

# An Adaptive IMC-MPC Controller for Improving LFC Performance

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# An Adaptive IMC-MPC Controller for Improving LFC Performance

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**Abstract**—Load frequency control becomes one of the important parts in a power system since frequency deviation is a crucial issue in power system stability. This paper proposed a new IMC controller by combining an adaptive model with MPC controller. A three area power system is chosen to test this controller. Result of simulation show that this new controller has good response in handling the frequency deviation by reducing the peak responses of the prime mover.

**Keywords**—IMC, MPC, LFC, Power system.

## I. INTRODUCTION

A power system may consist 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. For multi area power system, the complexity is increases and so highly dynamic operation will be introduced. Some researchers have previously worked in the area of frequency control i.e. [1] designed an LFC using the model predictive control (MPC) or 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 recently [4] discussed total tie line power flow by replacing the LFC model.

Internal Model Control (IMC) and Model Predictive Control (MPC) are well known as model based process controllers. The process control has been influenced since both IMC and MPC were proposed few decades ago and until now the variant of both controllers are increased as well as those performance. The merit of MPC and MPC is the ability to predict the future behavior of the controlled plant based on those internal models. While a mismatch model can reduce both controllers performance. Therefore it will be a challenge to provide a great model for the controllers.

An adaptive model may be a solution to provide perfect model for both IMC and MPC since the model can be updated in a certain time to do corrections for the existing model.

Many previous searches have succeeded to apply the adaptive model into a controller i.e. PI/PID [10]-[11],[14], Fuzzy controller [19], or MPC [22]. The use of internal model has been proposed in [20] by using neural network. In this paper an adaptive IMC controller is built by employing an MPC and an internal model in adaptive scheme to control a load frequency of a power system.

## II. METHODOLOGY

### A. Control Performance

The method to evaluate control performance can be done over time and peak criterions. In this case, peak criterion will be the focus to determine control performance where the criterion is spread into peak overshoot ratio (POR) and decay ratio (DR) of the system step responses. Both POR and DR ratio can be expressed in following equations [7].

$$POR = \frac{f_0}{sp} \quad (1)$$

$$DR = \frac{so}{f_0} \quad (2)$$

Where  $f_0$ ,  $so$ , and  $sp$  are first peak height, second peak height and set point step respectively.

### B. Adaptive Model

As proposed in this research, an adaptive model will be used to provide a perfect model of the plant. Along the simulation, the adaptive model is built by utilizing input and output data. Then the model is generated to a state space model.

In order to realize the adaptive model in MATLAB environment, the state space model can be estimated using `sstest` command. Using this command, a state space model can be generated from a given system identification data by using prediction error minimization (PEM) algorithm. A numerical optimization is used by the PEM algorithm to minimize the cost function. Recently the PEM algorithm in MATLAB environment is only provided with the cost function as follows [23].

$$V_N(G, H) = \sum_{t=1}^N e^2(t) \quad (3)$$

Where  $e(t)$  is the difference between the measured output and the predicted output  $G$  of the model with  $N$  number of samples.

### III. CONTROLLER

#### A. 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 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 [7].

An IMC controller will build its internal model base on the mathematical model of a plant. 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 (4). The Laguerre function is derived by building its space form in (5) and its initial condition in (6), where  $N$  is the length of Laguerre network,  $a$  is called time scaling factor,  $A_l$  is a Toeplitz matrix of parameters  $a$  and  $\beta = (1-a^2)$ , and  $L$  is the Laguerre function's state vector [5], [7].

$$\Gamma_N = \frac{\sqrt{1-a^2}}{1-az^{-1}} \left( \frac{z^{-1}-a}{1-az^{-1}} \right)^{N-1} \quad (4)$$

$$L(k+1) = A_l L(k) \quad (5)$$

$$L(0)^T = \sqrt{\beta} \left[ 1 - a \ a^2 - a^3 \dots (-1)^{N-1} a^{N-1} \right]^T \quad (6)$$

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

$$J = \sum_{m=1}^{N_p} x(k+m|k)^T Q x(k+m|k) + \eta^T R \eta \quad (7)$$

The control law with optimal gain  $K_{mpc}$  for close loop system can then be obtained in (8).

$$x(k+1) = (A - BK_{mpc})x(k) \quad (8)$$

$$K_{mpc} = L(0)^T \eta \quad (9)$$

$$\Delta u = -K_{mpc} x \quad (10)$$

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

#### B. Internal Model Control

Internal model is a process model that simulates the response of the system in order to estimate the outcome of a system disturbance. An Internal Model Control (IMC) can use the internal model to predict the future output of the plant and also to make correction of the output. This controller can be used to control a plant [9], to tune other controller [17], or to combine with the other controller such as PI/PID [12]-[17], Fuzzy controller [18], [19], Neural Network [22] or MPC [19]-[22].

