DATA ARTIKEL ILMIAH

Judul	:	An Adaptive Internal Model for Load Frequency Control Using Extreme Learning Machine
Penulis	:	Adelhard Beni Rehiara, He Chongkai, Yutaka Sasaki, Naoto Yorino, Yoshifumi Zoka
Abstrak	:	As an important part of a power system, a load frequency control has to be prepared with a better controller to ensure internal frequency stability. In this paper, an Internal Model Control (IMC) scheme for a Load Frequency Control (LFC) with an adaptive internal model is proposed. The effectiveness of the IMC control has been tested in a three area power system. Results of the simulation show that the proposed IMC with Extreme Learning Machine (ELM) based adaptive model can accurately cover the power system dynamics. Furthermore, the proposed controller can effectively reduce the frequency and mechanical power deviation under disturbances of the power system.
Keywords	:	ELM; IMC; LFC; MPC; power system
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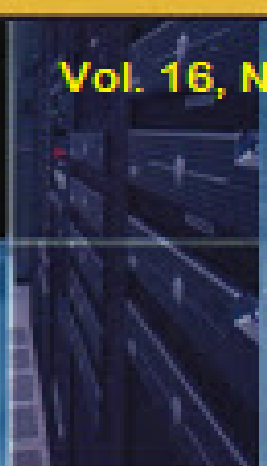

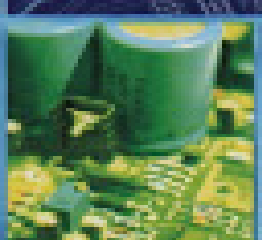

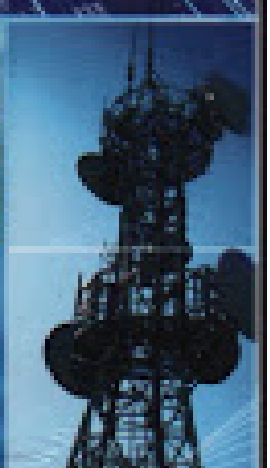

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Vol 16, No 6

December 2018

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Table of Contents

A Novel Structure of a Wideband Zero-Bias Power Limiter for ISM Band PDF
Khalifa Echchakhaoui, Elhassane Abdelmounim, Jamal Zbitou, Hamid Bennis, Ahmed Errkik, Angel Mediavilla Sanchez 2481-2491

Design and Analysis of Broadband Elliptical Microstrip Patch Antenna for Wireless Communication PDF
Ali Khalid Jassim, Raad H. Thaher 2492-2499

Optimization a Scheduling Algorithm of CA in LTE ADV PDF
Sarmad K. Ibrahim, Nasser N. Khamiss 2514-2521

Performance Evaluation of Low-Cost GPS Time Server Based on NTP PDF
Heri Andrianto, Yohana Susanthi, Denny Suryadi 2528-2535

Hybrid Filter Scheme for Optimizing Indoor Mobile Cooperative Tracking System PDF
Rafina Destiarti Ainul, Prima Kristalina, Amang Sudarsono 2536-2548

A Compact Reconfigurable Dual Band-Notched Ultra-Wideband Antenna using Varactor Diodes PDF
Sam Weng Yik, Zahriladha Zakaria, Herwansyah Lago, Noor Azwan Shairi 2557-2562

RS Codes for Downlink LTE System over LTE-MIMO Channel PDF
Ghasan Ali Hussain, Lukman Audah 2563-2569

A Two-stages Microstrip Power Amplifier for WiMAX Applications PDF
Amine Rachakh, Larbi El Abdellaoui, Jamal Zbitou, Ahmed Errkik, Abdelali Tajmouati, Mohamed Latrach 2500-2506

Electromagnetic Characteristics Measurement of Organic Material Absorber PDF
Reza Septiawan, Sardjono Trihatmo, Juliati Junde, Dody A. Winarto, Arief Rufiyanto, Erik Madyo Putro, Budi Sulistya, Arky Astasari 2507-2513

Loss Quantization of Reflectarray Antenna Based on Organic Substrate Materials PDF
H. I Malik, M. Y Ismail, Sharmiza Adnan, S. R Masrol 2570-2577

Comparison of Raindrop Size Distribution Characteristics Across the Southeast Asia Region PDF
Manhal Alhilali, Lam Hong Yin, Jafri Din 2522-2527

Proposed Model for Interference Estimation in Code Division Multiple Access PDF
Dalal Kanaan Taher, Adheed Hassan Sallomi 2549-2556

Multiuser Detection with Decision-Feedback Detectors and PIC in MC-CDMA System PDF
Leila Sahraoui, Djemil Messadeg, Saliha e Hariz, Noureddine Doghmane 2578-2587

Different Multilayer Substrate Approaches to Improve Array Antenna Characteristics for Radar Applications PDF
N. Chater, T. Mazri, M. Benbrahim 2588-2596

Analysis Predicted Location of Harmonic Distortion in RF Upconverter Structure PDF
Sirmayanti Sirmayanti, Mike Faulkner 2608-2615

