A Novel Adaptive LFC Based on MPC Method

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IEEJ TRANSACTIONS ON ELECTRICAL AND ELECTRONIC ENGINEERING
IEEJ Trans 2019; **14**: 1145–1152
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI:10.1002/tee.22912

Paper

A Novel Adaptive LFC Based on MPC Method

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This article presents a novel load frequency control (LFC) method using an adaptive internal model of a power system, where model predictive control (MPC) technique is applied to the internal model, which is being updated on-line. The proposed method will improve the LFC performance by reducing model identification error and by handling the disturbance effectively. Novelty lies in the combination of MPC and the effective use of the internal model to meet the response time of real world LFC control, which is typically equivalent to generation dispatch control cycle. The effectiveness of the proposed control is confirmed by simulations using a three-area power system model. The results show that the proposed method can accurately identify the target plant and successfully handle disturbances to realize a reliable LFC. © 2019 Institute of Electrical Engineers of Japan. Published by John Wiley & Sons, Inc.

Keywords: IMC; MPC; LSM; LFC; power system

Received 8 June 2018; Revised 9 January 2019

1. Introduction

The objective of load frequency control (LFC) often referred to as AGC is to maintain the power system frequency against continuous load changes and fluctuations. Elgerd and Fosha [1] first addressed the optimal control concept for frequency control design of an interconnected power system and a multi-area power system started to be considered for LFC synthesis. Then, various works proposed numerous schemes in LFC control [2–14]. Many recent studies are concerned with robust control techniques such as $H\infty$, LMI to deal effectively with system disturbances and uncertainties [4]. Some intelligent methods were also applied to the LFC problem including neural networks [5–7], fuzzy logic, and genetic algorithms [8–10]. Recently, model predictive control (MPC) has received much attention, in which a design of MPC for a system including wind turbines was reported in ref. [11] and a comparison with conventional proportional–integral (PI) control was reported in Ref. [12].

Internal model control (IMC) is well known as model-based controllers. IMC can use the internal model to predict the future output of the plant and also to make correction of the output. This method can be used to control SISO systems [15], or to combine with the other controllers such as PI/PID controller [15–22], fuzzy controller [23,24], neural network [25], or MPC [24–27]. The combined design of IMC and MPC was proposed a few decades ago [11,12] and until now the variant of both controllers has been increasing for the process controls. The merit of these approaches is the ability to predict the future behavior of the controlled plant based on the internal models, while a mismatch of the internal model can degenerate the performance of the controllers. An adaptive model may be a solution. Many previous research studies have succeeded to apply the IMC adaptive model into a controller i.e. PI/PID [15,16,21], fuzzy controller [24], or MPC [26].

Nowadays, frequency stability is a major issue in power system operation due to a rapid increase in renewables such as wind and solar generations. The complexity is increasing in the operation of a multi-area power system, where the system characteristics may vary depending on system conditions. While the system conditions are changing, the present LFC control cycle is relatively slow, equivalent to the generation dispatch control cycle in a typical power system. Therefore, a more sophisticated LFC method is required to identify the target system characteristics to improve the stability.

This article presents a novel LFC method, where an adaptive MPC using an IMC model that was repeatedly updated by LSM in real time operation is proposed. Novelty lies in the effective combination of IMC and MPC techniques to meet typical LFC conditions that is a slow control cycle for various systems. It is shown that the proposed adaptive MPC effectively works keeping the system frequency at a desired set point, while the target model is successfully identified. The effectiveness of the proposed controller is demonstrated by the simulations using a standard LFC model representing a three-area interconnected power system.

2. Proposed Controller

2.1. Outline

Figure 1 outlines the control scheme for LFC. An IMC structure is used to identify LFC dynamics by observing plant input and output signals. LSM is used for adaptive parameter estimation of the plant model. MPC is adopted as the main controller, where the Laguerre function is used to provide optimal control. In this power system model, the individual areas are interconnected by tie lines. Inside the area, each block is described as below.

