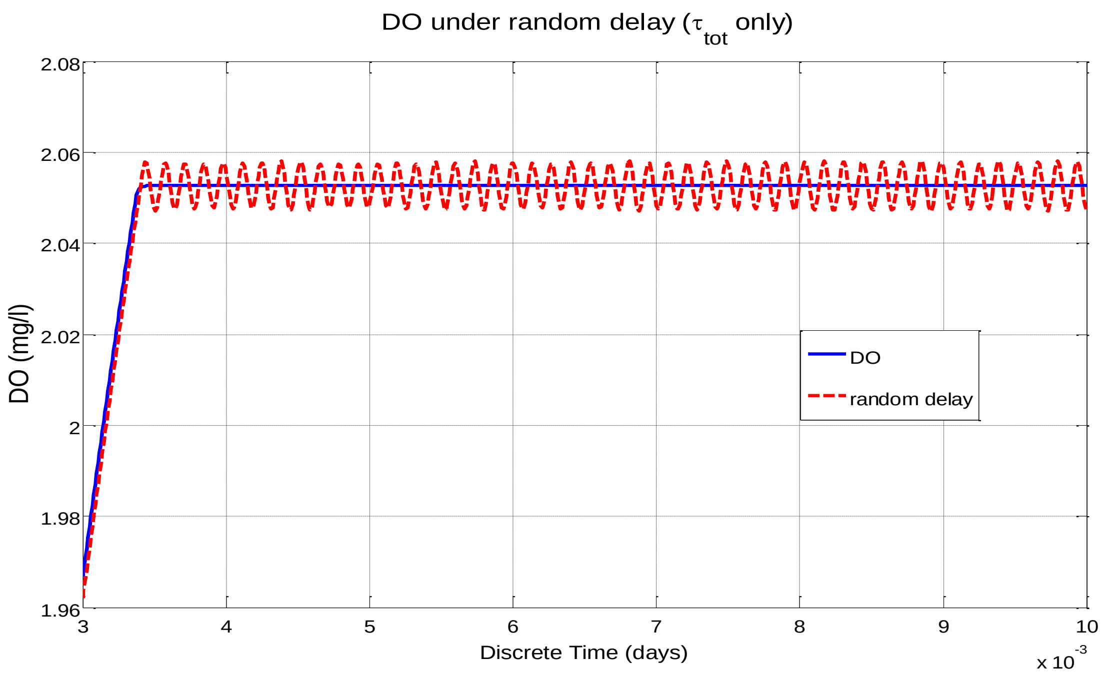

Figure 4.20: Case 1, τ_{ca} = 0.000014 days, τ_{sc} = 0.000013 days, τ_{tot} = 0.000027 days,

T_i = 8000, K_p = 3.2

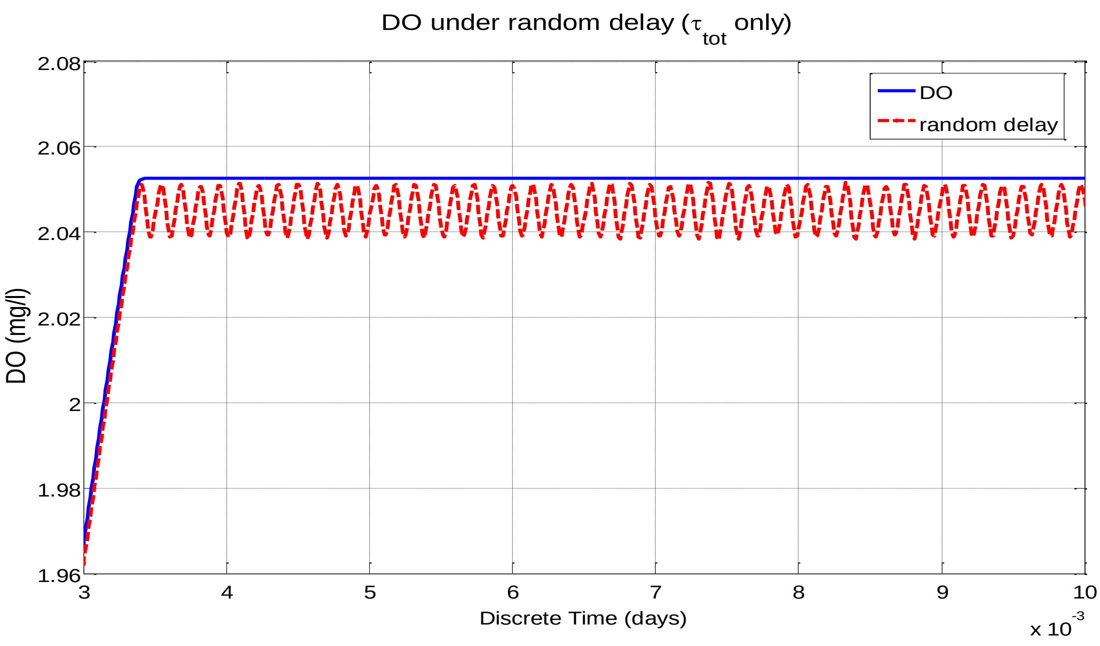

Figure 4.21: Case 1, τ_{ca} = 0.000014 days, τ_{sc} = 0.000013 days, τ_{tot} = 0.000027 days,

T_i = 8000, K_p = 3.7

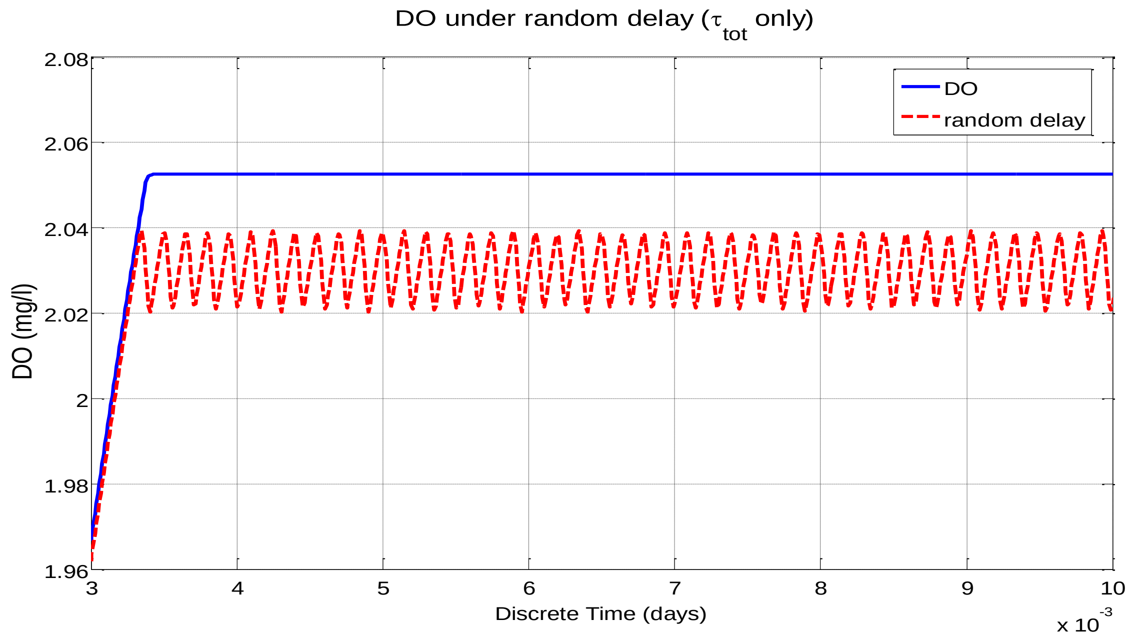

Figure 4.22: Case 1, τ_{ca} = 0.000014 days, τ_{sc} = 0.000013 days, τ_{tot} = 0.000027 days, T_i = 8000, K_p = 5.24.6.2

Simulation results of case 2: K_p is constant at 3.2 while T_i varies from 2000 to 14000

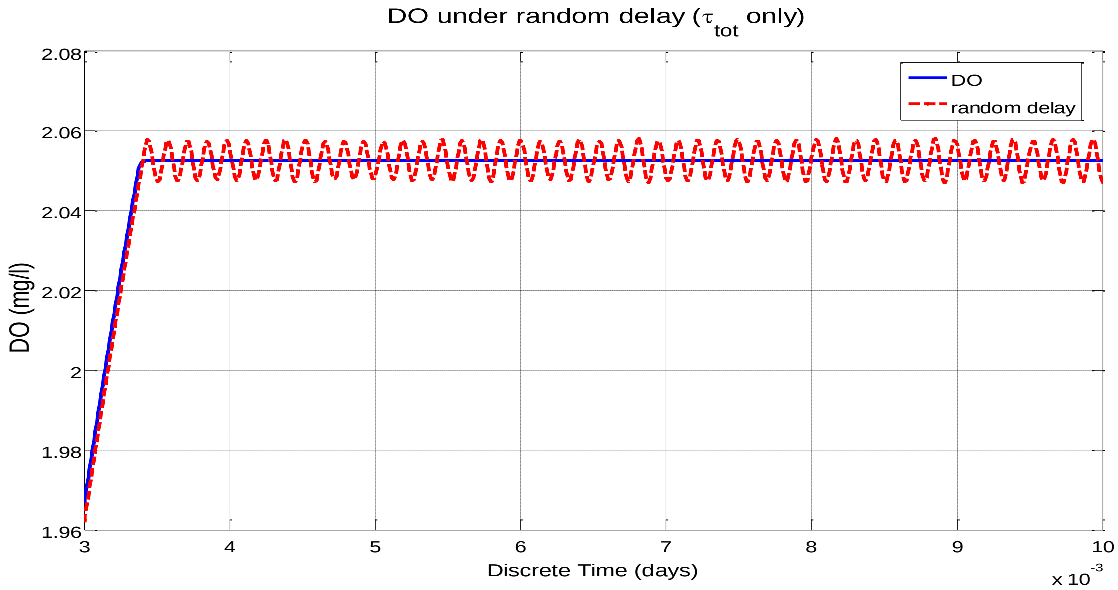

Figure 4.23: Case 2, τ_{ca} = 0.000014 days, τ_{sc} = 0.000013 days, τ_{tot} = 0.000027 days, K_p = 3.2, T_i = 2000

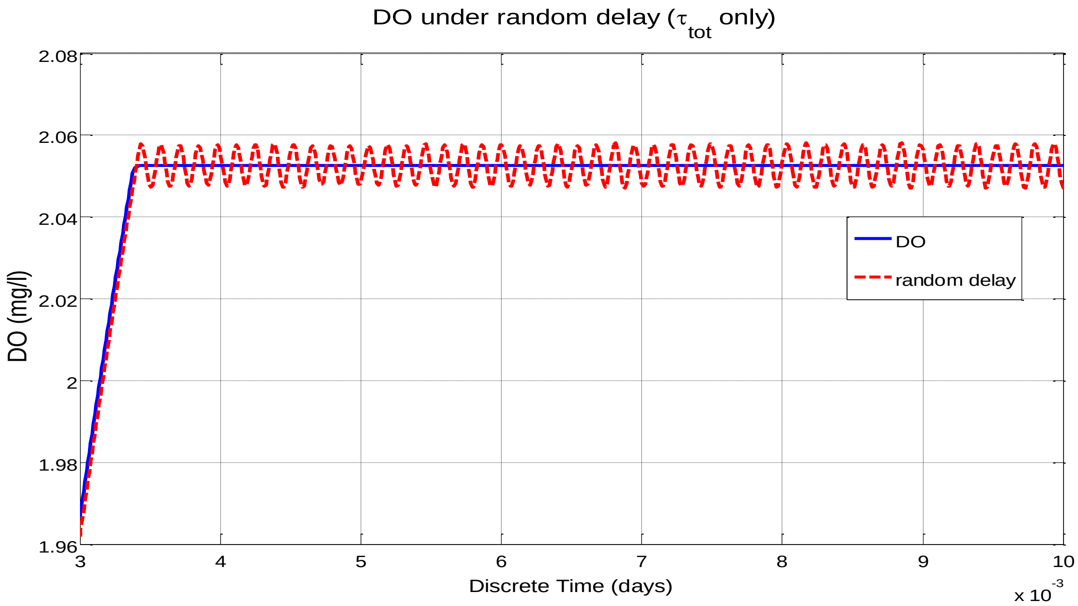

Figure 4.24: Case 2, τ_{ca} = 0.000014 days, τ_{sc} = 0.000013 days, τ_{tot} = 0.000027 days, K_p = 3.2, T_i = 5000

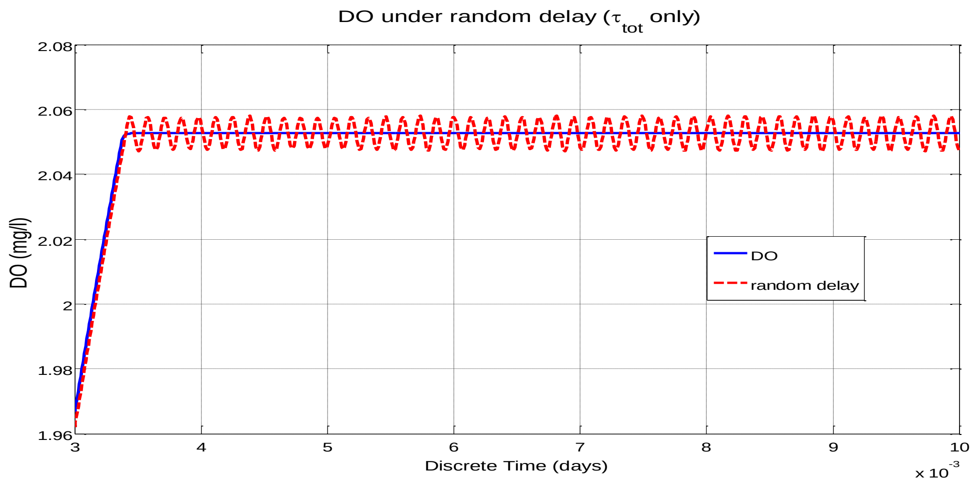

Figure 4.25: Case 2, τ_{ca} = 0.000014 days, τ_{sc} = 0.000013 days, τ_{tot} = 0.000027 days,

K_p =3.2, T_i = 8000

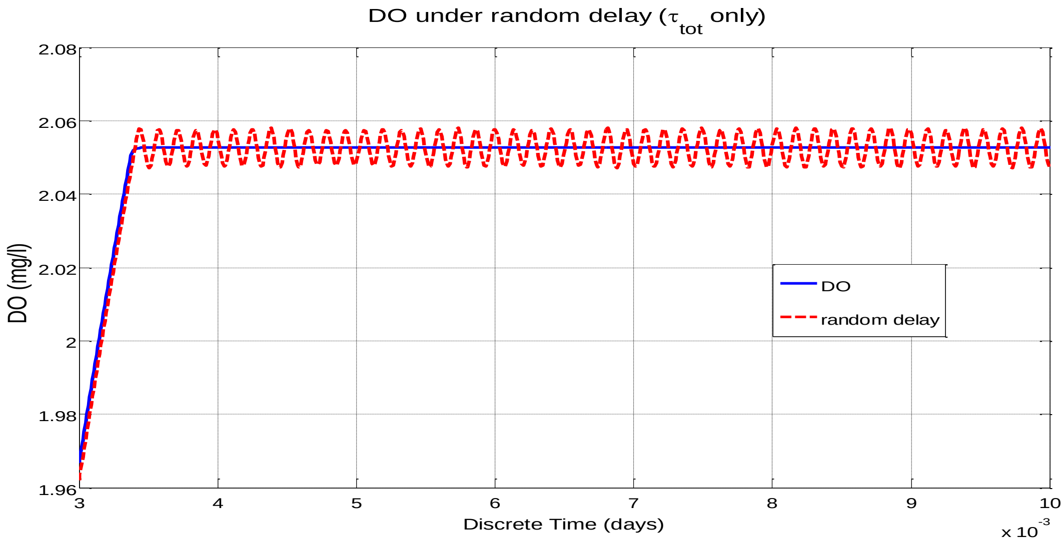

Figure 4.26: Case 2, τ_{ca} = 0.000014 days, τ_{sc} = 0.000013 days, τ_{tot} = 0.000027 days,

K_p = 3.2, T_i = 11000

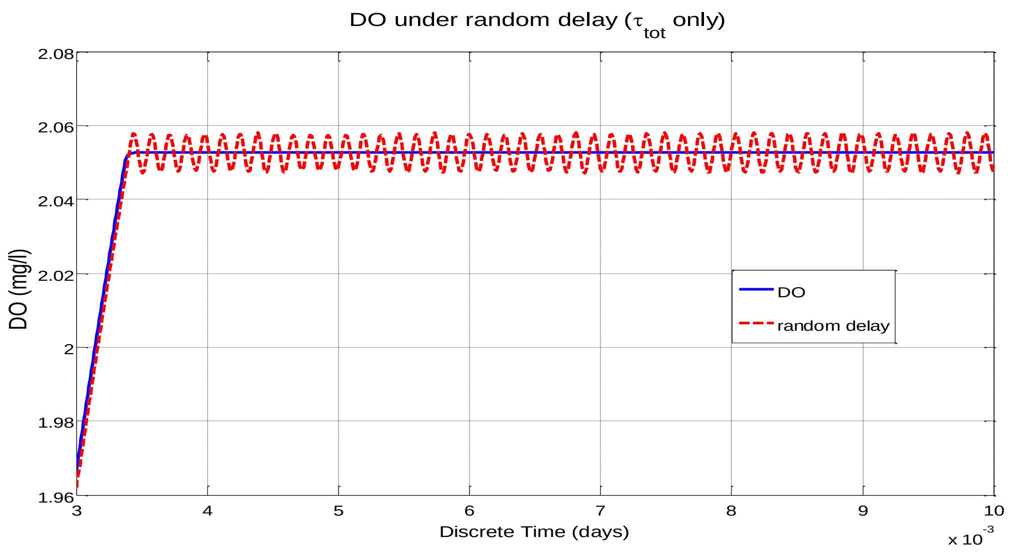

Figure 4.27: Case 2, τ_{ca} = 0.000014 days, τ_{sc} = 0.000013 days, τ_{tot} = 0.000027 days,

K_p = 3.2, T_i = 14000

4.6.3 Simulation results of case 3: Both K_p and T_i are increased from a minimum value to maximum (from 2.2 to 5.2 for K_p and from 2000 to 14000 for T_i).

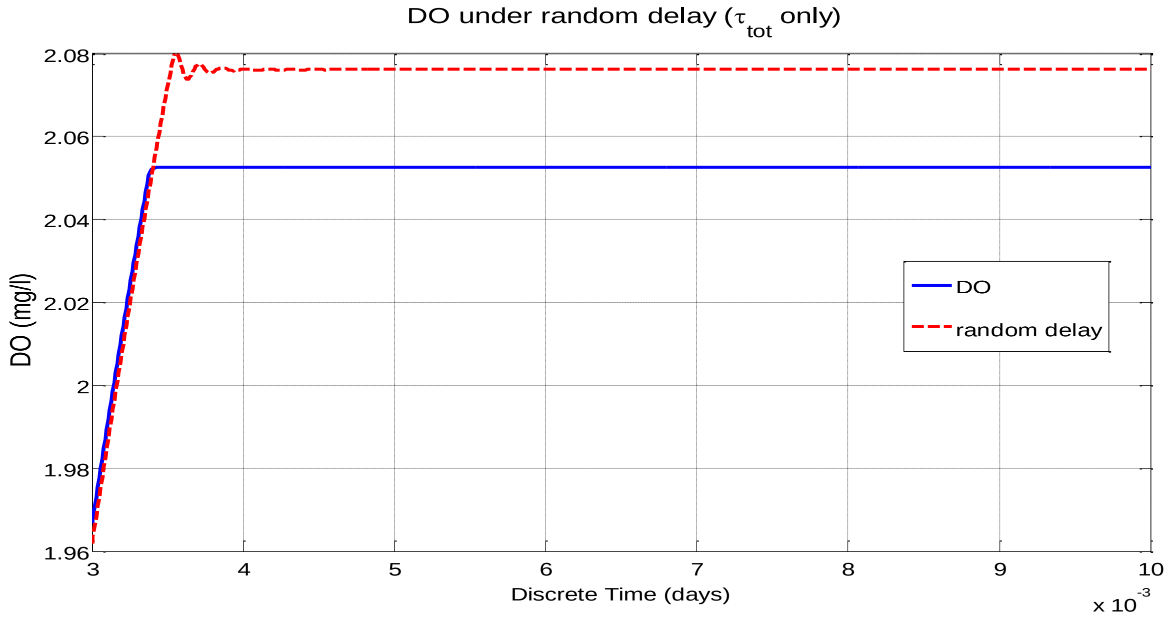

Figure 4.28: Case 3, τ_{ca} = 0.000014 days, τ_{sc} = 0.000013 days, τ_{tot} = 0.000027 days,

K_p = 2.2, T_i = 2000

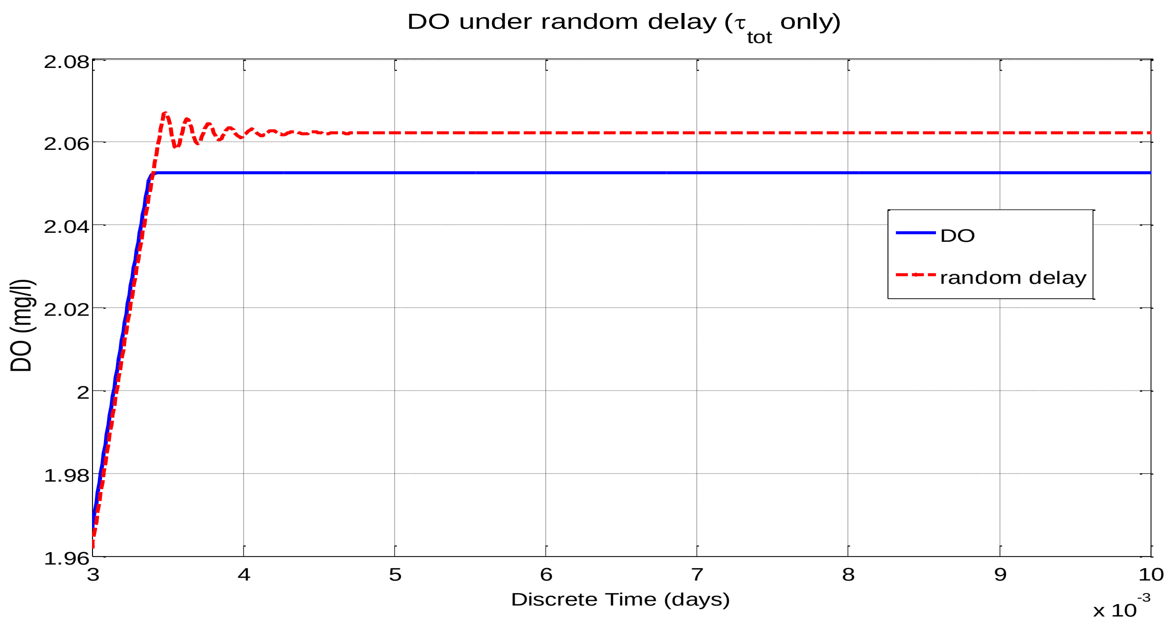

Figure 4.29: Case 3, τ_{ca} = 0.000014 days, τ_{sc} = 0.000013 days, τ_{tot} = 0.000027 days,

K_p = 2.7, T_i = 5000

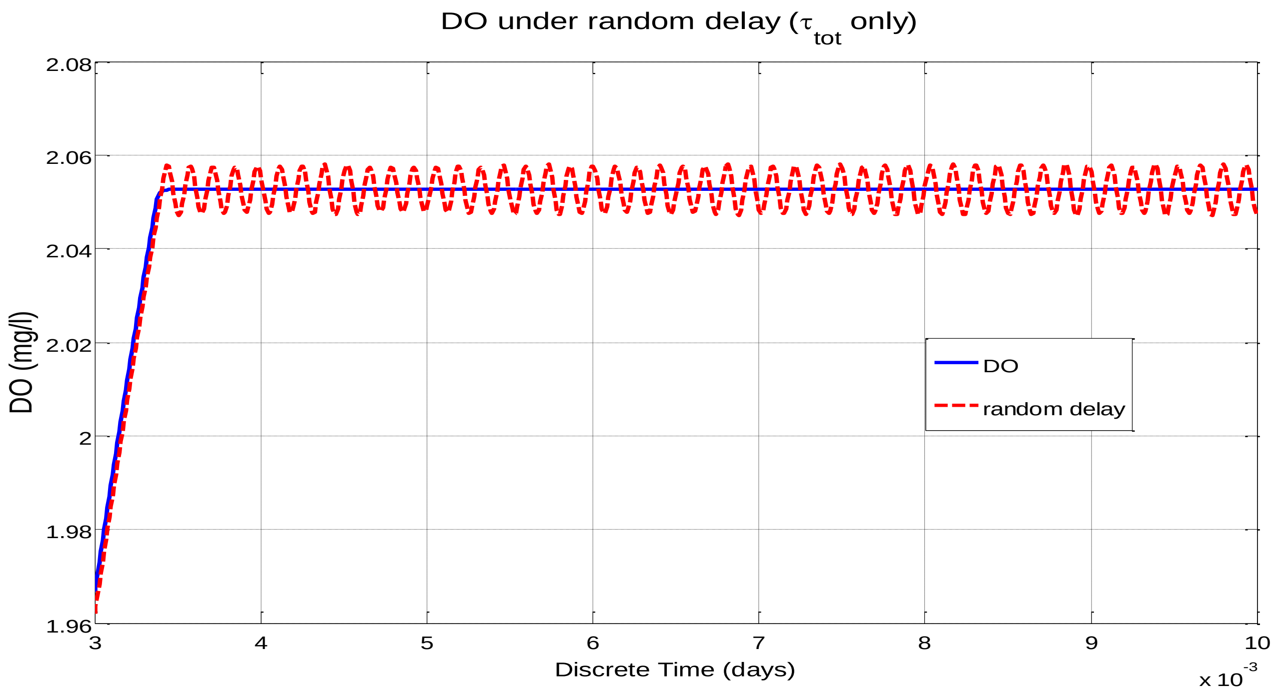

Figure 4.30: Case 3, τ_{ca} = 0.000014 days, τ_{sc} = 0.000013 days, τ_{tot} = 0.000027 days,

K_p = 3.2, T_i = 8000

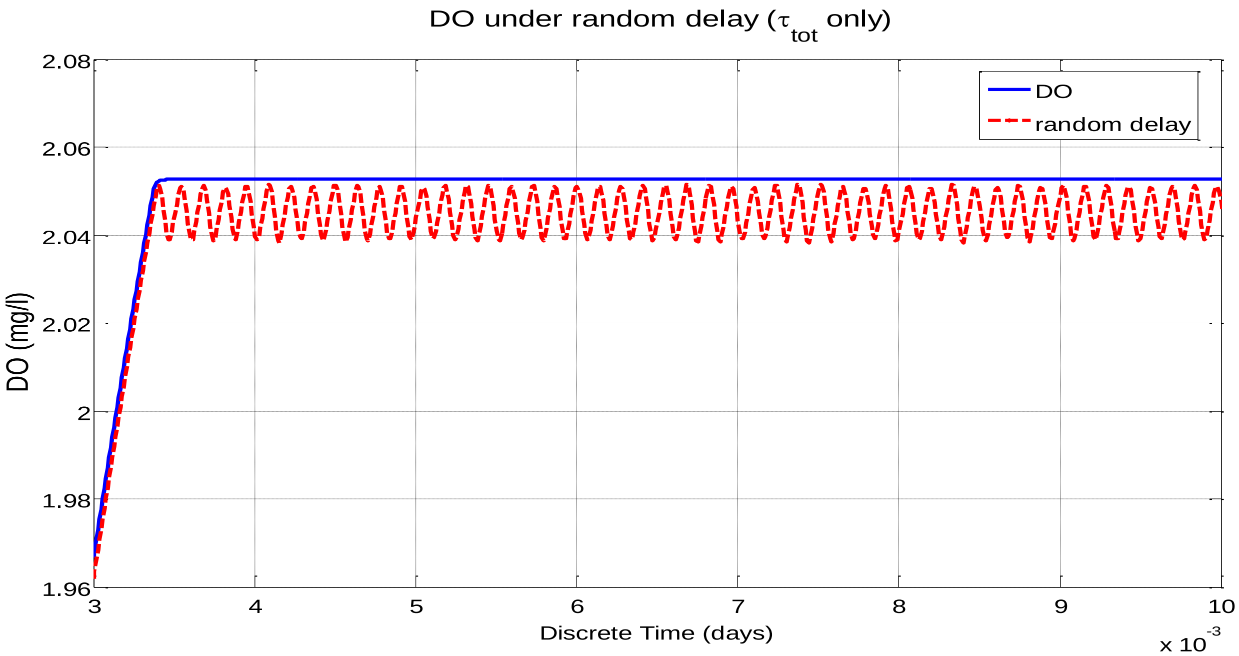

Figure 4.31: Case 3, τ_{ca} = 0.000014 days, τ_{sc} = 0.000013 days, τ_{tot} = 0.000027 days,

K_p = 3.7, T_i = 11000

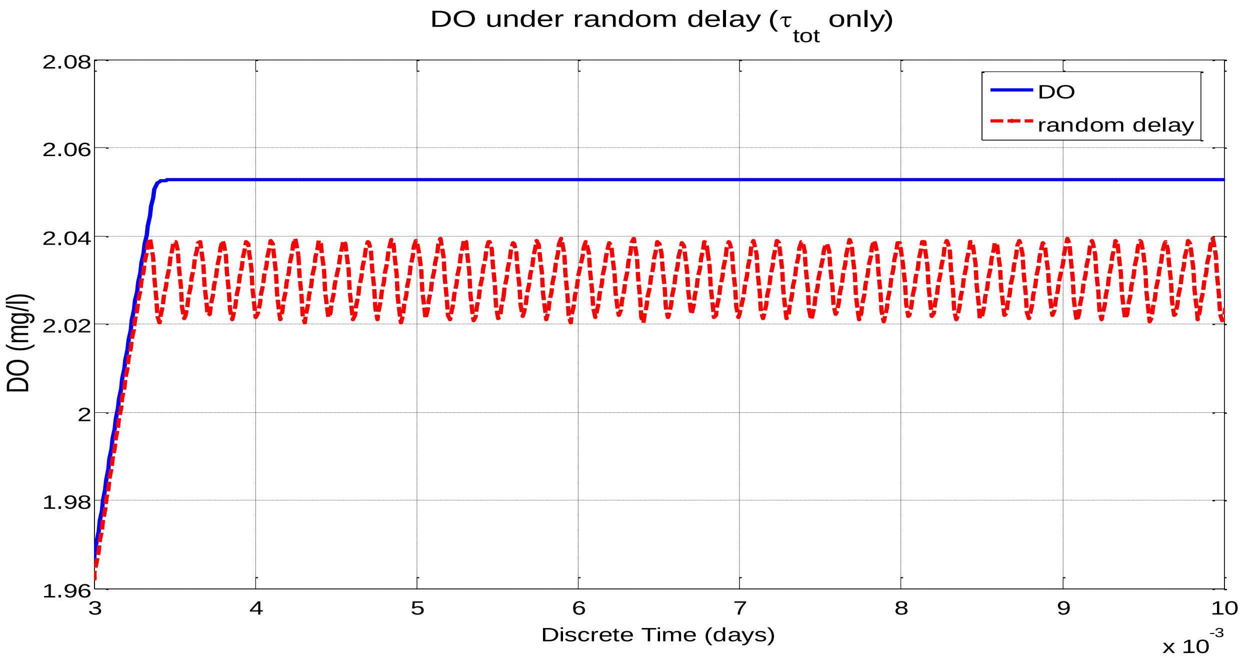

Figure 4.32: Case 3, τ_{ca} = 0.000014 days, τ_{sc} = 0.000013 days, τ_{tot} = 0.000027 days,

K_p = 5.2, T_i = 14000

Table 4.3: Performance indices of the closed loop DO process under random time delays with varying controller parameters (K_p and T_i)

Measurement Conditions	Time delay Values (days)	Kp	Ti	Rise Time (days)	Settling Time (days)	Percentage Overshoot (%)	Steady State Error (mg/l)	Oscillation Amplitude (mg/l) Min; max.	Delay in Response (days)
Case 1									
	0.000027	2.2	8000	0.002014	0.003400	4.01	-0. 0801	2.0738, 2.0801	0.000014
	0.000027	2.7	8000	0.002014	0.003414	3.35	-0.0627	2.0583, 2.0671	0.000014
$\tau_{tot} = \tau_c$	0.000027	3.2	8000	0.002014	0.003414	2.90	-0.0525	2.047, 2.058	0.000014
	0.000027	3.7	8000	0.002014	0.003414	2.57	-0.0449	2.038, 2.0515	0.000014
	0.000027	5.2	8000	0.002014	0.003414	1.97	-0.0296	2.0202, 2.0394	0.000014
Case 2									
	0.000027	3.2	2000	0.002014	0.003400	2.90	-0.0525	2.047, 2.058	0.000014
	0.000027	3.2	5000	0.002014	0.003414	2.90	-0.0525	2.047, 2.058	0.000014
$\tau_{tot} = \tau_c$	0.000027	3.2	8000	0.002014	0.003414	2.90	-0.0525	2.047, 2.058	0.000014
	0.000027	3.2	11000	0.002014	0.003414	2.90	-0.0525	2.047, 2.058	0.000014
	0.000027	3.2	14000	0.002014	0.003414	2.90	-0.0525	2.047, 2.058	0.000014
Case 3									
	0.000027	2.2	2000	0.002014	0.003400	4.01	-0. 0801	2.0738, 2.0801	0.000014
	0.000027	2.7	5000	0.002014	0.003414	3.35	-0.0627	2.0583, 2.0671	0.000014
$\tau_{tot} = \tau_c$	0.000027	3.2	8000	0.002014	0.003414	2.90	-0.0525	2.047, 2.058	0.000014
	0.000027	3.7	11000	0.002014	0.003414	2.58	-0.0449	2.0383, 2.0515	0.000014
	0.000027	5.2	14000	0.002014	0.003414	1.95	-0.0296	2.0203, 2.0389	0.000014

4.6.4 Analysis of the results of the DO Process under random delays with varying controller parameters (K_p and T_i)

In case 1, K_p was increased to be (2.2, 2.7, 3.2, 3.7, 5.2) while T_i was kept constant at 8000. It could be observed that with increase in K_p , the DO process experienced decrease in percentage overshoot, steady state error and oscillation amplitude. However the delay in system response and the rise time remained constant. This is shown in Figures 4.18 to 4.22 and Table 4.3. It could also be observed that with the values of the less than 3.2, the DO process did not experience a sustained oscillation. This suggests that the critical delay for the values of K_p less than 3.2 must be more than 0.000027 days that was obtained in Table 4.2.

In case 2, K_p was kept constant at 3.2 while T_i was increased to be (2000, 5000, 8000, 11000, 14000). Despite the increase in T_i , the system response remained the same as shown in Figures 4.23 to 4.27 and Table 4.3. This suggests that the constant K_p must have made the DO process response the same (constant) despite the variations in the values of T_i .

In case 3, both K_p and T_i were varied. K_p was increased to be (2.2, 2.7, 3.2, 3.7, 5.2) while T_i was also increased to be (2000, 5000, 8000, 11000, 14000). The DO process system performance in case 3 was found to be consistent with case 1 as shown in Figures 4.18 to 4.22, Figures 4.23 to 4.27 and Table 4.3 in terms of percentage overshoot, steady state error, delayed system response and rise time. The only noticeable difference could be found in the oscillation amplitude and steady state error. In case 3, the system experienced 1.95% percentage overshoot as compared to 1.97% in case 1. This occurred when T_i in case 3 was 14000 as compared to 8000 in case 1. Possible explanation could be that the higher value of T_i of 14000 has helped to improve the system performance by reducing percentage overshoot in case 3 when compared to case 1 with a T_i lower value of 8000. Just like the cases 1 and 2, the system's delayed response and rise time were not affected with the increased K_p and T_i.

From this investigation, one could therefore conclude that the value of the critical delay is not only dependent on the magnitude of the random delays introduced into the control system, it is also dependent on the choice of the controller parameters K_p and T_i as seen in Table 3, case 1. This dependency is found to be more with K_p than T_i. Increasing the value of K_p for the DO process from 2.2 to 5.2 showed some initial improvement in system performance as seen in cases 1 and 3 by reducing percentage overshoot, steady state error and oscillation amplitude but at 3.2, a sustained oscillation was experienced from where the DO process control system became unstable. There would therefore be the need to design a new controller that would take cognizance of the random time delays in its design in order to be able to provide robustness and stability for the DO process under the influence of random time delays.

4.7. Discussion of results

The DO concentration with a time constant delay in the range of minutes (Brien et al., 2011) would reach a sustained oscillation (critical delay) in 0.000614 days (53.0496 seconds or 0.88 minutes) delays while the same system would attain critical delay in 0.000027 days (2.3328 secs.) with random delays. This means that the critical random time delay is 16.5 times less than the constant one. The presence of large network time delays in the DO process causes large oscillations and deviation from the desired set point of 2mg/l as shown in Figures 4.11 and 4.17. From Tables 4.1 and 4.2, it could be observed that the DO process oscillation amplitude goes to -0.2 mg/l. Possible explanation could mean that at this point, Oxygen supply is completely cut off from the microorganism in the ASP. Although this phenomenon could result in minimal electrical energy usage in the ASP, it could also hinder the breaking down and elimination of organic substances in the wastewater (Vlad et al, 2001, Chotkowski et al, 2005). The overall effect would be inefficiency in the performance of the ASP.

4.8 The influence of saturation disturbance on the dynamics of the closed loop DO process

During the simulation of the nonlinear linearising controller with the DO process, the closed loop DO process sometimes encountered computational errors (nan/ifn) that could stop the simulation. These errors arose from the implementation of the simulation of mathematical algorithm of the controller and acts as additional random delays in the simulation process. The error nan occurs if a negative value is fed into the Simulink log function block while error inf occurs if a value is divided by zero which results in infinity. In order to overcome these challenges, the saturation block in Simulink is introduced into the nonlinear linearising controller. The purpose of the saturation block is to impose the specified upper and lower values on an input signal (Mathworks, 2014). In this case, it prevent the values going into the Simulink log function block from becoming zero or a negative value. This saturation block allows the user to fix a minimum and maximum saturation value within which the values under consideration must remain. For the purpose of this investigation, the saturation lower and upper limits used are 0.001 and 5 days respectively. The chosen values are determined based on simulation and considered to be the best values for the DO process. The saturation block is shown in

Figure 4.33 while the closed loop DO process in the absence of network delays after the saturation values are fixed is shown in Figure 4.34. It could be seen from the Figure 4.35 that the enlarged closed loop DO process response due to inclusion of saturation block is similar to the random delays responses of Figures 4.13 and 4.16. One could therefore infer that the saturation block introduced into the nonlinear linearising controller is responsible for the randomness in the closed loop DO process response shown in Figure 4.34 and 4.35 even in the absence of network induced time delays.

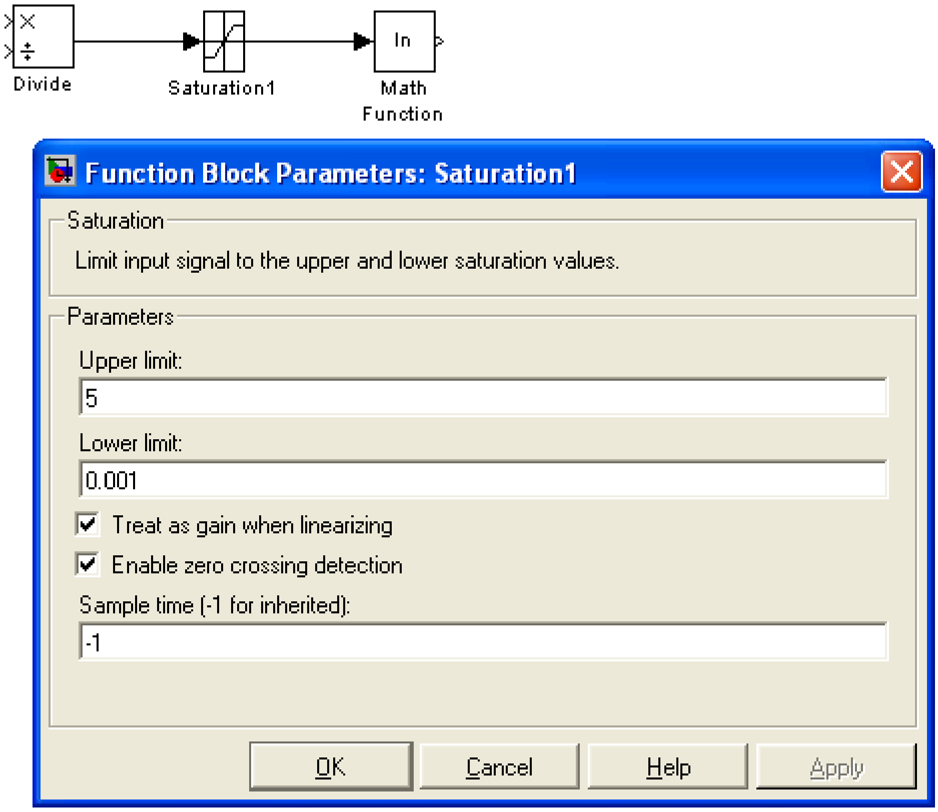

Figure 4.33: Simulink block of the saturation in relation to divide and the log function blocks.