Performance Enhancement of Wideband Reflectarray Antennas Embedded on Paper Substrate Materials PDF
M. Y. Ismail, H. I. Malik 2616-2621

Proposed P-shaped Microstrip Antenna Array for Wireless Communication Applications PDF
Raad H. Thaher, Noor Baqir Hassan 2597-2607

Underwater Image De-nosing using Discrete Wavelet Transform and Pre-Whitening Filter PDF
Mohanad Najm Abdulwahed, Ali Kamil Ahmed 2622-2629

Implementation of Integration VaaMSN and SEMAR for Wide Coverage Air Quality Monitoring PDF
Yohanes Yohanie Fridelin Panduman, Adnan Rachmat Anom Besari, Sritrusta Sukaridhoto, Rizqi Putri Nourma Budiarti, Rahardhita Widyatra Sudibyo, Funabiki Nobuo 2630-2642

Secure Code Generation for Multi-Level Mutual Authentication PDF
Gregor Alexander Aramice, Jaafar Qassim Kadhim 2643-2650

Modified DCT-based Audio Watermarking Optimization using Genetics Algorithm PDF

Ledya Novamizanti, Gelar Budiman, Irma Safitri 2651-2660

PDF

Numerical Method for Evaluating E-Cash Security
Dany Eka Saputra, Sarwono Sutikno, Suhono Harso Supangkat 2668-2675

Statistical Tuning Chart for Mapping Porosity Thickness: a Case Study of Channel Sand Bodies in the Kutei Basin Reservoir PDF
Abdul Haris, Agus Riyanto, Sri Mardiyati 2676-2682

Repair and Replacement Strategy for Optimizing Cost and Time of Warranty Process using Integer Programming PDF
Ardy Januantoro, Riyanarto Sarno 2683-2691

PDF

Determining Strategies on Playing Badminton using the Knuth-Morris-Pratt Algorithm
Lala Septem Riza, Muhammad Irfan Firmansyah, Herbert Siregar, Dian Budiana, Alejandro Rosales-Pérez 2763-2770

PDF

Towards Adaptive Sensor-cloud for Internet of Things
I Made Murwantara, Hendra Tjahyadi, Pujianto Yugopuspito, Arnold Aribowo, Irene A. Lazarusli 2771-2781

PDF

Design Mobile App for Increase the Visitor Museum using Gamification Method
Novian Adi Prasetyo, Suyoto Suyoto 2791-2798

A New Framework for Information System Development on Instant Messaging for Low Cost Solution PDF
I Made Sukarsa, I Ketut Gede Darma Putra, Nyoman Putra Sastra, Lie Jasa 2799-2808

PDF

Using Alpha-cuts and Constraint Exploration Approach on Quadratic Programming Problem
Yosza Dasril, Zahriladha Zakaria, Ismail Bin Mohd 2782-2790

PDF

Message Oriented Middleware For Library's Metadata Exchange
Ni Wayan Wisswani, I Wayan Kandi Wijaya 2756-2762

PDF

Fuzzy Rule-based Classification Systems for the Gender Prediction from Handwriting
Lala Septem Riza, Aldi Zainafif, Rasim Rasim, Shah Nazir 2725-2732

Speech Recognition Application for the Speech Impaired using the Android-based Google Cloud Speech API PDF
Nenny Anggraini, Angga Kurniawan, Luh Kesuma Wardhani, Nashrul Hakiem 2733-2739

Integrated Analytical Hierarchy Process and Objective Matrix in Balanced Scorecard Dashboard Model for Performance Measurement PDF
Okfalisa Okfalisa, Septia Anugrah, Wresni Anggraini, Muhammad Absor, S.S.M. Fauzi, Saktioto Saktioto 2703-2711

PDF

Reinforced Island Model Genetic Algorithm to Solve University Course Timetabling
Alfian Akbar Gozali, Shigeru Fujimura 2747-2755

PDF

The Readiness of Palm Oil Industry in Enterprise Resource Planning
Darius Antoni, Deni Fikari, Muhamad Akbar, Ferry Jie 2692-2702

PDF

A Review of Energy-aware Cloud Computing Surveys
Azlan Ismail, Nor Adzlan Jamaludin, Suzana Zambri 2740-2746

Thermodynamic Performance and Wave Propagation Sensor System of Fiber Bragg Grating in Liquid Media PDF
Romi F. Syahputra, Ridho Kurniawan, Yunita I. Lubis, Mesra Sania, Okfalisa Okfalisa, Saktioto Saktioto 2661-2667

Image Analysis using Color Co-occurrence Matrix Textural Features for Predicting Nitrogen Content in Spinach PDF
Yusuf Hendrawan, Indah Mustika Sakti, Yusuf Wibisono, Muchnuria Rachmawati, Sandra Malin Sutan 2712-2724

Assessment of Internet Banking Services Continued Use: Role of Socio-Cognitive and Relational View PDF
Mira Kartiwi, Ali Rfieda 2817-2827

Anomaly Detection based on Control-flow Pattern of Parallel Business Processes PDF
Hendra Darmawan, Riyanarto Sarno, Adhatus Solichah Ahmadiyah, Kelly Rossa Sungkono, Cahyaningtyas Sekar Wahyuni 2809-2816

