International Journal of Electrical and Electronic Engineering & Telecommunications Vol. 7, No. 3, July 2018

# Experimental Validation for Dynamic Fuzzy-Controlled Energy Storage System to Maximize Renewable Energy Integration

Invited Paper

Jianhui Wong and Yun Seng Lim
Universiti Tunku Abdul Rahman, Sungai Long Campus, Kajang, Selangor, Malaysia
Email: wongjh@utar.edu.my; yslim@utar.edu.my

***Abstract*—Energy storage systems are expected to play a significant role in providing ancillary services for future power systems due to its recent technologies improvement. Increased penetration from grid-connected renewable energy sources is expected to have significant growth. However, power curtailment is the usual approach imposed by the utility company to ensure the power quality works within the tolerance. In this paper, Park's transformation is proposed to analyze and assess network performance by using near-real time data acquisition to identify the most crucial phase due high degree of voltage unbalanced factor caused by the large penetration of single-phase PV systems. A novel fuzzy logic controller for the three single-phase energy storage system (ESS) is used to manipulating the power flows in response to the voltage deviations from the nominal voltage and power balance between generation and demand. Results have demonstrated that the ESS driven by the fuzzy logic controller has effectively maintains the network voltage unbalance factor (VUF) within the tolerance statutory limit. By ensuring the power quality works within the tolerance statutory limit can eliminate the energy curtailment, hence maximize the renewable energy (RE) integration.**

***Index Terms*—fuzzy logic control, distribution network, energy storage system, photovoltaic system**

## I. INTRODUCTION

Conventional power systems have been existence for more than a century, the capability of a typical power system inclusive generating, transmitting and distributing the electrical power to consumer works perfectly in a unidirectional power flow manner. However, the growing of new technologies such as the Renewable Energy (RE) sources, Particularly Photovoltaic (PV) systems and Electric Vehicles (EV) integrated to the electric network bring new challenges to the management of the local generations and loads.

Malaysia is expected to receive significant growth of the grid-connected renewable energy sources of 2080 MW in near future, contributing to approximately 7.8% of the total installed capacity. The growth of grid-connected RE sources without proper coordination can cause various technical issues, such as voltage rise, Voltage Unbalances Factor (VUF), reverse power flow, poor power factor and flickers. All these issues can lead to the malfunction of electronic-based equipment, reduction in the network efficiency, improper operation of power protection system and rapid deterioration of transformers which gives high cost impact for the stakeholders, curtailing renewable energy and limits the amount of grid-connected renewable energy have always been applied in order to avoid the deterioration of electrical power quality. However, all these measures greatly reduce the generation of clean energy and affect the government commitment to cut down 40% of GHG emission by 2020.

Various investigations have been conducted to study the impacts of large penetration by grid-connected renewable energy sources on the existing power systems. Among all these technical issues, VUF can be the most crucial issues in Malaysia due to the nature of installation for single-phase PV systems are rather arbitrary and not monitored by utility companies [1]. Recent study also shown that when renewable energy sources, particularly photovoltaic system reaches sufficiently high level, approximately 10-20% of the total generation, the intermittency nature of the PV generation can be noticed [2].

Power curtailment is the common approach imposed by the utility company to ensure that the power quality is still within the required tolerance [3]-[5]. Despite, this method is not preferable as it limits the cut down of carbon footprint and greenhouse gaseous. Besides, customers who are eligible for selling renewable energy back to the utility company gain less revenue and period for return of investment are prolonged. Adjusting the tap setting for on load tap changer (OLTC) transformers can be one of the voltage control strategies [6]. Nevertheless, this may not be effective for mitigating voltage unbalance because it is not practical to change the tap setting for regulating particular phase voltage on the distribution networks. Changing the tap setting too frequent may shorten the lifespan of the transformer.

Another method proposed to use auto adaptive voltage regulator to coordinate and control active and reactive power across several distributed generators such that

---

Manuscript received March 7, 2018; revised June 22, 2018.

doi: 10.18178/ijeetc.7.3.83-89

these distributed generators supply power without causing power quality issues [7]. Authors in [8], [9] further improve the performance by incorporating fuzzy controller into the auto adaptive voltage regulator. These methods are similar to energy curtailment, as it does not fully utilize the available renewable energy.

