Predictive Controller Design for Networked Systems

by

Anand Singh

Department Of Electrical Engineering

National Institute Of Technology, Rourkela

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Anand Singh
Roll No.: 210EE3236

Under the supervision of
Prof. Bidyadhar Subudhi
&
Prof. Shubhojit Ghosh

Department Of Electrical Engineering

National Institute Of Technology, Rourkela

Rourkela – 769008, Odisha, India

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ABSTRACT

This thesis considered the analysis and design of networked control systems with the communication delay and data loss, which are responsible for degradation of the control performance. Predictive control strategy is applied to compensate the communication delay and data loss in the NCS. The stability and the system performance of the close-loop networked control system are analyzed. Also, this control strategy is applied to a DC servo control system with communication delay and data packet loss. The stability of the closed-loop networked predictive control system has been analyzed and the comparison with other existing networked control methods like *H_∞ control [20] , Networked predictive control for random network delays in both forward and feedback channels [21] and Model-based control* [22].

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Anand Singh

Rourkela, May 2012

Department of Electrical Engineering
National Institute of Technology, Rourkela
Odisha, India – 769 008

CERTIFICATE

This is to certify that the thesis titled "***Predictive Controller Design for Networked Systems***", submitted to the National Institute of Technology, Rourkela by **Mr. Anand Singh**, Roll No. **210EE3236** for the award of **Master of Technology** in **Control & Automation**, is a bona fide record of research work carried out by him under our supervision and guidance.

The candidate has fulfilled all the prescribed requirements.

The Thesis which is based on candidate's own work, has not submitted elsewhere for a degree/diploma.

In our opinion, the thesis is of standard required for the award of a Master of Technology degree in Control & Automation.

To the best of our knowledge, he bears a good moral character and decent behavior.

Prof. Bidyadhar Subudhi **Prof. Subhojit Ghosh**

Place : Rourkela
Date :

To My Loving Grand Father, My Parents, My brother Alok, My sisters ShashiPrabha & Sadhana and dear friends Shilpi, Saurabh, Ashish and Anuj

CONTENTS

ABBREVIATIONS

NCS	Networked Control System
ASF	Average Inverter Switching Frequency
CAN	Controller Area Network
LAN	Local Area Network
CNCCS	Centre For Networked Control Communication Control System
ADAC	Advanced Diagnosis, Automation and Control
P2P	Point-to-Point
ZOH	Zero Order Hold
PID	Proportional–Integral–Derivative
LQR	Linear-Quadratic Regulator
DCS	Delay Control System
PI	Proportional-Integral
QoP	Quality of Performance
MPC	Model Predictive Control
NPSC	Networked Predictive Control System
NDC	Network Delay Compensator
SPNCS	Smith Predictor based Networked Control System

NOTATIONS

r	Reference signal
y	Output signal
u	Control signal
T	Sampling period
K	Time index
τ^{sc}	Sensor to Controller delay
τ^{ca}	Controller to Actuator delay
τ^{w}	Waiting time delay
τ^{f}	Frame time delay
τ^{p}	Propagation time delay

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

In many control systems like vehicles, manufacturing plants and spacecrafts, communication networks are employed to exchange information and control signals between spatially distributed systems components, like supervisory computers and controllers. When a system component is directly connected to the network, it is called a node. When a control loop is connected through a communication channel, we call it a networked control system (NCS).

When two or more than two devices connected by some means, so that they can share information is called a network. Mainly we interested in data communication between devices available in industry. Here we can break our problem in various parts and we can work with all of them in isolation of one another. The problems that plagued the early generation of network have been solved, making the easy and reliable enough to be used in the most critical applications.

The advent of communication networks, however, introduced remotely controlling a system, which gave birth to networked control system (NCS). When a traditional feedback control system is closed through a communication channel, which may be connected with other nodes outside the control system, then the control system is called as NCS. An NCS can also be defined as a feedback control system in which the control-loops are closed through a real time networks. The main feature of an NCS is that informations (reference input, plant output, control input, etc.) are exchanged using a network among control system components (actuators, sensors, controllers, etc. This is shown in Fig. 1.1).

The study of NCSs involves both computer networking and control theory. Feedback control system in which the loops are used to control the plant which is closed through a real-time communication network is known as Networked Control Systems. The main feature of an NCS is that the information or data is exchanged using a network among control system component.

It is well known that in many physical systems, the physical plant, controller, actuator and sensors are difficult to be placed at the same location, and so signals are required to transferred from one place to another. In this scenario, these components are always connected through network (digital band-limited communication channels).

Data networking technologies has been widely applied in the control of military and industrial applications. In these applications mainly manufacturing plants, automobiles and aircrafts are included. The application connected through a network can be remotely controlled from a long distance s. The networks used in the above mentioned applications are specific industrial networks, like CAN (Controller Area Networks) and LAN (Local Area Networks). In general the data networks such as Ethernet and internet are advancing very fast to be the networks of choice.

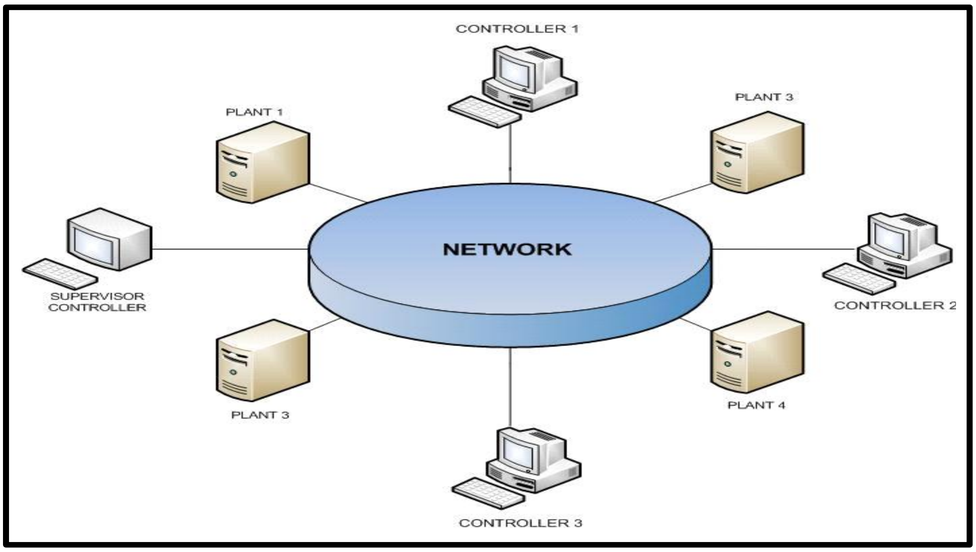

Fig.1.1. A networked control system [1]

Networked Control Systems (NCSs) are one of the distributed control system in which actuators, controllers and sensors are connected by communication networks. The study of NCSs is an interdisciplinary research area in which network and control theory both are connected. Now in the modern age of industrial and commercial system, it is required to integrate computing, communication and control into different levels of factory or machine process.

The traditional communication architecture for control system is point to point connection, that is, wire connected to the main control computer with each sensor or actuator point. Common bus introduces different forms of delay uncertainty between actuators, sensors and controllers. Mainly research in NCS has focused on two areas- controller design and communication protocols. Feedback control loops with communication network makes the analysis and designing of an NCS complex. Traditional control theories with many ideal assumptions, such as non delayed sensing and synchronized control and actuation, must be revaluated before they can be applied to NCSs. The main problem that needs to be addressed while designing an NCS include, **network-induced delays** that occurs while data transfer from one device to another, and **packet losses**, because of the unreliable network transmission path, where packets not only suffer transmission delays but, can be lost during transmission.

The most important feature, in an NCS, is the network induced delays, which are usually caused by limited bit rate of the communication channels, by a node waiting to send out a packet via a busy channel, or by signal processing and propagation. A signal transmitted with delays generally brings negative effect on NCS stability and performance.

Transmission of data from sensor to controller or control signal from controller to actuator occurs through communication network in Networked Control Systems. A challenging problem in control of network base system is **network delay effects.** The time to read a sensor and to send a control signal to an actuator via network depends on network characteristics such as their routing schemes, topologies, etc. The performance of a network-based control system can be affected by network delays. The delay does not only degrade the performance of a network-based control system, but also can unstable the system. In networked control systems, the data are transmitted in the form of packets. Networked control systems are used in many places such as aircrafts, manufacturing process, automobiles, spacecrafts etc.

The main advantages of NCS include simplicity and reliability. They are cheap and easy to use and maintain. But, these systems face problems such as network-induced delays, data loss in transmission etc. These problems may increase the instability of the system. Recent years have witnessed a large amount of work in the field of NCS. Many new protocols have been proposed to improve the transmission of data. Various methods relating the stability and reliability of the NCS are established.

In this project, a controller has been designed to maintain stability of an NCS in the presence of network-induced delay (controller-actuator delay and sensor-controller delay). A very easy and simple compensation technique has been proposed to minimize delay's effect.

1.2 BACKGROUND

The internet gave a huge base for millions of smaller domestic, academic and government networks, which together carry information and services, like, electronic mail, online chat, file transfer, interlinked web pages and other documents of the World Wide Web. In the last few years, there has also been a more increment in the development of wireless systems, which has triggered the development, easiness and research of distributed NCS. Network and controller are present in NCS background. There are several techniques used to transfer information via network. Now days all data network systems use binary digits (bits 0s and 1s) to send information, but there also must be techniques of carrying the bits across the network. Collecting real-time information over a network using sensors and processing the sensor data in an efficient manner are main research areas supplementing NCS. Thus NCS is not only a multidisciplinary area closely affiliated with computer networking, communication, image processing, robotics, information technology and control theory. It also puts all these together to achieve a single system which can efficiently work over a network. Some of well known research institutes and research labs working in NCS are given below [1].