Development of a Modular Unit of a Higher Level Framework or Tool for Basic Programming Course Teaching Through E-Learning Mode PDF
Radhika Pathi, G.V. Rao, P. Rama Krishna, P. Bharath Kumar 2828-2834

Stochastic Computing Correlation Utilization in Convolutional Neural Network Basic Functions PDF
Hamdan Abdellatef, Mohamed Khalil Hani, Nasir Shaikh Husin, Sayed Omid Ayat 2835-2843

PDF

Design of Dual Band Microstrip Antenna for Wi-Fi and WiMax Applications
Raad H. Thaher, Zainab S. Jamil 2864-2870

PDF

An Adaptive Internal Model for Load Frequency Control Using Extreme Learning Machine
Adelhard Beni Rehiara, He Chongkai, Yutaka Sasaki, Naoto Yorino, Yoshifumi Zoka 2879-2887

PDF

Sub-1 GHz Wireless Nodes Performance Evaluation for Intelligent Greenhouse System
I Nyoman Kusuma Wardana, Ngakan Nyoman Kutha Krisnawijaya, I Wayan Aditya Suranata 2888-2895

PDF

Voltage Regulation of Boost Converter using Observer based Sliding Mode Controller
Ramadhani Kurniawan Subroto, Sapriesty Nainy Sari, Zainul Abidin, Kuo Lung Lian 2896-2904

PDF

Application of EMG and Force Signals of Elbow Joint on Robot-assisted Arm Training

Riky Tri Yunardi, Eva Inaiyah Agustin, Risalatul Latifah, Winarno Winarno 2913-2920

Performance Evaluation of Centralized Reconfigurable Transmitting Power Scheme in Wireless Network-on-chip PDF
M. S. Rusli, A. A. H. Ab Rahman, U. U. Sheikh, N. Shaikh Husin, Michael L. P. Tan, T. Andromeda, M. N. Marsono 2844-2854

Radial Derivative and Radial Inversion for Interpreting 4D Gravity Anomaly Due to Fluids Injection Around Reservoir PDF
Muhammad Zuhdi, Sismanto Sismanto, Ari Setiawan, Jarot Setyowiyoto, Adi Susilo, Muhammad Sarkowi 2855-2863

The Application of General MOS Gas Sensors for Discriminating Formalin Content PDF
Arief Sudarmaji, Budi Gunawan, Shoufika Hilyana, Henry Fernando, Agus Margiwiyatno 2905-2912

A Small RLSA Antenna Utilizing the Specification of Back Fires 17 dBi LAN Antennas PDF
Teddy Purnamirza, Prayoga Budikesuma, Imran M. Bin Ibrahim, Depriwana Rahmi, Rika Susanti 2871-2878

Low-Cost Fiber Optic Chemical Sensor Development for Fishpond Application PDF
Budi Mulyanti, Yuski Maolid Rizki Faozan, Ajuni B. Pantjawati, Roer Eka Pawinanto, Lilik Hasanah, Wahyu Sasongko Putro 2921-2929

Sensorless Control of a Fault-Tolerant Multi-Level PMSM Drive PDF
Kamel Saleh, Mark Sumner 2930-2942

Modified SEPIC Converter Performance for Grid-connected PV Systems under Various Conditions PDF
Rizky Ajie Aprilianto, Subiyanto Subiyanto, Tole Sutikno 2943-2953

Bank of Extended Kalman Filters for Faults Diagnosis in Wind Turbine Doubly Fed Induction Generator PDF
Imane Idrissi, Houcine Chafouk, Rachid El Bachtiri, Maha Khanfara 2954-2966

Transient Power Quality Performance of Multi Photovoltaics using MPPT P and O/MPPT Fuzzy PDF
Amirullah Amirullah, Agus Kiswantono, Ontoseno Penangsang, Adi Soeprijanto 2967-2979

Developing Fuzzy Inference System of the Observed Albireo Star's Trail using Surface Meteorological Parameter over ITERA Astronomical Observatory (IAO) PDF
Wahyu Sasongko Putro, Wirid Birastri, Robiatul Muztaba, Anissa Novia Indra Putri, Nindhita Pratiwi, Hakim Luthfi Malasan 2980-2987

Solar Panel Control System Using an Intelligent Control: T2FSMC and Firefly Algorithm PDF
Mardlijah Mardlijah, Zainullah Zuhri 2988-2998

Particle Filter with Integrated Multiple Features for Object Detection and Tracking PDF
Muhammad Attamimi, Takayuki Nagai, Djoko Purwanto 3008-3015

Optimal Control for Torpedo Motion based on Fuzzy-PSO Advantage Technical PDF
Viet Dung Do, Xuan Kien Dang 2999-3007

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Muhammad Attamimi, Ronny Mardiyanto, Astria Nur Irfansyah 3034-3044

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Sutrima Sutrima, Christiana Rini Indrati, Lina Aryati 3024-3033

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An Adaptive Internal Model for Load Frequency Control using Extreme Learning Machine

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Abstract

As an important part of a power system, a load frequency control has to be prepared with a better controller to ensure internal frequency stability. In this paper, an Internal Model Control (IMC) scheme for a Load Frequency Control (LFC) with an adaptive internal model is proposed. The effectiveness of the IMC control has been tested in a three area power system. Results of the simulation show that the proposed IMC with Extreme Learning Machine (ELM) based adaptive model can accurately cover the power system dynamics. Furthermore, the proposed controller can effectively reduce the frequency and mechanical power deviation under disturbances of the power system.