Energy storage system is a possible effective solution for these power quality issues due to the recent improvement in the storage technologies. The concept of multi-energy storage system is not new, and has potential to improve the reliability and economy performance of the low-voltage distribution network. Many works have been published to coordinate multiple ESSs [10]-[13]. In this context, a fuzzy logic controller is proposed to actively control the active and reactive power flow between the storage system and the distribution networks in order to maintain the power balance within the network. Hence, regulate the voltage issues caused by high penetration of RE power output.

## II. STRUCTURE AND CONTROLLER

### A. *Malaysian Electrical Network Topology*

The typical Malaysian low voltage (LV) distribution network adopted a radial three phase 4-wire system, where end users are normally associated at the feeders end. The distribution network intake is usually rated at 11 kV and stepped down to 400 V via a step down transformer. The common practice for grounding on distribution system is utilizing TT (Terra-Terra) system where the neutral point of the transformer and installation frame are earth.

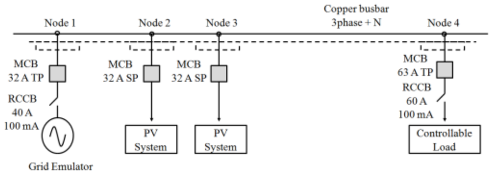
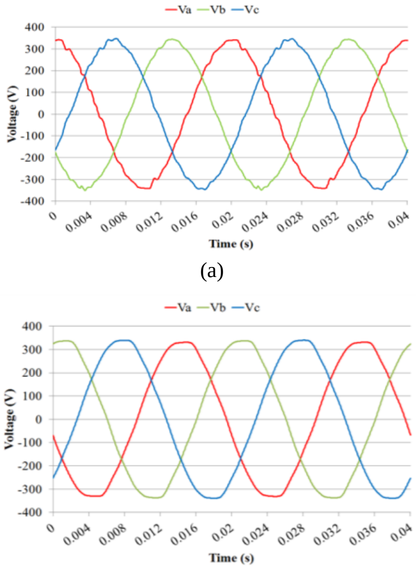


Figure 1. Typical network topology for Malaysian low-voltage distribution networks.



(a)

(b)

Figure 2. Three-phase voltage profile for (a) grid emulator and (b) low voltage distribution network

The experimental LV distribution network is designed in such a way to investigate the effectiveness of the proposed fuzzy driven ESS for mitigating voltage issues caused by the integration of renewable energy sources. Fig. 1 shows a section of the typical Malaysian LV distribution network consisting a grid emulator consists of a synchronous generator rated at 15 kVA coupled to an induction motor. A variable speed drive (VSD) is attached to the grid emulator to regulate the network frequency at 50 Hz. Grid emulator is designed in such a way to provide electrical isolation between the experimental network and utility grid as shown in Fig. 2. Besides, two units of commercial available single-phase photovoltaic systems rated at 3600 $W_p$ and a three-phase controllable resistive loads rated at 9000 W are connected to the copper busbar protected by two units of 32 A single pole (SP) miniature circuit breakers (MCB) and 63 A three poles (TP) miniature circuit breakers (MCB) respectively.

Generally, a symmetrical three-phase voltage have identical magnitude and an angle displacement of 120 degree apart from each phases. Although at the point of generation and transmission systems, symmetrical three-phase voltages are very likely to happen. However, it is quite often to have unbalance voltages to happen at the utilisation level due to unsymmetrical distribution of single-phase distributed generators and non-linear load. The degree of voltage unbalance can be defined using voltage unbalance factor (*VUF*) as follows:

$$VUF(\%) = \frac{V_n}{V_p} \times 100\% \tag{1}$$

where *VUF* indicates the degree of voltage unbalance; $V_n$ is the negative sequence voltage; and $V_p$ is the positive sequence voltage.

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & e^{j(2\pi/3)t} & e^{-j(2\pi/3)t} \\ 1 & e^{-j(2\pi/3)t} & e^{\,j(2\pi/3)t} \end{bmatrix}\begin{bmatrix} V_z \\ V_p \\ V_n \end{bmatrix} \tag{2}$$

where $V_a$, $V_b$ and $V_c$ are the phase voltages at phase A, B and C respectively. $V_p$ and $V_n$ and $V_z$ are the sequence voltages for positive, negative and zero respectively.