Alleyne Research Group at University of Illinois at Urbana-Champaign.

Centre For Networked Control Communication Control Systems (CNCCS) at University of Maryland at College Park.

Advanced Diagnosis, Automation and Control (ADAC) Laboratory at North Carolina State University.

Networked Control Systems Laboratory at National Taiwan University.

Interdisciplinary Studies Of Intelligent System at University of Notre Dame.

Networked Control Systems Laboratory at University of Washington, USA.

1.2.1 Networks and control

Networked control system is combination of two engineering fields, computer network and control. We use wired or wireless computer networks. Because NCSs are implemented over a network, a good underlying communication network protocols, such as Token Bus or Token Ring, Ethernet is required to analyze and model the system's characteristic.

1.2.2 Point-to-Point Architecture of a Control System

Architecture of centralized system may use a central computer with sensors and actuators respective for control signal calculation, actuation and sensing required for closed loop control. This scheme is shown in Fig.1.2 and called as a Point-to-Point (P2P). It needs huge wiring connected from sensors to computer and computer to actuators and more over becomes complicated on requirement of setting the physical setup and functionality.

To remove the above problems posed by centralized control, Networked Control System (NCS) has received considerable attention with advances in control and communication technologies.

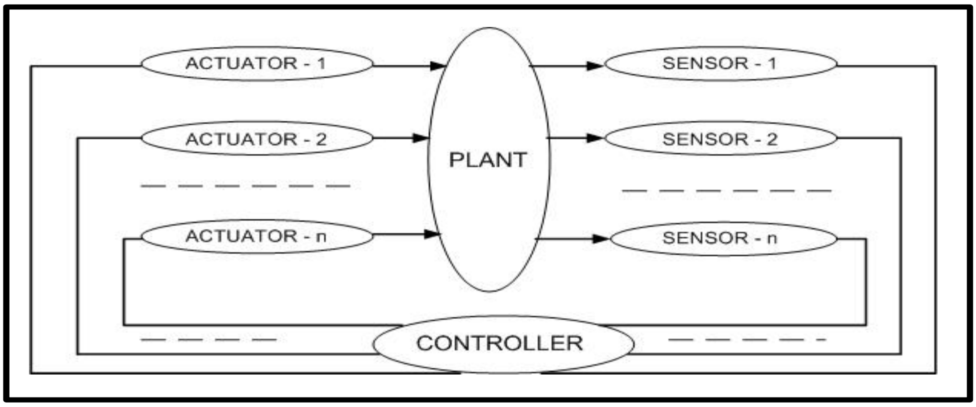

Fig.1.2. A point-to-point structure of control system [2]

1.2.3 Overview of NCS

A feedback control system in which the feedback loops are closed by means of a network is called as Networked Control Systems (NCS). A typical networked control system is shown in Fig. 1.3. The main advantages of an NCS are cost reduction, wiring and system maintenance. A networked control system (NCS) is a feedback control system where data from the sensors and the controllers is sent via an electronic communication network [8, 9]. NCSs give reduced cost and relatively simple structure, as well as greatly increased flexibility.

Network protocols have been designed specifically for use in control systems. NCSs are not without their drawbacks. At best, communication networks can introduce delays, but the network can also introduce time-varying random delays and data packet loss. There are two main approaches to design an NCS.

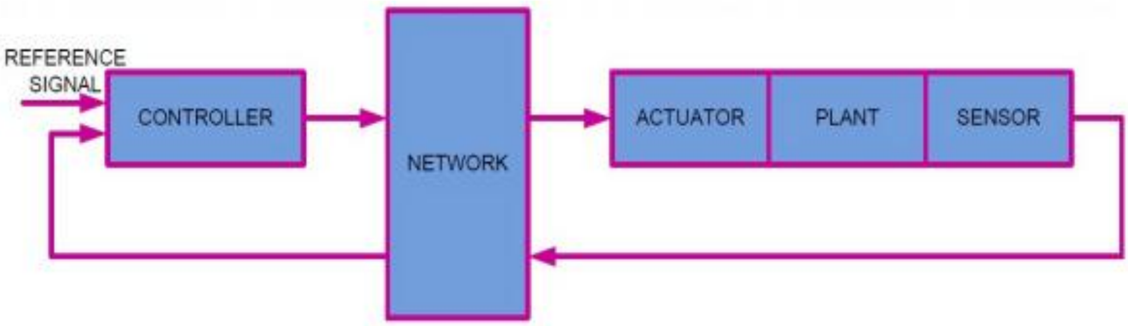

Fig.1.3. A block diagram of an Networked Control System

Hierarchical Structure: The first method is to have several subsystems from a hierarchical structure, in which each of the subsystems contains sensors, an actuator and a controller by itself, as depicted in Fig.1.4. These system components are attached to the same control plant. In this case, a subsystem remote controller receives a node from the central controller. The sensor data or status signal is communicated back through a network to the controller.

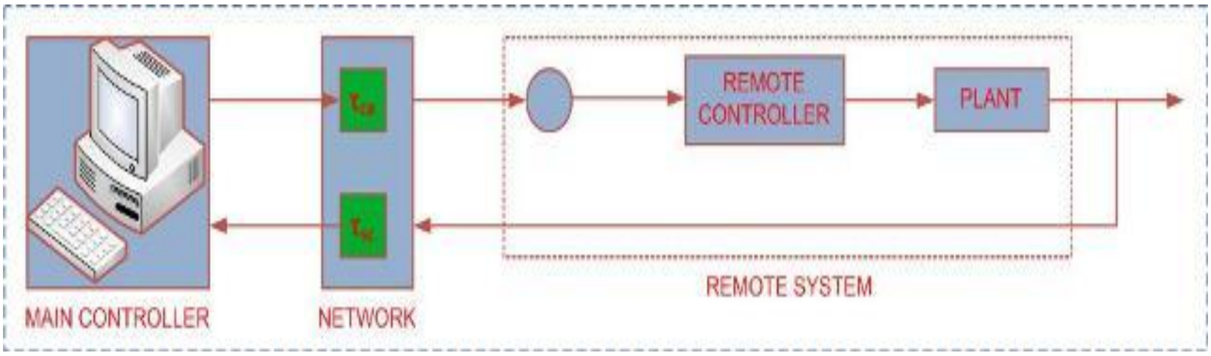

Fig.1.4. Data transfer using hierarchical structure of NCS [5]

Direct Structure: The direct structure of an NCS is shown in Fig.1.5. This structure has a sensor and an actuator of a control-loop connected through a network, directly. A sensor and an actuator are connected to a plant, while a controller is separated from the plant by a network.

The hierarchical and direct structures have their own advantages and disadvantages. Many networked control systems are a combination of the two structures.

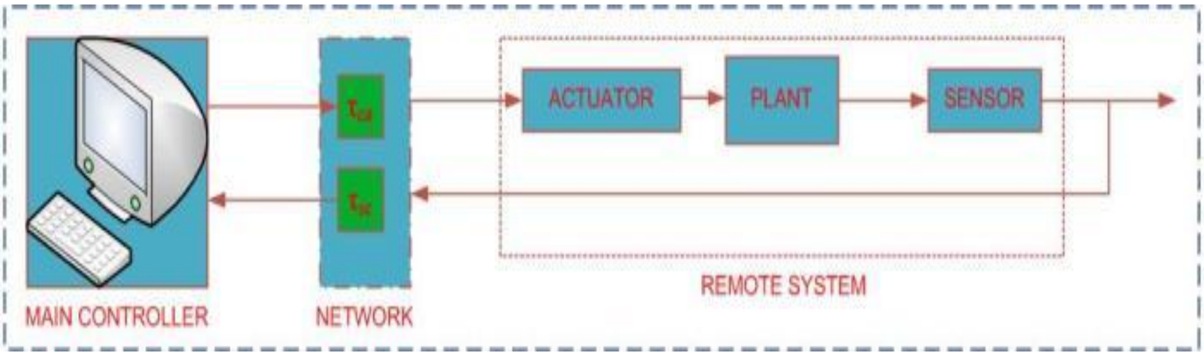

Fig.1.5. Data transfer using direct structure of NCS [5]

1.3 LITERATURE REVIEW

Networks between sensors, actuation and computation must be taken into account, and algorithms must address the accuracy and computation time. Networked Control Systems (NCSs) are one type of distributed control system in which sensors, actuators and controllers are interconnected by communication networks by T. C. Yang *et al.* in [6] which is shown in Fig.1.6.

A major trend in industrial and commercial systems is to integrate computing, communication and control into different levels of factory operations. The traditional communication architecture for control systems is point-to-point, which is, a wire connects the central control computer with each sensors or actuators. Now a days this is change to common-bus introduces different forms of time delay uncertainty between actuators, sensors and controllers. In a NCS, various delays occur due to sharing a common network, which are called network induced delays. These delays can vary widely according to transmission time of messages and the overhead time. The network induced delays in NCSs occurs when actuators, sensors and controllers exchange data across the network.

Advantages of using common bus network in networked control system are:

- It is easy to use global information to take intelligent decisions.
- Reconfiguration is easier.
- Connecting the control system component via a network can effectively reduce the cost.

The controlled system in NCS is assumed to be continuous time, and thus the actuator implements zero order hold (ZOH) holding the last control until the next one arrives or until the next sample time by Y. Tipuswan *et al.* in [5]. Most important role in NCS is to select the sample time. Traditionally, a small sample time is chosen to approximate the continuous time system as closely as possible and to enable accurate control.

A small sample time causes high network load and increasing risk of network congestion, which results in longer delay and hence lower performance. Thus the network induced delay and the sample times are coupled, and finding an optimal balance between the two is a core requirement for achieving well performance and stable NCS W. Zhang *et al.* in [3].

