A Performance Evaluation of Load Frequency Controller using Discrete Model Predictive Controller

by Adelhard Rehiara

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***Abstract*—Load frequency control becomes one of the important parts in a power system since frequency deviation is an important issue in power system stability. This paper has introduced model predictive controller to handle the frequency deviation when disturbance happen. Result of simulation in a three area power system shows that PI controllers have faster response than model predictive controllers, but calculation shows that model predictive controller will have decay faster than PI controllers. On the other hand, model predictive controllers showed better performance in overshoot and signal processing time which is verified with disturbance variations in long time simulation.**

***Keywords*— Power system, load frequency, PI, MPC.**

I. INTRODUCTION

A power system consists of generator, transmission and/or distribution line and load. Load that connected to the power system can change every time. This condition will then influence frequency of the system. Load frequency control (LFC) is one of the main parts on power system to maintain the frequency fluctuation of load change. The main function of LFC is to maintain the frequency stable during exchange power on the network where the generator dispatch must satisfy the load demand.

A multi area power system can be complex system and so it will have high dynamic operation. Frequency control in a multi area power system can be done in either centralized or decentralized control. Both systems have its advantage and disadvantage depends on which condition it will be applied.

Some researchers have worked in the area of frequency control i.e. [1] designed an LFC using the model predictive control (MPC) for a multi-area power system including wind turbines, [2] presented a comparison of MPC and PI against a conventional Automatic Generation Control, [3] presented an LFC method based on Fuzzy Logic controller (FLC), and [4] purposed FLC-PID based LFC for multi-area interconnected power system.

The previous researches have demonstrated the effectiveness of MPC to control a plant and also compared the MPC with classical PI/PID controller. On the other hand the MPC capability and performance are never taking into account, while both are also significant to be evaluated. In this paper, two discrete controllers were built to test the behavior of a three area power system when the demand load is changed. The controllers are based on PI and MPC control and both controllers act as centralized controllers of the system.

II. MODEL PREDICTIVE CONTROL

An MPC is a multivariable and iteration based control algorithm that uses a process model, previous control moves and an objective function J throughout its prediction horizon to count its optimal control moves. In some condition the objective function should not violate any given constraints of the system. An MPC can be linear or nonlinear which is characterized by the use of its internal model and based on signal processing it is categorized as digital or continues MPC.

The objective of the predictive control system design is to have perfect model of the trajectory. A way to build the model is using an orthonormal function while the function can also be applied in dynamic system modeling. As MPC is a type of controller that used a model to predict the behavior of the controlled plant, this function will be used to define its model. Laguerre functions satisfy these properties and also possess simple Laplace transforms.

In general a plant model is built within continuous time framework. To be able to use in discrete time MPC, the model is needed to be discretized within a time sampling.

Laguerre function is built from its network that mainly applied in the system identification study and it is primarily built in continuous time. The function can be transformed to discrete time using z-transformation as shown in (1).

The Laguerre function is derived by building its state-space form in (2) and its initial condition in (3), where N is the length of Laguerre network, a is called time scaling factor, A_l is a Toeplitz matrix of parameters a and $1\text{-}a^2$, and L is the function's state vector [5].

$$\Gamma N = \frac{\sqrt{1-a^2}}{1-az^{-1}}\left(\frac{z^{-1}-a}{1-az^{-1}}\right)^{N-1} \tag{1}$$

$$L(k+1) = A_l\, L(k) \tag{2}$$

$$L(0) = \sqrt{1-a^2}\begin{bmatrix} 1 & -a & a^2 & -a^3 & \ldots & (-1)^{N-1}a^{N-1} \end{bmatrix} \tag{3}$$

Receding horizon control is done by taking a minimal solution of an objective function J as in (4).

$$J = \sum_{m=1}^{Np} x(k+m \mid k)^T Qx(k+m \mid k) + \eta^T R\eta \tag{4}$$

The control law with optimal gain K_{mpc} for close loop system can then be obtained in (5).