- Each area is represented by a typical model for the LFC study, which is explained in Section 2.2.
- The internal model structure is explained in Section 2.3, which is a simplified power system model. Parameters of

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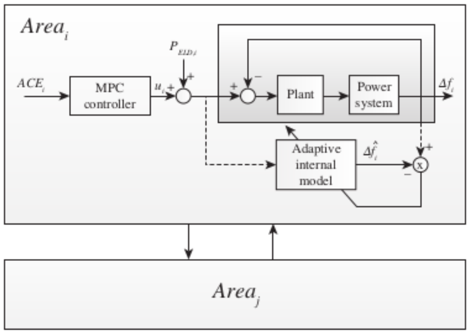


Fig. 1. Proposed adaptive LFC scheme based on MPC

the internal model are identified using the LSM algorithm as an adaptive model, which is used to determine optimal parameters for MPC.

- A MPC controller will be the main controller in the proposed LFC scheme where Laguerre functions are used. Section 2.4 describes the proposed control algorithm.

2.2. Power system model

Power system model in Fig. 1 is used to represent each area. Mathematical model is given in the Appendix. Based on the simulation using this model, control signal to the plant (P_{LFC}, $\widehat{P}(k|k-1)$, $P[k]$) and the response of the plant (area control error [ACE]) are observed. The ACE signal to the plant is obtained from (1).

$$ACE_i = \Delta P_{tie,i} + \beta_i \Delta f_i \tag{1}$$

Figure 2(a) represents a typical configuration of LFC for thermal power plants in each area. An important issue in a practical LFC is that the LFC signal to the plant, P_{LFC}, is added to ELD signals whose sum is the total demand $\widehat{P}(k|k-1)$ predicted at $k-1$. The control signals are sent to thermal power plants typically of the order of minutes to change the set points of the individual plants; in the measurement of ACE, a low-pass filter is usually used to eliminate fast component of the signal [28]. This implies that the LFC signal should be determined based on a suitable plant model whose time scale meets the LFC control cycle. This point is neglected in most of the previous works. Furthermore, the plant input signals are limited by ramp rate constraints of individual plants, typically 3%/min (0.05%/s). Therefore, this article utilizes the singular perturbation method [29] to focus on the slow dynamics of LFC control. In this method, the original system

$$\begin{aligned} \dot{x}_{\mathrm{S}} &= f_{\mathrm{S}}(x_{\mathrm{S}}, x_{\mathrm{F}}, u) \\ \varepsilon \dot{x}_{\mathrm{F}} &= f_{\mathrm{F}}(x_{\mathrm{S}}, x_{\mathrm{F}}, u) \end{aligned} \tag{2}$$

is represented by the first order approximation of the slow subsystem as below:

$$\begin{aligned} \dot{x}_{\mathrm{S}} &= f_{\mathrm{S}}(x_{\mathrm{S}}, x_{\mathrm{F}}, u) \\ 0 &= f_{\mathrm{F}}(x_{\mathrm{S}}, x_{\mathrm{F}}, u) \end{aligned} \tag{3}$$

ε is a parameter for time scale separation, which is assumed about 1 min in this study according to typical real system setting. This treatment is equivalent to the manipulation that all the time constants less than 1 min are set to zero. As a result, the fast dynamic equations for AVR, speed governor, and power system stabilizer are treated as static equations. In this situation, the

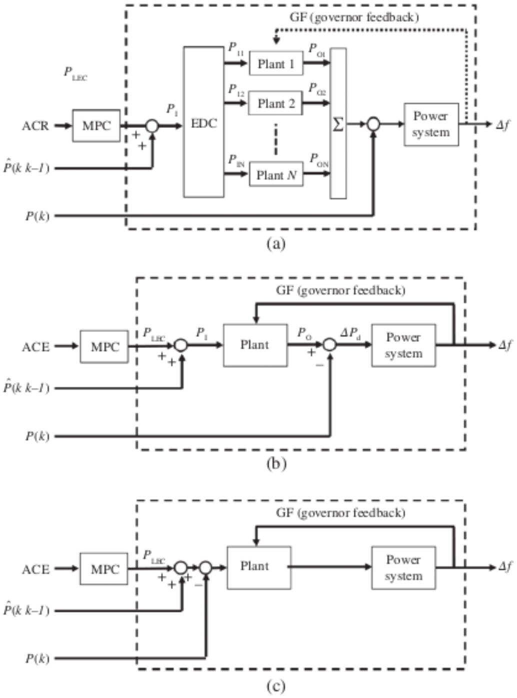


Fig. 2. Detailed and simplified models. (a) Detailed model, (b) intermediate model (c) simplified model