Keywords*: IMC, MPC, ELM, LFC, power system.*

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1. Introduction

In the power system operation, deviation of frequency would be a critical issues since the deviation could cause many troubles to devices connected to the power system. It is reported that the frequency change will affect operation and speed control of both synchronous and asynchronous motors, increase reactive power consumption and furthermore degrade load performance,overload transmission lines, and finally interfere system protection. An LFC is a main part of a power system to minimize frequency variation by maintaining power exchange between power system areas. Some works have been done in the area of LFC [1-9], including [1] designed a model predictive control (MPC) based LFC for a multi-area power system considering wind turbines operation, [2] compare MPC and PI performance against a conventional AGC system, [3] presented fuzzy controller for LFC of three area power system and recently [4] discussed a new LFC method for multi-area power system.

Internal Model Control (IMC) is a well-established control structure and it is widely applied in process control applications. An IMC incorporates a plant model into its structure as an internal model so that the controller output will be based on the difference between internal model and plant output. Morari in [10] has proved that the controller has dual stability, zero offset, and perfect control properties. Since plant models are mostly linearized models, it is almost impossible for an IMC to be a perfect control. An adaptive model will be a solution to be close to the “perfect control” since it can be updated in a certain time to do corrections for the existing model. Many previous researches have succeeded to apply the adaptive model into a controller i.e. PI/PID [10-13], Fuzzy controller [14], or MPC [15].

Since introduced a decade before, extreme learning machine (ELM) has been used in many cases and applications. It has accurate predictions in short time training compared to its ancestor which is a feed-forward neural network. An adaptive internal model has been introduced in [7] using prediction error minimization (PEM) algorithm. Due to time-consuming, this method is not appropriated to be used in an online application. Therefore, an ELM with its features is a good candidate to replace the PEM method. In this paper, an ELM based adaptive IMC controller is built by employing an internal model in an adaptive scheme and an MPC as the main controller to control a load frequency of a power system.

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2. Research Method

2.1. Model Predictive Control

MPC is an advanced control method that used a plant model to predict the optimal movement of the plant. A Laguerre based MPC would be a solution for online computation compare to classical MPC [16, 17]. In addition, a Laguerre based MPC can increase the feasible region of the optimization problem [16]. Accurate approximation of control signal Δu may need many parameters that cause poor numerical solutions and heavy computational load when classical MPC is implemented in rapid sampling, complicated process dynamics and/or high demand on closed-loop performance [16, 17].

The discrete Laguerre function is transformed from its original using invert z-transformation as shown in (1). The Laguerre function vector and initial condition shown in (2) and (3) respectively [6, 8, 17].

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

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

$$L(0)^T = \sqrt{\alpha}\left[1 \quad -a \quad a^2 \quad -a^3 \ldots (-1)^{N-1} a^{N-1}\right]^T \tag{3}$$

Minimization of output errors for *m* sampling instant is done by taking a minimal solution of an objective function *J* as in (4). Closed loop feedback control with optimal gain K_{mpc} (6) is formulated in (5) and receding horizon control law is realized in (7).

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

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

$$K_{mpc} = L(0)^T \Omega^{-1} \Psi \tag{6}$$

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

where,

$$A_l = \begin{bmatrix} a & 0 & 0 & 0 & \cdots & 0 \\ \alpha & a & 0 & 0 & \cdots & 0 \\ -a\alpha & \alpha & a & 0 & \cdots & 0 \\ a^2\alpha & -a\alpha & \alpha & a & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & 0 \\ -a^{N-2}\alpha & -a^{N-3}\alpha & -a^{N-4}\alpha & \cdots & -a^{N-N}\alpha & a \end{bmatrix}$$

$$\eta = \Omega^{-1}\Psi$$

$$\Omega = \sum_{m=1}^{Np} \phi(m) Q \phi(m)^T + R_L$$

$$\Psi = \sum_{m=1}^{Np} \phi(m) Q A^m$$

The parameters of *N, a, A_l* and *L* are the length of Laguerre network, time scaling factor, a Toeplitz matrix with $\alpha = (1-a^2)$, and Laguerre function's state vector respectively. The matrices of $Q \in \Re^{ns \times ns}$ and $R \in \Re^{ni \times ni}$ are weighting matrices, $\eta \in \Re^{ns \times N}$ is the parameter vector of *N* Laguerre function and ϕ is a Hessian matrix. *Np* is the number of prediction horizon and Δu is a vector of the control parameter.