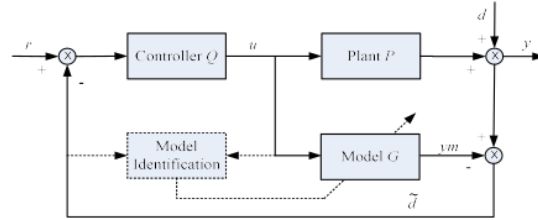


Fig. 1. IMC Principle

An IMC principle can be figured out in fig.1 without dotted line. The input reference  $r$  will be given as the reference input to controller  $Q$ . The controller will respond the input by sending any command  $u$  to the plant  $P$  and as the same time it is fed to the internal/efferent model  $G$ . The plant then moves to the desired output  $y$ . In case disturbance(s)  $d$  happen, the signal correction  $\tilde{d}$  as result of the desired output of both plant and efferent model will be fed back to the controller. Control law applied for the IMC control can be written as follows [12].

$$y = PQR + (1 - GQ)d \quad (11)$$

$$u = QR - Qd \quad (12)$$

$$e = (1 - PQ)r - (1 - GQ)d \quad (13)$$

The difference between classical controller and an IMC is that an IMC will correct the actual output before it is fed back. Since an IMC uses the efferent model, the model should be a perfect model to have the highest control performance. The way to provide the model in an IMC can be in forward model, inverse models, combination of both forward and inverse models, or adaptive model.

### C. Adaptive IMC Control

An adaptive IMC controller refers to a model and/or controller that can be updated in a certain time. By tuning a proper gain to the model and/or controller following the disturbance, the controller can be adaptive to the disturbance.

Figure 1 shows the diagram of an IMC with adaptive model as indicated with dotted line. In this case, the efferent model has been adapted using data identification.

### IV. POWER SYSTEM MODEL

Power system model is described using a differential algebraic equation (DAE) as [2],[7]:

$$\dot{x} = f(x, q, u, w) \quad (14)$$

$$0 = g(x, q, u, w) \quad (15)$$

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 (14) and (15). The (14) is called differential variable and (15) is an algebraic equation or well known as a constraint.

Power system dynamics which include tie line power change can be redrawn in Fig. 3 [1],[6]-[8].

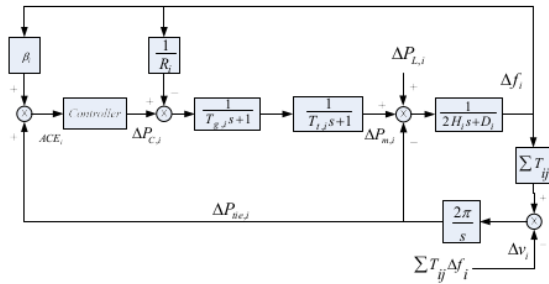


Fig. 2. Power system dynamics

The tie-line power change  $P_{tie}$  is calculated for area  $n$  using (16) 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 (17) as follows[1],[7].

$$\Delta P_{tie,i} = \frac{2\pi}{s} \left[ \sum_{j=1}^n T_{ij} \Delta f_j - \sum_{j=1}^n T_{ij} \Delta P_{tie,j} \right] \quad (16)$$

$$ACE_i = \Delta P_{tie,i} + \beta_i \Delta f_i \quad (17)$$

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

$$\dot{x}(t) = Ax(t) + Bu(t) + Fw(t) \quad (18)$$

$$y(t) = Cx(t) + Du(t) \quad (19)$$

where

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

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

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

$$y(t) = \text{Output variable} = ACE_i$$

The feed forward matrix of the can be removed from the system matrices model since there is no direct connection between input and output variable. Therefore all of the matrices of the system model can be written in (20)-(23) [1],[7].

$$A = \begin{bmatrix} -\frac{1}{T_{g,i}} & 0 & -\frac{1}{R_i T_{g,i}} & 0 \\ \frac{1}{T_{t,i}} & -\frac{1}{T_{t,i}} & 0 & 0 \\ 0 & \frac{1}{2H_i} & -\frac{D_i}{2H_i} & -\frac{1}{2H_i} \\ 0 & 0 & 2\pi \sum_{j=1}^N T_{ij} & 0 \\ & & j \neq i & \end{bmatrix} \quad (20)$$

$$B = \begin{bmatrix} \frac{1}{T_{g,i}} & 0 & 0 & 0 \end{bmatrix}^T \quad (21)$$

$$C = \begin{bmatrix} 0 & 0 & \beta_i & 1 \end{bmatrix} \quad (22)$$

$$F = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ -\frac{1}{2H_i} & 0 \\ 0 & -2\pi \end{bmatrix} \quad (23)$$

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  $\beta_i$  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. SIMULATIONS

A three area power system is chosen to test the effectiveness of the proposed controller. The decision is based on variables needs and also time consuming for the simulation. Therefore this simulation can be extended to a larger area power system under consequence for long simulation time. The configuration of investigated multi-area power system is depicted in Fig. 3.