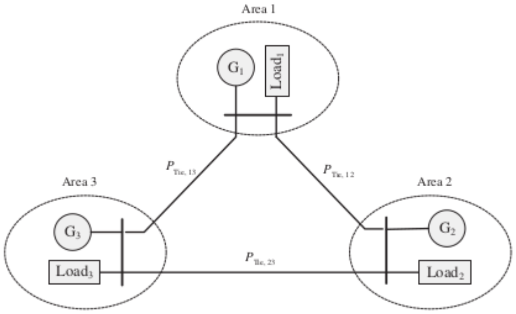


Fig. 3. Three area power system model

original model is approximated by Fig. 2(b) and furthermore by Fig. 2(c) by aggregating all the power plants.

Note that the ELD signal at time point k is computed based on the demand prediction at $k-1$ in the past, while the total demand is measured at time k, the present time. The error of the demand prediction is counted as a disturbance. In the original model, control signal to the plant (P_{LFC}, $\widehat{P}(k|k-1)$, $P[k]$) and the response of the plant (ACE) are observed.

2.3. Simplified power system model for study area

This article uses an internal model of the target system that consists of essential frequency dynamics restricted by the ramp rate constraint, where by essential is meant, the system dynamics of the order of 10 s to minutes that exclude fast transient dynamics. To capture the essential dynamics only, the following simplified model is used:

$$ACE(k+1) = \widehat{a} \cdot ACE(k) + \widehat{b} \cdot P_I(k) \tag{4}$$

Table I. Parameters of the three area power system

Area	d (pu/H$_z$)	$2H$ (pu s)	R (H$_z$/pu)	T_g (s)	T_t (s)	β (pu/H$_z$)	T_{ij} (pu/H$_z$)
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	$T_{31}=0.25$ $T_{32}=0.12$

Table II. Disturbance settings

	Disturbance	
	Random	Step change
Case I	Applied	Not applied
Case II	Applied	0.2 pu at $t=40$
Case III	Applied	-0.2 pu at $t=40$

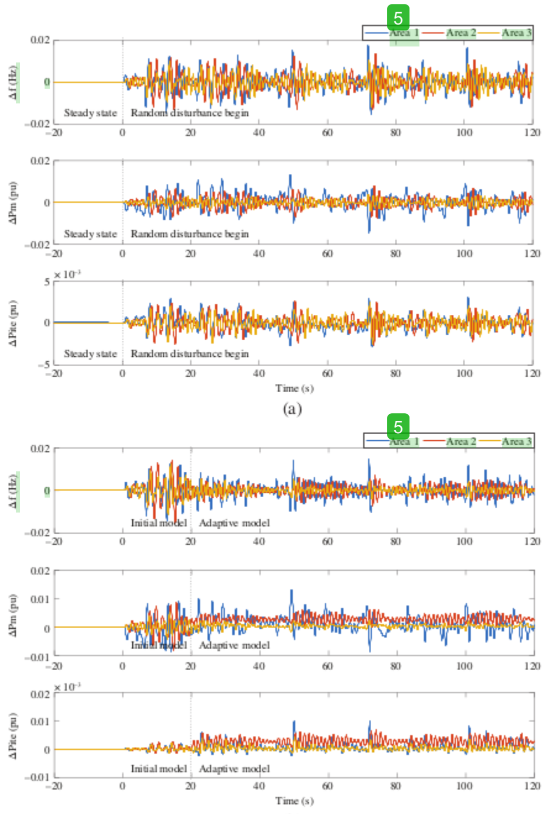


Fig. 4. Controller responses in case I. (a) Conventional MPC controller, (b) proposed adaptive controller

where

$$P_I(k)=\widehat{P}(k|k-1)+P_{\mathrm{LFC}}(k)-P(k) \tag{5}$$

Using the input and output signals measured in the real plant, adaptive parameter estimation is performed using LSM. In the actual power system, $(ACE(k)$ and $P_I(k))$ are observed, and therefore, the set of most recent data will be used to estimate the parameter set ($\widehat{a}$ and $\widehat{b}$) using the LSM algorithm. This process is very simple and reliable to obtain real-time estimation. Note that discrete system (4) is almost equivalent to the first lag system with sampling time h whose gain and time constants are given by:

$$K=\widehat{b}/(1-\widehat{a}),\quad T=h/(1-\widehat{a})$$

2.4. Formulation A MPC is a type control to predict the behavior of the controlled plant and then to determine an optimal control. To apply MPC, the plant model is redefined based on (4) as follows:

$$\begin{aligned} x(k+1)&=A\ x(k)+B\ P_I(k)\\ y(k)&=C\ x(k) \end{aligned} \tag{6}$$

or

$$\begin{bmatrix}\Delta ACE(k+1)\\ ACE(k+1)\end{bmatrix}=\begin{bmatrix}\widehat{a} & 0\\ \widehat{a} & 1\end{bmatrix}\begin{bmatrix}\Delta ACE(k)\\ ACE(k)\end{bmatrix}+\begin{bmatrix}\widehat{b}\\ \widehat{b}\end{bmatrix}\Delta P_I(k)$$

$$y(k)=[0\ \ 1]\begin{bmatrix}\Delta ACE(k)\\ ACE(k)\end{bmatrix}$$

where

$$\Delta ACE(k)=ACE(k)-ACE(k-1)$$

$$\Delta P_I(k)=P_I(k)-P_I(k-1)$$

It should be mentioned that all the parameters of (6) are already known by the parameter estimation by LSM. This parameter is based on the response of the real power system where all the operational constraints are embedded. Then, using the MPC theory, the following cost function is minimized.

$$J=\sum_{m=1}^{Np}\Delta ACE(k+m|k)^2+r_w\sum_{m=0}^{Nc-1}\Delta P_I(k+m)^2 \tag{7}$$

This minimization implies that based on the prediction of future states of the first term, $k+1,\ k+2,\ldots,\ k+Np$ at present time k, the series of the future and present inputs of the second term are optimized. There are several methods to obtain the solution. In this article, Laguerre functions are applied to represent the future inputs as below.

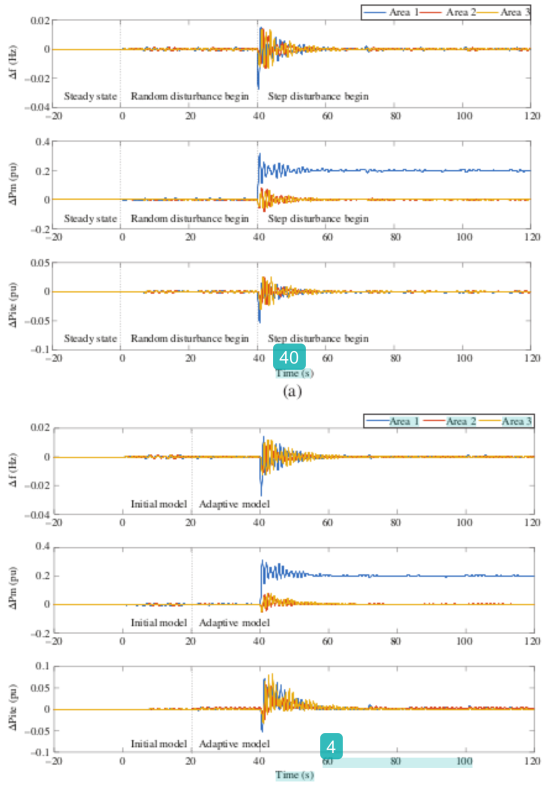
$$\begin{aligned}\Delta P_I(k+m)&=L(m)^T\cdot\eta=[l_1(m)\ \ldots\ l_N(m)][c_1\ \ldots\ c_N]^T\\ &=[l_1(m)\ \ldots\ l_N(m)][c_1\ \ldots\ c_N]^T\end{aligned} \tag{8}$$

here, $L(0)\ \ldots\ L(m)$ are the set of discrete Laguerre functions in the vector form. $l_i(m)$ is the discrete Laguerre functions $(i=1,\ldots,N)$ with the sampling instant k, and c_i is the coefficient $(i=1,\ldots,N)$ to be determined to minimize the cost function. After the minimization, the optimal feedback control at present time k can be determined as follows:

$$\Delta P_I(k)=-K_{\mathrm{mpc}}\ x(k) \tag{9}$$

Table III. Frequency deviation analysis

Area	Conventional MPC cases			Proposed IMC cases		
	I	II	III	I	II	III
Over shoot						
1	—	0.1541	0.2701	—	0.1402	0.2698
2	—	0.1380	0.1277	—	0.0884	0.1096
3	—	0.1358	0.1266	—	0.1172	0.1253
Standard deviation						
1	0.0044	0.0247	0.0146	0.0034	0.0256	0.0163
2	0.0040	0.0180	0.0105	0.0024	0.0139	0.0095
3	0.0035	0.0221	0.0130	0.0013	0.0204	0.0132



