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An integral square error-based model predictive controller for two area load frequency control

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Abstract. The main objective of load frequency control (LFC) is to keep the frequency value at nominal value and force deviation of the frequency to zero in case of load change. This paper suggests LFC by using a model predictive control (MPC), based on Integral Square Error (ISE) method designed to optimize the damping of oscillations in a two-area power system. The MPC is designed and simulated with a model system in state space, for robust performance in the system response. The proposed MPC is tuned by ISE to achieve superior efficiency. Moreover, its performance has been assessed and compared with the PI and PID conventional controllers. The settling time and overshoot with MPC are extremely minimized as compared with conventional controllers.

Keywords: load frequency control; model predictive control; integral square error technique

1. Introduction

The electrical power system composed of multi-area, each area structure from one generator or many generators, these areas are interconnected with each other by tie-lines and interconnected for power exchange. Frequency control, through the generation and load imbalance, denotes a very imperative issue for large-scale power systems. Automatic generation control (AGC) function ensures that the values at which the system works in abnormal operating condition are at nominal values (Yousef 2015, Kundur 1994, Saadat 1999, Sahu *et al.* 2015, Shabani *et al.* 2013). And is continually referred to as "load frequency control (LFC)" as cited by (Kundur 1994). LFC is a highly important for power system stabilizer, the frequency deviation causes changes in load and the LFC forced deviation of the frequency Δf to return to a specific nominal value that the system works in the normal state. LFC is accomplished via two various control actions, the first is the elementary velocity control, and the second is the supplementary speed turbine control made by the speed governor in an interconnected power system (Yousef *et al.* 2015, Khodabakhshian and Edrisi 2008, Pandey *et al.* 2013).

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The LFC is studied with Proportional Integral Derivative Control (PID) conventional or optimization methods and fuzzy logic control (FLC). PID controller and optimization techniques are design based on a bacterial foraging optimization algorithm (BFOA), particle swarm optimization (PSO) and imperialist competitive algorithm (ICA) (Shabani *et al.* 2013, Ali and Abd-Elazim 2013, Soundarrajan *et al.* 2010). The greatest value of the controller parameter is obtained by tuning methods, and it achieved high performance and fast response to the system. A fractional order PID (FOPID) was proposed in three area power system and this technique of the control have five parameters, based on genetic algorithm (GA) to determine the control parameters (Bayati *et al.* 2015). Minimizing integral square error (ISE) with natural filtered derivative action was proposed to design a robust Fractional Order PID controller in three areas reheat thermal system using a differential evolution algorithm (DEA) to compute the control parameters (Delassi *et al.* 2015). Fuzzy PID control with teaching learning-based optimization algorithm (TLBO) was studied in two area unequal connected thermal system (Sahu *et al.* 2015). A hybrid fuzzy PI/PID and fuzzy PID based on the optimization method to computing parameter of the controller. A differential evolution at pattern search (DEPS), local unimodal sampling (LUS-TLBO) and DE algorithm with derivative Filter (PIDF) are applied in multi-area multi-source interconnected power system through HVDC link (Sahu *et al.* 2015, 2016, 2014).

Model Predictive Control (MPC) is a component of the modern control principle and a practical technique that high performance. MPC is optimum control approach based on algebraic optimization. The control input is in the future and the response of the future plant is expected using a system model and improved periodically with deference to index performance. Supervisory predictive control is design to calculate the optimal set points for a decentralized local control in multi-area thermal and hydro power systems (Shiroei and Ranjbar 2014, Camponogara *et al.* 2002). The MPC technique in power system affects the uncertainty because of the governor, turbine parameter difference and the disturbance of load is minimized (Mohamed *et al.* 2011). Distributed MPC was studied in three areas interconnected power systems (Ma *et al.* 2014). The dynamic model of the system depends on Generation Rate Constraint (GRC) and load reference preset constraint are considered.

This paper suggests the ISE technique for optimal tuning of MPC controllers in two area to damping oscillations power system. The MPC control strategy is formulated as an optimization problem and the ISE is employed to search for optimal controller parameters by minimizing applicant time-domain based on objective function. The performance of the suggested MPC-based ISE is appraised by comparison with optimized conventional PI and PID controllers. The results of simulation on a two-area power system are obtainable to assure the authority of the proposed method compared with optimized conventional PI or PID controllers.