$$x(k+1) = (A - BK_{mpc})x(k) \tag{5}$$

$$K_{mpc} = L(0)^T \eta \tag{6}$$

$$\Delta u = -K_{mpc} x \tag{7}$$

Where $Q \in \Re^{ns \times ns}$ is a weighting matrix, Np is prediction horizon, Δu is control parameter vector, $R \in \Re^{ni \times ni}$ is a diagonal matrix contains tuning parameters for the desired closed-loop performance and $\eta \in \Re^{ns \times N}$ is an optimal solution of the parameter vector. The ni and ns are the number of input and state variable.

III. Controller Evaluation

A. Process Capability

The aim of a process capability study is to evaluate an output of a process whether it is capable to meet the process specification. Process capability can be measured in its index Cp as follows [6, 7].

$$Cp = \frac{USL - LSL}{6\sigma} \tag{8}$$

where, σ is the standard deviation and USL/LSL are upper/lower limit of process specifications. The process observations are covered by the process specification if Cp>1.0.

In case the process is asymmetrical, capability index is measured by taking the minimum value of the specification process using following equation [6, 7], while μ is a mean of the process.

$$C_{pk} = \min\left[\frac{USL - \mu}{3\sigma} - \frac{\mu - LSL}{3\sigma}\right] \tag{9}$$

B. Controller Performance

In general the measure of control performance can be in both time and peak criteria. In time criteria, the time of response, including rise time, peak time and settling time, are measured. On the other hand in peak criteria the other attribute of the response *i.e.* peak overshoot ratio and decay ratio are counted. All of the attribute can be seen in Fig. 1.

Rise time Tr is time needed for the process to first cross the set point and peak time Tp is the time for reaching the first peak while settling time Ts is the time for the process to remain within a band of about 5% of set point. In case there is no overshoot then only settling time is measured.

Peak overshoot ratio (POR) and decay ratio (DR) are formulated in (10) and (11) [8, 9].

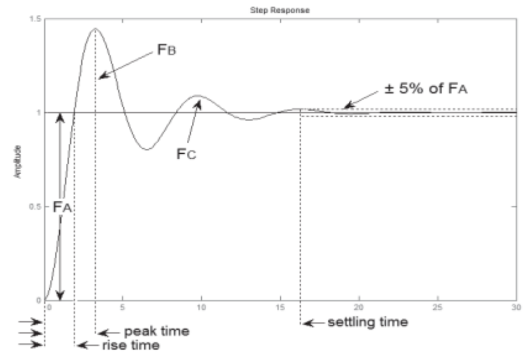

Fig. 1. Performance criteria

$$POR = \frac{1^{st}\ peak\ height}{setpoint\ step} = \frac{F_B}{F_A} \tag{10}$$

$$DR = \frac{2^{nd}\ peak\ height}{1^{st}\ peak\ height} = \frac{F_C}{F_B} \tag{11}$$

IV. Power System Model

Power system model is described using a differential algebraic equation (DAE) as [2]:

$$\dot{x} = f(x, q, u, w) \tag{12}$$

$$0 = g(x, q, u, w) \tag{13}$$

Where x, q, u and w are the dynamic system states, the algebraic system states, the controller inputs and the system disturbance respectively. The algebraic states are not appeared in DAE so that it can be removed from the (12) and (13). The (12) is called differential variable and (13) is an algebraic equation or well known as a constraint.

Power system dynamics which include tie line power change can be redrawn in Fig. 2 [1, 10].