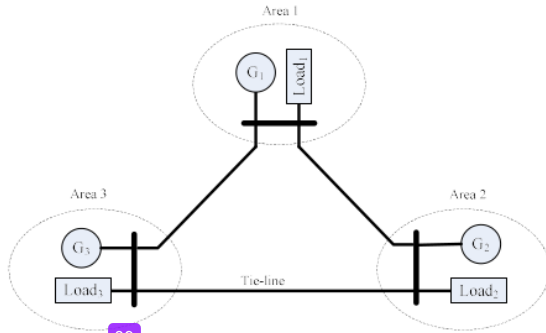


Fig. 3. Multi area power system configuration

TABLE I. PARAMETERS OF THE THREE AREA POWER SYSTEM

Area	$D$ [pu/Hz]	$2H$ [pu s]	$R$ [Hz/pu]	$T_g$ [s]	$T_i$ [s]	$\beta$ [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	$T_{31}=0.25$ $T_{32}=0.12$

The power system configuration is based on [5] and [6] with its parameter as shown in table I while the system dynamics are figured in fig. 2. Simulations were done in three cases which are with step disturbance and some noises, without disturbance and very high noises, and with mismatch model in point A-C as follows.

#### A. Case I: Step Disturbance

Nonlinear discrete type of MPC controller is 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 0.3 and 4.

The step about 0.2 pu and disturbances with maximum 0.1 pu of the generator capacity are applied to area 1 to 3. Therefore the measured properties of the response are given in table IV while the simulation result is shown in fig. 4.

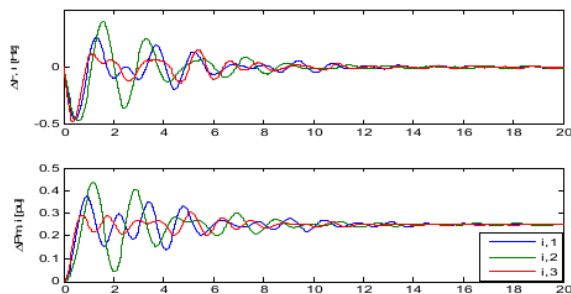


Fig. 4. MPC controller responses in case I

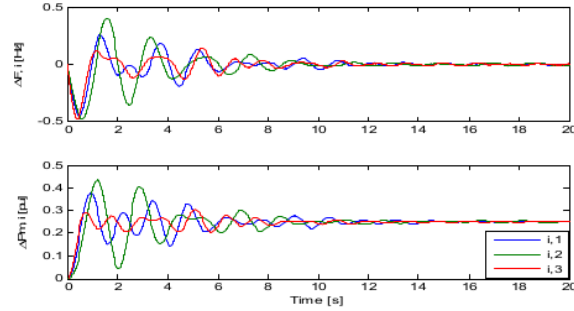


Fig. 5. Adaptive IMC-MPC controller responses in case I

An adaptive IMC-MPC scheme has been built to be applied to the system. In this case the model will be updated each second with the input output data. The data is then used to build the adaptive model. With the same treatment as in MPC controller, the adaptive IMC-MPC simulation result is shown in fig. 5.

#### B. Case II: Very High Noises

The MPC and IMC-MPC are then used in another case with very noisy. In this case I, the step disturbance is set to zero and a random about maximum 0.5 pu of the generator capacity is applied to all areas. Responses of the both controller are then figured in fig. 6 for MPC and fig. 7 for IMC-MPC.