2. Two area power system

An interconnected two-area power system is shown in Fig. 1. Each area has its own control system affected by disturbances that occur in related areas, because of the changing demands loads, preferably connecting all regions unified network (Das *et al.* 2012). Control signal through the governor speed re-adjust the speed of the turbine by controlling the valve to restore the scheduled frequency value (Ali and Abd-Elazim 2013, Alrifai and Zribi 2005). The equation which describes this system as follows

$$X = A\,x + B\,u + L\,d \tag{1}$$

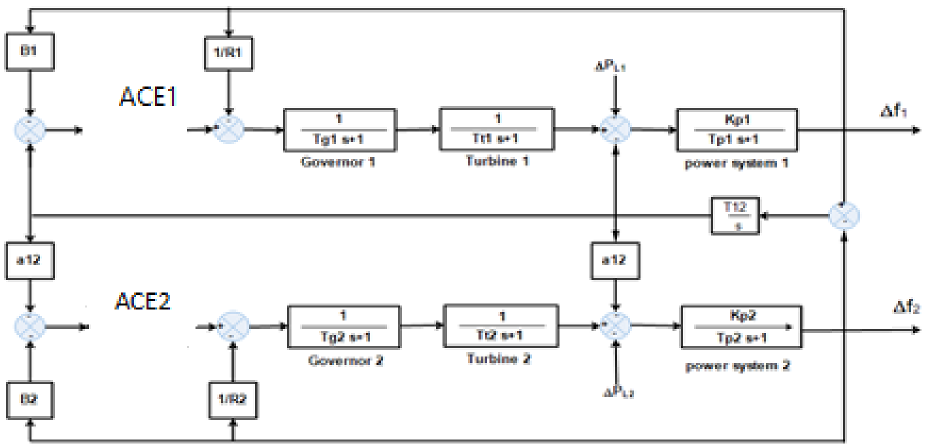

Fig. 1 Two-area interconnected power system

$$y= C\,x \tag{2}$$

where A is the system matrix, B is the input matrix, L is the disturbances matrix, and $x(t)$, $u(t)$ are state control vectors, $d(t)$ is the load disturbance vectors.

$$A=\begin{bmatrix} -\frac{1}{Tp_1} & \frac{Kp_1}{Tp_1} & 0 & 0 & 0 & 0 & -\frac{Kp_1}{Tp_1} & 0 & 0\\ 0 & -\frac{1}{T_{t1}} & \frac{1}{T_{t1}} & 0 & 0 & 0 & 0 & 0 & 0\\ \frac{1}{R_1T_{g1}} & 0 & -\frac{1}{T_{g1}} & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & -\frac{1}{Tp_2} & \frac{Kp_2}{Tp_2} & 0 & -\frac{Kp_2}{Tp_2} & 0 & 0\\ 0 & 0 & 0 & 0 & -\frac{1}{T_{t2}} & \frac{1}{T_{t2}} & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{1}{R_2T_{g2}} & 0 & -\frac{1}{T_{g2}} & 0 & 0 & 0\\ T_{12} & 0 & 0 & -T_{12} & 0 & 0 & 0 & 0 & 0\\ -B_1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0\\ 0 & 0 & 0 & -B_2 & 0 & 0 & -a_{12} & 0 & 0 \end{bmatrix} \tag{3}$$

$$B=\begin{bmatrix} 0 & 0\\ 0 & 0\\ \frac{1}{T_{g1}} & 0\\ 0 & 0\\ 0 & 0\\ 0 & \frac{1}{T_{g2}}\\ 0 & 0\\ 0 & 0\\ 0 & 0 \end{bmatrix}\quad d(t)=\begin{bmatrix} -\frac{Kp_1}{Tp_1} & 0\\ 0 & 0\\ 0 & 0\\ 0 & -\frac{Kp_2}{Tp_2}\\ 0 & 0\\ 0 & 0\\ 0 & 0\\ 0 & 0\\ 0 & 0 \end{bmatrix},\quad x=\begin{bmatrix} x_1\\ x_2\\ x_3\\ x_4\\ x_5\\ x_6\\ x_7\\ x_8\\ x_9 \end{bmatrix}$$

$u = [u_1\ u_2]^T$, $y = [y_1\ y_2]^T = [ACE_1\ ACE_2]^T$

where

T_{12}=the synchronizing constant between the area 1 and area 2.
T_t=time constant of the turbine.
T_g=time constant of the governor.
B=the bias constant for each area.
R=the regulation constant for each area.
ΔP_d=the power load demand change.
K_p=gain for each area power system.
T_p=time constant for each area power system.

