Model Predictive Control Approach Based Load Frequency Controller

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Abstract:-The present paper investigates the design of Load-Frequency Control (LFC) system for improving power system dynamic performance over a wide range of operating conditions based on model predtictive control MPC technique. The objectives of load frequency control (LFC) are to minimize the transient deviations in area frequency and tie-line power interchange variables . Also steady state error of the above variaables forced to be zeros. The two control schems namely Fuzzy logic control and proposed model predictive control are designed. Both the two controllers empoly the local frequency deviation signal as input signal. The dynamic model of two-area power system under study is estabilished . To validate the effectiveness of the proposed MPC controller, two-area power system is simulated over a wide range of operating conditions. Further, comparative studies between the fuzzy logic controller (FLC), and the proposed MPC load frequency control are evaluated.

Keywords:- Model predictive control - Fuzzy logic controller, Load Frequency Control, Two area power system.

1 Introduction

The control strategy is classified into two controls, firstly, conventional control as integral and PID control. Secondary is advanced control such as model predictive control, fuzzy logic control and neural network and etc., The salient feature of the fuzzy logic approach is that they provide a model-free description of control systems and do not require model identification. The fuzzy LFC systems have large over and/or under shoots response and large settling time in non-linear model [1,2]. Although the active power and reactive power have combined effects on the frequency and voltage, the control problem of the frequency and voltage can be decoupled. The frequency is highly dependent on the active power while the voltage is highly dependent on the reactive power. Thus the control issue in power systems can be decoupled into two independent problems. One is about the active power and frequency control while the other is about the reactive power and voltage control. The active power and frequency control is referred to as load frequency control (LFC) [3].
The foremost task of LFC is to keep the frequency constant against the randomly varying active power loads, which are also referred to as unknown external disturbance. Another task of the LFC is to regulate the tie-line power exchange error [4]. Therefore, the requirement of the LFC is to be robust against the uncertainties of the system model and the variations of system parameters in reality. In summary, the LFC has two major ssignments, which are to maintain the standard value of frequency and to keep the tie-line power exchange under schedule in the presences of any load changes [3,4]. In addition, the LFC has to be robust against unknown external disturbances and system model and parameter uncertainties. The high-order interconnected power system could also increase the complexity of the controller design of the LFC. The foremost task of LFC is to keep the frequency constant against the randomly varying active power loads, which are also referred to as unknown external disturbance. Another task of the LFC is to regulate the tie-line power exchange error. A typical large-scale power system is composed of several areas of generating units. In order to enhance the fault tolerance of the entire power system, these generating units are connected via tie-lines. The usage of tie-line power imports a new error into the control problem, i.e., tie-line power exchange error. When a sudden active power load change occurs to an area, the area will obtain energy via tie-lines from other areas. But eventually, the area that is subject to the load change should balance it without external

support. Otherwise there would be economic conflicts between the areas. Hence each area requires a separate load frequency controller to regulate the tie-line power exchange error so that all the areas in an interconnected power system can set their set points differently. Another problem is that the interconnection of the power systems results in huge increases in both the order of the system and the number of the tuning controller parameters. As a result, when modeling such complex high-order power systems, the model and parameter approximations cannot be avoided [11-14]. Therefore, the requirement of the LFC is to be robust against the uncertainties of the system model and the variations of system parameters in reality. Model Predictive Control (MPC) refers to a class of computer control algorithms that utilize an explicit process model to predict the future response of a plant. At each control interval an MPC algorithm attempts to optimize future plant behavior by computing a sequence of future manipulated variable adjustments. The first input in the optimal sequence is then sent into the plant, and the entire calculation is repeated at subsequent control intervals. Originally developed to meet the specialized control needs of power plants and petroleum refineries, MPC technology can now be found in a wide variety of application areas including chemicals, food processing, automotive, and aerospace applications. Several recent publications provide a good introduction to theoretical and practical issues associated with MPC technology [5]. A more comprehensive overview of nonlinear MPC and moving horizon estimation, including a summary of recent theoretical developments and numerical solution techniques are presented [6].

Model predictive control is also called recede horizon control [8]. The receding horizon concept is used because at each sampling instant the optimized control values for the model system over the prediction horizon are brought up to date, and at each sampling instant only the first control signal of the seguence calculated will be used to control the real system [9,10]. There are two important parameters in MPC which are prediction horizon and control horizon. Prediction horizon is the length of time for the process outputs to approach steady state values. Also, the control horizon is the number of discrete time control actions to be optimized along a future prediction horizon.