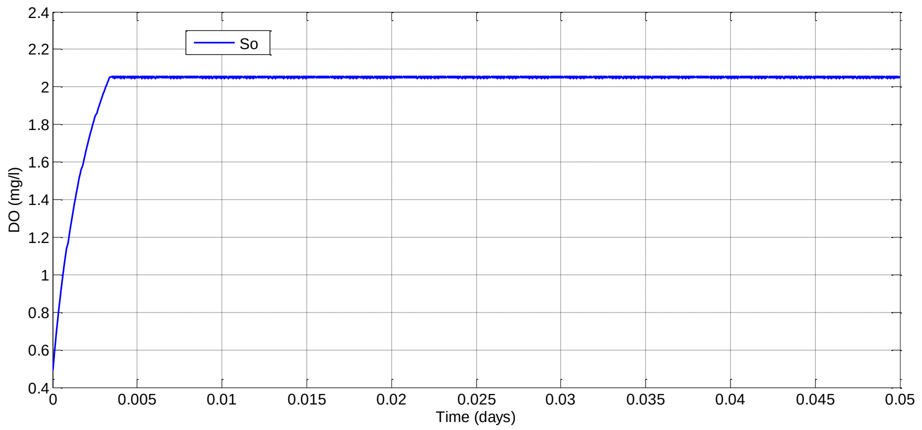

Figure 4.34: Closed loop DO process response under computational disturbance without time delays

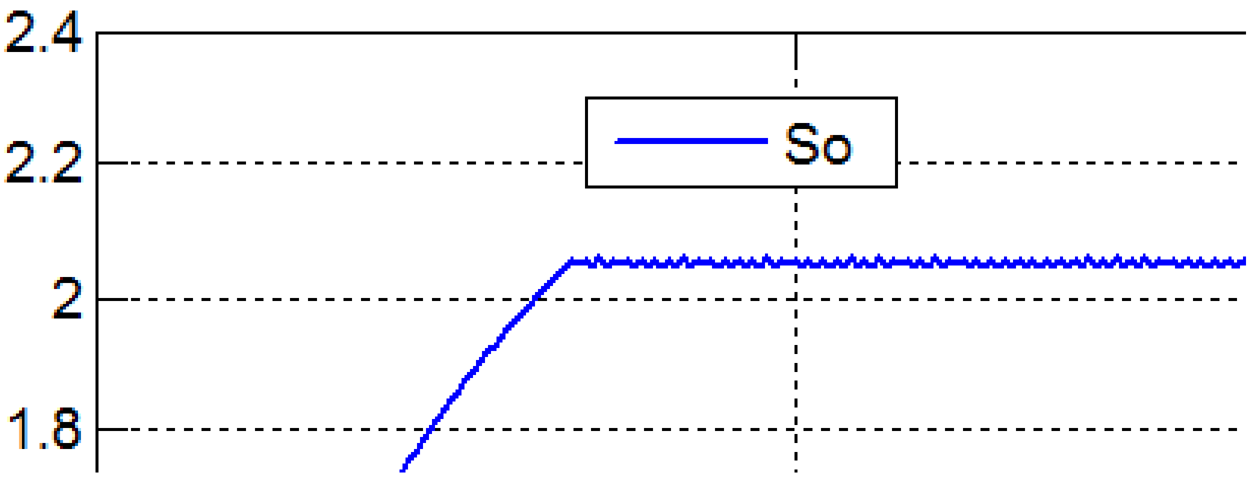

Figure 4.35: Enlarged Closed loop DO process response under saturation disturbance in the absence of network induced time delays

Although this procedure succeeds in overcoming the simulation challenges, it also introduces some type of delay/disturbances (noise) into the system as shown in the response of the closed loop DO process in Figure 4.34. The saturation values are assumed in this section a form of disturbance in the closed loop DO process. In other words, the closed loop DO process under the condition described above does not only have to cope with network induced time delays, it also has to cope with the disturbances introduced into the closed loop control system by the inclusion of the saturation values.

The effects of disturbances on the closed loop DO process as a result of the inclusion of saturation values as well as the capability of the developed Smith predictor to compensate for them are further investigated in Chapters five and six.

4.9 Conclusion

In this Chapter, the effects of the network induced time delays on the DO process behaviour in the ASP are investigated. Simulation results reveal that network induced time delays have adverse effect on the stability and performance of the closed loop DO process by reducing or even depleting the amount of oxygen available for microorganism metabolism resulting in the wastewater not adequately cleaned up and eventual inefficiency of the ASP. The network induced time delays (τ_{ca}, τ_{sc} and combined delay τ_{tot}) have varying influences on the control system (ranging from delayed system response to system overshoot) depending on which of the time delays is in operation at a particular time. The value of the critical delay was also found to vary depending on the type of delay (constant or random delay) and the magnitude of and choice of controller parameters (K_p and T_i). Good choice of K_p for the DO process was found to improve system stability and performance to a certain degree by delaying sustained oscillation while T_i slightly improved the steady state error. It was also found that the introduction of saturation limits to solve some computational errors could result in additional random delays and which are assumed as a form of disturbance in the closed loop DO process. To effectively mitigate the presence of network time delays in the networked DO process and possible disturbances, there is therefore the need to use the information given in this chapter to develop a robust nonlinear networked controller that incorporates the network induced time delays in its design. This networked controller would be able to compensate for networked induced time delays and improve stability and performance for the DO process behaviour in a networked WWTP control. This robust networked controller design for the linearised model of the DO process, is the focus of Chapter five.

CHAPTER FIVE

DESIGN OF A ROBUST SMITH PREDICTOR COMPENSATION SCHEME FOR THE NETWORKED CLOSED LOOP CONTROL OF THE DO PROCESS USING THE TRANSFER FUNCTION APPROACH

5.1 Introduction

In this Chapter, a Smith predictor compensation scheme is designed in order to compensate for the communication drawbacks (time delays) in the closed loop DO process control system as investigated in chapter four. The aim is to ensure that the DO process is able to maintain its desired trajectory despite the presence of network imperfections. Two approaches are used in this thesis depending on where the network induced time delays are placed in relation to the DO process. This chapter uses one of the approaches known as the transfer function approach.

Section 5.2 introduces the Smith predictor compensation scheme. Section 5.3 examines the two different design approaches of Smith predictor design. Section 5.4 deals with the derivation of the Smith predictor scheme using the transfer function approach while section 5.5 considers the simulation of the closed loop DO process behaviour under constant delays and Smith predictor compensation. The simulation results of the DO process under constant delays is discussed in section 5.6. In section 5.7, the simulation of the closed loop DO process behaviour under random delays and Smith predictor compensation are considered and the results discussed in section 5.8. Section 5.9 investigates the behavior of the closed loop DO process under time delays and saturation disturbance while the Chapter concludes in section 5.10.

5.2. The Smith predictor compensation scheme.

The Smith predictor is a control strategy designed by O.J.M. Smith in 1957 (Smith, 1957). It is a form of predictive control to mitigate the challenges of dead-time in a control system. It is found to be the best and most implemented dead-time compensator scheme (Smith, 1957, Smith, 1985, Kuzu and Songuler, 2012) employed to stabilise control systems. The structure of the traditional Smith predictor (Smith, 1957) is such that if there is a plant $G_p(z)$ as shown in Figure 5.1 that has a pure time delay Z^{-k} and if a controller $G_c(z)$ is designed for this plant in the absence of time delay, a closed loop $CL(z)$ transfer function is obtained as shown in equation (5.2).

$$CL(z) = \frac{G_c(z)G_p(z)}{1 + G_c(z)G_p(z)} \tag{5.1}$$

If a controller $\hat{G}_c$ is designed for the plant with network delays $G_p(z^{-k})$, the closed loop transfer function which is $CL(z)$ would become $CL(z)z^{-k}$.

$$\hat{C}L(z) = \frac{\hat{G}_c G_p(z) z^{-k}}{1 + \hat{G}_c G_p(z) z^{-k}} \tag{5.2}$$

This control function has a time delay included in its denominator which means that its transition behaviour will depend on the time delay. The aim is to design for a special expression of the $CL(z)$ such that the $CL(z) = CL(z)z^{-k}$. Then it can be written

$$\frac{\hat{G}_c G_p(z) z^{-k}}{1 + \hat{G}_c G_p(z) z^{-k}} = z^{-k} \frac{G_c G_p}{1 + G_c G_p} \tag{5.3}$$

$$\hat{G}_c = \frac{G_c}{1 + G_c G_p (1 - z^{-k})} \tag{5.4}$$

Equation (5.4) shows that the required $CL(z)$ will be obtained if the designed closed loop controller incorporates the transfer function of the controller designed for the system without delay, the model of the plant of the process and the model of the time delay. The controller is implemented as shown in Figure 5.1 where $G_p(z)$ has been changed to $\hat{G}_p(z)$ to indicate that it is a model used by the controller.

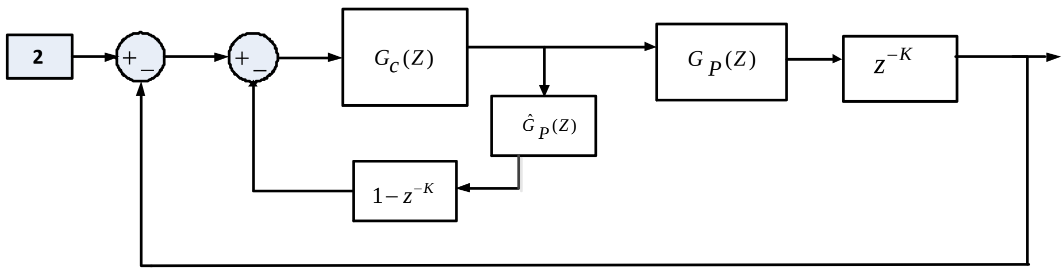

Figure 5.1: The structure of the Smith predictor

The arrangement as shown in Figure 5.1 has two feedback loops. The outer control loop feeds outdated information back to the input due to network time delays. As a result, it would not provide a satisfactory system performance. So for the k seconds during which no fresh information is available, the system is controlled by the inner loop which contains a predictor of what the (unobservable) output of the plant $G_p(z)$ currently is. Re-arranging the scheme as shown in Figure 5.2, the outcome is that the outer and middle loop cancels while the system makes use of the inner loop to give a satisfactory result. The only constraint is that the plant model used for designing the Smith predictor $\hat{G}_p(z)z^{-k}$ and the original plant model $G_p(z)z^{-k}$ must match each other. In other words, model uncertainty is a factor that can adversely impact on the Smith predictor performance. It must be noted however that the Smith predictor since the time it was proposed by O.J. Smith had undergone several modifications. For the purpose of this study, it is assumed that there exists no model uncertainty in the COST benchmark model of the ASP used in this thesis.

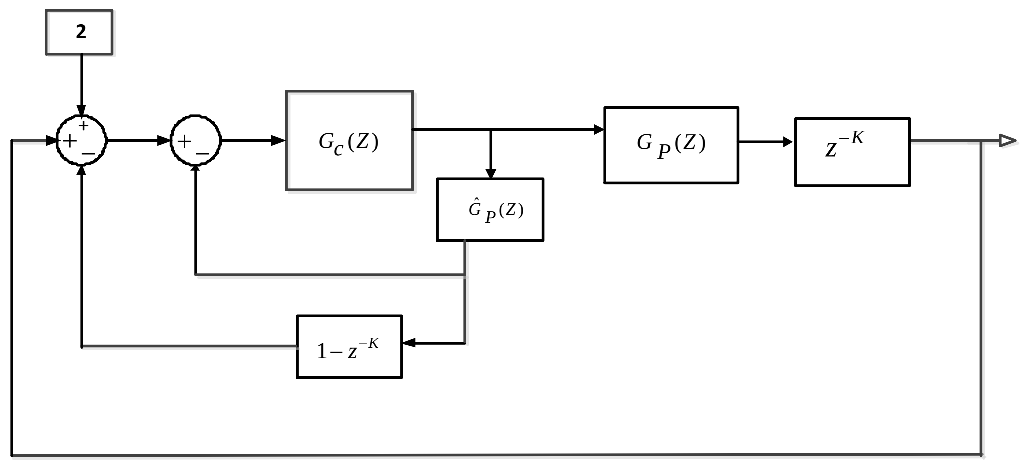

Figure 5.2: The rearranged structure of the Smith predictor

5.3 Arrangements for implementation of the Smith predictor

Since the purpose of the Smith predictor in this study is to compensate for the time delays in the networked DO process control system, two different cases or arrangements for implementing the compensation scheme are investigated. These are shown in Figure 5.3.

Case 1: The nonlinear controller and the DO process together results in a linearised model of the closed loop system. In other words, this is a scenario where the PI controller is being used to control the linearised model of the linearised closed loop DO process and the two (PI controller and the linearised DO process) are separated by a communication network. This allows a closed loop transfer function to be used to describe the behaviour of the linearised closed loop system (Kravaris and Wright, 1989). The Smith predictor compensation scheme is performed on the side of the PI controller only. This is shown in Figure 5.3, case 1. Case 2: In this case, the PI and the nonlinear controller are far from the DO process. In other words, the two controllers (PI and nonlinear linearising controller) are used to control the nonlinear DO model of the DO process over a communication network as shown in Figure 5.3, case 2. This implies that a transfer function cannot be applied to model the DO process. The Smith predictor in case 2 is performed on the side of the controllers (PI and nonlinear linearising controller).

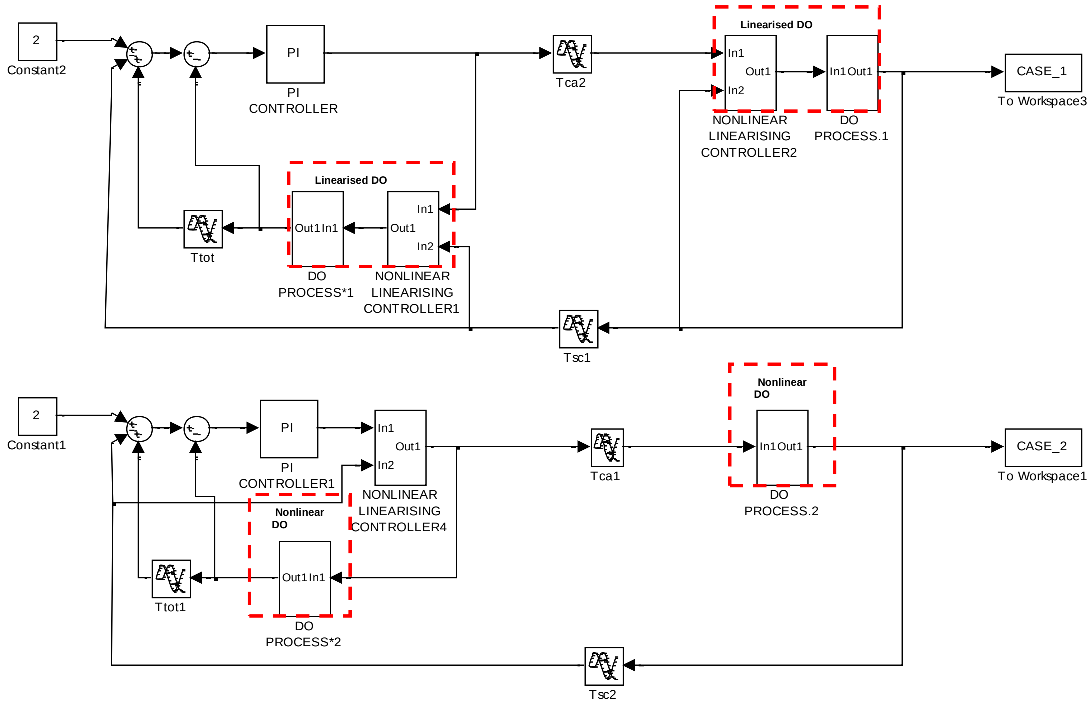

Figure 5.3: Simulink block showing different implementations of the Smith predictor

In this Chapter, the approach in case 1 is used while case 2 is the subject of Chapter six. It must be noted that in some cases, the Smith predictor can be performed on the side of the plant (Du Feng and Zhi, 2009).

Figure 5.4 shows the block diagram of the networked DO process without Smith predictor while in Figure 5.5, the Smith predictor compensation scheme proposed in this thesis is introduced to compensate for the time delays. $G_p(s)$ is the transfer function of the closed loop system consisting of the DO process and the nonlinear linearising controller. As such, it is now regarded as a linear DO process because its dynamics have been transformed from nonlinear to that of an equivalent linear DO process. $G_p^m(s)$ is the model of the linear DO process that is used in the design of the Smith predictor. $C(s)$ is the transfer function of the PI controller designed to control the linear DO process to ensure that its desired set point value is maintained. $R(s)$ is the desired set point to be followed.

5.4 Derivation of the transfer function of the closed loop system incorporating the Smith predictor

The derivation of the transfer function for the closed loop system of the DO process under the influence of network time delays and incorporating the proposed Smith predictor scheme in Figure 5.6 is as follows:

$$S_o(s) = G_p(s)e^{-\tau_{ca}s}C(s)E(s) \tag{5.5}$$

$$E(s) = R(s) - S_o(s)e^{-\tau_{sc}s} - G_p^m(s)\left[1 - e^{-(\tau_{ca}+\tau_{sc})s}\right]C(s)E(s) \tag{5.6}$$

From equation (5.6)

$$E(s)\left[1 + G_p^m(s)\left[1 - e^{-(\tau_{ca}+\tau_{sc})s}\right]C(s)\right] = R(s) - S_o(s)e^{-\tau_{sc}s} \tag{5.7}$$

From equation (5.7)

$$E(s) = \frac{R(s) - e^{-\tau_{sc}s}S_o(s)}{\left[1 + G_p^m(s)\left[1 - e^{-(\tau_{ca}+\tau_{sc})s}\right]C(s)\right]} \tag{5.8}$$

Substitute equation (5.8) into equation (5.5)

$$S_o(s) = G_p(s)e^{-\tau_{ca}s}C(s)\frac{R(s) - e^{-\tau_{sc}s}S_o(s)}{\left[1 + G_p^m(s)\left[1 - e^{-(\tau_{ca}+\tau_{sc})s}\right]C(s)\right]} \tag{5.9}$$

$$S_o(s) = \frac{G_p(s)e^{-\tau_{ca}s}C(s)R(s)}{\left[1 + G_p^m(s)\left[1 - e^{-(\tau_{ca}+\tau_{sc})s}\right]C(s)\right]} - \frac{G_p(s)e^{-\tau_{ca}s}C(s)e^{-\tau_{sc}s}S_o(s)}{\left[1 + G_p^m(s)\left[1 - e^{-(\tau_{ca}+\tau_{sc})s}\right]C(s)\right]} \tag{5.10}$$

From equation (5.10), is expressed as

$$S_o(s)\left[1 + \frac{G_p(s)e^{-(\tau_{ca}+\tau_{sc})s}C(s)}{1 + G_p^m(s)\left[1 - e^{-(\tau_{ca}+\tau_{sc})s}\right]C(s)}\right] = \frac{G_p(s)e^{-(\tau_{ca})s}C(s)R(s)}{1 + G_p^m(s)\left[1 - e^{-(\tau_{ca}+\tau_{sc})s}\right]C(s)} \tag{5.11}$$

Transfer function of the closed loop system is

$$\frac{S_o(s)}{R(s)} = \frac{G_p(s)e^{-(\tau_{ca})s}C(s) \Big/ \left\{1 + G_p^m(s)\left[1 - e^{-(\tau_{ca}+\tau_{sc})s}\right]C(s)\right\}}{1 + \dfrac{G_p(s)e^{-(\tau_{ca}+\tau_{sc})s}C(s)}{1 + G_p^m(s)\left[1 - e^{-(\tau_{ca}+\tau_{sc})s}\right]C(s)}} \tag{5.12}$$

Given that $G_p(s) = G_p^m(s)$,the transfer function for the closed loop linearised DO process is

$$\frac{S_o(s)}{R(s)} = \frac{G_p(s)e^{-\tau_{ca}s}C(s)}{1 + G_p(s)C(s)}$$

This could be re-arranged as

$$\frac{S_o(s)}{R(s)} = \frac{G_p(s)C(s)e^{-\tau_{ca}s}}{1+G_p(s)C(s)} \tag{5.13}$$

It could be observed that in equation (5.13), the delay $e^{-\tau_{ca}s}$ is only present in the numerator while network induced time delays in the denominator are completely eliminated. As a result, the time delays in the system are compensated because the stability of the system is determined mostly by the denominator of the transfer function.

The Smith predictor is a compensator (corrector) that attempts to virtually hide the time delays in the closed loop system in order to make available a virtual system without time delays to the PI controller (Raju, 2009). As shown in Figure 5.6, the Smith predictor has two feedback loops namely the outer and the inner feedback loops. The outer feedback loop is not good enough for process control due to the presence of a combined effect of network induced time delays (τ_{ca} and τ_{sc}). As a result, the outer feedback loop will only produce outdated information. In order to sustain the performance of the control system when no fresh information is available to the PI controller, the inner feedback loop which contains a Smith predictor takes over. This inner feedback loop consists of a modified model of the linear DO process $G_p^m(s)$, the PI controller $C(s)$ and the communication delay (τ_{tot}). τ_{tot} is the sum of τ_{ca} and τ_{sc} where τ_{ca} is the controller to actuator delay and τ_{sc} is the sensor to controller delay and (τ_{ca} and τ_{sc}) are random delays that are varying and uniformly distributed. The Smith predictor functions in a way such that the presence of τ_{tot} in the control system assists in eliminating (cancels out) the negative effects of communication drawbacks (τ_{ca} and τ_{sc}) in the outer feedback loop of the closed loop DO process. The aim is to ensure that the feedback signal made available to the PI controller is without network induced time delays.

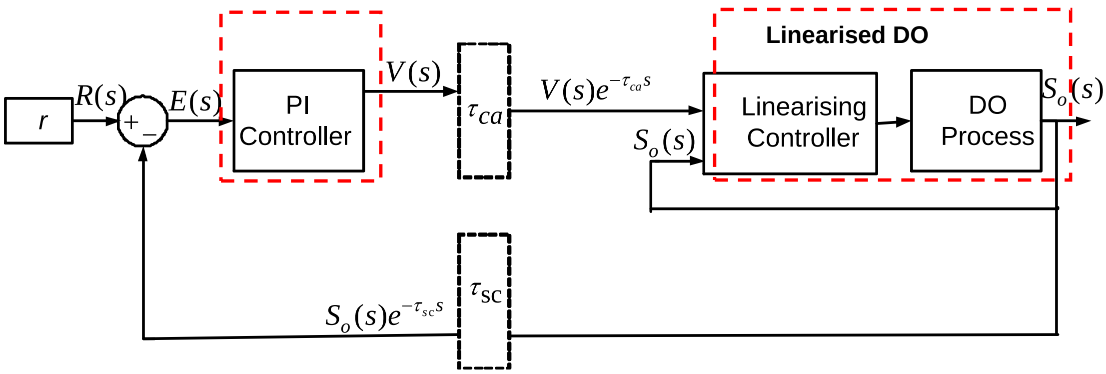

Figure 5.4: PI controller with the linearised closed loop DO process under the influence of the network induced time delays

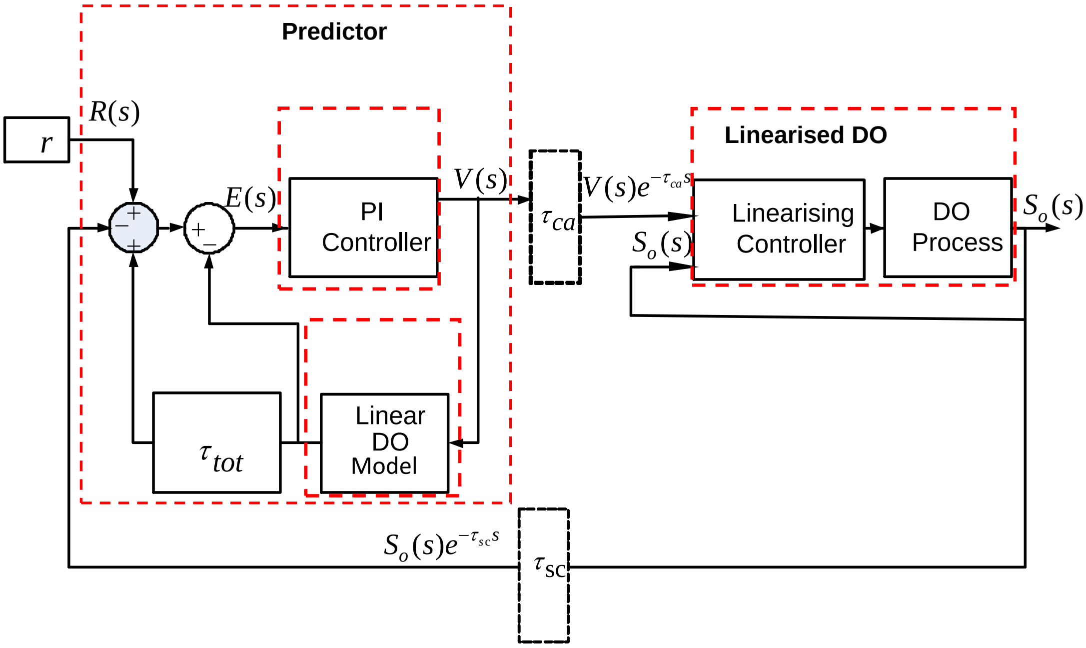

Figure 5.5: Smith predictor for the linearised closed loop DO process under the influence of network induced time delays

It should be noted that the traditional Smith predictor shown in Figures 5.1 and 5.2 has time delays only in the forward path (τ_{ca}) but the proposed Smith predictor scheme in this thesis as shown in Figure 5.5 is designed to compensate for time delays in the forward and feedback paths. In (Velagic, 2008), the author assumed that ($\tau_{ca} = \tau_{sc}$). and developed a network predictive Smith controller using the mean of previous and past values of τ_{ca} and τ_{sc}. In this study, total delay τ_{tot} to be compensated is assumed to be the sum of τ_{ca} and τ_{sc}.

5.5 Simulation of the closed loop DO process under constant delays and Smith Predictor compensation scheme

In order to investigate the performance of the proposed Smith predictor compensation scheme, the DO process control system is simulated under the influence of constant time delays and the Smith predictor compensation scheme. The Simulink block is shown in Figure 5.6 and the MATLAB program (experiment6.m), the values of the model and the controller parameters are given in Appendix (C5.1). This Simulink block is developed to consist of three types of investigations. First, the closed loop linearised DO process is simulated without network induced time delays. In the second investigation, communication delays are considered to be part of the closed loop control system. Models of network delays in the form of transport delays are introduced to be part of the closed loop DO process. The third investigation incorporates both the network delays and the Smith predictor scheme. The essence of this is to investigate the effects of the proposed Smith predictor compensation scheme in eliminating the deadtime in the DO process control system. Investigations were performed for four cases:

- $\tau_{ca} + \tau_{sc} = \tau_{tot} < \tau_c$, Figure 5.7,
- $\tau_{ca} + \tau_{sc} = \tau_{tot} = \tau_c$, Figures 5.8,
- $\tau_{ca} + \tau_{sc} = \tau_{tot} > \tau_c$, Figures 5.9,
- $\tau_{ca} + \tau_{sc} = \tau_{tot} >> \tau_c$, Figures 5.10.

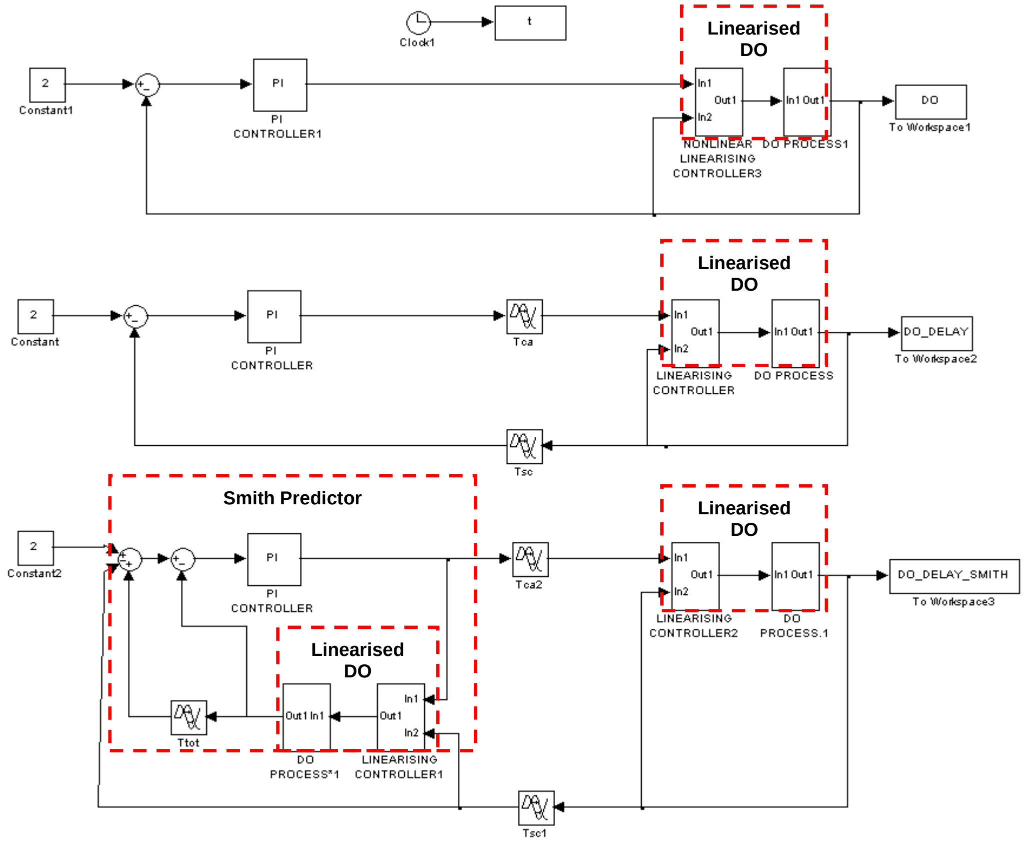

Figure 5.6: Simulink diagrams for investigation of the Smith predictor compensation scheme for the DO process under constant time delays

Case 1:The network induced constant delays are less than the critical delay ($\tau_{ca} + \tau_{sc} = \tau_{tot} < \tau_c$)

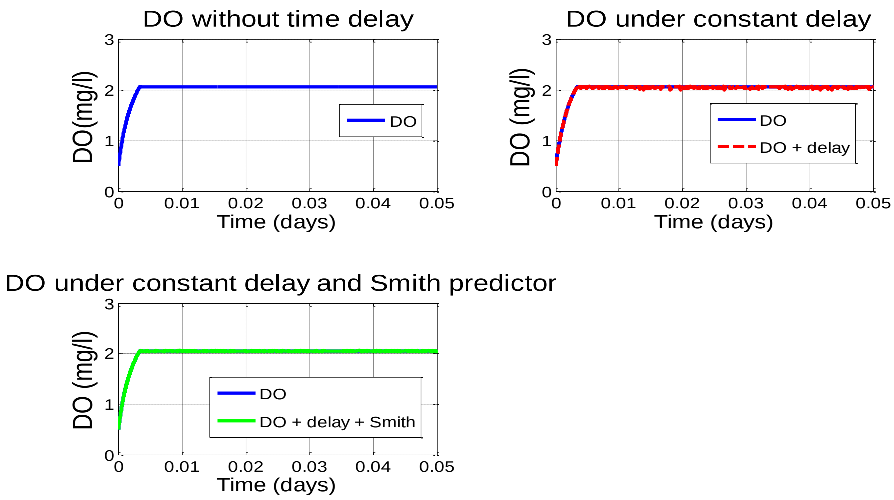

Figure 5.7: a. Simulation results of the DO process closed loop behaviour without time delays b.) DO process under random delays c.) DO process under random delay and Smith predictor. $\tau_{tot} < \tau_c$ **= 0.000033 days (2.85 secs.)**

Case 2: The network induced constant delays are equal to the critical delay ($\tau_{ca} + \tau_{sc} = \tau_{tot} = \tau_c$)

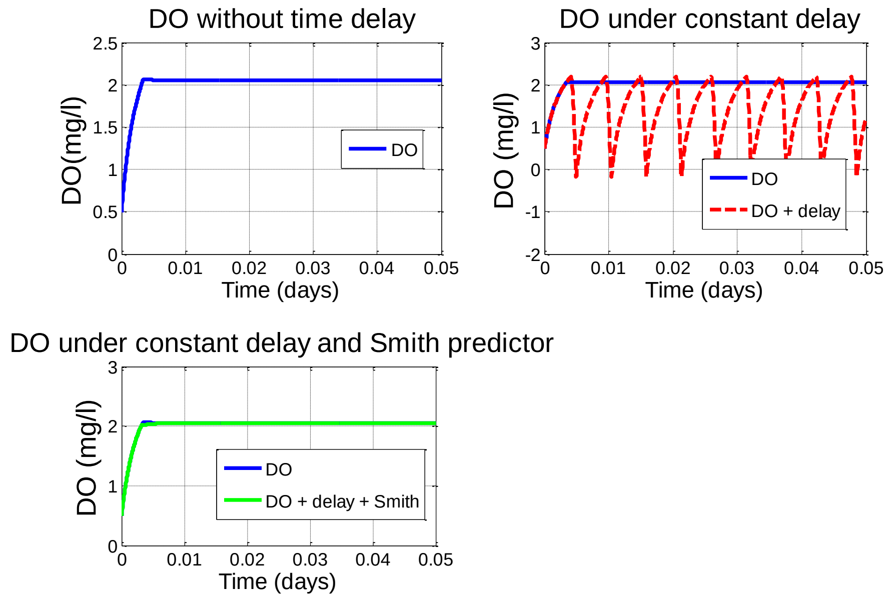

Figure 5.8: a. Simulation results of the DO process closed loop behaviour without time delays b.) DO process under random delays c.) DO process under random delay and Smith predictor. $\tau_{tot} = \tau_c$ **= 0.000752 days (64.9 secs.)**

Case 3: The network induced constant delays are greater than the critical delay ($\tau_{ca} + \tau_{sc} = \tau_{tot} > \tau_c$)

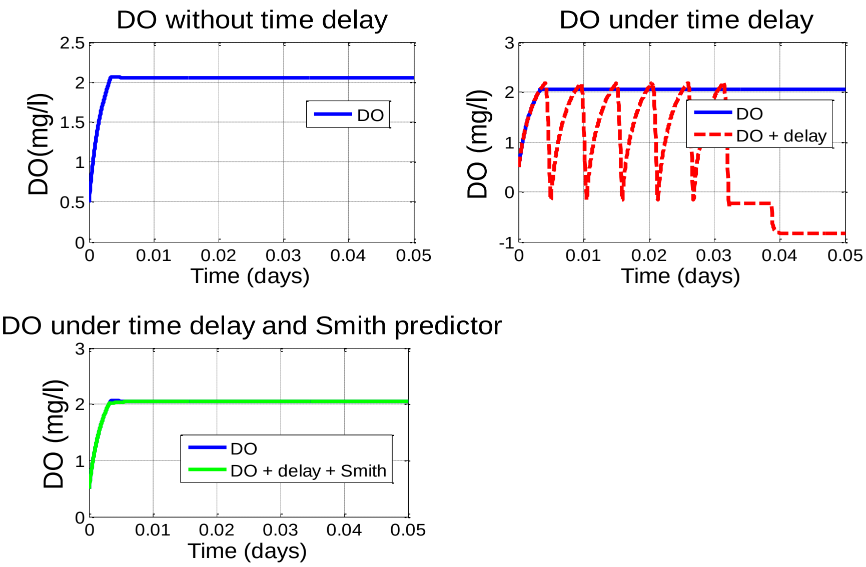

Figure 5.9: a.) Simulation results of the DO process closed loop behaviour without time delays b.) DO process under random delays c.) DO process under random delay and Smith predictor. $\tau_{tot} > \tau_c$ = 0.000754 days (65.14 secs.)

Case 4: The network induced constant delays are much greater than the critical delay ($\tau_{ca} + \tau_{sc} = \tau_{tot} >> \tau_c$)

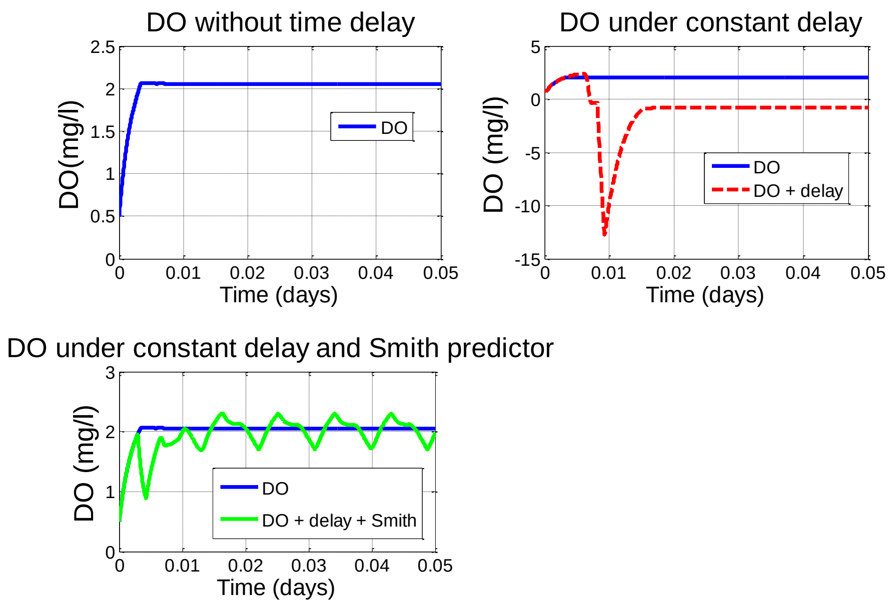

Figure 5.10: a.) Simulation results of the DO process closed loop behaviour without time delays b.) DO process under random delays c.) DO process under constant delay and Smith predictor. $\tau_{tot} >> \tau_c$ = 0.00286 days (247secs.)

5.6. Discussion of results of the DO process under constant delays and the Smith predictor

It could be observed from simulation results in Figures 5.7 to 5.10 and Table 5.1 that the presence of network induced time delays in this case of a of linearised DO process resulted in system overshoot only but did not lead to delay in the system response. It could be that the placement of the nonlinear controller close to the DO process to form a linearised process of the DO as described in sections 4.4 and 5.3, might have compensated for the delays that could have been experienced in the DO process response. As the value of the network induced time delay increased, there was increase in the percentage overshoot and oscillation amplitude for all the cases investigated, however the rise time of the system remained constant. At a critical delay equal to 0.000754 days (65.1456 seconds), the system under constant time delays experienced a sustained oscillation as shown in Figure 5.8b. Beyond this critical delay, the PI controller was no longer able to stabilize the closed loop DO process but the Smith predictor was able to provide robust stability for the system by eliminating the oscillations, reducing oscillation amplitude and percentage overshoot, as shown in Figure 5.8c and Table 5.1. In Figure 5.9c, the DO concentration went below zero, possible explanation for this is that at this time delay of 0.000754 (65.14 secs.), the oxygen in the wastewater is completely depleted. The implication is that there is no more oxygen available for the microorganism. This situation can inhibit the performance of the microorganisms and lead to failure of the ASP (Macnab, 2014). It could be seen from Figure 5.9c that even at this stage, the proposed Smith predictor scheme is still able to stabilise the DO process. However, it could be seen from Figure 5.10 that at a delay value equal to 0.00286 days (247 secs.), the Smith predictor compensation scheme became unstable and no longer adequate to provide the necessary stability for the system under constant delays. This delay is not a realistic one and it can not exist during the normal work of the system. Table 5.1 shows the performance indices of the closed loop DO process control system under different conditions of constant time delays and the proposed Smith predictor compensation scheme.

Table 5.1: Performance indices of the behaviour of the closed loop with and without Smith predictor DO process under different constant delay conditions.

