ROBUST SPEED CONTROL OF NETWORKED INDUCTION MOTOR WITH UNCERTAIN TIME DELAY

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Abstract

In the present time, the control systems have evolved into Network Control Systems (NCS) distinguishing this period as the third generation of control system. Due to advancement of communication methodologies, control strategies and computing technology, network control systems are extensively used in many applications. For this reason, both industry as well as academia are extending their research in the domain of Networked Control Systems.

Network Control System are the control systems in which data is exchanged between the plant and the controller through a communication medium. The insertion of communication network in closed loop control systems offers many benefits but at the same time, it brings challenges such as delay prompted due to network, information loss, network capacity issues, disturbance of the medium and others. These issues can deteriorate the performance of such systems to an extent that can brings in instability into the system therefore these issues must be addressed to utilize the benefits of NCS.

Here the network related issues is kept limited to network induced delay for the sake of simplicity and limited knowledge of communication technology.

The speed control of induction motors has been playing a key role in the power industry. Employing network control system for industrial control of induction motors makes it more sizeable and attractive. The corrigendum of this research is to control the motor speed when the time delay arises in the network medium.The network delay letdowns the control action of the controller.

The network time delay is stochastic in nature. Designing an altogether distinct controller for network is time-consuming and costly. Therefore, in this thesis we propose to utilize the existing controller in a networked environment through gain middleware design. Gain middleware design not only simplifies the controller design but also saves time and cost.

Time delay is estimated using time delay observer. The control system employed using proportional integral (PI) controller together with gain middleware to resolve the issue of network induced delay. The methodology suggested here demonstrates satisfactory performance while handling the network induced delays.

List of Symbols

F	supply frequency in Hertz
ia, ib, ic	stator phase (a, b, c) currents
ids, vds	d-axis stator current and d-axis stator voltage respectively
idr, vdr	d-axis rotor current and d-axis rotor voltage respectively
iqs, vqs	q-axis stator current and q-axis voltage respectively
iqr, vqr	q-axis rotor current and q-axis rotor voltage respectively
Te	electrical torque (in Nm)
Tl	load torque (in Nm)
wr	speed of rotor (in rad/sec)
ws	synchronous speed (in rad/sec) ; ws=2*pi*F
J	inertia of motor in Nm
N	number of poles
P	number of poles pairs
Rs	resistance of stator (in ohms/phase)
Rr	resistance of rotor (in ohms/phase)
Ls	per phase inductance of stator
Lr	per phase inductance of rotor
Lm	per phase mutual inductance
Kp	Proportional gain of PI controller
Ki	Integral gain of the PI controller

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Chapter 1

Introduction to Network Control System

1.1 Introduction

For the past few decades, Networked Control Systems (NCSs) have been intensely concentrated for research by both academics and industrial worlds.

The advent of communication network has given rise to the concept of controlling remotely through Network Control System. In Networked Control System (NCS), the control loops are closed by means of a communication network [1]. The sensors measure the process value from the plant. This data is sent to the controller located at remote location through communication link. The controller receives the data sent by the sensors. The controller manipulates and process the data to calculate the control action to be sent back to actuators located at plant. This saves the cost of cabling and offers flexibility to make changes in the system design easily.

Point to point control system connects all element of the system (including sensor, actuator, and controller) with the help of a dedicated wire as shown in Fig.1.1 [2]. It is not reliable and reasonable to employ point to point architecture for Multiple Input Multiple Output (MIMO) system as it upturns the cost of installation and maintenance [3].

Also, point to point control system is not feasible as all the system components needs to be re-wired to implement reconfiguration. Such systems are devoid of benefits like reliability and interchangeability which are an emerging needs of modern control system [4]. Also, the remote network control technology is the only solution for systems like spacecraft, tracking system for missiles or risky zones such as nuclear power plants.

Network Control System overcomes such shortcomings of the conventional point to point control systems, such as susceptibility to electrical noise and inconvenience of amendment and maintenance.

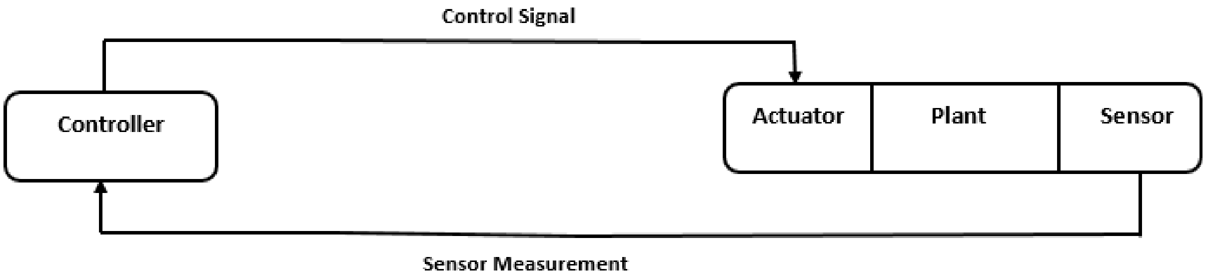

Figure 1.1 Conventional Control System

1.2 Elements of Network Control System

Network Control System consists of five basic elements:

- Plant-any system to be controlled
- Sensor- to acquire information from plant
- Controller- to generate signal required for control operation
- Actuator- responds the control command by performing mechanical operation
- Communication network- to enable exchange of information between controller and plant

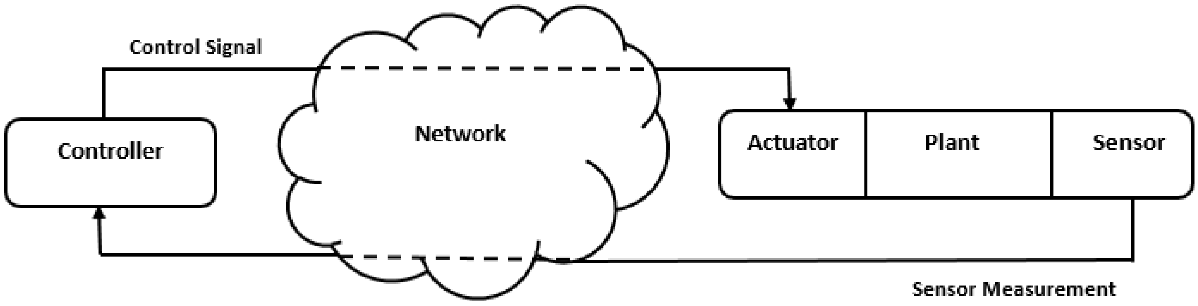

Figure 1.2 Network Control System

1.3 Types of NCS Architecture

The two types of NCS configurations are listed below:

1.3.1 Direct Structure of NCS

For this configuration, the controller and the plant are positioned at different physical locations. The control action is performed remotely through network.

The control signal and the sensor measurement are delivered in the form of packets or frame. The control signal is captured in a packet and sent to actuator via network. The actuator performs the operation. The sensor measurement is returned back to controller through network in the form of packet.

Speed Control for a DC motor & distance learning lab are some instances of direct configuration of NCS [5].

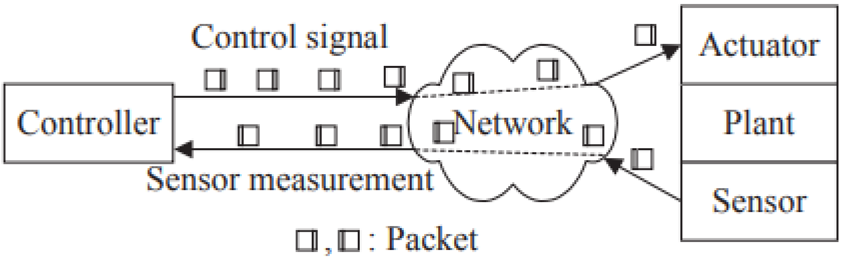

Figure 1.3 Direct Structure of NCS [5]

1.3.2 Hierarchical Structure of NCS

The hierarchical configuration consists of two controllers; main controller and a remote controller. The remote controller is placed with the plant.

The main controller calculates and generates the reference signal in the form of packets or frames through network on periodic basis. The remote controller receives the signal from main controller and performs closed loop control locally. The sensor measurement is then packed in network packets and sent to main controller. This cycle is repeated periodically throughout the operation.

Hierarchical configuration can be utilized in mobile robot control as mentioned by Tipsuwan & Chow and teleoperation.

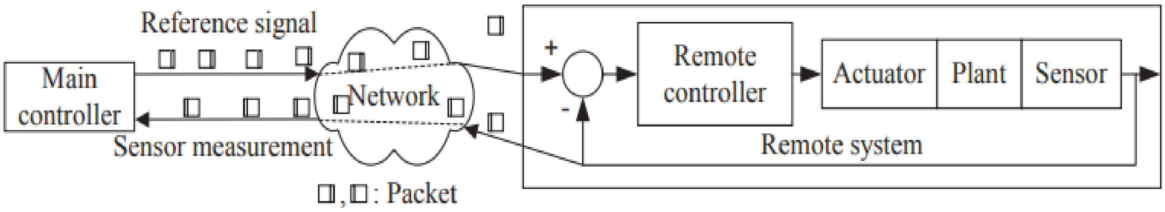

Figure 1.4   Hierarchical Structure of NCS[5]

The choice of NCS architecture depends on the type of system to be controlled and preferences of the control designer.

For example, for remote mobile robot, a number of motors needs to be rotated simultaneously at the robot joint, this makes hierarchical configuration most suitable for this application to control several motors efficiently.

On the other hand, we require faster response for speed control of networked DC motor therefore we prefer to use direct NCS architecture for this as suggested by Tipsuwan & Chow.

1.4 Advantages of Network Control System

NCS has been extensively used in various fields due to numerous reasons. A network control system has many advantages such as low cost, less wiring, decentralized control, remote operation, simpler installation, easier maintenance and so on.

Controlling of the control system components over network lessens the control system complexity with minimal economical contribution. NCS reduces the complication of the system by reducing the hardware requirement, this facilitates to update changes in the system with minimum cost thus making it viable for the users.

The main advantage of NCS is that it allows remote operation of the system and enable execution of tasks from long distance. The allowance of the data through network controllers would make it easy to gather the global information and would help it to take the correct decisions over a wide physical space.

Due to flexibility and numerous benefits offered by NCS over traditional wired communication network they are more acceptable in the growing industry.

1.5 Applications of NCS

The global trend of Internet has inspired to explore it further in the arena of Network Control Systems. The usage of NCS varies from large scale automations such as automation of factory and monitoring of plant to smaller yet challenging applications such as autonomous robots and smart cars.

Network Control System offers diversified prospects in numerous different capacities like remote surgery, intelligent energy management system for the buildings, smart transportation management systems, automated control of energy plants and water distribution networks to name a few.

Network Control System can be used to monitor and manage transportation system intelligently by keeping the driver updated regarding traffic conditions ahead and helps to track traffic overcrowding across the network[7].