2.1 Area control error (ACE)

$$ACE = \Delta P_{tie} + B_f \Delta f = (P_{tie} - P_{tie,sched}) + B_f (f - f_s) \quad (3)$$

where ΔP_{tie} is the power deviation in tie line, B_f is called a frequency bias constant, ΔF is the frequency deviation, $P_{tie,sched}$ is the power value scheduled in tie line, F_s is the frequency value nominal. P_{tie} is the new power value in tie line, F is the new frequency value when the power system is disturbance. A control center in each area monitors performance of units and power flow, frequency and demand loads (Glover *et al.* 2012).

3. Model predictive control (MPC)

MPC has been adopted widely in the industry as an operative way to deal with the problem of multi variable control constrained, and form a clear system to predict the future path of the system and output (Ang *et al.* 2005). Fig. 2 shows model predictive controls with the plant, the terminal mo, ref, and mv are measured output signal, reference signal and manipulated variables (mv) by solving a quadratic program (QP) respectively. The technique of controller based on the optimal procedure performed at each sampling period over the expectation horizon, resulting in optimum action control, and gives more elasticity in the operation of the unit process (Bevrani 2009, Mohamed *et al.* 2010). Horizon control is then the number samples that are calculated for optimum input. With control horizon is shorter than the prediction horizon complication of the problem can be reduced. The input signal only counted the first element of the system application. The controller performance index is based on control and output signals

$$J(N_1, N_2, N_u) = \sum_{j=N_1}^{N_2} \beta(j)[\hat{y}(k+j|k) - w(k+j)]^2 + \sum_{j=1}^{N_u} \lambda(j)[u(k+j-1)]^2 \quad (4)$$

where N_1, N_2 are lower and upper prediction horizons over the output, N_u is the horizon of control, $\beta(j)$ and $\lambda(j)$ are weighting factors. Horizon control permits to reduce the number of future calculated per the relationship control ($\Delta u\ (k+j)$=0 for $j \geq N_u$). The $w(k+j)$ it represents a reference about the future path horizon. Limitations on control reference, and output control you can add reference to change the function of the costs as follows

$u_{min} \leq u(k) \leq u_{max}$, $\Delta\ u_{min} \leq u(k) \leq \Delta u_{max}$, $y_{min} \leq y(k) \leq y_{max}$.

Design of MPC in state space it depends on the following

$$x(k+1) = A\ x(k) + B1\ e(k) + B2\ u(k). \quad (5)$$

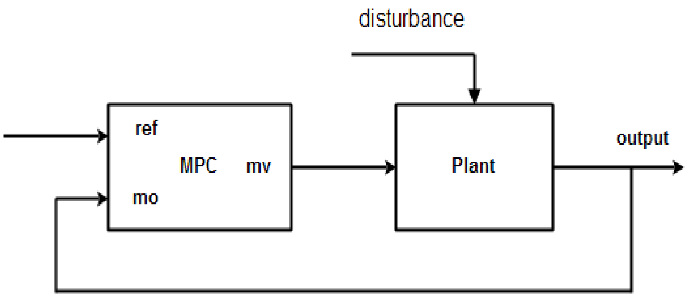

Fig. 2 MPC scheme

$$x(k+1) = A\,x(k) + B1\,e(k) + B2\,u(k). \tag{6}$$

Where $x(k)$ is the state of the system, $e(k)$ is manipulated values or input signals, $u(k)$ is a measurement of disturbances, $y(k)$the system outputs.