Measurement Conditions	Time delay Values (days)	Rise Time (days)	Settling Time (days)	Percentage Overshoot (%)	Steady State Error (mg/l)	Oscillation Amplitude (mg/l)	Delay in Response (days)
Delay							
$\tau_{tot} = 0$	0	0.002000	0.003600	2.0	-0.04000	2.040	0
$\tau_{tot} < \tau_c$	0.000033	0.002000	0.003800	3.6	1.916	1.988, 2.072	0
$\tau_{tot} = \tau_c$	0.000752	0.002000	0.003800	9.2	-0.349	-0.166, 2.183	0
$\tau_{tot} > \tau_c$	0.000754	0.002000	0.040000	9.2	-1.0154	-0.8324, 2.183	0
Delay +Smith							
$\tau_{tot} = 0$	0	0.002000	0.003600	2.0	-0.04000	2.040	0
$\tau_{tot} < \tau_c$	0.000033	0.002000	0.003800	3.2	1.9700	2.035, 2.065	0
$\tau_{tot} = \tau_c$	0.000752	0.002000	0.005800	2.6	1.9684	2.0209, 2.0525	0
$\tau_{tot} > \tau_c$	0.000754	0.002000	0.005800	2.6	1.9684	2.0209, 2.0525	0

5.7 Simulation of the closed loop DO process under random delays and Smith predictor compensation scheme

Due to the fact that communication drawbacks in the Ethernet which is the network of choice in the thesis are not constant but random, it therefore means that a Smith predictor scheme under constant delays condition only would not provide adequate compensation for a real-life scenario. As a result of this, the networked DO process was simulated under the influence of random time delays. During this simulation, the performance of the PI controller was compared with the developed Smith predictor compensation scheme in controlling the linear (linearised) closed loop DO process. The Simulink block for this is shown in Figure 5.11. The MATLAB program (experiment7.m) with the values of the model and the controller parameters is given in Appendix (C5.2). The Simulink block in Figure 5.11 is sued for the investigations of the closed loop DO process without time delays, with time delays and with time delays and Smith predictor compensation scheme. In each of these cases, τ_{ca} and τ_{sc} are summed as ($\tau_{tot} = \tau_{ca} + \tau_{sc}$).The investigations of the transient behaviour of the two schemes from Figure 5.11 are done for the three cases of random delays:

- $\tau_{ca} + \tau_{sc} = \tau_{tot} < \tau_c$, Figure 5.12
- $\tau_{ca} + \tau_{sc} = \tau_{tot} = \tau_c$, Figure 5.13
- $\tau_{ca} + \tau_{sc} = \tau_{tot} > \tau_c$, Figure 5.14
- $\tau_{ca} + \tau_{sc} = \tau_{tot} >> \tau_c$, Figure 5.15

The last value in Figure 5.15 is not realistic but is used to check the performance of the system with the Smith predictor in extreme conditions. The generation of the random time delays was carried by adopting the method used in section 4.5.2 and Figures 4.10 and 4.11 where the time delays (τ_{ca} and τ_{sc}),were assumed to be random variables which are uniformly distributed (Velagic, 2008). The Zero Order Hold (ZOH) method was applied to discretize the DO process with a sampling rate of T = 0.00001days (0.864 secs.). The probability distribution was selected such that the noise to signal ration is 10% (Searchnetworking, 2014). The simulation results are in Figure 5.12 to 5.15.

5.8 Discussion of results from the simulation of the DO process under random delays and the Smith predictor

Simulation carried out on the DO process under the influence of random time delays and the Smith predictor compensation scheme reveal that as the network induced constant and random delays increase, the DO process behaviour was similar. This is in relation to the increase in system overshoot, oscillation amplitude and percentage overshoots. There was no delay in the system response and as such, the rise time was constant as well as the system settling time. This could be observed in Figures 5.12 to 5.14 and Table 5.2. It must be noted however that the random critical delay was attained at 0.000027 days compared to 0.000752 days in the case of constant delays. This means that the critical random delay is 21.1 times less the value of the constant critical delay. The Smith predictor in the case of random delays was also observed to out-perform the PI controller in stabilizing the DO process. At the 0.000027 days random critical delay, the PI controller failed to provide good performance and stability for the DO process but the developed Smith predictor continues to stabilize the system until 0.01978 days (1709 secs.) when the Smith predictor attained a sustained oscillation. This could be said to be the critical delay for the DO process Smith predictor under random time delays.

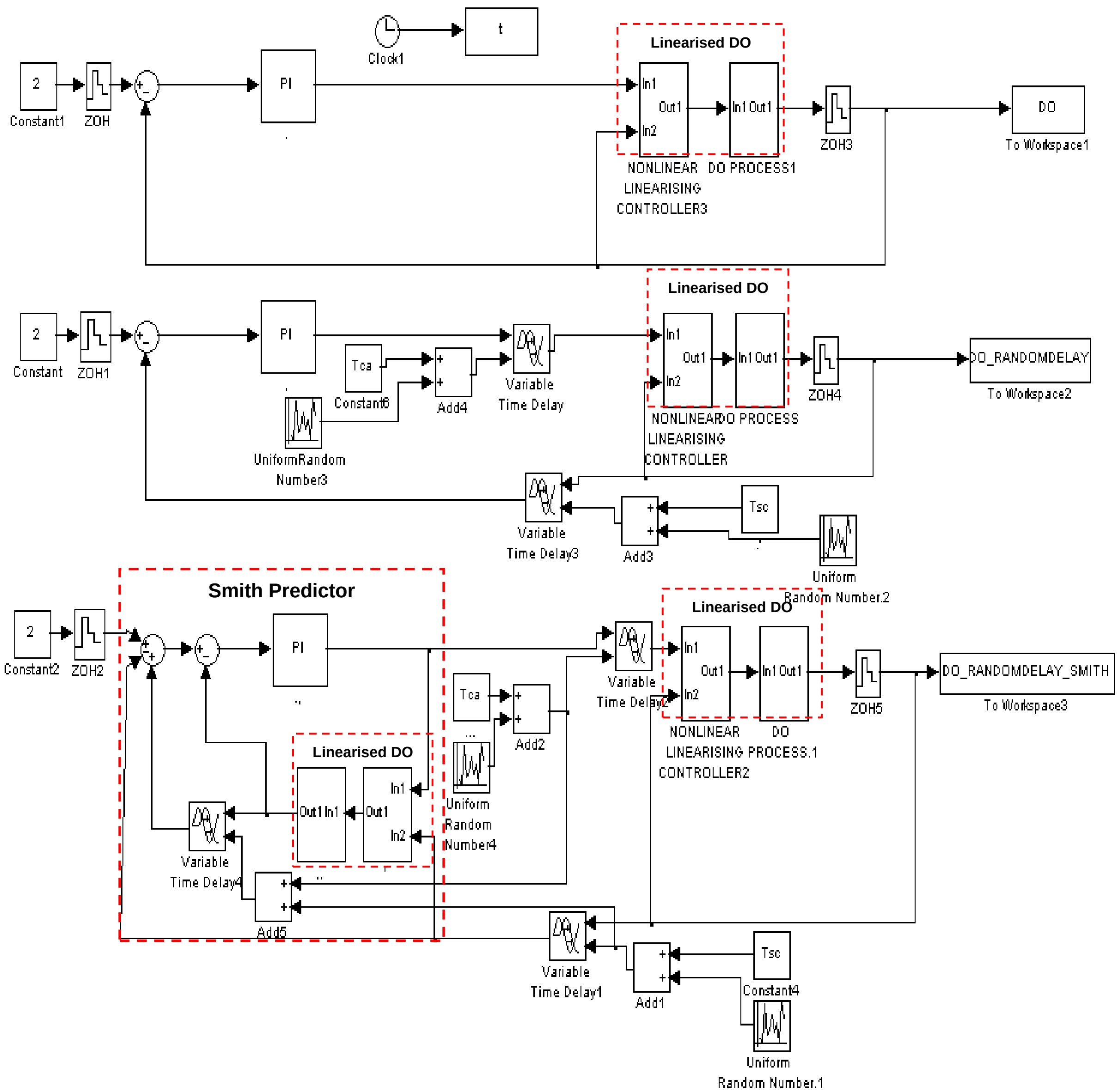

Figure 5.11: Simulink diagrams for investigation of the Smith predictor compensation scheme for the DO process under random delays

Case 1:The network induced constant delays are less than the critical delay ($\tau_{ca} + \tau_{sc} = \tau_{tot} < \tau_c$)

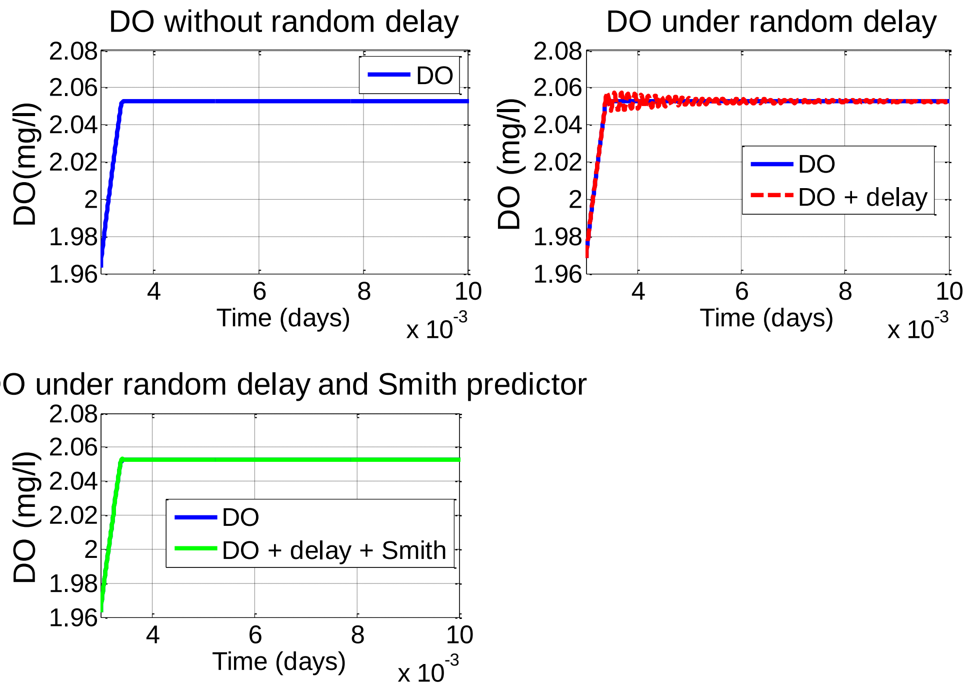

Figure 5.12: a.) Simulation results of the DO process closed loop behaviour without time delays b.) DO process under random delays c.) DO process under random delay and Smith predictor. $\tau_{tot} < \tau_c$ = 0.000026 days (2.85 secs.)

Case 2: The network induced constant delays are equal to the critical delay ($\tau_{ca} + \tau_{sc} = \tau_{tot} = \tau_c$)

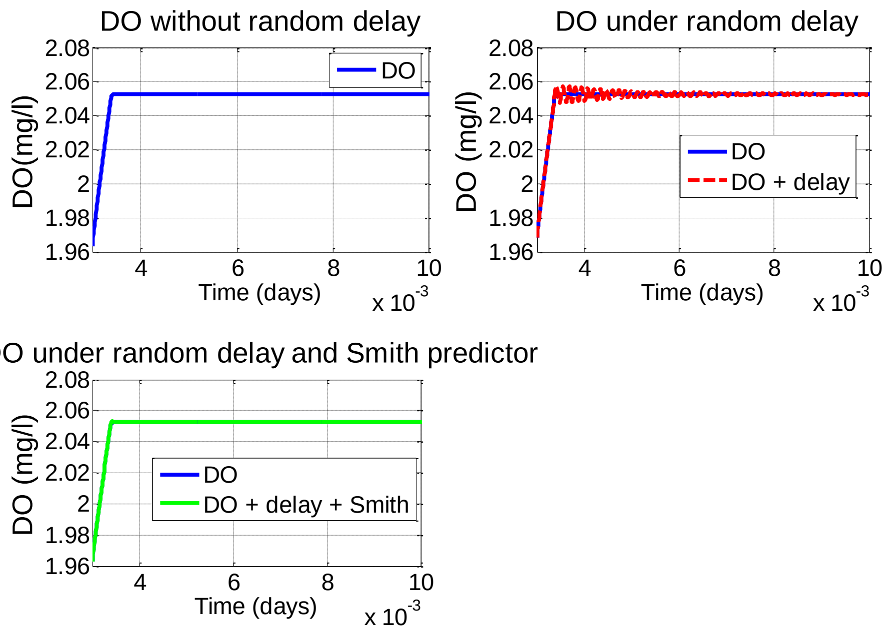

Figure 5.13: a.) Simulation results of the DO process closed loop behaviour without time delays b.) DO process under random delays c.) DO process under random delay and Smith predictor. $\tau_{tot} = \tau_c$ = 0.000027 days (0.233 secs.)

Case 3: The network induced constant delays are greater than the critical delay ($\tau_{ca} + \tau_{sc} = \tau_{tot} > \tau_c$)

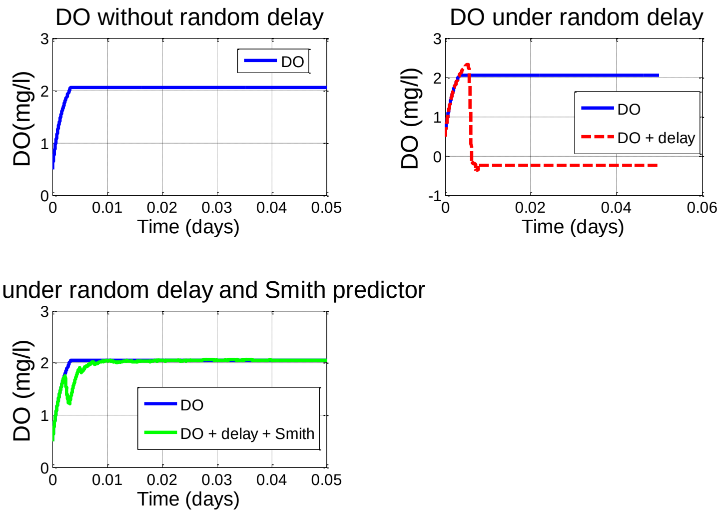

Figure 5.14: a.) Simulation results of the DO process closed loop behaviour without time delays b.) DO process under random delays c.) DO process under random delay and Smith predictor. $\tau_{tot} > \tau_c$ **= 0.00204 days (176 secs.)**

Case 4: The network induced constant delays are much greater than the critical delay ($\tau_{ca} + \tau_{sc} = \tau_{tot} >> \tau_c$)

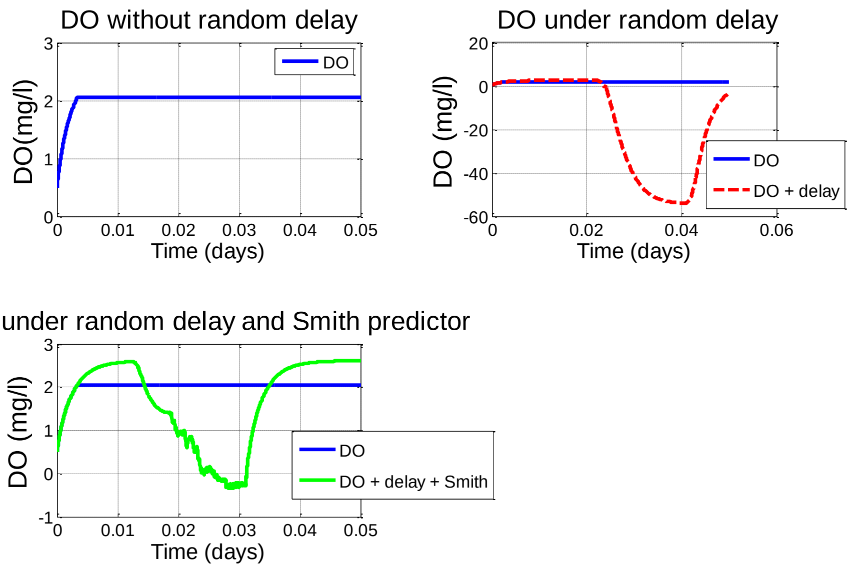

Figure 5.15: a.) Simulation results of the DO process closed loop behaviour without time delays b.) DO process under random delays c.) DO process under random delay and Smith predictor. $\tau_{tot} >> \tau_c$ **= 0.01978 days (1709 secs.)**

Table 5.2 contains the performance indices of the closed loop DO process control system under network induced random time delays and the proposed Smith predictor compensation scheme.

Table 5.2: Performance indices of the behaviour of the closed loop DO process with PI and (PI + Smith controllers) and under different random delay conditions.

Measurement Conditions	Time delay values (days)	Rise Time (days)	Settling Time (days)	Percentage Overshoot (%)	Stead StateError (mg/l)	Oscillation Amplitude (mg/l)	Delay in Response (days)
Delays							
$\tau_{tot} = 0$	0	0.0020	0.0036	3.0	0.052600	2.05260	0
$\tau_{tot} < \tau_c$	0.000026	0.0020	0.0036	2.87	-0.0530	2.048, 2.058	0
$\tau_{tot} = \tau_c$	0.000027	0.0020	0.0036	2.88	-0.0470	2.048, 2.0475	0
$\tau_{tot} > \tau_c$	0.020400	0.0020	0.0036	30.0	27.7000	-54.000,2.600	0
	Delays +Smith						
$\tau_{tot} = 0$	0	0.0020	0.0036	3.0	0.0526	2.0526	0
$\tau_{tot} < \tau_c$	0.000026	0.0020	0.0036	2.65	-0.0490	2.032, 2.066	0
$\tau_{tot} = \tau_c$	0.000027	0.0020	0.0036	2.66	-0.0700	2.020, 2.070	0
$\tau_{tot} > \tau_c$	0.020400	0.0020	0.0036	30.0	0.8900	-0.380, 2.613	0

5.9 Investigation of the performance of the Smith predictor-based DO process using the transfer function approach under the influence of network induced time delays and disturbances.

The investigations of time delays effect on the closed loop DO process performed in this section incorporates the saturation limits in the nonlinear linearising controller for the closed loop DO process control. As discussed in section 4.8, the inclusion of saturation limits is assumed to be a form of disturbance in the closed loop DO process control. The purpose of this investigation of the closed loop DO process by incorpotating saturation limits is to evaluate the robustness of the developed Smith predictor comensation scheme for the DO process under the influence of time delays and saturation disturbances. The saturation limit values used are 0.001 for the lower limit and 5 for the upper limit. Simulations are performed to determine the behaviour of the closed loop DO process and to evaluate the robustness of the developed nonlinear approach of the Smith predictor design under large time delays and saturation disturbances. The Simulink block diagram for constant delays in Figure 5.6 for constant time delays is adapted. The only difference between the previous investigations in Chapter five and this investigation is the inclusion of saturation limits as a form of disturbance in the closed loop DO process dynamics. Figures 5.16 to 5.18 are the results of simulations performed on the DO process under constant time delays and saturation disturbance. For the purpose of the investigation, values of time delays were varied from a minimum to a given maximum while the disturbance lower and upper limits were kept constant. Figure 6.16 reveals that the Smith predictor-based DO process using the transfer function approach is successful to an extent in stabilising the DO process under time delays and saturation disturbance.

5.9.1 Discussion of Simulation results.

It could be observed from Figures 5.16 when a time delay of 0.00044 days is induced that the DO process under the time delay and saturation disturbance exhibits good performance in terms of rise time, steady state error, settling time and system overshoot.

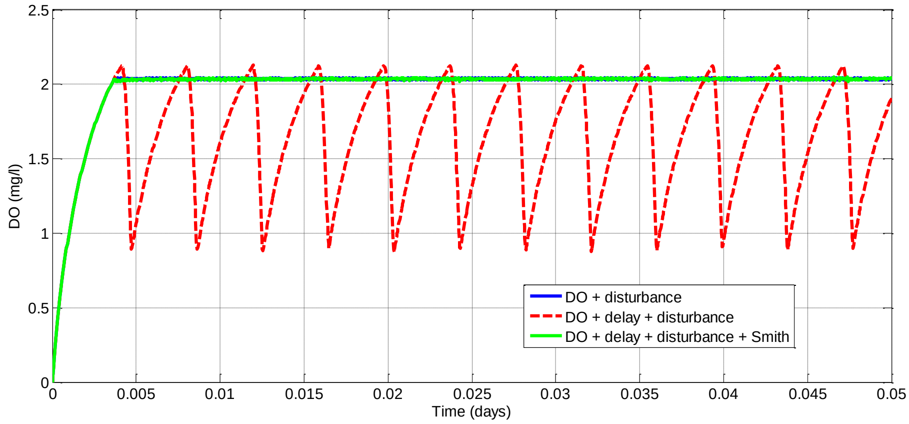

Figure 5.16 : a.) Simulation results of the DO process closed loop behaviour under constant network induced time delays and saturation disturbance. τ_{tot} **= 0.00044 days (380.16 secs.)**

As the time delays increase to 0.01 days in Figure 5.17 and to 0.06 days in figure 5.18, the performance of the system becomes poorer. However despite the presence of large time delays and saturation disturbance, the DO process control exhibits good rise time as shown in Figures 5.16 to 5.18

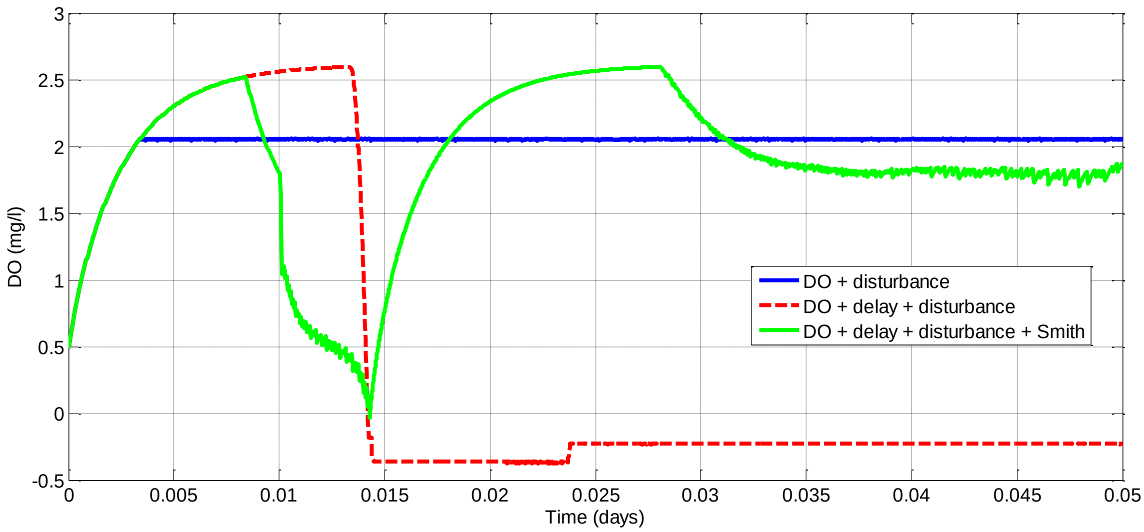

Figure 5.17: a.) Simulation results of the DO process closed loop behaviour under constant network induced time delays and saturation disturbance. τ_{tot} **= 0.01 days (8640 secs.)**

Form the cases investigated one could therefore infer that the DO process closed loop control using the transfer function Smith predictor approach exhibits the following behaviour:

- Robust control and good system performance when the time delays and disturbances are small but performs poorly with large time delays and disturbances
- Good rise time weather the time delays and disturbances are small or large. In other words, the rise time does not depend on the value of induced time delays or disturbances.
- The Smith predictor compensation scheme developed using the transfer function approach out-performs the (PI + nonlinear linearising) controllers without Smith predictor in providing robustness and good performance for the closed loop DO process

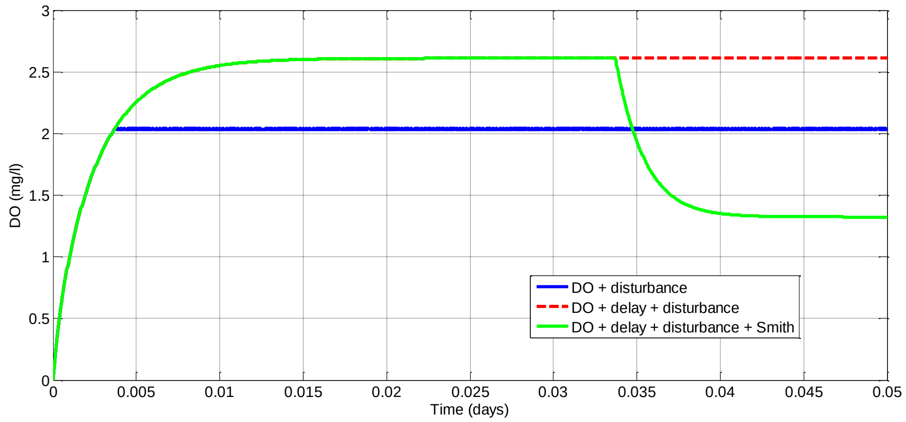

Figure 5.18: a.) Simulation results of the DO process closed loop behaviour under constant network induced time delays and saturation disturbance. τ_{tot} = 0.06 days (51840 secs.)

The real-time simulation for this investigation would be carried out in Chapter seven using LabVIEW.

5.10 Conclusion

In this chapter, a Smith predictor compensation scheme is developed to mitigate random delays in a networked DO process of wastewater control. The focus here is the Activated Sludge Process. In other to mitigate the adverse effect of communication drawbacks on the ASP, a Smith predictor is developed. Two cases of Smith predictor implementation were presented depending on the placement of the network delays relative to the DO process model. Case 1 which allowed transfer function to be used in describing the behaviour of the closed loop DO process was used in this chapter to design a Smith predictor scheme to compensate for the communication imperfections. Simulation was performed for both constant and random time delays.

The robustness of the developed transfer function approach is Smith predictor under large time delays and saturation disturbance is evaluated. Analytical and simulation results confirm the effectiveness of the Smith predictor scheme over the (PI + nonlinear linearising) controller without Smith predictor to provide robustness for the control of the DO process under the influence of constant and random communication delays and disturbances. Chapter six would be concerned with the Smith predictor implementation for the DO process using the approach in case 2 described in this chapter in which transfer function cannot be used to describe the system performance.

CHAPTER SIX

DESIGN OF A ROBUST SMITH PREDICTOR COMPENSATION SCHEME FOR THE CLOSED LOOP CONTROL OF THE DO PROCESS USING THE NONLINEAR LINEARING CONTROLLER DESIGN APPROACH

6.1 Introduction

In Chapter five, a Smith predictor compensation scheme was designed in order to compensate for the communication drawbacks (time delays) in the closed loop DO process using the transfer function approach. In this chapter, the arrangement of the time delays is such that the PI controller and the nonlinear linearising controller are positioned side by side and far from the nonlinear DO process. As such, the transfer function approach cannot be used to describe the behaviour of the nonlinear DO process. The nonlinear linearising approach of designing a Smith predictor is therefore adopted to provide robustness and stable performance for the DO process. To design the nonlinear linearising controller, the feedback linearization technique is used.

Section 6.2 introduces the feedback linearization technique and the need for it. Section 6.3 revises the Smith predictor compensation scheme and re-examines the two different approaches of Smith predictor design. Section 6.4 is about the derivation of the Smith predictor compensation scheme using the nonlinear linearising controller design method. In section 6.5, simulation of the DO process under constant delays are performed and the simulation results on constant delays discussed in section 6.6. In Section 6.7 the simulation of the DO process under random delay is performed and the results discussed in section 6.8.The results of the two Smith predictor design approaches are compared in section 6.9. Section 6.10 considers the behavior of the closed loop DO process under time delays and saturation disturbances while the Chapter concludes with section 6.11.

6.2 Nonlinear systems and the need for feedback linearisation

Linear control system theory has been used successfully in control systems for a long time for dynamic system modelling, system identification and control design but it has its limitations. This occurs when a system experiences frequent and unexpected changes in steady state as a result of disturbances. In such a case, the linear control theories might no longer be adequate to control the system (Slotine and Li, 1991). The nonlinear model of the system is used to accurately describe the system dynamics. Nonlinear systems require nonlinear controllers. However the use of nonlinear controllers has its challenges due to varying parameters in the system and disturbances which the system is subjected to. To overcome this challenge, feedback linearization is often applied to make the nonlinear system behave like a linear one and then linear methods of controller designs are applied to it. An example of this is the wastewater treatment plant. In this Chapter, the Smith predictor compensation scheme for the closed loop DO process control is developed using the feedback linearization approach.

6.2.1 Feedback Linearisation.

Feedback linearisation is concerned with a situation in which the dynamics of a nonlinear system is algebraically transformed to that of a fully or partially linear system. In other words, it could be seen as the changing the original system model into an equivalent model of a simple form. So in feedback linearization, the nonlinearities in the nonlinear system are cancelled such that the resulting closed loop system is a linear one (Hensor and Seborg, 1997) and then linear control design methods such as the PI, LQR, pole placement and so on could be applied. It is an approach that is gradually becoming popular in the recent times and it is different from Jacobian linearization in which the transformation is achieved by linear approximation of the system dynamics. In the case of feedback linearization, the transformation is achieved by exact state transformation and feedback (Slotine and Li, 1991).

6.2.2 The theory of feedback linearization.

Control systems can broadly be classified into linear and nonlinear systems. Equation 6.1 is that of a linear system while 6.2 is the equation of a nonlinear system.

$$\dot{x}(t) = Ax(t) + Bu(t) \quad (6.1)$$

$$\dot{x}(t) = Ax(t) + Bu(t) + f(x,u,t) \quad (6.2)$$

Where $x \in \Re^n$ is the state variable vector, $u \in \Re^m$ is the control vector, A is the n x n continuous matrix while B is the n x m continuous matrix. $f : \Re^n$ x $\Re^m \rightarrow \Re^n$ is a vector continuous function. In order to investigate the controllability of a nonlinear system, the usual practice is to linearise it around a given operating point x_0 after which linear methods are applied. If the control functions and the dependent variables are expressed as deviations from the nominal operating states x_0 and control u_0,

$$x(t) = x_0 + \Delta x(t) \quad (6.3)$$

$$u(t) = u_0 + \Delta u(t) \quad (6.4)$$

If the Tailor's expansion method is applied about x_0, u_0, then the resulting nonlinear system is as shown in equation (6.5) where $J_x(x_0,u_0)$ and $J_u(x_0,u_0)$ are the Jacobian matrices of the nonlinear function $f(x,u,t)$ of (6.2).

$$\frac{d\Delta X(t)}{dt} = [A + J_x(x_0,u_0)]\Delta x(t) + [B + J_u(x_0,u_0)]\Delta u(t) \quad (6.5)$$

For the fact that linear approximation is mostly accurate within a small range around (x_0, u_0), this makes the Jacobian method to be limited even though it exhibits some degree of accuracy (Henson and Seborg, 1997). The feedback linearization concept can be applied if the system can be transformed to the following class of nonlinear systems represented in the companion or canonical form. A system is said to be in the companion form if its dynamics can be represented by equation (6.6) (Slotine and Li, 1991).

$$\dot{x}^{(n)}(t) = f(x,t) + b(x,t)u(t) \qquad (6.6)$$

Where u is the scalar control input, x is the vector of state of interest, $x^{(n)}$ is the nth derivative of the state vector X, and $f(x,t)$ and $b(x,t)$ are nonlinear functions of the states.

Presenting a canonical form of the system using the control input $b(x,t)$ which is assumed to be non-zero, the nonlinear control can be computed as shown in equation (6.7).

$$u(t) = \frac{1}{b(x,t)}[v(x,t) - f(x,t)] \qquad (6.7)$$

Using the control $u(t)$ from equation (6.7) and substituting into equation (6.6), the nonlinearities can be eliminated resulting in a simple input-output relationship.

$$x^{(n)}(t) = v(x,t)$$

where $v(x,t)$ is the linear control input to the nonlinear linearising controller. After this, the linear control law is calculated as in the form presented in equation (6.8)

$$v(x,t) = -k_0 x(t) - k_1 \dot{x}(t) - \ldots - k_{n-1} x(t)^{(n-1)} \qquad (6.8)$$

An exponentially stable system is obtained by choosing k_1 such that the polynomial $s^n + k_{n-1}s^{n-1} + \ldots k_0$ has its roots in the left half of the plane (Slotine and Li, 1991).

If $e(t) = x(t) - x_d(t)$, is the tracing error, where x_d is the desired system output or set-point (Slotine and Li, 1991), the linear control can be expressed as

$$v(t) = x_d^{(n)}(t) - k_0 e - k_2 \dot{e}(t) - \ldots - k_{n-1} e^{(n-1)}(t) \qquad (6.9)$$

In order to apply the feedback linearization to a system, it has got to be put in the controllable canonical form. If it is not, it might be good to apply algebraic transformation to it in order to convert it to the canonical form.

In an attempt to linearise a nonlinear system, two approaches of linearization are usually employed namely (Slotine and Li, 1991):

- Input-state linearization
- Input-output linearization

These two approaches use a certain type of nonlinear control law. In some applications, it is done with a nonlinear static state feedback law (Kravaris and Wright, 1989) of the form

$$u(t) = \alpha(x,t) + \beta(x,t)v(t) \tag{6.10}$$

In which $\alpha(x,t)$ is an m-dimensional vector nonlinear functions and $\beta(x,t)$ is a m x m matrix nonlinear function. In some cases where the static law fails, a dynamic state feedback control law is used as shown in equation (6.11) (Slotine and Li, 1991).

$$\dot{\eta} = \vartheta(x,\eta) + \psi(x,\eta)v(t) \tag{6.11}$$

$$u(t) = \alpha(x,\eta) + \beta(x,\eta)v(t) \tag{6.12}$$

Where η is a q-dimensional vector controller state variable; ϑ is a q-dimensional vector of nonlinear functions; and ψ is a q x m matrix of nonlinear functions (Henson and Seborg, 1997; Nketoane, 2009)

6.2.3 Input-state linearization

In this method of linearization, two steps are involved. In the first step, there is a nonlinear change of coordinates or what is referred to as a state transformation. The second step is the nonlinear state feedback or what is known as the input transformation.

Considering a nonlinear affine system represented by

$$\dot{x}(t) = f(x,t) + g(x,t)u(t) \tag{6.13}$$

$$y(t) = h(x,t) \tag{6.14}$$

where $x(0) = x_0$

x is the n dimensional vector and u is a scalar $f(x,t)$ is n-vector function of state and $g(x,t)$ is n x m matrix function of state, $h(x,t)$ is the l x n vector function of the output.

An affine system is one in which the input u appears linearly in the state space equation

First, there is a state transformation applied to the nonlinear system 6.13 to 6.14 of the form

$$z = T(x) \tag{6.15}$$

where z are the new states for all the variables such that the nonlinear system is transformed into a controllable canonical form. Then the state feedback control is expressed in the form shown in equation (6.10). As such, the original nonlinear system is now expressed as a linear state space system as shown in equations (6.16), (6.17)

$$\dot{z}(t) = Az(t) + Bv(t), z(0) = z_0 \tag{6.16}$$

$$y(t) = h(T^{-1}(z)) \tag{6.17}$$

On the basis of the equations (6.16) and (6.17), a linear control design technique such as the pole placement could be applied to the linearised system.

So it could be seen that the input-state linearization is a linearization by a feedback nonlinear controller or feedback linearization.

6.2.4 Input-output linearization

The continuous time affine system as shown in equation (6.13) and (6.14) is considered.

Output derivative (Slotine and Li, 1991) $\frac{\delta h}{\delta t} = \frac{\delta h}{\delta X}\dot{x} + \frac{\delta h}{\delta t}$

$$\dot{y}(t) = \frac{\delta h}{\delta x}[f(x(t)) + g(x(t))u(t)] = L_f h(x(t)) + L_g h(x)u(t) \tag{6.18}$$

In which case $L_f h(x,t) = \frac{\delta h}{\delta x} f(x,t)$ and $L_g h(x,t) = \frac{\delta h}{\delta x} g(x,t)$ are referred to as the Lie derivatives of h along f and g functions.

Further expression of the Lie derivatives show that (Slotine and Li, 1991).

$$L_g L_f h(x,t) = \frac{\delta(L_f h(x))}{\delta x} g(x,t) \tag{6.19}$$

$$L_f^2 h(x,t) = \frac{\delta(L_f h(x,t))}{\delta x} f(x,t) \tag{6.20}$$

$$L_f^k h(x,t) = L_f L_f^{k-1} h(x,t) = \frac{\delta(L_f^{k-1} h(x,t))}{\delta x} f(x,t) \tag{6.21}$$

$$L_f^0 h(x) = h(x,t) \tag{6.22}$$

Recall that it is possible to express $\dot{y}$ as

$$\dot{y}(t) = L_f h(x,t)) + L_g h(x,t)u(t) \tag{6.23}$$

If $L_g h(x) = 0$, then

$$\dot{y}(t) = L_f h(x,t) \tag{6.24}$$

is independent of u

If a higher order derivative for y is considered, then

$$\ddot{y}(t) = \frac{\delta(L_f h(x,t)}{\delta x}[f(x,t)) + g(x,t))u(t)] = L_f^2 h(x,t) + L_g L_f h(x,t)u(t) \tag{6.25}$$

From the above equation (6.25) one would discover that when $L_g L_f h(x,t) = 0$, $\ddot{y} = L_f^2 h(x,t)$ and the gain is independent of u. This process can be repeated in order to find if $h(x)$ satisfies

$$0 = L_g L_f^{i-1} h(x,t) \quad (i = 1, 2, ..., p-1) \tag{6.25}$$

$$0 \neq L_g L_f^{p-1} h(x,t) \quad (6.26)$$

It could be seen that the control u does not appear in the equations $y, y, ..., y^{p-1}$ so it is now easy to re-present the p^{th} order differential equation for y such that

$$y^{(p)} = L_f^p h(x,t) + L_g L_f^{p-1} h(x,t) u(t) \quad (6.27)$$

From this, it can be seen that the system is input/output linearisable if the control variables are expressed such that: (Slotine and Li, 1991).

$$u(t) = \frac{1}{L_g L_f^{p-1} h(x,t)} [L_f^p h(x,t) - v(t)] \quad (6.28)$$

The nonlinear controller is found to reduce the input/output map to

$$y^{(p)}(t) = v(t) \quad (6.29)$$

This gives a chain of p integrators. It should be noted however that p is usually referred to as the relative degree of the nonlinear system.

The input-output (state feedback) method is used for the design of the Smith predictor compensation scheme for the DO process.

6.3 The Smith predictor compensation scheme

In Chapter 5 section 5.2, two cases under which the Smith predictor compensation scheme could be implemented were discussed, namely the transfer function approach for an equivalent linearised DO process and the nonlinear linearising approach. The transfer function approach referred to as case 1 was implemented in Chapter five was implemented in that Chapter. In Chapter six, the case 2 approach is considered which is the nonlinear feedback linearization approach. The arrangement of the time delays under this approach is as shown in Figure 6.1. It would be observed that both the PI controller and the nonlinear linearising controller are placed together and far from the nonlinear DO process.

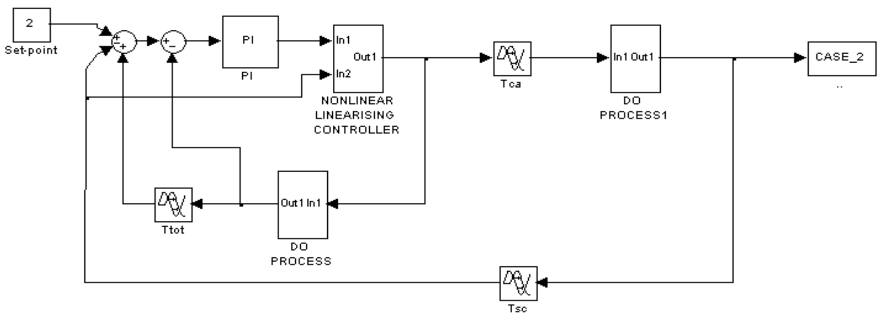

Figure 6.1: Simulink diagram of the Smith predictor implementation using the nonlinear feedback linearising approach

In order to solve this problem, the method in (Kravaris and Wright, 1989) is adopted. In (Kravaris and Wright, 1989), a Smith predictor idea was extended to a linear system in state space and later extended to nonlinear systems also in state space. This principle was then used to propose a Smith predictor compensation scheme for nonlinear systems in state space in order to eliminate dead time and obtain a delay-free control system.

6.3.1 A Smith predictor for linear systems with deadtime (Kravaris and Wright,1989).

Let a linear system with dead time be considered:

$$\dot{x} = Ax(t) + Bu(t - \tau_{tot})$$

$$y = Cx(t) \tag{6.30}$$

Where $x \in R^n$ is the state variable vector, $u \in R^m$ is a control vector, A and B are respectively the n x n and n x m continuous matrices. The $\det(sI - A)b$ and $cAdj(sI - A)b$ have all roots in the left-half plane. In a situation in which $\tau_{tot} = 0,$ it means the system is free of delay and the system is subject to static state feedback $u = r - Kx,$ the closed loop transfer function is given in equation (6.31) and shown in Figure 2.1 where $r(s)$ is the set-point vector.

$$\frac{y(s)}{r(s)} = \frac{cAdj(sI - A)b}{\det(sI - A) + KAdj(sI - A)b} \tag{6.31}$$

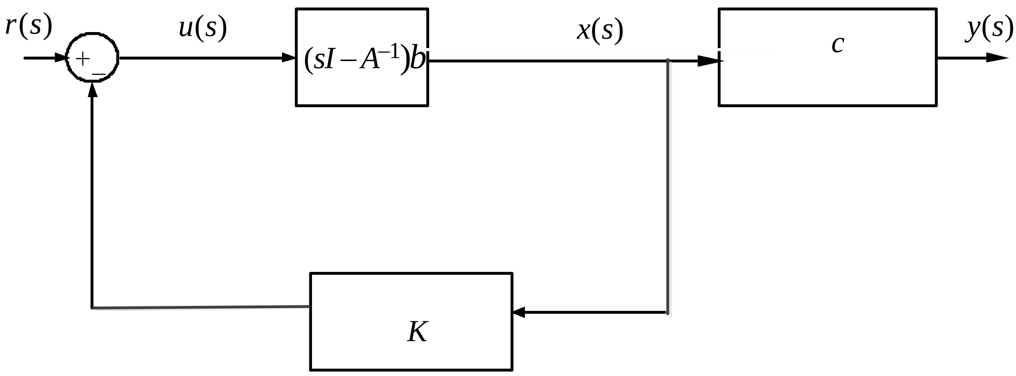

Figure 6.2: State feedback for a linear system in the absence of delay (Adapted from, Kravaris and Wright, 1989)

Assuming that the system being considered is not deadtime free $(\tau_{tot} \notin 0),$ it is still possible to obtain a deadtime free system. To achieve this, a corrective signal is added to the state measurements obtained by simulating the difference between the delayed and the undelayed states as shown in Figure 6.3. Then the closed loop transfer function is given by equation (6.32) which is the same as the deadtime free transfer function in equation (6.31) except for the factor $e^{-\tau_{tot}s}$.