### B. *Structure for Energy Storage System*

Many energy storage technologies are available for the application in power system, such as electrochemical storage (e.g. lithium ion, lead acid, nickel cadmium batteries) and mechanical storage (e.g. flywheel). In this Many energy storage technologies are available for the application in power system, such as electrochemical storage (e.g. lithium ion, lead acid, nickel cadmium batteries) and mechanical storage (e.g. flywheel). In this work, lead acid was chosen due to its cost and capacity demand. Fig. 3. shows the physical architecture of the three-phase ESS is developed with three units of single-phase bi-directional inverters integrated with battery bank arranged for Phase A, B and C respectively.

Three units of single-phase bi-directional inverters were coupled together to form a three-phase ESS in order to manipulate the power flow of each phase individually. It is designed and developed in such a way to mitigate the voltage issues, particularly voltage rise and voltage unbalance caused by the large penetration of grid-connected PV systems on the LV distribution network. Information exchange can be achieved via communication link. It is established between the centralized controller and the ESS via module (RS485/ RS232), a digital power meter (DPM) is allocated for each of the point of common connection (PCC) denoted with Nodes 1, 2, 3, 4 and 5 as shown in Fig. 3 to monitor the network parameters.

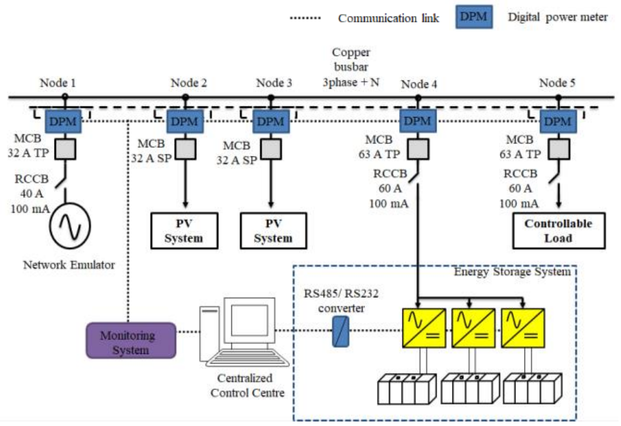


Figure 3. Proposed data acquisition for the three-phase ESS, digital power meters and the centralized controller

### C. FLC Control Hierarchy

One of the reasons to develop the controller using fuzzy logic controller (FLC) is that the three-phase voltages fluctuate throughout the day without any trend. Furthermore, many research projects have concluded that that FLC is always effective as compared to PI and PID [15]-[18]. As the batteries are one of the most expensive assets, the state of health must be taken into consideration when designing the controller. To address this issue, one of the modifications is done by correlation the power ratio with the ESS state of charge ($\mathrm{SoC_{ESS}}$). In this method, the FLC considered two input memberships, namely $\Delta V_{\mathrm{cal}}$ and $\mathrm{SoC_{ESS}}$ to generate four linguistic outputs through fuzzification, and make used of rule-based decision to produce one current instruction ($I_k$) as the output of defuzzification for manipulating the power ratio of the bi-directional inverter until the voltage magnitude at the crucial phase is restored. Once the voltage is restored, the VUF will be reduced.

The power output of the ESS is dynamically controlled overtime according to the instantaneous grid voltage and SoC level. The allowable range for battery $\mathrm{SoC_{ESS}}$ to operate is depending on the type of batteries specification.

In this work, the permissible $\mathrm{SoC_{ESS}}$ range is determined between 40% - 100%. If the $\mathrm{SoC_{ESS}}$ dropped to 60%, the ESS will be alert and limit the amount of active power output to be dispatched to the network in order to preserve the power availability. In the case of $\mathrm{SoC_{ESS}}$ approaching 40%, the controller opt to protect the health of the ESS by terminating any active power dispatch in order to avoid any deep discharging situation.