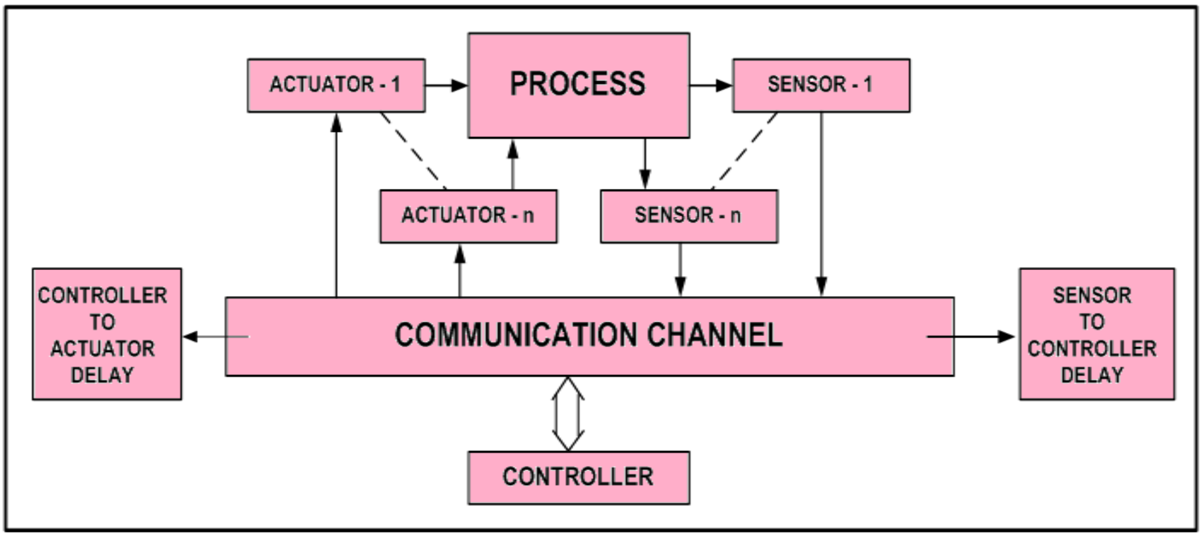

Fig.1.6. General NCS architecture

The networked environment presents many challenges for traditional control system design. Like, many well known methods have been developed and performed to analyze and design control system subject to the effects of discretization. Time delay occurs in NCS when the transfer of data among actuators, sensors and controllers connected via shared medium. These delays affect the system performance degradation and reduce stability of the closed loop system by Y. Jianyong [7]. For compensating these time delays in networked control system (NCS) there are various time delay compensation techniques developed by different researchers. These are for example, PID controller, LQR controller and fuzzy controller. In this thesis, a Predictive controller is designed and used to compensate the time delays in the networked control system. The main motivations for using networks for data communication in control systems are reduced system wiring, ease of system diagnosis as all information is available everywhere in the system, and increased system agility and relibility.

1.4 MOTIVATION

When a communication network is inserted in the feedback control loop, the analysis and design of NCS becomes more complex and induces some delays which is the cause of degradation of the system's performance and system instability. There are some issues that influence performance of an NCS respectively: network induced delay, sampling period, data packet dropout, network scheduling and stability. The networked environment presents many new challenges for traditional control system design. For example, many well-known methods have been developed and perfected to analyze and design control systems subject to the effects of discretization. Similarly, much attention has been devoted to the analysis of constant loop delay and its destabilizing effects on the stability of feedback close-loop control systems. The main issue raised in NCS is the unreliable transmission paths because of limited bandwidth and large amount of data packet communication paths because of limited bandwidth and large amount of data packet communicated over one line. This thesis presents a development for design of a networked dc motor control system for solving the issues due to use of communication network. The technique used for compensating the networked induced delay is very useful for system performance and increase the system stability also.

1.5 CONTRIBUTION OF THE THESIS

The major contributions of this thesis are

- Review of the Networked Control System (NCS).
- Design of an observer for a network controlled plant.
- Design of an observed state feedback based predictive controller for a networked controlled plant.
- Analysing the effectiveness of the predictive controller in avoiding instability arising out of delays in the network controlled plant.

1.6 THESIS LAYOUT

In **chapter 2-** Delay in NCS and different time delay compensation techniques.

In **chapter 3-** Analysis and design of a Networked Predictive Control scheme is discussed.

In **chapter 4-** Conclude the thesis and points to possibilities of future scope for the further work.

CHAPTER 2

ISSUES IN NETWORKED CONTROL SYSTEM

2.1 INTRODUCTION

This chapter contains detail about main issues in the networked control system. In a networked control system the main issue is delay. The effect of this delay is instability and system performance degradation of NCS. In this section many compensation techniques by which delay will compensate are also given.

2.2 PROBLEM IN NCS

In networked control system, there are mainly two problems. First one is the networked induced delays which are induced in the system due to communication channel. Second one is the data packet dropouts due to the node failure and data collision.

2.2.1 Networked Induced Delays

The main problem of NCS is the delay of data transmission between the units of NCS. The networked induced delay appears from sensor to controller, and controller to actuator. If control system will constructed without considering these delays, system will have low performance and reliability. These delays can degrade the performance of the control systems designed without considering it and can even destabilized the system. As we know that NCS works over a network, data communicates between controller and remote system will induce network delays in addition to the controller delay.

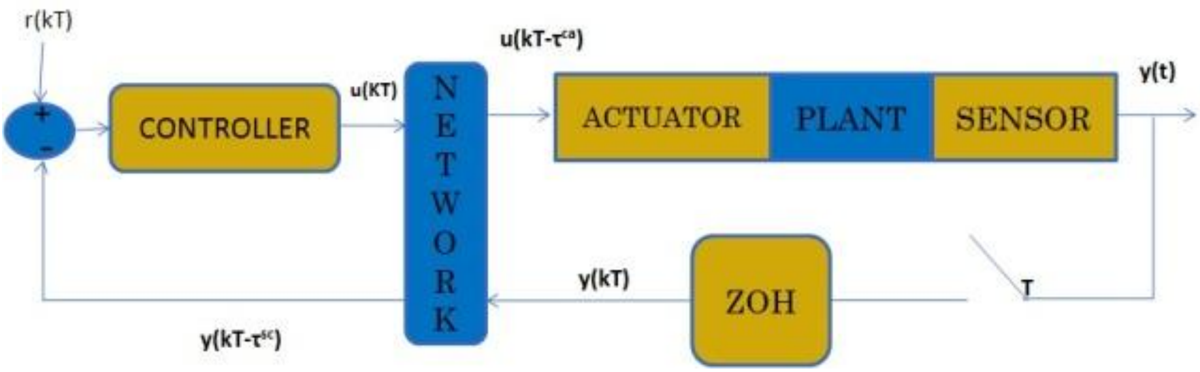

Fig.2.1. NCS configuration and network delays for NCS formulation [5]

Above Figure shows delays in control loop, where r is reference signal, y is output signal, u is the control signal T is sampling period and K is the time index. Many of the networked control methodologies use the discrete time formulation as shown in Fig.2.1. Network delays in NCS can be divided from the direction of data transfer as sensor to controller delay τ^{sc} and controller to actuator delay τ^{ca}. The delays are described as

$$\tau^{sc} = t^{cs} - t^{sc} \qquad\qquad \tau^{ca} = t^{rs} - t^{ce}$$

where, t^{cs} is the time instant that the controller starts processing in the delivered frame or packet, t^{sc} is the time instant that the remote system measurement to a frame, t^{rs} is the time instant that the remote system starts processing the control signal, and t^{ce} is the time instant that the main controller encapsulate the control signal to a packet to be sent. Both network delays τ^{sc} and τ^{ca} can be greater and shorter than the sampling time T.

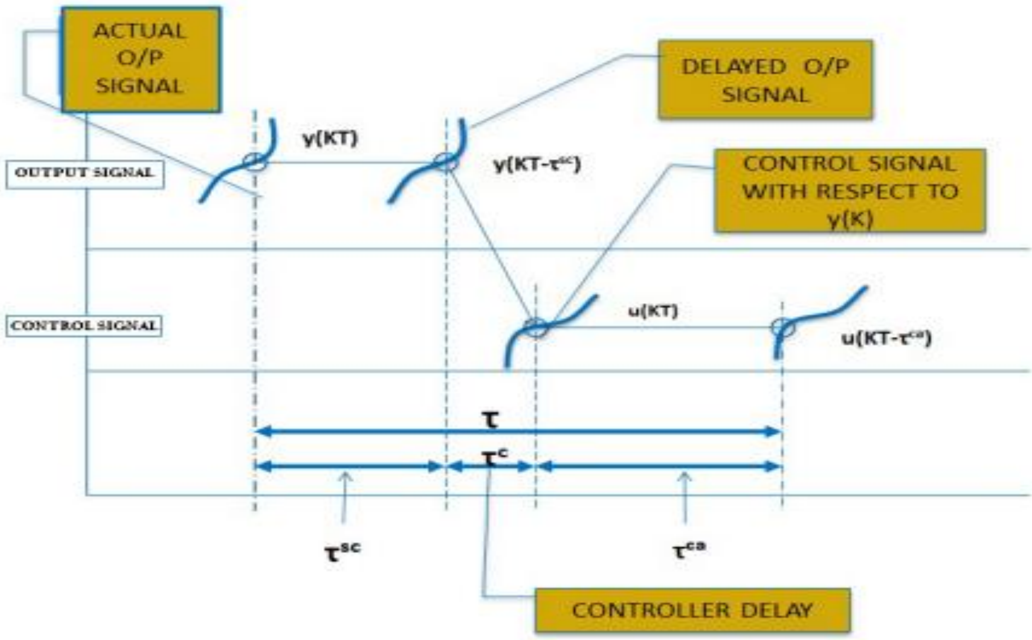

Fig.2.2 Timing diagram of network delay propagation

The controller processing delay τ^c and both network delays can be treated as the control delay t for easiness. Although the controller processing delay τ^c always exits, this delay is usually small compared to the network delays, and could be negligible.