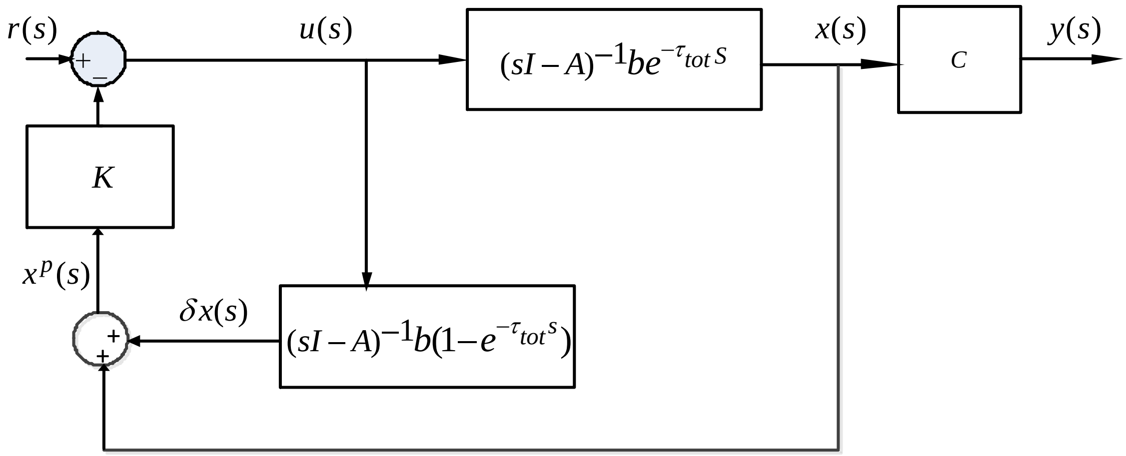

Figure 6.3: Smith predictor structure in state space for linear systems (Adapted from, Kravaris and Wright, 1989)

$$\frac{y(s)}{r(s)} = \frac{cAdj(sI-A)b}{\det(sI-A)+KAdj(sI-A)b}e^{-\tau_{tot}s} \quad (6.32)$$

From equation (6.32), a pole placement method could then be used to position the closed-loop poles for a deadtime free part of the process. This principle could be applied to nonlinear systems as exemplified in the next section.

6.2.2 A Smith predictor for nonlinear systems with deadtime (Kravaris and Wright,1989).

A nonlinear system without time delays (deadtime) as shown in equation (6.33) is considered with the following assumptions:

Assumption A: The process is open-loop stable

Assumption B: The system has stable zero dynamics

$$\dot{x} = f(x)(t) + g(x)u(t)$$

$$y = h(x) \quad (6.33)$$

The model of the system represented by equation (6.33), can not be described by a transfer function. In order to design a controller for this system, the input/output feedback technique is applied to linearise the nonlinear system in order to make it to behave like a linear system.

If the system in equation (6.33) has a relative order of p, in other words, the smallest integer for which equation (6.34) is not non-zero.

$$L_f^{p-1}h(x) \neq 0 \tag{6.34}$$

Then the static state feedback in equation (6.35) would make the input/output system behaviour to be described by the equation (6.36).

$$u(x,v) = \frac{v - \sum_{k=0}^{p} k_k L_f^k h(x)}{k_p L_g L_f^{p-1} h(x)} \tag{6.35}$$

$$v = \sum_{k=0}^{p} k_k \frac{d^k y}{dt^k} \tag{6.36}$$

The coefficients k_k are determined based on some of the methods for design of linear controller.

Now applying equations (6.33) through (6.36) to the case of nonlinear system with deadtime in equation (6.8), it should be noted however that equation (6.37) fulfils assumption A and B above.

$$\dot{x} = f(x)(t) + g(x)u(t - \tau_{tot})$$

$$y = h(x) \tag{6.37}$$

Since equation (6.37) has deadtime, a causal state feedback that will eliminate the deadtime might not be possible. There is therefore the need to develop a state feedback with predictive action resembling the Smith predictor. As the case in equations (6.30) to (6.32), a corrective signal is computed using the state space-based Smith predictor and it is used to predict what the state would have been in the absence of deadtime. The predicted state is then sent into the static feedback controller for improvement of the closed loop system performance as shown in Figure 6.4.

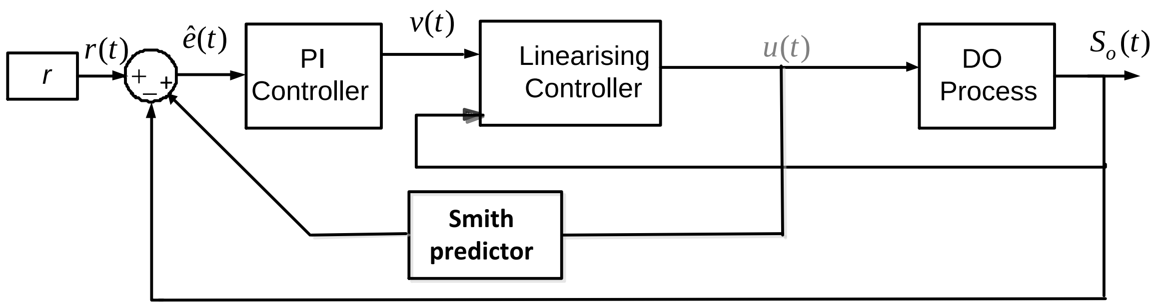

Figure 6.4: State space-based Smith predictor for improvement of the closed loop DO process

The equation 6.37 represents in the general form the dynamics of the dissolved oxygen equation when it is considered as part of the Networked Control Systems. In the next section, the Smith predictor is designed to overcome the network induced time delays effect on the DO process control system due to the influence of the network induced time delays.

6.4 Derivation of the Smith predictor compensation scheme for the nonlinear DO process

6.4.1 Without time delay- input-output linearization-based controller

The approach in section 6.2.2 is applied to the nonlinear DO process. Let the nonlinear DO process without time delays (deadtime) as shown in Figure 6.4 be considered. The benchmark model of the DO process given in equation (3.5) is shown below:

$$\frac{dS_o(t)}{dt} = \frac{Q}{V}\left(S_{o,in}(t) - S_o(t)\right) + K_{La}(t)(S_{o,sat} - S_o(t)) + r_{s_0}(t)$$

$$K_{La} = k_1(1 - e^{-k_2 u})$$

$$\dot{S}_o(t) = \frac{Q}{V}\left(S_{o,in}(t) - S_o(t)\right) + k_1(1 - e^{-k_2 u})(S_{o,sat} - S_o(t)) + r_{s_0}(t) \tag{6.38}$$

In order to apply the input-output feedback linearization approach to derive the nonlinear linearization controller, the system (6.38) has to be presented in an affine form. As the control u is part of a nonlinear expression and linearly entering the process model Artificial control u_1 is introduced as follows:

$$u_1 = -k_1 e^{-k_2 u}$$

$$\dot{S}_o(t) = \frac{Q}{V} S_{o,in}(t) - \frac{Q}{V} S_o(t) + r_{s_0}(t) + k_1(S_{o,sat} - S_o(t)) + u_1(S_{o,sat} - S_o(t))$$

The above equation can be expressed in the standard affine form in equation (6.39), as follows:

$$\dot{S}_o(t) = f(S_o(t)) + g(S_o(t)u_1(t) + g_1(S_o(t))S_{o,in}(t) + g_2(S_o(t))r_{s_0}(t)$$

$$y = h(S_o) = S_o(t) \tag{6.39}$$

where

$$f(S_o(t)) = -\frac{Q}{v} S_o(t) k_1\left(S_{o,sat} - S_o(t)\right)$$

$$g(S_o(t)) = \left(S_{o,sat} - S_o(t)\right)$$

$$g_1(S_o(t)) = \frac{Q}{v} = cons\tan t$$

$$g_2(S_o(t)) = 1 = cons\tan t$$

In order to linearise the nonlinear DO process model, the input-output approach is applied. The Lie derivative principle is applied in its general form for a relative degree of the system p as follows:

$$y^{(p)} = L_f^p h + L_g^{p-1} h u_1 = \alpha(x,t) + \beta(x,t)u(t) \equiv v(x,t) \tag{6.40}$$

$$u(t) = \frac{1}{\beta(x,t)}\left[v(x,t) - \alpha(x,t)\right] \tag{6.41}$$

$$u(t) = \frac{v(x,t) - \sum_{k=0}^{p} k_k L_f^k h(x,t)}{k_p L_g L_f^{p-1} h(x,t)} \tag{6.42}$$

where p is the relative degree or the number of derivatives carried out to obtain $(\beta(x,t)u(t) \neq 0)$

The output of the DO process is given below

$$y(t) = h(S_o,(t)) = S_o(t)$$

$$\dot{y}(t) = \frac{dh}{dS_o}\dot{S}_o, \dot{S}_o = f(S_o(t)) + g(S_o(t))u_1(t) + g_1(S_o(t))S_{o,in}(t) + g_2(S_o(t))r_{so}(t), \frac{dh}{dS_o} = 1 \tag{6.43}$$

On the basis of (6.43), the following is received

$$\dot{y}(t) = f(S_o(t)) + g(S_o(t))u_1(t) + g_1(S_o(t))S_{o,in}(t) + g_2(S_o(t))r_{so}(t)$$

u_1 appears in the first derivative of y, it therefore follows that the relative degree for the DO process is equal to 1.

In the above equation (6.43),

$$\alpha(x) = f(S_o(t))$$

$$\beta(x) = g(S_o(t))u_1$$

Then it can be written that

$$u_1(t) = \frac{v(t) - f(S_o(t)) - g_1(S_o(t))S_{o,in}(t) - g_2(S_o(t))r_{so}(t)}{g(S_o(t))} \tag{6.44}$$

$$u_1(t) = -k_1 e^{-k_2 u(t)}$$

The real control $u(t)$ can be calculated as follows:

$$e^{-k_2 u(t)} = \frac{u_1(t)}{-k_1}$$

$$\ln\left(\frac{u_1(t)}{-k_1}\right) = \ln(e^{-k_2 u(t)}) = k_2 u(t)$$

$$u(t) = -\frac{1}{k_2}\ln\left[\frac{u_1(t)}{-k_1}\right]$$

Then the input-output linearization control $u(t)$ can be finally represented by Equation (6.45)

$$u(t) = -\frac{1}{k_2}\ln\frac{1}{k_1}\left[\frac{(a+\frac{Q}{V}+k_1)S_o(t)+bv(t)-k_1S_{o,sat}-\frac{Q}{V}S_{o,in}-r_{so}(t)}{(S_{o,sat}-S_o(t))}\right] \tag{6.45}$$

where the linear control $v(t)$ is given by a PI controller. The closed loop system structure is shown in Figure 6.5. The derived nonlinear equation given in equation (6.45) is further used to design the Smith predictor.

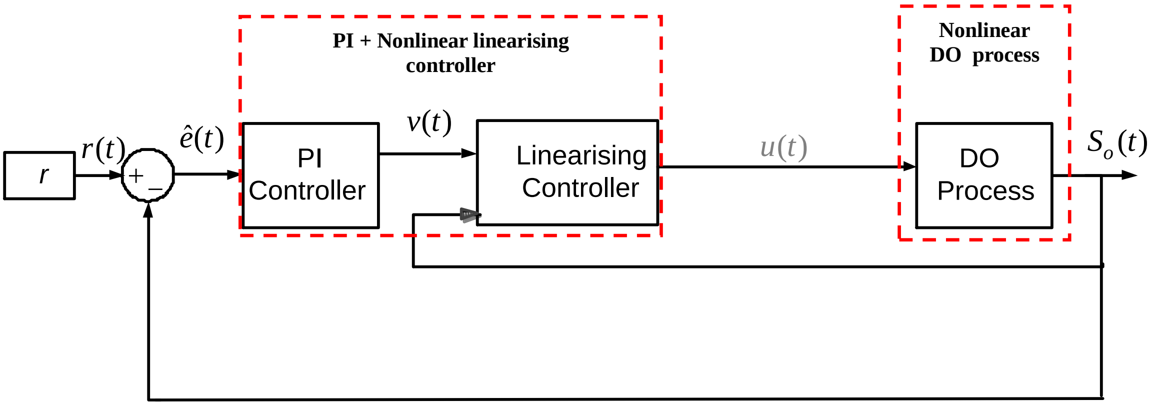

Figure 6.5: Nonlinear DO process with PI and nonlinear linearising controller without time delays

6.4.2 With time delay – input-output linearization-based controller

In this case, the nonlinear DO process described in the standard affine form (6.43) under the influence of the network induced time delays (τ_{tot}) is considered. This is shown in Figure 6.6

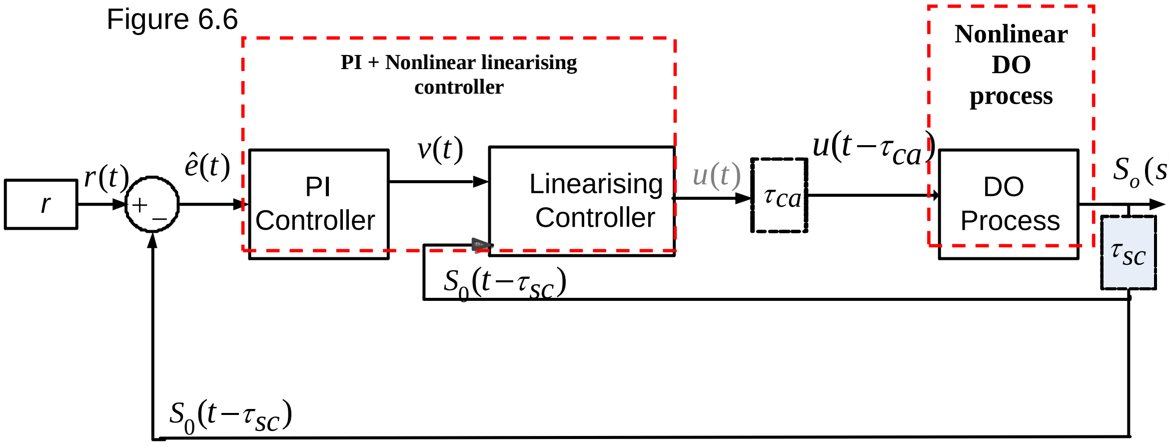

Figure 6.6: Nonlinear DO process with PI and nonlinear linearising controller under time delays.

Expressing the DO process benchmark model in the standard affine form (6.43) under the influence of time delays, the following is obtained:

$$\dot{S}(t) = f(S_o(t)) + g(S_o(t))u_1(t-\tau_{tot}) + g_1(S_o(t))S_{o,in}(t) + g_2(S_o(t))r_{so}(t)$$

$$y = h(S_o(t)) \qquad (6.46)$$

where $\tau_{tot} = \tau_{ca} + \tau_{sc}$

$$f(S_o(t)) = -\frac{Q}{v}S_o(t)k_1\left(S_{o,sat} - S_o(t)\right)$$

$$g(S_o(t)) = \left(S_{o,sat} - S_o(t)\right)$$

$$g_1(S_o(t)) = \frac{Q}{v} = cons\tan t$$

$$g_2(S_o(t)) = 1 = cons\tan t$$

6.4.2.1 Design of a nonlinear input-output linearising controller based on a desired model of the linearised system

Let the desired model for the for the behaviour of the linearised system under time delays be:

$$y^{(p)}(t) = aS_o(t) + bv(t) \qquad (6.47)$$

Which poses more strict requirements towards the dynamics of the linearised system in composition with $y^{(p)}(t) = v(t)$

In order to linearise the DO process, the first time derivative of the DO process output is found

$$\dot{y} = \frac{dh}{dS_o}\dot{S}_o, \frac{dh}{dS_o} = 1$$

$$\dot{S}_o = f(S_o(t)) - g(S_o(t))u_1(t-\tau_{tot}) - g_1(S_o(t))S_{o,in}(t) - g_2(S_o(t))r_{so}(t) \qquad (6.48)$$

As $u_1(t-\tau_{tot})$ appears in the first derivative of y it therefore follows that the relative degree for the DO process is equal to 1. In this case, $y^{(p)} = y^{(1)}$ and the desired model is

$$y^{(1)} = aS_o(t) + bv(t)$$

And it can be written as:

$$aS_o(t) + bv(t) = f(S_o(t)) + g(S_o(t))u_1(t-\tau_{tot}) + g_1(S_o(t))S_{o,in}(t) + g_2(S_o(t))r_{so}(t) \qquad (6.49)$$

$$\dot{S}_o(t) = aS_o(t) + bv(t) - f(S_o(t)) + g(S_o(t))u_1(t-\tau_{tot}) + g_1(S_o(t))S_{o,in}(t) + g_2(S_o(t))r_{so}(t) \qquad (6.50)$$

From here, the nonlinear input-output linearising controller is

$$u_1(t-\tau_{tot}) = \frac{aS_o(t) + bv(t) - f(S_o(t)) - g_1(S_o(t))S_{o,in}(t) - g_2(S_o(t))r_{so}(t)}{g(S_o(t))} \qquad (6.51)$$

$$u_1(t-\tau_{tot}) = \frac{(a+\frac{Q}{V}+k_1)S_o(t)+bv(t)-k_1S_{o,sat}-\frac{Q}{V}S_{o,in}-r_{so}(t)}{(S_{o,sat}-S_o(t))} \tag{6.52}$$

In an attempt to derive the original nonlinear control $u(t)$, the following transformation is carried out in which,

$$u_1(t-\tau_{tot}) = -k_1 e^{-k_2 u(t-\tau_{tot})}$$

$$e^{-k_2 u(t-\tau_{tot})} = \frac{u_1-\tau_{tot}}{-k_1}$$

$$\ln\left(\frac{u_1(t-\tau_{tot})}{-k_1}\right) = \ln(e^{-k_2 u(t-\tau_{tot})}) = k_2 u(t-\tau_{tot})$$

$$u(t-\tau_{tot}) = -\frac{1}{k_2}\ln\left[\frac{u_1(t-\tau_{tot})}{-k_1}\right]$$

$$u(t-\tau_{tot}) = -\frac{1}{k_2}\ln\frac{1}{k_1}\left[\frac{(a+\frac{Q}{V}+k_1)S_o(t)+bv(t)-k_1S_{o,sat}-\frac{Q}{V}S_{o,in}-r_{so}(t)}{(S_{o,sat}-S_o(t))}\right] \tag{6.53}$$

where $v(t)$ is produced by a PI controller.

6.4.1 Derivation of the linear control $v(t)$ for the DO process under time delays

In order to derive the linear control $v(t)$ for the DO process under the influence of time delays, a Smith predictor compensation scheme is used. Figure 6.7 shows the block diagram of this scheme. The Smith predictor compensation scheme in Figure 6.6 is formed by making use of the nonlinear model of the DO process, the (PI + nonlinear linearising) controllers, and the model of the total network induced time delays (τ_{tot} in the closed loop system). τ_{tot} is the sum of τ_{ca} and τ_{sc} where τ_{ca} is the controller to actuator delay and τ_{sc} is the sensor to controller delay delays. This arrangement is different from the case in Chapter 5, Figure 5.5 in which the Smith predictor is formed using the model of the linearised DO process. This linearised DO process is formed by placing the nonlinear linearising controller side by side with the model of the nonlinear DO process. Similar to the Figure 5.5, the Smith predictor scheme being considered has two feedback loops which are the inner feedback loop and the outer feedback loop. The outer feedback loop in Figure 6.6 delivers outdated information as a result of combined communication imperfections (τ_{ca} and τ_{sc}), and so it is not adequate for the control system stability. The Smith predictor functions are such that the model of the nonlinear DO process and the model of the total network delays ($\tau_{ca} + \tau_{sc} = \tau_{tot}$), are added to the closed loop DO process control system as shown in Figure 6.6. As a result, the effects of network induced time delays in the closed loop system are eliminated and the feedback signal $\hat{e}(t)$ getting to the PI controller is free of deadtime and so the linear control $v(t)$ is also free of time delay.

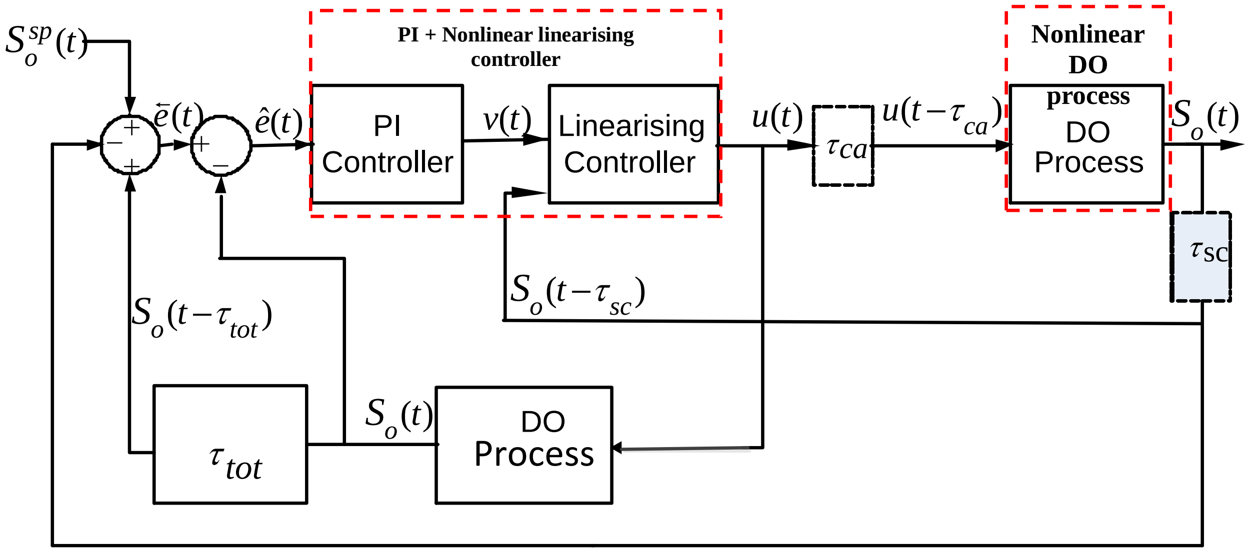

Figure 6.7: Block diagram of the Smith predictor compensation for the nonlinear DO process

Following the scheme in Figure 6.7, the PI controller $v(t)$ is expressed as:

$$v(t) = K_p \left[\hat{e}(t) + \frac{1}{T_1} \int \hat{e}(t) dt \right] \tag{6.55}$$

$$\hat{e}(t) = \bar{e}(t) - S_o(t) \tag{6.56}$$

$$\hat{e}(t) = \left[S_o^{sp}(t) - S_o(t - (\tau_{ca} + \tau_{sc})) + S_o(t - \tau_{tot}) \right] - S_o(t) = S_o^{sp}(t) - S_o(t) \tag{6.57}$$

Then In equation (6.57), the expression $-S_O(t - \tau_{tot}) + S_O(t - \tau_{tot})$ cancels out resulting in equation (6.58) and so the network delay is compensated leaving a $v(t)$ without time delays.

$$v(t) = K_p \left[S_o^{sp}(t) - S_o(t) + \frac{1}{T_1} \int \left[S_o^{sp}(t) - S_o(t) \right] dt \right] \tag{6.58}$$

and the nonlinear control can be expressed as

$$u(t-\tau_{tot}) = -\frac{1}{k_2}\ln\left[\frac{\left[K_p\left[S_o^{sp}(t)-S_o(t)+\frac{1}{T_1}\int\left[S_o^{sp}(t)-S_o(t)\right]dt\right]\right] + (a+\frac{Q}{V}+k_1)S_o(t)-k_1 S_{o,sat}-\frac{Q}{V}S_{o,in}-r_{so}(t)}{-k_1(S_{o,sat}-S_o(t))}\right] \quad (6.60)$$

$$\hat{e}(t) = S_o^{sp}(t) - S_o(t) \quad (6.61)$$

$$u(t-\tau_{tot}) = -\frac{1}{k_2}\ln\left[\frac{(a+\frac{Q}{V}+k_1)S_o(t)+K_p\left[\hat{e}(t)+\frac{1}{T_1}\int\hat{e}(t)dt\right]-k_1 S_{o,sat}-\frac{Q}{V}S_{o,in}-r_{so}(t)}{-k_1(S_{o,sat}-S_o(t))}\right] \quad (6.62)$$

In the equation (6.62), $v(t)$ is now a linear control input to the linearized closed loop system whose dynamics are free of time delays (deadtime). The Smith predictor compensation scheme had succeeded in virtually hiding the time delays in the closed loop DO process and it made available to the PI controller a virtual system without network induced time delays. As it could be observed in Figure 6.7, instead of receiving outdated information from the outer loop of the DO process due to induced network time delays (τ_{ca} and τ_{sc}), the inner loop containing the Smith predictor takes over the DO process control. This is done in order to ensure that fresh information is constantly received by the PI controller and to sustain the DO process performance. In this way, the time delays are compensated for using the Smith predictor by ensuring that the signal $\hat{e}(t)$ made available to the PI controller is deadtime-free. As a result, the Smith predictor compensation scheme represented by equation (6.62) is now deadtime-free just as equation (4.5) in Chapter four.

The pole placement method, Linear Quadratic Regulator (LQR) or any other method can now be applied to design the linear PI controller that provides a linear control input to the linearized DO process. In the course of this study, the pole placement technique is adopted for the design of the PI controller.

6.4.2.3 Design of the PI controller on the basis of the pole placement method

The parameters of the PI controller are calculated on the basis of the pole placement method. This is described as follows:

- Determining the transfer function of the linearized process
- Determining the Proportional Integral (PI) controller transfer function

- Determining the closed loop transfer function
- Finding the characteristic equation of the closed loop transfer function and calculation of the PI controller parameters

1.) Determining the transfer function of the linearised process

Considering the desired linear plant model

$$\dot{S}_o(t) = aS_o(t) + bv(t) \tag{6.63}$$

The Laplace transform, of (6.63)

$$s\dot{S}_o(s) = aS_o(s) + bv(s) \tag{6.64}$$

$$(s-a)S_o(s) = bv(s) \tag{6.65}$$

The transfer function of the linear model is

$$G_p(s) = \frac{S_o(s)}{v(s)} = \frac{b}{(s-a)} \tag{6.66}$$

where $G_p(s)$ is the transfer function of the linearised closed loop system.

2.) Determining the Proportional Integral (PI) controller transfer function

For the (PI) controller, recall from equation (6.55) that

$$v(t) = K_p\left[\hat{e}(t) + \frac{1}{T_1}\int \hat{e}(t)dt\right]$$

Where is the input and the output of the proportional integral controller is $v(t)$. From equation (6.61) $\hat{e}(t) = S_o^{sp}(t) - S_o(t)$

Transfer function of the PI controller

$$G_c(s) = \frac{v(s)}{E(s)} = K_p\left[1 + \frac{1}{T_i s}\right] \tag{6.67}$$

3.) Closed loop transfer function

The closed loop combines the transfer function of the linearised DO process and the transfer function of the PI controller. It is described by the equation below:

$$G_{CL}(s) = \frac{G_C(s)G_p(s)}{1+G_C(s)G_p(s)}$$

Substitutiing for $G_c(s)$ and $G_p(s)$ in $G_{CL}(s)$

$$G_{CL}(s) = \frac{K_p\left[1+\frac{1}{T_i s}\right]*\frac{b}{(s-a)}}{1+K_p\left[1+\frac{1}{T_i s}\right]*\frac{b}{(s-a)}} \tag{6.68}$$

$$G_{CL}(s) = \frac{K_p\left[T_i s+1\right]b}{T_i s^2 + T_i s(K_p - a) + K_p b} \tag{6.69}$$

4.) Characteristic equation of the closed loop transfer function and calculation of the PI controller parameters

The closed loop system characteristic equation

$$\square_{CL} = T_i s^2 + T_i s(K_p - a) + K_p b = 0 \tag{6.70}$$

Dividing through by T_i, this is obtained: $s^2 + s(K_p - a) + \frac{K_p b}{T_i} = 0$ (6.71)

In order to stabilise the system, and to achieve the desired behaviour of the closed loop system, to be with critical damping, the desired poles are selected to be placed at the points

$$\square_{des} = (s-s_1)(s-s_2) = s^2 - ss_2 - ss_1 + s_1 s_2 = s^2 - (s_1+s_2)s + s_1 s_2$$

$$\square_{des} = s^2 - (-4)s + 2 = s^2 + 4s + 2$$

The desired and the closed loop characteristic equations are compared $\square_{des} = \square_{CL}$ and the PI parameters are calculated as follows:

For $s^0, \frac{K_p b}{T_i} = 2$

For $s^1, K_p - a = 4$

From here, $K_p = 4 + a$

$$T_i = \frac{K_p b}{2} = \frac{(4+a)b}{2}$$

Recall that from equation (6.69) that $v(t) = K_p\left[\hat{e}(t) + \frac{1}{T_1}\int \hat{e}(t)dt\right]$

Substituting equation (6.75) into (6.69)

$$v(t) = (4+a)\left[\hat{e}(t) + \frac{1}{b((4+a)/2}\int \hat{e}(t)dt\right] \quad (6.72)$$

It should be noted that the value of a and b are determined by the desired wastewater model in use for the design.

Now substituting $v(t)$ from equation (6.72) into (6.53) the following is obtained

delay)

$$u(t-\tau_{tot}) = -\frac{1}{k_2}\ln\frac{1}{k_1}\left[\frac{(a+\frac{Q}{V}+k_1)S_o(t) + (4+a)\left[\hat{e}(t) + \frac{1}{(4+a)b/2}(t)\int \hat{e}(t)dt\right] - k_1 S_{o,sat} - \frac{Q}{V}S_{o,in} - r_{so}(t)}{(S_{o,sat} - S_o(t))}\right] \quad (6.73)$$

It could be seen from (6.73) that the control reaches the plant with delays τ_{tot} but it compensates the time delay effects over the behaviour of the closed loop system because of the compensation of the delays due to the Smith predictor.

6.5 Simulation of the closed loop Smith predictor-based DO process under constant delays

The Simulink block for this investigation is shown in Figure 6.8. The MATLAB program (experiment8.m) with the values of the model and the controller parameters is given in Appendix (D6.1). The Simulink block in Figure 6.8 was developed for three conditions of the investigations. In the first Simulink block resembles the traditional control system in which the closed loop DO process is without network induced time delays. In the second part, communication delays are introduced in form of transport delays and are considered to be part of the closed loop DO process. The Smith predictor scheme is included in the third part of the Simulink block in order to compensate for the network induced time delays. Using this Simulink block in Figure 6.7, four cases are investigated:

- $\tau_{ca} + \tau_{sc} = \tau_{tot} < \tau_c$, Figure 6.8
- $\tau_{ca} + \tau_{sc} = \tau_{tot} = \tau_c$, Figure 6.9
- $\tau_{ca} + \tau_{sc} = \tau_{tot} > \tau_c$, Figure 6.10

- $\tau_{ca} + \tau_{sc} = \tau_{tot} >> \tau_c$, Figure 6.11

Simulation was carried out for the cases of $\tau_{tot} < \tau_c$ as shown in Figure 6.8, $\tau_{tot} = \tau_c$ in Figures 6.9 and $\tau_{tot} > \tau_c$ in Figures 6.10 and 6.11.

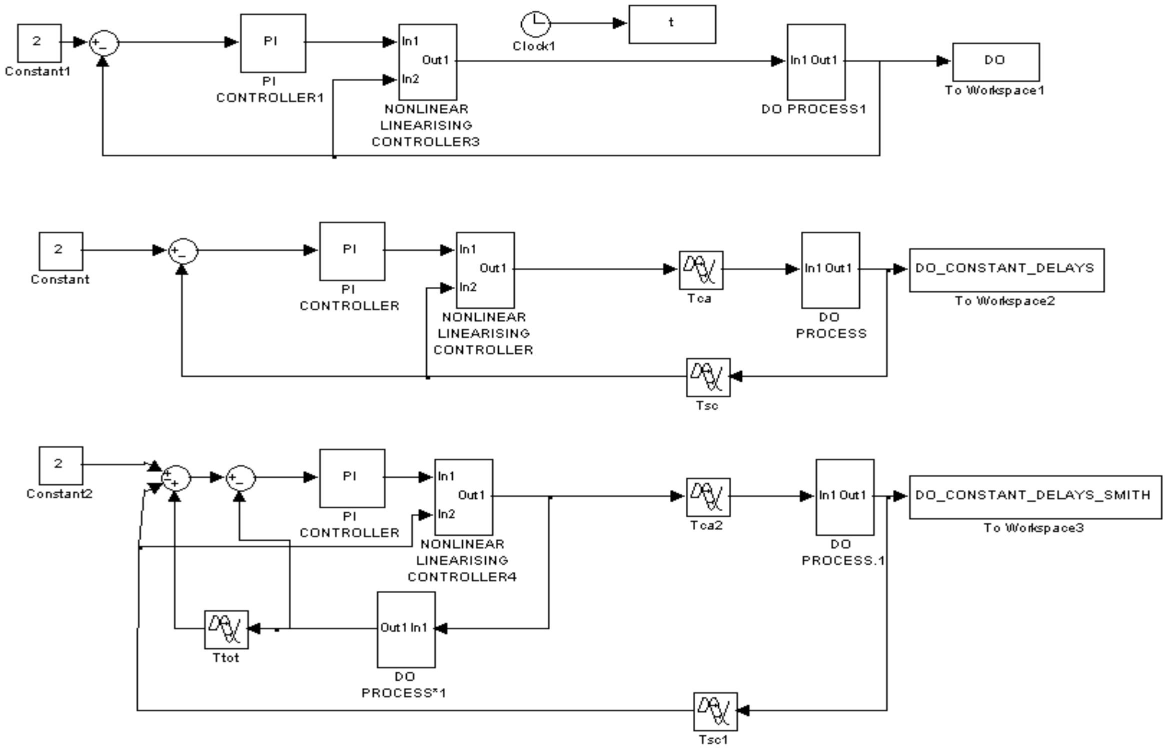

Figure 6.8: Simulink diagram of the closed loop Smith predictor-based DO process under constant delays

Case 1: The network induced constant delays are less than the critical delay $\tau_{ca} + \tau_{sc} = \tau_{tot} < \tau_c$

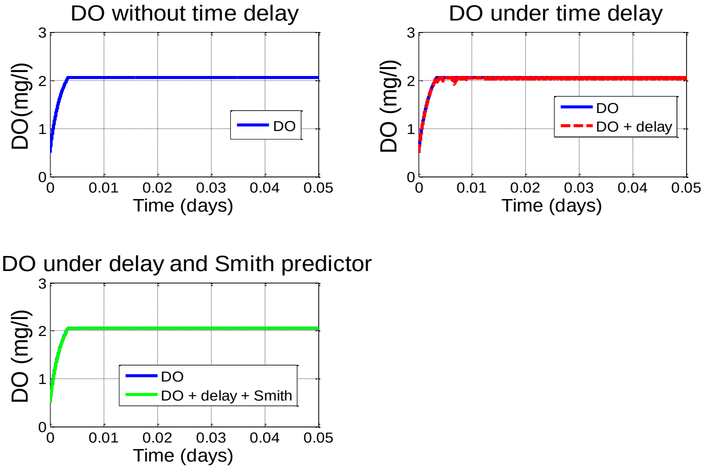

Figure 6.9: Simulation results of a.) DO process closed loop behaviour without time delays b.) DO process under constant delays c.) DO Smith predictor-based process under constant delay, $\tau_{tot} < \tau_c$ = 0.000016 days (1.38 secs.)

Case 2: The network induced constant delays are equal to the critical delay $\tau_{ca} + \tau_{sc} = \tau_{tot} = \tau_c$

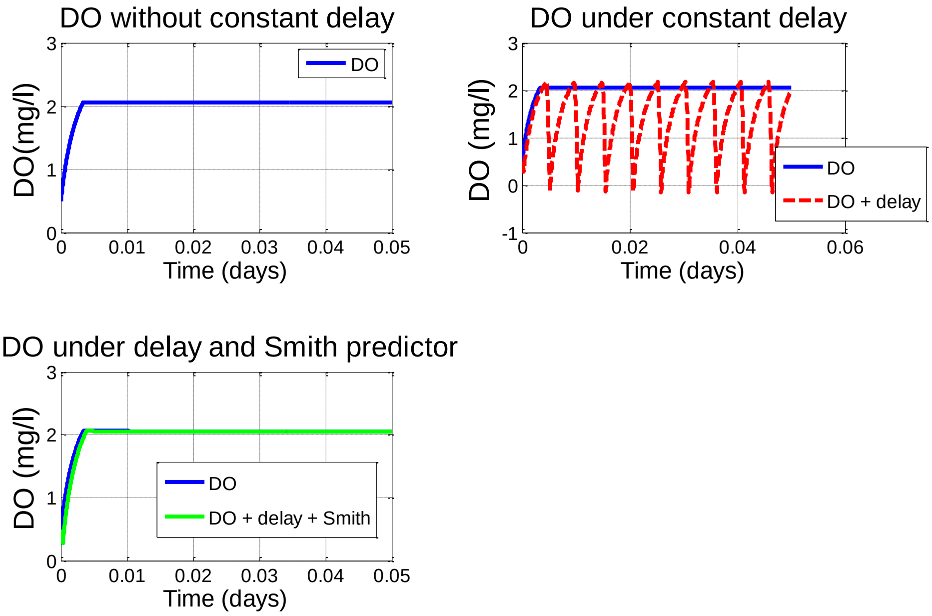

Figure 6.10: Simulation results of a.) DO process closed loop behaviour without time delays b.) DO process under constant delays c.) DO Smith predictor-based process under constant delay. $\tau_{tot} = \tau_c$ = 0.000614 days (53.04 secs.)

Case 3: The network induced constant delays are greater than the critical delay $\tau_{ca} + \tau_{sc} = \tau_{tot} > \tau_c$

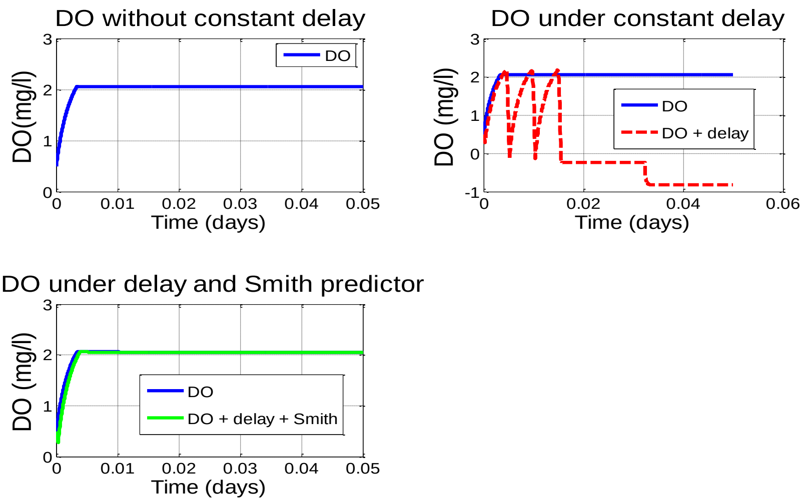

Figure 6.11: Simulation results of a.) DO process closed loop behaviour without time delays b.) DO process under constant delays c.) DO Smith predictor-based process under constant delay $\tau_{tot} > \tau_c$ = 0.000615 days (53.136 secs.)

Case 4:The network induced constant delays are greater than the critical delay $\tau_{ca} + \tau_{sc} = \tau_{tot} >> \tau_c$

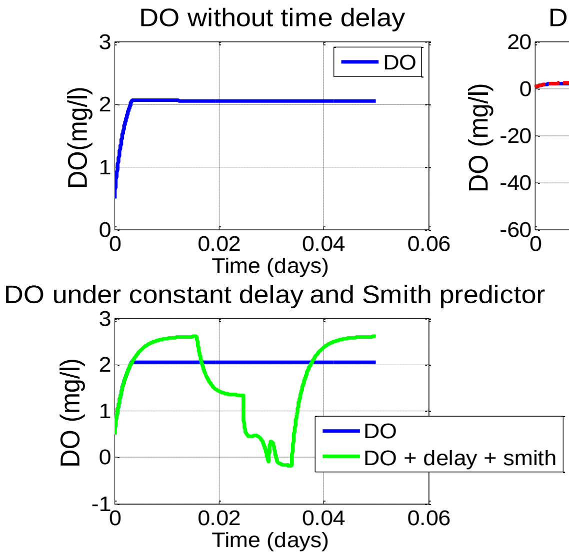

Figure 6.12: a.) DO process closed loop behaviour without time delays b.) DO process under constant delays c.) DO Smith predictor-based process under constant delay $\tau_{tot} >> \tau_c$ = 0.0246 days (2125.44 secs. or 35 minutes)

The performance indices of the closed loop DO process under constant time delays are shown in Table 6.2.

