Total power deficiency estimation of isolated power system network using full-state observer method

M.Saifuzam Jamri, Muhammad Nizam Kamarudin, Mohd Luqman Mohd Jamil
Centre for Robotics and Industrial Automation (CeRIA), Universiti Teknikal Malaysia Melaka, Malaysia

Article Info

Article history:

Received May 9, 2021
Revised Jul 16, 2021
Accepted Aug 4, 2021

Keywords:

Full-state observer
Input state estimation
Isolated power system
Pole placement
Power deficiency

ABSTRACT

An isolated electrical network with an independent local distributed generator is very sensitive towards the contingencies between load demand and supply. Although the network system has less complexity in term of structure, its stability condition is crucial due to its stand-alone operating condition. The total power deficit in the network gives the important information related to the dynamical frequency responses which may directly affect the system's stability level. In this paper, the approach to estimate the total power deficiency for the isolated electrical network was presented by utilized the Luenberger observer method. Although the power deficit is not the state variable in the network mathematical model, the solution of estimation problem was feasible by introducing the new variable using additional dummy system. The simulation was carried out by using MATLAB/Simulink environment and the designed estimator was verified using multifarious load demand changes. The results show that the estimated signal was successfully tracked the expected actual signal with minimum error.

Corresponding Author:

Mohd Saifuzam bin Jamri
Centre for Robotics and Industrial Automation (CeRIA)
Faculty of Electrical Engineering
Universiti Teknikal Malaysia Melaka
Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
Email: saifuzam@utem.edu.my

1. INTRODUCTION

An isolated electrical network with low voltage system is commonly used under stand-alone operating condition. The same situation also applied to the network with local generator that has disconnected from the utility supply due to some contingencies problem. This situation is considerable as islandic condition and the network is very sensitive towards any disturbance due to the mixed energy demand and sources [1]-[3]. The stability condition is achieved when the dynamical behavior in the generation side is able to sustain for any level of demand and ensured the dynamical frequency network within the permissible level. A review on stability in power system network has been discussed in [4]-[9]. The investigations on the influence of frequency load control on the islandic power system network fed by mixed generation sources are reported in [10]-[13]. For multiple area power system network with local generator, the multifarious of load demand give significant impact to the dynamical frequency responses as summarized in [14]-[18].

Total power deficit is defined as the size of the mismatch between load demand and generated supply. The state of the power deficit basically can be referred through the general swing equation. From this equation, the size of the power deficit was translated into the form of frequency dynamic. There are several considerable amount of works in literature that investigated the behavior of network frequency towards the changes of power deficit [19]-[22]. All of these works are directly utilized the swing equation to estimate the power deficit plus, the system structure with parameters are assumed to be well-known. Thus, the estimated power deficit does not introduce any conservatism in its behavior. Moreover, in [23]-[26], the total power deficit was estimated through the rate of change of frequency decay after the first triggered of load shedding scheme. This approach shows the independency of estimation method towards the generator inertia constant which known as one of the crucial parameters that highly affect the initial frequency slope.

In this paper, the approach to estimate the power deficit using full-state observer is discussed. The dynamical of frequency response is observed after the load demand changed and then the power deficit is estimated. The work deal with derivations of the mathematical model for isolated electrical power system network fed by single generator. Then the well-known full-state observer equation was augmented to the network equation to assure that the solution of estimation process is feasible and the estimation error performance can be verified.

2. RESEARCH METHOD

The isolated electrical network that has been studied in this work is considered as a low voltage system fed by single local generator as shown in Figure 1. The typical generator system may consist of the integration with turbine system and the governor system. In this work, the physical model of isolated electrical network was translated into the mathematical equation which described by the differential equation in state-space realization.

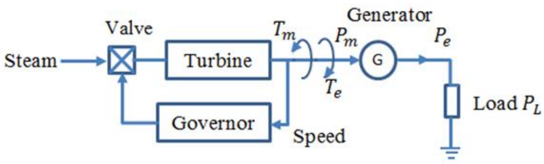

Figure 1. Isolated electrical network fed by single local generator

The behavior of generator rotor rotation can be represented by the rotating mass model with the equation written, this equation shows the influence of the dynamical frequency response $\Delta\omega$ towards the power deficit between mechanical power ΔP_m and electrical power ΔP_e. However, the initial slope of frequency decay after the disturbance is depends on the inertia constant parameter which denoted by H. The d/dt term denotes that the equation is in the form of first-order differential equation.