Fig. 4 shows the architecture layout of the proposed centralized control consists of phase selector and fuzzy logic controller. The centralized controller measures the three-phase voltages, $V_a$, $V_b$ and $V_c$ respectively and transform them into positive, negative and zero sequence voltages, $V_p$, $V_n$ and $V_z$ respectively by using Park's Transformation as shown in (3).

$$\begin{bmatrix} V_p \\ V_n \\ V_z \end{bmatrix} = \left( \frac{1}{3} \begin{bmatrix} 1 & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\ 1 & \cos(\omega t + \frac{2\pi}{3}) & \cos(\omega t - \frac{2\pi}{3}) \\ 1 & 1 & 1 \end{bmatrix} \right) \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{3}$$

The most crucial phase to be corrected first is then determined by the centralized controller using the sequence voltages to estimate the network VUF and voltage excursion concurrently as shown in Equation (4).

$$\begin{bmatrix} dV_a \\ dV_b \\ dV_c \end{bmatrix} = \left( \frac{1}{3} \begin{bmatrix} 1 & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\ 1 & \cos(\omega t + \frac{2\pi}{3}) & \cos(\omega t - \frac{2\pi}{3}) \\ 1 & 1 & 1 \end{bmatrix} \right)^{-1} \begin{bmatrix} 0 \\ -V_n \\ -V_z \end{bmatrix} \tag{4}$$

Equation (4) is equivalent to the differences between the phase voltage and the average voltage [14]. The rectification will take place at the most crucial phase where the maximum voltage excursion is engaged,

$$d_{k(\max)} = \max\{dV_a, dV_b, dV_c\} \tag{5}$$

The phase selector will collect and transmit the information of the designated phase voltage and $\mathrm{SoC_{ESS}}$ to the FLC to compute the required power ratio. The FLC will be triggered to dynamically control the active power ratio of the three-phase ESS to maintain the power balance within the electrical network, hence regulate the voltage and reduce the network VUF.

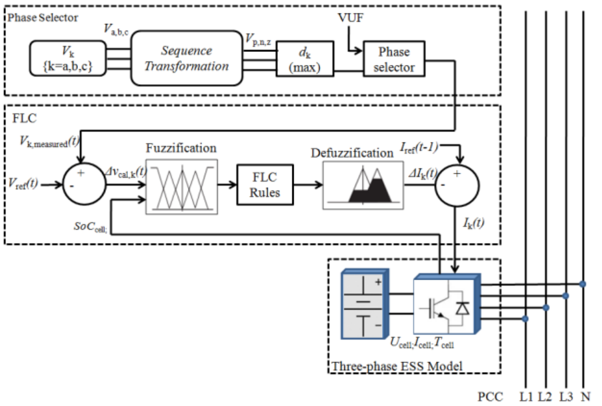


Figure 4. Architecture of the proposed centralized controller consists of phase selector and fuzzy logic controller.

Fig. 5 shows the fuzzy membership for voltage excursion ($\Delta V_{\mathrm{cal}}$) is defined into seven different voltage levels as below:-

1. SUV - Severely undervoltage,

2. VUV - Very undervoltage,
3. UV - Undervoltage,
4. N - Normal voltage,
5. OV - Overvoltage,
6. VOV - Very overvoltage, and
7. SOV - Severely overvoltage.

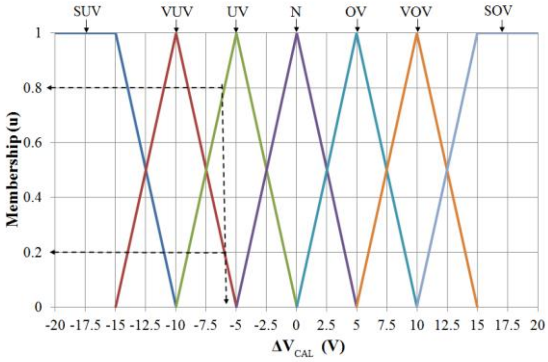


Figure 5. Pre-defined fuzzy membership for voltage excursion ($\Delta V_{\text{cal}}$).

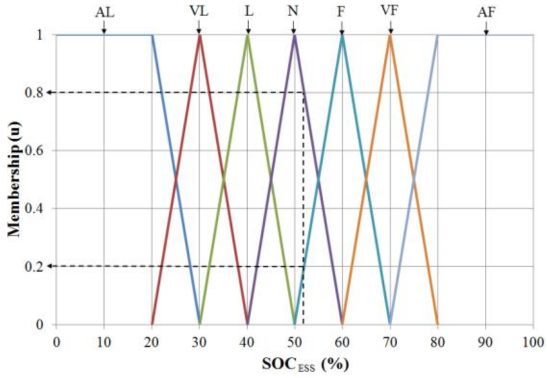


Figure 6. Pre-defined fuzzy membership for the battery $\text{SoC}_{\text{ESS}}$.