Design MPC based on ISE and can be minimized of the objective function

$$J = \int_0^t ISE^2\,dt = \int_0^t (ACE_1^2 + ACE_2^2)\,dt \tag{7}$$

The design control proposed based on the following values:
Control interval (time units)=0.1
Prediction horizon (interval)=8
Control horizon (interval)=2

4. Simulation results and discussion

The suggested two-area power system interconnected based MPC is shown in Fig. 3. The proposed scheme of the system by MPC has been simulation using MATLAB program Simulink, and simulated in state space using three control techniques MPC, conventional PI controller, and conventional PID controller. In this part, different comparative cases are examined to show the efficacy of the suggested ISE method for optimizing controller parameters of MPC. Results are presented in response to a compared between the suggested schemes MPC, PI and PID conventional control. Table 1 shows the parameters of the simulated system (Kassem 2010):

Table 1 parameters of the simulated system

B_1=B_2		0.4 MW/Hz		T_{t1}=T_{t2}	0.3sec
T_{g1}=T_{g2}	0.08sec	R_1=R_2	2.4Hz/pu MW	T_{12}	0.545pu MW
T_{P1}=T_{P2}	20sec	K_{p1}=K_{P2}	120	a_{12}	-1

4.1 Case 1: 3% step increase demand in the first area (ΔP_{L1})

In this case, a 3% step increase in demand load of the first area (ΔP_{L1}) is applied. The variation in frequency of the first area Δf_1, the variation in frequency of the second area Δf_2, and variation in tie-line power system are shown in Figs. 4-6. The system response through conventional PI