In some cases the sampling periods of main controller and remote system may be different. There are some more delays are present in the system:

Waiting time delay τ^w – The waiting time delay is the delay, of which a source (main controller or remote system) has to wait for queuing and network availability before sending a frame or a packet out.

Frame time delay τ^f – The delay during the moment that the source is placing a packet or a frame on the network is known as frame time delay.

Propagation time delay τ^p – The delay induce for a frame or a packet travelling through a physical media is called as propagation delay. This delay totally depends on the speed of signal communication and the distance between the source and destination.

These three delays are fundamental delays that occur on a local area network (LAN). When the control or sensor data travel across network, there may be additional delays such as the waiting delay at a switch or a router, and the propagation delay between network nodes. The delays τ^{sc} and τ^{ca} also depend on other factors like maximal bandwidths from protocol specifications, frame and packet size. The controlled plant in NCS is assumed to be continuous time and thus the actuator implements zero order hold (ZOH) holding the last control until the next one arrives or until the next sample time. As the networks are used for transmitting the measurements from the plant output to the controller, the plant has to be sampled, which motivates the use of discrete time controller. In NCS, there are many sources of delays. The network dynamics affect the delay also the signal processing and computational delays that depends on scheduling policies should be taken into consideration. The network may also be exposed to failures which would increase the delay variance.

If all the components of the NCS are time driven an additional delay will produce which is known as synchronization delay, because the components have to wait until the next sample instant until they can work.

2.2.2 Data Packet Dropout

Network communication can be viewed as a web of unreliable communication of data. In transmissions of data packet, some data packets do not only suffer from communication delay but also may be lost during the transmission. So, we have to see how much data dropouts affect the performance and stability of an NCS. The reason behind the data dropout in NCS is node failure and message collisions. To remove this problem many network protocols are equipped with transmission retry mechanisms, but they retransmit for a limited time. After that time the packets are dropped. Feedback controlled systems can remove a certain amount of data loss, but it is valuable to determine whether the system is stable when only transmitting the packets at a certain rate or not.

An NCS is designed with data dropouts as asynchronous switched system [4, 14]. This approach replaces the true switched system with an average system and then provides some stability conditions. The achieved result is very conservative due to the average dropout rate. We can reduce the network traffic, for a given sampling frequency, implementing estimation methods in an NCS, by increasing the bandwidth of the system [15].

2.3 DELAY CHARACTERISTICS

There are several models are available for network delays depending on the type of and protocols used. Generally available network delay models are considered. The delay characteristics on Networked Control Systems (NCS) depend on the type of a network used. Networks are described as,

Random Access Network- Random access local area networks such as Controller Area Network (CAN) and Ethernet involve with more uncertain delays. The main part of random network delays is the waiting time delay.

In the networking are, random network delays have been modelled by using various formulation based on probability and the characteristics of sources and destinations.

Cyclic Service Network- In local area protocols with cyclic services the control and sensor data's are transmitted in a cyclic order with deterministic behaviour. The delays are periodic and can be simply modelled as a periodic function.

2.4 DELAY CONTROL SYSTEM (DCS) FOR NETWORK INDUCED DELAY

As in above section mentioned the network induced delay in NCS occurs when actuators, sensors and controllers exchange data across the networks. These delays can degrade the performance of the control systems designed without considering it and even destabilize the system. The network delay model of network system is shown in Fig. 2.3. In which τ^{sc} is the delay between the sensor to controller and τ^{ca} is the delay between controllers to actuator.

By considering this design the generalized mathematical model of delay control system (DCS) can be designed. During construction of DCS the DCS divided into three parts as the controlled system (Plant), the controller and the network system which bounds these first two parts. Through this designing the system analysis will be easy.

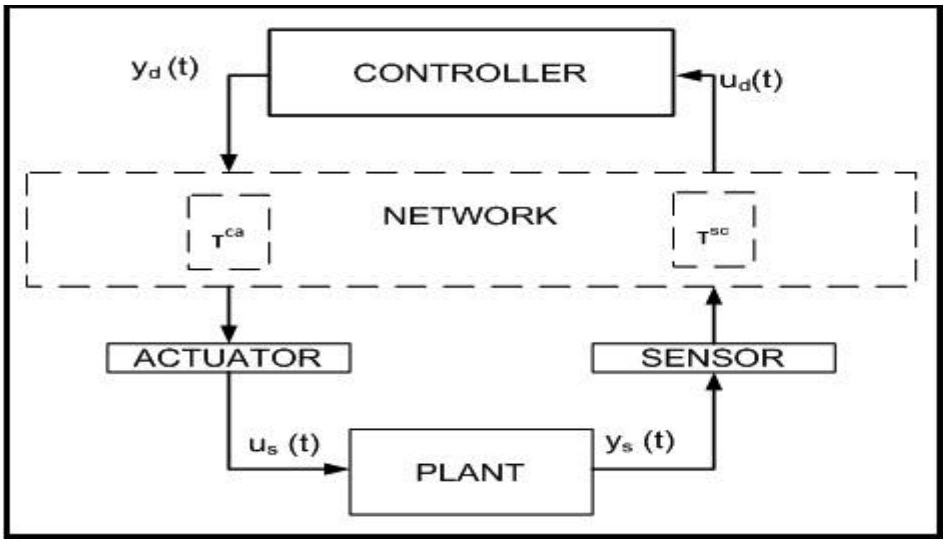

Fig.2.3 Model of network induced delay

When we analyze the networked control system with network delay [12] we use two models of the network delays:

1. Constant Delay
2. Random Delay which are independent between τ^{sc} and τ^{ca} .

Model (1) is the simplest model for every transfer in communication network and it may be a good model even if the network has varying delays. There is a way to achieve constant delay by introduction of timed buffer for each transfer. When we make these buffers longer than the delay time, the transfer time can be seen as being constant [11]. A disadvantage in this method is that the delay time often is longer, which lead to decrease the performance of the system [12, 13]. Generally, network delays are random because of several sources, waiting for idle network.

In model (2), it is assume that the transfer delay is independent of the previous delay and has different probability distribution of $\tau^{\mathbf{sc}}$ and $\tau^{\mathbf{ca}}$.

2.5 EFFECT OF DELAY IN LOOP

The main problem occurred due to the delays in control loop are widely known to degrade system performance and destabilization of a control system. The data or packets of the information totally spoiled or lost due to these delay. If we construct the control system without considering these delays has a low performance and reliability. Delays in the loop including network delays in an NCS can destabilize the system by reducing the system stability margin.

The closed loop proportional-integral (PI) control system with delays in Fig.2.4 is used to briefly illustrate system performance degradation by delays in the loop, where $\mathrm{R}(\mathrm{s})$, $\mathrm{Y}(\mathrm{s})$, $\mathrm{U}(\mathrm{s})$ and $\mathrm{E}(\mathrm{s})$ are the reference signal, output signal, control input and error signal in Laplace domain [5].

where, $$\mathrm{E}(\mathrm{s}) = \mathrm{R}(\mathrm{s}) - \mathrm{Y}(\mathrm{s}) \quad (1.1)$$

The transfer function of the controller and the plant are described, respectively, as follows:

$$G_c(s) = \frac{\beta K_p (s+(K_I + K_p))}{s} \quad (1.2)$$

$$\mathrm{Kp} = 0.1701,\ \mathrm{K_I} = 0.378, \quad (1.3)$$

$$G_p(s) = \frac{2029.826}{(s+26.29)(s+2.296)} \quad (1.4)$$

Where $G_c(s)$ is a PI controller, β is the parameter to adjust Kp and $\mathrm{K_I}$, is Kp is the proportional gain, $\mathrm{K_I}$ is the integral gain, $G_p(s)$ is the plant of DC motor [13].

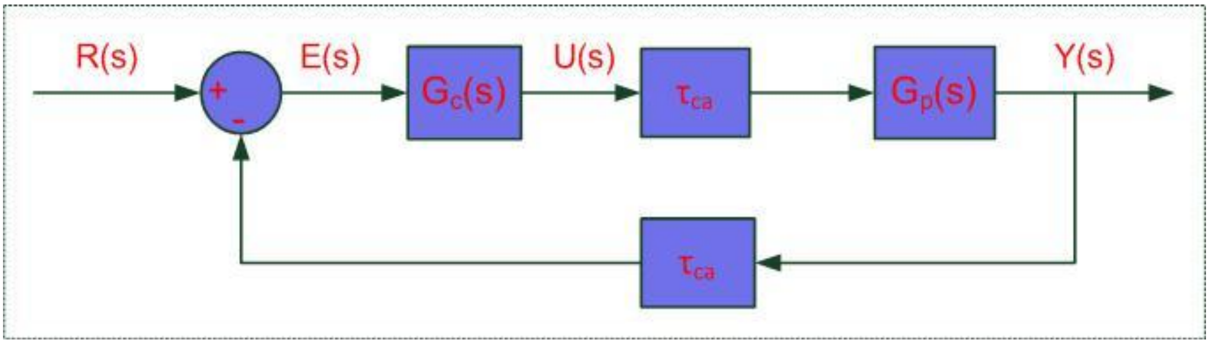

Fig.2.4 Closed loop control system

For solving the above closed loop system, β = 1 and $\tau^{ca} = \tau^{sc} = \tau/2$. As shown in Fig. 2.5, system performance degradations are the higher overshoot and the longer settling time. Based on different performance measure we can evaluate other kind of performance degradation. On the effect of delays on system performance measure can be used for developing appropriate networked control methodologies [14].

Again we can say that the system in Fig. 2.4 is used to illustrate how the delay can reduce the stability. There have been many studies to derive stability criteria for an NCS in order to guarantee that the NCS can remain stable in certain contain. We can't apply generic stability analysis on every NCS. Many of the stability analysis techniques are subject to network configurations, control techniques and network protocols.