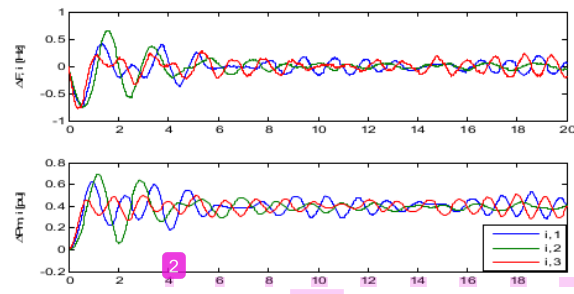


Fig. 6. MPC controller responses in case II

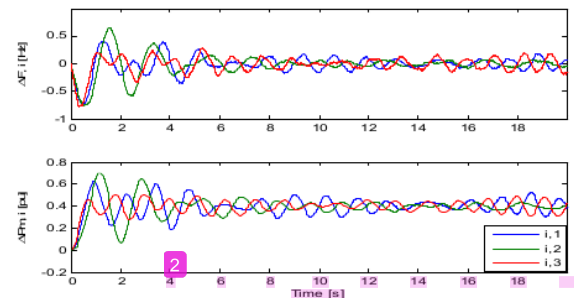


Fig. 7. Adaptive IMC-MPC controller responses in case II



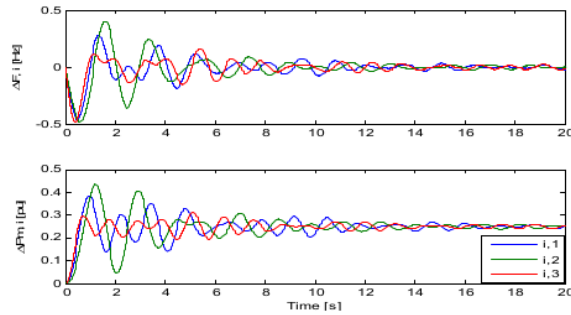


Fig. 8. MPC controller responses in case III

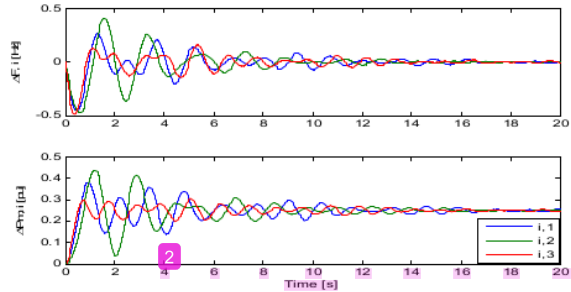


Fig. 9. Adaptive IMC-MPC controller responses in case III

### C. Case III: Mismatch Model

In this case, a mismatch model is applied to all areas in term of governor time constant. The time constant is change for each area generator by increasing (area 1 and 3) and decreasing (area 2) its values by 0.01s. After the changes, the system is then tested with a 0.2 pu. step disturbance for all areas. Result for the system responses is figured in fig. 8 and 9 for MPC and IMC-MPC respectively.

### D. Performance Evaluation

Base on system response in fig.4 to 9, the overshoot decay ratio and standard deviation are analyzed and the result is provided in Table II and Table III. For case I and II, IMC-MPC controller gives very good response in area 1 and 3. On the other hand IMC-MPC controller is superior in all area of case III. On the other hand IMC-MPC controller has high decay ratio in most area and cases which indicate that this controller can slowly reduce the frequency deviation.

TABLE II. FREQUENCY DEVIATION ANALYSIS

	Area	MPC			IMC-MPC		
		case I	case II	case III	case I	case II	case III
Overshoot	1	0.2582	0.4128	0.2738	0.2574	0.4115	0.2737
	2	0.4049	0.6605	0.4025	0.4049	0.6608	0.4024
	3	0.1191	0.2037	0.1643	0.1181	0.2026	0.1614
Decay Ratio	1	0.7378	0.9617	0.7213	0.7570	0.9779	0.7850
	2	0.6090	0.5687	0.6104	0.6153	0.5687	0.6192
	3	0.3168	0.8391	0.4802	0.3391	0.6935	0.3995
Standard Deviation	1	0.0916	0.1673	0.0943	0.0921	0.1665	0.0938
	2	0.1233	0.1976	0.1229	0.1234	0.1975	0.1223
	3	0.0808	0.1581	0.0847	0.0809	0.1532	0.0844

TABLE III. PRIME MOVER DEVIATION ANALYSIS

	Area	MPC			IMC-MPC		
		case I	case II	case III	case I	case II	case III
Overshoot	1	0.1465	0.2354	0.1464	0.1441	0.2321	0.1004
	2	0.1729	0.2713	0.1718	0.1719	0.2709	0.1209
	3	0.1652	0.2649	0.1661	0.1612	0.2597	0.1195
Decay Ratio	1	0.9156	0.9633	0.9142	0.9254	0.9722	0.9406
	2	0.8937	0.8728	0.9081	0.8940	0.8712	0.9077
	3	0.9149	0.9239	0.9386	0.9164	0.9746	0.9240
Standard Deviation	1	0.0294	0.0531	0.1464	0.0318	0.0504	0.2738
	2	0.0443	0.0710	0.1718	0.0466	0.0691	0.4024
	3	0.0278	0.0534	0.1661	0.0700	0.0500	0.1614

About prime mover deviation, IMC-MPC controller has perfect overshoot in all areas and all cases comparing to the MPC controller. It is also shown that IMC-MPC controller is more dynamic than MPC controller as it has high standard deviation and decay ratio values.

## VI. CONCLUSION

This paper has introduced a new combination of an adaptive IMC-MPC controller and based on the authors' knowledge, this controller is recognized as a new type of IMC controller. The controller has been validated in handling load frequency control of a three area power system. Result of simulation shows that the IMC-MPC controller provides good response in most system response, especially in the case of mismatch model where the adaptive IMC-MPC controller demonstrates its superiority.

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