The Model Predictive and Fuzzy Logic Control are applied in the two-area load frequency power system model. Moreover, comparison between all controllers at different condition are evaluated. In general, the engineering tool MATLAB/Simulink is used to simulate both model predictive and fuzzy logic control in the power system under study [7].

2 Dynamic Model of the Power System

Figure 1 shows a block diagram of the i^th area of an N-area power system. Because of small changes in the load are expected during normal operation, a linearized area model can be used for the load-frequency control [15]. The following one area equivalent model for the system is modeled. The system investigated comprises an interconnection of two areas load frequency control.

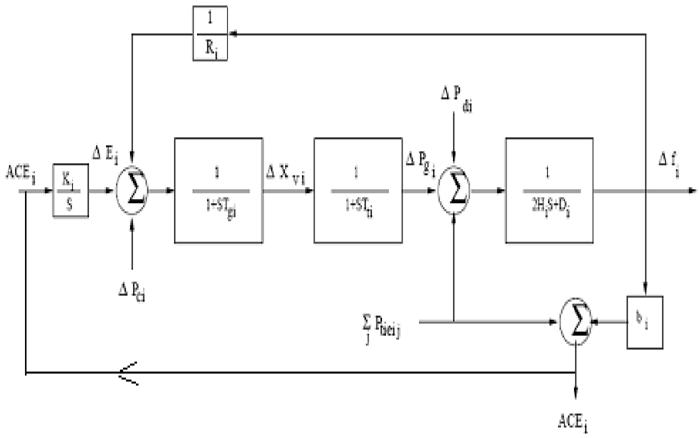

Fig. 1: Block diagram of the i^{th} area

The differential equation for the speed governor is such:

$$\Delta \dot{x}_{vi}(t) = -\frac{1}{T_{gi}}\Delta x_{vi}(t) - \frac{1}{T_{gi}R_i}\Delta f_i(t) + \frac{1}{T_{gi}}\Delta p_{ci}(t) - \frac{1}{T_{gi}}\Delta E_i(t) \qquad (1)$$

The differential equation for the turbine generator is such:

$$\Delta \dot{p}_{gi}(t) = -\frac{1}{T_{ti}}\Delta p_{gi}(t) + \frac{1}{T_{ti}}\Delta x_{vi}(t) \qquad (2)$$

The differential equation for the power system is such:

$$\Delta \dot{f}_i(t) = -\frac{D_i f_o}{2H_i}\Delta f_i(t) - \frac{f_o}{2H_i} * (\Delta p_{tie,i}(t) - \Delta p_{gi}(t) + \Delta p_{di}(t)) \qquad (3)$$

The tie-line power equation is such:

$$\Delta \dot{p}_{tie,i}(t) = \sum_{i=1}^{N} T_{ij}(\Delta f_i(t) - \Delta f_j(t)) \qquad (4)$$

And

$$\Delta E_i(t) = K_i \Delta p_{tie,i}(t) - K_i b_i \Delta f_i(t) \qquad (5)$$

Where;

Δf_i = the incremental frequency deviation for the ith area;

Δp_{ci} = the incremental change in speed changer position for the ith area;

Δp_{di} = the incremental change in load demand for the ith area;

Δp_{gi} = the incremental change in power generation level for the ith area;

Δp_{tie} = the incremental tie-line power;

Δx_{vi} = incremental change in valve position for the ith area;

ΔE_i = the incremental change in the integral control for the ith area;

f_o = the nominal frequency of the system;

D_i = the load frequency constant for the ith area;

H_i = the inertia constant for the ith area;

b_i = the bias constant for the ith area;

K_i = the gain constant for the ith area;

R_i = the regulation constant for the ith area;

T_{gi} = the governor time constant for the ith area;

T_{ij} = the synchronizing constant between the ith and jth area;

T_{ti} = the turbine time constant for the ith area;

Let

$$\Delta p_{tie}(t) = \Delta p_{tie,1}(t) = -\Delta p_{tie,2}(t) \qquad (6)$$

The overall state vector for two-area load frequency control system is defined such:

$x_1(t) = \Delta p_{tie}(t)$; $x_2(t) = \Delta f_1(t)$;

$x_3(t) = \Delta p_{g1}(t)$;