(a)

(b)

Fig. 5. Controller responses in case II. (a) Conventional MPC controller, (b) proposed adaptive controller

where

$$K_{\mathrm{mpc}} = L(0)^T \Omega^{-1} \Psi \tag{10}$$

$\Omega = \sum_{m=1}^{N_p} \phi(m)\ Q\ \phi(m)^T + R_L,\ \Psi = \sum_{m=1}^{N_p} \varphi(m)\ Q\ A^m,\ \varphi(m) = \sum_{i=0}^{m} A^{m-i-1}\ B\ L(i)^T, Q = C^T C,\ R_L = r_w \cdot \mathrm{diag}[1,\ \ldots,1].$

See Appendix for the treatment of Laguerre functions, $L(0)$ to $L(m)$.

Then, the LFC control signal to the power system can now be updated as follows.

$$P_{\mathrm{LFC}}(k) = P_{\mathrm{LFC}}(k-1) + \Delta P_I(k) \tag{11}$$

For MPC control design, it is required to select the time scaling factor, a, and the number of the weighting coefficient, N. Although in theory any selection of parameter can be an approximation, an adequate selection may provide better control performance.

2.5. Computational procedure

The computational procedure for the proposed control is given as follows.

Step 1: At the control center, using control signal to the plant P_I and measured ACE, adaptive model identification is performed using the least square method to estimate $(\hat{a}$ and $\hat{b})$.

Step 2: Gain K_{mpc} is computed and LFC input is determined, which is divided and added to ELD signals to the individual power plants.

Repeat steps 1–2.

Note that the actual control cycle for LFC is usually equivalent to the ELD control cycle, which is about 1 s to 1 min with a ramp rate limit, which is typically around 3% of plant capacity per minute. This implies that such a simple model of (6) is sufficient. In the next section, the control cycle is assumed 1 s, where past 20 s of measured data are used to determine the LFC signal taking account of 3% ramp rate limit.

3. Simulations

A three-area system cited from Refs [4,13] in Fig. 3 is used as an original system whose parameters are given in Table I. In this system, capacity of each area is 1 GW = 1 pu. The LFC capacity is assumed to be 0.02 pu, while the ramp rate limit is set to 5%/s assuming that all the generation comes from thermal power plants.

Inside the three area power system model, the detailed model given in the Appendix is used for each area.

The proposed controller will be computed as follows. The system identification is carried out using the available input/output data of the plant. An initial value of K_{mpc} of the controller is computed based on the initial setting of the internal model, which will be updated using the updated internal model from $t = 20$.

The proposed control scheme is verified, compared with an existing controller that is also a nonlinear MPC controller with the Laguerre function internal model. The scaling factor $a = 0.3$ and network lengths $N = 4$ are used for the existing controllers, which have no adaptive nature different from the proposed controller. The gain of the existing controller was preliminary computed off-line, which is applied for the whole simulation period.

Simulations are performed in three cases with different disturbances as shown in Table II, where random and step disturbances are imposed on the load in area 1. The disturbances are caused by the load changes. The 'random' implies white noise with maximum 0.1 pu changes in the load, which is applied from $t = 0$. The 'step disturbance' is 0.2 pu change in load, which is applied at $t = 40$ for cases II and III in addition to the white noise.