Prime mover model is the mathematical model that describe the behavior of turbine system. The role of turbine system is to feed the source of mechanical power for the rotating mass. In this work, the prime mover model was derived to relate the mechanical power output ΔP_m to the governor power ΔP_{gv} from the governor system with the time constant τ_t as shown in (2).

$$2H.\frac{d\Delta\omega}{dt} = \Delta P_m - \Delta P_e \quad (1)$$

$$\frac{d\Delta P_m}{dt} = \frac{1}{\tau_T}(\Delta P_{gv} - \Delta P_m) \quad (2)$$

The governor system is the crucial part in the generator system that responses to the variation of network disturbances. These disturbances commonly been translated as the variation of load demand in the network which will influence the amount of kinetic energy stored in the rotating system. The kinetic energy can be seen in the dynamical of the frequency transient. The speed governor performance is referred to the governor characteristic derived by the slope R as shown in Figure 2. While the (3) shows the differential equation that describes the governor system. Noted that, the ΔP_{ref} is the reference power deviation for the governor system to achieved and is assumed equal to zero because the work does not consider the automatic generation control (AGC).

$$\frac{d\Delta P_{gv}}{dt} = \frac{1}{\tau_{gv}}\left(\Delta P_{ref} - \frac{\Delta\omega}{R} - \Delta P_{gv}\right) \quad (3)$$

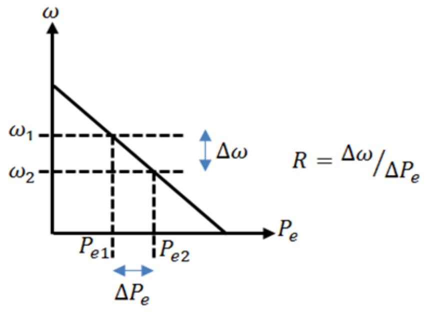

Figure 2. The speed governor characteristic

2.1. The state-space representation

The (1), (2) and (3) can be written into the state-space representation as shown in (4). From the equation, the state variables are $\Delta\omega$, ΔP_m and ΔP_{gv} while the input state is the load demand ΔP_e. Noted that the symbol Δ used in these equations is to represent the deviations of the state.

$$\dot{v}(t) = av(t) + bu \tag{4}$$

The matrix a and b is arranged as shown in (5) and (6).

$$a = \begin{bmatrix} 0 & {}^{1}/_{2H} & 0 \\ 0 & {}^{-1}/_{\tau_T} & {}^{1}/_{\tau_T} \\ {}^{-\Delta P_{ref}}/_{T_{gv}R} & 0 & {}^{-1}/_{T_{gv}} \end{bmatrix} \tag{5}$$

$$b = \begin{bmatrix} {}^{-1}/_{2H} & 0 & 0 \end{bmatrix}^T \tag{6}$$

2.2. Estimator design

The purpose of this work is to estimate the total power deficit of the isolated electrical network fed by single local generator as shown in Figure 1. The proposed configuration is depicted in Figure 3. The goal of this formulation is to observe the frequency dynamic of the generator and estimate the total power deficit of the network. An additional system denoted by the low pass filter was introduced to convert the input state into the state variable. This is because the power deficit to be estimated is related to the input state. Thus, the whole system size is now become the fourth order. Augmenting the network equation with the additional low pass system, the new state-space realization can be written,

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{7}$$

$$y(t) = Cx(t) \tag{8}$$

$$z(t) = C_d x(t) \tag{9}$$

With A, B and C are the state matrix for the augmented system respectively while C_d is the output matrix for the state vector to be estimated. It is assumed that the dimensions of all matrices and matrix C_d are known. The general state-space equation for the full-state observer is written as,

$$\dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) + L[y(t) - \hat{y}(t)] \tag{10}$$

$$\hat{y}(t) = C\hat{x}(t) \tag{11}$$

Note that L is the $n \times m$ gain matrix for the observer. Substituting the (11) into the observer's state equation in (10) yields the following alternative forms for the observer model.

$$\dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) + Ly(t) - LC\hat{x}(t) = (A - LC)\hat{x}(t) + Bu(t) + Ly(t) \tag{12}$$

The $(A - LC)$ is the state matrix for the observer. If the system (A, C) is completely observable, then the gain matrix L can be chosen to place the eigenvalues of $(A - LC)$ at arbitrary location in the left-half of the complex plane, then the observer system is asymptotically stable. The block diagram for the full-state observer is shown in Figure 4.

