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Performance of Networked DC Motor with Fuzzy Logic Controller

B Sharmila[1] and N Devarajan[2]

[1] Department of EIE, Sri Ramakrishna Engineering College
Coimbatore, Tamilnadu 641022, India

[2] Department of EEE, Government College of Technology
Coimbatore, Tamilnadu 641013, India

Abstract

In the recent years the usage of data networks has been increased due to its cost effective and flexible applications. A shared data network can effectively reduce complicated wiring connections, installation and maintenance for connecting a complex control system with various sensors, actuators, and controllers as a networked control system. For the time-sensitive application with networked control system the remote dc motor actuation control has been chosen. Due to time-varying network traffic demands and disturbances, the guarantee of transmitting signals without any delays or data losses plays a vital role for the performances in using networked control systems. This paper proposes Fuzzy Logic Controller methodology in the networked dc motor control and the results are compared with the performance of the system with Ziegler-Nichols Tuned Proportional-Integral-Derivative Controller and Fuzzy Modulated Proportional-Integral-Derivative Controller. Simulations results are presented to demonstrate the proposed schemes in a closed loop control. The effective results show that the performance of networked control dc motor is improved by using Fuzzy Logic Controller than the other controllers.

Keywords: *Networked Control System, Fuzzy Logic Controller, DC Motor.*

1. Introduction

The adaptation of communication network for information exchange between controllers, sensors and actuators to realize a closed control loop is called as Networked Control System (NCS). Networks reduce the complexity in wiring connections and the costs of Medias; provide ease in maintenance and also enable remote data transfer and data exchanges among users. Therefore, NCS is used widely in many industrial applications. Two major challenges as networked induced delay and data losses in the network affects the performance of the system. Hence the challenges have to be compensated. Thus, with a networked controlled dc motor system this paper illustrates the proposed Fuzzy Logic Controller (FLC) for the compensation of the challenges and also compares FLC simulation results with the Fuzzy Modulated Proportional-Integral-Derivative Controller (FMPID) and Zeigler Nichols tuned Proportional-Integral-Derivative (PID) Controller.

There are two approaches to utilize a data network as Hierarchical Structure and Direct Structure. The Hierarchical Structure is shown in Fig. 1 where the dc motor is controlled by its own remote controller at remote station. The central controller provides the set point to the plant (dc motor) via remote controller and the sensor measurements of the system are sent from the remote station to central controller. The remote controller controls the plant by providing the control signal in the remote unit. The set points and sensor measurements are transmitted through network. This approach has a poor interaction between the central and remote unit because of not transmitting the control signal from central controller. Whereas in the Direct Structure Fig. 2 approach the network is used for the direct transfer of the control signal and the sensor measurements between a remote unit and a central controller. The central controller is connected to the dc motor through an interface unit. Due to the transfer of control signal directly to plant this approach provided better interaction of data’s between central controller and the plant than the hierarchical structure.

Recently the stability analysis and control design for NCS have attracted considerable research interest [3], [4], [6] and [11]. The work of Nesic and Teel [2] presents an approach for stability analysis of NCS that decouples the scheduling protocol from properties of network free nominal closed-loop system. Nesic and Tabbara [3] extended [2] by stochastic deterministic protocols in the presence of random packet dropouts and inter transmission time and they also proposed wireless scheduling protocol for non-linear NCS in [6]. The networked predictive control scheme for forward and feedback channels having random network delay was proposed in [4], and [5] addresses the problems of how uncertain delays are