2.2. Internal Model Control

An internal model that placed into a normal closed-loop control system, including controller, plant and/or sensor, may perform Internal Model Control systems as shown in Figure1. The difference between signal correction *ŕ* and set-point *r* is the command to the controller to signal *u* to the plant. Control law applied for the IMC control can be written as follows [18].

$$y = PQr + (1 - GQ)d_m \tag{8}$$

$$u = Qr - Qd_m \tag{9}$$

$$e = (1 - PQ)r - (1 - GQ)d_m \tag{10}$$

The difference between IMC and the classical controller is that an IMC will correct the actual output before it is fed back. An IMC can use the internal model to predict the future output of the plant and also to make correction of the output. It can also work with another controller to control a plant [10], to tune other controller [19], or to combine with the other controller such as PI/PID[13, 18-22], Fuzzy controller [14, 23], Neural Network [24] or MPC [15, 24, 25].

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. In order to perform adaptive scheme of an IMC, another block for system identification should be presented inside the IMC structure as appeared in the dotted block of Figure1.

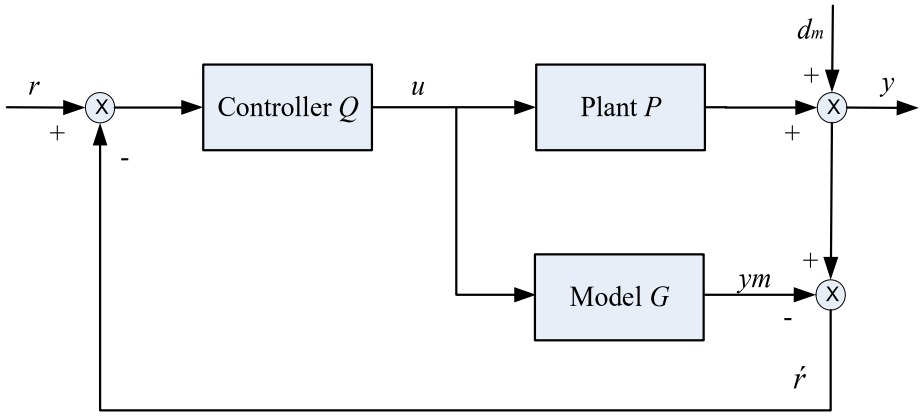


Figure 1.IMC principle

2.3. Extreme Learning Machine

An ELM is basically a single hidden layer feed-forward neural network (SLFN) which has an excellent training algorithm. Input weight and hidden layer biases are not necessarily adjusted and those can be chosen arbitrarily in this algorithm. Then the output weight of the SLFNs can be determined by a generalized inverse operation of the hidden layer output matrices. In fact, this procedure has been fastening this algorithm.

For a given $\tilde{n}$ training set samples (x_j, t_j) where $x_j=[x_{j1}, x_{j2},\ldots, x_{j\tilde{n}}]^T$ and $t_j=[t_{j1}, t_{j2},\ldots, t_{j\tilde{n}}]^T$, an SLFN with $\tilde{N}$ hidden neurons and activation function $g(x)$ is expressed as [26, 27]

$$\sum_{i=1}^{\tilde{N}} \beta_i' g(x_j) = \sum_{i=1}^{\tilde{N}} \beta_i' g(w_i x_j + b_i) = o_j, j = 1,2,...,\tilde{n} \quad (11)$$

where $w_i=[w_{i1}, w_{i2},\ldots, w_{i\tilde{n}}]^T$, $\beta'_i=[\beta'_{i1}, \beta'_{i2},\ldots, \beta'_{i\tilde{n}}]^T$, b_i, and o_j are the connecting weight of i^{th} hidden neuron to input neuron, the connecting weights of the i^{th} hidden neuron to the output neurons, the bias of the i^{th} hidden node, and the actual network output with respect to input x_j respectively. Because the standard SLFN can minimize the error between t_j and o_j, (11) can be rewritten as follows.

$$\sum_{i=1}^{\tilde{N}} \beta_i' g(w_i x_j + b_i) = t_j, j = 1,2,...,\tilde{n} \quad (12)$$

In simple (12) can be $H\beta'=T$ so that the output weight matrix β' can be solved by least square solution as in (13).

$$\beta' = H^{\dagger} T \quad (13)$$

The hidden layer output matrix H and the network output T are formulated as follows.

$$H(w_i, b_i) = \begin{bmatrix} g(w_1 x_1 + b_1) & \cdots & g(w_{\tilde{N}} x_1 + b_{\tilde{N}}) \\ \vdots & \cdots & \vdots \\ g(w_1 x_{\tilde{n}} + b_1) & \cdots & g(w_{\tilde{N}} x_{\tilde{n}} + b_{\tilde{N}}) \end{bmatrix}, \text{ and } T = \begin{bmatrix} t_1^T \\ \vdots \\ t_{\tilde{n}}^T \end{bmatrix} \quad (14)$$