This is more challenging when stability analysis for an NCS with the random network delays is present.

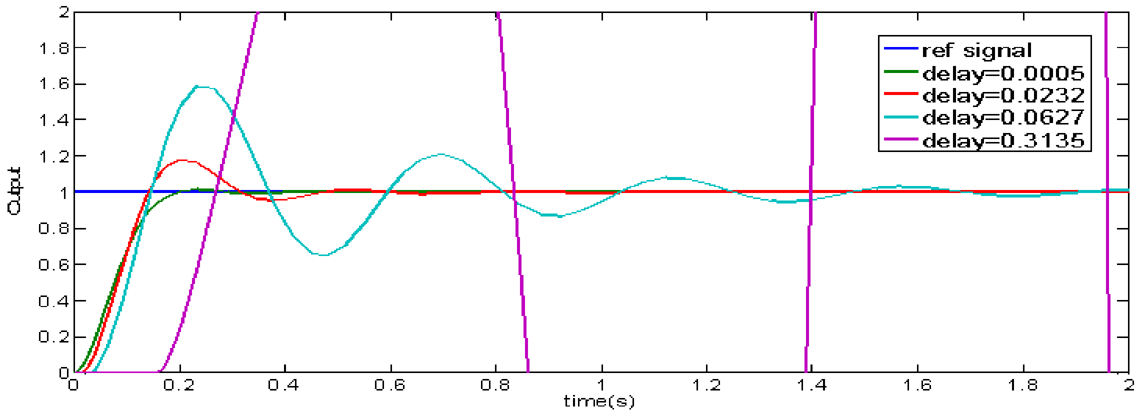

Fig.2.5 Step response w.r.t. various τ, where $\tau^{ca} = \tau^{sc} = \tau / \mathbf{2}$ are constant, and $\beta = 1$

The time delays in the NCS may degrade the system performance and causes the system instability. So it is most important to design a controller which can compensate for the time delays and improve the control performance. When the sensor to data is used by the controller to generate the control signal, the sensor to controller delay introduces which is known. But when controller to actuator delay introduces the controller doesn't know how much length it is, and how long it will take the control signal to reach actuator. So at this time no exact correction can be made.

The main goal of the networked control system is to maintain the Quality of Performance (QoP) of the control system. To compensate the delay of the NCS, there should be the robust system. For control calculation, an estimator can be used to predict an undelayed plant. Estimator of NCS must estimate the full state of the plant using partial state measurements and also compensate to sensor delay. To present the delay compensation techniques it is important to told the following:

1. The process speed is fast
2. The sampling time T is greater than the network induced delay τ for capturing all the relevant process dynamics.
3. The entire control and measurement signal should be sent in single packet.

4. There is no packet loss occur during the communication.
5. Network communication should be error free.

2.6 VARIOUS TYPES OF TIME DELAY CONTROL SCHEMES IN NCS

To compensate the time delays induces in the NCS there are various time delay compensation techniques are used by many researchers. Different type of time delay compensation techniques are as follows:

1. Adaptive Controller
2. Optimal Controller
3. Robust Control
4. PID Controller
5. Smith Predictor
6. Sliding Mode Controller
7. Fuzzy Controller

As above mentioned various control techniques have been developed for network control system, a technique to actively compensation of the random network delay is not available. In the present work, network predictive control scheme has been applied to compensate the network delay in network control systems. In chapter 3, the stability analysis and design of closed-loop networked predictive control system will be discussed.

2.7 MODEL PREDICTIVE CONTROL

2.7.1 Introduction

Model Predictive Control (MPC) is a type of control in which the current control signal is obtain by solving online, at each sampling instant, a finite horizon open loop control problem, using the current state of the system as the initial state, the optimization needs an optimal control signal and the first control in this signal is applied the system.

All MPC systems are based on the idea of generating values for process model and other measurements. In MPC structure there is a feedback or feed forward path to compute the process measurements. There are various forms are available to make model predictive controller:

Feedback MPC- This type of MPC mitigates shrinkage of feasible region.

Robust MPC- Through this type of MPC we get feasibility and stability of the system.

Decentralized MPC- For very fast response decentralized MPCs are used.

Pre-computed MPC- In this MPC the optimization is an off-line process. Mainly the parameters are solved by linear or quadratic programming.

2.7.2 Model predictive control structure

There are mainly three components are available in MPC structure [15]:

1. The process model
2. The cost function
3. The optimizer

The information about the controlled process and prediction of the response of the process values according to the manipulated control variables are done by the process model. Then the error is reduced by the minimization of the cost function.

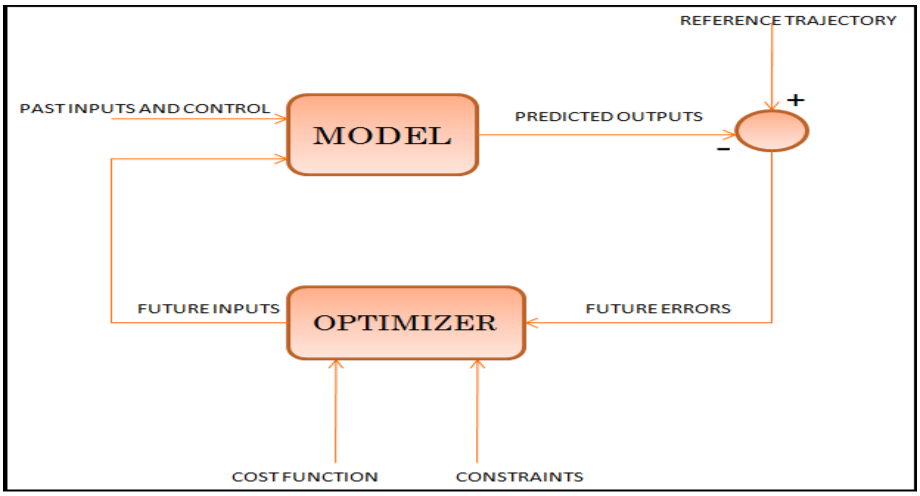

Fig.2.6 Basic structure of Model Predictive Controller

In the last step various types of optimization techniques are used and the output gives to the input sequence for the next prediction horizon.

2.7.3 Characteristics of MPC

The main characteristics of MPC are [15]:

1. Performance based time domain formulation,
2. Moving horizon technique implementation,
3. In MPC, an explicit system model is using for prediction of future plant dynamics,
4. Constraints values are incorporated.

2.7.4 Advantages of MPC

Many advantages of MPC are available due to these reasons the MPC should be use.

1. Structural changes are available,
2. In this tune method is easy,
3. Actuator limitations are accountable,
4. Through this method we can handle unstable system and non-minimal phase,

2.7.5 Applications

There are various applications are available in which we can use MPC-

1. Hydrocracker,
2. Distillation column,
3. Servo mechanism,
4. Robot arm,
5. Pulp and paper plant etc.

CHAPTER 3

ANALYSIS AND DESIGN OF NETWORKED PREDICTIVE CONTROLLER

3.1 INTRODUCTION

Feedback control system in which the control loop is closed through a real time network is called as a networked control system (NCS). NCS is a completely real time feedback control system that is combination of actuators, sensors, controllers and communication networks. This provides data communication between devices in order that users at different locations can realize the resource sharing and coordinate.

Many researchers apply type of various control approaches have been developed for networked control systems to stable the system. In this chapter a new control strategy to compensate the network delay in networked control systems is discussed which is known as networked predictive control. After that in next chapter simulation is discussed for the networked predictive control systems.

3.2 NETWORKED PREDICTIVE CONTROL STRATEGY

On the basis of location of networks in the system, there are different types of structures are available for NCS. For example, in NCS the network may be located between the actuator and the controller, between the controller and the sensor, and/ or between the controller and the reference. For this a networked predictive control system (NPSC) structure is shown in Fig.3.1.

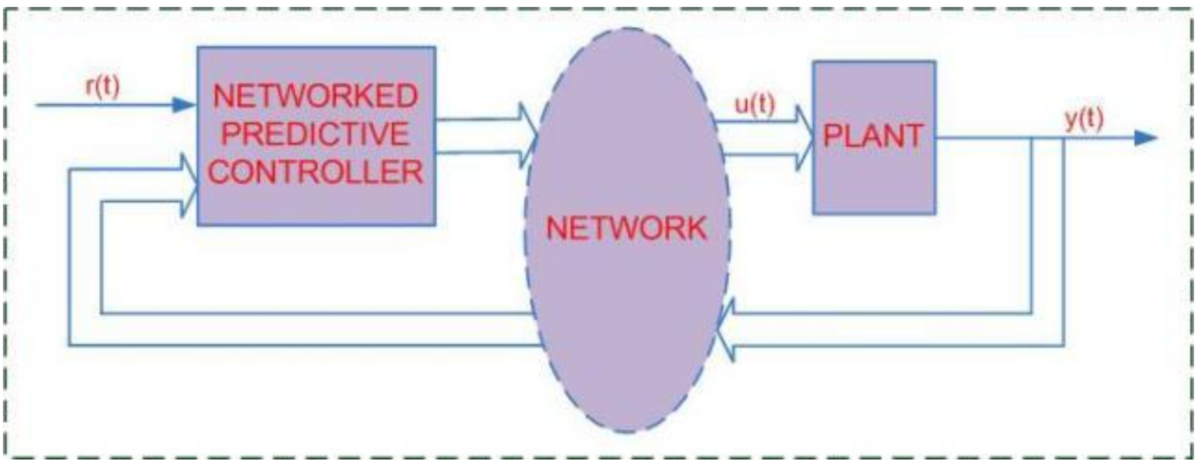

Fig.3.1 Basic structure of networked predictive control system

In practical networked control system the data loss will exists. When a data packet does not reach at destination in a certain communication time, it means that the data is lost during the transmission. Also it is natural to assume that only few number of consecutive data dropouts can be avoidable. For an NCS, the time stamp of data communicated through a network is very important.