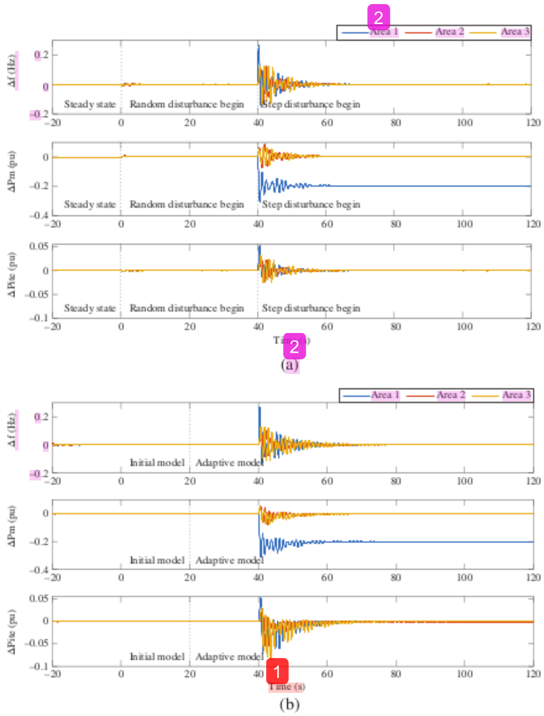


Fig. 6. Controller responses in case III. (a) Conventional MPC controller, (b) proposed adaptive controller

3.1. Case I

Simulation results are shown in Fig. 4(a) for the conventional MPC method and in Fig. 4(b) for the proposed method. The results are summarized in Fig. 8 and Table III. It is observed that the proposed controller shows slightly better performance compared to the existing MPC controller.

3.2. Case II

The step disturbance is applied at $t = 40$ in addition to the random disturbance. The results are shown in Fig. 5(a) for the existing MPC and Fig. 5(b) for the proposed controller. They are summarized in Fig. 8 and Table III.

A better performance is observed. It is noted that although the proposed method is based on much simpler internal model compared with the existing controller, the control performance is even better. This is an advantageous feature of the proposed method.

3.3. Case III

An outage of generator producing 0.2 pu real power is applied at $t = 40$. Similar to two previous cases, slightly better performance in the proposed LFC is observed compared to the existing controller as shown in Fig. 6(b), Fig. 8 and Table III.

3.4. Performance evaluation

This section quantitatively summarizes the performance of the proposed methods based on the simulation results.

Figure 7(a) and (b) show how the internal model parameters are identified. It is observed from Fig. 7(a) that initial gain K is updated as soon as the model identification process is completed at $t = 20$, which is a consistent value based on the LSM. Figure 7(b) shows that the initial time constant is updated very slightly around 1.0. Those values are continuously updated around the converged values.