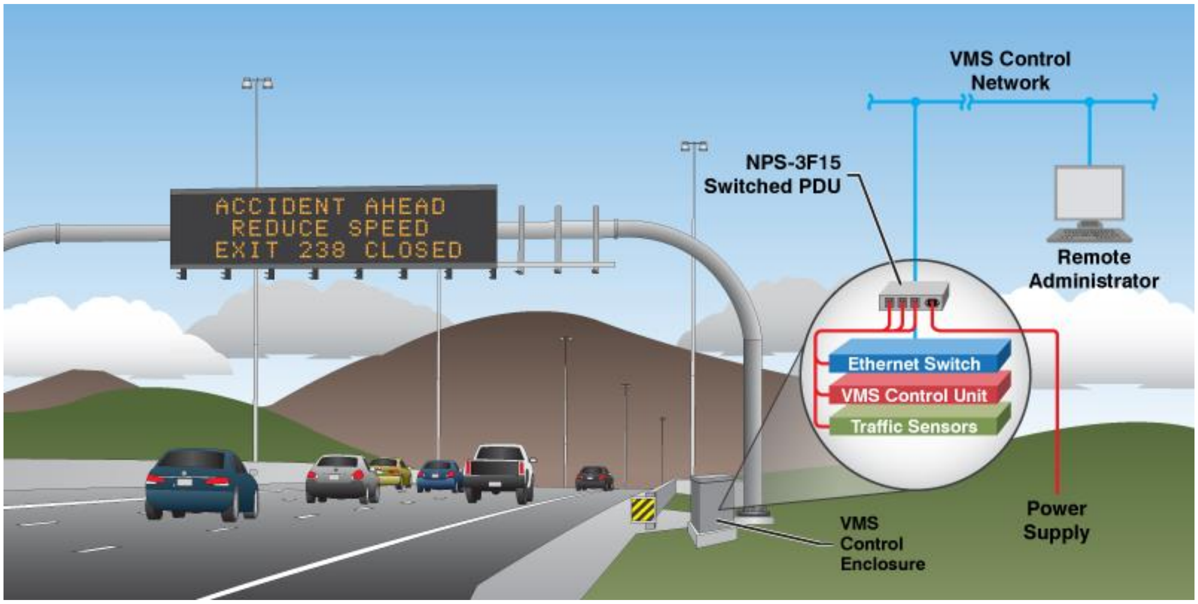

Figure 1.5 Intelligent Transportation System through NCS [7]

Another astounding application of Network Control System is telesurgery. The surgeon is at one location and performs a surgery at a different location with the aid of a robot[8].

Figure 1.6 Remote Robotic Surgery[8]

Network Control Systems are used for remote control at hazardous and inconvenient locations such as space, war zone, offshore wind turbines, chemical and nuclear plants.

Distance Learning can also be practiced through NCS technology by developing virtual and remote control lab for remote experimentation.

1.6 Fundamental Issues of NCS

Although NCS allows to achieve more complicated tasks efficiently, however it brings the cost making the design phase more complex and the obligation of sophisticated analysis tools. Network Control System brings in a number of problems due to its limitation of bandwidth. For example: the communication network may suffer due to time varying delays, information loss due to packet missing, flawed information exchange due to corrupted packets etc.

The above-mentioned side effects of the network highly affect the control law performance in the presence of network. Therefore, it is utmost importance to address these issues to utilize the benefits of Network Control System technology.

The network control system must be made robust enough to deal with negative effects of the network by characterizing stability conditions for these systems and minimizing the quantum of information to be exchanged over network.

NCS is a cross-functional subject converging the concepts of control system theory, communication networks and computer technology. NCS requires large amount of data to be processed with limited resources This makes it challenging to design network control systems that are robust to deal with communication constraints like random time delay, limited bandwidth and packet loss or missing.

This makes NCS different from traditional control systems. NCS offers many benefits in comparison to traditional control system, however network induced delay and other network constraints of communication network degrades the performances of closed loop control systems over network.

1.7 Network Time Delay

In Network Control System, different nodes such as sensor, actuator and controller must use network to exchange the data to complete the control tasks.

Due to bandwidth limitation of the communication network, the signals transmitted over network faces unreliable performance of the network medium.

The delay caused by the network communication is called network-induced delay. There are basically three sources of delays:

- T_{sc} i.e. delay from sensor to the controller,
- T_{ca}, i.e. delay from the controller to the actuator and
- Tc, delay due to computations required by the controller

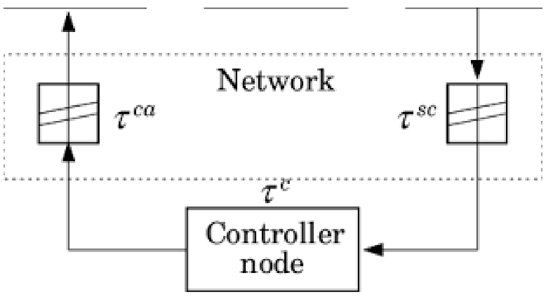

Figure 1.7 Control Systems in the Presence of Network Induced Delays [9]

Sensor to Controller Time Delay (Tsc) can be measured by calculating the difference between the time when the data from sensor is available at the controller to be used and the time when the data is sent from the sensor.

Controller to Actuator Time Delay (Tca) can be measured by calculating the difference between the time when the control command was sent from the controller and the time when the control command reaches the actuator.

Computational Delay (T_c) is the time taken by the controller to process and generate the control signals.

The timing diagram of the signals to and from the plant and controller in a networked diagram is as follows:

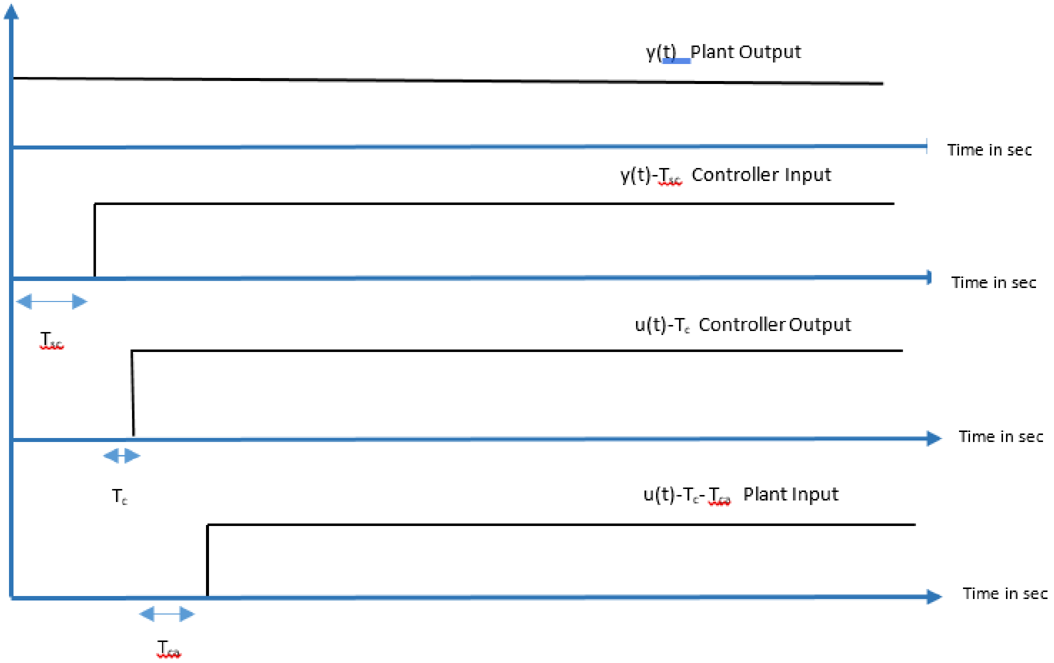

Figure 1.8 Timing Diagram of Network Control System

The computational delay is negligible and can be merged with controller to actuator delay.

Total Network Delay = $T_{sc} + T_{ca}$

In order to main stability of the system, the maximum time period between two consecutive signal transmissions must be smaller than the maximum limit of time interval allowed, that is known as Maximum Allowable Transfer Interval (MATI).

1.7.1 Modelling of Network Time Delay

To analyze the network control system, network time delay has to be modelled in control loop. This Network Delay is stochastic in nature and varies as per the network condition due to scheduling policies in the network medium and the network nodes and discrepancy in network load.

Network time delay can be constant or time-varying. The simplest method for modelling network delay is to model the delay as a constant delay. For time-varying delay we can assume time delay to vary slowly such that the constant time delay model can be used for time varying delay.

1.7.2 Time Delay Estimation In NCS

The most convenient way to estimate time delay is by round trip time (RTT) delay estimation [6]. Round Trip Time delay is the time taken by the signal to be transmitted from a specified point to a specified target and then back to the initial point again.

In NCS terminology, the starting point or computer that transmits the signal is called source and the end point or computer at remote location that receives the signal sent by the source is called destination.

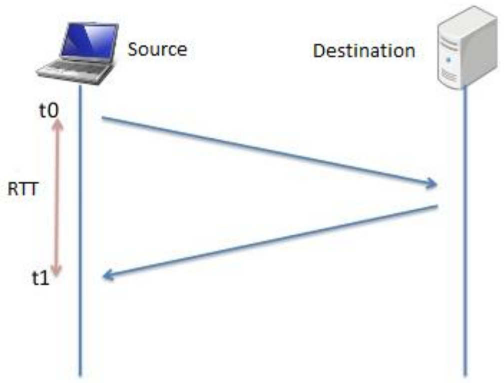

Figure 1.9 Round Trip Time (RTT) Delay

On the internet, Round Trip Time can be assessed by pinging the IP address. The ping command-line reflects back a request on a server and calculates the time taken by the ping to reach back the user device. Real Round Trip Time may be greater than that calculated by pinging due to server throttling and network congestion.

Some of the factors affecting the Round-Trip Time through network are mentioned below:

- the distance between source and destination
- types of transmission medium used
- transfer rate of network data
- network traffic
- the number of nodes between source and destination
- external interference or noises

1.8 Focus of Research

In spite of several advantages offered by network control system, the performance of a control system deteriorates in the presence of network-induced delays. In this study, the key objective is to improve the control system performance over network by suggesting a methodology to compensate the adverse effects of the time delay induced over network.

1.9 Thesis Organization

The following presents the outline of the work in details.

Chapter 1: This chapter gives an overview explanation of Network Control System. It discusses the benefits and fundamental challenges of Network Control System.

Chapter 2: Network Control System has been the area of attention and focus by many researchers. This chapter highlights the research carried out on the subject in the literature.

Chapter 3: This chapter represents the dynamic model of Induction Motor and defines the control strategy for speed control of the motor in a non-networked environment.

Chapter 4: This chapter describes the modelling and control of Induction Motor in a networked environment

Chapter 5: This chapter summarize the simulations carried out in this thesis and results of the research.

Chapter 6: This chapter concludes the thesis.

Chapter 2

2 Literature Review

Several researchers have addressed the nature of issues associated with Network Control System and their possible solutions.