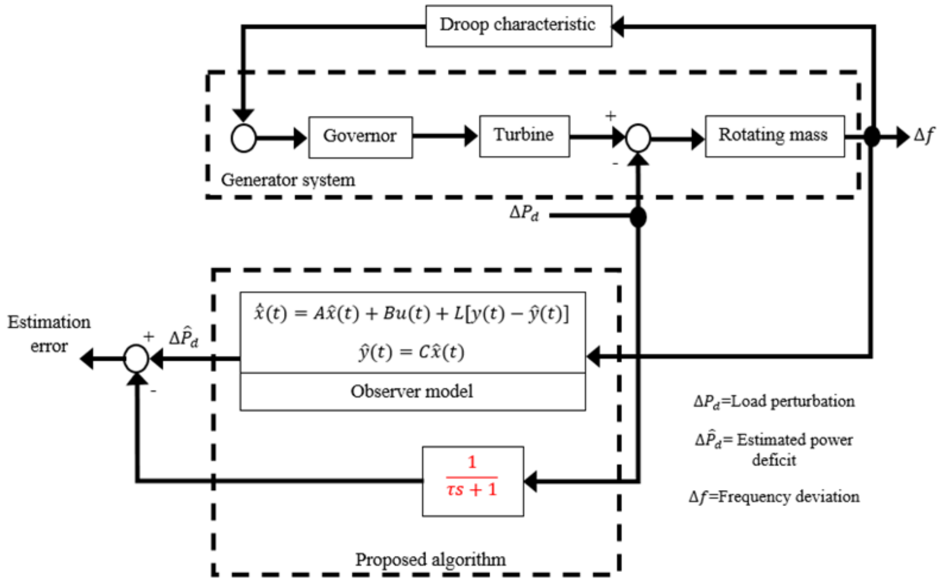

Figure 3. Proposed estimator algorithm and configuration

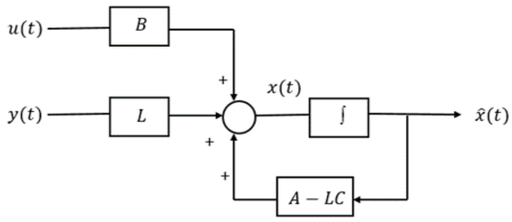

Figure 4. The block diagram of a continuous-time full-state observer

2.2.1 Observer gain determination.

In this work, the output state matrix of the augmented system in (8) is not fully observable. Therefore, the solution for the observer gain in the pole placement is not feasible. Hence, to ensure the feasibility of the pole placement and achieve the stable observer system, the output state of the augmented system $y(t)$ in (8) was modified by adding with the output state matrix $z(t)$ in (9). Then, the equation can be written.

$$y_n(t) = (C + C_d)x(t) = C_n x(t) \tag{13}$$

Hence, the observer matrix shown in (12) can be written as $(A - LC_n)$ and the observer gain L was determined by using the Ackerman's formula. This formula is the heuristic method that normally been used for solving the pole allocation problem for time-invariant system.

2.3. Simulation setup

The model of isolated electrical network was simulated in linear time invariant in MATLAB/Simulink platform. The parameters that was chosen and used as shown in Table 1. Noted that all the values are approximated and the simulation was carried out in per unit.

For the observer, the pole of the gain L was arbitrarily placed and all the eigenvalues of the observer matrix $(A - LC_n)$ are located on the same place in the left-half of the complex plane. The reason is to make easy to determine the optimum pole and achieved the lowest estimated error.

Table 1. Parameters of isolated power system model

Parameter name	Value
Governor time constant, Tgv	0.2
Governor speed regulation, R	0,05
Generator inertia constant, H	5
Turbine time constant, Tt	0.5

3. RESULTS AND DISCUSSION

3.1. Isolated electrical network

Figure 5 shows the dynamical behavior of the frequency in per unit for the isolated electrical network under the multifarious load demand change. The model was tested for the first changed of load demand at 5 second by 0.2pu followed by 0.3pu at 15 second. The results were verified, and it is confirmed that the steady-state of the frequency goes to the new operating point in every load demand changed. The higher the load demand changed will result the lower the frequency operating point. This phenomenon happened because the model was derived without considering the automatic generation control (AGC).