For simplicity, the following assumptions are compulsory to be made:

1. The transmission delay in feedback path (from sensor to controller) is random but bounded by n_b.
2. The transmission delay in the forward path (from controller to actuator) is random but bounded by n_f.
3. The number of data packet drops in both the feedback and forward path is not greater than n_d.
4. The data communications through the network are with a time stamp.

The synchronization is also having very important value in NCS. The synchronization of time clocks in digital components can be done by various ways. By many researchers the study of the problem of synchronization errors and their effect on systems has done [15].

For designing of networked predictive controller, consider the following linear discrete-time model;

$$\begin{aligned} x_{t+1} &= Ax_t + Bu_t \\ y_t &= Cx_t \end{aligned} \tag{3.1}$$

where, $x_t \in \Re^n, y_t \in \Re^l$, and $u_t \in \Re^m$ are the state, output, and input vectors of the system, respectively, and $A \in \Re^{n\times n}, B \in \Re^{m\times m}$, and $C \in \Re^{l\times n}$ are the system matrices.

From assumptions 1–3 which are mentioned above, let $\tau = n_f + n_d$ and $k = n_b + n_d$.

It is assumed that the states of the plant are not measurable.

So, for obtaining the state vector of the plant for the controller design on the controller side, an observer is designed,

$$\begin{aligned} \hat{x}_{t-k+1/t-k} &= A\hat{x}_{t-k/t-k-1} + Bu_{t-k} + L(y_{t-k} - \hat{y}_{t-k}) \\ \hat{y}_{t-k} &= C\hat{x}_{t-k/t-k-1} \end{aligned} \tag{3.2}$$

where,

$\hat{x}_{t-i/t-j} \in \Re^{n}(i < j)$ denotes the state prediction for time $t-i$ on the basis of the information up to time $t-j$,

$\hat{y}_{t} \in \Re^{l}$ is the output vector of the observer at time t,

$L \in \Re^{n \times l}$ is the gain matrix, which can be designed using normal observer design approaches.

As the observer provides a one-step ahead prediction of the states using the output at time $t-k$, the state predictions from time $t-k+2$ to $t+\tau$ are still not known. According to the information available on the controller side, the other state predictions up to time $t+\tau$ can be constructed by

$$\hat{x}_{t-k+i/t-k} = A\hat{x}_{t-k+i-1/t-k} + Bu_{t-k+i-1} \tag{3.3}$$

for $i = 2, 3, \ldots, k+\tau$.

From assumptions 1–3, it is clear that both τ and k are fixed. Then, all control inputs from $t-k$ to $t+\tau-1$ be available on the controller side, and some of them are not applied to the plant at time t. Thus, the state predictions given by (3.3) can be solved based on the available output y_{t-k} of the system. When the states of the plant are estimated, there are various control methods available for the system. To illustrate the networked predictive control strategy [16], the observer based state-feedback control (OBSFC) method is employed. Therefore, the control prediction to be generated on the controller side is

$$u_{t+\tau/t-k} = K\hat{x}_{t+\tau/t-k} \tag{3.4}$$

where, $K \in \Re^{m \times n}$ is the controller gain matrix. On the actuator side, the control input is

$$u_t = u_{t/t-k-\tau} = K\hat{x}_{t/t-k-\tau} \tag{3.5}$$

It is clear that the delay may be compensated by the above control technique. In [17], this already has been shown that the control performance of the closed loop networked predictive control system (NPCS) is similar to the one without a network.

3.3 DESIGN OF NETWORK DELAY COMPENSATOR (NPC)

Since the transmission delays and data dropouts are involved, the description of closed loop NCSs plays an important role in the design of the predictive controller.

An effective compact description of closed-loop networked predictive control systems (NPSC) introduced in Section 3.2 is derived below.

A strategy of designing the predictive controller for networked systems is given here.

From (3.2) that if the time is shifted for k steps forward, the observer can be rewritten as

$$\begin{aligned} \hat{x}_{t+1/t} &= A\hat{x}_{t/t-1} + Bu_t + L(y_t - \hat{y}_t) \\ \hat{y}_t &= C\hat{x}_{t/t-1} \end{aligned} \tag{3.6}$$

Subtracting (3.6) from (3.1) results in the following state error equation:

$$e_{t+1} = (A - LC)e_t \tag{3.7}$$

where $e_t = x_t - \hat{x}_{t/t-t}$.

From the state prediction equation (3.3), it can be obtained that

$$\hat{x}_{t+\tau/t-k} = A^{k+\tau-1}\hat{x}_{t-k+1/t-k} + \sum_{i=2}^{k+\tau} A_{k+\tau-i}Bu_{t+\tau-k-1} \tag{3.8}$$

Similarly,

$$\hat{x}_{t+\tau/t-k+1} = A^{k+\tau-2}\hat{x}_{t-k+2/t-k+1} + \sum_{i=3}^{k+\tau} A^{k+\tau-i}Bu_{t+i-k-1}$$

$$= A^{k+\tau-2}(A\hat{x}_{t-k+1/t-k}Bu_{t-k+1} + L(y_{t-k+1} - \hat{y}_{t-k+1})) + \sum_{i=3}^{k+\tau} A^{k+\tau-i}Bu_{t+i-k-1}$$

$$= A^{k+\tau-1}\hat{x}_{t-k+1/t-k} + \sum_{i=2}^{k+\tau} A^{k+\tau-i}Bu_{t+i-k-1} + A^{k+\tau-2}LCe_{t-k+1} \tag{3.9}$$

which uses (3.2). Subtracting (3.9) from (3.8) we get:

$$\hat{x}_{t+\tau/t-k} = \hat{x}_{t+\tau/t-k+1} - A^{k+\tau-2}LCe_{t-k+1} \tag{3.10}$$

Using the above recursively result in

$$\hat{x}_{t+\tau/t-k} = \hat{x}_{t+\tau/t-k+1} - \sum_{i=0}^{k+\tau-2} A^{i}LCe_{t+\tau-i-1} \tag{3.11}$$

Let $(t+\tau)$ be replaced by t in the above equation, which gives

$$\hat{x}_{t/t-k-\tau} = \hat{x}_{t/t-1} - \sum_{i=0}^{k+\tau-2} A^{i}LCe_{t-i-1} \tag{3.12}$$

From the networked predictive control strategy, the control input of the plant in (3.5) is

$$u_t = K\hat{x}_{t/t-k-\tau} = K(\hat{x}_{t/t-1} - \sum_{i=0}^{k+\tau-2} A^{i}LCe_{t-i-1}) \tag{3.13}$$

Substituting u_t in (3.1) by (3.13) leads to

$$\begin{aligned} x_{t+1} &= Ax_t + BK(\hat{x}_{t/t+1} - \sum_{i=0}^{k+\tau-2} A^{i}LCe_{t-i-1}) \\ &= Ax_t + BK(x_t - e_t - \sum_{i=0}^{k+\tau-2} A^{i}LCe_{t-i-1}) \\ &= (A+BK)x_t - BK(e_t + \sum_{i=0}^{k+\tau-2} A^{i}LCe_{t-i-1}) \end{aligned} \tag{3.14}$$

Therefore it is clear from (3.7) and (3.14) that the closed-loop system can be described as

$$\begin{aligned} x_{t+1} &= (A+BK)x_t - BKe_t - \sum_{i=0}^{k+\tau-2} BKA^{i}LCe_{t-i-1} \\ e_{t-j-1} &= (A-LC)e_{t-j}, \ldots. for..j = 0,1,\ldots.,k+\tau-1. \end{aligned} \tag{3.15}$$

The above is equivalent to the following compact form:

$$\begin{pmatrix} x_{t+1} \\ E_{t+1} \end{pmatrix} = \begin{pmatrix} \Gamma & \Theta(k,\tau) \\ 0 & \Lambda \end{pmatrix} \begin{pmatrix} x_t \\ E_t \end{pmatrix} \tag{3.16}$$

where, $E_t = \left[e_t^T e_{t-1}^T ......e_{t-\tau-n_b+1}^T \right]^T \in \Re^{n(\tau+n_b)\times 1}$, $\Gamma = A + BK \in \Re^{n\times n}$,

$\Lambda = diag\left\{ A-LC\ A-LC.......A-LC \right\} \in \Re^{n(n_b+\tau)\times n(n_b+\tau)}$,

$\Theta(k,\tau) = \left[-BK\ -BKLC\ -BKALC.......-BKA^{t+\tau-2}LC\ 0.... \right] \in \Re^{n\times n(n_b+\tau)}$, and $e_t = x_t - \hat{x}_{t/t-1}$.

So, with the networked predictive controller given by (3.5), the closed-loop Networked Predictive Control System can be described by (3.16). It is compulsory that an up-triangular system is stable iff its sub matrices in the diagonal line of the closed-loop system matrix are stable [18]. Therefore, it is clear from (3.16) that the closed-loop networked predictive control system is stable if and only if the eigenvalues of matrices Γ and Λ are within the unit circle. This implies that the eigenvalues of matrices $(A + BK)$ and $(A - LC)$ must be within unit circle.

Clearly, the stability of the closed-loop networked predictive control systems is not related to communication delays. This is a significant step to design the networked predictive control systems.

From the above, it indicates that the separation principle for the observer-based state feedback control is still held in the networked predictive control system. Therefore, the predictive controller of networked systems can be designed using the following two-stage design scheme.

1) Designing of the observer gain matrix L. This can follow the normal design procedure of observers.

2) Designing of the feedback gain matrix K. This can be achieved using the same design procedure of local control systems (there is no network in the closed-loop system). Since the networked predictive control technique can provide the similar control performance as the one given by the local control system [17], the above design scheme largely simplifies the design procedure of the predictive controllers for networked systems.