These techniques can be clustered into following three sets:

i. Control Approaches: This method involves the controller to be designed for a given network by taking into account the uncertainty due to network and non-deterministic behaviour to satisfy the system performance requirements.
ii. Scheduling Approaches: This technique implicates the controller to be designed for a non-networked system first. Next, a scheduling algorithm is implemented to diminish the contrary network effects.
iii. Scheduling And Controller Co- Design Approaches: For this class, Quality of Services (QOS) is achieved through scheduling technique. At the same time, the controller is designed to reach the desired system performance, while taking into account the limitations of the network.

In this chapter, we have reviewed some of the major literature work which involves the ways and means of controlling over network while compensating the time delay induced due to network.

Walsh employed the theory of perturbation for modelling the network time delay as perturbation and nonlinear control is applied for realizing the performance requirements. [10].

Y. Tipsuwan & M.-Y. Chow proposes a new technique for networked control system for DC motor [11]. As QoS requirements of a network may change due to time varying network conditions. The controller gains can be attuned by the end user to reach the best possible closed loop performance in the presence of time-varying QoS. As per the changing network QoS, the controller gains are proactively adjusted by using cost function methodology.

A. Ray & R. Luck proposed the employment of buffers to minimize the effects of time-varying network time delay [12]. The observer-based approach is proposed for estimating overdue states then state transition matrix is used to envisage the present state. The algorithm is tested for controlling the velocity of a DC servomotor in real time. However, this approach has two main checks:

i. The sensor-to-controller and controller-to actuator delay is treated as a constant and known sum , t
ii. The synchronization of sampling instants of the controller and the sensor.

H. Chan and U. Ozguner also used the buffers by exploiting data of the queue length to predict no-delay state values [13]. Since it is not feasible to obtain the exact value of the delay, the information of the queue length is utilized. It is assumed that whenever the sensor sends packet through the communication network, it includes the knowledge regarding the existing amount of data present in the queue appended to the data. This information is known and is shared every time the sensor data is sent to the controller.

B. Wittenmark, J. Nilsson & B. Bernhardsson framed the network time delay effects as a problem from Linear-Quadratic-Gaussian (LQG) domain and proposed a new approach based on optimal stochastic control [14]. The probability distribution of the time delays is presumed to be identified. The signals from sensor and controller are time-stamped with the time of signal generation such that the controller can find knowledge of former time delays. This approach is unable to handle control delay larger than the sampling interval as the order of the samples arriving at the controller and the plant actuator are not assured.

The scheduling algorithm introduced by S. H. Hong improved the utilization of network resources as well as satisfies the performance requirement of integrated communication and control system [15]. Large sampling time obtained by this method guarantees the stability of networked control system.

These algorithms make lots of assumptions that might not be appropriate for application in the real world.

M.-Y. Chow & Y. Tipsuwan introduced gain scheduling middleware to utilize the in effect non-networked controller for network control systems [16]. This saves the cost and inconvenience of controller replacement. The output of the present controller is amended based on the algorithm of gain scheduling according to existing network traffic scenario. The next part of this paper mentions the possibility of teleoperation of mobile robot through gain scheduling algorithm[17].

Chapter 3

3 Dynamic Modelling of Induction Motor for Speed Control

3.1 Introduction

The control design require effective modeling the dynamics of the controlled system in particular. The mathematical model of an electric machine signifies all equations that define the core electrical and mechanical quantities.

There are two main approaches for modelling the induction motor: phase coordinate model and orthogonal (dq) model [18]. The equations of phase coordinate model include mutual inductances of stator and rotor with values that vary as per the position of the rotor which causes the model to become non-linear hence complicated for the research.

While equations of orthogonal (dq) model are independent of rotor position. For designing a control system, it is required to have system quantities as dc quantities even though the real variables are sinusoidal in nature. As the reference frame of dq model is rotating at an angular speed as that of sinusoidal variable, then the degree of difference between speeds is equal to zero which causes the sinusoid being observed as dc signal with respect to reference frame. This simplifies the machine model and makes it more convenient for analysis and control design.

Therefore here, the induction motor is modelled in direct and quadrature axes to study the dynamic behaviour of the motor. We have used rotor reference frame model where rotor speed is used as the angular speed of the reference frame. This type of reference frame is particularly suitable where power the switching elements are controlled on the side of rotor. Also the d-axis rotor current acts closely as the phase A rotor current when rotor reference frame is used. This saves the time to calculate phase a rotor current at every stage of digital integration. Hence the rotor reference frame is most suitable when one need to study the quantities in rotor side [2].

3.2 Model Assumptions

Following assumptions are needed for the model:

i. Air gap is uniform
ii. Inductor vs rotor position is sinudoidal

iii. Rotor and stator windings are balanced with sinusoidally distributed mmf
iv. Saturation and changes in parameters are neglected; and
v. Hysteresis and eddy current losses and skin effects are neglected.

3.3 Mathematical Equations of Motor

The model of Induction motor is represented in rotor reference frame. The induction motor basic equations and dynamic model that are used here are mainly inspired from the book R. Krishan, “Electric motor drives: Modelling, analysis and control [2]. The terminal voltage of stator and rotor winding can be represented as the sum of voltage drop in the resistances and inductances of the windings.

$$\begin{pmatrix} vqs \\ vds \\ vqr \\ vdr \end{pmatrix} = \begin{pmatrix} Rs + Lsp & wrLs & Lmp & wrLm \\ -wrLs & Rs + Lsp & -wrLm & Lmp \\ Lmp & 0 & Rr + Lrp & 0 \\ 0 & Lmp & 0 & Rr + Lrp \end{pmatrix} \begin{pmatrix} iqs \\ ids \\ iqr \\ idr \end{pmatrix} \text{.......(1)}$$

Where p represents differential operator d/dt

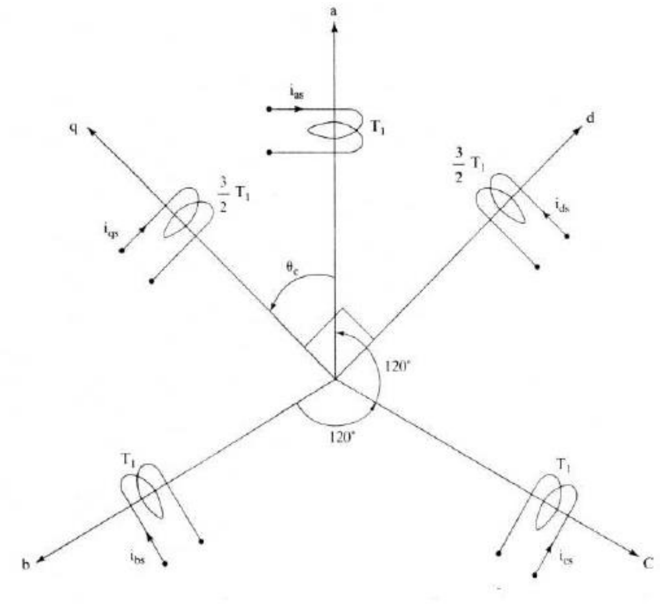

Figure 3.1 Two Phase and Three Phase Winding [19]

Squirrel cage induction motor is used and its rotor windings are short circuited therefore

Vdr=0 also Vqr=0

The mechanical equations of the motor are given as:

$Te = \frac{3}{2}\frac{N}{2}\ Lm(iqsidr - idsiqr)$ …….(2)

$\frac{dwr}{dt} = \frac{1}{J}(Te - Tl)$ …….(3)

Machine load is chosen as:

Tl= $3+31.5*10^{6}* w^{2}$…….(4)

3.3.1 MATLAB/SIMULNK Implementation:

The simulation presented here takes into study the following parameters of an induction motor:

Parameters	Symbols	Values
Supply Frequency	F	60 Hz
Motor Inertia	J	0.03 Nm
Number of Pole Pairs	P	1
Synchronous Speed	Ws	404 rad/sec
Resistance of Stator	Rs	0.15 Ω
Resistance of Rotor	Rr	0.15 Ω
Inductance of Stator	Ls	0.0469 H
Inductance of Rotor	Lr	0.0485 H
Mutual Inductance	Lm	0.045 H

Table 1 Parameters of Three Phase Induction Motor

The MATLAB block diagram is presented as follows:

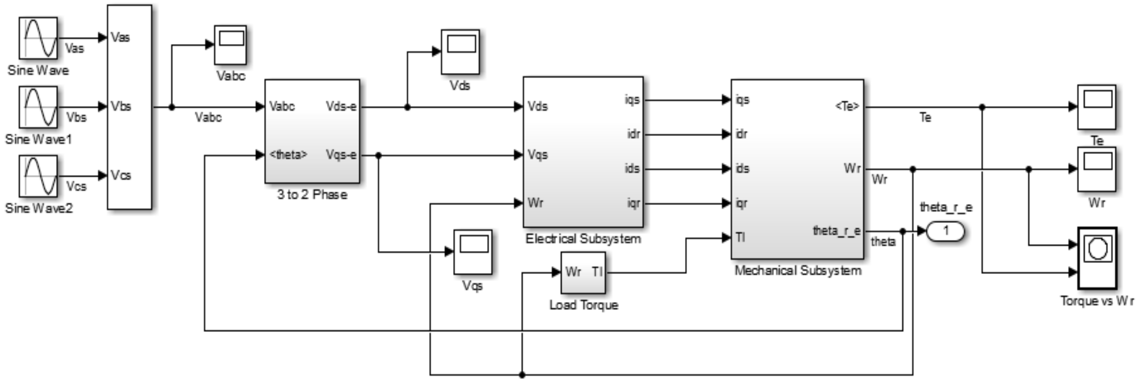

Figure 3.2 Three Phase Induction Motor MATLAB/Simulink Model

Three phase AC input voltage and load torque are applied as inputs to the induction motor. On the other hand, three phase AC output voltage, rotor speed and electrical torque are captured as outputs of the induction motor.

First, Clarke and Park transformation is applied to transform three phase stator voltages into two phase dq voltages.The Clarke's transformation was developed by E. Clarke where abc three phase signals are transformed to a two phase stationary reference frame αβ. The stationary two-phase α-axis and β-axis are orthogonal.