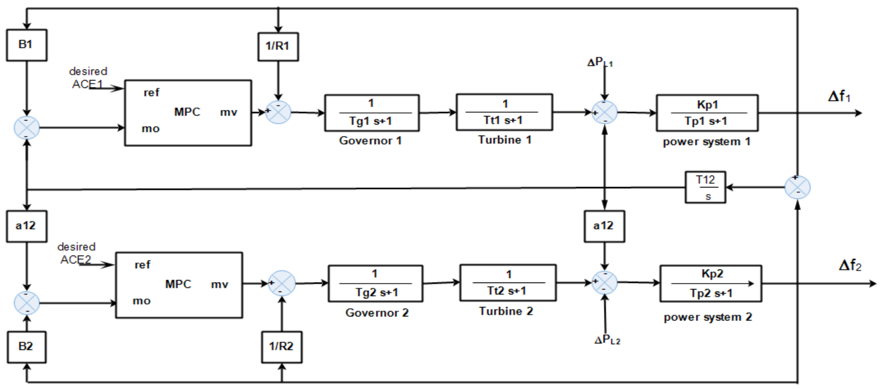

Fig. 3 Proposed two-area LFC scheme by using MPC

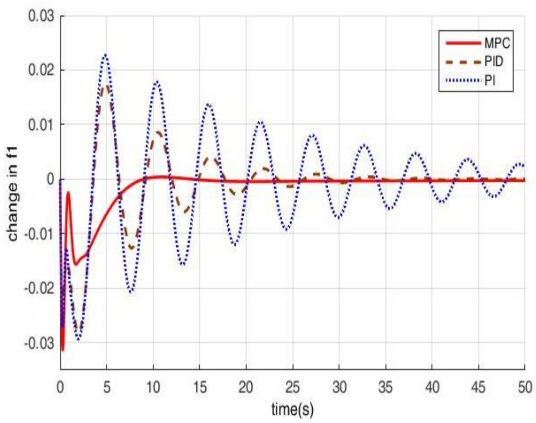

Fig. 4 Change in f_1 for 3% step increment in P_{L1}

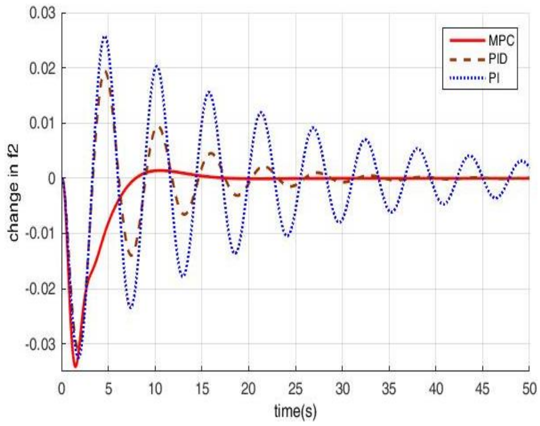

Fig. 5 Change in f_2 for 3% step increment in P_{L1}

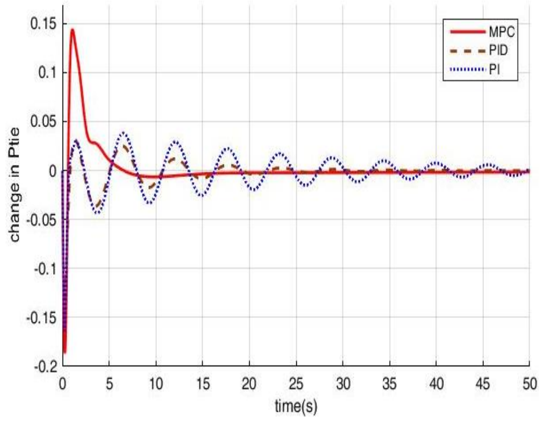

Fig. 6 Change in P_{tie} for 3% step increment in P_{L1}

controller has high settling time and undesirable oscillations. Also, compared with conventional PID controller, the settling time in suggested method is minimized and distinctive damping of power system is achieved.

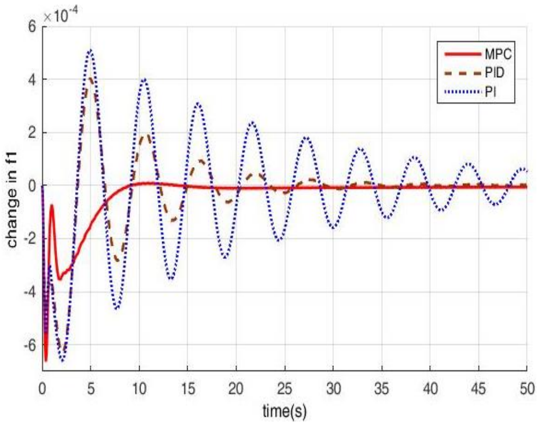

Fig. 7 Change in f_1 for 3% step increment in P_{L2}

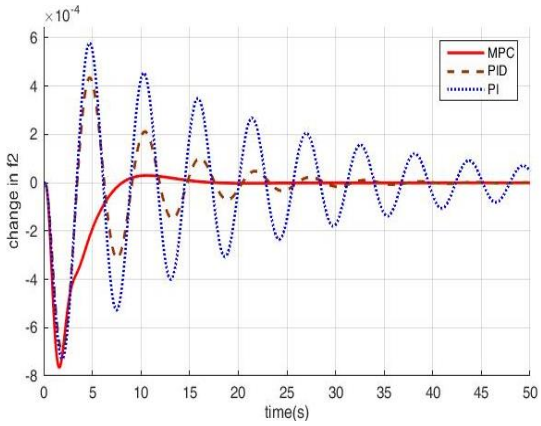

Fig. 8 Change in f_2 for 3% step increment in P_{L2}

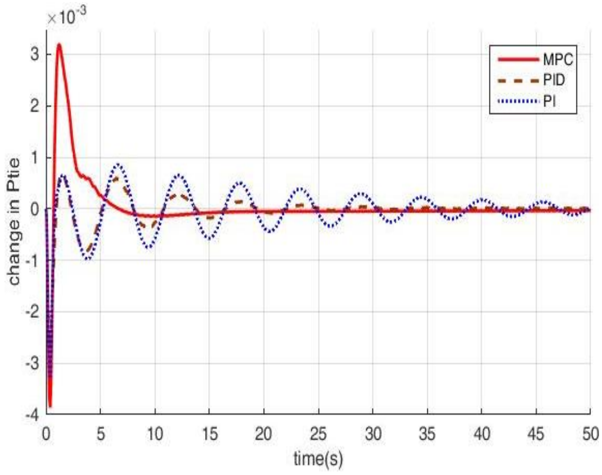

Fig. 9 Change in P_{tie} for 3% step increment in P_{L2}

4.2 Case 2: 3% step increase demand in the second area (ΔP_{L2})

In this case, a 3% step increase is applied as a change demand in the second area (ΔP_{L2}). The variation in frequency of the first area Δf_1, the variation in frequency of the second area Δf_2 and variation in the tie-line power system are shown in Figs. 7-9. From these figures, it can be seen that oscillations are disappeared in the presence of the suggested controller. The suggested method is superior and outlasts conventional PID controller in damping oscillations effectively and reducing settling time. MPC based ISE significantly enhances the system stability.