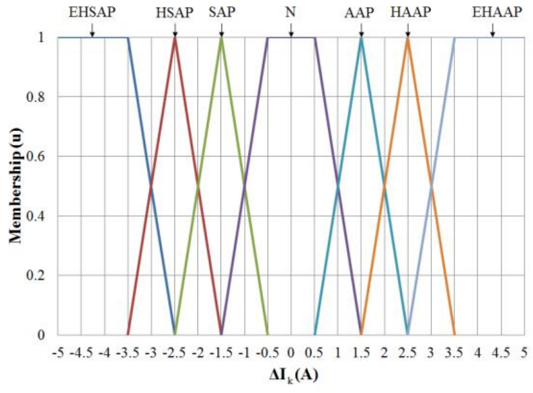


Figure 7. Pre-defined fuzzy output membership for current instruction ($\Delta I_k$) to bi-directional inverter

TABLE I: MAPPING FOR THE FUZZY OUTPUT MEMBERSHIP FOR CURRENT INSTRUCTION ($\Delta I_k$)

| $\text{SoC}_{\text{ESS}}$ | $\Delta V_{cal}$ | | | | | | |
|---|---|---|---|---|---|---|---|
| | EUV | VUV | UV | N | OV | VOV | EOV |
| AL | SAP | N | N | N | HAAP | EHAAP | EHAAP |
| VL | SAP | SAP | N | N | HAAP | EHAAP | EHAAP |
| *L* | SAP | SAP | SAP | N | HAAP | EHAAP | EHAAP |
| *N* | HSAP | HSAP | SAP | N | HAAP | HAP | HAAP |
| *F* | EHSAP | EHSAP | HSAP | N | AAP | AAP | AAP |
| VF | EHSAP | EHSAP | HSAP | N | N | AAP | AAP |
| AF | EHSAP | EHSAP | HSAP | N | N | N | AAP |

Fig. 6 shows the pre-defined fuzzy membership for battery state of charge ($\text{SoC}_{\text{ESS}}$) is defined into seven different states as follows:

1. AL - Abnormally low,
2. VL - Very low,
3. L - Low,
4. N - Normal,
5. F - Full,
6. VF - Very full, and
7. AF - Abnormally full.

The defuzzification mapped all the possibility of the four linguistic outputs with each other to determine the amount of current output ($\Delta I_k$) in Table I and Fig. 7. There are seven categories of current instructions:

1. EHSAP - Extremely high supply active power,
2. HSAP - High supply active power,
3. SAP - Supply active power,
4. N - Normal,
5. AAP - Absorb active power,
6. HAAP - High absorb active power, and
7. EHAAP - Extremely high absorb active power.

Equation (4) and (5) show the categories and degrees of the instructions used to define the area enclosed in the fuzzy memberships.

$$\Delta V_{\text{cal}}^{k} = \left\{ \begin{array}{ll} \text{SUV if} & -20 \le \Delta V_{\text{cal}}(t) \le -10 \\ \text{VUV if} & -15 \le \Delta V_{\text{cal}}(t) \le -5 \\ \text{UV if} & -10 \le \Delta V_{\text{cal}}(t) \le 0 \\ N \text{ if} & -5 \le \Delta V_{\text{cal}}(t) \le 5 \\ \text{OV if} & 0 \le \Delta V_{\text{cal}}(t) \le 10 \\ \text{VOV if} & 5 \le \Delta V_{\text{cal}}(t) \le 15 \\ \text{SOV } if & 10 \le \Delta V_{cal}(t) \le 20 \end{array} \right\} \tag{4}$$

$$\text{SoC}_{\text{ESS}}^{k} = \left\{ \begin{array}{ll} \text{AL } if & 0 \le SoC_{ESS}(t) \le 30 \\ \text{VL if} & 20 \le \text{SoC}_{\text{ESS}}(t) \le 40 \\ L \text{ if} & 30 \le \text{SoC}_{\text{ESS}}(t) \le 50 \\ N \text{ if} & 40 \le \text{SoC}_{\text{ESS}}(t) \le 60 \\ F \text{ if} & 50 \le \text{SoC}_{\text{ESS}}(t) \le 70 \\ \text{VF if} & 60 \le \text{SoC}_{\text{ESS}}(t) \le 80 \\ \text{AF if} & 70 \le \text{SoC}_{\text{ESS}}(t) \le 100 \end{array} \right\} \tag{5}$$

Fig. 8 shows a sample of the FLC working principle undergoing fuzzification and defuzzification. In this example, assuming the two input memberships $\Delta V_{cal}$ and battery *SoC* are recorded at -6 V and 53% respectively.