Table 6.1: Performance indices of the closed loop with and without Smith predictor DO process under constant time delays.

Measurement Conditions	Time delay Values (days)	Rise Time (days)	Settling Time (days)	Percentage Overshoot (%)	Steady State Error (mg/l)	Oscillation Amplitude (mg/l) Min; Max	Delay in Response (days)
Delay							
$\tau_{tot} = 0$	0	0.002000	0.003050	1.50	-0.0300	2.030	0
$\tau_{tot} < \tau_c$	0.000026	0.002013	0.005113	2.83	-0.0566	1.920, 2.056	0.000013
$\tau_{tot} = \tau_c$	0.000614	0.002307	0.003800	8.00	-0.1600	-0.130, 2.160	0.000307
$\tau_{tot} > \tau_c$	0.000615	0.002308	0.003800	9.00	-0.1800	-0.20, 2.180	0.000308
Delay +Smith							
$\tau_{tot} = 0$	0	0.002000	0.003050	1.50	-0.0300	2.030	0
$\tau_{tot} < \tau_c$	0.000026	0.002013	0.005113	2.64	-0.0566	2.0380, 2.0528	0.000013
$\tau_{tot} = \tau_c$	0.000614	0.002307	0.005500	3.32	-0.0663	2.0532, 2.0663	0.000307
$\tau_{tot} > \tau_c$	0.000615	0.002308	0.005600	3.30	-0.0660	2.0526, 2.0660	0.000308

6.6 Discussion of results from the simulations of the DO Smith predictor-based process under constant delays

It could be observed from simulation results in Figures 6.9 to 6.11 and Table 6.1 that the presence of network induced time delays in this case of a of linearised DO process resulted in the system overshoot and delay in system response. As the value of the induced delay increased, there was increase in the percentage overshoot and oscillation amplitude for all the cases investigated as well as the rise time of the system. At a critical delay equal to 0.000614 days (53.04 secs.), the system under constant time delays experienced a sustained oscillation as shown in Figure 6.10. Beyond this critical delay, the (PI + nonlinear linearising) controller was no longer able to stabilize the closed loop DO process but the Smith predictor was able to provide robust stability for the system by eliminating the oscillation, reducing oscillation amplitude and percentage overshoot as shown in Figure 6.11c and Table 6.1. However, it could be seen from Figure 6.12 that at a delay value equal to 0.0246 days (2125.44 secs. or 35 minutes), the Smith predictor compensation scheme became unstable and no longer adequate to provide the necessary stability for the system under constant delays.

6.7 Simulation of the closed loop DO Smith predictor-based process under random delays

In order to perform investigation that is close to a real life situation, the DO process was investigated under random time delays. This is because the communication Ethernet network which is the case study for this thesis is random in nature. Just as it was done in Chapter five, the performance of the PI controller was also compared with the developed Smith predictor compensation scheme in controlling the nonlinear closed loop DO process. The Simulink block for this is shown in Figure 6.13. The MATLAB program (experiment9.m) with the values of the model and the controller parameters is given in Appendix (D6.2). The Simulink block in Figure 6.13 is sued for the investigations of the closed loop DO process without time delays, with random time delays and then with random time delays and the Smith predictor compensation scheme. τ_{tot} is also computed by summing τ_{ca} and τ_{sc} ($\tau_{tot} = \tau_{ca} + \tau_{sc}$). The investigations are carried out for the cases of

- $\tau_{ca} + \tau_{sc} = \tau_{tot} < \tau_c$,
- $\tau_{ca} + \tau_{sc} = \tau_{tot} = \tau_c$,
- $\tau_{ca} + \tau_{sc} = \tau_{tot} > \tau_c$,
- $\tau_{ca} + \tau_{sc} = \tau_{tot} >> \tau_c$,

In order to test the performance of the developed Smith predictor in extreme conditions, the last case in Figure 6.17 (though unrealistic) is also carried out. Adopting the method used in section 4.5.2 and Figures 4.10 and 4.11, random delays were generated in which (τ_{ca} , τ_{ca}

and τ_{ca}) were assumed to be random variables which are uniformly distributed (Velagic, 2008). The DO process was converted to the discrete domain using the Zero Order Hold (ZOH) technique and at a sampling rate of T = 0.00001days (0.864 secs.). The noise to signal ration of 10% (Searchnetworking, 2014) was chosen for the probabilistic distribution of the random delays. The simulation results are shown in Figures 6.14 to 6.17. Table 6.2 is the performance indices of the transition behaviour of the closed loop systems.

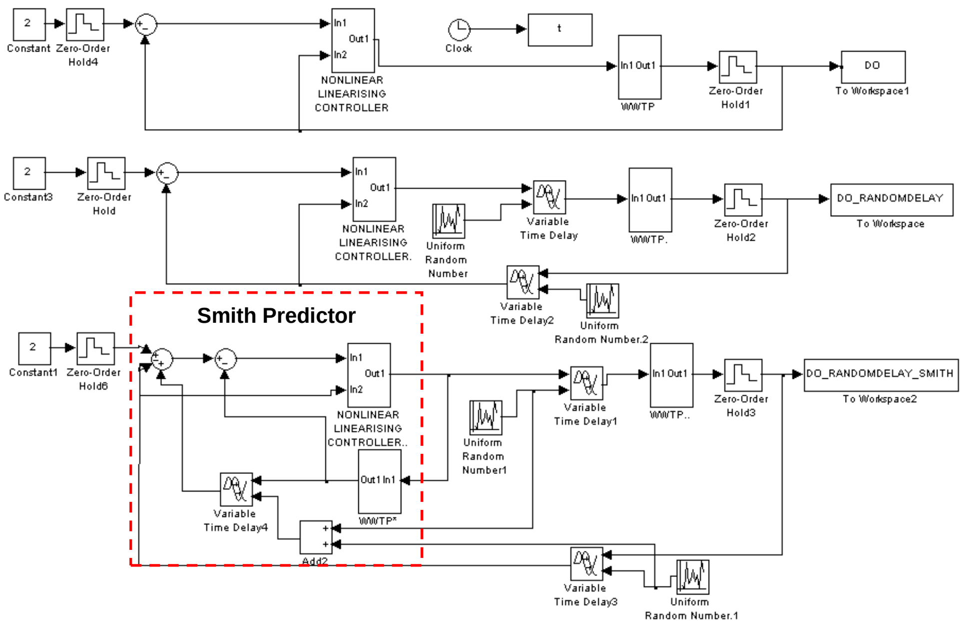

Figure 6.13: Simulink diagram of the Smith predictor-based compensation scheme for the DO process under random delays

Case 1:The network induced random delays are less than the critical delay $(\tau_{ca} + \tau_{sc} = \tau_{tot} < \tau_c)$

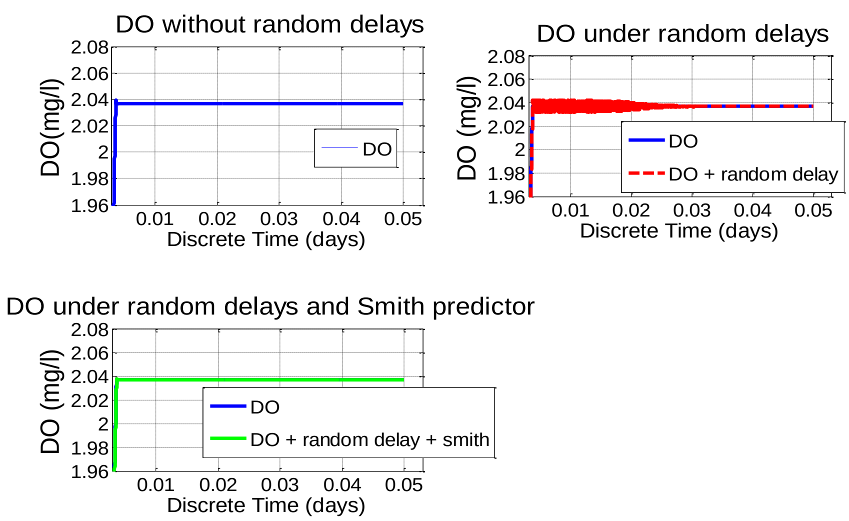

Figure 6.14: Simulation results of a.) DO process closed loop behaviour without time delays b.) DO process under random delays c.) DO Smith predictor-based process under random delays, $\tau_{tot} < \tau_c$ = 0.000026 days (2.85 secs.)

Case 2:The network induced random delays are equal to the critical delay $(\tau_{ca} + \tau_{sc} = \tau_{tot} = \tau_c)$

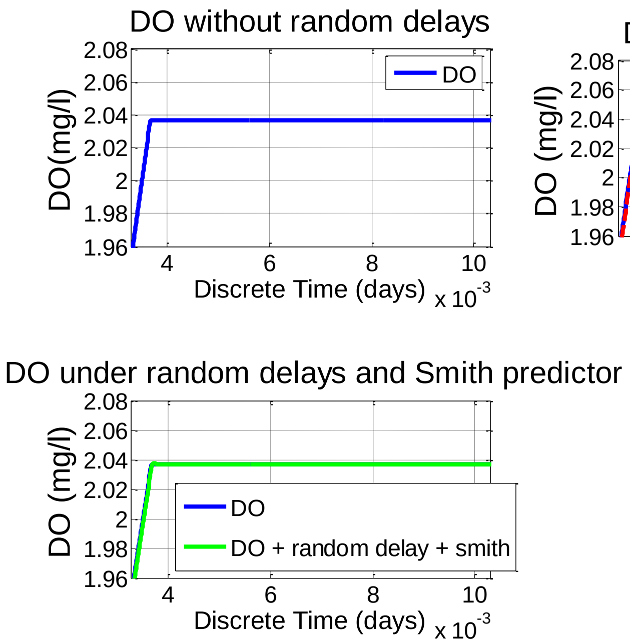

Figure 6.15: Simulation results of a.) DO process closed loop behaviour without time delays b.) DO process under random delays c.) DO Smith predictor-based process under random delays, $\tau_{tot} = \tau_c$ = 0.000027 days (0.233 secs.)

Case 3:The network induced random delays are greater than the critical delay $(\tau_{ca} + \tau_{sc} = \tau_{tot} > \tau_c)$

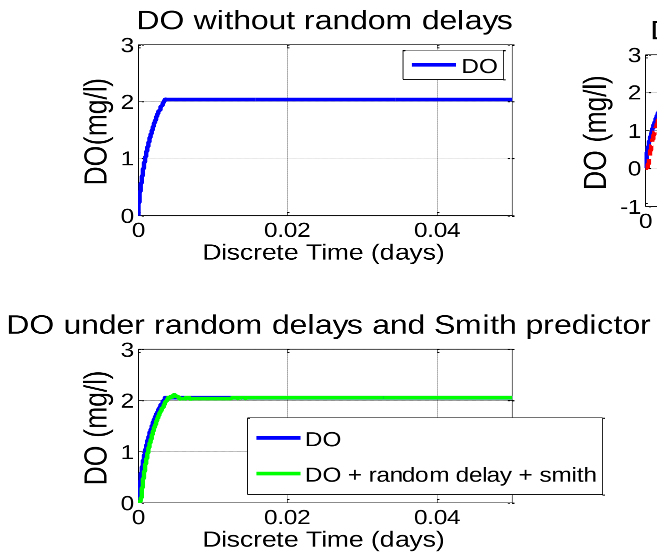

Figure 6.16: Simulation results of a.) DO process closed loop behaviour without time delays b.) DO process under random delays c.) DO Smith predictor-based process under random delays, $\tau_{tot} > \tau_c$ = 0.0008 days (69.12 secs. or 1.15 mins.)

Case 4: The network induced random delays are much greater than the critical delay $(\tau_{ca} + \tau_{sc} = \tau_{tot} >> \tau_c)$

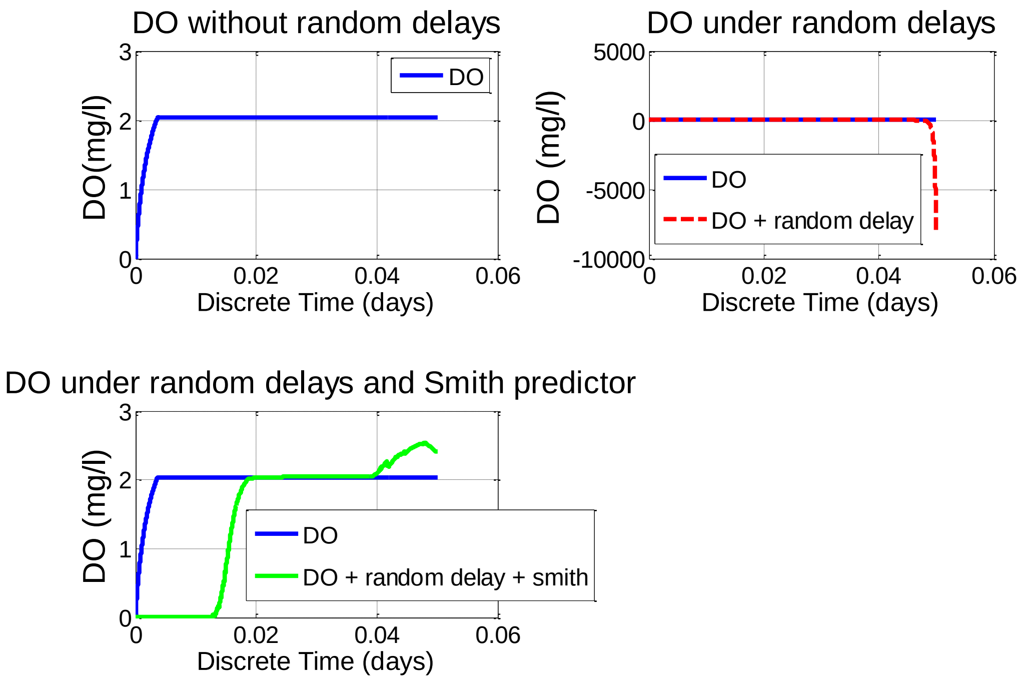

Figure 6.17: Simulation results of a.) DO process closed loop behaviour without time delays b.) DO process under random delays c.) DO Smith predictor-based process under random delays, $\tau_{tot} >> \tau_c$ = 0.028 days

The performance indices of the closed loop DO process under different random delay conditions are shown in Table 6.2.

Table 6.2: Performance indices of the closed loop with and without Smith predictor DO process under different random delay conditions.

Measurement Conditions	Time delay values (days)	Rise Time (days)	Settling Time (days)	Percentage Overshoot (%)	Stead State Error (mg/l)	Oscillation Amplitude (mg/l)	Delay in Response (days)
Delays							
$\tau_{tot} = 0$	0	0.002600	0.00350	2.63	-0.052500	2.05260	0
$\tau_{tot} < \tau_c$	0.000026	0.002613	0.003513	2.87	-0.052600	2.0477, 2.0575	0.000013
$\tau_{tot} = \tau_c$	0.000027	0.002614	0.003514	2.90	-0.052500	2.047, 2.058	0.000014
$\tau_{tot} > \tau_c$	0.000800	0.003000	0.003900	9.70	1.085000	-0.364,2.194	0.000400
	Delays +Smith						
$\tau_{tot} = 0$	0	0.002600	0.00350	2.63	-0.052500	2.05260	0
$\tau_{tot} < \tau_c$	0.000026	0.002613	0.003513	1.88	-0.0377	2.0367, 2.0377	0.000013
$\tau_{tot} = \tau_c$	0.000027	0.002614	0.003514	1.89	-0.0378	2.0368, 2.0378	0.000014
$\tau_{tot} > \tau_c$	0.000800	0.003000	0.003900	4.92	-0.0985	2.0203, 2.0985	0.000400

6.8 Discussion of results for the Smith predictor-based DO process under random delays

The results of the simulation of the nonlinear DO process under the influence of random time delays and the Smith predictor compensation scheme in Table 6.1 reveal some consistency with the constant delay simulation in Table 6.1. This consistency is in terms of rise time, settling time, and percentage overshoot and oscillation amplitude. However, there was little variation in the steady state error in the case of time delay greater than the critical delay. One could also notice some delays in the system response. This delayed response could be seen to be the exact value of the controller to actuator delay (τ_{ca}) induced by the network as shown in Table 6.2. This behaviour is also consistent with the case of constant delays in Table 6.1. As a result of the delay experienced in the system response, the rise time and settling time of the system rose slightly. The main difference between the constant delay simulation in Figures 6.9 to 6.12 and the random delays in Figures 6.14 to 6.17 is that the DO process under constant delays attained its critical value in 0.000614 days (53.04 secs.) as shown in Figure 6.10. The critical delay value is 0.000027 days (0.233 secs.) under random time delays as shown in Figure 6.15. The random delay is found to be 22.7 times less the value of the constant critical delay. Just as it was in the case of constant delays, the Smith predictor was also found to out-perform the PI controller and the nonlinear linearising controller combined in order to stabilise the DO process. From the critical delay of 0.000027 days, the (PI + nonlinear linearising) controller failed to stabilise the DO process under increasing time delays. The developed Smith predictor continues to stabilize the system until 0.028 days when the Smith predictor attained its critical value.

6.9 Comparison of the results obtained from the simulations of the closed loop systems different approaches of the Smith predictor design

The different arrangements of the developed Smith predictor compensation scheme gives rise to the transfer function approach which is used in Chapter five and the nonlinear linearising approach used in Chapter six. The detailed description of the arrangements leading to these different approaches are described in section 5.3 and Figure 5.3. As a result of these arrangements, the formation of the Smith predictor compensation scheme and the results obtained from the simulations also vary. For example, in the transfer function approach of Chapter five, linear control design methods are used and the Smith predictor is formed using a model of the linearised DO process while in the case of the nonlinear linearising controller of Chapter six, linear method of controller design can not be used since the DO process is originally a nonlinear system. As a result, feedback linearization is used to linearise the nonlinear DO process before linear control design methods are used. The Smith predictor in this case is designed using the model of the nonlinear DO process. The derivation of the Smith predictor using the transfer function approach is found to be less rigorous in terms of computation when compared to the nonlinear linearising approach. In terms of performance when compensating for the network induced time delays, the transfer function approach of Chapter five is found to outperform the nonlinear linearising approach of the Smith predictor design in Chapter six considering the rise time, percentage overshoot and settling time. For instance, it could be observed from Tables 5.1 and 5.2 and Figures 5.7 to 5.9 that the DO process under network induced time delays experienced only system overshoot but no delay in the system response. In the case of the nonlinear linearising approach as shown in Tables 6.1, 6.2 and Figures 6.8 to 6.15, the DO process did not only undergo system overshoot, there is also a noticeable delay in the response of the system. As a result of this, the Smith predictor-based DO process using the transfer function is found to rise faster than the Smith predictor using the nonlinear linearising approach.

When induced with random time delays, both the transfer function and the nonlinear linearising approaches reached their critical delays in 0.000027 days (2.33secs.). However, the Smith predictor-based DO process using the transfer function approach was able to compensate for the random delays better with a percentage overshoot of 1.89% which is lower than the percentage overshoot of 2.66% obtained in the case of the Smith predictor designed by the nonlinear linearising approach. This is shown in Table 6.2 and Figures 5.13 and 6.14. This confirms that the transfer function approach of Smith predictor design provides more robustness than the nonlinear linearising approach.

The investigation with constant time delays reveals that the DO process using the different approaches reached their critical delays at different times unlike the case of random delays in which both approaches reached the critical delay at the same time (0.000027 days). As shown in Table 5.1, the linearised DO process under the influence of constant time delays in Chapter five reached the critical delay in 0.000752 days (64.9secs.) as shown in Figure 5.9 which is longer than 0.0000614 days (53.04 secs.) as shown in Figure 6.10 in the case of the nonlinear DO process used in of Chapter six. It could be concluded from this that the Smith predictor based DO process using the nonlinear linearising approach in Chapter six is more prone to disturbances and network imperfections than the Smith predictor-based DO process following the transfer function approach of Chapter five which takes a longer time to reach its critical delay. A possible reason for this could be that the placement of the nonlinear linearising controller close to the nonlinear DO process and far from the PI controller, thus forming a linearised DO process as described in section 5.3 case 1 could have provided some kind of robustness for the linearised DO process as the control action $u(t)$, not $u(t-\tau_{tot})$ acts on the process.

Apart from these notable differences, there are some similarities in the behaviour of the Smith predictor based DO process using the transfer function approach in Chapter five and the nonlinear linearising approach in Chapter six. In both cases, the DO process control system results in system overshoot that affects the stability of the control system. As the network induced time delays are increased from a given minimum value to a maximum value, there is a corresponding increase in the percentage overshoot until a sustained oscillation (critical delay) is attained as shown in Figures 5.8, 5.13 in Chapter five and Figures 6.9, 6.15 in Chapter six. A further increase in the network delays beyond the critical delay leads to a situation whereby the dissolved oxygen concentration goes to zero. The practical implication is that the oxygen in the ASP is depleted and there is no more available for microorganisms to live on and to perform their wastewater cleaning activities. This can be seen in Figures 5.9, 5.14 in Chapter five and Figures 6.11, 6.16 in Chapter six. This could lead to poor effluent quality and failure of the ASP. In both approaches the DO process with Smith predictor compensation schemes outperformed the DO process without Smith predictor in eliminating network imperfections and returning the DO process to its desired set-point. This can be seen in Tables 5.1, 5,2, 6.1 and 6.2.

In summary, the Smith predictor-based DO process using the transfer function approach is found to perform better than the Smith predictor-based DO process using the nonlinear linearising approach on the basis of rise time and percentage overshoot. It is also found to be more reliable in terms of robustness to provide system stability. It is less rigorous in terms of mathematical computation when compared to the nonlinear linearising approach. A demerit of this approach might be that it derived in the frequency domain and might not be suitable for Many Input Many Output (MIMO) control systems while the nonlinear linearising approach is done in state space and so it is easy to implement in a MIMO set-up. Even though in theory, the transfer function approach of Smith predictor design is found to outperform the nonlinear linearising approach in terms of robustness and system performance, it might not be a very realistic approach in terms of real-life (practical) implementation because most real-life systems are nonlinear in nature.

6.10 Investigation of the performance of the Smith predictor-based DO process using the nonlinear linearising approach under the influence of network induced time delays and disturbances.

The effects of network induced time delays and saturation disturbances are investigated in this section in order to evaluate the robustness and performance of the Smith predictor scheme developed in this Chapter. Similar to section 5.10, the saturation limits are introduced (as a form of disturbance) in the nonlinear linearising control algorithim used for the DO process closed loop control. Saturation limit values 0.001 and 5 are chosen for the lower saturation limit and upper saturation limit respectively. The Simulink block diagram for constant delays in Figure 6.8 is adapted. Figures 6.18 to 20 are the results of simulations performed on the DO process under constant time delays and saturation disturbance. It could be seen from the results of Figures 6.18 to 6.20 that even though constant delays were induced into the control system, a close observation of the simulation results reveal that the DO process under consideration exhibits some type of random behaviour. This could be seen in Figure 6.18. One could therefore conclude that the random behaviour of the constant delays induced in the control system would have been as a result of the disturbance incorporated in the closed loop system by the use of saturation.

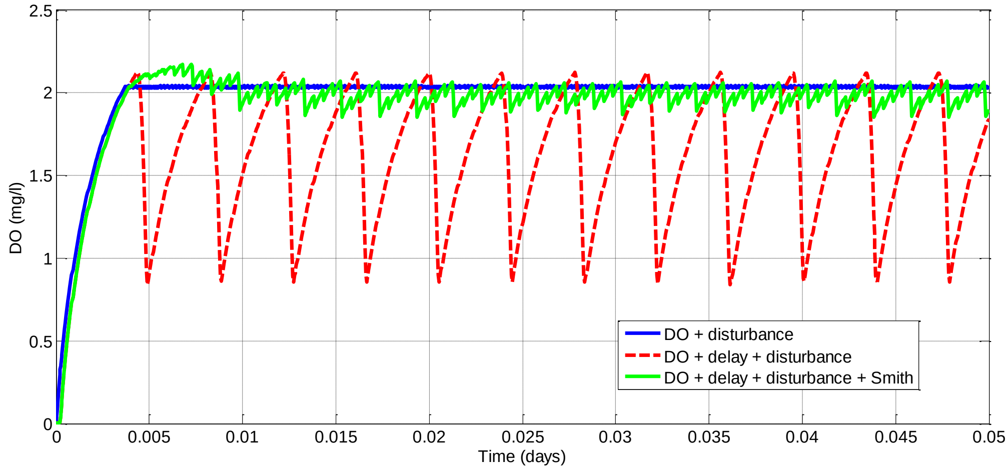

Figure 6.18: Simulation results of the DO process closed loop behaviour under constant network induced time delays and saturation disturbance. τ_{tot} = 0.00044 days (380.16 secs.)

In Figure 6.18, a time delay of 0.0044 days is induced in the control system. The Smith predictor-based DO process using the nonlinear approach is still able to provide some compensation for the time delay and disturbances to stabilise the closed loop control system. It should be noted however that the in this case, the steady state error is poor.

When larger time delays of 0.01 days and 0.06 days are induced in the closed loop control as shown in Figure 6.19 the closed loop DO process is observed to exhibit delayed system response of 0.005 days but there is improvement in settling time when compared to Figure 6.19.

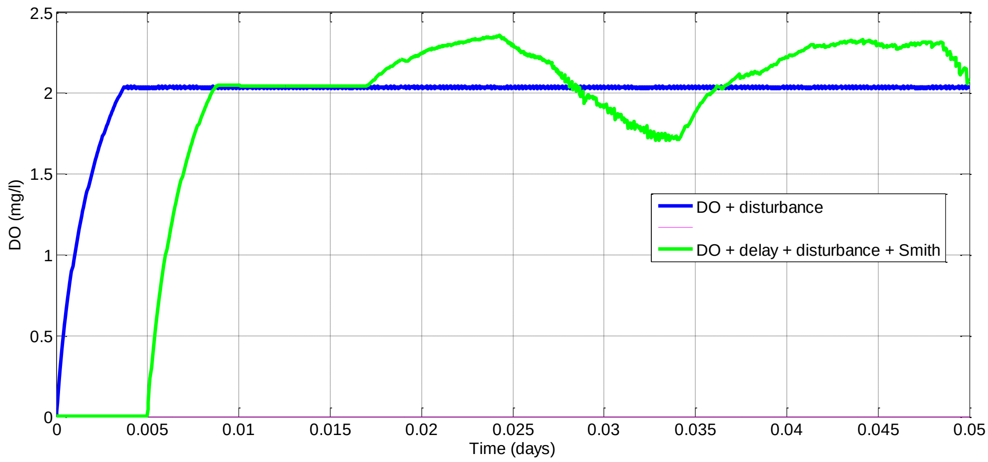

Figure 6.19: Simulation results of the DO process closed loop behaviour under constant network induced time delays and saturation disturbance. τ_{tot} = 0.01 days (8640 secs.)

In Figure 6.20, the time delay is increased to 0.06 days. The closed loop DO process simulation result reveal good performance in steady state error, system overshoot but poor response in terms of rise time. Even though the control system is delayed for 0.003 days before responding, it is still able to stabilise the system to the desired trajectory of 2 mg/l. One can infer from the simulation results that the nonlinear method of Smith predictor compensation scheme developed in this Chapter exhibits the following behaviours:

Poor performance with small delays and disturbances in terms of steady state error and settling time but the performance with larger induced time delays and disturbances. Poor performance in term of rise time due to delayed system response. With increased induced time delays and disturbances, the rise time of the control system become poorer. The Smith predictor compensation scheme developed using this method outperforms the (PI + nonlinear linearing) controllers without smith predictor in providing robustness and good performance for the closed loop DO process.

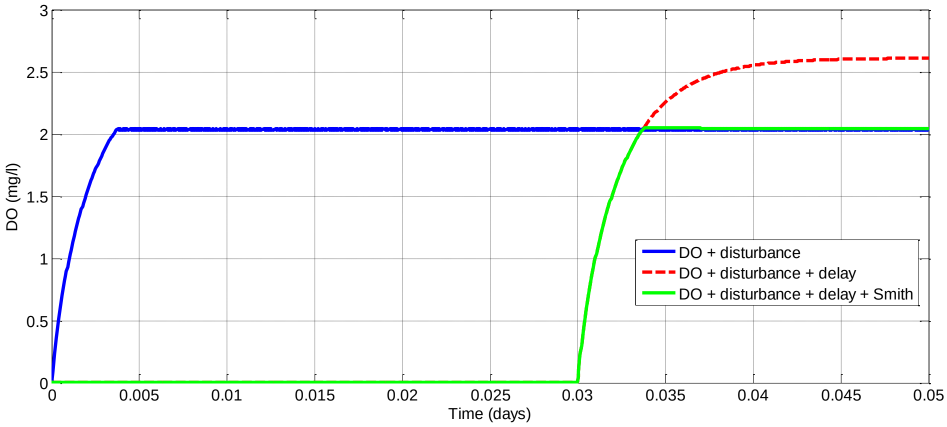

Figure 6.20: Simulation results of the DO process closed loop behaviour under constant network induced time delays and saturation disturbance. τ_{tot} = 0.06 days (51840 secs.)

A real-time implementation of the developed nonlinear linearing approachof designing the Smith predictor in the LabVIEW real-time environment.

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6.10 Conclusion

A Smith predictor compensation scheme is developed to compensate for constant and random delays induced into the DO process by the network in this chapter. The behaviour of the DO process under constant and random delays is similar in terms of rise time, settling time, percentage overshoot and oscillation amplitude but differ in the terms of the critical delay. The nonlinear DO process was found to attain critical delay 22.7 times faster than with constant delays. Analytical and simulation results confirm the effectiveness of the Smith predictor scheme over the (PI + nonlinear linearising) controller without Smith predictor to provide robustness for the control of the DO process under the influence of constant and random communication delays. The transfer function and the nonlinear linearising approaches of Smith predictor designs for the DO process were compared. Simulation results reveal that the transfer function approach outperformed the nonlinear linearising approach to provide robustness and performance for the DO process. The next Chapter will involve the real-time implementation of the developed Smith predictor scheme.

CHAPTER SEVEN

REAL-TIME SIMULATION BASED ON THE SMITH PREDICTOR COMPENSATION SCHEME OF THE DO PROCESS CLOSED LOOP BEHAVIOUR

7.1 Introduction

This chapter is concerned with the simulation of the networked DO process closed loop behaviour in a real-time environment. The essence of this simulation is to validate the networked controllers designed in this thesis in a scenario that is similar to what obtains in real-life situations. The LabVIEW environment is chosen for the real-time implementation because it is a graphical programming language that presents the dynamics of the control system under consideration in a visual and graphical format which the user can easily relate with. There are two main configurations under which NSC is implemented and they are the direct and the hierarchical structures. These configurations have been covered in section 2.3.1.2. The direct structure is adopted in this thesis. The Smith predictor scheme is implemented under the two approaches developed for the DO process in the thesis Chapters five and six, and compared.

Section 7.2 describes the modelling of the COST Benchmark model of the ASP in the LabVIEW environment and presents the open loop DO response. Section 7.3 is concerned with the closed loop DO process with PI controller combined with nonlinear linearising controller in the absence of network induced time delays. Section 7.4 describes the real-time simulations of the closed loop DO process. Section7.5 presents the discussion of results. In section 7.6, the nonlinear linearising approach of Smith predictor is compared with the transfer function approach while the Chapter concludes with section 7.7.

7.2 Modelling of the COST Benchmark model of the ASP using LabVIEW

LabVIEW stands for the Laboratory Virtual Instrument Engineering Workbench. It is a graphical (G) programming tool developed by the National Instruments (NI) where icons are dragged and dropped to define functionalities. The LabVIEW functions are referred to as Virtual Instruments (vi) (Mkodweni, 2014). Virtual instruments have been used to teach students in environments where the necessary hardware requirements are inadequate or not available (Basher and Isa, 2005; Plummer et al., 2002, Rajesh et al., 2002). Modelling of a control system in LabVIEW could be carried out either by conversion of existing MATLAB/Simulink model to LabVIEW or modelling the plant or controller from the scratch using the Control Design and

Simulation tools in LabVIEW or a combination of the two approaches. The control design and simulation loop is shown if Figure 7.1

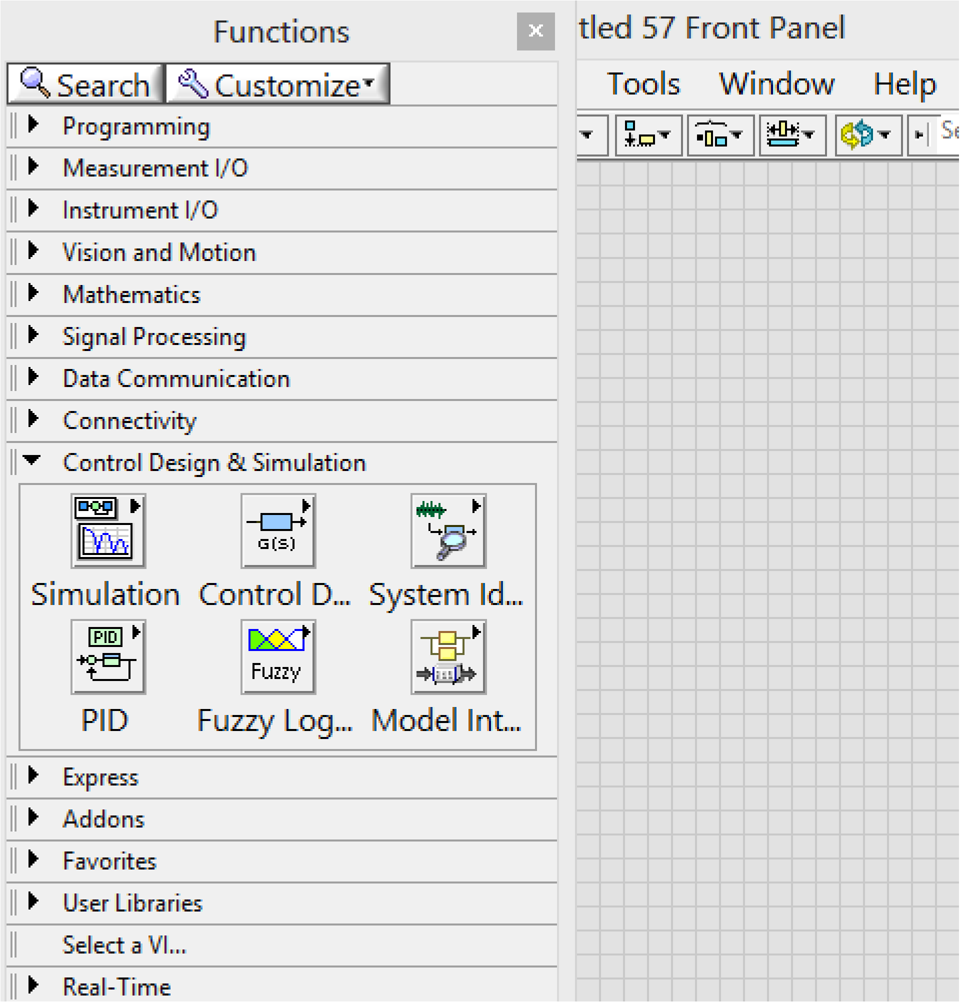


Figure 7.1: Control design and simulation tools in LabVIEW (LabVIEW, 2013)

The modelling of the COST Benchmark model in the LabVIEW environment is achieved using a combination of the two approaches described above. The process involves the use of Simulation Model Converter (SMC) in LabVIEW to convert Simulink model of the WWTP to equivalent LAbVIEW vi(s) which could later be adjusted appropriately to conform to the LabVIEW programming formats. Figures 7.1 to 7.3 show the process of converting MATLAB/Simulink model of the WWTP to a LabVIEW-based equivalent. In order to achieve this conversion, the following steps are followed:

- From the LabVIEW main menu, click on tools

- From the drop down that appears, select Control Design and Simulation in order to locate the simulation model converter dialog box. This is illustrated in Figure 7.2.
- From the pop-up, click on Simulation Model Converter (SMC). The simulation model converter dialog box appears as shown in Figure 7.3.
- Select the file or directory to be translated and the directory to output the converted files
- Click on convert

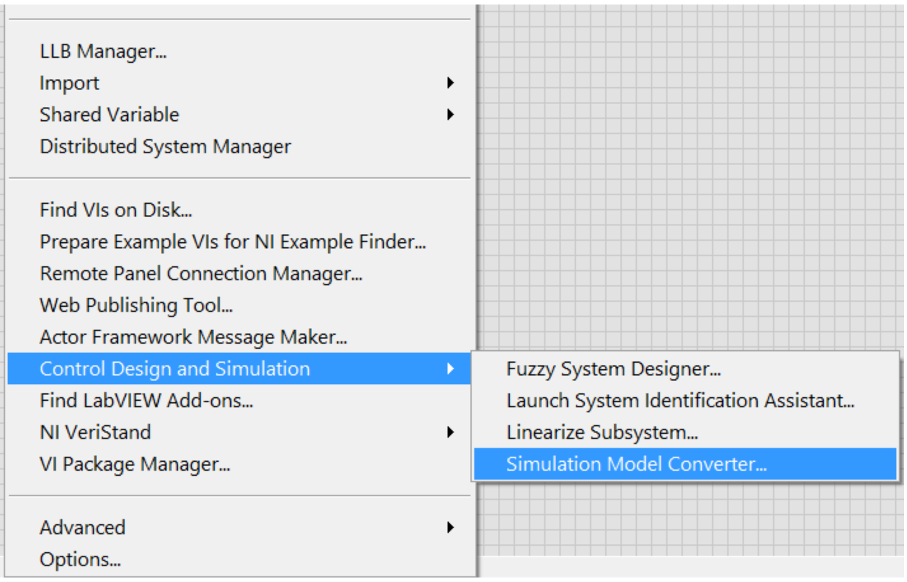


Figure 7.2 Location of the simulation model converter in LabVIEW

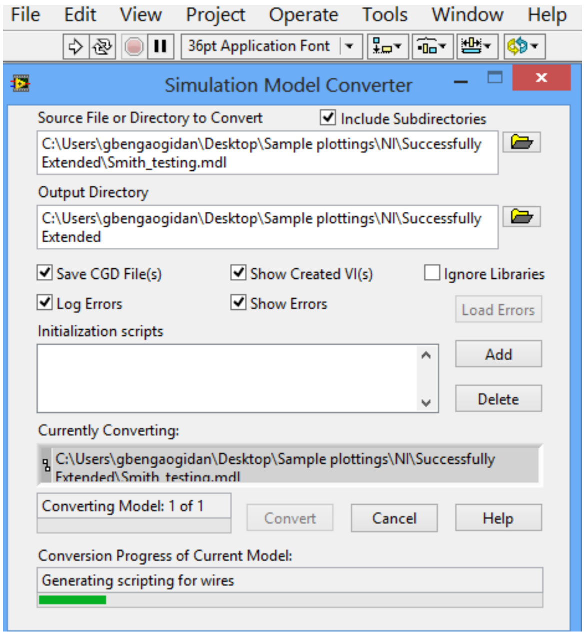
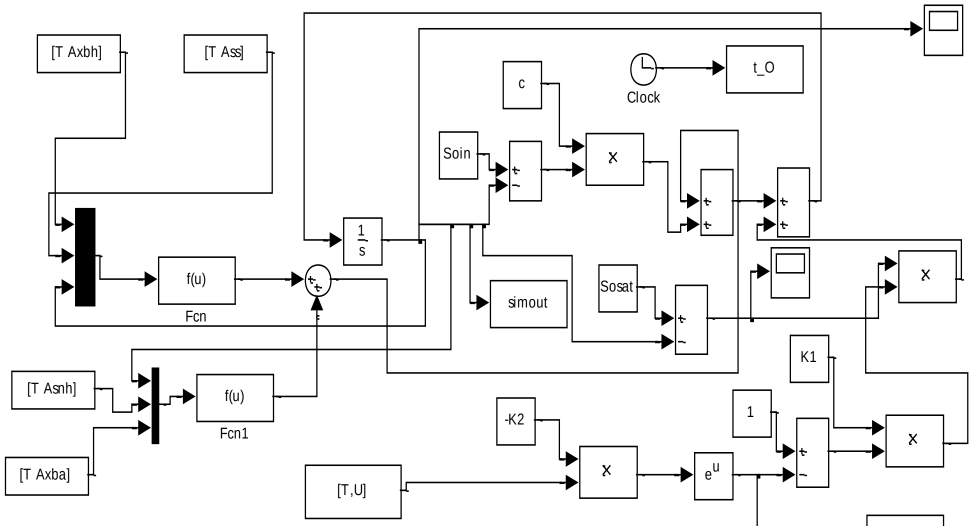


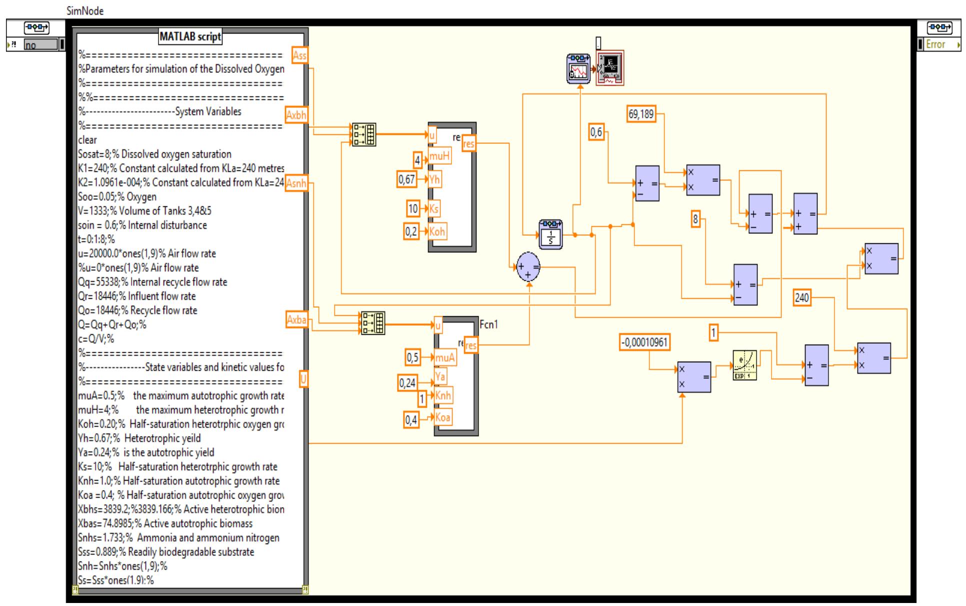
Figure 7.3: The simulation model converter dialog box in the LabVIEW environment

In this thesis, the above procedure is followed to convert the open loop and closed loop DO process models from the MATLAB/Simulink environment to the LabVIEW environment. However, there are some differences between the two environments. For instance, LabVIEW does not read data directly from the MATLAB mfiles, as a result mathscript codes are to be written in compliance with the LabVIEW syntaxes and rules in order to present the original Mathscript data used in the MATLAB/Simulink environment to the new environment of LabVIEW vi(s).