As above it is mentioned that, the states of the plant are not measurable. So, for obtaining the state vectors of the plant for the controller design on the controller side, an observer is designed, the structure of the observer is shown in Fig.3.2.

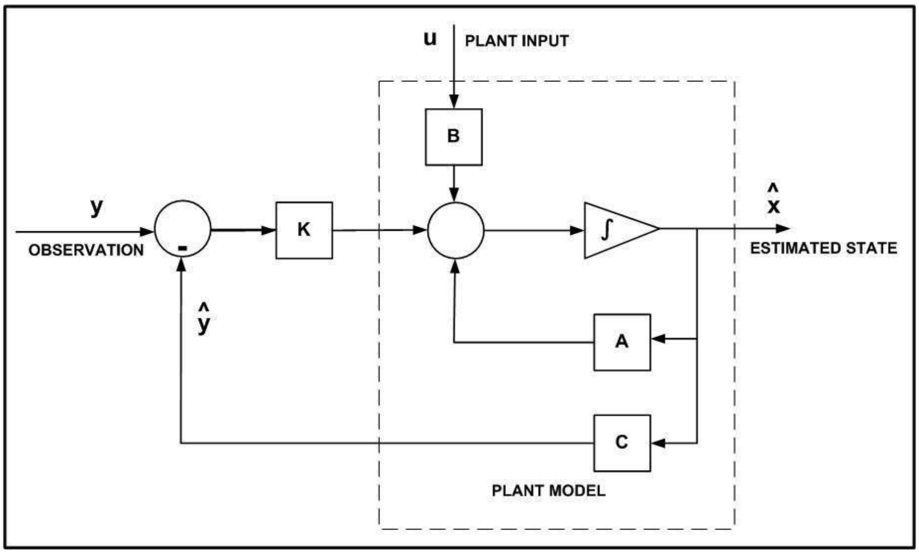

Fig.3.2 Full order observer for linear model

EXAMPLE 1.

The Networked Predictive Control Scheme (NPCS) has been applied on a servo control system. The considered servo system is in discrete-time system a model of that is described by [21],

$$A=\begin{bmatrix} 1.12 & 0.213 & -0.335 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}, \qquad B=\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \qquad C=\begin{bmatrix} 0.0541 & 0.1150 & 0.0001 \end{bmatrix}$$

For discretization the sampling period is used of 0.04 sec.

To design the observer based feedback networked predictive controller first of all the observer is designed.

To illustrate the above system the initial conditions of the system states and the observer states are taken to be $[5,5,-5]$ and $[0,0,0]$.

As the design strategy of the networked predictive controller described in previous chapter, to design the observer, let the desired poles of the closed-loop state feedback control system without a network is $[-0.4,\ 0.7+0.6i,\ 0.7-0.6i]$ and the desired poles of the observer are $[0.1,\ 0.3,\ 0.5]$.

Using Ackerman formula the observer gain matrix and feedback gain matrix are

$$L = \begin{bmatrix} 4.9113 \\ -0.4055 \\ 9.2845 \end{bmatrix},$$

$$K = \begin{bmatrix} -0.1200 & -0.5030 & -0.0050 \end{bmatrix}$$

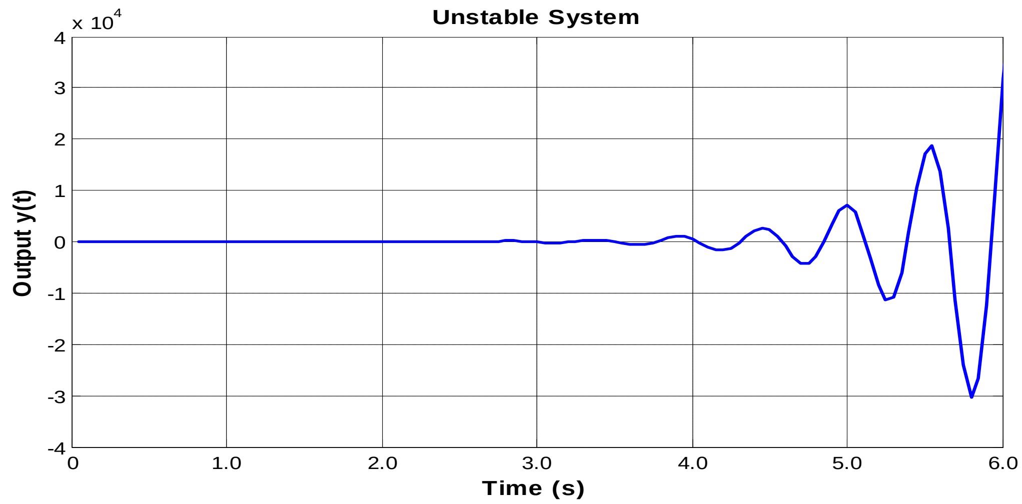

Fig.3.3 Step response of the networked DC servo motor without compensating the communication delay

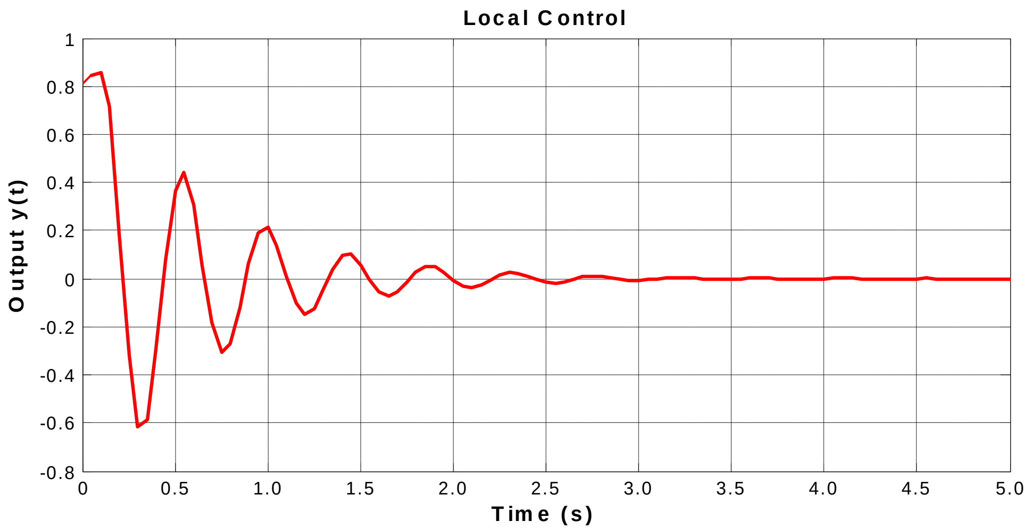

Fig.3.4 Step response of the networked DC servo motor to compensate the communication delay using a Local controller

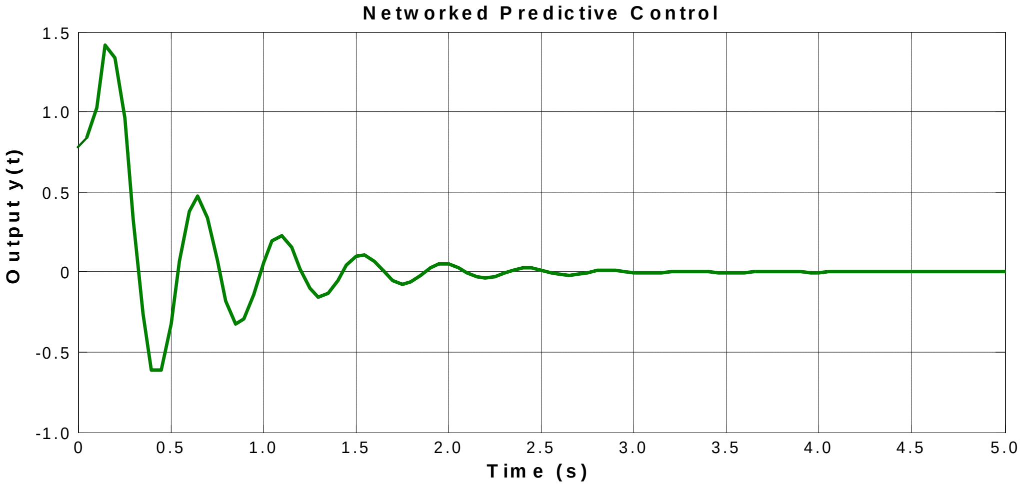

Fig.3.5 Step response of the networked DC servo motor to compensate the communication delay using Networked Predictive Controller (NPC)

From Fig. 3.3, the system is an unstable system which is due the communication delay occurred in the networked.

For controlling the unstable system first of all I have applied a local control (Feedback Controller) which controls the system and also the system comes stable (Fig.3.4) but it does not remove or compensate the data packet loss. There are two cases to analyze the results:

Case (1) Networked Control without Delay Compensation (Fig.3.3)

In this case, the delay in the communication channels is not compensated. In this case, the networked predictive control strategy is not implemented, but a normal feedback control is used.

It is assumed that there exists a one-step communication delay in the forward channel and no delay in the feedback channel. So, the controller is given by $u_t = K\hat{x}_{t-1/t-2}$. The simulation result in Fig.3.3 shows that the system is unstable.

Case (2) Networked Predictive Control (Fig.3.4 & 3.5)

The networked predictive control strategy is applied to compensate the communication delay. The parameters of the networks in the forward and feedback channels are:

n_f = 3 (the maximum delay in the forward channel),

n_b = 2 (the maximum delay in the feedback channel), and

n_d = 1 (the maximum number of consecutive data loss in each communication channel).

The simulation results given in Fig.3.4 and Fig.3.5, are for the comparison, the output curve of the networked predictive control system is shifted for seven sampling steps backward (seven (3+2+1+1) is the maximum communication delay in the system, which is the worst case), shows that the closed-loop system is stable, and the performance of the closed-loop networked predictive control system is the same as that of the local closed-loop control system (there is no network in the closed-loop system), except the 1st several steps.