Referring to Fig. 5, a voltage excursion of −6 V to the respective input membership generates two linguistic outputs as follows:

a) 0.8 (80%) of undervoltage (UV) and
b) 0.2 (20%) of very undervoltage (VUV)

Fig. 6 shows the battery$\text{SoC}_{\text{ESS}}$ recorded at 53% gives two linguistic outputs;

a) 0.8 (80%) of normal (N) and
b) 0.2 (20%) of full $SoC_{ESS}$ (F).

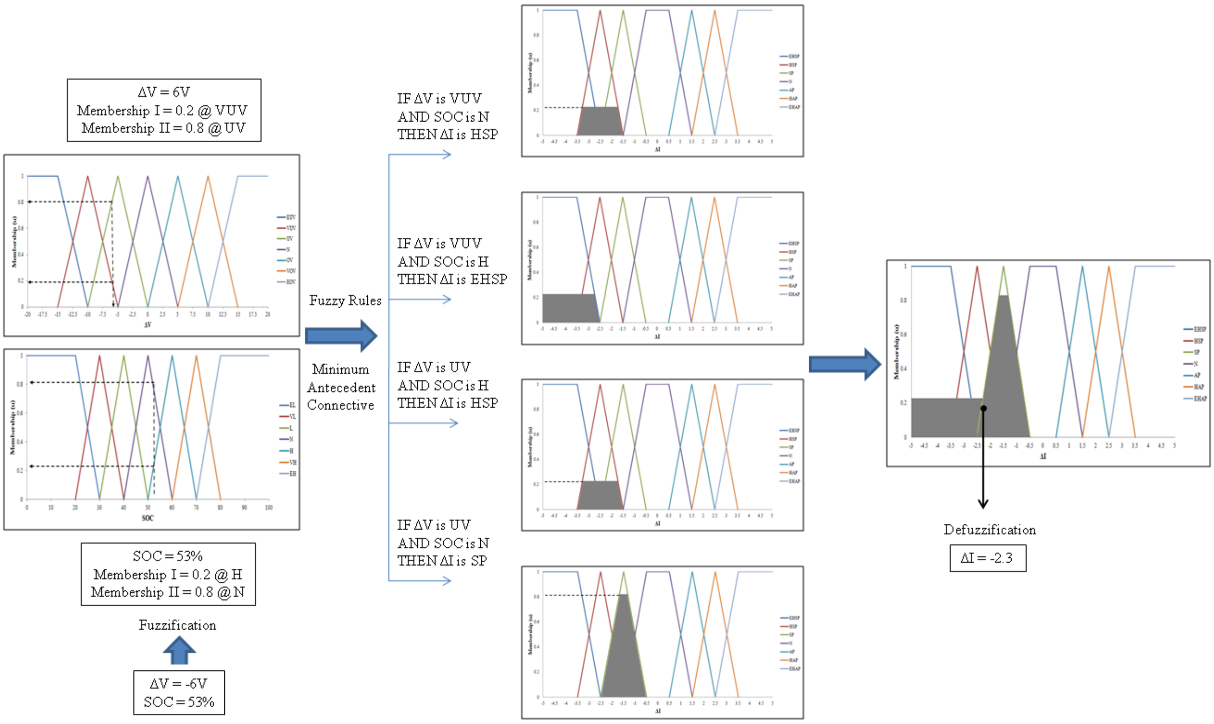


Figure 8. Working principles of the proposed fuzzy and defuzzification process.