4.3 Case 3: 3% step decrease demand in the second area (ΔP_{L1})

In this case, a 3% step decrease is applied as a change of demand in the first area (ΔP_{L1}). The variation in frequency of the first area Δf_1, the variation in frequency of the second area Δf_2 and variation in tie-line power system are shown in Figs. 10-12. The proposed method is really more efficient in improving the damping characteristic of the power system.

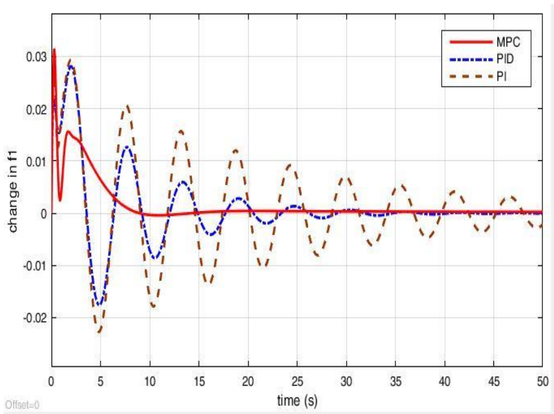

Fig. 10 Change in f_1 for -3% step increment in P_{L1}

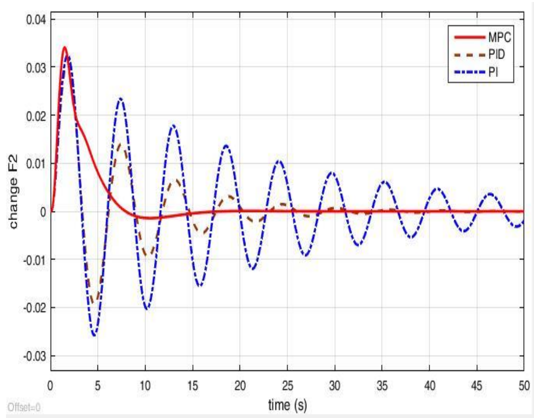

Fig. 11 Change in f_2 for -3% step increment in P_{L1}

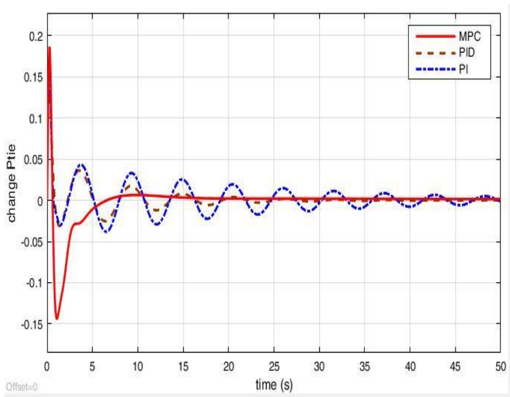

Fig. 12 Change in P_{tie} for -3% step increment in P_{L1}

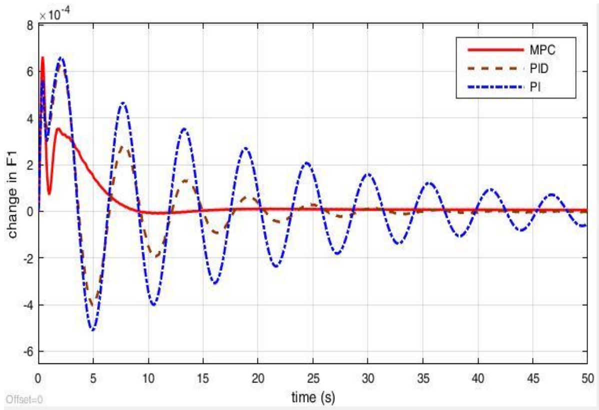

Fig. 13 Change in f_1 for -3% step increment in P_{L2}

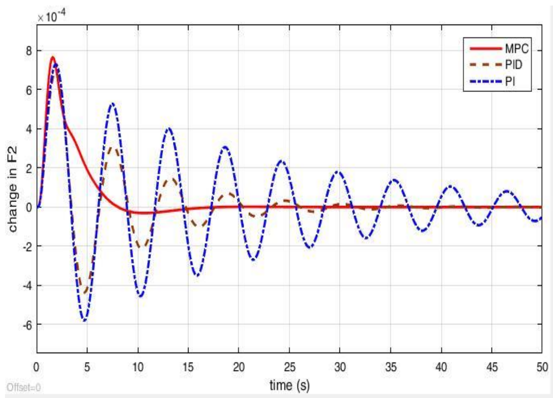