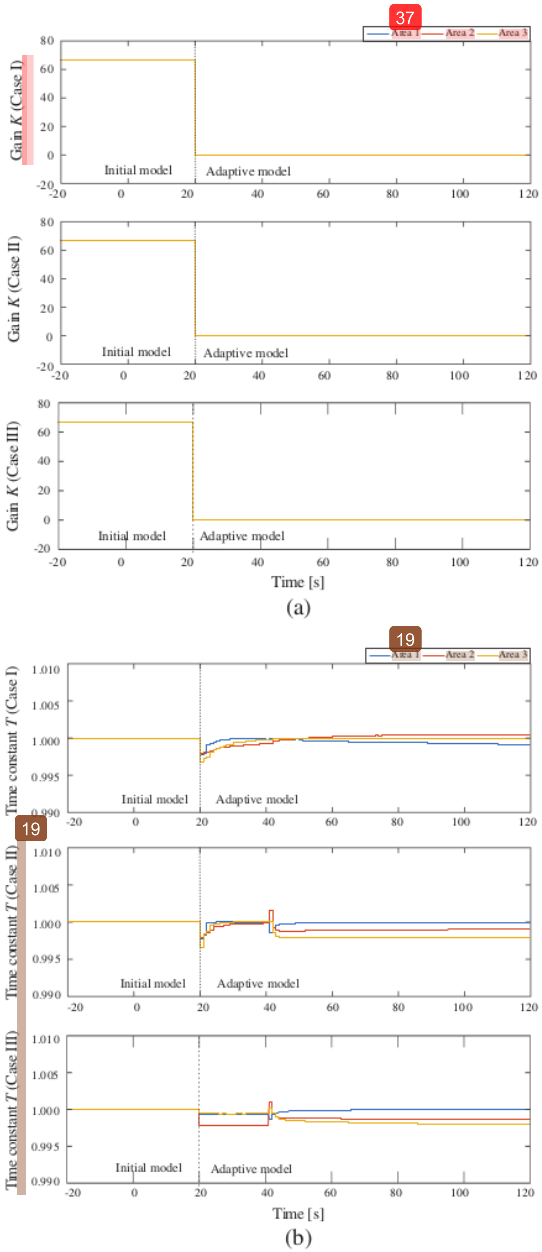


Fig. 7. Adaptive model identification process. (a) Gain K, (b) time constant T

Table III lists measured values of the overshoot for the step disturbance, and the standard deviations of frequency oscillations for all cases, which are given in Fig. 8 in a bar graph. It is seen from the table and figure that the performance of the proposed method is equivalent or better than the conventional MPC controller. This implies that the proposed controller can successfully identify the target model and handle the power system disturbances. In the same way, the controller keeps the system conditions successfully at the set points.

3.5. Computational burden

Simulations are carried out on PC with Intel Core i7 2.9 GHz CPU and 16 GB RAM

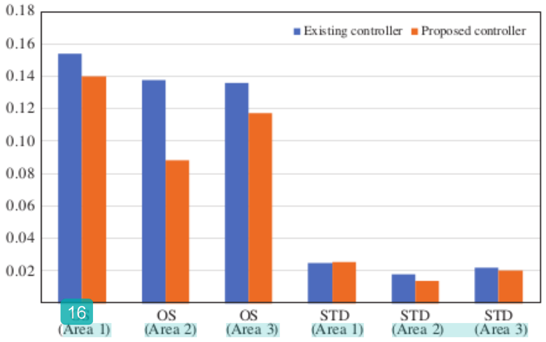


Fig. 8. Overshoot (OS) and standard deviation (STD) of area 1–3 in case II

Table IV. Simulation time (s)

	Conventional MPC (Off-line)	Proposed IMC (On-line)
System Identification	—	0.0084
Optimal gain computation	0.4509	0.0051 (updated)

using MATLAB 2016a under Windows 10. CPU times for the computation of controllers are listed in Table IV. The conventional method assumes that the system dynamic performance was fixed, and, therefore, no update process would be required. However, this is not the case for the present power system situation, in which the dynamic performance is continuously varying. In this case, the conventional method also requires model updates. From this point of view, the proposed method is considerably advantageous.

4. Conclusions

This article proposes a new adaptive LFC method, where the internal model of MPC is adaptively updated on-line using the Least Square Method. Based on the authors' knowledge, this controller is recognized as a new type of controller for LFC. The performance of the controller is fair in handling load disturbances by using a relatively slow control cycle of actual systems.

An important feature is that the system identification is carried out at the control center using the real LFC signal and the real system response, where the effective constraints are unknown at the control center. However, the unknown constraints are embedded in the identified system, which is used in the adaptive control.

Simulation results show that the internal model parameters were updated on-line to guarantee a high performance of the proposed controller. Based on the investigation of the system performance and the computation time, the proposed control scheme has shown its superiority compared to the existing MPC controller.

We have used a fixed value of 3% of ramp rate limit for generators. However, in actual systems, the constraints including ramp rates for LFC vary from minute to minute depending on various factors such as the pattern of load change, the number of generators participating in LFC, their generation dispatch patterns, and so on, whose exact modeling is difficult. The proposed approach is a challenge for this problem using the adaptive control strategy with a real-time system identification. However, we should mention that a further study is required to deal with the constraints more accurately.

Acknowledgments

The first author would like to thank the University of Papua as well as Indonesian Ministry of Research, Technology, and Higher Education Directorate via General of Higher Education that support his study and research in Hiroshima University.

Nomenclature

Abbreviations	
ACE	area control error
AGC	automatic generation control
ELD	economic load dispatch
IMC	internal model control
LFC	load frequency control
LMI	linear matrix inequalities
LSM	least square method
MPC	model predictive control
PI(D)	proportional–integral (derivative) controller
Variable numbers	
A, B, C, D, F	state space matrices
α_l	Laguerre Toeplitz matrix
a	Discrete time scaling factor
f_i	Grid frequency of area i
J	Cost function
K	Adaptive model gain
K_{mpc}	MPC gain vector
L	Laguerre function
m	Sampling instant
n	Number of area
N	Number of sample
N_{p}	Prediction horizon
$P(k)$	Measured total demand at k.
$\widehat{P}(k\|k-1)$	Total demand at k predicted at $k-1$
P_{LFC}	LFC signal to plant
Q	Weighting matrix
q	Output variable
$R \in \Re^{\mathrm{ni} \times \mathrm{ni}}$	Diagonal matrix contains tuning parameters
T	Adaptive model time constant
u	Control output
x	State matrix
y	System output
α	Toeplitz matrix element $= a - 1$
$\eta \in \Re^{\mathrm{ns} \times N}$	Optimal solution vector
ΓN	Discrete Laguerre network
$P_{m,i}$	Mechanical power
v_i	The area interface