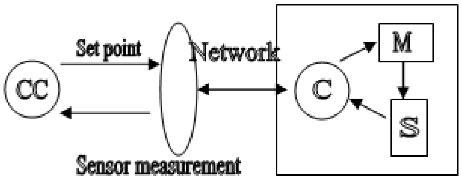

Fig. 1 Hierarchical Structure

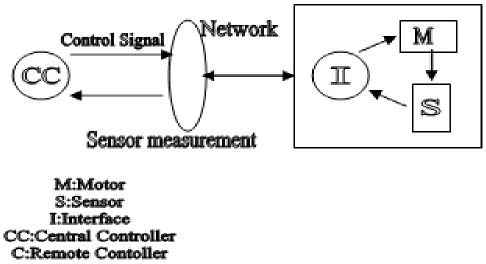

Fig. 2 Direct Structure

smaller than one sampling period which affects the stability of the NCS and how these delays interact with maximum allowable transfer interval and the selected sampling period. Robust feedback controller design for NCS with uncertainty in the system model and the network induced delay has been addressed in [7]-[8], whereas [9] handles the case of state feedback stabilization of NCS with varying sampling period. Seiler and Sengupta [1] measure the networked vehicle control performance using an H infinity norm with linear matrix inequalities conditions and markovian jumping parameters in communication losses. In case of time varying transmission times, model based NCSs has been proposed for stabilization problem of NCS. The stability analysis and controller synthesis problems are investigated in [11] for the NCSs with random packet losses by using H infinity control and linear matrix inequalities. A moving horizon method was developed by Godwin et. [12], which was applied as a quantized NCS in a practical context. Since these methods transmit data specifying only a region in which the measurements lie, it will reduce the network stabilization of the NCS. However, this method could reduce the stability of the control system by introducing uncertainty in the control system. The issues of limited bandwidth, time delay and data dropouts was taken into consideration when NCSs controllers were designed in [12] – [14]. The networked control system performance depends on the control algorithm and the network conditions. Several network conditions such as bandwidth, end-to-end delay, and packet loss rate are major impacts on networked control systems. Depending upon the control algorithm and network conditions the overall performance of the networked system may vary and hence the stability of the system.

2. Modeling

A networked control system can be divided into three parts: 1) the remote unit; 2) the central controller; and 3) the data network. A general block diagram of the networked control system under investigation is shown in Fig. 3. In order to focus our discussion on the performance of networked closed loop control system with network conditions (delay, data loss), a networked dc motor control system has been illustrated as in [16].

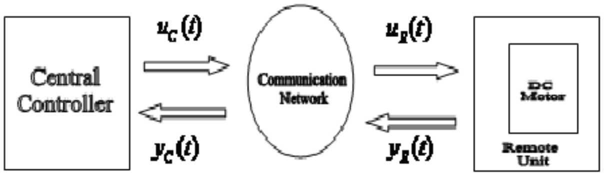

Fig. 3 An overall real-time networked control system

2.1 Remote Unit

The Remote Unit consists of the plant (dc motor), sensor and an interfacing unit. Via the network the remote unit can send measurements like motor speed, current, temperature, and local environment information, back to the central controller. Using the state-space description, the dynamics of the remote process can be described as shown in Eq. (1), where the state vector $X_R = [x_{R1} \ldots x_{Rn}]^T$ € X^n the state space; the input vector $U_R = [u_{R1} \ldots\ldots u_{Rr}]^T$ € U^r, the input space; $S_R = [s_{R1} \ldots\ldots s_{Rq}]^T$ € R^q are the system parameters; t € R^+ is the time parameter; and F_R € R^n is the state transfer function of the remote unit

$$\dot{X} = F_R(X_R, S_R, U_R, t) \tag{1}$$

Depending on the design of the networked control system, the remote interface, G_R performs a certain task, such as regulating the performance of the plant, as described by Eq.(2).

$$U_R = G_R(\gamma_R, \cdot) \tag{2}$$

where $\gamma_R = [\gamma_{R1}, \ldots, \gamma_{Ra}]^T$ is the adjustable controller parameter vector and $(\cdot)$ is other appropriate information. The combination of the remote plant and remote interface is viewed as a remote unit. The remote unit dynamics can be described by a set of differential equations

$$\dot{X} = F_R(X_R, S_R, G_R(\gamma_R, \cdot), t) \tag{3}$$

For the discussion a network based controlled dc motor is used as remote unit. The electro-mechanical dynamics of the dc motor can be described by the loop equation as first order differential equations.

$$u(t) = e_a = L\frac{di_a}{dt} + Ri_a + e_b \tag{4}$$

where u=e_a is the armature winding input voltage; $e_b = K_b\omega$ is the back-electromotive-force (EMF) voltage; L is the armature winding inductance; i_a is the armature winding current; R is the armature winding resistance; K_b is the back-EMF constant and ω is the rotor angular speed. Based on Newton's law the mechanical-torque balance equation is

$$J\frac{d\omega}{dt} + B\omega + T_l = Ki_a \tag{5}$$

J is the system moment of inertia; B is the system damping coefficient; K is the torque constant and T_l is the load torque.