The Clarke's transformation is given by the following equations:

$$V\alpha = Va$$

$$V\beta = \frac{2\,Vb + Va}{\sqrt{3}}$$

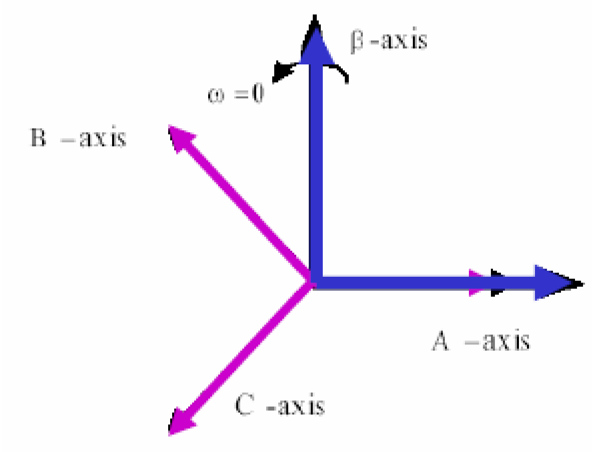

Figure 3.3 Clarke's Transformation

The two phase stationary reference frame is converted into two phase rotating reference frame by Parks's Transformation given by the following equations:

$$\begin{bmatrix} Vd \\ Vq \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} V\alpha \\ V\beta \end{bmatrix}$$

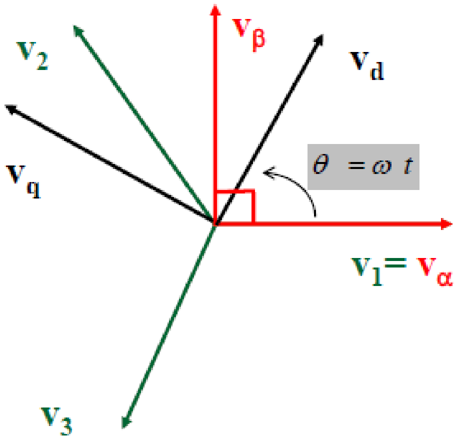

Figure 3.4 Park's Transformation

The electrical and mechanical equations are then implemented as given from eq(1) to eq(4) in the previous section.

The electrical and mechanical equations of the machine are modeled by the following blocks:

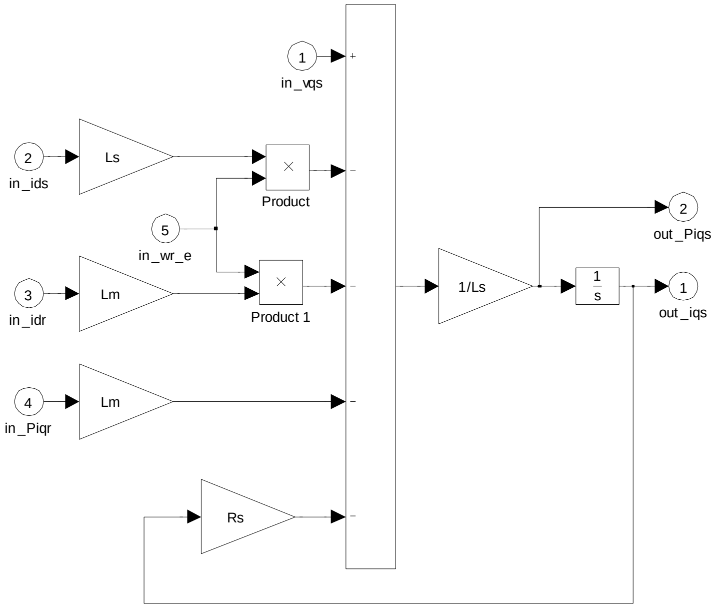

Figure 3.5 Block Diagram for iqs

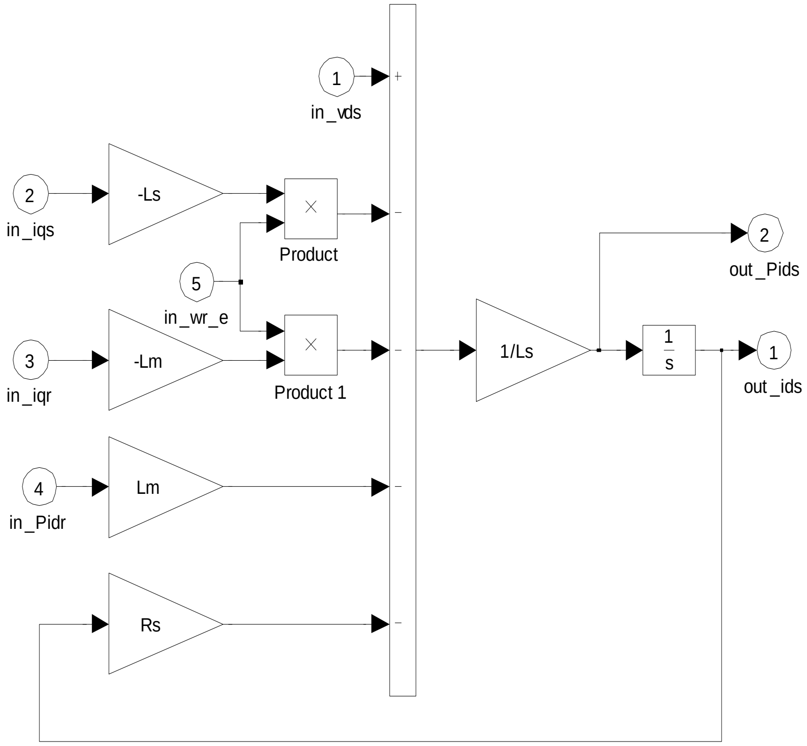

Figure 3.6   Block Diagram for ids

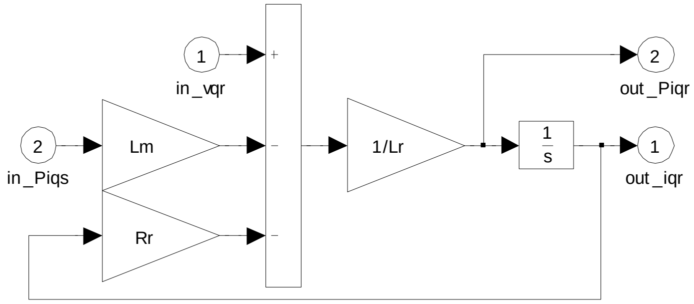

Figure 3.7 Block Diagram for iqr

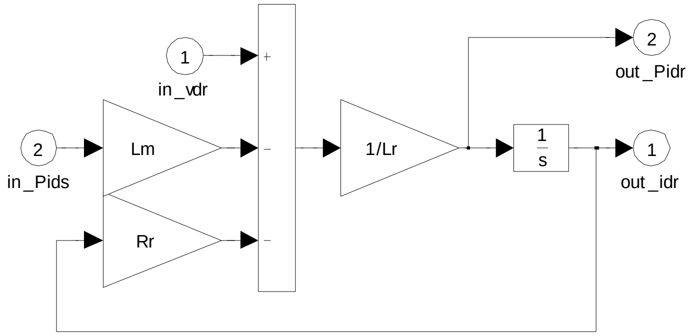

Figure 3.8 Block Diagram for iqr

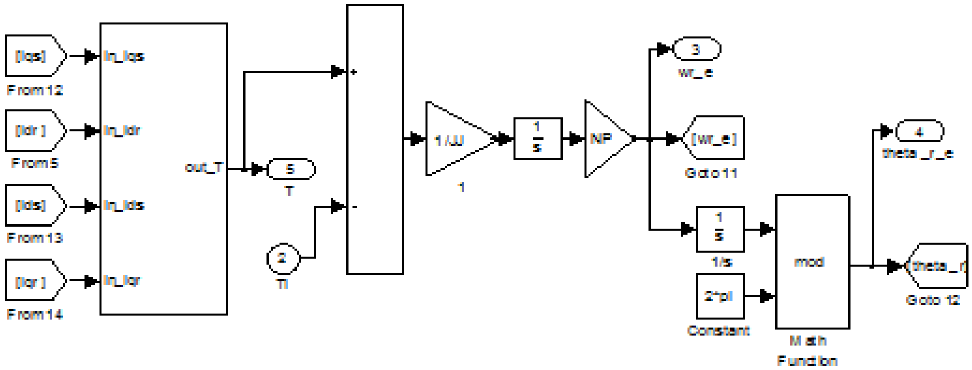

Figure 3.9 Block Diagram for Mechanical Equations

The torque equation is presented in the next figure:

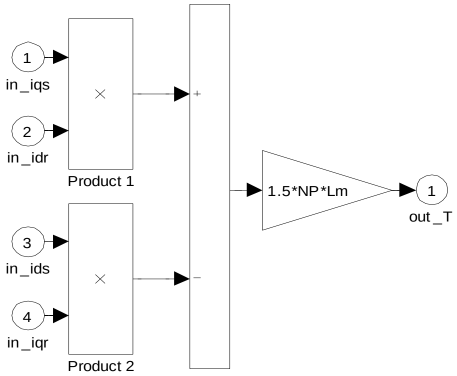

Figure 3.10   Block Diagram for Torque

The simulation results can be visualized by the graphs given below:

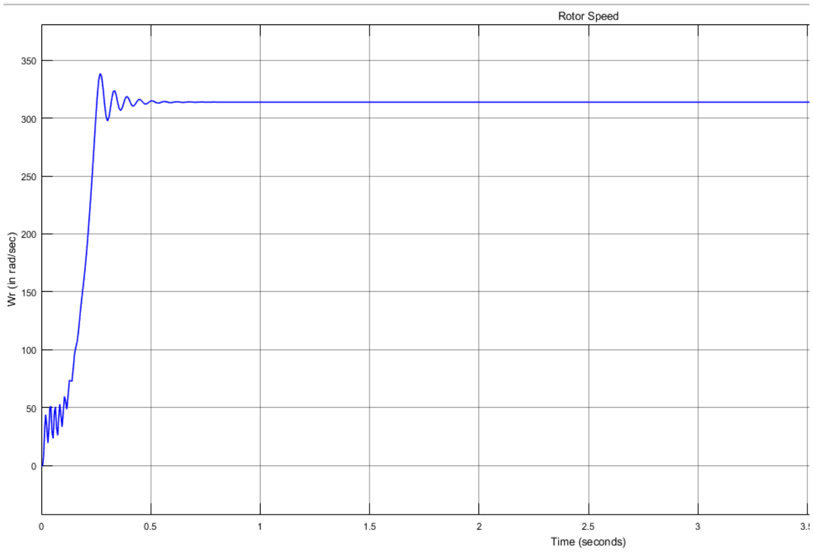

Figure 3.11 Open Loop Response for Rotor Speed

The machine reaches the steady state speed of 314 rad/sec which is equal to 2*pi*f where f is electrical frequency applied (chosen to be equal to 50 Hz).

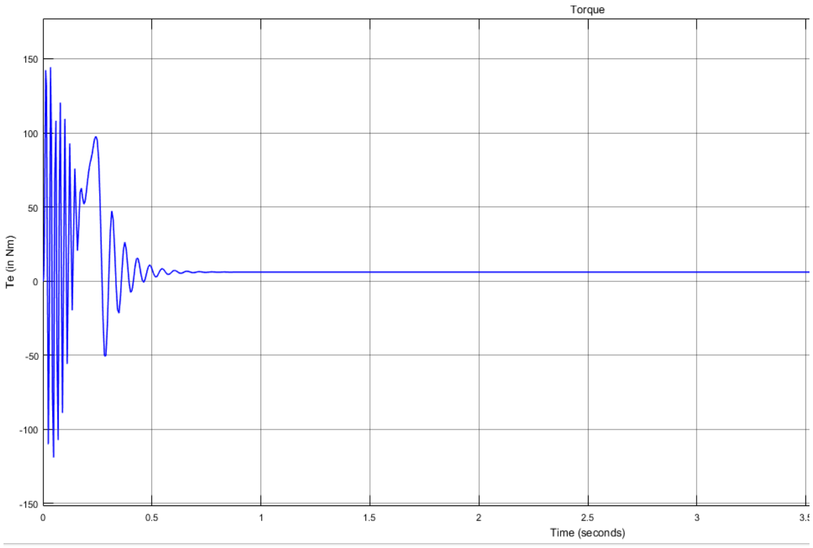

Figure 3.12 Open Loop Response for Torque

The torque oscillates at the beginning, this is due to that the rotor field is not yet created and it will require three rotor constant times to establish it. After the field is build the torque goes smooth.