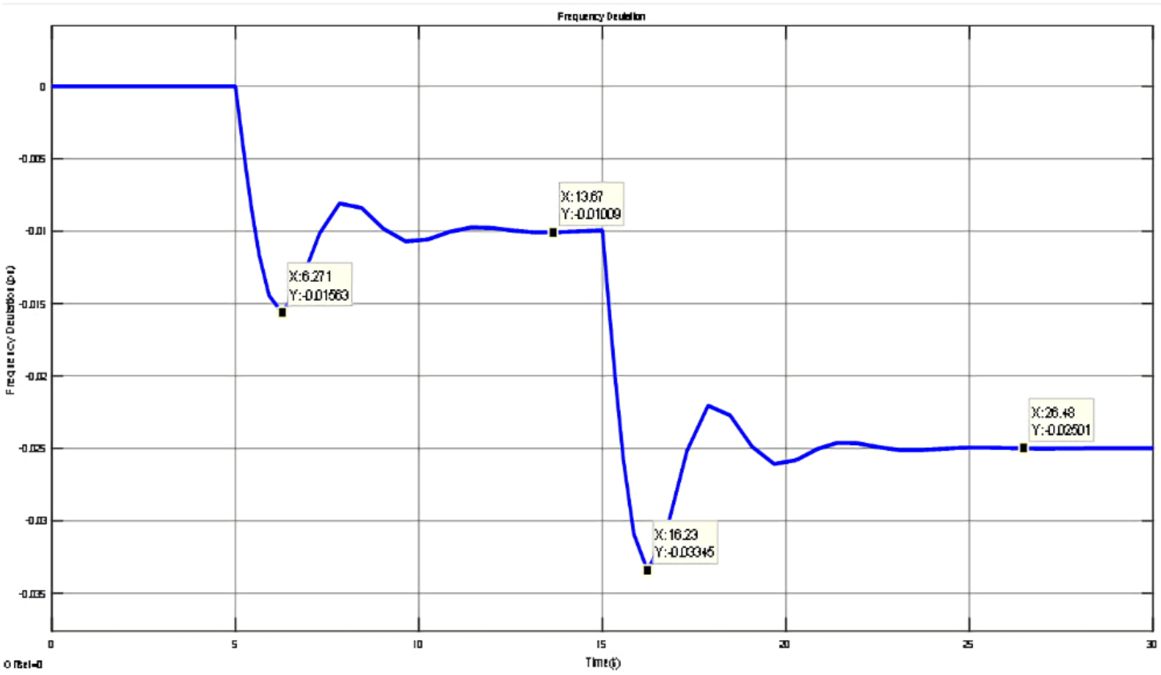

Figure 5. The dynamical frequency response of the isolated electrical network.

3.2. Power deficit estimation

For the observer, the value of gain L is depends to the pole location which corresponds to the negative eigenvalues of the observer matrix $(A - LC_n)$ and confirmed the stability. Table 2 shows the analysis of the estimation performance towards the different pole location assigned on each state vectors ranged arbitrarily from -5 to -40 of the real axis. Figure 6 shows the summarization of the error percentage towards the pole's location illustrated in the line graph.

From the analysis, it is confirmed that the pole location of observer state matrix $(A - LC_n)$ may influenced the estimation performance that correspond to the decision of optimal value for the observer gain. The estimation error performance become lower as the pole location near to the imaginary of the complex plane. Thus, this work proposed to choose -35 as the most optimized pole for the estimator gain. This pole gives the lowest estimation error and settling time. Figure 7 shows the power deficit estimation result while

Figure 8 shows the estimation error dynamic. The results shows that the estimated power deficit yields the similar performance as the actual but not during the first load demand changed and its obviously seen the very short spiking in the error performance graph.