By letting $x_1 = i_a$ and $x_2 = \omega$, the electromechanical dynamics of the dc motor can be described by the following state-space description:

$$\dot{x}_1(t) = -\frac{R}{L}x_1 - \frac{K_b}{L}x_2 + \frac{1}{L}u \tag{6}$$

$$\dot{x}_2(t) = \frac{K}{J}x_1 - \frac{B}{J}x_2 + \frac{1}{L}T_l \tag{7}$$

The parameters of the motor table 1 are used for determine the state space model of dc motor. To keep the illustration simple, the remote unit receives the data sent from the central controller as u_R, which can be mathematically expressed as

$$u_R(t) = u_c(t - \tau_R) \tag{8}$$

where τ_R is the time delay to transmit the control signal u_C from the central controller to the remote unit. The remote unit also sends the sensors signals $y_R(t)$ of the remote system back to the central controller, $y_C(t)$, and these two signals are related as

$$y_c(t) = y_R(t - \tau_c) \tag{9}$$

where τ_C is the time delay to transmit the measured signal from the remote unit to the central controller.

The parameters of the ½ hp dc motor which are used in this paper are shown in table 1.

Table 1. DC Motor parameter

J	Moment of Inertia	42.6 e-6 Kg-m^2
L	Inductance	170 e-3 H
R	Resistance	4.67 Ω
B	Damping Coefficient	47.8 e-6 Nm-sec/rad
K	Torque Constant	14.7 e-3 Nm/A
K_b	Back EMF constant	14.7 e-3 Vsec/rad

There are also processing delays as τ_{PC} and τ_{PR}, at the central and remote unit, respectively which could be approximate small constants or even neglected because these delays are usually small compared to τ_C and τ_R.

2.2 Central Controller

The central controller will provide the control signal $u_C(t)$ to the remote systems. Let z^{-t} be a time delay operator and the current network conditions n(t) provided by the network are defined as

$$u_R(t) = u_c(z^{-t_R}, n(t)) \tag{10}$$

$$y_c(t) = y_R(z^{-t_c}, n(t)) \tag{11}$$

where t_R is the time delay in transmitting a signal from the central controller to the remote unit, and t_C is the time delay in transmitting a signal from the remote unit to the central controller. The network conditions n(t) and time delays z^{-t} are functions of network variables such as the network throughput, the network management/policy used, the type and number of signals to be transmitted, the network protocol used, and the controller processing time, and the network traffic congestion condition.

The central controller will monitor the network conditions of the remote unit link and provide appropriate control signals to each remote unit. In this paper, the Fuzzy Logic Controller is proposed to be the central controller.

2.3 Data Network

There are different ways to define network conditions for point-to-point (from the central control to a specific remote unit). Two of the most popular network measures are the point-to-point network throughput and maximal delay bound of the largest data.

One factor of interest is the sampling time. In this paper, we have chosen sampling time as 0.5ms and simulations are done.

3. Controller Design for NCS

In this session the proposed Fuzzy Logic Controller for the central controller is described and the results are compared with the Fuzzy Modulated PID controller and PID controller.

3.1. Fuzzy Logic Controller

In general, fuzzy logic control is used for the control of a plant where the plant modeling is difficult. For such systems that are difficult to model, fuzzy logic controller has been successful by Mamdani. The basic principle of fuzzy logic lies in the definition of a set where any element can belong to a set with a certain degree of membership. Using this idea, the knowledge of an expert can be expressed in a relatively simple form and the inference for given inputs can be implemented very efficiently. Due to these advantages, fuzzy logic control is a very attractive method for NCS whose modeling is very difficult because of the stochastic and discrete nature of the network. Figure (4) shows the structure of FLC for a single input single output plant. In this figure, the control signal and plant output are transmitted through the network. Due to the use of the network, the control signal and feedback signal (plant output) inevitably contain the network induced delay and losses of data. In Fig.4 r(t) is the reference input, y(t) is the plant output, e(t) is the error signal between the reference input and plant output and $U_c(t)$ is the control signal.