The COST Benchmark model of the ASP presented in MATLAB/Simulink environment in Figure 3.6 and its open loop response shown in Figure 3.7 after the conversion process are presented in the LabVIEW vi(s) formats as shown in Figures 7.3 and 7.4 respectively.

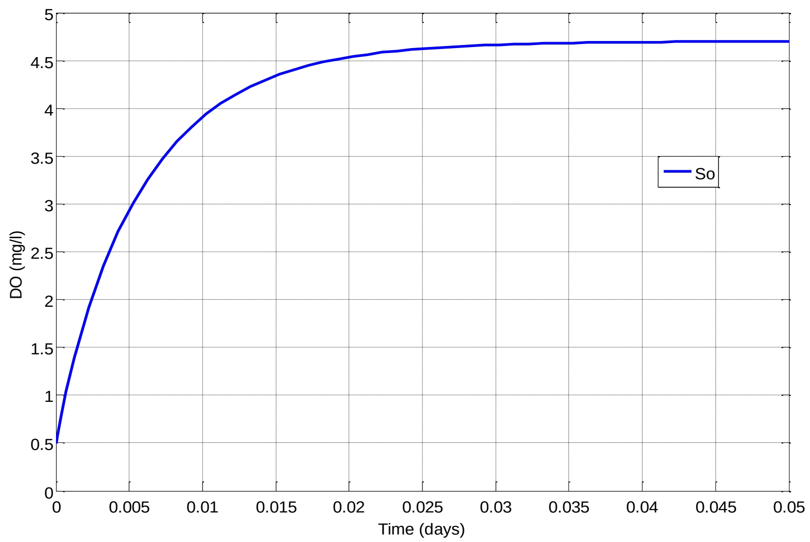


MATLAB/Simulink model of the DO process

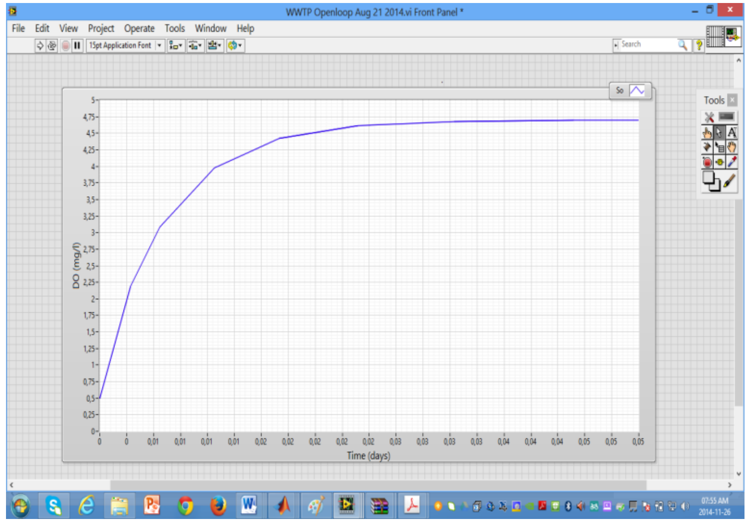


LabVIEW model of the DO process

Figure 7.4: Comparison between the developed models of the DO process in MATLAB/Simulink and the LabVIEW environments



MATLAB/Simulink open loop response of the DO process.



LabVIEW open loop response of the DO process

Figure 7.5: Comparison between the open loop responses of the DO concentration in MATLAB/Simulink and the LabVIEW environments

7.3 Closed loop DO process implementation in the LabVIEW environment

After the modelling of the DO process in the LabVIEW environment and obtaining appropriate open loop response, the (PI + nonlinear linearising) controllers of section 4.3 were implemented for the DO process in the LabVIEW environment using the tools in Control and Simulation Toolbox. Figure 7.6 is the LabVIEW block diagram of the closed loop DO process with (PI + nonlinear linearising) controllers while Figure 7.7 is the closed loop response in the absence of network induced time delays.

For the purpose of this investigation on the effects of time delays and disturbance in the closed loop DO process, the saturation lower and upper limits used are 0.001 and 5 respectively as described in Chapter four, section 4.8. This the closed loop DO process in the absence of network delays after the saturation values are fixed is shown in Figure 7.8. It could be seen from the Figure 7.8 that the enlarged closed loop DO process response due to inclusion of satutation block is similar to the random delays responses of Figures 4.13 and 4.16. One could therefore infer that the saturation block introduced into the nonlinear linearising controller is responsible for the randomness in the closed loop DO process response shown in Figure 7.8 and 7.9 Although this procedure succeeded in overcoming this challenge, it also introduced some type of delay/disturbances (noise) into the system. This could be seen in the response of the closed loop DO process in Figures 7.8 and 7.9. As a result, the closed loop DO process under consideration in this chapter does not only have to cope with network induced time delays, it also has to cope with the disturbances introduced into the system by the saturation Simulink block. The real-time simulations carried out in this Chapter are therefore performed with a focus on how the developed Smith predictor approaches developed in Chapters five and six are able to overcome time delays and the disturbances.

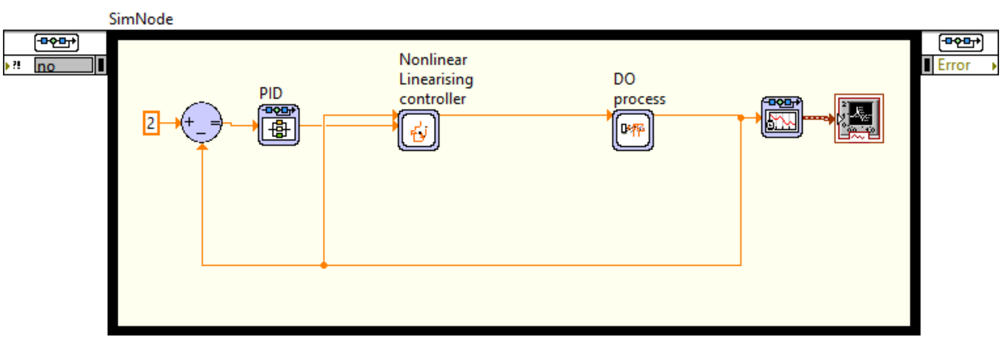


Figure 7.6: LabVIEW block diagram of the closed loop DO process without network delays

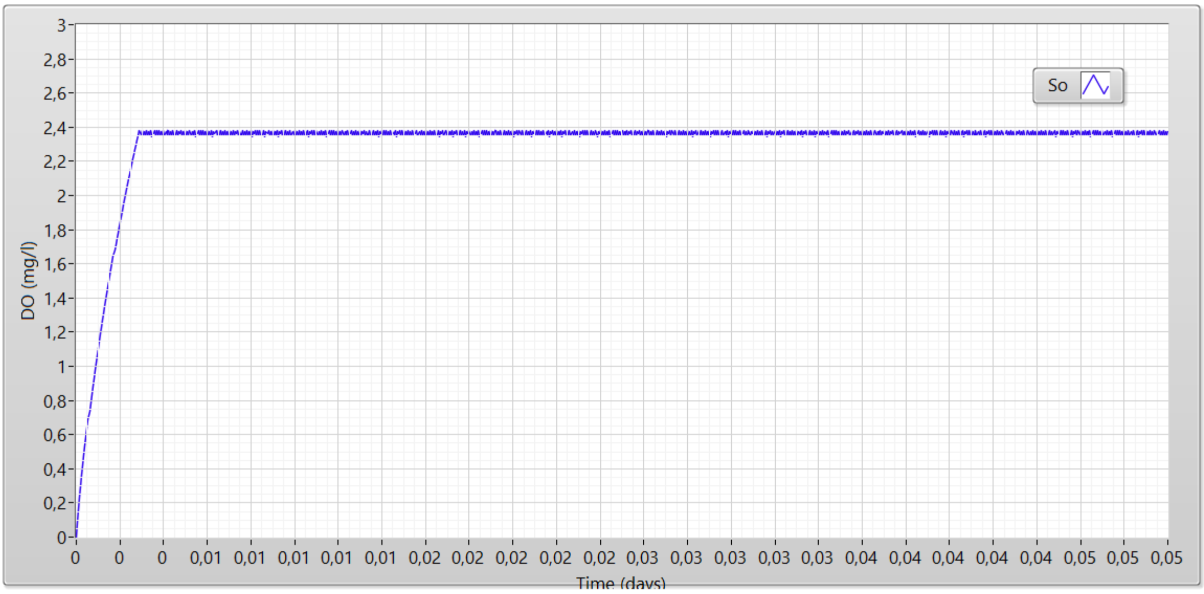


Figure 7.7: LabVIEW front panel closed loop response of the DO process without network delay

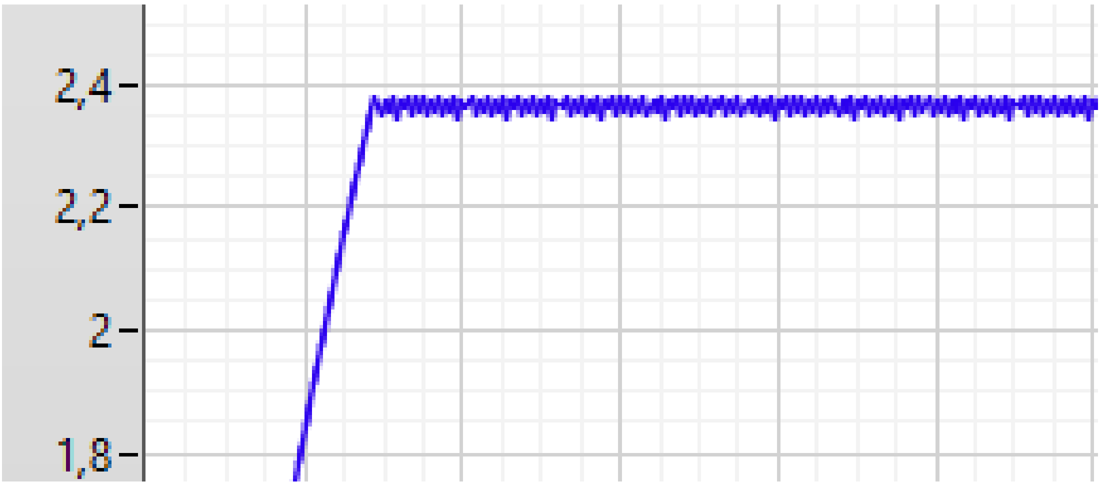


Figure 7.8: An enlarged diagram of the LabVIEW front panel closed loop response under disturbance of the DO process without network delay

7.4 Real-time simulation of the Smith predictor-based closed loop DO process under network induced time delays and disturbances

Real-time simulations are performed in order to investigate the influence of network induced time delays and disturbances on the DO process and the performance of the developed Smith predictor compensation scheme. To achieve this, network induced time delays in the form of transport delays are introduced in to the closed loop DO process. The transfer function and the nonlinear linearising approach of the Smith predictor scheme design are investigated. The arrangements for the two approaches as described in section 5.3 are used. The random time delays are represented with transport delays and placed between the DO process and the (PI + nonlinear linearising) controllers as shown in Figure 7.9 for the nonlinear linearising case and for the transfer function approach, the delays are placed between the PI controller and the linearised DO process. This is shown in Figure 7.10

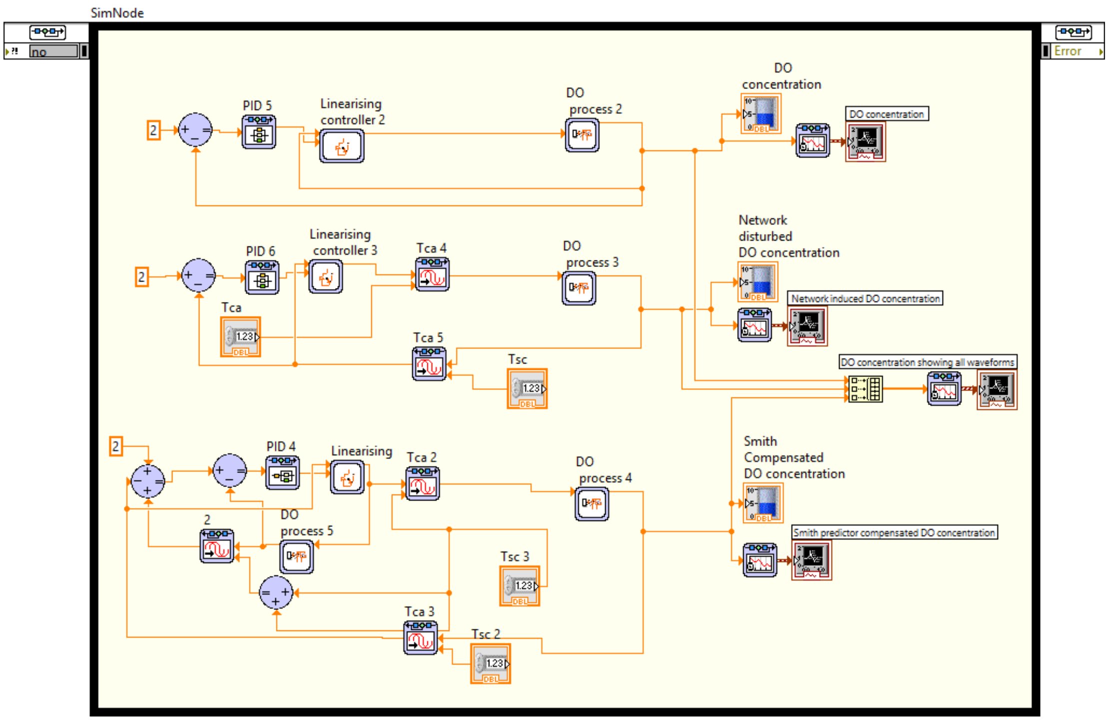


Figure 7.9: LabVIEW block diagram of real-time simulation of the Smith predictor-based compensation scheme for the closed loop DO process using the nonlinear linearising approach

For each of the block diagrams in these Figures, the delays are increased from a given minimum value to a mximum value until a sustained oscillation (critical delay is reached). In Figures 7.9 and 7.10 the first cases investigated are those of the closed loop DO process without network delays. In the second cases, the closed loop DO process behaviour is subjected to time delays and disturbances incorporated into the closed loop DO process using saturation block in LabVIEW, while in the third cases, the Smith predictor compensation schemes are applied in order to provide robustness for the network induced closed loop DO process.

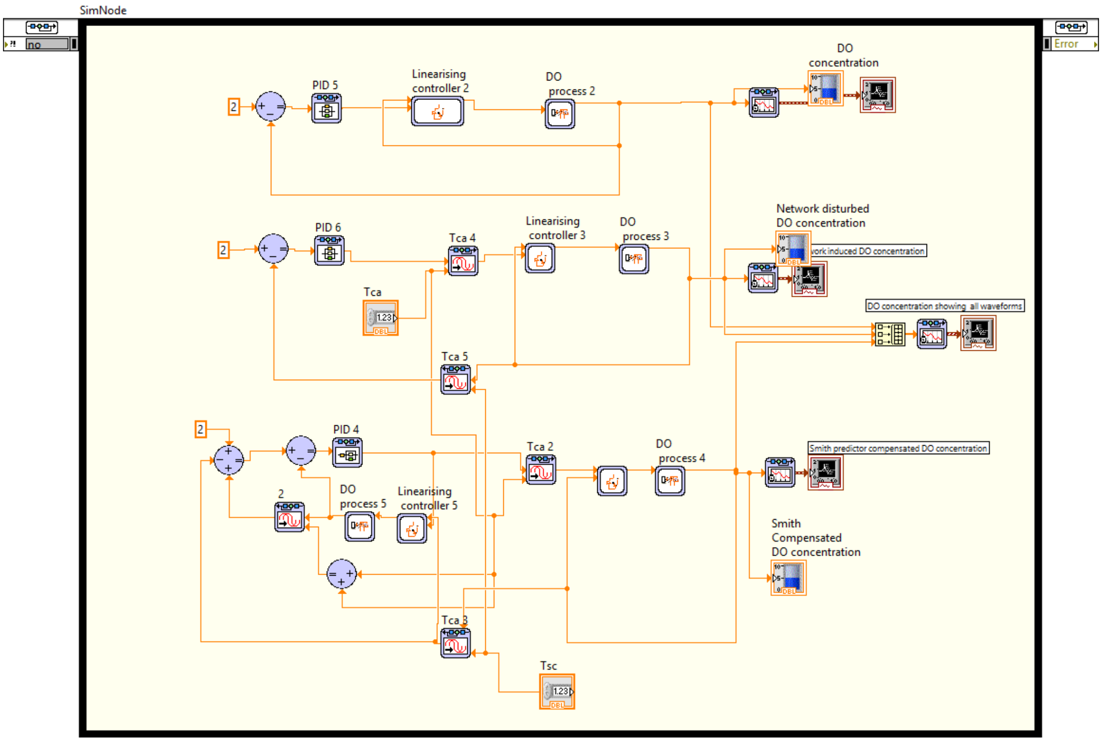


Figure 7.10: LabVIEW block diagram of real-time simulation of the Smith predictor-based compensation scheme for the closed loop DO process using the nonlinear linearising approach

7.4.1 Description of the developed real-time simulation environment

Figure 7.11 is an example of the developed user-friendly interface that display in real-time a graphical (visual) form the changes experienced in the behaviour of the DO process as a result of the network time delays and disturbances. The interface affords the user the opportunity to evaluate in real-time the capability and performance of the developed Smith predictor approaches in chapters five and six in terms of their robustness. From the Figure 7.11, three different graphs are used to separately display the real-time simulation results of the DO process without time delays, with time delays and with time delays and the Smith predictor. The fourth graph combines the graphical results of all the three scenarios investigated. Three cylindrical tanks could be seen in the Figure 7.11 with colours blue, red and green. The first cylinder with blue colour represents the dissolved oxygen (DO) concentration level of the closed loop DO process when there is no network induced time delay or other forms of disturbance. It could be seen that the DO concentration level in the blue tank is 2.4mg/l. The red tank represents the DO concentration level of a disturbed closed loop DO process under time delays. The green tank represents the Smith predictor compensated DO concentration level of the DO process under the influence of network induced time delays and other forms of disturbances. The purpose of the Smith predictor scheme is to eliminate the communication network time delays and disturbances in the control system. It is meant to compensate for the network induced time delays and other forms of disturbances in the red tank and to make the green tank revert to the level of the blue tank which is the desired DO process trajectory.

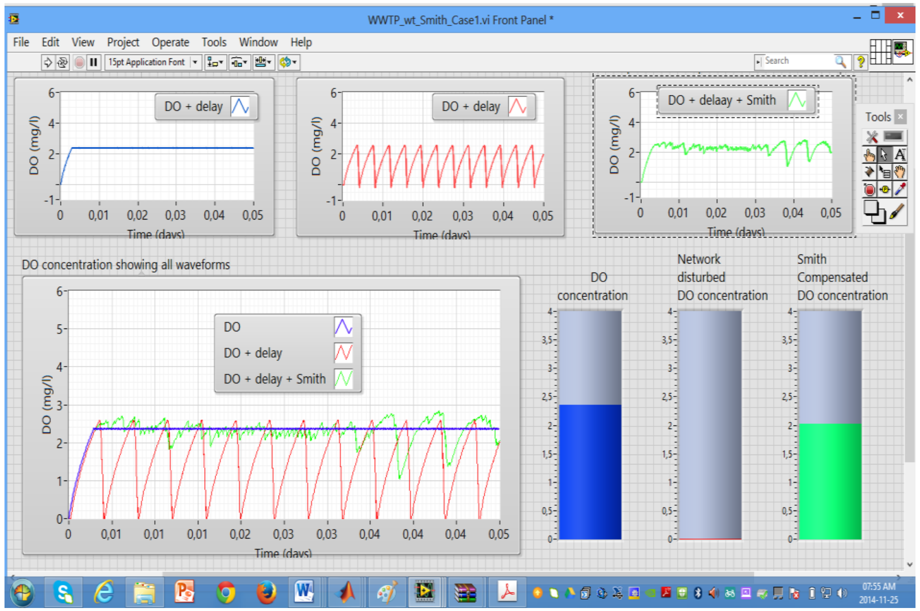
During the simulation, the DO concentration level in the blue tank remained constant but the red coloured tank due to communication time delays and disturbances is seen to be going up and down throughout the process of simulation as the value of the delays are increased. It could also be observed that the green cylinder might experience some disturbances earlier in the real-time simulation, but it gradually reached steady state due to the presence of the Smith predictor compensation scheme.

7.4.2 Real-time simulation of the Smith predictor-based DO process using the nonlinear linearising approach and the transfer function approaches

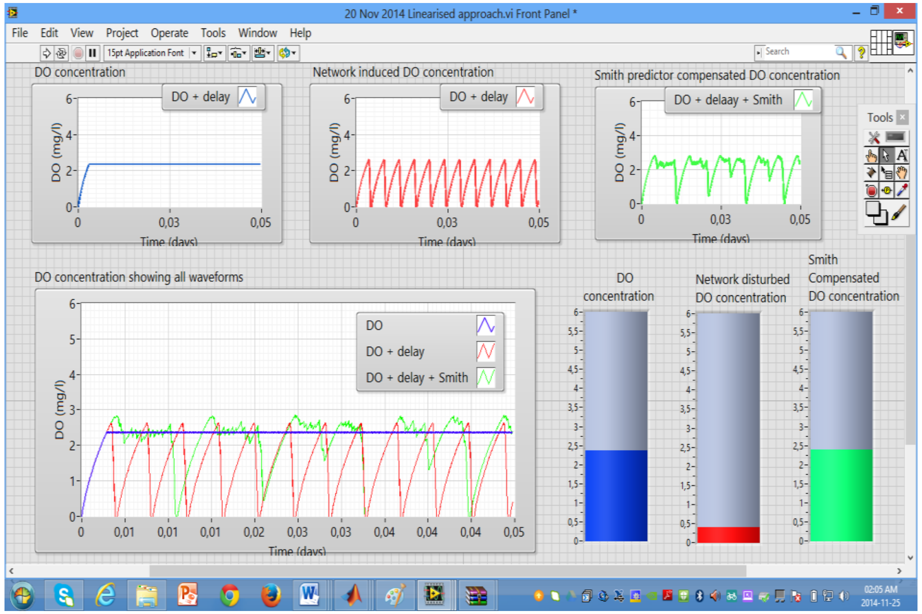
The real-time simulations performed in this Chapter are previously done in Chapters 5 section 5.10 and Chapter six section for the transfer function approach and the nonlinear linearising approach respectively in the MATLAB/Simulink environment. The reason for performing the investigations in a real-time environment using the NI-LabVIEW is to validate the results previously obtained. The real-time environment also offers a more user-friendly interface where the changes taking place in the DO process dynamics can be viewed in a more interactive way. It should be noted that simulations performed in the MATLAB/Simulink environment have very close similarities with the ones performed in the LabVIEW environment. However, there could be some situations where very few differences exist. The reason for this might be due to the fact that LabVIEW is designed for a real-time simulation which is not the case with MATLAB/Simulink

7.5 Discussion of results

Figures 7.12 and 7.13 show the real-time simulation of the DO process under network induced time delays and disturbances. It could be observed from Figure 7.11 that when a constant delay of 0.00044 days and disturbances are induced in the closed loop DO process as shown in Figure 7.9, the Smith predictor scheme based on the nonlinear linerising approach in Figure 7.11a is found to exhibit robust performance in terms of system overshoot and settling time more than the Smith predictor with transfer function approach in Figure 7.11b.



a) Nonlinear linearising approach

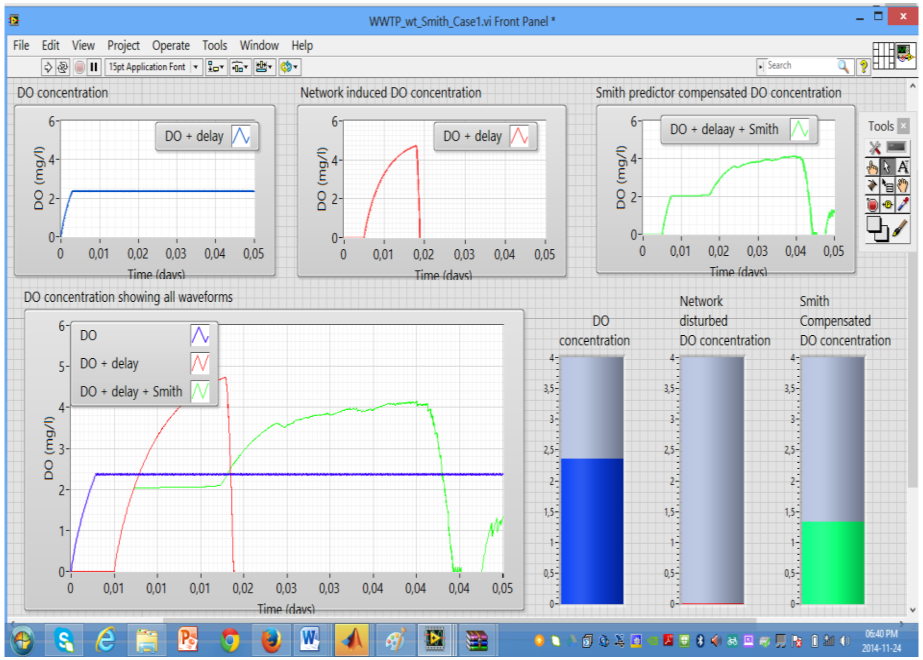


b) Transfer function approach

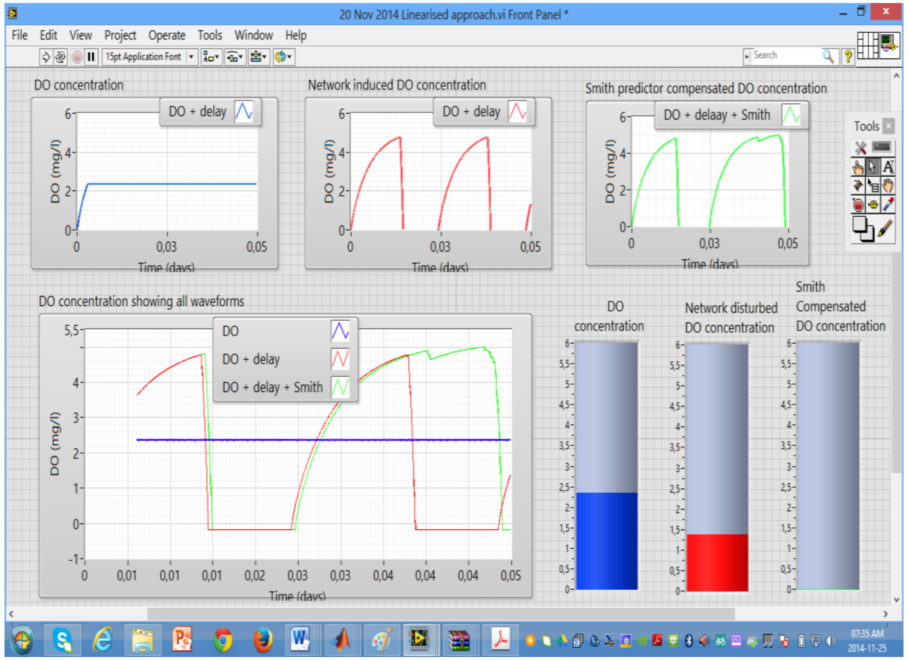
Figure 7.11: LabVIEW real-time simulation of the Smith predictor-based compensation scheme for the closed loop DO process using a) Nonlinear linearising approach b) Transfer function approach, τ_{tot} = 0.00044 days

This could be observed from the colour green graph representing the Smith predictor compensated DO concentration in the two Figures. Figure 7.12 shows the results when the network induced time delays are increased to 0.01 days while the saturation limiting values (assumed disturbance) are kept constant at a lower limit of 0.01 and upper limit of 5. Real-time simulation results in Figure 7.12 shows that even though the DO process in the two approaches performed poorly due to large network time delays and disturbances, the nonlinear linearising approach in Figure 7.12a is able to provide some degree of robustness and fair performance when compared to the transfer function approach in Figure 7.12b. For instance, one would observe that the green cylinder in Figure 7.12 representing the Smith predictor compensated DO concentration level is at a zero level in the transfer function approach, as a result of the effects of time delays and other forms of disturbances. This is an undesirable condition for the DO process because at this time, the oxygen is completely depleted. This condition could lead to a complete failure of the Activated Sludge Process (ASP). This is because the DO concentration is one of the very important variables on which the successful performance of the ASP depends. Under this same condition of large time delays and disturbance, the nonlinear linearising Smith predictor approach in Figure 7.12a is still able to compensate for the perturbations (time delays and disturbance) to a good extent. Even though the desired set-point of 2mg/l is not achieved, the nonlinear linearising Smith predictor approach is able to achieve 1.4 mg/l of DO concentration.

In Figures 7.13, the results of simulation are shown when the perturbation is increased to 0.06 days while the saturation limiting value is kept constant. Figure 7.13b shows the transfer function approach with a DO concentration of 5 mg/l instead of the desired trajectory of 2mg/l. This DO concentration is not good for the DO process. Too high DO concentration leads to a situation in the wastewater control whereby very high electrical energy is required to pump oxygen into the wastewater for microorganism metabolic activities. This is not economical. Another disadvantage of too high DO concentration is that it interferes negatively with the process of de-nitrification. The result is that it leads to poor flock formation, poor sludge and effluent quality. (Samsudin et al., 2013; Hong-tao et al., 2013; Macnab et al., 2014). In Figure 7.13b, the nonlinear linearising approach is still able to maintain the DO concentration at 2.1 mg/l.

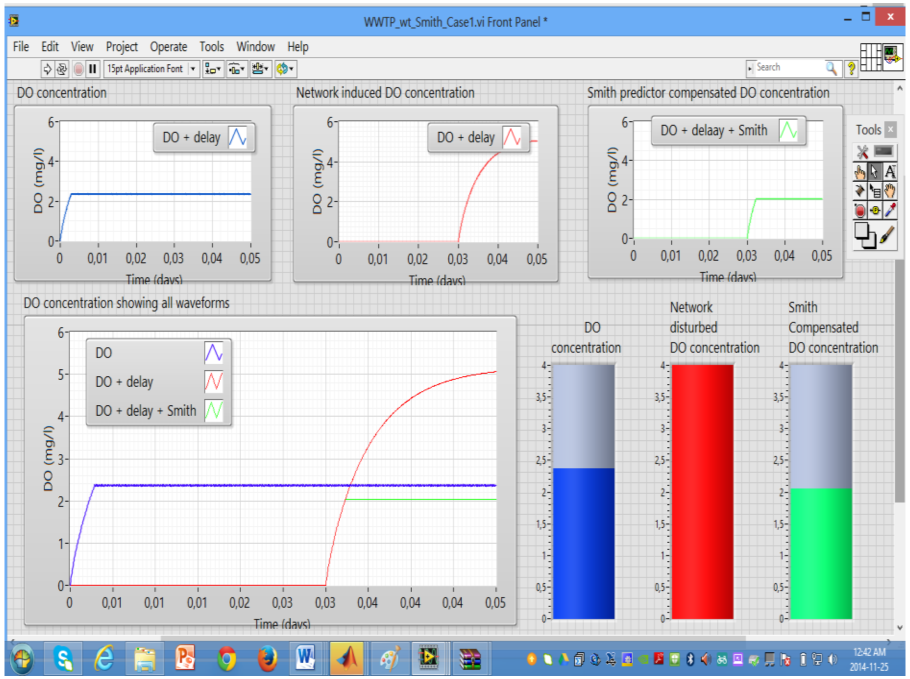


a) Nonlinear linearising approach

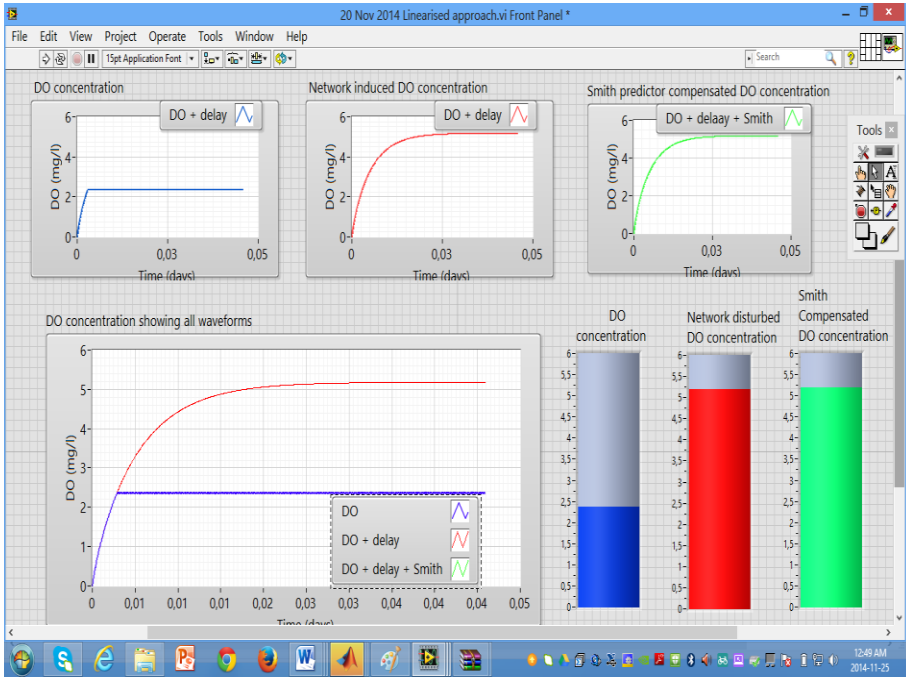


b) Transfer function approach

Figure 7.12: LabVIEW real-time simulation of the Smith predictor-based compensation scheme for the closed loop DO process using a) Nonlinear linearising approach, b) Transfer function approach, τ_{tot} = 0.01 days



Nonlinear linearising approach



Transfer function approach

Figure 7.13: LabVIEW block diagram of real-time simulation of the Smith predictor-based compensation scheme for the closed loop DO process using the nonlinear linearising approach τ_{tot} = 0.06 days

The transfer function approach of Smith predictor derivation has some advantages when compared to the nonlinear linearising approach. For instance, the transfer function approach exhibits fast rise time. This can be seen in Figures 7.12b and 7.13b. In figure 7.13b, when a delay of 0.06 days is induced, into the DO process, the transfer function approach responds immediately. For the nonlinear linearising approach, there was a delayed system response of 0.03 days before the system responds. However when the system eventually responds, it is able to stabilise the DO process at a desired trajectory of 2 mg/l as shown in Figure 7.13a. In the case of the transfer function approach that responded faster, it achieved a DO concentration level of 5 mg/l which is not desirable for the DO process both for economic (energy usage) ad process (sludge quality) reasons.

Another merit of the transfer function approach is that it is less rigorous in terms of mathematical computation. The transfer function approach is derived in the frequency domain and might not be very suitable when it comes to MIMO (many input many output) application. For the case of nonlinear linearising approach, it is derived in the time domain and so it would be suitable for MIMO applications.

Form these investigations; one could therefore draw some inferences as follows:

- The Smith predictor compensation schemes derived for the DO process using the transfer function and nonlinear linearising approaches out-perform the (PI+nonlinear linearising) controller without Smith predictor in providing robust control for the closed loop DO process under constant delays, random delays and disturbances.
- The transfer function approach exhibits faster rise time when compared with the nonlinear linearing approach of the Smith predictors. Even though the nonlinear linearising approach experiences some delay in system response, simulation results reveal that it is still able to provide adequate control for the DO process in terms of robustness and good performance.

The transfer function approach produced better results in MATLAB/Simulink environment than in the real-time simulation environment when subjected to the same value of time delay and disturbances when compared to the nonlinear linearising approach. The transfer function is able to perform well with small delay values but fails with larger values of time delays and disturbances. Whereas in the case of the nonlinear linearization approach, it is still able to cope even in the presence of large delays and disturbances. Possible reason for this could be due to the fact that the transfer function Smith predictor scheme is formed using a linearised model of the DO process in which linearization is done around a small range of values.

Possible reasons could be that the Smith predictor designed using the linearised model of the DO process in the transfer function approach might not be adequate to envisage the nonlinearities and unknown disturbances in a real-time scenario so as to estimate and compensate for them. The Smith predictor in the nonlinear linearising approach of the Smith predictor compensation scheme is formed using the nonlinear model of the DO process. It could be that its inherent nonlinear properties could be of help in providing robustness (Moreno et al., 2012) in real-time (real-life) situations which are mostly nonlinear in nature.

Possible solution for the future work could be the development of a disturbance rejection scheme (Tasdelen and Ozbay, 2013, Kuku and Songular, 2012), for the Smith predictor designed using the transfer function approach to make it perform better in real-time situations.

7.6 Conclusion

In this Chapter, a real-time simulation is performed for the closed loop DO process under the influence of time delays and disturbances. The transfer function and the nonlinear linearising approaches of Smith predictor design were compared in terms of their robustness to stabilise the DO process in the presence of time delays and disturbances. Simulation results confirm the Smith predictors effectiveness over the (PI + nonlinear linearising) controller without Smith predictor. It was also found that with small time delays, the transfer function method seems to be better in the MATLAB/Simulink environment and with small time delay in real-time environment. Under large delays and disturbances, the Smith predictor designed by the nonlinear linearising approach performed better than the transfer function method. Future work could involve the design of disturbance rejection scheme for the closed loop DO process. Chapter eight is the conclusion and recommendations of the studies carried out in this thesis.

CHAPTER EIGHT

CONCLUSION, DELIVERABLES, APPLICATION AND FUTURE WORK

8.1 Introduction

In this thesis, the networked control of distributed wastewater treatment plants is considered with a focus on the control of Dissolved Oxygen (DO) concentration as part of the Activated Sludge Process of wastewater treatment. This is a new concept in wastewater treatment in which the controller and the wastewater treatment plant being controlled are separated by wide geographical distance. As a result, a communication medium is required between them. The effects of network induced time delays on the dissolved oxygen process behaviour due to communication drawbacks are investigated. It is found that communication drawbacks (controller to actuator delays and the sensor to controller delays) adversely affect the stability of closed loop DO process. As a result, time delay compensation schemes based on the Smith predictor are developed to compensate for the network induced time delays.

The Activated Sludge Process (ASP) is one of the strategies of wastewater treatment during which oxygen is injected into wastewater in order to make it clean so as to meet the required effluent quality standard. ASP is the most widely applied biological wastewater treatment strategy (Vlad, 2011).The disadvantage of this method however is the very high electrical energy required to pump oxygen into the wastewater for the use of micro-organisms that are responsible for breaking down organic substances, thereby making the water safe to be released into the environment. The concentration of DO in the ASP also plays very important role in the quality of the effluent and the sludge produced during the wastewater treatment. It therefore becomes imperative to control the DO concentration in the ASP both for economy (reduction of electricity consumption) and process quality reasons (Sanches and Katebi, 2003; Vlad, 2011).