Table 2. Analysis of estimation performance

	Actual value	Estimate value		
-5	0.20	1.16	480	7.52 − 5 = 2.52
-10	0.20	0.49	145	6.33 − 5 = 1.33
-15	0.20	0.33	65	5.87 − 5 = 0.87
-20	0.20	0.26	30	5.64 − 5 = 0.64
-25	0.20	0.23	15	5.50 − 5 = 0.50
-30	0.20	0.21	5	5.37 − 5 = 0.37
-35	0.20	0.20	0	5.32 − 5 = 0.32
-40	0.20	0.20	0	5.34 − 5 = 0.34

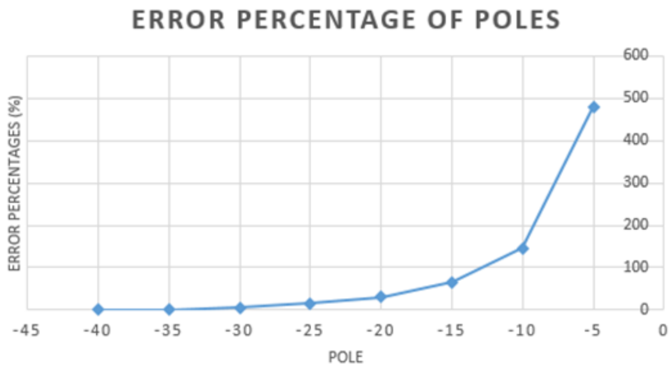

Figure 6. The influence of the error percentage

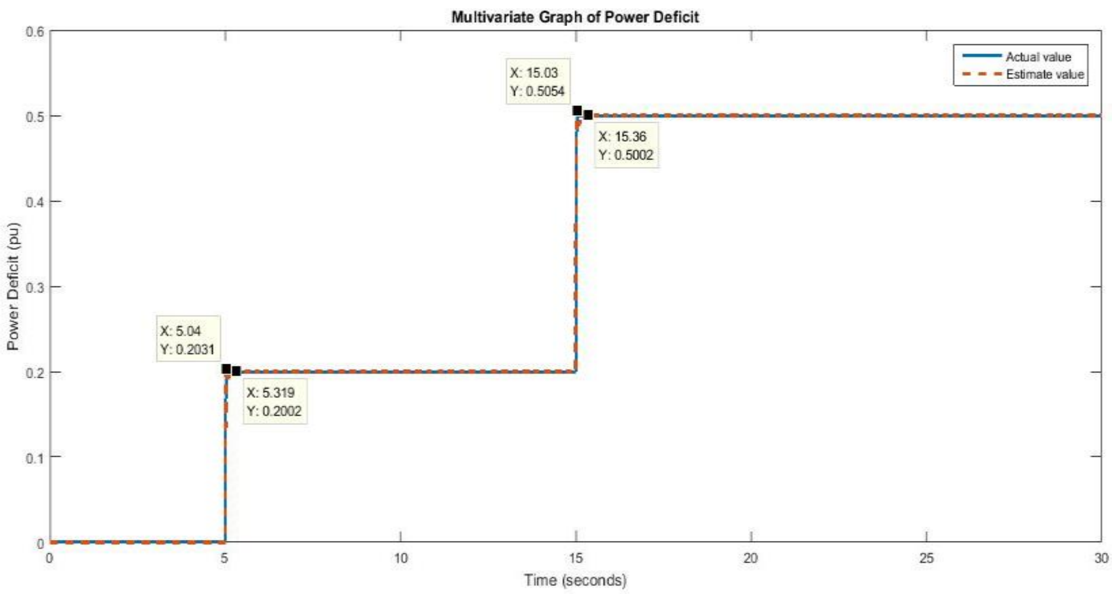

Figure 7. Power deficit estimation performance

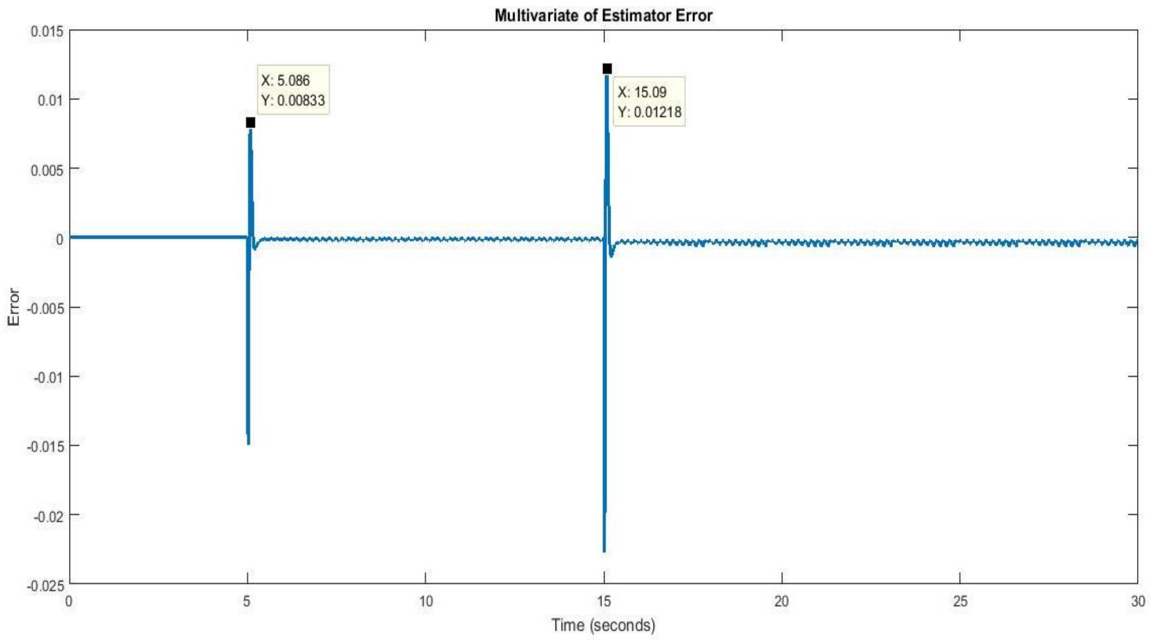

Figure 8. Estimation error performance

4. CONCLUSION AND FUTURE WORK

The state-space mathematical model for isolated electrical network with single generator has been derived without considering the automatic generation control. To estimate the power deficit, an additional low pass filter was introduced and augmented into the derived mathematical network model and made the overall system changed to become fourth-order system. The frequency dynamic has been selected as the only state variable to be monitored by the observer. The observer matrix was successfully formulated to confirm the stability. However, the estimation error performance was depending on the pole location which directly affect to the observer gain value. This pole dependency made the approach of pole determination using Ackerman's formula become heuristic and only approximated based on the trial-and-error. In the future work, it is suggested that an optimization problem can be exploited to obtain the most appropriate observer gain value. Furthermore, the research for unknown model parameter augmented with dynamic filtering problem could be considered so that the robustness performance can be analyzed and achieved.