After the membership inputs are fuzzified, the AND (Minimum) antecedent utilizing the smallest degree of the input membership as the true value (1) of the aggregated rule antecedent. Hence, the smallest degree of any two linguistic terms is chosen as the true value as below:-

a) If $\Delta V_{cal}$ is 0.8 degree of undervoltage (UV) AND $SoC_{ESS}$ is 0.8 degree of normal stage (N);
THEN current instruction ($\Delta I_k$) is considered to supply at Supply Active Power (SAP) with the membership value of 0.8 degree.

b) If $\Delta V_{cal}$ is 0.8 degree of undervoltage (UV) AND $SoC_{ESS}$ is 0.2 degree of full stage (F);
THEN current instruction ($\Delta I_k$) is considered to supply at High Supply Active Power (HSAP) with the membership value of 0.2 degree.

c) If $\Delta V_{cal}$ is 0.2 degree of very undervoltage (VUV) AND $SoC_{ESS}$ is 0.8 degree normal stage (N);
THEN current instruction ($\Delta I_k$) is considered to supply at High Supply Active Power (HSAP) with the membership value of 0.2 degree.

d) If $\Delta V_{cal}$ is 0.2 degree of very undervoltage (VUV) AND $SoC_{ESS}$ is 0.2 degree of full stage (F);
THEN current instruction ($\Delta I_k$) is considered to supply at Extra High Supply Active Power (EHSAP) with the membership value of 0.2 degree.

The current instruction ($\Delta I_k$) for the ESS is compute at -2.3 A via defuzzified using center of area (CoA) method.

## III. PERFORMANCE EVALUATION

### A. *Case I:Evaluation of Network Voltage Unbalance with Intermittent PV Power Output*

This case study is performed to show the effect of high penetration of single-phase PV systems under symmetrical load condition on the network VUF. The three-phase voltages at the point of common connection (PCC) are measured and recorded every second with data logger at near real-time, and the VUF is calculated accordingly. In this context, a symmetrical load condition, where 1000 W for each phases and one unit of PV system is attached at Phase C.

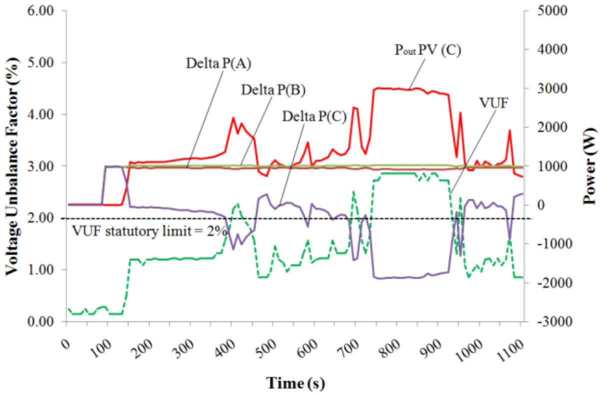


Figure 9. Impact of high penetration single-phase PV power output on VUF

Fig. 9 shows that the PV system supplies 1100 W to the network once it has synchronized at approximately *t*=140s. At *t*= 400s, the PV power output is recorded to be intermittent at approximately 2500 W causing the VUF to be 2.3%.

### B. *Case II:Performance of the ESS on Network Voltage Unbalance with Intermittent PV Power Output And Load Variations*

This case study explores the effectiveness of the phase selector and FLC method to mitigate the VUF with two units of PV systems installed any two phases under a symmetrical load condition. A constant load of 1500 W is introduced to the experimental network and two units PV systems rated at 3600 $W_p$ are attached to Phase B and C respectively. Fig. 10 shows the network VUF, power outputs of the PV systems and the power ratio for ESS for each phase. It is noticed that the PV power output fluctuates rapidly at the two different phases. At t =520 s, the ESS connected on Phase C escalate its power absorption from 200 W to 500 W while the ESS on Phase B boost up its power absorption from 200 W to 1200 W at 1300 s. As a result, the excess power generated by the PV systems are stored in the ESS, hence reducing the VUF to 0.5%. As the PV power output is intermittent, it is observed that the power output suddenly drop, causing the VUF to increase from 0.5% to 1.5%. However the FLC makes necessary rectification at t= 2620s to reduce the VUF to an acceptable value. By actively regulating the three-phase voltages, it is evident that energy curtailment can be avoided, hence, maximize the utilization renewable energy.