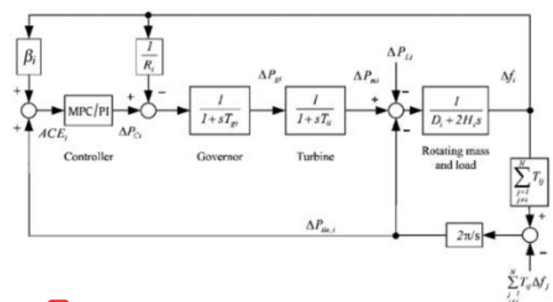

Fig. 2. Power system dynamics

The tie-line power change P_{tie} is calculated for all area n using (14) and the area control error (ACE) which is a suitable linear combination of frequency f and tie-line power changes for each area is found using (15) as follows [1].

$$\Delta P_{tie,i} = \frac{2\pi}{s}\left[\sum_{\substack{j=1 \\ j\neq i}}^{n} T_{ij}\Delta f_i - \sum_{\substack{j=1 \\ j\neq i}}^{n} T_{ij}\Delta f_j\right] \tag{14}$$

$$ACE_i = \Delta P_{tie,i} + \beta_i \Delta f_i \tag{15}$$

State space model for Fig. 2 is described in following equation.

$$\dot{x}(t) = Ax(t) + Bu(t) + Kw(t) \tag{16}$$

$$y(t) = Cx(t) + Du(t) \tag{17}$$

where

x(t) = State variables = $[\Delta P_{g,i}\ \Delta P_{m,i}\ \Delta f_i\ \Delta P_{tie,i}]^T$

u(t) = Input variables = $[\Delta P_{L,i}\ \Delta v_i]^T$

w(t) = Control variable = $\Delta P_{c,i}$

y(t) = Output variable = ACE_i

The Δv_i from the state space model is defined as control area interface and it is formulated as [1, 10]:

$$\Delta v_i = \sum_{\substack{j=1 \\ j\neq i}}^{n} T_{ij}\Delta f_j \tag{18}$$

The feed forward matrix of the state space model is zero since there is no direct connection between input and output variable. Therefore the matrix can be removed from the system matrices model. Then matrices of the system model are written in (19)-(23) [1].

$$A = \begin{bmatrix} -\frac{1}{T_{g,i}} & 0 & -\frac{1}{R_i T_{g,i}} & 0 \\ \frac{1}{T_{t,i}} & -\frac{1}{T_{t,i}} & 0 & 0 \\ 0 & \frac{1}{2H_i} & -\frac{D_i}{2H_i} & -\frac{1}{2H_i} \\ 0 & 0 & 2\pi\sum_{\substack{j=1 \\ j\neq i}}^{N} T_{ij} & 0 \end{bmatrix} \tag{19}$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ -\frac{1}{2H_i} & 0 \\ 0 & -2\pi \end{bmatrix} \tag{20}$$

$$K = \begin{bmatrix} \frac{1}{T_{g,i}} & 0 & 0 & 0 \end{bmatrix}^T \tag{22}$$

$$C = \begin{bmatrix} 0 & 0 & \beta_i & 1 \end{bmatrix} \tag{23}$$

Where $P_{g,i}$ is the governor output, $P_{m,i}$ the mechanical power, $P_{L,i}$ is the load/disturbance, $P_{c,i}$ is the control action, y_i is the system output, H_i is the equivalent inertia constant, d_i is the equivalent damping coefficient, R_i is the speed droop characteristic and β_i is the a frequency bias factor of area i. T_{ij} is the tie-line synchronizing coefficient with area j, $T_{g,i}$ and $T_{t,i}$ are the governor and turbine time constants of area i.

V. Case Studies

The configuration of investigated multi-area power system is depicted in Fig. 3. The power system configuration is based on [13] with its parameter as shown in table I while the system dynamics are figured in fig. 2.