$x_4(t) = \Delta x_{v1}(t)$ $x_5(t) = \Delta E_1(t)$; $x_6(t) = \Delta f_2(t)$;

$x_7(t) = \Delta p_{g2}(t)$; $x_8(t) = \Delta x_{v2}(t)$ $x_9(t) = \Delta E_2(t)$

The control vector is such:

$$u(t) = \begin{bmatrix} u_1(t) \\ u_2(t) \end{bmatrix} = \begin{bmatrix} \Delta p_{c1}(t) \\ \Delta p_{c2}(t) \end{bmatrix}$$

The two-area power system can be written in state-space form as follows

$$\dot{x}(t) = Ax(t) + Bu(t) + d(t) \qquad (7)$$

Where;

$$A = \begin{bmatrix} 0 & T_{12} & 0 & 0 & 0 & -T_{12} & 0 & 0 & 0 \\ \frac{-f_o}{2H_1} & \frac{-f_o D_1}{2H_1} & \frac{f_o}{2H_1} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{-1}{T_{t1}} & \frac{1}{T_{t1}} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{-1}{T_{g1}R_1} & 0 & \frac{-1}{T_{g1}} & \frac{-1}{T_{g1}} & 0 & 0 & 0 & 0 \\ K_1 & -K_1 b_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{f_o}{2H_2} & 0 & 0 & 0 & 0 & \frac{-f_o D_2}{2H_2} & \frac{f_o}{2H_2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{-1}{T_{t2}} & \frac{1}{T_{t2}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{-1}{T_{g2}R_2} & 0 & \frac{-1}{T_{g2}} & \frac{-1}{T_{g2}} \\ -K_2 & 0 & 0 & 0 & 0 & -K_2 b_2 & 0 & 0 & 0 \end{bmatrix} \qquad (8)$$

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \\ x_9 \end{bmatrix}, \qquad B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{1}{T_{g1}} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{1}{T_{g2}} \\ 0 & 0 \end{bmatrix}, \qquad (9)$$

$$d(t) = \begin{bmatrix} 0 \\ \dfrac{-f_o}{2H_1}\Delta p_{d1}(t) \\ 0 \\ 0 \\ 0 \\ \dfrac{-f_o}{2H_2}\Delta p_{d2}(t) \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

3 Design of Fuzzy Logic Load Frequency Control System

Fuzzy interference system (FIS) consists of input block, output block and their respective membership functions. The rules are framed according to the requirement of the frequency deviation. More number of rules gives more accurate results. A normalized values of two inputs frequency error (deviation) e and change in frequency error (deviation) ce and defuzzified value of control command (Δu) as an output are considered. Basically, Fuzzy system includes three processes: a) Normalization b) Fuzzification and c) Defuzzification. Fig. 2 depicts the stages of fuzzy system. A centroid method is implemented for defuzzification stage. Fuzzification mamdani method is used.

Fuzzy logic has an advantage over other control methods due to the fact that it does not sensitive to plant parameter variations. The fuzzy logic control approach consists of three stages ,namely fuzzification, fuzzy control rules engine, and defuzzification. To design the fuzzy logic load frequency control, the input signals is the frequency deviation e(k) at sampling time and its change ce(k). While, its output signal is the change of control signal ΔU(k) . When the value of the control signal (U(k-1)) is added to the output signal of fuzzy logic controller, the result control signal U(k) is obtained. While the fuzzy membership function variable signals e , ce, and Δu are shown in Fig. 3. Fuzzy control rules are illustrated in table 1. The membership function shapes of error and error change are chosen to be identical with triangular function for fuzzy logic control.

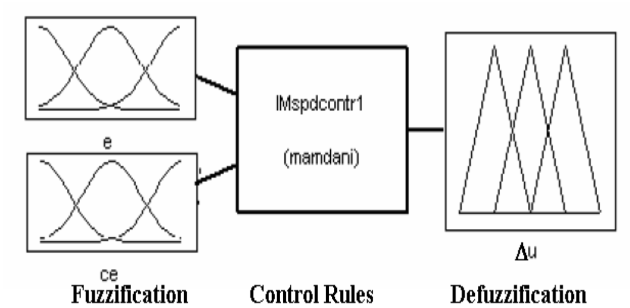

Fig. 2 **:** The three stages of fuzzy system

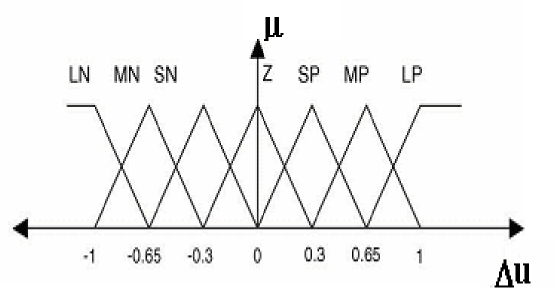

Fig. 3: The features of output membership function

Table 1: Fuzzy logic control rules of Δu .