Fig. 14 Change in f_2 for -3% step increment in P_{L2}

4.4 Case 4: 3% step decrease demand in the second area (ΔP_{L2})

In this case, a 3% step decrease is applied as a change of demand in the first area (ΔP_{L2}). The

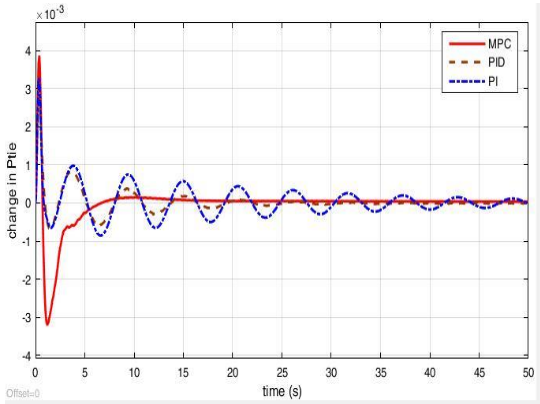

Fig. 15 Change in P_{tie} for -3% step increment in P_{L2}

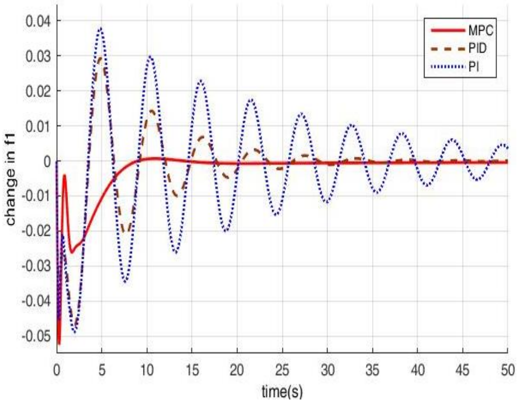

Fig. 16 Change in f_1 for 5% step increment in P_{L1}

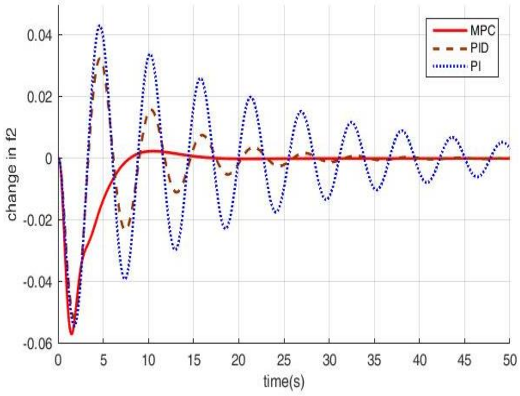

Fig. 17 Change in f_2 for 5% step increment in P_{L1}

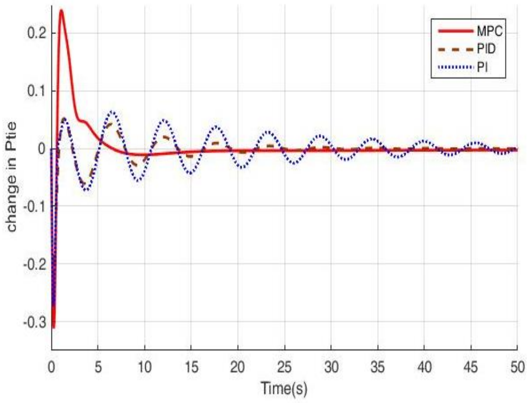

Fig. 18 Change in P_{tie} for 5% step increment in P_{L1}

variation in frequency of the first area Δf_1, the variation in frequency of the second area Δf_2 and variation in tie-line power system are shown in Figs. 13-15. The proposed MPC technique greatly boosts the system stability and improves the damping characteristics of power system.