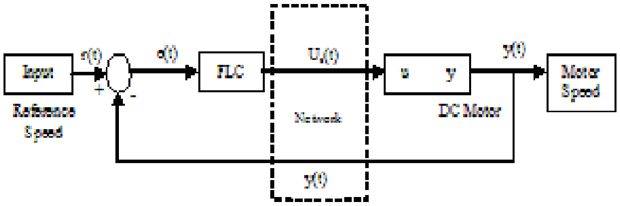

Fig. 4 Fuzzy Logic Controller for NCS

The FLC consists of three parts as 1) Fuzzifier that converts the error signal into linguistic values, 2) Inference engine that creates the fuzzy output using fuzzy control rules generated from expert experience and 3) Defuzzifier that calculate the control input to the plant from the inferred results. The input and output signals to the FLC are error signal e(t) and control signal $U_c(t)$ respectively. In this paper, the trapezoidal fuzzy members are selected for membership functions. Three fuzzy linguistic variables, i.e., Small, Medium and Large are defined. The coefficients of the membership function depend upon the set point and are determined by several trial and error experiments with the plant without the network. In order for faster execution of the fuzzy logic controller, the Mamdani's min-max inference method and the central average defuzzifier are used. The rules used in this paper are as

If e(t) is small then $U_c(t)$ is small
If e(t) is medium then $U_c(t)$ is medium
If e(t) is large then $U_c(t)$ is large

The FLC reduces the effects of network induced delays, losses and disturbance and they also reduces the effects of the disturbances in the input reference signal. The simulation results are shown in the Session 4.

3.2. Fuzzy Modulated PID Controller

The fuzzy modulated PID controller for the networked control dc motor is shown in the Fig. 5. The model is based on modulating the control signal $U_{PID}(t)$ provided by the PID controller with a single parameter β. The fuzzy modulator receives the input as the error signal e(t) which is the difference between the reference signal and the plant output signal y(t) in addition to the output from the PID controller $U_{PID}(t)$. The fuzzy modulator produces an output as modulation parameter β which is used to compensate the affects of the network induced time delay and data losses. The control signal produced by the fuzzy modulated networked PID controller is

$$U_c(t) = \beta U_{PID}(t) \tag{12}$$

Two fuzzy linguistic variables, i.e., Small and Large are defined. The coefficients of the membership functions are determined by several trial and error methods with the plant and without the network. The fuzzy logic modulator used in this paper is composed of the following rules.

If e(t) is small and $U_{PID}(t)$ is small, then β is β_1
If e(t) is large and $U_{PID}(t)$ is large, then β is β_2

Such that $\beta < \beta_1 < \beta_2 < 1$ where β_i, i=1,2 are the consequent parameters corresponding to the modulation parameter β [19].

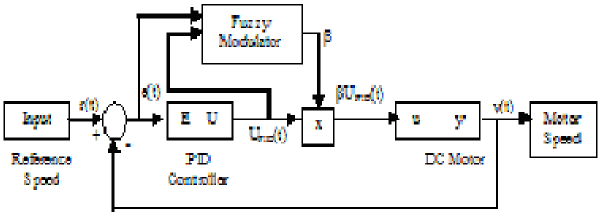

Fig. 5 Fuzzy Modulator PID Controller for NCS

3.3. PID Controller

It is used to compute the control signal to the remote dc motor for step tracking, based on the monitored system signals sent from the remote unit via the network link Fig. 6. The Proportional-Integral-Derivative (PID) controller used is

$$U_{PID}(t) = K_p e(t) + K_I \int_0^t e(t)dt + K_D \frac{de(t)}{dt} \tag{13}$$

where K_p is the proportional gain; K_I is the integral gain; K_D is the derivative gain; r(t) is the reference signal for the system to track; y(t) is the system output; and e(t) is the error function. In our case, y = ω is the motor speed, and $U_{PID}(t)$ is the input voltage to the motor system.