2.4. Proposed Controller

As proposed in this research, an adaptive model will be used to provide an updated model of the plant. The adaptive model is generated by using a classification based extreme learning machine (ELM) algorithm by utilizing input and output data. The proposed controller uses MPC controller as its main controller combining with an adaptive ELM model as the internal model. The complete block diagram of the proposed controller is shown in Figure 2. The ELM model was trained using controller output Δu and frequency deviation Δf as input and output data respectively. After trained, the ELM model is used to predict frequency deviation Δf for a given controller signal Δu. The algorithm for simulation is written in Algorithm 1.

```
Algorithm 1 : Adaptive IMC
1.  set disturbances and noises
2.  configure ELM model
3.  for j=1 to simulation time
4.        ⋮
5.     for i=1 to n-area
6.        calculate Δu
7.        update state matrix Δẋi
8.        train ELM model
9.        predict ELM output Δymi
10.       calculate Δẏi=Δyi-Δymi
11.       ⋮
12.    end
13. end
```

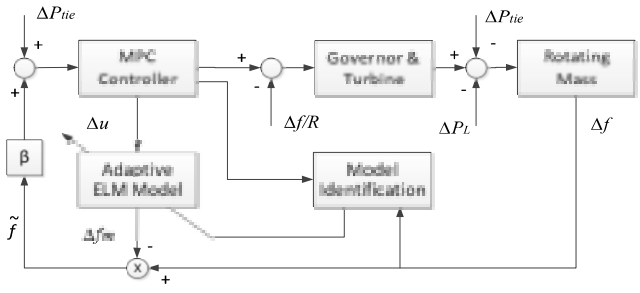


Figure 2.Proposed Adaptive IMC Scheme

2.5. Power system model

A model of power system dynamics can be redrawn in Figure 3. The frequency deviation of the power system, including tie-line power interchange, is expressed as follows.

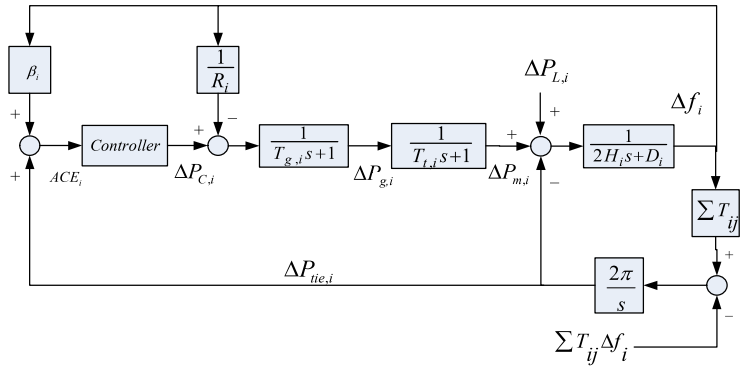


Figure 3. Power system dynamics

$$\Delta \dot{f}_i = \frac{1}{2H_i}\left(\Delta P_{m,i} - \Delta P_{L,i} - d_i\ \Delta f_i - \Delta P_{tie,i}\right) \tag{15}$$

The prime mover P_m, governor output P_g, tie-line power interchange P_{tie} are for n areas are formulated in (16-18). Area Control Error (*ACE*) is chosen as the controller input which is the result of frequency f and tie-line power changes within a control area of the power system defined in (19) [1].

$$\Delta \dot{P}_{m,i} = \left(\frac{1}{T_{g,i}}\right)\Delta P_{g,i} - \left(\frac{1}{T_{t,i}}\right)\Delta P_{m,i} \tag{16}$$

$$\Delta \dot{P}_{g,i} = \frac{1}{T_{g,i}}\left(\Delta P_{C,i} - \frac{\Delta f_i}{R_i} - \Delta P_{g,i}\right) \tag{17}$$

$$\Delta \dot{P}tie,i = 2\pi\left[\sum_{\substack{j=1 \\ j\neq i}}^{n} T_{ij}\Delta f_i - \sum_{\substack{j=1 \\ j\neq i}}^{n} T_{ij}\Delta f_j\right] \tag{18}$$

$$ACE_i = \Delta P_{tie,i} + \beta_i \Delta f_i \tag{19}$$

where $P_{L,i}$ is the load/disturbance, $P_{C,i}$ is the controller output, H_i is the equivalent inertia constant, d_i is the damping coefficient, R_i is the speed droop characteristic and β_i is the bias of frequency. T_{ij} is the tie-line synchronizing coefficient between area i and j, $T_{g,i}$ is the governor time constants and $T_{t,i}$ is the turbine time constants of area *i.*

3. Results and Analysis

3.1. Simulation

The power system configuration for testing the proposed controller is based on [6, 8] with the parameters as shown in Table 1 while the system dynamics are figured in Figure 4. Simulations were done in two cases and the simulation setup is configured in Table 2, where step and random disturbance are imposed on the load in all area. The random disturbance implies load changes of white noise with a maximum 0.1 pu while step disturbance is assumed as load change in constant for a certain time.