A. Appendix

A.1 Power System Model

State space model of a power system including governor, turbine, rotating mass, demand and tie-line power, bias, and frequency droop characteristics is represented by the following equations.

$$\dot{x}_i(t) = A_i x_i(t) + B_i u_i(t) + F_i w_i(t) \tag{A1}$$

$$y_i(t) = C_i x_i(t) + D_i u_i(t) \tag{A2}$$

$$|\dot{u}_i(t)| \le r_{\max\, i=1 \ldots n} \tag{A3}$$

where

$x_i(t) =$ state variables $= [\Delta P_{g,i} \;\; \Delta P_{m,i} \;\; \Delta f_i \;\; \Delta P_{\mathrm{tie},i}]^{\mathrm{T}}$

$u_i(t) = \text{control variable} = \Delta P_{LFC,i}$.
$w_i(t) = [\Delta P_{L,i} \ \ \Delta v_{,i}]^{\mathrm{T}}$.
$y_i(t) = \text{output variable} = ACE_i$

Tie-line power change P_{tie} and the area control error (ACE) are as follows.

$$\Delta P_{\text{tie},i} = \frac{2\pi}{s}\left[\sum_{\substack{j=1\\ j\neq i}}^{n} T_{ij}\Delta f_i - \sum_{\substack{j=1\\ j\neq i}}^{n} T_{ij}\Delta f_j\right] \tag{A4}$$

$$ACE_i = \Delta P_{\text{tie},i} + \beta_i \Delta f_i \tag{A5}$$

$$\Delta v_i = \sum_{\substack{j=1\\ j\neq i}}^{N} T_{ij}\,\Delta f_j \tag{A6}$$

The matrices in (A1) are given as follows.

$$A_i = \begin{bmatrix} -\frac{1}{T_{g,i}} & 0 & -\frac{1}{R_i T_{g,i}} & 0 \\ \frac{1}{T_{t,i}} & -\frac{1}{T_{t,i}} & 0 & 0 \\ 0 & \frac{1}{2H_i} & -\frac{d_i}{2H_i} & -\frac{1}{2H_i} \\ 0 & 0 & 2\pi \sum\limits_{\substack{j=1\\ j\neq i}}^{n} T_{ij} & 0 \end{bmatrix} \tag{A7}$$

$$B_i = \begin{bmatrix} \frac{1}{T_{g,i}} & 0 & 0 & 0 \end{bmatrix}^T \tag{A8}$$

$$C_i = \begin{bmatrix} 0 & 0 & \beta_i & 1 \end{bmatrix} \tag{A9}$$

$$D_i = [0] \tag{A10}$$

$$F_i = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ -\frac{1}{2H_i} & 0 \\ 0 & -2\pi \end{bmatrix} \tag{A11}$$

where $r_{\max}$ is the maximum ramp rate constraint, $P_{g,i}$ is the governor output, $P_{m,i}$ the mechanical power, $P_{L,i}$ is the load/disturbance, v_i is the area interface, $P_{\text{LFC},i}$ 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 characteristics, and β_i is the 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.La.

A.2 Laguerre Functions

Laguerre functions satisfying the following difference equation is used in this article.

$$L(k+1) = A_l \ \ L(k) \tag{A12}$$

The initial condition is given by

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

$$A_l = \begin{bmatrix} a & 0 & 0 & 0 & \vdots \\ \beta & a & 0 & 0 & \vdots \\ -a\beta & \beta & a & 0 & \vdots \\ a^2\beta & -a\beta & \beta & a & \vdots \\ \cdots & \cdots & \cdots & \cdots & a \end{bmatrix}$$

a is the discrete pole of the Laguerre network and $\beta = (1-a^2)$. $N = 5$ is used in this article.

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