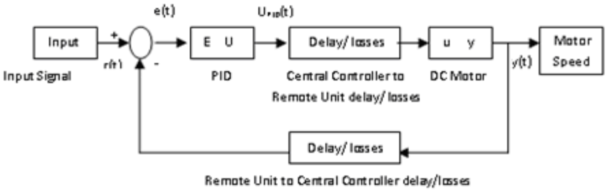

Fig. 6 ZN Tuned PID Controller for NCS

4. Simulation Setup and Results

In the simulation scenario, the direct structure of the networked DC motor control system is simulated using MATLAB/ SIMULINK under fully controlled environments for Fuzzy Logic Controller, PID Controller and Fuzzy Modulated PID Controller. The motor Eq.(4) and Eq.(5) are used as the main model, and it is controlled by the fuzzy logic controller with the insertions of network delays according to Eq.(8) and Eq.(9). The delays are varied according to different effects of interests. The disturbance and loss of input signal, control signal and the feedback signal were made for few milliseconds at each stage and the results were studied. The system setup is illustrated in Fig.4, Fig.5 and Fig.6. Using Eq.(6), Eq.(7) and table I, the state model of the dc motor is obtained. Then the results of the FLC are compared with the PID controller and fuzzy Modulated PID Controller.

Output Responses of the system are obtained for all controllers used in this paper. Figure 7 shows the comparison of the system performance for all controllers without delays and data losses.

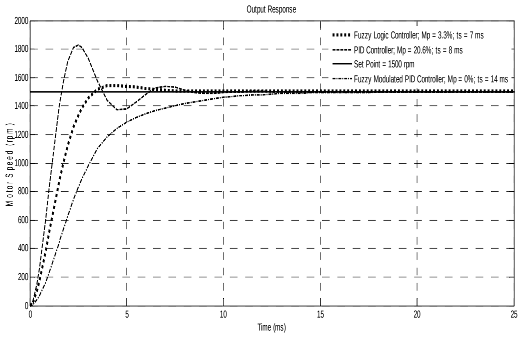

Fig. 7 Comparison of System Responses for FLC, Conventional PID Controller and FMPID Controller without delay and losses.

In Fig. 8 – 10 shows the response of the system for the controllers with different network induced delays and the comparison of these performances are tabulated in table 2. In Fig.11 and Fig. 12 the system responses of all the controllers with missing of input data and disturbances in the input data are shown respectively. Similarly the system response for missing of control signal, disturbances in control signal, missing of feedback signals and disturbance in feedback signals are shown in Fig. 13-16 respectively. Thus the system performance with data loss in the input signal, control signal and feedback signal are obtained. Finally the system responses with delay and data losses are obtained as shown in the Fig.17. From the simulation results obtained as in Fig.7-17, the overall system performance with Fuzzy Logic Controller is improved than the PID controller and fuzzy modulated PID controller.

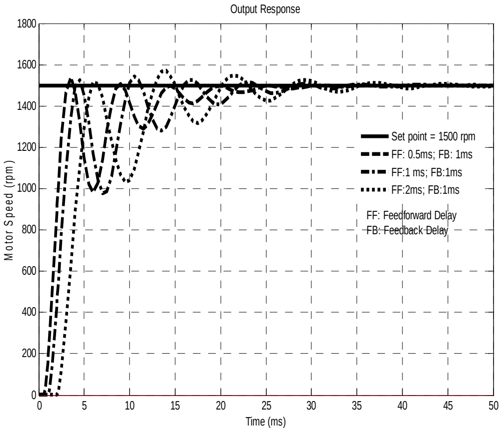

Fig. 8 Output Response of the System using PID Controller with varying delays in forward and feedback path of NCS.