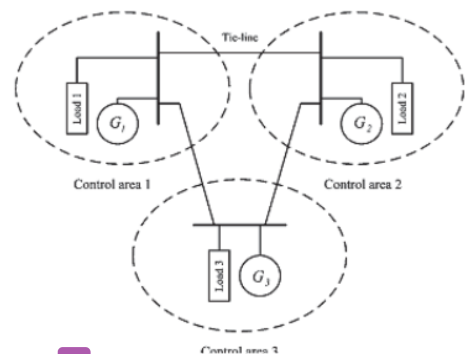

Fig. 3. Multi area power system configuration

TABLE I. Parameters of the Three Area Power System

Area	D [pu/Hz]	$2H$ [pu s]	R [Hz/pu]	T_g [s]	T_t [s]	β [pu/Hz]	T_{ij} [pu/Hz]
1	0.015	0.1667	3.00	0.08	0.40	0.3483	T_{12}=0.20 T_{13}=0.25
2	0.016	0.2017	2.73	0.06	0.44	0.3827	T_{21}=0.20 T_{23}=0.12
3	0.015	0.1247	2.82	0.07	0.30	0.3692	T_{31}=0.25 T_{32}=0.12

Both PI and MPC controllers are simulated in MATLAB by applying disturbances or load changes about 0.6 p.u. in all areas of the power system. The performance of both controllers is then evaluated using (8)-(11) and the result will be explained as follows.

A. Uncontrolled System

The simulation is done by applying 0.6 p.u. disturbance for all area in about 30s without the any controller applied to the system. It seems that frequency deviation (Δf) in all areas is going to decay in the point of 1.6 Hz below normal frequency. In case frequency deviation about 1 Hz, LFC have to be operated or it may activate protection relay [10]. By the way prime mover (P_m) in all area should supply the demand power to be injected to the system.

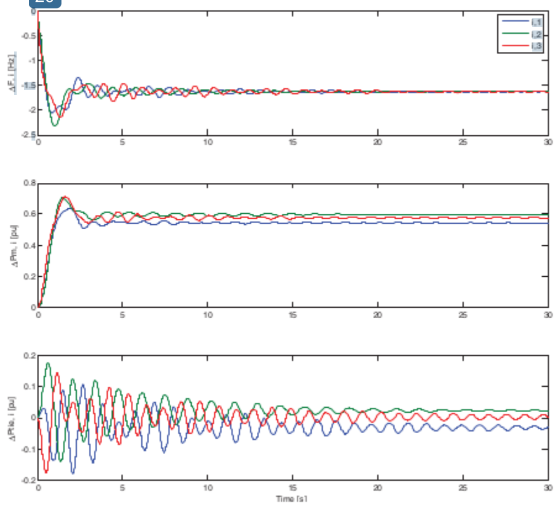

Fig. 4. System behavior without controller

The system will need any controller to drive the frequency back by occupying some generators in the system. The system is fully controllable and observable. It is shown by the rank of each area's state matrix about 4 that is same with its dimension.

B. Controlling System with PI Controller

PI controllers for the simulation have integral gain about -0.3, -0.2 and -0.4 for area 1 to 3 respectively and result of the simulation is captured in fig. 5. The gain for the PI controllers is robust [10].

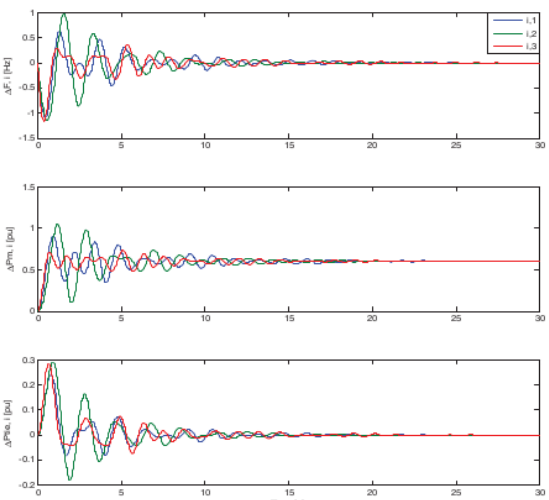

Fig. 5. System behavior with PI controller

The process is measured in frequency fluctuation. At this moment the step of each area will be 0.6 p.u. and the measured properties of the response are given in table II.