In the traditional wastewater treatment, the controller and the WWTP are usually in the same place (Sanches and Katebi, 2003; Vlad, 2011, Tzoneva 2007, Nketoane, 2009). This thesis considers a new concept in wastewater treatment in which the controller and the WWTP to be controlled are not in the same location but separated from each other by a wide geographical distance. As a result, there must be a means of communication between them. This requires a form of Networked Control Systems (NCS) which has the advantages of flexibility, modularity, and ease of maintenance to mention a few (Gupta and Chow, 2010). This networked wastewater distributed systems (NWDS) involves communication between the controller and the remote

WWTPs and as such communication drawbacks such as network induced time delays, data drop out, jitter and other types of network imperfections (Nilsson, 1998) are introduced into the control system. These drawbacks make it difficult to apply traditional control strategies in order to control the plant. Network induced time delays are examined in this thesis.

For the ASP of WWTP, the inclusion of a network between the controller and the process results in network induced time delays and this brings about instability of the closed loop DO process. Apart from time delays due to the communication network, another source of dead time (delay) in the ASP is the time it takes the sensor and analysers to perform their measurement or analyses. In an attempt to calculate the oxygen uptake rate r_{so} in the ASP, Chemical Oxygen Demand (COD) has to be measured and analysed. This process could last between 3 to 15 minutes in some cases for a measurement range of 10 to 1500 mg/litre COD. (Environmentalexpert, 2014). In a case of automatic control of DO concentration, this time lag (delay) could adversely affect the stability of the DO process. In this thesis, the delay due to the COD analysis is assumed to be part of the feedback delays (sensor to controller delays).

This thesis therefore investigates the effects of time delays (deadtime) on the behaviour of the DO process and time delay compensation strategies based on the Smith predictor compensation scheme are developed. Smith predictor (Smith, 1957) is the most widely applied scheme for eliminating deadtime in process controls (Tanaka et al., 2013). The traditional Smith predictor (Smith, 1957) was originally designed to compensate for only time delays in the forward path (τ_{ca}) (Smith, 1957; Ding and Fang, 2013), hence the reason for several modifications to improve it. The Smith predictor adopted in this thesis is a modification of the work done by Velagic (2008). In the case of Velagic (2008), the author used the average (mean) of the delays in the forward path that is, the controller to actuator delays (τ_{ca}) and the feedback path that is the sensor to controller delays (τ_{sc}) to predict the total time delays (τ_{tot}) needed to compensate the control system. This thesis uses the sum of the controller to actuator delays (τ_{ca}) and the sensor to controller delays (τ_{sc}) to predict the total time delays (τ_{tot}). A similar approach to the approach of this thesis is used by Ding and Fang (2013). This compensation scheme is applied in this thesis to eliminate dead time, provide robustness and improve controller performance of the DO process. Two approaches are adopted in the thesis for the design of the Smith predictor compensation scheme. The first is the transfer function approach that allows a linearized model of the DO process be described in the frequency domain while the second in the nonlinear feedback linearising approach in the time domain. These two approaches are derived and applied with comparative results obtained. The developed Smith predictor compensation schemes for the DO process were later implemented in a real-time platform using the NI-LabVIEW software.

In this Chapter, section 8.2 describes the problems solved in the thesis while section 8.3 discusses the thesis deliverables. The softwares developed in the thesis are discussed in section 8.4. Section 8.5 discusses the summary of the results obtained in the thesis. Section 8.6 outlines the benefits of the developed methods, section 8.7 focuses on the application of the thesis and deliverables. Future directions of the research and publications obtained are outlined in sections 8.8 and 8.9 respectively. The Chapter concludes in section 8.10.

8.2 Problems solved in the thesis

The problems addressed in this thesis can be grouped under two categories:

- Design based sub-problems
- Real-time simulation sub-problems

8.2.1 Design based sub-problems

Sub-problem 1: Overview and investigation of existing models of the wastewater plants to ascertain if they adequately represent the plant. This is done through literature review and simulations.

Sub-problem 2: Analysis and design of a nonlinear controller for the wastewater treatment plant in the absence of network induced time delays

Sub-problem 3: Analysis of DO process closed loop behaviour in the presence of network induced time delays

Sub-problem 4: Determination of the maximum value of time delays that result in instability of the DO process under different conditions through simulation

Sub-problem 5: Investigation of controller design methods that incorporate network induced time delays for the DO process using the Smith predictor compensation scheme

Sub-problem 6: Development of the Smith predictor compensation scheme for the DO process under the influence of time delays using the transfer function approach

Sub-problem 7: Development of the Smith predictor compensation scheme for the DO process under the influence of time delays using nonlinear feedback linearising approach in state space

8.2.2 Real-time simulation based sub-problems

Sub-problem 1: Developing a model of the COST Benchmark structure in the LabVIEW environment

Sub-problem 2: Development of a nonlilear linearising controller for the closed loop DO process in the absence of and also in the presence of network time delays.

Sub-problem 3: Real-time simulation of the developed Smith predictor compensation schemes using the nonlinear feedback linearising approach and the transfer function approach developed in the thesis.

8.3 The Deliverables of this thesis

The following deliverables have been accomplished in the thesis.

8.3.1 Literature Review

The aim of the literature review of Networked Control Systems (NCS) carried out in this thesis is to examine the past and ongoing researches in NCS with a view to selecting the appropriate methodology for the research and to contribute to existing body of knowledge where necessary. The review is grouped under the following: history of NCS, NCS Communication Protocols such as the TCP and UDP protocols, network induced time delays, their causes and effects on the closed loop control system NCS, network control methodologies as well as the Smith predictor compensation scheme for eliminating time delays (deadtime) in process control systems. Various implementation strategies in NCS are also considered in the review.

8.3.2 Mathematical modelling of the WWTP in the MATLAB/Simulink environment

In this thesis, investigations are carried out with one of the internationally accepted models of the wastewater treatment plant known as the COST Benchmark structure of the ASP. The mathematical model is developed using Simulink blocks in the MATLAB/Simulink environment and the open loop response is obtained. The response is that of a nonlinear first order system. The COST Benchmark model provides a basis for controller design and time delay investigations where the actual lab-scale wastewater treatment plants are not available. It also affords the opportunity of comparing the designed controllers in this thesis with the results obtained by other researchers working in the field of wastewater control and NCS.

8.3.3 Design of nonlinear linearising control for the closed loop DO process

In order to provide closed loop control for the DO process, a nonlinear linearising controller is used. The nonlinear linearsing controller developed to stabilize the DO process in this thesis was proposed by Nketoane (2009). It has two components:

Input/output nonlinear linearising control $u(t)$ that makes the nonlinear DO process closed loop to behave like an equivalent linear system with a desired stable behavior $S_o(t) = aS_o(t) + bv(t),$ where a and b are the state and control coefficients and $v(t)$ is the linear control input to the linearized closed loop system. Linear control $v(t)$ makes the linearised closed loop behaviour of the DO process to follow some desired set point. The closed loop DO process resulting from the application of the nonlinear linearising controller is used as the basis for further investigations in this thesis.

8.3.4 Investigation of the influence of constant network induced time delays on the DO process of WWTP

In order to develop appropriate networked control for the DO process, it is necessary to determine the types, nature, position of time delays and the extent to which these time delays affect the dynamics of the DO process. The information gathered from these investigations is supposed to form the basis for the design/development of a robust controller that take cognisance of the network imperfections in its design in order to provide performance and stability for the DO process in the midst of the imperfections. To achieve this, three different types of investigations are done. They include:

- Investigation of the DO process behaviour under constant time delays
- Investigation of the DO process behaviour under random time delays
- Investigation of the DO process behaviour under various PI controller parameters $(K_p$ and $T_i)$

For each of these cases, transport delays in the MATLAB/Simulink environment are placed in the forward path (controller to actuator delay) and the feedback path (sensor to controller delay) of the closed loop DO process. Simulations are carried out in the MATLAB/Simulink environment by varying the value of the transport delays from a given minimum to a maximum value. It is found that the DO process response becomes unstable as a result of the presence of the network induced time delays but the DO process control system is also able to regain its stability. With larger time delay induced into the closed loop DO process, a sustained oscillation is attained during which the control system is no longer able to regain its stability.

Investigations done with constant and random delays reveal that the DO process reaches this sustained oscillation (critical delay) earlier with random delays than constant delays. This explains why random delays are more difficult to eliminate than constant delays. Due to the stochastic nature of random delays, they are described with a probability distribution function in this thesis.

Investigations are also carried out to determine the influence of the linear PI control parameters $(K_p$ and $T_i)$ on the DO process under random time delays. It is found out that the value of the critical delay did not only depend on the magnitude of induced time delays but also on the choice of the PI controller parameters $(K_p$ and $T_i)$. Good choice of K_p can improve to a certain extent the stability of the DO process under time delays while T_i value can slightly improve the steady state error.

8.3.5 Development of a Smith predictor compensation scheme based on the transferfunction approach for the DO process

In an attempt to mitigate the effects of network induced time delays on the behaviour of the closed loop DO process, a Smith predictor compensation scheme is developed. Two method of Smith predictor scheme are investigated. They are:

- The transfer function approach
- The nonlinear linearising approach

These two strategies are used in this thesis for the derivation of the Smith predictor compensation scheme for the DO process under consideration.

In this case of Smith predictor derivation, the positioning of the time delays is arranged such that the PI controller is placed far away from the linearising controller and the nonlinear DO process. Section 5.3 and Figure 5.3 explains this arrangement. This makes the nonlinear linearising controller combined with the nonlinear DO process to behave like an equivalent linearised DO process. As a result, the transfer function approach is applied to derive the Smith predictor compensation scheme so as to eliminate time delays from the closed loop DO process control system. The derivation of the Smith predictor and simulation of the DO process under constant and random time delays are presented in the thesis using MATLAB/Simulink software. Simulations were carried out for cases namely:

- when the time delay is below the critical delay
- when the time delay is equal to the critical delay
- when the time delay is above the critical delay
- when the Smith predictor reaches its critical delay

The last case – when the Smith predictor reaches its critical delay is not a realistic one in terms of the DO process performance but it is used for determining the robustness of the developed Smith predictor compensation scheme. Simulation results reveal the superiority of the developed Smith predictor-based feedback linearised DO process over the PI controlled feedback linearised DO process without Smith predictor in stabilising the DO process under constant and random time delays.

8.3.5 Development of a Smith predictor compensation scheme based on the nonlinear linearising approach for the DO process

In this approach, the nonlinear feedback linearising strategy of deriving the Smith predictor compensation scheme is also applied in the time domain to mitigate the effects of time delays on the DO process. The arrangement in this case is such that the PI controller and the nonlinear feedback linearising controller are placed far away from the nonlinear DO process as described in section 5.3. The derivation of the Smith predictor compensation scheme in the state space domain using the feedback linearization technique is presented. The feedback linearisation is used to convert the nonlinear DO process to a simple linear one. After this, the pole placement technique is used to design a linear controller for the DO process. Simulation of the DO process under constant and random time delays with the Smith predictor scheme is performed using MATLAB/Simulink. Similar to the transfer function approach, the cases simulated using the nonlinear linearising approach include:

- when the time delay is below the critical delay
- when the time delay is equal to the critical delay
- when the time delay is above the critical delay
- when the Smith predictor reaches the critical delay

This approach show similar result in the ability of the developed Smith predictor scheme to outperform the nonlinear linearising controller to provide stability for the DO process.

When the transfer function and the nonlinear linearising approaches of deriving the Smith predictor compensation scheme were compared, Simulation results reveal that the transfer function approach performed better than the nonlinear linearising approach in terms of rise time and percentage overshoot. The Transfer function approach is found to exhibit more robustness in compensating for constant and random time delays. The similarity of the approaches is that both of them out-perform the PI controller and nonlinear linearising controller without Smith predictor in providing stability for the close loop DO process.

8.3.7 Real-time simulation of the DO process in LabVIEW

As a follow up to the designed Smith predictor compensation scheme for the DO process, a real-time simulation is performed in the LabVIEW environment. The aim is to show how the methods designed in this thesis are likely to validate the previous investigations in a real-time scenario. The real-time simulation would give the student or researcher a more graphical (visual) representation of the changes in the DO process dynamics. The simulation is done under the following sub-problems:

- **Sub-problem 1: Development of a model of the closed loop DO process in the LabVIEW environment.**

  This is done by first modeling the COST Benchmark structure of the ASP in the LabVIEW environment using the Control and Simulation Toolbox as well as the LabVIEW Virtual Instruments (vi(s)). The open loop response is obtained and found to compare favourably with what is obtained in the MATLAB/Simulink environment. After this, the nonlinear linearising controller for the closed loop DO process is developed in the presence of network time delays using the LabVIEW vi(s) and the Control and Simulation Toolbox.

- **Sub-problem 2: Building the Smith predictor compensation scheme for the DO process in the LabVIEW environment.**

  The developed Smith predictor scheme in MATLAB/Simulink is replicated in the LabVIEW environment. The model of the controller and model of the plant run on the same personal computer in the LabVIEW environment. Transport delays in LabVIEW are used to model the communication network.

Sub-problem 3: Real-time simulation of the closed loop DO process under network time delays and the Smith Predictor compensation schemes

The simulation of the closed loop DO process is performed for the transfer function approach and the nonlinear feedback linearising approach of Smith predictor design. Simulation results reveal that the developed Smith predictor controllers exhibit robustness in compensating for time delays and disturbances in the closed loop DO process. However, the transfer function approach has good response time and was found to be more suitable for systems under small delays. It fails under large delays and disturbances. On the other hand, the nonlinear linearising approach responds slowly and is more suitable for system under large time delays and disturbances.

8.4 Software developed in the thesis

The software developed in the thesis and used for the development of the control strategies include MATLAB/Simulink software software. The name and the functions performed by each of them are shown in the Tables 8.1 and 8.2.

Table 8.1: List of the software (MATLAB script files) developed in the thesis

MATLAB PROGRAMS (script files)	Name	Function
Experiment_1.m	Appendix A	Simulation of the open loop DO process
Experiment_2.m	Appendix B4.1	Simulation of the closed loop DO process without time delays
Experiment_compare.m	Appendix B4.1b	Simulation of the closed loop DO process under time delays to compare the response of the transfer function and the nonlinear approach
Experiment_3.m	Appendix B4.2	Simulation of the closed loop DO process under constant delays
Experiment_rand.m	Appendix B4.3.1	Simulation of the closed loop DO process under random delays to generate random numbers to validate the selected random distribution function
Experiment_4.m	Appendix B4.3	Simulation of the closed loop DO process under random delays
Experiment_5.m	Appendix B4.4	Simulation of the closed loop DO process under random delays to investigate the effects of PI controller parameters
Experiment_6.m	Appendix C5.1	Simulation of the closed loop DO process under constant delays with Smith predictor scheme using transfer function approach
Experiment_7.m	Appendix C5.2	Simulation of the closed loop DO process under random delays with Smith predictor scheme using transfer function approach
Experiment_8.m	Appendix D6.1	Simulation of the closed loop DO process under constant delays with Smith predictor scheme using nonlinear feedback linearisation approach
Experiment_8.m	Appendix D6.2	Simulation of the closed loop DO process under random delays with Smith predictor scheme using nonlinear feedback linearisation approach

Table 8.2: List of the Simulink models developed in the thesis

Simulink PROGRAMS (block diagrams)	Name	Function
DO_open.mdl	Figure 3.7	Simulation of the open loop DO process
DO_closed.mdl	Figure 4.4	Simulation of the closed loop DO process without time delays
DO_compare.mdl	Figure 4.6	Simulation of the closed loop DO process under time delays to compare the response of the transfer function and the nonlinear approach
DO_constant.mdl	Figure 4.7	Simulation of the closed loop DO process under constant delays

DO_rand1.mdl	Figure 4.12	Simulation of the closed loop DO process under random delays to generate random numbers to validate the selected random distribution function
DO_rand1.mdl	Figure 4.13	Simulation of the closed loop DO process under random delays
DO_PI.mdl	Figure 4.14	Simulation of the closed loop DO process under random delays to investigate the effects of PI controller parameters
DO_smith_constant.mdl	Figure 5.6	Simulation of the closed loop DO process under constant delays with Smith predictor scheme using transfer function approach
DO_smith_random.mdl	Figure 5.11	Simulation of the closed loop DO process under random delays with Smith predictor scheme using transfer function approach
DO_smith_constant1.mdl	Figure 6.8	Simulation of the closed loop DO process under constant delays with Smith predictor scheme using nonlinear feedback linearisation approach
DO_smith_random1.mdl	Figure 6.13	Simulation of the closed loop DO process under random delays with Smith predictor scheme using nonlinear feedback linearisation approach

8.5 Summary of the results obtained in the thesis

The results of the investigations in this thesis reveal that the presence of large network induced time delays have adverse effect on the stability and performance of the closed loop DO process by reducing or even depleting the amount of oxygen available for microorganism metabolism, resulting in the wastewater not adequately cleaned up and eventual inefficiency of the ASP. This is because it affects the cost of running the WWTP and the effluent quality (Hong-tao et al., 2013; Samsudin et al., 2013). This result on the effect of large disturbance on the DO process and the negative effects on the ASP is consistent with Hong-tao et al. (2013), Yang et al. (2013), Macnab (2014). The main difference is that while these other studies consider the disturbances due to time varying influent of the WWTP (Carp et al., 2013), the oxygen uptake rate and so on, this thesis is considering the disturbances as a result of network induced communication time delays. Another finding in this thesis is that the values of the PI controller parameters K_p and T_i do have some compensating effect on the stability of the DO process. This agrees with the findings of Samsudin et al. (2013) but it is found in this thesis investigations that the PI controller parameters K_p and T_i do not adequately provide robust stability for the DO process in the midst of large network induced time delays.

The model of the WWTP used in this thesis, the ASM1 is also used in Hong-tao et al. (2013), Yang et al. (2013), Carp et al. (2013) and this allows for comparison of obtained with that of other researchers around the world. In Carp et al. (2013), the ASM1 model is linearised after which Quantitative Feedback Theory (QFT) method is applied to provide robust stability for the DO process under time varying influent.

Mei-jin and Fei. (2014) differs from the linearization approach adopted in this thesis. Instead of transforming the nonlinear model of the WWTP to a linear one, the authors in their effort to control the DO concentration used an adaptive nonlinear approach where Neural Network (NN) and Radial Basis Function (RBF) methods are used to approximate all the uncertainties in the system during the controller design.

The deadtime compensation method used in this thesis is the Smith predictor (Smith, 1957). Simulation results confirm the effectiveness of the Smith predictor to provide stability and robust control for the DO process under constant and random time delays. Two different approaches are adopted in the thesis for the derivation of the Smith predictor compensation scheme for the DO process. The first is the transfer function approach in the frequency domain and normally used for linear systems. The detail of its derivation is covered in Chapter five. Studies consistent with the transfer function approach in deriving the Smith predictor include Puwade (2010), Dang et al. (2012) and Tanaka (2013). The second approach which is the nonlinear linearising approach is derived for the DO process in this thesis in Chapter six. In this approach, the nonlinear DO process is transformed to a simpler linear model using the feedback linearization technique such that linear control strategies such as the linear PID controller could be applied. The Smith predictor scheme is combined with the linear PI controller and nonlinear linearising controller to compensate for the time delays in the DO process control system. This method is consistent with the works of Roca et al. (2009) and Roca et al. (2014) in which feedback linearisation is also used for transforming the model of a solar plant collector field to a simple linear model. The combination of linear control laws such as PI and MPC combined with the Smith predictor are used to provide stability and robustness for the solar plant. The comparison between the results of the Smith predictor scheme using the transfer function approach and Smith predictor using the nonlinear linearising approach have been discussed in section 6.8.

There are other approaches in literature used for implementing the Smith predictor compensation scheme which differ from the methods used in this thesis but which produce similar satisfactory performances. For example, Du Feng and Zhi (2013) differs from the linear PI control design method used in this thesis due to the fact that a nonlinear PID (NPID) is combined with the Smith predictor to eliminate random time delays in the control system. Bolea et al. (2014) used a gain scheduling PID control method combined with a Smith predictor to handle large variations in a canal operating condition. In Gavez, (2007), a nonlinear Model Predictive Controller (NMPC) is designed called Nonlinear Extended Prediction Self-Adapting Control (NEPSAC). A Smith predictor is then added to this NMPC to control a solar power plant.

Although the Smith predictor is effective for the compensation of time delays (deadtime) in process control systems, the demerits include the fact that it is a model based compensation scheme and as such requires an exact model of the process being controlled. Also, it does not exhibit a good load disturbance rejection. In order to address these challenges in this thesis, the DO model is used in place of the real WWTP. This same DO model is also used in the formation of the Smith predictor compensation schemes in the thesis. For the investigations performed in this thesis, an assumption is made that there are no model uncertainties or mismatch between the DO process model representing the real WWTP and the model of the DO process used for designing the Smith predictors schemes. The time delays investigated in this thesis are network induced time delays (τ_{ca}, τ_{sc} and τ_{tot}) and the delay due to Chemical Oxygen Demand (COD) analysis (τ_{COD}). In this thesis, the delay due to COD analysis is considered to be part of the sensor to controller delay (τ_{sc}).These time delays are modelled using transport delays in the Simulink environment and they are considered as part of the closed loop process. This approach is used by Velagic (2008). In this way, due consideration is given to the delays in order to design a robust controller that would adequately compensate for the network induced time delays in the closed loop DO process.

Applying the strategies discussed above, the nonlinear DO process with large time delays/disturbances and nonlinearities (Samsudin et al., 2013; Gaya et al., 2013) is transformed to a simpler linear form by feedback linearisation strategy. The delays are modelled as transport delays and considered as part of the closed loop DO process control system. After this, robust Smith predictor compensation schemes are designed for this DO process using the transfer function and the nonlinear feedback linearising approaches. The developed Smith predictor controllers in each of the approaches is found to outperform the (PI + nonlinear feedback linearsing) controller without Smith predictor in providing stability and robust performance for the closed loop DO process under the influence of network communication imperfections. Further studies could involve how to improve the robustness of the developed Smith predictor strategies

8.6 Benefits of the developed methods

- The developed LabVIW user-friendy interface for the DO process would serve as a valuable tool for researchers and learning tool for control engineering students in the field of wastewater control and NCS especially where actual lab-scale WWTP is not available
- This study would form the research base for further studies in the field of distributed WWTP control
- Flexibility: This research provides a method by which WWTP can be controlled from a remote location thereby leading to flexibility of WWTP control
- Scalability: More WWTP can be easily added to the existing centralized controller and as such expansion of WWTP facility is enhanced
- Economy: Two or more WWTPs can be controlled with a central controller which is more economical that each WWTP having its controller

8.7 Applications of the developed methods and algorithims

The methods developed in this thesis can be successfully applied in the following industries:

- Water/Wastewater treatment plants for flexible and remote plant control
- Process control plants where distributed control is required
- Nuclear reactor plant where it is necessary to remotely control plants in hazardous environments
- Research and educational institutions can use the developed user-friendly software package where the actual lab-scale WWTP is not available

8.8 Future developments of the methods and possible applicability

- Real-time (on-line) implementation of the developed Smith predictor schemes on a Local Area Network using the Ethernet cable as communication medium
- Application of the developed methods in actual wastewater treatment facilities
- Application of the developed methods in other process industries apart from WWTP
- Development of a web-interface for the developed DO process trainer such that researchers and students could access it over the internet as a form of remote WWTP laboratory

8.9 Publications in connection with the thesis

- Investigation of the Influence of Network Induced Time Delays on the Activated Sludge Process Behaviour in the Networked Wastewater Distributed Systems.

Accepted by the Institute of Electrical Engineerings of Japan (IEEJ) Transactions on Electrical Electronic Engineering. Vol. 10 No. 2, March 2015 issue.

- Networked Wastewater Control with Time Delay Compensation scheme for the Activated Sludge Process. Submitted to the Advances in Electrical and Computer Engineering (AECE) journal.

8.10 Conclusion

This Chapter gives a brief overview of the problems solved in the thesis and the approaches used. It also gives an outline of the research deliverables as well the possible applications of the developed strategies. Possible future directions for the research are outlined and the publications obtained from the thesis.

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APPENDICES

APPENDIX A

```
% experiment1.m
%=========================================================================
==
%The script file below specifies the parameters for simulation of the open
loop Dissolved Oxygen Concentration of the Activated Sludge Process (ASP)
%=========================================================================
==%
%=========================================================================
==
% the system variables are as follows:
%=========================================================================
==

clear
Sosat=8;            % Dissolved oxygen saturation
K1=240;             % Constant calculated from KLa=240 metres cubed per day
K2=1.0961e-004;     % Constant calculated from KLa=240 metres cubed per day
Soo=0.491;          % Oxygen
V=1333;             % Volume of Tanks 3,4&5
Soin=0.6;           % Internal disturbance
t=0:1:8;
u=50000.0*ones (1,9)      %Air flow rate
Qq=55338;                 %Internal recycle flow rate
Qr=18446;                 % Influent flow rate
Qo=18446;                 % Recycle flow rate
Q=Qq+Qr+Qo;
c=Q/V;
%=========================================================================
=
%State variables and kinetic values for the Activated Sludge Model 1 (ASM1)
%=========================================================================
==

muA=0.5;                  %the maximum autotrophic growth rate
muH=4;                          %the maximum heterotrophic growth rate
Koh=0.20                  ;%Half-saturation heterotrphic oxygen growth rate
Yh=0.67;                  %Heterotrophic yeild
Ya=0.24;                  %is the autotrophic yield
Ks=10;                          %Half-saturation heterotrphic growth rate
Knh=1.0;                  %Half-saturation autotrophic growth rate
Koa =0.4;                 %Half-saturation autotrophic oxygen growth rate
Xbhs=3839.166;            %Active heterotrophic biomass
Xbas=74.8985;                          %Active autotrophic biomass
Snhs=1.733;               %Ammonia and ammonium nitrogen
Sss=0.889;                %Readily biodegradable substrate
Snh=Snhs*ones (1,9);
Ss=Sss*ones (1,9);
Xba=Xbas*ones (1,9);
Xbh=Xbhs*ones (1,9);
T=t';
U=u'
Ass=Ss';
Asnh=Snh';
Axba=Xba';
Axbh=Xbh';
```

APPENDIX B 4.1

```
% experiment2.m
% Parameters for simulation of the closed loop DO process with nonlinear
% linearising controller without network induced time delays
%
% Olugbenga Kayode Ogidan, 2014
%
%===========================================================================
% Network induced time delay values
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear all
Tca = 0           % Controller to actuator delay
Tsc = 0           % Sensor to controller delay
Ttot = 0          % Total delay which is the sum of Tca and Tsc

%========================================================================
% DO process system variables
%========================================================================
Sosat=8           %Dissolved oxygen saturation
K1=240;           %Constant calculated from KLa=240 metres cubed per day
K2=1.0961e-004; %Constant calculated from KLa=240 metres cubed per day
Soo=0.491;        %Oxygen
V=1333;           %Volume of Tanks 3,4&5
Soin=0.2;         %Internal disturbance
t=0:1:8;
Qq=55338;         %Internal recycle flow rate
Qr=18446;         %Influent flow rate
Qo=18446;         %Recycle flow rate
Q=Qq+Qr+Qo;
c=Q/V;
a=-0.8;
%a=0;
b=15000;
d=1;
%========================================================================
%State variables and kinetic values for ASM1
%========================================================================
muA=0.5;          %the maximum autotrophic growth rate
muA=0.5           %the maximum autotrophic growth rate
muH=4;            %the maximum heterotrophic growth rate
Koh=0.20;         %Half-saturation heterotrphic oxygen growth rate
Yh=0.67;          %Heterotrophic yeild
Ya=0.24;          %is the autotrophic yield
Ks=10;            %Half-saturation heterotrphic growth rate
Knh=1.0;          %Half-saturation autotrophic growth rate
Koa =0.4;         %Half-saturation autotrophic oxygen growth rate
Xbhs=2559.444;    %Active heterotrophic biomass
Xbas=149.797;     %Active autotrophic biomass
Snhs=1.733;       %Ammonia and ammonium nitrogen
Sss=0.889;        %Readily biodegradable substrate
Snh=Snhs*ones(1,9);
Ss=Sss*ones(1,9);
Xba=Xbas*ones(1,9);
Xbh=Xbhs*ones(1,9);
%v=v*ones(1,9);
T=t';
Ass=Ss';
Asnh=Snh';
Axba=Xba';
Axbh=Xbh';
```

```
%=======================================================================
%Calculation of the oxygen uptake rate
%=======================================================================
rso=-muH*((1-Yh)/Yh)*(Ss/(Ks+Ss))*(Soo/(Koh+Soo))*Xbhs-muA*((4.57-
Ya)/Ya)*(Snhs/(Knh+Snhs))*(Soo/(Koa+Soo))*Xbas
rso1=rso*ones(1,9);
rso2=rso1';
%=======================================================================
%PI Controller Parameters
%=======================================================================
Ti=b*(4+a)/6
Kp=(4+a)
P=Kp;
I=P/Ti
```

APPENDIX B 4.1b

```
% experiment_compare.m
% Parameters for simulation of the closed loop DO process with nonlinear
% linearising controller without network induced time delays
%
% Olugbenga Kayode Ogidan, 2014
%
%===========================================================================
% Network induced time delay values
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear all
Tca = 0.0001225         % Controller to actuator delay
Tsc = 0.0001225         % Sensor to controller delay
Ttot = 0.000245         % Total delay which is the sum of Tca and Tsc

%========================================================================
% DO process system variables
%========================================================================
Sosat=8             %Dissolved oxygen saturation
K1=240;             %Constant calculated from KLa=240 metres cubed per day
K2=1.0961e-004;     %Constant calculated from KLa=240 metres cubed per day
Soo=0.491;          %Oxygen
V=1333;             %Volume of Tanks 3,4&5
Soin=0.2;           %Internal disturbance
t=0:1:8;
Qq=55338;           %Internal recycle flow rate
Qr=18446;           %Influent flow rate
Qo=18446;           %Recycle flow rate
Q=Qq+Qr+Qo;
c=Q/V;
a=-0.8;
%a=0;
b=15000;
d=1;
%========================================================================
%State variables and kinetic values for ASM1
%========================================================================muA
=0.5;                 %the maximum autotrophic growth rate
muA=0.5               %the maximum autotrophic growth rate
muH=4;                %the maximum heterotrophic growth rate
Koh=0.20;             %Half-saturation heterotrphic oxygen growth rate
Yh=0.67;              %Heterotrophic yeild
Ya=0.24;              %is the autotrophic yield
Ks=10;                %Half-saturation heterotrphic growth rate
Knh=1.0;              %Half-saturation autotrophic growth rate
Koa =0.4;             %Half-saturation autotrophic oxygen growth rate
Xbhs=2559.444;        %Active heterotrophic biomass
Xbas=149.797;         %Active autotrophic biomass
Snhs=1.733;           %Ammonia and ammonium nitrogen
Sss=0.889;            %Readily biodegradable substrate
Snh=Snhs*ones(1,9);
Ss=Sss*ones(1,9);
Xba=Xbas*ones(1,9);
Xbh=Xbhs*ones(1,9);
%v=v*ones(1,9);
T=t';
Ass=Ss';
Asnh=Snh';
Axba=Xba';
Axbh=Xbh';
```

```
%======================================================================
%Calculation of the oxygen uptake rate
%======================================================================
rso=-muH*((1-Yh)/Yh)*(Ss/(Ks+Ss))*(Soo/(Koh+Soo))*Xbhs-muA*((4.57-
Ya)/Ya)*(Snhs/(Knh+Snhs))*(Soo/(Koa+Soo))*Xbas
rso1=rso*ones(1,9);
rso2=rso1';
%======================================================================
%PI Controller Parameters
%======================================================================
Ti=b*(4+a)/6
Kp=(4+a)
P=Kp;
I=P/Ti
```

APPENDIX B 4.2

```
% experiment3.m
% This simulation is performed to investigate the behaviour of the closed
loop DO process with (PI + nonlinear linearising) controller under the
influence of constant network induced time delays
%
% Olugbenga Kayode Ogidan, 2014
%
%========================================================================
% DO process system variables
%========================================================================
clear all
Sosat=8          %Dissolved oxygen saturation
K1=240;          %Constant calculated from KLa=240 metres cubed per day
K2=1.0961e-004; %Constant calculated from KLa=240 metres cubed per day
Soo=0.491;       %Oxygen
V=1333;          %Volume of Tanks 3,4&5
Soin=0.2;        %Internal disturbance
t=0:1:8;
Qq=55338;        %Internal recycle flow rate
Qr=18446;        %Influent flow rate
Qo=18446;        %Recycle flow rate
Q=Qq+Qr+Qo;
c=Q/V;
a=-0.8;
%a=0;
b=15000;
d=1;
%========================================================================
%State variables and kinetic values for ASM1
%========================================================================
muA=0.5;         %the maximum autotrophic growth rate
muA=0.5          %the maximum autotrophic growth rate
muH=4;           %the maximum heterotrophic growth rate
Koh=0.20;        %Half-saturation heterotrphic oxygen growth rate
Yh=0.67;         %Heterotrophic yeild
Ya=0.24;         %is the autotrophic yield
Ks=10;           %Half-saturation heterotrphic growth rate
Knh=1.0;         %Half-saturation autotrophic growth rate
Koa =0.4;        %Half-saturation autotrophic oxygen growth rate
Xbhs=2559.444;   %Active heterotrophic biomass
Xbas=149.797;    %Active autotrophic biomass
Snhs=1.733;      %Ammonia and ammonium nitrogen
Sss=0.889;       %Readily biodegradable substrate
Snh=Snhs*ones(1,9);
Ss=Sss*ones(1,9);
Xba=Xbas*ones(1,9);
Xbh=Xbhs*ones(1,9);
%v=v*ones(1,9);
T=t';
Ass=Ss';
Asnh=Snh';
Axba=Xba';
Axbh=Xbh';

%========================================================================
%Calculation of the oxygen uptake rate
%========================================================================
rso=-muH*((1-Yh)/Yh)*(Ss/(Ks+Ss))*(Soo/(Koh+Soo))*Xbhs-muA*((4.57-
Ya)/Ya)*(Snhs/(Knh+Snhs))*(Soo/(Koa+Soo))*Xbas
rso1=rso*ones(1,9);
```

```
rso2=rso1';
%=========================================================================
%PI Controller Parameters
%=========================================================================
Ti=b*(4+a)/6
Kp=(4+a)
P=Kp;
I=P/Ti

%============================================================================
% Network induced time delay values when the constant time delay is less
% than the critical delay
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear all
Tca  = 0.000033         % Controller to actuator delay
Tsc  = 0.000033         % Sensor to controller delay
Ttot = 0.00066          % Total delay which is the sum of Tca and Tsc

        subplot(2,2,1)
        plot(t, DO, '- b')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO(mg/l)', 'FontSize',22);
        title(' DO under \tau_c_a  ','FontSize',22');

        subplot(2,2,2)
        plot(t, DO, '- b', t, delay, 'r')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under \tau_s_c','FontSize',22');


        subplot(2,2,3)
        plot(t, DO, '- b', t, smith, 'c')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under \tau_t_o_t ','FontSize',22');
        legend('DO', 'DO + delay')

     % The simulation is also carried out for the case of network delay is
     % equal to the critical delay as shown below
     % ======================================================================
         Tca = 0.000307       % Controller to actuator delay
        Tsc  = 0.000307       % Sensor to controller delay
        Ttot = 0.000614       % Total delay which is the sum of Tca and Tsc

        subplot(2,2,1)
        plot(t, DO, '- b')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO(mg/l)', 'FontSize',22);
        title(' DO under \tau_c_a  ','FontSize',22');

        subplot(2,2,2)
        plot(t, DO, '- b', t, delay, 'r')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under \tau_s_c','FontSize',22');
```

```
subplot(2,2,3)
plot(t, DO, '- b', t, smith, 'c')
grid on
xlabel('Time (days)','FontSize',18);
ylabel('DO (mg/l)', 'FontSize',22);
title(' DO under \tau_t_o_t ','FontSize',22');
legend('DO', 'DO + delay')


% The simulation is also carried out for the case of network delay
% is greater than the critical delay as shown below
% ====================================================================
Tca = 0.000308          % Controller to actuator delay
Tsc  = 0.000307         % Sensor to controller delay
Ttot = 0.000615         % Total delay which is the sum of Tca and Tsc

subplot(2,2,1)
plot(t, DO, '- b')
grid on
xlabel('Time (days)','FontSize',18);
ylabel('DO(mg/l)', 'FontSize',22);
title(' DO under \tau_c_a  ','FontSize',22');

subplot(2,2,2)
plot(t, DO, '- b', t, delay, 'r')
grid on
xlabel('Time (days)','FontSize',18);
ylabel('DO (mg/l)', 'FontSize',22);
title(' DO under \tau_s_c','FontSize',22');


subplot(2,2,3)
plot(t, DO, '- b', t, smith, 'c')
grid on
xlabel('Time (days)','FontSize',18);
ylabel('DO (mg/l)', 'FontSize',22);
title(' DO under \tau_t_o_t ','FontSize',22');
legend('DO', 'DO + delay')
```

APPENDIX B 4.3.1

```
% experiment_rand.m
% This simulation is performed to generate random numbers using the
& probability distribution function
%
% Olugbenga Kayode Ogidan, 2014
%
%========================================================================
% DO process system variables
%========================================================================
clear all
Sosat=8          %Dissolved oxygen saturation
K1=240;          %Constant calculated from KLa=240 metres cubed per day
K2=1.0961e-004;  %Constant calculated from KLa=240 metres cubed per day
Soo=0.491;       %Oxygen
V=1333;          %Volume of Tanks 3,4&5
Soin=0.2;        %Internal disturbance
t=0:1:8;
Qq=55338;        %Internal recycle flow rate
Qr=18446;        %Influent flow rate
Qo=18446;        %Recycle flow rate
Q=Qq+Qr+Qo;
c=Q/V;
a=-0.8;
%a=0;
b=15000;
d=1;
%========================================================================
%State variables and kinetic values for ASM1
%========================================================================
muA=0.5;         %the maximum autotrophic growth rate
muA=0.5          %the maximum autotrophic growth rate
muH=4;           %the maximum heterotrophic growth rate
Koh=0.20;        %Half-saturation heterotrphic oxygen growth rate
Yh=0.67;         %Heterotrophic yeild
Ya=0.24;         %is the autotrophic yield
Ks=10;           %Half-saturation heterotrphic growth rate
Knh=1.0;         %Half-saturation autotrophic growth rate
Koa =0.4;        %Half-saturation autotrophic oxygen growth rate
Xbhs=2559.444;   %Active heterotrophic biomass
Xbas=149.797;    %Active autotrophic biomass
Snhs=1.733;      %Ammonia and ammonium nitrogen
Sss=0.889;       %Readily biodegradable substrate
Snh=Snhs*ones(1,9);
Ss=Sss*ones(1,9);
Xba=Xbas*ones(1,9);
Xbh=Xbhs*ones(1,9);
%v=v*ones(1,9);
T=t';
Ass=Ss';
Asnh=Snh';
Axba=Xba';
Axbh=Xbh';

%========================================================================
%Calculation of the oxygen uptake rate
%========================================================================
rso=-muH*((1-Yh)/Yh)*(Ss/(Ks+Ss))*(Soo/(Koh+Soo))*Xbhs-muA*((4.57-
Ya)/Ya)*(Snhs/(Knh+Snhs))*(Soo/(Koa+Soo))*Xbas
rso1=rso*ones(1,9);
rso2=rso1';
%========================================================================
```

```
%PI Controller Parameters
%========================================================================
Ti=b*(4+a)/6
Kp=(4+a)
P=Kp;
I=P/Ti

%===========================================================================
% Network induced time delay values when the random time delay is less than
% than the critical delay
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear all
Tca  = 0.000014         % Controller to actuator delay
Tsc  = 0.000013         % Sensor to controller delay
Ttot = 0.000027         % Total delay which is the sum of Tca and Tsc

%========================================================================
%Weight of distribution for the random delays are based on the probability
%distribution of 10% of the delay value as shown below
%========================================================================
a_ca = -0.0000014;      % Min. Weight of the distribution for the
                        % controller to actuator delay
b_ca =  0.0000014;      % Max. Weight of the distribution for the
                        % controller to actuator delay

a_sc = -0.0000013;      % Min. Weight of the distribution for the
                        % sensor to controller delay

b_sc =  0.0000013;      % Max. Weight of the distribution for the
                        % sensor to controller delay


        subplot(2,1)
        plot(t, DO, '- b')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO(mg/l)', 'FontSize',22);
        title(' controller to actuator delay ','FontSize',22');

        subplot(2,2)
        plot(t, DO, '- b')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' sensor to controller delay ',22');
```