e	Ce						
	LN	MN	SN	Z	SP	MP	LP
LN	LP	LP	LP	MP	MP	SP	Z
MN	LP	MP	MP	MP	SP	Z	SN
SN	LP	MP	SP	SP	Z	SN	MN
Z	MP	MP	SP	Z	SN	MN	MN
SP	MP	SP	Z	SN	SN	MN	
LN	SP	Z	SN	MN	MN	MN	LN
LP	Z	SN	MN	MN	LN	LN	LN

Where; LN: large negative membership function; MN: medium negative; SN: small negative; Z: zero; SP: small positive; MP: medium positive; LP: large positive.

4 Model Predictive Control

MPC is a generic term for computer control algorithms that utilizes an explicit process model to predict future response of the plant [16]. An optimal input is computed by solving an open-loop optimal control problem over a finite time horizon, i.e. for a finite number of future samples. The number of samples one looks ahead is called the prediction horizon Np. In some MPC formulations a difference is made between prediction horizon and control horizon Nu. The control horizon is then the number of samples that the optimal input is calculated for. With a shorter control horizon than prediction horizon the complexity of the problem can be reduced. From the calculated input signal only the first element is applied to the system. This is done at every time step. The idea is thus to go one step at a time and check further and further ahead. The method can be described as ”repeated open-loop optimal control in feedback fashion”.

In an MPC-algorithm there are four important elements:

4.1 Model prediction

The MPC plant model is defined in discrete time state space as follows :

$$x(k+1) = Ax(k) + Bu(k) + B_{MD}\, u_{MD}(k)$$

$$y(k) = C\, x(k). \quad (10)$$

where $x(k)$ is the state vector, $u(k)$ the input vector, $u_{MD}(k)$ is called the vector of measured disturbances, i.e. input signals that are not calculated by the controller, and $y(k)$ is the output vector.

4.2 Cost function

The cost function is designed depending on what to minimize. Common is a quadratic cost function which penalizes both deviation from a state reference and changes in the control signal and is defined in the following equation [8,17].

$$\min \left\{ \begin{array}{l} \left(x_{N_p} - x_{ref,N_p}\right)^T S \left(x_{N_p} - x_{ref,N_p}\right) + \\ \sum_{i=0}^{N_p-1} \left[\begin{array}{l} \left(x_i - x_{ref,i}\right)^T Q_x \left(x_i - x_{ref,i}\right) \\ + \Delta u_i^T Q_u \Delta u_i \end{array} \right] \end{array} \right\} \quad (11)$$

Where

$$\Delta u_i = u(k+i) - u(k+i-1)$$

x_{ref} = state reference

x_{N_p} = state predicted

Q_x = weight matrices

Q_u =weight matrices

S =weight matrices

A penalty on Δu_i punishes rapid changes in the input signal, which can be used to reduce oscillations. According to a penalty on rapid changes in the input signal, it introduces integral action. However, this is coupled to the prediction horizon. Stationary errors can appear even if integral action is introduced via a penalty on Δu_i if the prediction horizon is not long enough.

In the cost function stated above, the prediction horizon (N_p) and the control horizon (N_u) are the same. Instead of a shorter control horizon, there is a penalty on x_{N_p} , which plays a similar role. MPC-toolbox, which will be used for implementation in Simulink, uses the formulation where N_u are distinct from N_p. The matrices S, Q_x and Q_u are weight matrices who decide the penalty on each term in the cost function. Most effort is put on minimizing the term with largest penalty. The general form of the cost function is defined by Eqn. (12)

$$\min J\,(x_{k+1}) = \textstyle\sum_{k=0}^{\infty} I(x_k, u_k) \quad (12)$$

Where;

$$x_{k+1} = f(x_k, u_k)$$

According to this definition of the cost function, a simple criterion function will be

$$J = \textstyle\sum_{k=0}^{\infty} [(y_k - w_k)^2 + \gamma u_k^2] \quad (13)$$

Where y_k is the predicted output at sampling time k.

w_k is the reference trajectory at sampling time k and

Now the controller output sequence u_{opt} over the prediction horizon is obtained by minimization of J at each sampling instant.