TABLE II. PROPERTIES OF PI CONTROLLER SIMULATION

Area	F_A	F_B	F_C	*Tr*	*Tp*	*Ts*
1	50	0.4473	0.2323	0.781	1.059	0
2	50	0.7202	0.5287	0.972	1.366	0
3	50	0.6579	0.415	0.692	0.77	0

From the properties in table II, peak overshoot ratio and decay ratio are calculated as follows.

$$POR_{PI,1} = 1 + \frac{0.4473}{50} = 1.0089$$

$$DR,_{PI,1} = \frac{0.2323}{0.4473} = 0.5193$$

In case oscillation peak about 2% is acceptable then for standard frequency 50Hz, the acceptable peak is about ± 1 Hz. Therefore the difference between USL and LSL is about 2 Hz.

Since the responses have center oscillation, control performance index of is calculated using (1) and the calculation result is shown in table III.

$$Cp_{PI,1} = \frac{2}{6(0.1775)} = 1.8779$$

TABLE III. PI CONTROLLER PERFORMANCE

Area	*POR*	*DR*	*USL*	*LSL*	σ	*Cp*
1	1.0089	0.5193	1	-1	0.1775	1.8779
2	1.0144	0.7341	1	-1	0.1960	1.7007
3	1.0132	0.6308	1	-1	0.1798	1.8539

C. Controlling System with MPC Controller

Nonlinear discrete type of MPC controllers are built to control the power system frequency and the Laguerre function is chosen to build the MPC model. The scaling factor *a* and network lengths *N* for the model are same for each area about 0.9 and 10. Prediction and control horizon are set about 20 and 4. The parameters are chose according to the best performance the MPC.

The step about 0.6 p.u. is applied to all area as same as in PI controller treatment. Therefore the measured properties of the response are given in table IV while the simulation result is shown in fig. 6.

TABLE IV. PROPERTIES OF MPC CONTROLLER SIMULATION

Area	F_A	F_B	F_C	*Tr*	*Tp*	*Ts*
1	50	0.6901	0.6086	1.039	1.444	0.675
2	50	1.2135	0.6413	1.2005	1.710	1.903
3	50	0.3777	0.3669	0.962	1.329	0.604

TABLE V. MPC CONTROLLER PERFORMANCE

Area	*POR*	*DR*	*USL*	*LSL*	σ	*Cp*
1	1.0138	0.8819	1	-1	0.2105	1.5835
2	1.0243	0.5285	1	-1	0.2987	1.1159
3	1.0076	0.9714	1	-1	0.1946	1.7129

Peak overshoot ratio, decay ratio and performance index of MPC controllers are calculated using (8), (10) and (11) as follows.

$$POR_{MPC,1} = 1 + \frac{0.6901}{50} = 1.0138$$

$$DR,_{MPC,1} = \frac{0.6086}{0.6901} = 0.8819$$

$$Cp_{MPC,1} = \frac{2}{6(0.2105)} = 1.5835$$

Overall calculations can be summarized in table V. It shows that MPC controllers for all area are acceptable since those controllers have performance index more than 1.