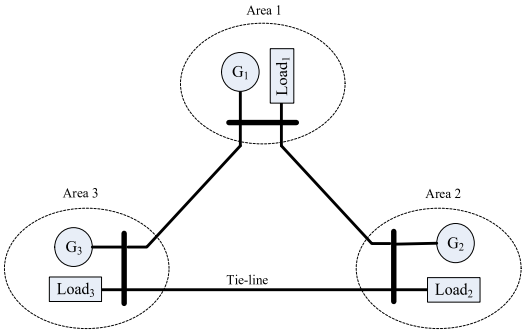


Figure 4. Three-area power system configuration

Table 1. Three Area Power System Parameters

Area	d [pu/Hz]	$2H$ [pu s]	R [Hz/pu]	T_g [s]	T_i [s]	[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

Table 2. Simulation Setup

Case	Step Disturbance [pu]	Random Disturbance [pu]
I	0.2	0.1
II	0.2	-

A Laguerre function based MPC controller is built to control a three area power system frequency. To ensure the MPC stability, the scaling factor a is tuned to 0.1 while network lengths N is set to 4 for each area controller. The model will be updated each second with the input-output data using ELM method. Overall simulation responses of frequency and mechanical power deviation for both existing and proposed controller are plotted in Figures 5 and 6.

3.2. Discussion

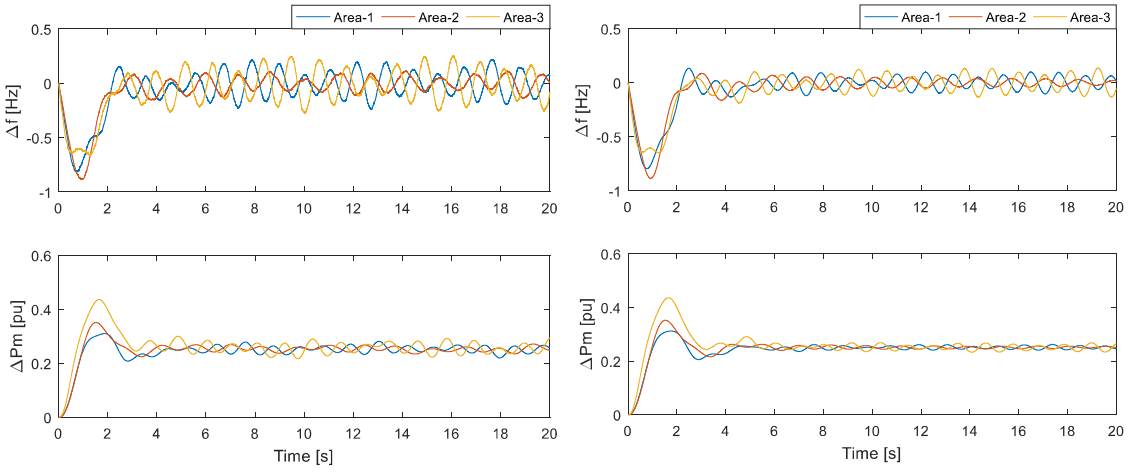
The controller performance is evaluated based on system responses and signal measures. Standard deviation is also provided to indicate how sensitive the controller to response the errors.

For the system responses based evaluation, overshoot and standard deviation are analyzed and the results are provided in Table 3 as well as its visual in Figure 7 and 8 based on system responses in Figure 5 and 6. According to the figures and table, it can be simply known that the proposed controller has very good response overshoot of frequency and mechanical power compared to the existing MPC controller in all areas of both cases. On the other hand, the proposed controller slightly aggressive to the disturbances as shown in high standard deviations in some areas and cases. These are the evidence that the proposed controller can accurately cover the power system dynamics and also it shows the ability to increase controller performance by sending proper feedback to the controller by utilizing the adaptive model.

By the treatment as same as in the case I, the other adaptive internal model for LFC application introduced in [7] has overshoot responses 0.1465, 0.1729, and 0.1652 and standard deviation 0.0294, 0.0443, and 0.0278 for area 1-3 respectively. Compared to the proposed controller, it is proved that the proposed controller has smaller overshoot and higher standard deviation compared. These are the indications that the proposed controller is more active to maintain the frequency change during the simulation and so it only has a small overshoot on the simulation.

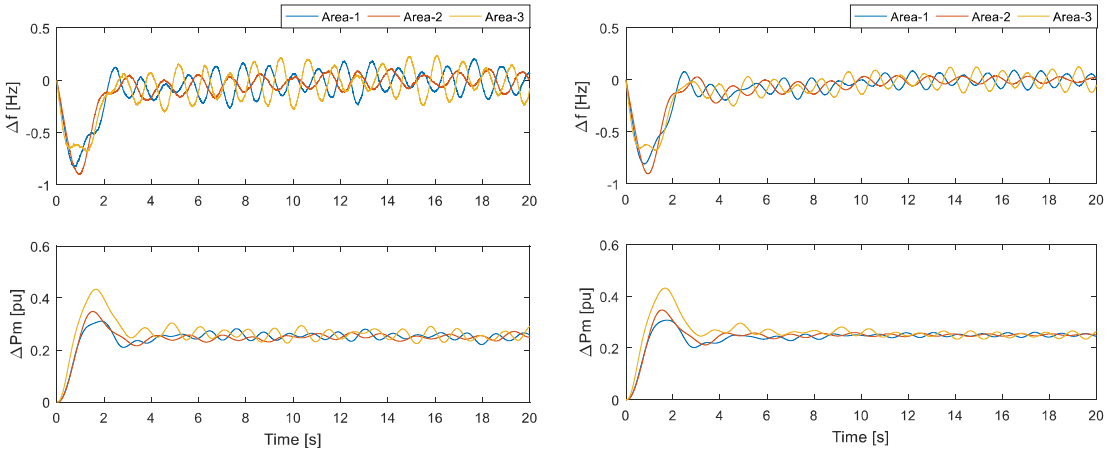
Table 3. Frequency and Mechanical Power Deviation Analysis