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Center for Robotics and Industrial Automation, Universiti Teknikal Malaysia Melaka (CeRIA) for the research facilities and support, to the Center for Research and Innovation Management (CRIM) for the funding and publication facility.

REFERENCES

[1] G. R. Prudhvi Kumar, D. Sattianadan and K. Vijayakumar, "A survey on power management strategies of hybrid energy systems in microgrid," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, no. 2, pp. 1667-1673, April 2020, doi:10.11591/ijece.v10i2.pp1667-1673.

[2] G. Reina, M. Mauledoux, and O. A. Avilés, "Simulation of a microgrid for a non-interconnected zone that integrates renewable energies," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 11, no. 1, pp. 201-216, February 2021, doi:10.11591/ijece.v11i1.pp201-216.

[3] D. C. K. Reddy, S. Satyanarayana, and V. Ganesh, "Design of Hybrid Solar Wind Energy System in a Microgrid with MPPT Techniques," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 8, no. 2, pp. 730-740, April 2018, doi:10.11591/ijece.v8i2.pp730-740.

[4] M. N. Kamarudin, N. Shaharudin, N. H. A. Rahman, M. H. Hairi, S. Md. Rozali, and T. Sutikno, "Review on load frequency control for power system stability," *TELKOMNIKA Telecommunication, Computing, Electronics and Control*, vol. 19, no. 2, pp. 638-644, April 2021, doi:10.12928/telkomnika.v19i2.16118.

[5] M. M. A. Hassan, X. Sun, and A. Ate, “FLC based on static var compensator for power system transient stability enhancement,” *TELKOMNIKA Telecommunication, Computing, Electronics and Control*, vol. 18, no. 5, pp. 2665-2673, 2020, doi:10.12928/telkomnika.v18i5.15605.