4.3 Constraints

Quadratic Optimization approach (QP) is used to solve the MPC problem. The QP is a convex problem, i.e. if a solution is found uniqueness is guaranteed. To get a QP the constraints need to be linear [17]. They are thus on the form:

$$x_o = given$$
$$u_{\min} \le u_i \le u_{\max,} \quad i = 0,....., N_p - 1$$
$$y_{\min} \le W x_i \le y_{\max,} \quad i = 1,\ldots,N_p \tag{14}$$

where the matrix W is the output states.

4.4 Optimization problem and algorithm

The optimization vector is:

$$U = \left[u^T(k),\ldots,u^T(k+N_p-1)\right]^T.$$

If a shorter control horizon than prediction horizon is used, it is assumed that

$u(k+i) = u(k+N_u-1)$ for all $i \ge N_u$. The problem now needs to be rewritten in terms of U only. This is in principle straightforward since [16]:

$$x(k) = A^k x(0) + \sum_{j=0}^{k-1} A^{k-1-j}(Bu(j) + B_{MD}u_{MD}(j)) \tag{15}$$

Finally the optimization problem becomes:

$$U_{\min} \le U^T HU + h^T U \tag{16}$$

where the matrices H and the vector h are build up by x_{ref}, u_{ref}, x_0,Q_x,Q_u, S, A, B and C.

The MPC-algorithm can now be summarized as:

a. Measure the current state $x(k)$ or estimate it using an observer.

b. Solve the k-th optimization problem to obtain

$$U = \left[u^T(k),\ldots,u^T(k+N_p-1)\right]^T.$$

c. Apply $u(k)$ to the system.

d. Update time k=k+1 and repeat from step 1.

Figure 4 depicts the proposed MPC applied on the two-area load frequency control model.

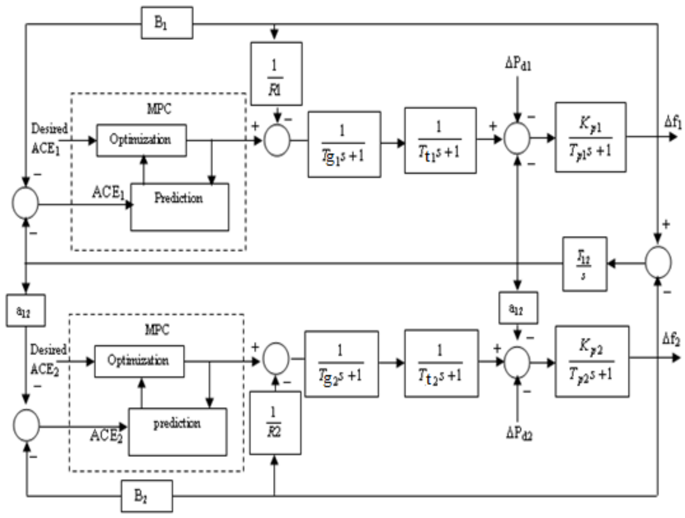

Fig. 4: The proposed MPC of the two-area load frequency control.

5 Digital Simulation Results

The block diagram of the two-area load frequency control with the proposed MPC is shown in Fig. 4. The entire system has been simulated and subjected to different parameters changes on the digital computer using the Matlab program and Simulink software package. The power system frequency deviations are obtained. A comparison between the power system responses using the conventional FLC and the proposed MPC are evaluated. The system investigated parameters are [1]:

f_o=60 HZ *R1=R2=2.4 HZ/per unit MW*
Tg1=Tg2=0.08 s *Tr=10.0s* *T_{t1}=T_{t2} =$_0$.3s*
TR=5 s *D1=D2=0.00833 Mw/HZ*