	Area	Frequency Deviation				Mechanical Power Deviation			
		MPC Cases		Adaptive IMC Cases		MPC Cases		Adaptive IMC Cases	
		I	II	I	II	I	II	I	II
Overshoot	1	0.1346	0.2190	0.0923	0.2047	0.3437	0.3401	0.3080	0.3109
	2	0.0860	0.1162	0.0407	0.1147	0.4164	0.4165	0.3473	0.3484
	3	0.1374	0.2530	0.1259	0.2384	0.4605	0.4625	0.4318	0.4340
Standard Deviation	1	0.1762	0.1967	0.1767	0.1946	0.0372	0.0428	0.0442	0.0814
	2	0.1786	0.1838	0.1795	0.1842	0.0418	0.0432	0.0354	0.0514
	3	0.1714	0.2012	0.1714	0.1976	0.0522	0.0580	0.0450	0.0738



(a) (b)

Figure 5. MPC controller responses (a) case i and (b) case II



(a) (b)

Figure 6. Adaptive IMC controller responses (a) case i and (b) case ii

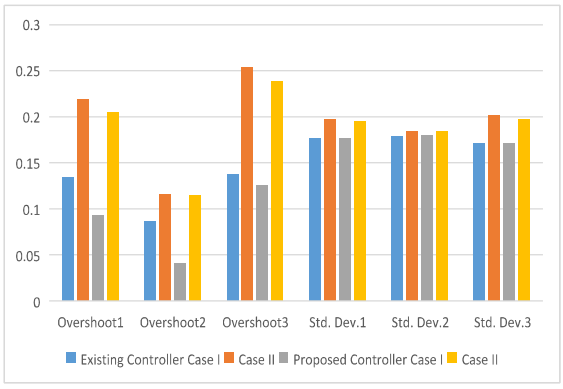


Figure 7. Frequency deviation

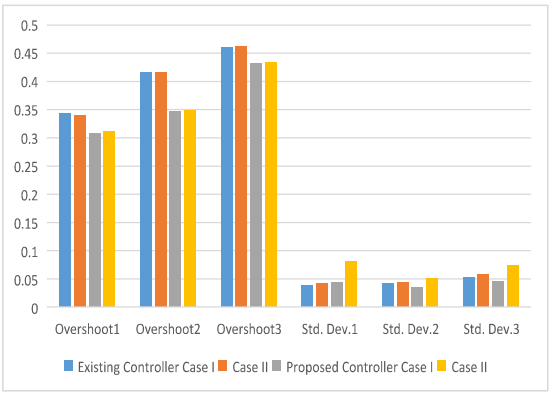


Figure 8. mechanical power deviation

The signal measured based evaluation of the proposed controller including Integral of the absolute value of the error (IAE), Integral of the square value of the error (ISE) and Integral of the time-weighted absolute value of the error (ITAE) are provided in Table 4. It is shown that the proposed controller has small errors in IAE and ITAE index while it has high deviation in the ISE index in both cases. These are the validation that the proposed controller has no persisting high errors and it adaptively follows the load changes in the simulation.

The specifications of the machine to run the simulation runs are Intel Core i7 2.9 GHz CPU and 16 GB RAM using MatLab 2016a under Windows 10 environment. CPU time for both cases of MPC, and case I and II of adaptive IMC are 1.5509, 1.5446, 6.6927 and 6.4599 seconds respectively. It seems like the proposed controller will need time 4 times longer than the existing controller since it needs to build its own model in a certain period which is in this cases every second. This may not degrade the performance in real operation since the CPU time is still littler than simulation setting time.

Table 4. Controller Index Analysis

	Area	MPC			Adaptive IMC		
		IAE	ISE	ITAE	IAE	ISE	ITAE
Case I	1	1.9340	0.6858	10.6362	1.9039	0.6900	10.1068
	2	1.6508	0.7028	6.9319	1.6532	0.7118	6.8517
	3	2.1407	0.6593	14.1713	2.0966	0.6589	13.4449
	avg	1.9085	0.6827	10.5798	1.8846	0.6869	10.1345
Case II	1	2.2608	0.7425	15.0622	2.2289	0.7444	14.4818
	2	1.6748	0.7204	6.8818	1.6792	0.7297	6.8696
	3	2.6418	0.7685	20.5055	2.5884	0.7626	19.6189
	avg	2.1924	0.7438	14.1498	2.1655	0.7456	13.6567

4. Conclusion

A novel adaptive IMC controller based on ELM method has been introduced in this paper. A three area power system is chosen to validate the controller in handling load frequency control including step and random disturbance. Simulation results show that the proposed controller presents superior responses in all areas of both cases compared to the existing MPC controller.

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