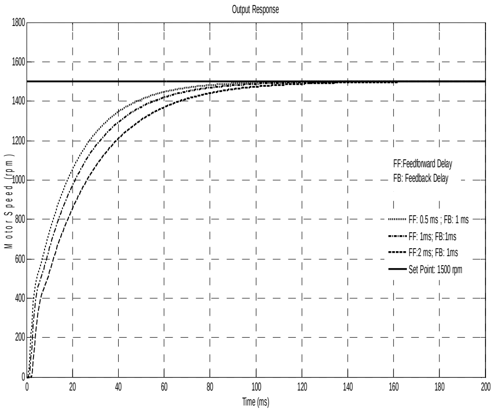

Fig. 9 Output Response of the System using FMPID Controller with varying delays in forward and feedback path of NCS.

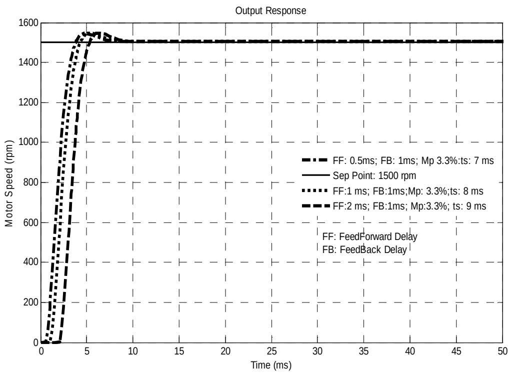

Fig.10 Output Response of the System using FLC with varying delays in forward and feedback path of NCS.

Table 2. Comparison of performance of the networked dc motor control system with delay in FLC, PID and FMPID Controller (Set point = 1500 rpm; Sampling Time = 0.5ms)

Time delay (ms)		Maximum overshoot (%)			Settling Time (ms)		
Feed forward path	Feed back path	PID	FMPID	FLC	PID	FMPID	FLC
0.5	1	3.3	-	3.3	30	100	7
1	1	3.3	-	3.3	40	110	8
2	2	6.6	-	3.3	62	150	9
2	3	8	-	3.3	70	180	9
3	2	9	-	3.3	75	190	9

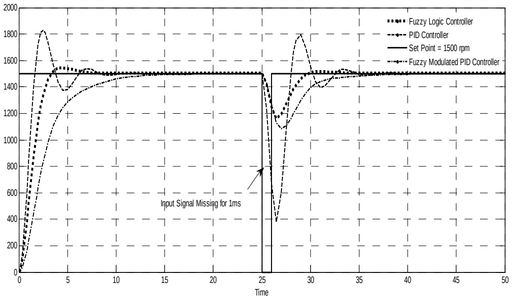

Fig.11 Comparison of system responses for missing of the input signal using FLC, PID and FMPID Controllers.

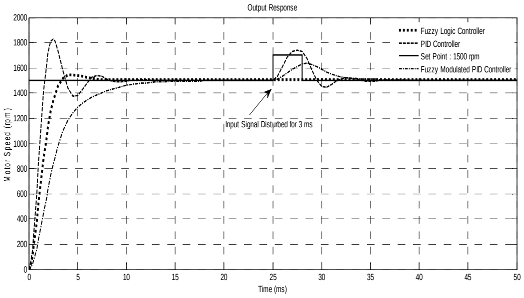

Fig.12 Comparison of system responses for disturbance in the input signal using FLC, PID and FMPID Controllers.

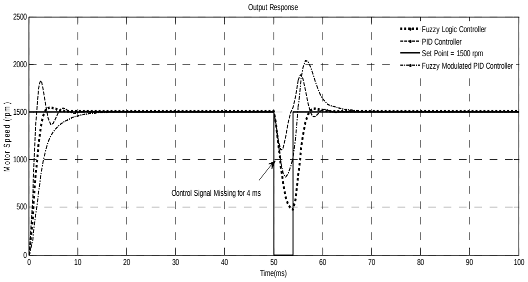

Fig.13 Comparison of system responses for missing of the control signal using FLC, PID and FMPID Controllers.