T1=48.7s *T2=0.513s* , Tp1= Tp2=20
Kp1=120; a12=-1;
Kp2=120; T_{12}=0.545 MW

From Eqns. (8, 9), the A matrix and B input vector are calculated as:

$$A=\begin{bmatrix} 0 & 0.54 & 0 & 0 & 0 & -0.54 & 0 & 0 & 0 \\ -6 & -.05 & 6 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -3.33 & 3.33 & 0 & 0 & 0 & 0 & 0 \\ 0 & -5.2 & 0 & -12.5 & -12.5 & 0 & 0 & 0 & 0 \\ 1 & -0.542 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 6 & 0 & 0 & 0 & 0 & -0.05 & 6 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -3.33 & 3.33 & 0 \\ 0 & 0 & 0 & 0 & 0 & -5.2 & 0 & -12.5 & -12.5 \\ -1 & 0 & 0 & 0 & 0 & -0.542 & 0 & 0 & 0 \end{bmatrix}$$

$$B=\begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 12.5 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 12.5 \\ 0 & 0 \end{bmatrix}$$

And , choice of MPC :
control horizon = 18
prediction horizon = 5

Figure 5 shows the system responses due to 5% load disturbance in area-1 without any control. Fig. 6 displays the frequency deviation response in pu. of area-1 due to 0.05p.u. load disturbance in area-1 of the two- area power system with FLC and proposed MPC. Fig.7 shows the frequency deviation response in pu. of area-2 due to 0.05p.u.load disturbance in area-1 of the two- area power system with FLC and proposed MPC. Fig. 8 shows the tie-line power deviation response in pu. of area-1 due to 0.05p.u.load disturbance in area-1 of the two- area power system with FLC and proposed MPC. Fig. 9 shows the frequency deviation response in pu. of area -1 due to 0.05p.u.load disturbance in area-2 of the two- area power system. Also, Fig. 10 depicts the frequency deviation response in pu. of area -2 due to 0.05p.u.load disturbance in area-2 of the two- area power system. Fig.11 depicts the tie-line power deviation response in pu. due to 0.05p.u.load disturbance in area-2 of the two- area power system with FLC and proposed MPC. Table 2 discribes the settling time and under shoot calculation with FLC and MPC.

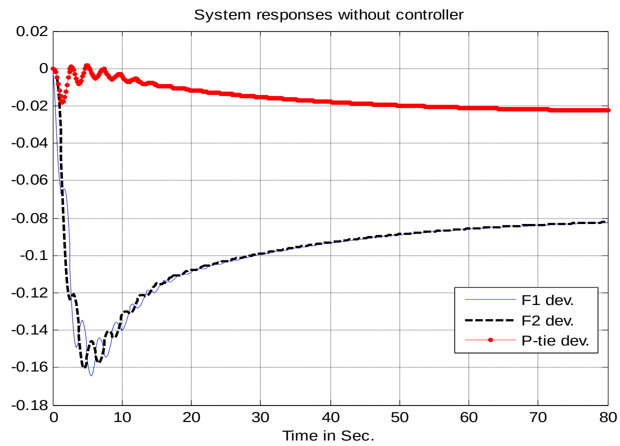

Fig. 5: The system responses in pu. due to 5% disturbance without any control

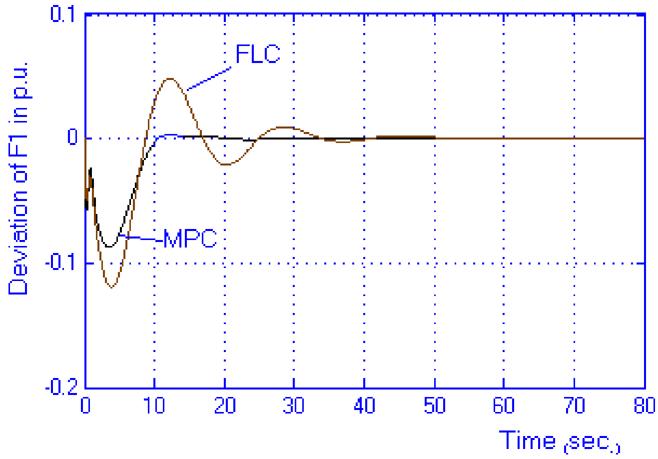

Fig. 6: Frequency deviation response in pu. of area-1 due to 0.05 p.u. load disturbance in area-1 of the two- area power system with FLC and proposed MPC.