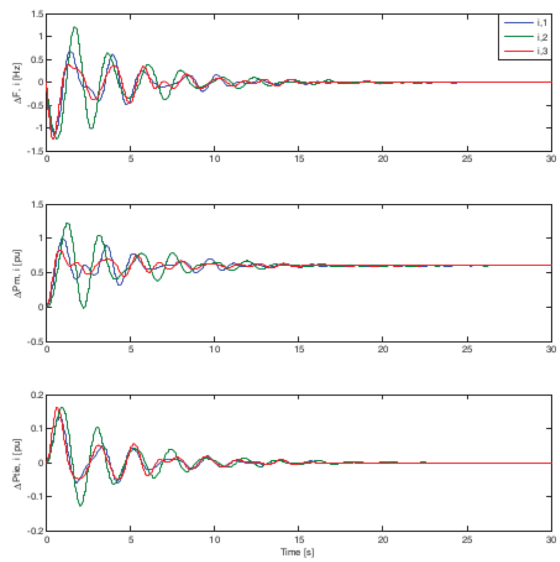

Fig. 6. System behavior with MPC controller

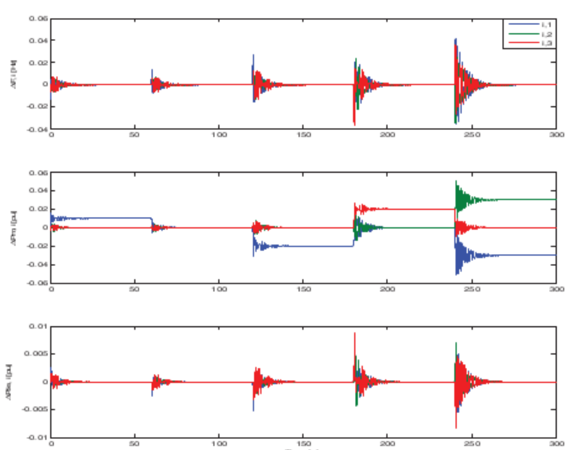

Fig. 7. Sequence disturbances using PI controller

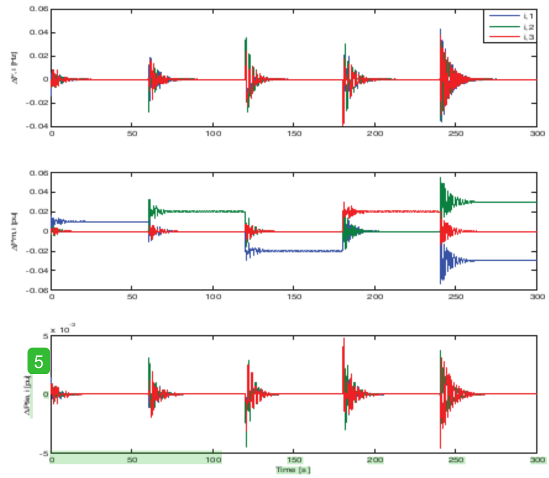

Fig. 8. Sequence disturbances using MPC controller

D. Sequence Disturbances

The system is treated in long time simulations that are done with some sequence disturbances setting in about 5 minutes (300s). The disturbances are changed every 1 minute in each area as shown in table VI and the response for sequence disturbances are then plotted in Fig. 7 and 8.

TABLE VI. DISTURBANCE SETTING (P.U.)

Area	1st	2nd	3rd	4th	5th
1	0.01	0	-0.02	0	-0.03
2	0	0.02	0	0	0.03
3	0	0	0	0.02	0

Both controller responses for long time simulation in Fig. 7 and 8 show that there is no significantly different in the time responses, except the tie line power deviation of the system. The deviation of PI controllers are crossing ±0.005 p.u. at 2nd, 3rd, 4th, and 5th disturbances but MPC controllers are never passed the boundary in any disturbance even in the large change of disturbance.

The other consideration is about simulation time. In the simulation PI controllers take about 32.7930s while MPC controllers consume 31.8222s in processing time.

E. Performance Evaluation

Base on time criteria, PI controllers have the rise time and peak time faster than MPC but those are late to reach the steady state. It was shown in the settling times that have high value compared to MPC controller. From the POR and DR calculations, it can be seen that PI controllers have small POR and high DR than MPC controllers. It means that PI controllers have little overshoots but high decay ratio.

According to CPU time for long time simulation using some variation of disturbances, PI controllers consume more time to finish the simulation of three area power system.

Overall it can be said that PI controllers have faster response with small overshoot but those maybe late to reach the steady state and also those need more time for completely finishing the simulation compared to MPC controllers.

VI. Conclusion

This paper has introduced the comparison performance between PI and MPC` controllers that act as load frequency control in a three area power system.

Result of calculation shows that PI controllers have faster response than MPC controllers but MPC controllers have well decay ratio and faster in simulation time that insure the controllers to reach steady state sooner.

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