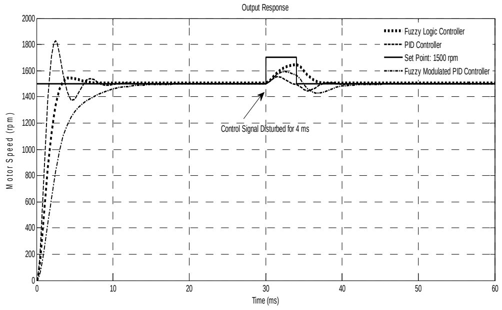

Fig.14 Comparison of system responses for disturbance in control signal with FLC, PID and FMPID Controllers.

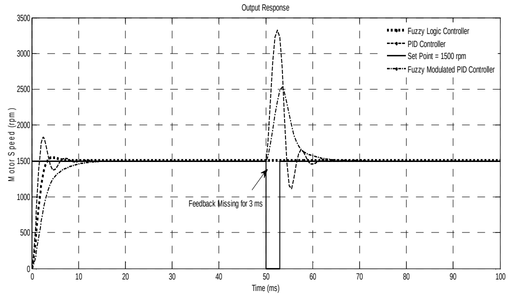

Fig. 15 Comparison of system responses for missing of the feedback signal with FLC, PID and FMPID Controllers.

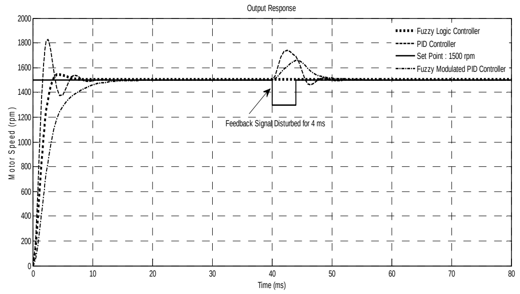

Fig.16 Comparison of system responses for disturbance in feedback signal with FLC, PID and FMPID Controllers.

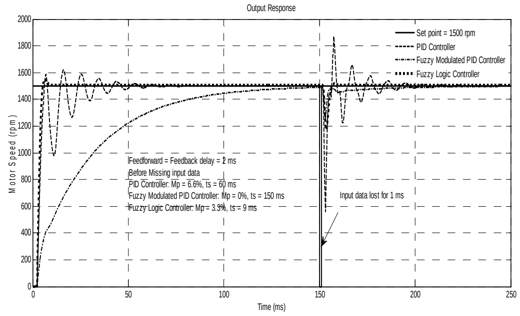

Fig.17 Comparison of system responses of FLC, PID and FMPID Controllers with delay and losses.

5. Conclusions

Networks and their applications play a promising role for real-time high performance networked control in industrial applications. The major concerns are the network induced delays and data losses that are provided by the network which affects the performance of the networked control systems. This paper has describes and formulates the Fuzzy Logic Controller in a networked DC motor control. The numerical result are obtained and compared for Fuzzy Logic Controller, Fuzzy Modulated PID Controller and PID Controller. The effective results show that the performance of networked control DC motor is improved by using Fuzzy Logic Controller than the other controllers in all network variations and deteriorations. The analysis on using intelligent controls improves and strengthens the networked control systems concepts in the future.

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Dr.N.Devarajan received B.E (EEE) and M.E (Power Electronics) from GCT Coimbatore in the year 1982 and 1989 respectively. He received Ph.D in the area of control systems in the year 2000. He is currently working as Assistant Professor in the department of EEE at Government College of Technology, Coimbatore. He published 133 papers in the national and international conferences. He published 37 papers in international journals and 12 in national journal. Under his supervision currently 10 research scholars are working and 7 scholars completed their Ph.D. His areas of interests are control systems, electrical machines and power systems. He is member of system society of India, ISTE and IE(India).

B.Sharmila completed B.E (EIE) from Tamilnadu College of Engineering, Coimbatore in the year 2000. She completed her M.E (Applied Electronics) from Maharaja College of Engineering, Coimbatore in the year 2004. She is a currently working as Senior Lecturer in the department of EIE at Sri Ramakrishna Engineering College, Coimbatore. She is a Ph.D. research scholar and published 4 papers in national and international conference. Her areas of interests are networked control system and intelligent controllers. She is a member of IEEE and ISTE.