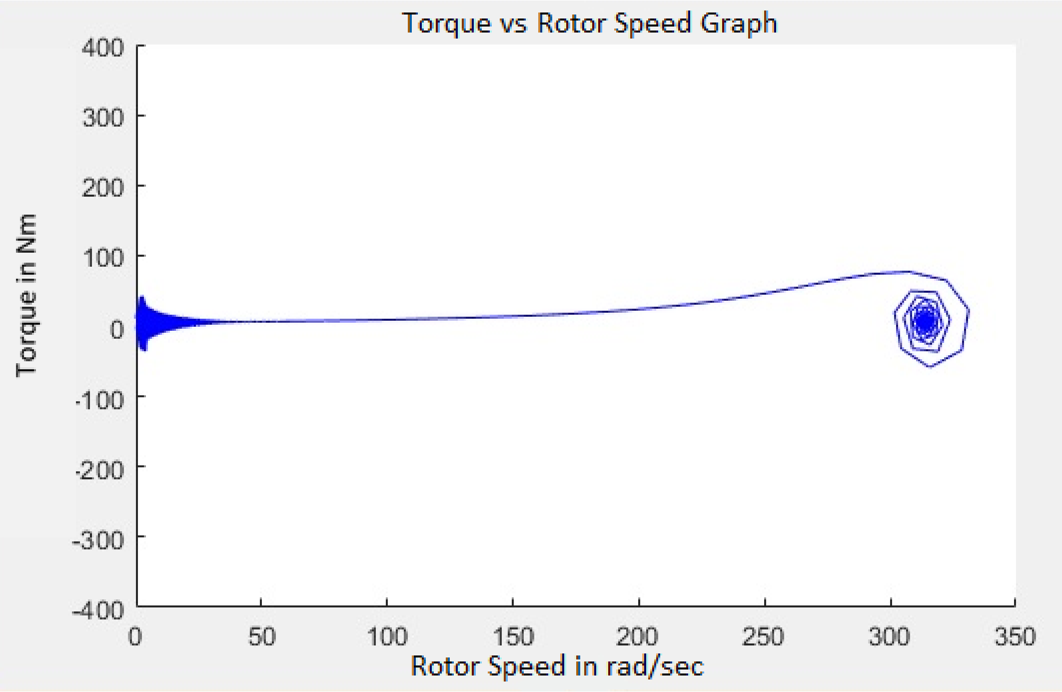

Figure 3.13 Torque vs Rotor Speed Graph (Open Loop Response)

3.4 Field Oriented Control (FOC) for Motor Speed Control:

Decoupled torque and flux are needed for controlling electric drive with high performance. This opportunity is provided by Field Oriented Control (FOC). FOC scheme involves coordinate transformations and current controllers. FOC converts the current into two components: torque-producing current component iq and the flux-producing component id.

There are two types of FOC:

3.4.1 Direct FOC

Using direct FOC, rotor flux vector is obtained by mounting a flux sensor in air gap or it can be calculated using terminal voltage and current.

3.4.2 Indirect FOC

Using indirect FOC, the rotor position is derived using speed feedback signal from rotor. This method eradicates most of the glitches related with flux sensors as they are absent. It provides independent control of flux and torque and control characteristics are linearized analogous to DC motor.

Here we have used indirect field oriented control.

3.5 Field Observer Design

The subsequent stage is to design a field observer. The field observer design ensures robust regulation and estimates electrical parameters that defines the motor performance. In order to get the currents in the flux field of reference, imr and ρ are calculated through field observer.

The implementation of the rotor flux FOC needs information of the space angle i.e. position and modulus of the rotor flux-linkage space phasor which can be obtained by implementing the following equations.

$$Tr * \frac{\partial imr}{\partial t} + imr = ids \qquad \frac{\partial \rho}{\partial t} = wr + \frac{iqs}{Tr * imr} \qquad Tr = \frac{Lr}{Rr}$$

Where

imr = magnetizing rotor current

Tr = rotor constant

ρ=instantaneous position of the rotor flux with respect to stator axis

This eliminates the necessity of flux sensor thus eliminates the issues associated with those sensors.

The block diagram of field observer is given below:

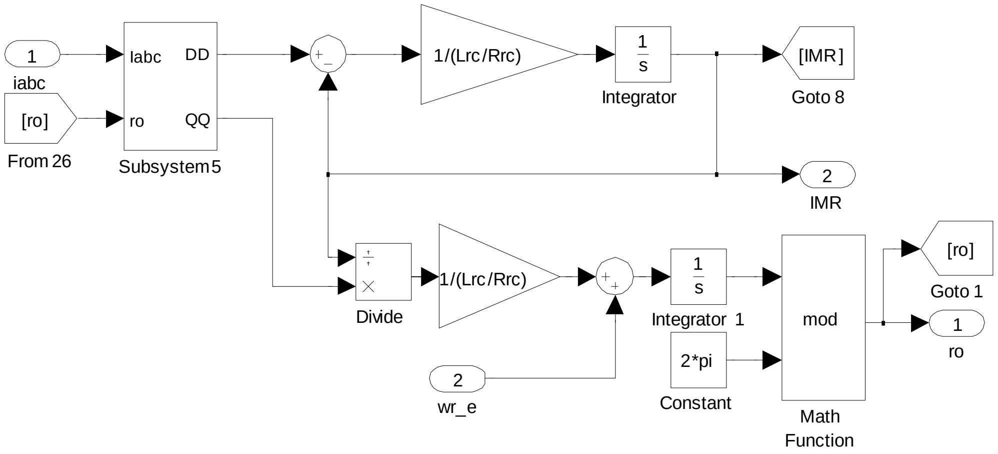

Figure 3.14 Block Diagram for Field Observer

3.6 Field Controller

The speed of induction motor is controlled through Proportional Integral (PI) controller.

Proportional Integral is the most frequently used feedback controller. It calculates the difference between the measured value of the variable and the desired reference variable. This difference also called the “error” value. The PI control action minimizes this error value by regulating the control inputs of the process.

If y(t) is the output of the controller, the output equation of PI algorithm is given as:

$$y(t) = Kp.e(t) + Ki\int_0^t e(t)dt$$

Where

y(t) is the controller output

e(t) is the calculated error signal

Kp is the propotional gain, a tuning parameter

Ki is the integral gain, a tuning parameter

t=time

The error signal is calculated as:

$$e(t) = \ u(t) - r(t)$$

Where u (t) is the measured value of the process variable

r(t) is the set reference value of the process variable

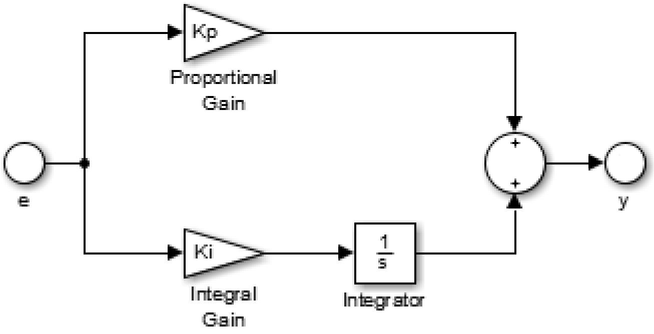

Figure 3.15 Proportional Integral Controller

The stator currents are transformed into two components, the flux producing component along d-axis and torque producing component along q- axis using d-q coordinate transformation.Here we design controller for both components.

For the torque controller (Wr) controller, the selected values are Kp=1 and Ki=3.

The Speed command is delayed by 1.5 seconds (3 rotor time constants Lr/Rr) respect to the field command (Imr) so the rotor field is established by this time.

For the field controller (Imr), the selected values are Kp=20 and Ki=2.

The gains of the voltage controller which is located in the inverter were chosen Kp=500 and Ki=20.

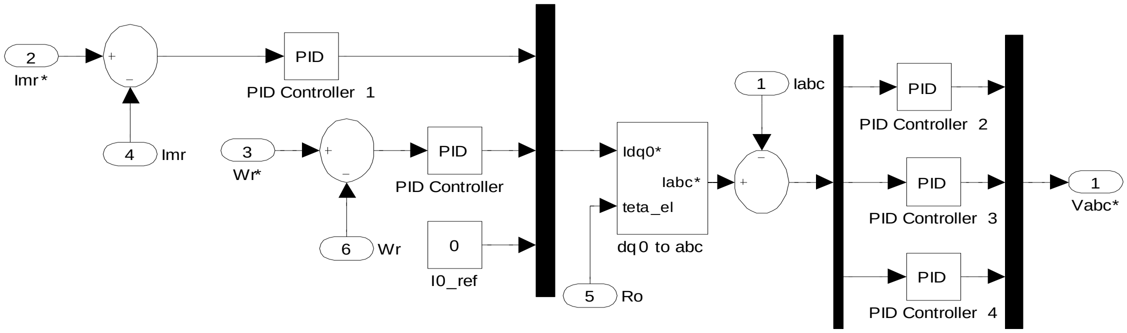

Figure 3.16 Field Controller Block Diagram

The above figure shows the Simulink implementation of the field controller. Also the speed controller for the induction motor is designed with the help of Indirect Field Oriented Control technique as modelled by the succeeding block diagram:

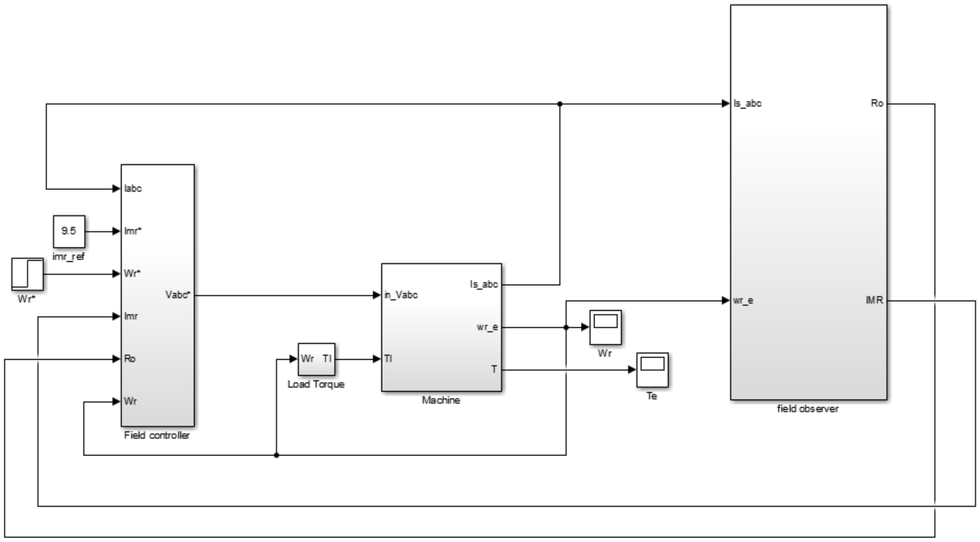

Figure 3.17 Field Oriented Control Block Diagram

The simulation results are as given below:

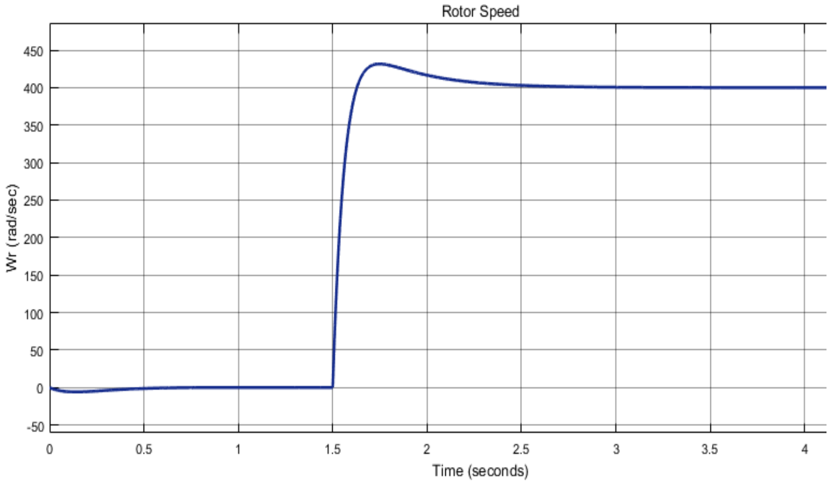

Figure 3.18 Closed Loop Response for Rotor Speed

The motor was given a reference speed of 400 rad/sec and the numerical simulation confirms the feasibility of the design.

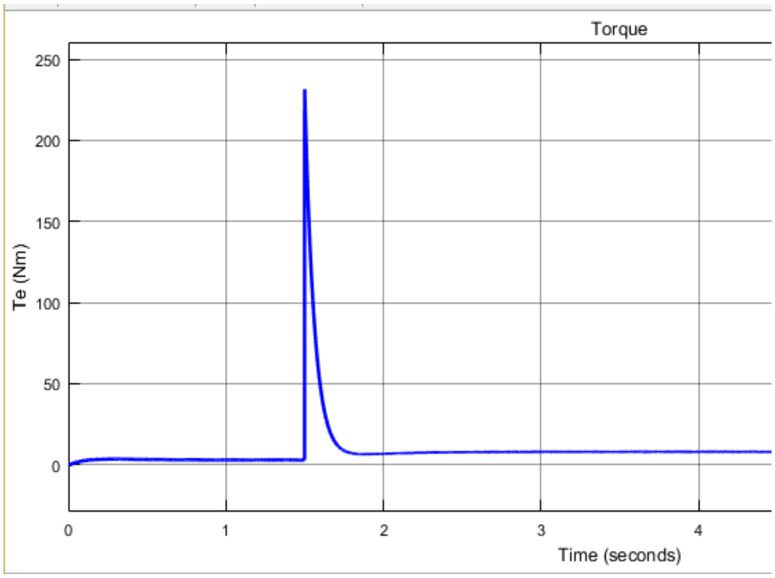

Figure 3.19 Closed Loop Response for Torque

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Chapter 4

4 Modelling and Control of Networked Induction Motor

4.1 Problem Statement

Network induced delays destabilize the system and results in performance degradation. Therefore we need to design a control scheme to control the speed of the motor in a networked environment and an appropriate algorithm will be applied to guard the robustness of the system against the network induced delay.

4.2 Model Assumptions

i. Time driven sensor
ii. Event driven actuator
iii. Event driven controller
iv. No computational delay of the controller
v. No data loss due to network transfer
vi. Sensor to controller delay Tsc & controller to actuator delay Tca are equal
vii. Network-induced time delay varies slowly with time

4.3 Network Control System Modelling Approach

Network Control System can be modelled in either continuous or discrete time domain. We have opted for continuous time modelling approach. The foremost benefit of continuous time modeling approach is the option to incorporate time-delays larger than the sampling period without causing complexity of the model.

4.4 What is Middleware?

The term middleware has been around for some time, middleware is used in a large number of systems executing behind the scenes, helping as a linkage between two systems that need to communicate but can’t communicate directly due to some reason.

Middleware technology would take an incoming signal, process it and then send it to another system in a format that is understood by the second entity.

4.5 Gain Middleware Design for NCS

The gain middleware serves as the linkage between two applications. The output of the controller is adapted through gain scheduling mechanism.

System dynamics of the remote system to be controlled are given as:

$$\dot{x} = f(x, u, p_x, q)$$

$$y = h(x, u, p_x)$$

Controller rule for the system is:

$$c = g(y, \gamma p_u)$$

where

x= state variable of the remote system

y= output of the remote system

c= output of the controller

p_x=parameters of remote system

p_u=parameters of controller

γ= adjustable gain

q= network variable representing network traffic conditions

To compensate the effects of network induced delays, p_u needs to be adapted externally by finding the external gain β such that:

$$\beta u = \beta g(y, p_u) \cong g(y, \gamma p_u)$$

A relation between β and γ is complicated to find. Therefore, we will gather simulation data then apply a look-up table.

The gain scheduler middleware basically consists of three components:

- Network Traffic Estimator – monitors and approximates the existing network traffic condition q

- Feedback Pre-processor – pre-processes data such as noise filtering and predicting remote system states
- Gain Scheduler- adjusts the output of controller according to network traffic condition q

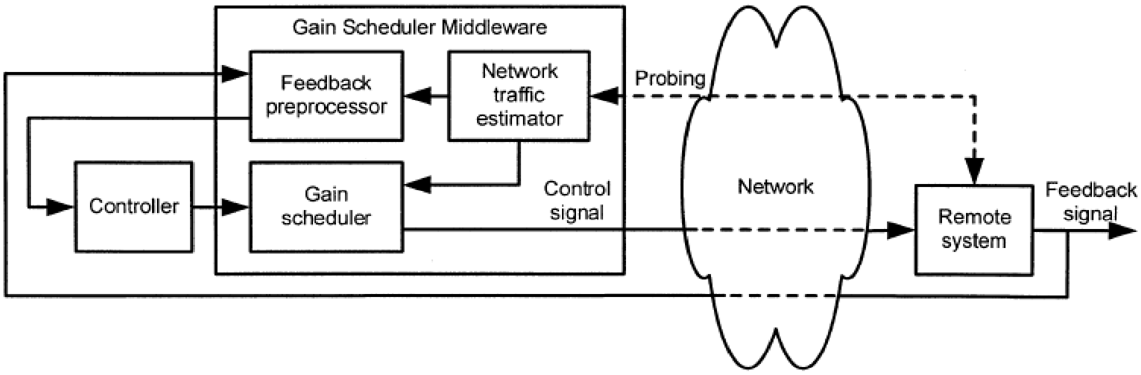

Figure 4.1 Gain Scheduler Middleware Design [16]

With the addition of network time delay, the existing controller gains do not satisfy the performance requirement. The performance of the system deteriorates also it may cause the system to turn out to be unstable. To maintain the best possible performance, these gains need to be adjusted as per the network conditions. For this we add an external gain β (such that $\beta>0$) which acts as a factor of multiplication to adjust the gains of controller such that the same controller can be used for different network conditions.

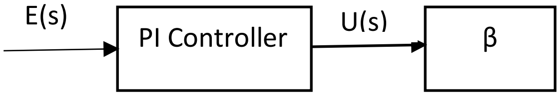

Figure 4.2 Gain Middleware Design

We design two gain middle-wares each for flux producing component, i_d and torque producing component, i_q. The gain β has to be optimized for both middle-wares individually. To optimize β, we define a cost function:

$J = w_1J_1 + w_2J_2 + w_3J_3$

$J_1 = (MSR-MSR_0)^2 \qquad MSR > MSR_0$

$J_1 = 0 \qquad MSR \leq MSR_0$

$J_2 = (P.O-P.O_0)^2$ $PO > PO_0$

$J_2 = 0$ $PO \leq PO_0$

$J_3 = (t_r - t_{r0})^2$ $t_r > t_{r0}$

$J_3 = 0$ $t_r \leq t_{r0}$

Where w_1, w_2 and w_3 are weights used to specify the implication of cost functions J_1, J_2 and J_3 relative to each other.

MSR is mean square error,

MSR_0 is nominal mean square error,

PO is percent overshoot,

PO_0 is nominal percent overshoot,

t_r is rise time and

t_{r0} is nominal rise time.

The value of β is selected such that minimizes the cost function.

4.6 Estimation of Delay :

The gain middleware β is scheduled to pay off for the network induced time delay, we first need to devise a mechanism to estimate the network delay.

Since it is difficult to estimate the sensor to controller delay and controller to actuator delay separately, we will consider the Round Trip Time (RTT) delay instead. Network Delay Estimator is used to estimate the network time delay. The estimator functions by sending a signal on network and then perceiving the time between it's revert back version through probing technique. This process is repeated on periodic basis as the network induced time delays are stochastic in nature and vary with time. Variable time delay is taken as a constant by repeating the process repeatedly and acquiring the mean value of the observed delay.

Chapter 5

5 Simulation & Results

Simulink Tool Box of MATLAB is used to simulate the proposed control scheme for the purpose of validation and verification.

The following machine parameters are used for simulation of the induction motor on MATLAB.

Parameters	Symbols	Values
Supply Frequency	F	60 Hz
Inertia of Motor	J	0.03 Nm
Number of Pole Pairs	P	1
Synchronous Speed	Ws	404 rad/sec
Resistance of Stator	R_s	0.15 Ω
Resistance of Rotor	R_r	0.15 Ω
Inductance of Stator	L_s	0.0469 H
Inductance of Rotor	L_r	0.0485 H
Mutual Inductance	L_m	0.045 H

Table 1 Induction Motor Specifications

5.1 System Response in the Presence of Network Delay

First we consider network time delay as constant. When delay was added from sensor to controller, the response showed increase in the percent overshoot upto delay of 3 msec. When delay was further increased, the system response becomes sluggish and unstable.

The below plot shows the system response when Tsc=4 msec.