[6] S. R. Salkuti, “Study on the performance indicators for smart grids: a comprehensive review,” *TELKOMNIKA Telecommunication, Computing, Electronics and Control*, vol. 17, no. 6, pp. 2912-2918, Dec. 2019, doi:10.12928/telkomnika.v17i6.13285.

[7] L. Zhu and D. J. Hill, “Stability Analysis of Power Systems: A Network Synchronization Perspective,” *SIAM Journal on Control and Optimization*, vol. 56, no. 3, 2018, pp. 1640-1664, doi:10.1137/17M1118646.

[8] H. Han and Z. Wang, “Power system transient stability analysis based on branch potential characteristics,” *IOP Conf. Series: Materials Science and Engineering*, 2017, doi:10.1088/1757-899X/231/1/012075.

[9] M. Mynuddin, K. M. Roknuzzaman, P. Biswas, and M. Tanjimuddin, “Stability Study of Power System,” *Int. Journal of Energy and Power Engineering*, vol. 4, no. 2, pp. 43-50, 2015, doi:10.11648/j.ijepe.20150402.15.

[10] N. Salim, A. Khamis, A. N. Nazmin, and N. A. Zambri, “Frequency Control Reserve Via Micro grid for the Future Renewable Malaysian Power System,” *IEEE PES Asia-Pacific Power and Energy Engineering Conference*, 2018, pp. 428-433, doi:10.1109/APPEEC.2018.8566361.

[11] M. N. Ambia, A. Al-Durra, C. Caruana, and S. M. Muyeen, “Islanding Operation of Hybrid Microgrids With High Integration of Wind Driven Cage Induction Generators,” *Sustain. Energy Technol. Assessments*, pp. 68-75, 2016, doi:10.1016/j.seta.2015.11.002.

[12] N. N. A. Bakar, M. Y. Hassan, M. F. Sulaima, M. N. Mohd Nasir, and A. Khamis, “Microgrid and load shedding scheme during islanded mode,” *A review. Renew. Sustain. Energy Rev*. 2017, pp. 161-169, 2017, doi:10.1016/j.rser.2016.12.049.

[13] M. Mehrasa, E. Pouresmaeil, B. N. Jørgensen, and J. P. S. Catalão, “A control plan for the stable operation of microgrids during grid-connected and islanded modes,” *Electr. Power Syst. Res*. 2015, pp. 10-22, 2015, doi:10.1016/j.epsr.2015.07.004.

[14] Usman and B. Divakar, “Simulation Study of Load Frequency Control of Single and Two Area Systems,” *IEEE Global Humanitarian Technology Conference*, Seattle, WA, 2012, pp. 214-219, doi:10.1109/GHTC.2012.38.

[15] S. A. Jeddi, S. H. Abbasi, and F. Shabaninia, “Load frequency control of two area interconnected power system (Diesel Generator and Solar PV) with PI and FGSPI controller,” *The 16th CSI International Symposium on Artificial Intelligence and Signal Processing (AISP 2012)*, 2012, pp. 526-531, doi:10.1109/AISP.2012.6313803.

[16] K. Ahmed M., “Neural Predictive Controller of a Two-Area Load Frequency Control For Interconnected Power System,” *Ain Shams Engineering Journal*, no. 5, pp. 49-58, 2010, doi:10.1016/j.asej.2010.09.006.

[17] M. S. Jamri, M. N. Kamarudin, and M. L. M. Jamil, “Average dynamical frequency behaviour for multi-area islanded micro-grid networks,” *TELKOMNIKA Telecommunication, Computing, Electronics and* Control, vol. 18, no. 6, Dec. 2020, doi:10.12928/telkomnika.v18i6.16805.

[18] H. Gao, Y. Chen, Y. Xu, and C. Liu, “Dynamic Load Shedding for An Islanded Micro-grid with Limited Generation Resources,” *IET Gener. Transm. Distrib*, vol. 10, no. 12, pp. 2953-2961, 2016, doi:10.1049/iet-gtd.2015.1452.

[19] N. Hajimohamadi and H. Bevrani, "Load Shedding in Micro-grids," *2013 21st Iranian Conference on Electrical Engineering (ICEE)*, Mashhad, 2013, doi:10.1109/IranianCEE.2013.6599531.