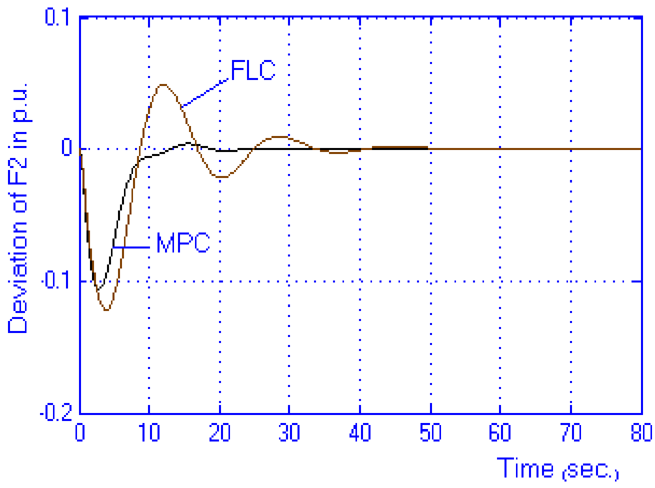

Fig. 7 **:** Frequency deviation response in pu. of area-2 due to 0.05 p.u. load disturbance in area-1 of the two- area power system with FLC and proposed MPC

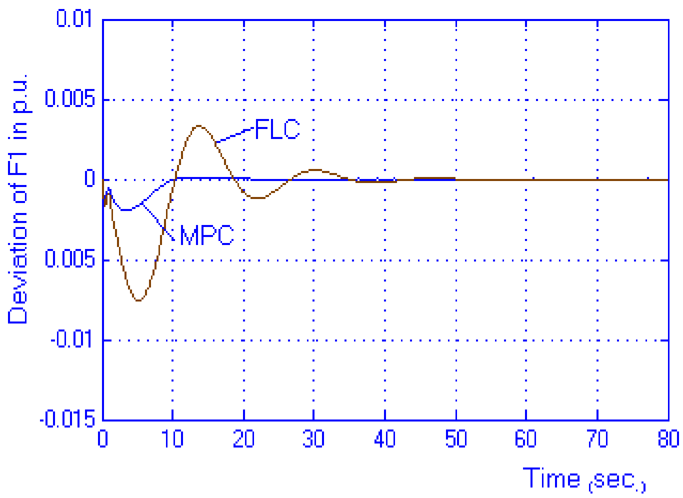

Fig. 9**: :** Frequency deviation response in pu. of area-1 due to 0.05 p.u. load disturbance in area-2 of the two- area power system with FLC and proposed MPC

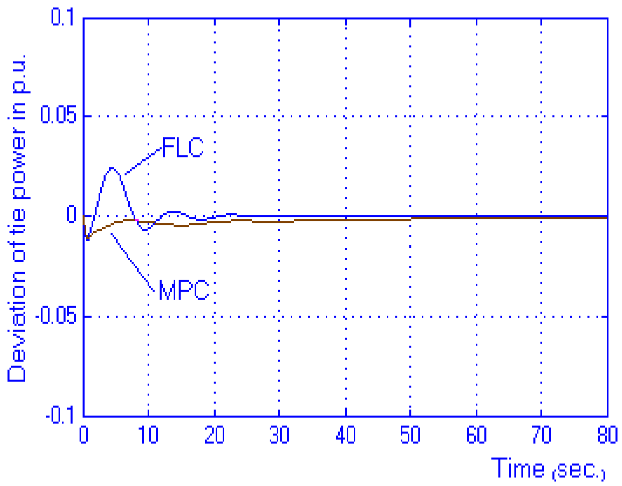

Fig. 8:Tie-line power deviation response in pu. due to 0.05p.u.load disturbance in area-1 of the two- area power system with FLC and proposed MPC .

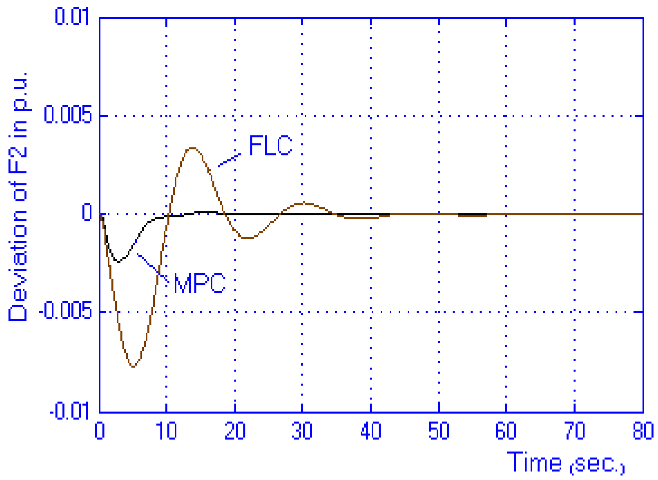

Fig. 10**:** Frequency deviation response in pu. of area-2 due to 0.05 p.u. load disturbance in area-2 of the two- area power system with FLC and proposed MPC.