When the communication delay increases, the performance and the stability of the closed- loop networked predictive control do not change.

3.4 SMITH PREDICTOR CONTROL

A classical Smith Predictor control is a feedback control strategy which has a minor loop as shown in Fig. 3.6., which is a Smith Predictor based NCS (SPNCS).

The plant model is considered in the minor feedback loop with a virtual time delay to compensate for networked induced delays. The outer feedback loop contains a actual plant as well feedback delay induced in that. Using the available information of the plant model and time delay, controller is designed using a Smith predictor.

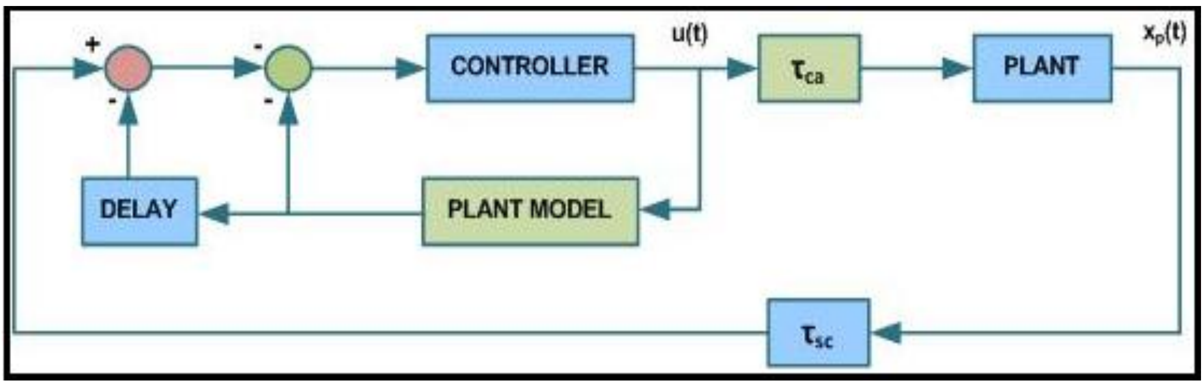

Fig. 3.6 Block diagram of a NCS with Smith Predictor

EXAMPLE 2.

A DC motor speed control using predictive controller,

Table 3.1 Parameters of the DC motor[26]

Parameters		Values
J	Inertia	$1.6511\text{x}10^{-4}\ kg.m^2$
L	Inductance	$3.14\text{x}10^{-3}\ H$
R	Resistance	4.961Ω
K	Torque Constant	$7.105\text{x}10^{-2}\ N.m/A$
B	Damping Coefficient	$23.64\text{x}e^{-6}\ N.m.\sec/rad$
K_b	Back-EMF Constant	$1.276\text{x}10^{-2}\ Vs/rad$

The electromechanical dynamics of the DC motor described as

$$\frac{di_a}{dt}=-\frac{R}{L}i_a-\frac{K_b}{L}\omega+\frac{1}{L}u \tag{3.17}$$

$$\frac{\omega}{dt}=\frac{K}{J}i_a-\frac{B}{J}\omega \tag{3.18}$$

where,

i_a = the armature winding current, ω = the rotor angular speed,

R = the armature winding resistance, L = the armature winding inductance,

K_b = the back EMF constant, u = the armature winding input voltage,

K = the torque constant, J = the system moment of inertia,

B = the system damping coefficient.

Let us take, $x\overset{\Delta}{=}\left[i_a,\omega\right]^T$, the DC motor can expressed as,

$$\begin{aligned}\dot{x}(t)&=Ax(t)+Bu(t)\\ y(t)&=Cx(t)+Du(t)\end{aligned} \tag{3.19}$$

where , $y(t)$ is the rotor angular speed and

$$A=\begin{bmatrix}-\frac{R}{L} & -\frac{K_b}{L}\\ \frac{K}{J} & -\frac{B}{J}\end{bmatrix} \qquad B=\begin{bmatrix}\frac{1}{L}\\ 0\end{bmatrix} \tag{3.20}$$

$$C=\begin{bmatrix}0 & 1\end{bmatrix} \qquad D=0$$

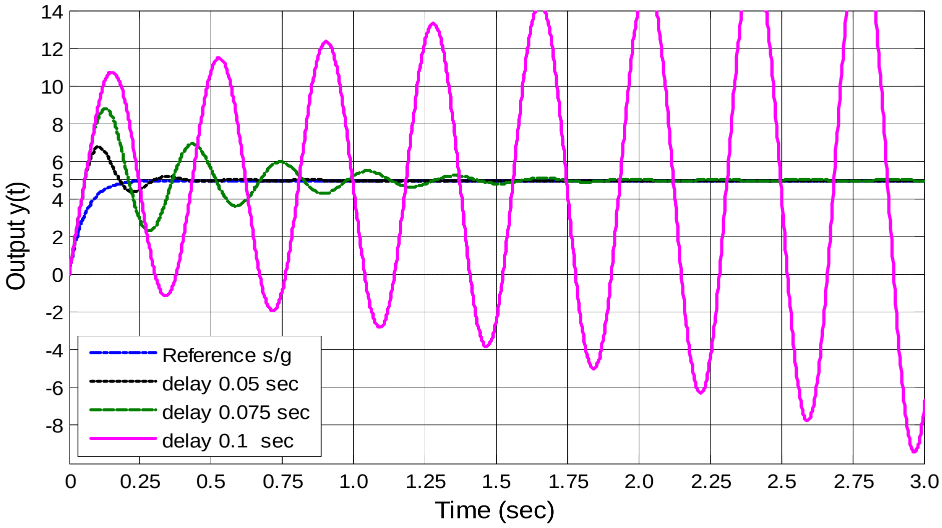

Fig. 3.7 Step response of the DC motor with various delays

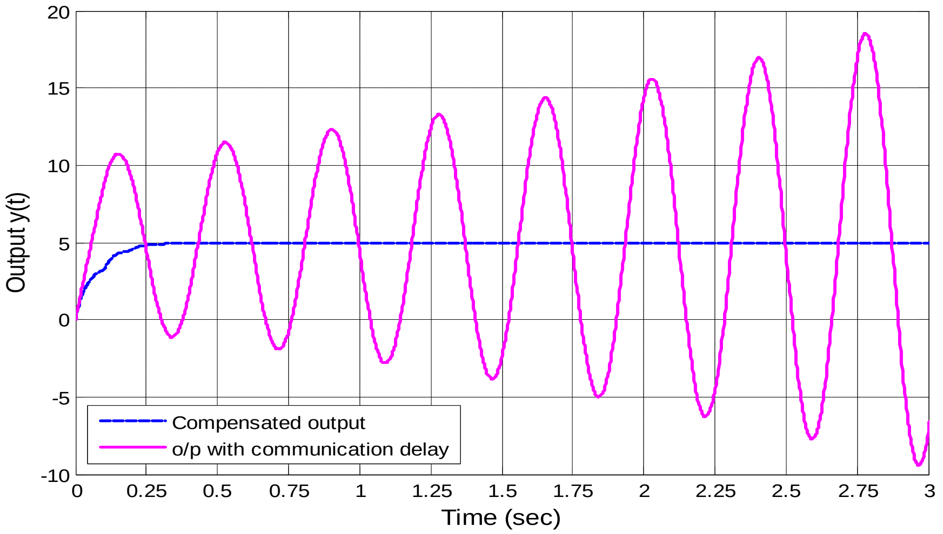

Fig. 3.8 DC motor speed control using predictive controller

From Fig. 4.4, the DC motor goes unstable system while increasing the delay in the system. A classical Smith predictor is applied to compensate the round trip delay. It is shown that robust stability of the closed-loop system is closely related to the maximal round trip delay [25]. In the results, smith predictive controller the system is stable and increases the performance of the system. Only some damping introduces in the response but settling time is unchanged.

CHAPTER 4

CONCLUSION AND SCOPE FOR FUTURE WORK

4.1 DISCUSSION

In the present work, a controller has been designed for a networked system considering transmission delay and data loss during the transmission. A networked predictive controller has been designed for networked system to compensate the communication delay and data loss. In the first chapter, it has been discussed about the various applications of networked control system like; aircraft, manufacturing, automobile industries etc. But along with various advantages like easiness and less complexity it introduces some delay in the system due to which the system performance degrades and also some data packet loss occurred.

The networked predictive control strategy has been applied to a DC servo system and the results are discussed in chapter 4. From the results, it is clear that the networked predictive controller compensates the delay induced in the system, also the performance and the stability of the networked predictive control system is unchanged with increasing the communication delay.

4.2 CONCLUSION

The thesis deals with the analysis, simulation and controller design of networked predictive control system. The networked predictive control scheme has been applied to compensate the network delay so that the closed-loop networked predictive control system can achieve the desired control performance and also the system stability is achieved. The stability of the closed-loop networked predictive control systems has been analyzed. The stability of the DC motor system using smith predictor, in which delay is predicted, compensation has been done. Comparison with other existing networked control methods, like *H_∞ control [23], Networked predictive control for random network delays in both forward and feedback channels [24] and Model-based control* [25]. The proposed networked predictive strategy offers two main advantages:

1. The control performance of the closed-loop networked control system is same as the closed-loop system without any delay induced by networking.

2. The necessary and sufficient conditions of the stability of closed-loop NCS are dependent only on transmission delay and data loss. Hence, the controller can be designed based only on these two components.

4.3 FUTURE SCOPE

In this thesis, only ideal plants (i.e. linear model) have been considered to design the networked predictive control systems. As we know that mainly all the physical control systems are nonlinear with uncertainties. Future work in this direction would involve application of predictive control strategies to nonlinear plants; work is also planned on design of optimal controller for networked experimental set-up.

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