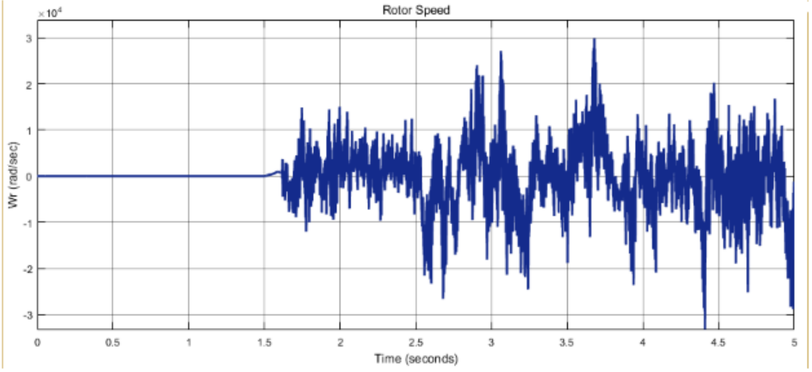

Figure 5.1 System Response in the Presence of Network Delay

However the MATLAB did not converge in the presence of controller to actuator delay.

5.2 System Response with Network Delay Compensation

In order to compensate the above-mentioned issue, we inserted gain middle ware in the system.

We first inserted sensor to controller and controller to actuator time delay for i_d and optimized β for it. It is assumed that the system experiences equal values of sensor to controller time delay and controller to actuator time delay. The value of β is chosen such as to optimize the cost function described in the last section.

The below graph plots the external gain value β vs round trip time delay for i_d.

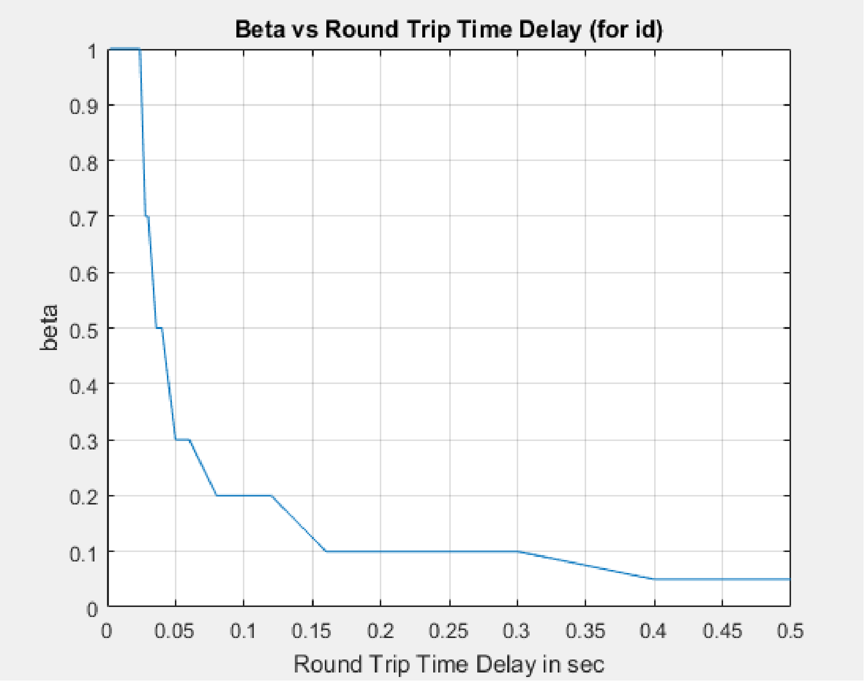

Figure 5.2 Beta vs Round Trip Time Delay (for id)

The system shows satisfactory performance with percent overshoot less than 16%.

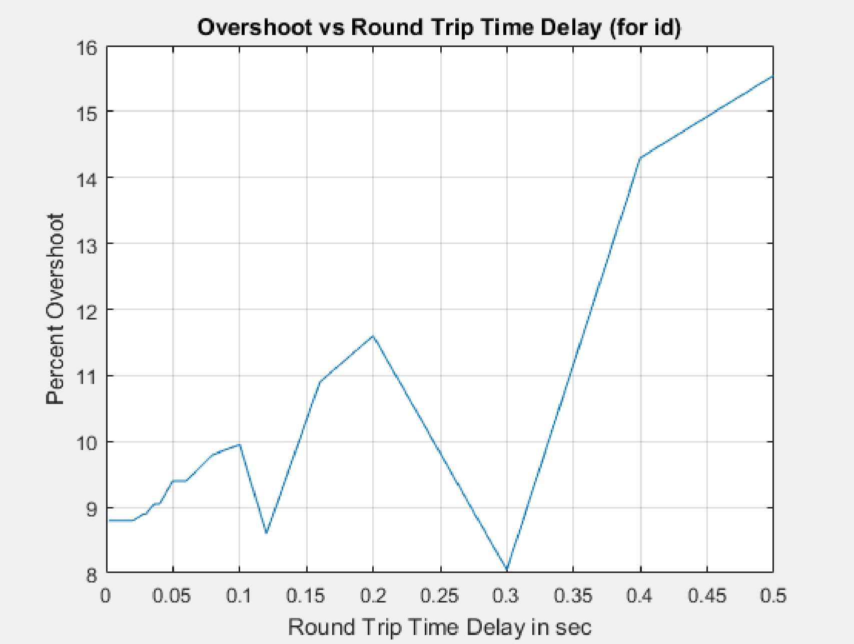

Figure 5.3 Overshoot vs Round Trip Time Delay (for id)

We then inserted sensor to controller time delay and controller to actuator time delay for i_q part. The value of β is then optimized for the second part.

With proper choice of β for both i_d and i_q individually, the system response was significantly improved.

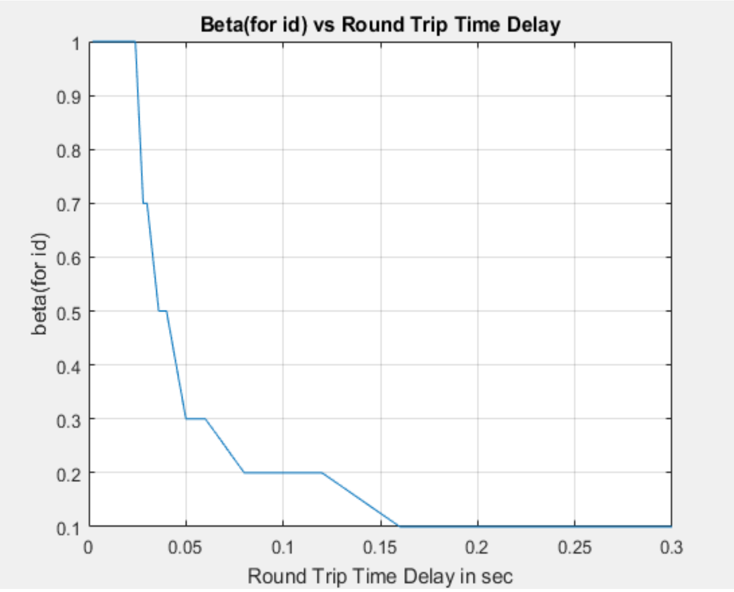

Figure 5.4 Beta (for id) vs Round Trip Time Delay

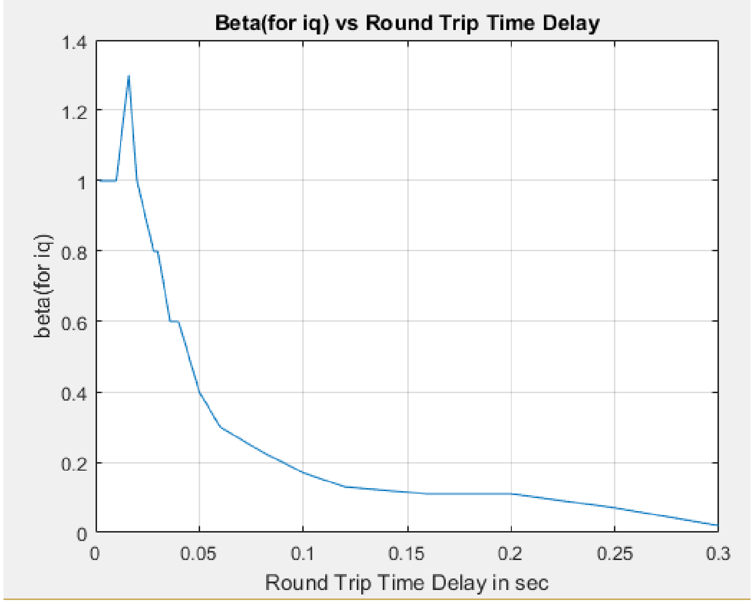

Figure 5.5 Beta (for iq) vs Round Trip Time Delay

However the gain middleware supports round trip time (RTT) delay upto a threshold of 60 msec with percent overshoot less than 30%. On further increasing the RTT, the system reached the required speed but with the increase in percent overshoot.

The graph showing percent overshoot against RTT delay with gain middleware adjustments is as follows:

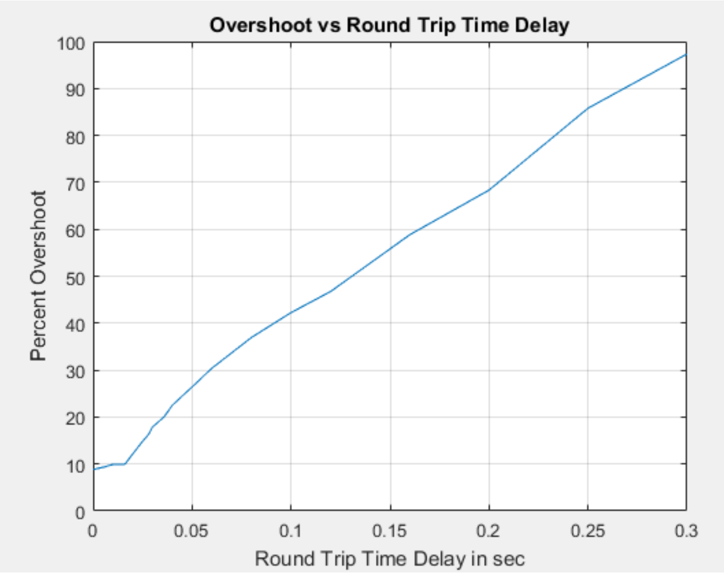

Fig 5.6 Overshoot vs Round Trip Time Delay

The graph shows that in-spite of the compensation technique, the percent overshoot increases with the increase in delay.

The same approach can be used for time varying delay assuming that the time delay is slow changing also the mean average value of the time delay is chosen for compensation.

Chapter 6

6 Contribution of the Research

In second chapter, we've gone through the related literature work already carried out in the area of Network Control System. Many researchers have worked on Networked Control Systems. The mainstream research lies in dealing with negative effects of network induced delays and their uncertainty.

In this chapter, we'll be discussing the contribution of our work.

Designing a new controller for Network Control System from the scratch is very time consuming and not a cost-effective solution to the problem. M.-Y. Chow & Y. Tipsuwan suggested gain middleware design to utilize the same non-networked controller in the existence of network [16]. They have applied the methodology on a linear model of DC motor given by the transfer function:

$$G(s) = \frac{2029.86}{(s + 26.29)(s + 2.296)}$$

First, PI Controller was designed to meet the following specifications without taking into account the network induced delays:

- Percent Overshoot ≤ 5%
- Settling time ≤ 0.309 sec
- Rise time ≤ 0.117 sec

Next, gain middleware was designed to address the network induced delay. The gain β was optimized using cost function J that was discussed in Chapter 4. The gain β was obtained for PI controller in discrete-time domain with a sampling time of 1 msec.