APPENDIX B 4.3:

```
% experiment4.m
% This simulation is performed to investigate the behaviour of the closed
% loop DO process with (PI + nonlinear linearising) controller under the
% influence of random network induced time delays
%
% Olugbenga Kayode Ogidan, 2014
%
%=========================================================================
% DO process system variables
%=========================================================================
clear all
Sosat=8          %Dissolved oxygen saturation
K1=240;          %Constant calculated from KLa=240 metres cubed per day
K2=1.0961e-004; %Constant calculated from KLa=240 metres cubed per day
Soo=0.491;       %Oxygen
V=1333;          %Volume of Tanks 3,4&5
Soin=0.2;        %Internal disturbance
t=0:1:8;
Qq=55338;        %Internal recycle flow rate
Qr=18446;        %Influent flow rate
Qo=18446;        %Recycle flow rate
Q=Qq+Qr+Qo;
c=Q/V;
a=-0.8;
%a=0;
b=15000;
d=1;
%=========================================================================
%State variables and kinetic values for ASM1
%=========================================================================
muA=0.5;         %the maximum autotrophic growth rate
muA=0.5          %the maximum autotrophic growth rate
muH=4;           %the maximum heterotrophic growth rate
Koh=0.20;        %Half-saturation heterotrphic oxygen growth rate
Yh=0.67;         %Heterotrophic yeild
Ya=0.24;         %is the autotrophic yield
Ks=10;           %Half-saturation heterotrphic growth rate
Knh=1.0;         %Half-saturation autotrophic growth rate
Koa =0.4;        %Half-saturation autotrophic oxygen growth rate
Xbhs=2559.444;  %Active heterotrophic biomass
Xbas=149.797;   %Active autotrophic biomass
Snhs=1.733;      %Ammonia and ammonium nitrogen
Sss=0.889;       %Readily biodegradable substrate
Snh=Snhs*ones(1,9);
Ss=Sss*ones(1,9);
Xba=Xbas*ones(1,9);
Xbh=Xbhs*ones(1,9);
%v=v*ones(1,9);
T=t';
Ass=Ss';
Asnh=Snh';
Axba=Xba';
Axbh=Xbh';

%=========================================================================
%Calculation of the oxygen uptake rate
%=========================================================================
rso=-muH*((1-Yh)/Yh)*(Ss/(Ks+Ss))*(Soo/(Koh+Soo))*Xbhs-muA*((4.57-
Ya)/Ya)*(Snhs/(Knh+Snhs))*(Soo/(Koa+Soo))*Xbas
rso1=rso*ones(1,9);
rso2=rso1';
```

```
%=========================================================================
%PI Controller Parameters
%=========================================================================
Ti=b*(4+a)/6
Kp=(4+a)
P=Kp;
I=P/Ti

%============================================================================
% Network induced time delay values when the random time delay is less than
% than the critical delay
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear all
Tca  = 0.000013         % Controller to actuator delay
Tsc  = 0.000013         % Sensor to controller delay
Ttot = 0.000026         % Total delay which is the sum of Tca and Tsc

%=========================================================================
%Weight of distribution for the random delays are based on the probability
%distribution of 10% of the delay value as shown below
%=========================================================================
a_ca = -0.0000013;      % Min. Weight of the distribution for the
                        % controller to actuator delay
b_ca =  0.0000013;      % Max. Weight of the distribution for the
                        % controller to actuator delay

a_sc = -0.0000013;      % Min. Weight of the distribution for the
                        % sensor to controller delay

b_sc =  0.0000013;      % Max. Weight of the distribution for the
                        % sensor to controller delay


        subplot(2,2,1)
        plot(t, DO, '- b')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO(mg/l)', 'FontSize',22);
        title(' DO under \tau_c_a  ','FontSize',22');

        subplot(2,2,2)
        plot(t, DO, '- b', t, delay, 'r')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under \tau_s_c','FontSize',22');


        subplot(2,2,3)
        plot(t, DO, '- b', t, smith, 'c')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under \tau_t_o_t ','FontSize',22');
        legend('DO', 'DO + random delay')
```

```
%==========================================================================
% Network induced time delay values when the random time delay is equal to
% the critical delay
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tca  = 0.000014         % Controller to actuator delay
Tsc  = 0.000013         % Sensor to controller delay
Ttot = 0.000027         % Total delay which is the sum of Tca and Tsc

%=======================================================================
%Weight of distribution for the random delays are based on the probability
%distribution of 10% of the delay value as shown below
%=======================================================================
a_ca = -0.0000014;      % Min. Weight of the distribution for the
                        % controller to actuator delay
b_ca =  0.0000013;      % Max. Weight of the distribution for the
                        % controller to actuator delay

a_sc = -0.0000014;      % Min. Weight of the distribution for the
                        % sensor to controller delay

b_sc =  0.0000013;      % Max. Weight of the distribution for the
                        % sensor to controller delay

        subplot(2,2,1)
        plot(t, DO, '- b')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO(mg/l)', 'FontSize',22);
        title(' DO under \tau_c_a  ','FontSize',22');

        subplot(2,2,2)
        plot(t, DO, '- b', t, delay, 'r')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under \tau_s_c','FontSize',22');


        subplot(2,2,3)
        plot(t, DO, '- b', t, smith, 'c')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under \tau_t_o_t ','FontSize',22');
        legend('DO', 'DO + random delay')


%==========================================================================
% Network induced time delay values when the random time delay is greater
% than the critical delay
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tca  = 0.0004           % Controller to actuator delay
Tsc  = 0.0004           % Sensor to controller delay
Ttot = 0.0008           % Total delay which is the sum of Tca and Tsc

%=======================================================================
%Weight of distribution for the random delays are based on the probability
%distribution of 10% of the delay value as shown below
%=======================================================================
```

```
a_ca = -0.00004;        % Min. Weight of the distribution for the
                        % controller to actuator delay
b_ca =  0.00004;        % Max. Weight of the distribution for the
                        % controller to actuator delay

a_sc = -0.00004;        % Min. Weight of the distribution for the
                        % sensor to controller delay

b_sc =  0.00004;        % Max. Weight of the distribution for the
                        % sensor to controller delay


        subplot(2,2,1)
        plot(t, DO, '- b')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO(mg/l)', 'FontSize',22);
        title(' DO under \tau_c_a  ','FontSize',22');

        subplot(2,2,2)
        plot(t, DO, '- b', t, delay, 'r')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under \tau_s_c','FontSize',22');


        subplot(2,2,3)
        plot(t, DO, '- b', t, smith, 'c')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under \tau_t_o_t ','FontSize',22');
        legend('DO', 'DO + random delay')
```

APPENDIX B 4.4:

```
% experiment5.m
% This simulation is performed to investigate the behaviour of the closed
% loop DO process under the influence of random network induced time delays
% with varying PI controller parameters (Kp and Ti)
%
% Olugbenga Kayode Ogidan, 2014
%
%=========================================================================
% DO process system variables
%=========================================================================
clear all
Sosat=8              %Dissolved oxygen saturation
K1=240;              %Constant calculated from KLa=240 metres cubed per day
K2=1.0961e-004;      %Constant calculated from KLa=240 metres cubed per day
Soo=0.491;           %Oxygen
V=1333;              %Volume of Tanks 3,4&5
Soin=0.2;            %Internal disturbance
t=0:1:8;
Qq=55338;            %Internal recycle flow rate
Qr=18446;            %Influent flow rate
Qo=18446;            %Recycle flow rate
Q=Qq+Qr+Qo;
c=Q/V;
a=-0.8;
b=15000;
d=1;
%=========================================================================
%State variables and kinetic values for ASM1
%=========================================================================
muA=0.5;         %the maximum autotrophic growth rate
muA=0.5          %the maximum autotrophic growth rate
muH=4;           %the maximum heterotrophic growth rate
Koh=0.20;        %Half-saturation heterotrphic oxygen growth rate
Yh=0.67;         %Heterotrophic yeild
Ya=0.24;         %is the autotrophic yield
Ks=10;           %Half-saturation heterotrphic growth rate
Knh=1.0;         %Half-saturation autotrophic growth rate
Koa =0.4;        %Half-saturation autotrophic oxygen growth rate
Xbhs=2559.444;   %Active heterotrophic biomass
Xbas=149.797;    %Active autotrophic biomass
Snhs=1.733;      %Ammonia and ammonium nitrogen
Sss=0.889;       %Readily biodegradable substrate
Snh=Snhs*ones(1,9);
Ss=Sss*ones(1,9);
Xba=Xbas*ones(1,9);
Xbh=Xbhs*ones(1,9);
%v=v*ones(1,9);
T=t';
Ass=Ss';
Asnh=Snh';
Axba=Xba';
Axbh=Xbh';

%=========================================================================
%Calculation of the oxygen uptake rate
%=========================================================================
rso=-muH*((1-Yh)/Yh)*(Ss/(Ks+Ss))*(Soo/(Koh+Soo))*Xbhs-muA*((4.57-
Ya)/Ya)*(Snhs/(Knh+Snhs))*(Soo/(Koa+Soo))*Xbas
rso1=rso*ones(1,9);
rso2=rso1';
%=========================================================================
```

```
%PI Controller Parameters
%==========================================================================
Ti=b*(4+a)/6
Kp=(4+a)
P=Kp;
I=P/Ti

%=============================================================================
% Network induced time delay values when the random time delay equal to the
% the critical delay, Kp is kept constant and Ti is varied
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tca  = 0.000014          % Controller to actuator delay
Tsc  = 0.000013          % Sensor to controller delay
Ttot = 0.000027          % Total delay which is the sum of Tca and Tsc

%==========================================================================
%Weight of distribution for the random delays are based on the probability
%distribution of 10% of the delay value as shown below
%==========================================================================
a_ca = -0.0000014;       % Min. Weight of the distribution for the
                         % controller to actuator delay
b_ca =  0.0000013;       % Max. Weight of the distribution for the
                         % controller to actuator delay

a_sc = -0.0000014;       % Min. Weight of the distribution for the
                         % sensor to controller delay

b_sc =  0.0000013;       % Max. Weight of the distribution for the
                         % sensor to controller delay


Kp = (2.2, 2.7, 3.2, 3.7 and 5.2); % Kp is the proportional gain of the PI
                         % controller
Ti = 8000;               % Kp is the integral gain of the PI controller

 plot(t, DO, '- b', t, delay, 'r')
grid on
xlabel('Time (days)','FontSize',18);
ylabel('DO (mg/l)', 'FontSize',22);
title(' DO under \tau_s_c','FontSize',22');
legend('DO', 'DO + delay, Kp, Ti')

%=============================================================================
% Network induced time delay values when the random time delay equal to the
% the critical delay, Ti is kept constant and Kp is varied
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tca  = 0.000014          % Controller to actuator delay
Tsc  = 0.000013          % Sensor to controller delay
Ttot = 0.000027          % Total delay which is the sum of Tca and Tsc

%==========================================================================
%Weight of distribution for the random delays are based on the probability
%distribution of 10% of the delay value as shown below
%==========================================================================
a_ca = -0.0000014;       % Min. Weight of the distribution for the
                         % controller to actuator delay
b_ca =  0.0000013;       % Max. Weight of the distribution for the
                         % controller to actuator delay

a_sc = -0.0000014;       % Min. Weight of the distribution for the
                         % sensor to controller delay
```

```
b_sc =  0.0000013;       % Max. Weight of the distribution for the
                         % sensor to controller delay


Kp = (2.2, 2.7, 3.2, 3.7 and 5.2); % Kp is the proportional gain of the PI
                         % controller
Ti = 8000;               % Kp is the integral gain of the PI controller



plot(t, DO, '- b', t, delay, 'r')
grid on
xlabel('Time (days)','FontSize',18);
ylabel('DO (mg/l)', 'FontSize',22);
title(' DO under \tau_s_c','FontSize',22');
legend('DO', 'DO + delay, Kp, Ti')


% ==========================================================================
% Network induced time delay values when the random time delay equal to the
% the critical delay, Kp and Ti are varied
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tca  = 0.000014          % Controller to actuator delay
Tsc  = 0.000013          % Sensor to controller delay
Ttot = 0.000027          % Total delay which is the sum of Tca and Tsc

%========================================================================
%Weight of distribution for the random delays are based on the probability
%distribution of 10% of the delay value as shown below
%========================================================================
a_ca = -0.0000014;       % Min. Weight of the distribution for the
                         % controller to actuator delay
b_ca =  0.0000013;       % Max. Weight of the distribution for the
                         % controller to actuator delay

a_sc = -0.0000014;       % Min. Weight of the distribution for the
                         % sensor to controller delay

b_sc =  0.0000013;       % Max. Weight of the distribution for the
                         % sensor to controller delay


Kp =  (2.2, 2.7, 3.2, 3.7 and 5.2); % Kp is the proportional gain of the PI
                          % controller
Ti = (2000, 5000, 8000, 11000, 14000); % Kp is the integral gain of the PI
                                      controller



plot(t, DO, '- b', t, delay, 'r')
grid on
xlabel('Time (days)','FontSize',18);
ylabel('DO (mg/l)', 'FontSize',22);
title(' DO under \tau_s_c','FontSize',22');
legend('DO', 'DO + delay, Kp, Ti')
```

APPENDIX C 5.1:

```
% experiment6.m
% This simulation is performed to determine the behaviour of the closed
loop DO process under constant network induced time delays and the Smith
predictor compensation scheme using the transfer function approach.
%
% Olugbenga Kayode Ogidan, 2014
%
%=========================================================================
% DO process system variables
%=========================================================================
clear all
Sosat=8          %Dissolved oxygen saturation
K1=240;          %Constant calculated from KLa=240 metres cubed per day
K2=1.0961e-004; %Constant calculated from KLa=240 metres cubed per day
Soo=0.491;       %Oxygen
V=1333;          %Volume of Tanks 3,4&5
Soin=0.2;        %Internal disturbance
t=0:1:8;
Qq=55338;        %Internal recycle flow rate
Qr=18446;        %Influent flow rate
Qo=18446;        %Recycle flow rate
Q=Qq+Qr+Qo;
c=Q/V;
a=-0.8;
%a=0;
b=15000;
d=1;
%=========================================================================
%State variables and kinetic values for ASM1
%=========================================================================
muA=0.5              %the maximum autotrophic growth rate
muH=4;               %the maximum heterotrophic growth rate
Koh=0.20;            %Half-saturation heterotrphic oxygen growth rate
Yh=0.67;             %Heterotrophic yeild
Ya=0.24;             %is the autotrophic yield
Ks=10;               %Half-saturation heterotrphic growth rate
Knh=1.0;             %Half-saturation autotrophic growth rate
Koa =0.4;            %Half-saturation autotrophic oxygen growth rate
Xbhs=2559.444;       %Active heterotrophic biomass
Xbas=149.797;        %Active autotrophic biomass
Snhs=1.733;          %Ammonia and ammonium nitrogen
Sss=0.889;           %Readily biodegradable substrate
Snh=Snhs*ones(1,9);
Ss=Sss*ones(1,9);
Xba=Xbas*ones(1,9);
Xbh=Xbhs*ones(1,9);
%v=v*ones(1,9);
T=t';
Ass=Ss';
Asnh=Snh';
Axba=Xba';
Axbh=Xbh';

%=========================================================================
%Calculation of the oxygen uptake rate
%=========================================================================
rso=-muH*((1-Yh)/Yh)*(Ss/(Ks+Ss))*(Soo/(Koh+Soo))*Xbhs-muA*((4.57-
Ya)/Ya)*(Snhs/(Knh+Snhs))*(Soo/(Koa+Soo))*Xbas
rso1=rso*ones(1,9);
rso2=rso1';
%=========================================================================
```

```
%PI Controller Parameters
%==========================================================================
Ti=b*(4+a)/6
Kp=(4+a)
P=Kp;
I=P/Ti

%============================================================================
% Network induced time delay values when the constant time delay is less
% than the critical delay
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear all
Tca  = 0.0000165        % Controller to actuator delay
Tsc  = 0.0000165        % Sensor to controller delay
Ttot = 0.000033         % Total delay which is the sum of Tca and Tsc

        subplot(2,2,1)
        plot(t, DO, '- b')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO(mg/l)', 'FontSize',22);
        title(' DO without time delay ','FontSize',22');
        legend('DO')


        subplot(2,2,2)
        plot(t, DO, '- b', t, delay, 'r')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under constant delays','FontSize',22');
        legend('DO', 'DO + delay')


        subplot(2,2,3)
        plot(t, DO, '- b', t, smith, 'c')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under constant delays and smith','FontSize',22');
        legend('DO', 'DO + delay + smith')


%============================================================================
% Network induced time delay values when the constant time delay is equal
% to the critical delay
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear all
Tca  = 0.000376         % Controller to actuator delay
Tsc  = 0.000376         % Sensor to controller delay
Ttot = 0.000752         % Total delay which is the sum of Tca and Tsc

        subplot(2,2,1)
        plot(t, DO, '- b')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO(mg/l)', 'FontSize',22);
        title(' DO without time delay ','FontSize',22');
        legend('DO')
```

```
        subplot(2,2,2)
        plot(t, DO, '- b', t, delay, 'r')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under constant delays','FontSize',22');
        legend('DO', 'DO + delay')


        subplot(2,2,3)
        plot(t, DO, '- b', t, smith, 'c')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under constant delays and smith','FontSize',22');
        legend('DO', 'DO + delay + smith')

%==========================================================================
% Network induced time delay values when the constant time delay is greater
% than the critical delay
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear all
Tca  = 0.000377         % Controller to actuator delay
Tsc  = 0.000377         % Sensor to controller delay
Ttot = 0.000754         % Total delay which is the sum of Tca and Tsc

        subplot(2,2,1)
        plot(t, DO, '- b')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO(mg/l)', 'FontSize',22);
        title(' DO without time delay ','FontSize',22');
        legend('DO')


        subplot(2,2,2)
        plot(t, DO, '- b', t, delay, 'r')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under constant delays','FontSize',22');
        legend('DO', 'DO + delay')


        subplot(2,2,3)
        plot(t, DO, '- b', t, smith, 'c')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under constant delays and smith','FontSize',22');
        legend('DO', 'DO + delay + smith')

%==========================================================================
% Network induced time delay values when the constant time delay is equal
% to the Smith predictor critical delay
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear all
Tca  = 0.0123           % Controller to actuator delay
Tsc  = 0.0123           % Sensor to controller delay
Ttot = 0.0246           % Total delay which is the sum of Tca and Tsc
```

```
subplot(2,2,1)
plot(t, DO, '- b')
grid on
xlabel('Time (days)','FontSize',18);
ylabel('DO(mg/l)', 'FontSize',22);
title(' DO without time delay ','FontSize',22');
legend('DO')


subplot(2,2,2)
plot(t, DO, '- b', t, delay, 'r')
grid on
xlabel('Time (days)','FontSize',18);
ylabel('DO (mg/l)', 'FontSize',22);
title(' DO under constant delays','FontSize',22');
legend('DO', 'DO + constant delay')


subplot(2,2,3)
plot(t, DO, '- b', t, smith, 'c')
grid on
xlabel('Time (days)','FontSize',18);
ylabel('DO (mg/l)', 'FontSize',22);
title(' DO under constant delays and smith','FontSize',22');
legend('DO', 'DO + constant delay + smith')
```

APPENDIX C 5.2:

```
% experiment7.m
% This simulation is performed to determine the behaviour of the closed
loop DO process under random network induced time delays and the Smith
predictor compensation scheme using the transfer function approach.
%
% Olugbenga Kayode Ogidan, 2014
%
%=========================================================================
% DO process system variables
%=========================================================================
clear all
Sosat=8          %Dissolved oxygen saturation
K1=240;          %Constant calculated from KLa=240 metres cubed per day
K2=1.0961e-004; %Constant calculated from KLa=240 metres cubed per day
Soo=0.491;       %Oxygen
V=1333;          %Volume of Tanks 3,4&5
Soin=0.2;        %Internal disturbance
t=0:1:8;
Qq=55338;        %Internal recycle flow rate
Qr=18446;        %Influent flow rate
Qo=18446;        %Recycle flow rate
Q=Qq+Qr+Qo;
c=Q/V;
a=-0.8;
b=15000;
d=1;
%=========================================================================
%State variables and kinetic values for ASM1
%=========================================================================
muA=0.5;         %the maximum autotrophic growth rate
muA=0.5          %the maximum autotrophic growth rate
muH=4;           %the maximum heterotrophic growth rate
Koh=0.20;        %Half-saturation heterotrphic oxygen growth rate
Yh=0.67;         %Heterotrophic yeild
Ya=0.24;         %is the autotrophic yield
Ks=10;           %Half-saturation heterotrphic growth rate
Knh=1.0;         %Half-saturation autotrophic growth rate
Koa =0.4;        %Half-saturation autotrophic oxygen growth rate
Xbhs=2559.444;  %Active heterotrophic biomass
Xbas=149.797;   %Active autotrophic biomass
Snhs=1.733;     %Ammonia and ammonium nitrogen
Sss=0.889;      %Readily biodegradable substrate
Snh=Snhs*ones(1,9);
Ss=Sss*ones(1,9);
Xba=Xbas*ones(1,9);
Xbh=Xbhs*ones(1,9);
%v=v*ones(1,9);
T=t';
Ass=Ss';
Asnh=Snh';
Axba=Xba';
Axbh=Xbh';

%=========================================================================
%Calculation of the oxygen uptake rate
%=========================================================================
rso=-muH*((1-Yh)/Yh)*(Ss/(Ks+Ss))*(Soo/(Koh+Soo))*Xbhs-muA*((4.57-
Ya)/Ya)*(Snhs/(Knh+Snhs))*(Soo/(Koa+Soo))*Xbas
```

```
rso1=rso*ones(1,9);
rso2=rso1';
%======================================================================
%PI Controller Parameters
%======================================================================
Ti=b*(4+a)/6
Kp=(4+a)
P=Kp;
I=P/Ti

%===========================================================================
% Network induced time delay values when the random time delay is less than
% the critical delay
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tca  = 0.000013         % Controller to actuator delay
Tsc  = 0.000013         % Sensor to controller delay
Ttot = 0.000026         % Total delay which is the sum of Tca and Tsc

%======================================================================
%Weight of distribution for the random delays are based on the probability
%distribution of 10% of the delay value as shown below
%======================================================================
a_ca = -0.0000013;      % Min. Weight of the distribution for the
                        % controller to actuator delay
b_ca =  0.0000013;      % Max. Weight of the distribution for the
                        % controller to actuator delay

a_sc = -0.0000013;      % Min. Weight of the distribution for the
                        % sensor to controller delay

b_sc =  0.0000013;      % Max. Weight of the distribution for the
                        % sensor to controller delay


        subplot(2,2,1)
        plot(t, DO, '- b')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO(mg/l)', 'FontSize',22);
        title(' DO without time delay ','FontSize',22');
        legend('DO')


        subplot(2,2,2)
        plot(t, DO, '- b', t, delay, 'r')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under random delays','FontSize',22');
        legend('DO', 'DO + random delay')


        subplot(2,2,3)
        plot(t, DO, '- b', t, smith, 'c')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under random delays and smith','FontSize',22');
        legend('DO', 'DO + random delay + smith')
```

```
%===========================================================================
% Network induced time delay values when the random time delay is equal to
% the critical delay
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tca  = 0.000014         % Controller to actuator delay
Tsc  = 0.000013         % Sensor to controller delay
Ttot = 0.000027         % Total delay which is the sum of Tca and Tsc

%========================================================================
%Weight of distribution for the random delays are based on the probability
%distribution of 10% of the delay value as shown below
%========================================================================
a_ca = -0.0000014;      % Min. Weight of the distribution for the
                        % controller to actuator delay
b_ca =  0.0000013;      % Max. Weight of the distribution for the
                        % controller to actuator delay
a_sc = -0.0000014;      % Min. Weight of the distribution for the
                        % sensor to controller delay
b_sc =  0.0000013;      % Max. Weight of the distribution for the
                        % sensor to controller delay


        subplot(2,2,1)
        plot(t, DO, '- b')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO(mg/l)', 'FontSize',22);
        title(' DO without time delay ','FontSize',22');
        legend('DO')


        subplot(2,2,2)
        plot(t, DO, '- b', t, delay, 'r')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under random delays','FontSize',22');
        legend('DO', 'DO + random delay')


        subplot(2,2,3)
        plot(t, DO, '- b', t, smith, 'c')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under random delays and smith','FontSize',22');
        legend('DO', 'DO + random delay + smith')


%===========================================================================
% Network induced time delay values when the random time delay is greater
% than the critical delay
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tca  = 0.0102           % Controller to actuator delay
Tsc  = 0.0102           % Sensor to controller delay
Ttot = 0.0204           % Total delay which is the sum of Tca and Tsc

%========================================================================
```

```
%Weight of distribution for the random delays are based on the probability
%distribution of 10% of the delay value as shown below
%=========================================================================
a_ca = -0.00102;        % Min. Weight of the distribution for the
                        % controller to actuator delay
b_ca =  0.00102;        % Max. Weight of the distribution for the
                        % controller to actuator delay
a_sc = -0.00102;        % Min. Weight of the distribution for the
                        % sensor to controller delay
b_sc =  0.00102;        % Max. Weight of the distribution for the
                        % sensor to controller delay


        subplot(2,2,1)
        plot(t, DO, '- b')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO(mg/l)', 'FontSize',22);
        title(' DO without time delay ','FontSize',22');
        legend('DO')


        subplot(2,2,2)
        plot(t, DO, '- b', t, delay, 'r')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under random delays','FontSize',22');
        legend('DO', 'DO + random delay')


        subplot(2,2,3)
        plot(t, DO, '- b', t, smith, 'c')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under random delays and smith','FontSize',22');
        legend('DO', 'DO + random delay + smith')

%============================================================================
% Network induced time delay values when the random time delay is equal to
% the Smith predictor critical delay
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tca  = 0.00802          % Controller to actuator delay
Tsc  = 0.00802          % Sensor to controller delay
Ttot = 0.01604          % Total delay which is the sum of Tca and Tsc

%=========================================================================
%Weight of distribution for the random delays are based on the probability
%distribution of 10% of the delay value as shown below
%=========================================================================
a_ca = -0.000802;       % Min. Weight of the distribution for the
                        % controller to actuator delay
b_ca =  0.000802;       % Max. Weight of the distribution for the
                        % controller to actuator delay
a_sc = -0.000802;       % Min. Weight of the distribution for the
                        % sensor to controller delay
b_sc =  0.000802;       % Max. Weight of the distribution for the
                        % sensor to controller delay
```

```
subplot(2,2,1)
plot(t, DO, '- b')
grid on
xlabel('Time (days)','FontSize',18);
ylabel('DO(mg/l)', 'FontSize',22);
title(' DO without time delay ','FontSize',22');
legend('DO')


subplot(2,2,2)
plot(t, DO, '- b', t, delay, 'r')
grid on
xlabel('Time (days)','FontSize',18);
ylabel('DO (mg/l)', 'FontSize',22);
title(' DO under random delays','FontSize',22');
legend('DO', 'DO + random delay')


subplot(2,2,3)
plot(t, DO, '- b', t, smith, 'c')
grid on
xlabel('Time (days)','FontSize',18);
ylabel('DO (mg/l)', 'FontSize',22);
title(' DO under random delays and smith','FontSize',22');
legend('DO', 'DO + random delay + smith')
```

APPENDIX D 6.1:

```
% experiment8.m
% This simulation is performed to determine the behaviour of the closed
loop DO process under constant network induced time delays and the Smith
predictor compensation scheme using the linearising approach.
%
% Olugbenga Kayode Ogidan, 2014
%
%========================================================================
% DO process system variables
%========================================================================
clear all
Sosat=8          %Dissolved oxygen saturation
K1=240;          %Constant calculated from KLa=240 metres cubed per day
K2=1.0961e-004;  %Constant calculated from KLa=240 metres cubed per day
Soo=0.491;       %Oxygen
V=1333;          %Volume of Tanks 3,4&5
Soin=0.2;        %Internal disturbance
t=0:1:8;
Qq=55338;        %Internal recycle flow rate
Qr=18446;        %Influent flow rate
Qo=18446;        %Recycle flow rate
Q=Qq+Qr+Qo;
c=Q/V;
a=-0.8;
%a=0;
b=15000;
d=1;
%========================================================================
%State variables and kinetic values for ASM1
%========================================================================
muA=0.5;         %the maximum autotrophic growth rate
muA=0.5          %the maximum autotrophic growth rate
muH=4;           %the maximum heterotrophic growth rate
Koh=0.20;        %Half-saturation heterotrphic oxygen growth rate
Yh=0.67;         %Heterotrophic yeild
Ya=0.24;         %is the autotrophic yield
Ks=10;           %Half-saturation heterotrphic growth rate
Knh=1.0;         %Half-saturation autotrophic growth rate
Koa =0.4;        %Half-saturation autotrophic oxygen growth rate
Xbhs=2559.444;   %Active heterotrophic biomass
Xbas=149.797;    %Active autotrophic biomass
Snhs=1.733;      %Ammonia and ammonium nitrogen
Sss=0.889;       %Readily biodegradable substrate
Snh=Snhs*ones(1,9);
Ss=Sss*ones(1,9);
Xba=Xbas*ones(1,9);
Xbh=Xbhs*ones(1,9);
%v=v*ones(1,9);
T=t';
Ass=Ss';
Asnh=Snh';
Axba=Xba';
Axbh=Xbh';

%========================================================================
%Calculation of the oxygen uptake rate
%========================================================================
rso=-muH*((1-Yh)/Yh)*(Ss/(Ks+Ss))*(Soo/(Koh+Soo))*Xbhs-muA*((4.57-
Ya)/Ya)*(Snhs/(Knh+Snhs))*(Soo/(Koa+Soo))*Xbas
rso1=rso*ones(1,9);
rso2=rso1';
```

```
%======================================================================
%PI Controller Parameters
%======================================================================
Ti=b*(4+a)/6
Kp=(4+a)
P=Kp;
I=P/Ti

%=========================================================================
% Network induced time delay values when the constant time delay is less
% than the critical delay
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear all
Tca  = 0.000008          % Controller to actuator delay
Tsc  = 0.000008          % Sensor to controller delay
Ttot = 0.000016          % Total delay which is the sum of Tca and Tsc

        subplot(2,2,1)
        plot(t, DO, '- b')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO(mg/l)', 'FontSize',22);
        title(' DO without time delay ','FontSize',22');
        legend('DO')


        subplot(2,2,2)
        plot(t, DO, '- b', t, delay, 'r')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under constant delays','FontSize',22');
        legend('DO', 'DO + delay')


        subplot(2,2,3)
        plot(t, DO, '- b', t, smith, 'c')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under constant delays and smith','FontSize',22');
        legend('DO', 'DO + delay + smith')

%=========================================================================
% Network induced time delay values when the constant time delay is equal
% to the critical delay
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear all
Tca  = 0.000307    % Controller to actuator delay
Tsc  = 0.000307          % Sensor to controller delay
Ttot = 0.000614          % Total delay which is the sum of Tca and Tsc

        subplot(2,2,1)
        plot(t, DO, '- b')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO(mg/l)', 'FontSize',22);
        title(' DO without time delay ','FontSize',22');
        legend('DO')
```

```
    subplot(2,2,2)
    plot(t, DO, '- b', t, delay, 'r')
    grid on
    xlabel('Time (days)','FontSize',18);
    ylabel('DO (mg/l)', 'FontSize',22);
    title(' DO under constant delays','FontSize',22');
    legend('DO', 'DO + delay')


    subplot(2,2,3)
    plot(t, DO, '- b', t, smith, 'c')
    grid on
    xlabel('Time (days)','FontSize',18);
    ylabel('DO (mg/l)', 'FontSize',22);
    title(' DO under constant delays and smith','FontSize',22');
    legend('DO', 'DO + delay + smith')

%==========================================================================
% Network induced time delay values when the constant time delay is greater
% than the critical delay
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear all
Tca  = 0.000308         % Controller to actuator delay
Tsc  = 0.000307         % Sensor to controller delay
Ttot = 0.000615         % Total delay which is the sum of Tca and Tsc

    subplot(2,2,1)
    plot(t, DO, '- b')
    grid on
    xlabel('Time (days)','FontSize',18);
    ylabel('DO(mg/l)', 'FontSize',22);
    title(' DO without time delay ','FontSize',22');
    legend('DO')


    subplot(2,2,2)
    plot(t, DO, '- b', t, delay, 'r')
    grid on
    xlabel('Time (days)','FontSize',18);
    ylabel('DO (mg/l)', 'FontSize',22);
    title(' DO under constant delays','FontSize',22');
    legend('DO', 'DO + delay')


    subplot(2,2,3)
    plot(t, DO, '- b', t, smith, 'c')
    grid on
    xlabel('Time (days)','FontSize',18);
    ylabel('DO (mg/l)', 'FontSize',22);
    title(' DO under constant delays and smith','FontSize',22');
    legend('DO', 'DO + delay + smith')

      %====================================================================
      ======
      % Network induced time delay values when the constant time delay is
      equal  % to the Smith predictor critical delay
      %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
      %%%%%%
      clear all
      Tca  = 0.0123           % Controller to actuator delay
      Tsc  = 0.0123           % Sensor to controller delay
```

```
Ttot = 0.0246          % Total delay which is the sum of Tca and Tsc

  subplot(2,2,1)
  plot(t, DO, '- b')
  grid on
  xlabel('Time (days)','FontSize',18);
  ylabel('DO(mg/l)', 'FontSize',22);
  title(' DO without time delay ','FontSize',22');
  legend('DO')


  subplot(2,2,2)
  plot(t, DO, '- b', t, delay, 'r')
  grid on
  xlabel('Time (days)','FontSize',18);
  ylabel('DO (mg/l)', 'FontSize',22);
  title(' DO under constant delays','FontSize',22');
  legend('DO', 'DO + constant delay')


  subplot(2,2,3)
  plot(t, DO, '- b', t, smith, 'c')
  grid on
  xlabel('Time (days)','FontSize',18);
  ylabel('DO (mg/l)', 'FontSize',22);
  title(' DO under constant delays and smith','FontSize',22');
  legend('DO', 'DO + constant delay + smith')
```

APPENDIX D 6.2:

```
% experiment9.m
% This simulation is performed to determine the behaviour of the closed
loop DO process under random network induced time delays and the Smith
predictor compensation scheme using the linerising approach.
%
% Olugbenga Kayode Ogidan, 2014
%
%======================================================================
% DO process system variables
%======================================================================
clear all
Sosat=8          %Dissolved oxygen saturation
K1=240;          %Constant calculated from KLa=240 metres cubed per day
K2=1.0961e-004; %Constant calculated from KLa=240 metres cubed per day
Soo=0.491;       %Oxygen
V=1333;          %Volume of Tanks 3,4&5
Soin=0.2;        %Internal disturbance
t=0:1:8;
Qq=55338;        %Internal recycle flow rate
Qr=18446;        %Influent flow rate
Qo=18446;        %Recycle flow rate
Q=Qq+Qr+Qo;
c=Q/V;
a=-0.8;
b=15000;
d=1;
%======================================================================
%State variables and kinetic values for ASM1
%======================================================================
muA=0.5;         %the maximum autotrophic growth rate
muA=0.5          %the maximum autotrophic growth rate
muH=4;           %the maximum heterotrophic growth rate
Koh=0.20;        %Half-saturation heterotrphic oxygen growth rate
Yh=0.67;         %Heterotrophic yeild
Ya=0.24;         %is the autotrophic yield
Ks=10;           %Half-saturation heterotrphic growth rate
Knh=1.0;         %Half-saturation autotrophic growth rate
Koa =0.4;        %Half-saturation autotrophic oxygen growth rate
Xbhs=2559.444;  %Active heterotrophic biomass
Xbas=149.797;   %Active autotrophic biomass
Snhs=1.733;      %Ammonia and ammonium nitrogen
Sss=0.889;       %Readily biodegradable substrateSnh=Snhs*ones(1,9);
Ss=Sss*ones(1,9);
Xba=Xbas*ones(1,9);
Xbh=Xbhs*ones(1,9);
%v=v*ones(1,9);
T=t';
Ass=Ss';
Asnh=Snh';
Axba=Xba';
Axbh=Xbh';

%======================================================================
%Calculation of the oxygen uptake rate
%======================================================================
rso=-muH*((1-Yh)/Yh)*(Ss/(Ks+Ss))*(Soo/(Koh+Soo))*Xbhs-muA*((4.57-
Ya)/Ya)*(Snhs/(Knh+Snhs))*(Soo/(Koa+Soo))*Xbas
rso1=rso*ones(1,9);
rso2=rso1';
%======================================================================
%PI Controller Parameters
```

```
%=========================================================================
Ti=b*(4+a)/6
Kp=(4+a)
P=Kp;
I=P/Ti

%============================================================================
% Network induced time delay values when the random time delay is less than
% the critical delay
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tca  = 0.000013        % Controller to actuator delay
Tsc  = 0.000013        % Sensor to controller delay
Ttot = 0.000026        % Total delay which is the sum of Tca and Tsc

%=========================================================================
%Weight of distribution for the random delays are based on the probability
%distribution of 10% of the delay value as shown below
%=========================================================================
a_ca = -0.0000013;      % Min. Weight of the distribution for the
                        % controller to actuator delay
b_ca =  0.0000013;      % Max. Weight of the distribution for the
                        % controller to actuator delay

a_sc = -0.0000013;      % Min. Weight of the distribution for the
                        % sensor to controller delay

b_sc =  0.0000013;      % Max. Weight of the distribution for the
                        % sensor to controller delay


        subplot(2,2,1)
        plot(t, DO, '- b')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO(mg/l)', 'FontSize',22);
        title(' DO without time delay ','FontSize',22');
        legend('DO')


        subplot(2,2,2)
        plot(t, DO, '- b', t, delay, 'r')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under random delays','FontSize',22');
        legend('DO', 'DO + random delay')


        subplot(2,2,3)
        plot(t, DO, '- b', t, smith, 'c')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under random delays and smith','FontSize',22');
        legend('DO', 'DO + random delay + smith'



%============================================================================
```

```
% Network induced time delay values when the random time delay is equal to
% the critical delay
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tca  = 0.000014          % Controller to actuator delay
Tsc  = 0.000013          % Sensor to controller delay
Ttot = 0.000027          % Total delay which is the sum of Tca and Tsc

%=========================================================================
%Weight of distribution for the random delays are based on the probability
%distribution of 10% of the delay value as shown below
%=========================================================================
a_ca = -0.0000014;       % Min. Weight of the distribution for the
                         % controller to actuator delay
b_ca =  0.0000013;       % Max. Weight of the distribution for the
                         % controller to actuator delay
a_sc = -0.0000014;       % Min. Weight of the distribution for the
                         % sensor to controller delay
b_sc =  0.0000013;       % Max. Weight of the distribution for the
                         % sensor to controller delay


        subplot(2,2,1)
        plot(t, DO, '- b')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO(mg/l)', 'FontSize',22);
        title(' DO without time delay ','FontSize',22');
        legend('DO')


        subplot(2,2,2)
        plot(t, DO, '- b', t, delay, 'r')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under random delays','FontSize',22');
        legend('DO', 'DO + random delay')


        subplot(2,2,3)
        plot(t, DO, '- b', t, smith, 'c')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under random delays and smith','FontSize',22');
        legend('DO', 'DO + random delay + smith')

%============================================================================
% Network induced time delay values when the random time delay is greater
% than the critical delay
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tca  = 0.0004            % Controller to actuator delay
Tsc  = 0.0004            % Sensor to controller delay
Ttot = 0.0008            % Total delay which is the sum of Tca and Tsc

%=========================================================================
%Weight of distribution for the random delays are based on the probability
%distribution of 10% of the delay value as shown below
%=========================================================================
a_ca = -0.00004;         % Min. Weight of the distribution for the
                         % controller to actuator delay
```

```
b_ca =  0.00004;         % Max. Weight of the distribution for the
                         % controller to actuator delay
a_sc = -0.00004;         % Min. Weight of the distribution for the
                         % sensor to controller delay
b_sc =  0.00004;         % Max. Weight of the distribution for the
                         % sensor to controller delay


        subplot(2,2,1)
        plot(t, DO, '- b')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO(mg/l)', 'FontSize',22);
        title(' DO without time delay ','FontSize',22');
        legend('DO')


        subplot(2,2,2)
        plot(t, DO, '- b', t, delay, 'r')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under random delays','FontSize',22');
        legend('DO', 'DO + random delay')


        subplot(2,2,3)
        plot(t, DO, '- b', t, smith, 'c')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO (mg/l)', 'FontSize',22);
        title(' DO under random delays and smith','FontSize',22');
        legend('DO', 'DO + random delay + smith')

%===========================================================================
% Network induced time delay values when the random time delay is equal to
% the Smith predictor critical delay
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tca  = 0.0140            % Controller to actuator delay
Tsc  = 0.0140            % Sensor to controller delay
Ttot = 0.0280            % Total delay which is the sum of Tca and Tsc

%========================================================================
%Weight of distribution for the random delays are based on the probability
%distribution of 10% of the delay value as shown below
%========================================================================
a_ca = -0.00140          % Min. Weight of the distribution for the
                         % controller to actuator delay
b_ca =  0.00140;         % Max. Weight of the distribution for the
                         % controller to actuator delay
a_sc = -0.00140;         % Min. Weight of the distribution for the
                         % sensor to controller delay
b_sc =  0.00140;         % Max. Weight of the distribution for the
                         % sensor to controller delay


        subplot(2,2,1)
        plot(t, DO, '- b')
        grid on
        xlabel('Time (days)','FontSize',18);
        ylabel('DO(mg/l)', 'FontSize',22);
```

```
title(' DO without time delay ','FontSize',22');
legend('DO')


subplot(2,2,2)
plot(t, DO, '- b', t, delay, 'r')
grid on
xlabel('Time (days)','FontSize',18);
ylabel('DO (mg/l)', 'FontSize',22);
title(' DO under random delays','FontSize',22');
legend('DO', 'DO + random delay')


subplot(2,2,3)
plot(t, DO, '- b', t, smith, 'c')
grid on
xlabel('Time (days)','FontSize',18);
ylabel('DO (mg/l)', 'FontSize',22);
title(' DO under random delays and smith','FontSize',22');
legend('DO', 'DO + random delay + smith')
```