[20] A. Ketabi and M. H. Fini, “An underfrequency load shedding scheme for islanded microgrids,” *International Journal of Electrical Power & Energy Systems*, vol. 62, pp. 599-607, 2014, doi:10.1016/j.ijepes.2014.05.018.

[21] A. Ketabi and M. H. Fini, “An Underfrequency Load Shedding Scheme for Hybrid and Multiarea Power Systems,” *IEEE Transactions on Smart Grid*, pp. 82-91, 2015, doi:10.1109/TSG.2014.2349999.

[22] M. Esmail, R. Tzoneva, and S. Krishnamurthy, “Review of Automatic Generation Control in Deregulated Environment,” *IFAC-PapersOnLine*, vol. 50, no. 2, pp. 88-93, 2017, doi:10.1016/j.ifacol.2017.12.016.

[23] Q. Jiang, M. Xue and G. Geng, “Energy Management of Microgrid in Grid-Connected and Stand-Alone Modes,” in *IEEE Transactions on Power Systems*, vol. 28, no. 3, pp. 3380-3389, Aug. 2013, doi:10.1109/TPWRS.2013.2244104.

[24] L. I. Minchala-Avila, L. Garza-Castañon, Y. Zhang, and H. J. A. Ferrer, “Optimal Energy Management for Stable Operation of an Islanded Microgrid,” in *IEEE Transactions on Industrial Informatics*, vol. 12, no. 4, pp. 1361-1370, Aug. 2016, doi: 10.1109/TII.2016.2569525.

[25] A. Rafinia, N. Rezaei, and J. Moshtagh, “Optimal design of an adaptive under-frequency load shedding scheme in smart grids considering operational uncertainties,” *International Journal of Electrical Power & Energy Systems*, vol. 121, 2020, doi:10.1016/j.ijepes.2020.106137.

[26] A. Ketabi and M. H. Fini, “Adaptive underfrequency load shedding using particle swarm optimization algorithm,” *Journal of Applied Research and Technology*, vol. 15, no. 1, pp: 54-60, 2017, doi:10.1016/j.jart.2016.12.003

BIOGRAPHIES OF AUTHORS

M. Saifuzam Jamri was born in October 1984. He received his bachelor degree in Electrical Engineering (Power Electronics & Drives) from Universiti Teknikal Malaysia Melaka, Malaysia in 2007 and received the Master Degree in Electrical Power Engineering from Universiti Teknologi Malaysia in 2009. He is currently worked with the Universiti Teknikal Malaysia Melaka (UTeM) as a lecturer and belongs to Centre for Robotics and Industrial Automation (CeRIA) group. His interest is in power system study and micro-grid including load frequency control (LFC) and renewable energy integration. He is currently persuing the PhD in University Tekninal Malaysia Melaka under Faculty of Electrical Engineering.

Muhammad Nizam Kamarudin was born in Selangor, Malaysia. He received the B.Eng (Hons.) Electrical from the Universiti Teknologi MARA, Malaysian in 2002, and M.Sc in Automation and Control from the University of Newcastle Upon Tyne, United Kingdom in 2007. He received the Doctor of Philosophy in Electrical Engineering from the Universiti Teknologi Malaysia in 2015. He is currently with the Universiti Teknikal Malaysia Melaka (UTeM). He is the member of the Board of Engineers, Malaysia and Institute of Engineers, Malaysia. His research interests include nonlinear controls and robust control systems. Before joining UTeM, he worked as a Technical Engineer at the magnetron department of Samsung Electronics Malaysia.

Mohd Luqman Mohd Jamil received B.Eng. degree from the Universiti Teknologi MARA, Shah Alam, Malaysia, in 2000, M.Sc. degree from Univeristy of Newcastle upon Tyne, U.K., in 2003, and Ph.D. degree from The University of Sheffield, Sheffield, U.K., in 2011, all in electrical engineering. He is currently an academician in Faculty of Electrical Engineering, University Teknikal Malaysia Melaka, Melaka, Malaysia. He is also an active researcher in Power Electronics and Drives Research Group (PEDG) that established under the same faculty. His research interests include the design, control and analysis of permanent-magnet machines.