In this paper, the authors have assumed that the delays TPC (plant to controller or sensor to controller delay) and TCP (controller to plant or controller to actuator delay) have similar characteristics. These delays were selected by dividing Round Trip Time Delay (RTT) data points by two and selecting different values of the data set for each type of delay.

The step response for three different scenarios were presented;:

Destination Host	T_{min}	T_{median}	T_{mean}	T_{max}
(a) www.lib.ncsu.edu	0.000435 sec	0.00471 sec	0.000580 sec	0.0862 sec
(b) www.visitnc.com	0.0166 sec	0.0232 sec	0.0326 sec	0.7562 sec
(c) www.utexas.edu	0.0622 sec	0.0627 sec	0.0629 sec	0.1187 sec
(d) www.ku.ac.th	0.0045 sec	0.3150 sec	0.3730 sec	227.7095 sec

Table 2 Statistical Measures of RTT Delay Measured from ADAC Lab at NCSU

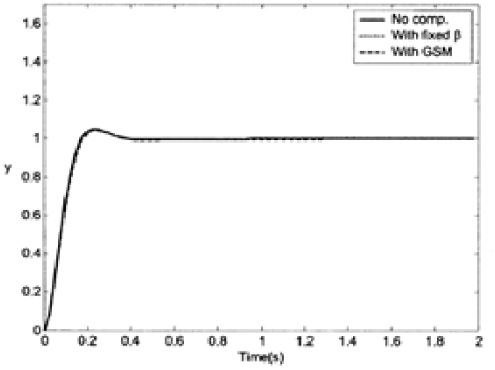

Figure 6.1 Case(a) www.lib.ncsu.edu

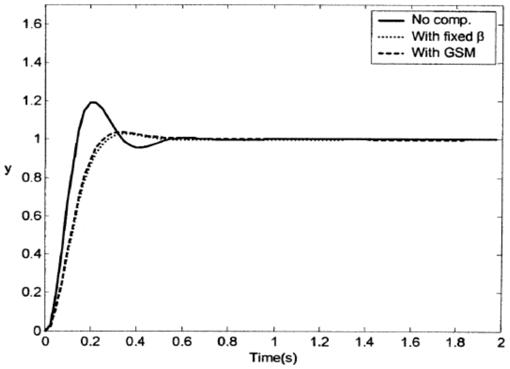

Figure 6.2 Case (b) www.visitnc.com

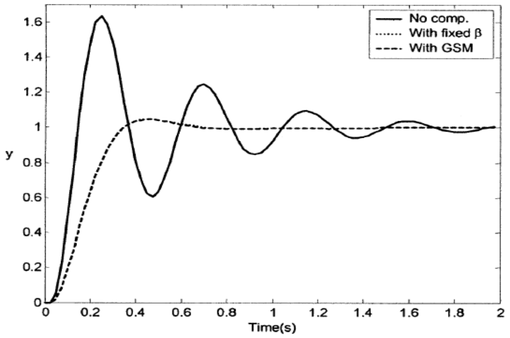

Figure 6.3 Case (c) www.utexas.edu

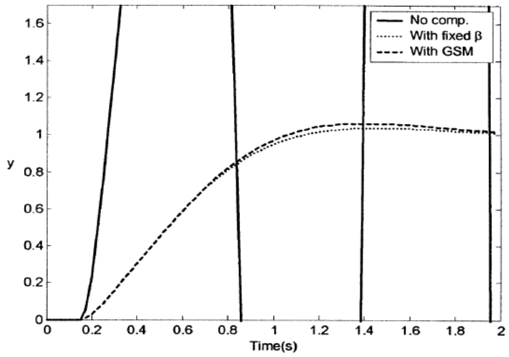

Figure 6.4 Case (d) www.ku.ac.th

We've extended the above-mentioned research work to a non-linear system of a three phase induction motor. The modelling and control design of a three-phase induction is itself a challenge due to its high non linearity in nature. The modelling and control design of the motor are discussed in the next chapter.

Next, we outspread the proposed designed for sensor less control using Indirect Field Oriented Control (IFOC) technique. This eliminates the need of position sensors to measure the rotor position. Instead, the position of rotor was estimated using the speed of rotor estimated by the observer. The gain of observer was chosen to be equal to rotor constant i.e. the ratio of rotor inductance to rotor resistance.

Indirect field-oriented control requires coordinate transformation and current controllers in addition to the observer, discussed above. The coordinate transformation was done through Park’s & Clarke’s transformation. The current controller was implement using PI Controller algorithm.

The PI Controller was designed to meet the below mentioned specifications:

- Percent Overshoot ≤ 8.8%
- Settling time ≤ 2.5 sec
- Rise time ≤ 1.75 sec

This controller was designed without considering the delays induced by the network. In the presence of network induced delays, we used the gain middleware technique to compensate the effect of network induced delay. Since, we have decoupled the electrical equations into d and q axis component therefore we need to design two gain middleware for d-axis component and q-axis component individually. The final response of the network control system is influenced by the combined effect of both middle-wares.

Lastly, in the last research the author has used discrete time modelling approach, while we have opted for continuous time modelling approach. The foremost benefit of continuous time modelling approach is the possibility to fit in time-delays larger than the sampling period without causing complexity of the model.

Also, the discrete time approach can be used for both continuous-time or discrete-time controller and plant, however the controller and plant must be linear. On the other hand, continuous time approach can be applied for non-linear controller and plant. This feature distinguishes it from discrete time approach.

Few results from the simulation of the proposed methodology are shown here:

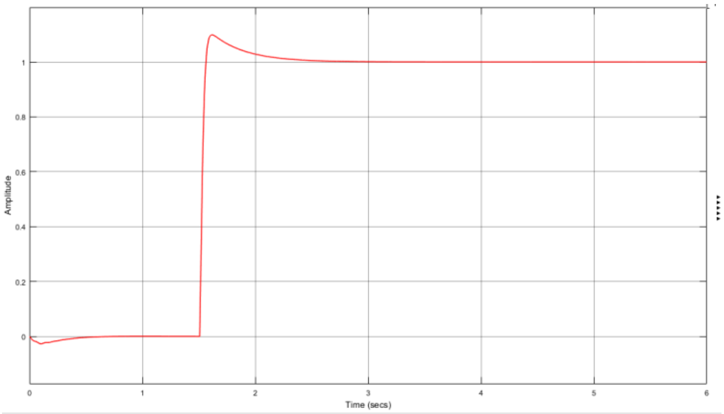

Figure 6.5 System Response when RTT=0.016 sec

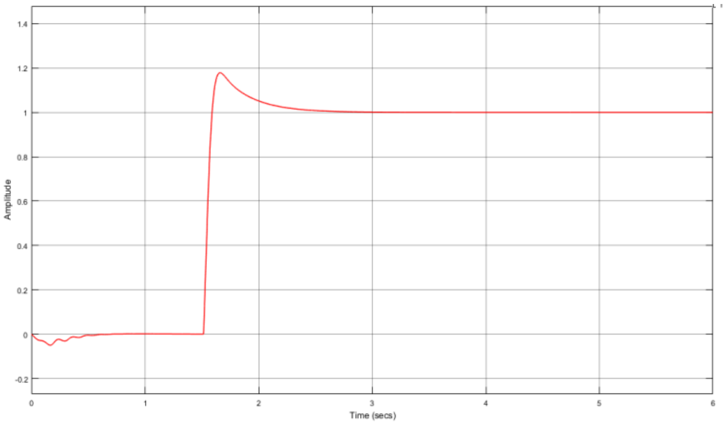

Figure 6.6 System Response when RTT = 0.03 sec

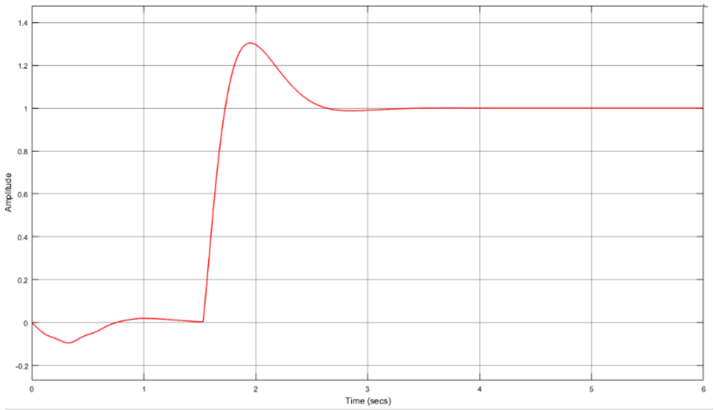

Figure 6.7 System Response when RTT-0.06 sec

It shows the system shows the satisfactory performance even in the presence of non-linearity, a feature that the previous research lacks also the time delay is not bounded by sampling interval which provides flexibility to accommodate variable nature of the network induced time delays.

Chapter 7

7 Conclusion

This thesis first gives an outlook of network control system and discusses the benefits and basic challenges of Network Control System.

Owing to the swift developments in the field of primary technologies of communication networks and control systems, Network Control Systems(NCS) have incredible prospects in numerous diverse ranges such as remote surgery ,intelligent energy management systems for building, intelligent transportation management systems, smart control of large-scale energy plants and water distribution networks to name a few. The current trend is to apply NCS for applications that demands time-sensitivity, such as remote-control machine actuation system.

Induction motor occupies a dominant part in industrial applications which is a complicated system due to the non-linearity dynamics of the motor. Often these motors are required to run at variable speed which require measurement of rotor speed by using sensors of some kind. These sensors spoil the ruggedness and simplicity of Induction Motor. In a hostile environment, sensors cannot even be mounted.

The contribution of this thesis is modelling and control of a three phase nonlinear AC induction motor in a networked environment. The modelling of three phase induction motor is itself a challenge as induction motor is highly non-linear in nature. Observer based Indirect Field Oriented Control (IFOC) is implemented for controlling the speed of motor. This eliminates the need of position sensors instead the rotor position is estimated by the field observer.

Then control algorithm is extended to control the networked motor speed in the presence of network induced time delay. We have limited our study to the issue of network induced delay only whereas all other issues are taken as ideal.

First open loop behavior of the plant was simulated to study the machine dynamics and performance parameters of the motor. We then applied a controller to the motor. The desired closed loop performance was achieved using the proposed controller in a non-networked environment. We then introduced network in the system. The performance of the system degrades in the occurrence of network-induced time delay. The controller was then adjusted to reach the required performance in the presence of network induced delay.

The idea proposed in this research has been analyzed by simulating it on MATLAB. The proposed strategy is computationally more efficient and shows satisfactory performance.

The use of network control system will provide a novel approach for variable speed operation of induction motor with reduced installation cost, better maintainability and increased flexibility. This will encourage maintenance free environment for industrial control and enhance the ease of controlling options with less managements and accurate results.

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