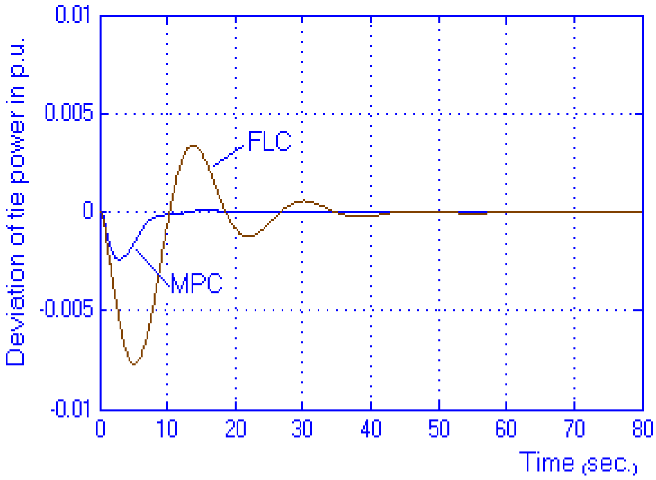

Fig. 11: Tie-line power deviation response in pu. due to 0.05p.u.load disturbance in area-2 of the two-area power system with FLC and proposed MPC.

Table 2: The settling time and under shoot calculation with FLC and MPC.

	5% Load disturbance in area No:1				5% Load disturbance in area No:2			
	FLC		MPC		FLC		MPC	
	T_s (Sec.)	Under Shoot in pu.	T_s (Sec.)	Under Shoot in pu.	T_s (Sec.)	Under Shoot in pu.	T_s (Sec.)	Under Shoot in pu.
Δf_1	40	-0.12	10	-0.07	40	-0.007	10	-0.001
Δf_2	41	-0.13	20	-0.1	42	-0.008	10	-0.002
Δp_{tie}	25	-0.025	20	-0.01	42	-0.008	10	-0.002

Where; T_s =The settling time in Sec.

6 Discussions

The Fuzzy Interference System (FIS) matrix for fuzzy logic controoler is devolped, considering 49 rules as in table-1 by using Gaussian, Trapizoidal and Triangular membership functions. Moreover, a MPC simulink is designed based on power system model , control horizon and prediction horizon. Various transient response curves of Δf_1, Δf_2 , $\Delta P_{tie-line}$ are drawn and comparative studies have been made. The following points may be noted:

1. From Fig. 5 notice that the two-area load frequency control power system has steady state error without any control.
2. From figures 6:11 and table 2, the frequency deviation responses based on proposed MPC is better than fuzzy logic control in terms of fast response and small settling time.
3. The tie line power is also fastly decreased in case of MPC than fuzzy logic control.
4. The performance of the MPC is seen in figures 6:11 and table 2 was effective enough to eliminate the oscillation after 10 Sec.
5. The performance of the FLC is seen in figures 6:11 and table 2 was not effective enough to eliminate the oscillation after 40 Sec.
6. In order to have a better prediction of the future behavior of the plant, the prediction horizon should be more than the period of the system.
7. Model predictive control has been shown to be successful in addressing many large scale non-linear control problems.

7 Conclusions

This paper addressed the load frequency control problem of interconnected power systems. Two control schemes are proposed for the system. The design of the proposed control schemes was based on fuzzy logic and model predictive controls. The load-frequency control system based MPC for enhancing power system dynamic performances after applying several disturbances was evaluated. The proposed controllers are robust and gives good transient as well as steady -state performance. To validate the effectiveness of the proposed controller a comparison among the FLC and proposed MPC controller is obtained. The proposed controller proves that it is robust to variations in disturbance changes from area-1 and area-2. The digital simulation results proved that the effectiveness of the proposed MPC over the FLC through a wide range of load disturbances. The superiority of the proposed MPC is embedded in sense of fast response with less overshoot and / or undershoot and less settling time.

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