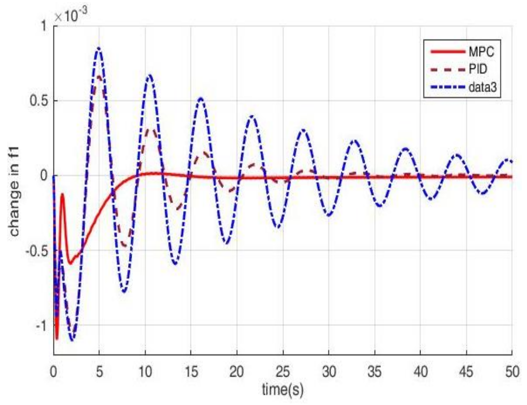

Fig. 19 Change in f_1 for 5% step increment in P_{L2}

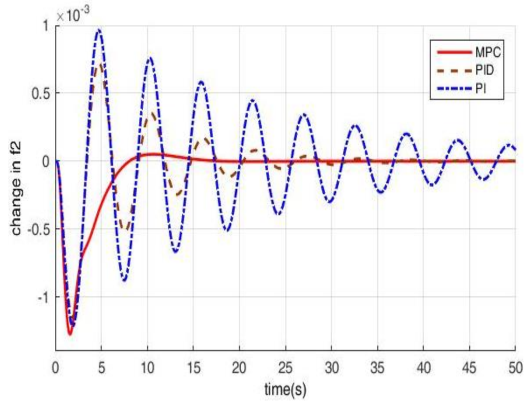

Fig. 20 Change in f_2 for 5% step increment in P_{L2}

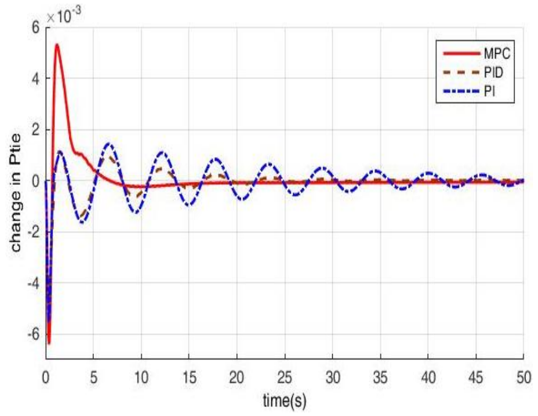

Fig. 21 Change in P_{tie} for 5% step increment in P_{L2}

4.5 Case 5: 5% step increase demand in the first area (ΔP_{L1})

In this case, a 5% step increase in demand load of the first area (ΔP_{L1}) is applied. The variation in frequency of the first area Δf_1, the variation in frequency of the second area Δf_2, and variation in tie-line power system are shown in Figs. 16-18. The superiority and potentiality of the suggested method over the conventional PI and PID is demonstrated.

4.6 Case 6: 5% step increase demand in the second area (ΔP_{L2})

In this case, a 5% step increase is applied as a change of demand in the second area (ΔP_{L2}). The variation in frequency of the first area Δf_1, the variation in frequency of the second area Δf_2 and variation in tie-line power system are shown in Figs. 19-21. The system response with the proposed MPC technique gives superior performance than PI and PID conventional techniques. Also, the rate of settling time and overshoot are minimized with MPC.

5. Conclusions

In this paper, the Model Predictive Control (MPC) technique, based on Integral Square Error (ISE) method to optimize load frequency in a two-area interconnected power system, was proposed. The ISE method is suggested to adjust the parameters of MPC controller. The simulation results confirmed that the design of MPC gives a robust performance to solve load frequency control (LFC) problem in case of disturbances that occur in area 1 and area 2. The system response, to damp oscillations using MPC, is fast and much better than conventional controllers. Moreover, the proposed MPC controller has a simple architecture and can be potentially implemented.

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