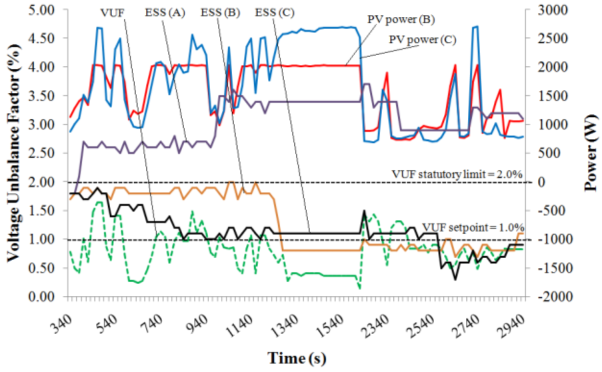


Figure 10. Performance evaluation of ESS under high penetration of two single-phase PV systems

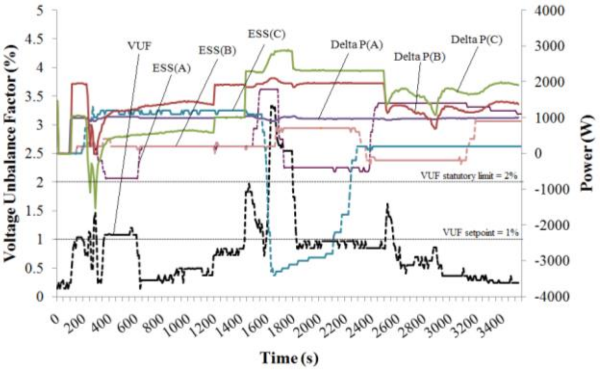


Figure 11. Three-phase ESS mitigating VUF caused by photovoltaic systems on phase A and B.

### C. Case III:Performance of the ESS on Network Voltage Unbalance with Intermittent PV Power Output And Load Variations

This case study is conducted to study the electrical impact of single-phase PV systems on network VUF with load variations. Fig. 11 shows the VUF and the network power balance at each phase ($\Delta P_{k\{k=a,b,c\}}= P_{\text{load}}-P_{\text{PV}}$). A constant load of 1000 W, 2000 W and 1000 W are introduced to Phase A, B and C respectively while two units of PV systems rated at 3600 $W_p$ are attached to Phase B and C respectively.

Fig. 11 shows the power balance $\Delta P_k$ for each phase is varying due to the intermittency of PV power outputs. At $t$=1500s, the load connected at Phase C is increased from 1000 W to 2500 W, causing the network VUF to escalate from 1.0% to 3.0%, which is higher than the statutory limit of 2.0%. The proposed algorithm worked on the most crucial Phase C and instructs the ESS to supply and compensate the excess power consumption at Phase C in a short period of time.

## IV. CONCLUSION

It is common that developing countries experienced continuous growth of load demand has increased the utilization of fossil duel which in turn has increase the amount of carbon footprint in the country. To overcome this issue, the Malaysian government has put in the initiatives to encourage the use of green technology. However, in view of the existing grid-infrastructure, the utility company limits the amount of grid-connected RE sources on the distribution networks. This measure served the purpose to ensure that the network power quality issues are well-maintained. In order to overcome this challenge, utilizing energy storage system may be one of the effective solutions to maximize the RE integration. In this paper, results have shown that the proposed FLC energy storage system has effectively restore the voltage unbalance factor caused by the single-phase PV systems on distribution network. It is observed that once the voltage is maintained, the utility company can considered allowing more capacity of grid-connected RE sources.

## REFERENCES

[1] J. Wong, Y. S. Lim, P. Taylor, and S. Morris, “Optimal utilisation of small-scale embedded generators in a developing country: A case study in Malaysia,” *Renewable Energy*, vol. 36, no. 9, pp. 2562-2572, 2011.

[2] G. Tverberg. (September 2016). How intermittent renewables are harming the electricity grid. *Oilprice*. [Online]. Available: https://oilprice.com/Energy/Energy-General/How-Intermittent-Renewables-Are-Harming-The-Electricity-Grid.html

[3] K. Oshiro and T. Masui, “Diffusion of low emission vehicles and their impact on $CO_2$ emission reduction in Japan,” *Energy Policy*, vol. 81, pp. 215-225, 2015.

[4] S. Ashina, J. Fujino, T. Masui, T. Ehara, and G. Hibino, “A roadmap towards a low-carbon society in Japan using backcasting methodology: Feasible pathways for achieving an 80% reduction in CO2 emission by 2050,” *Energy Policy*, vol. 41, pp. 584-598, 2012.

[5] A. Shafiu, T. Bopp, I. Chilvers, and G. Strbac, “Active management and protection of distribution networks with distributed generation,” in *Proc. IEEE Power Engineering Society General Meeting*, 2014, pp. 1098–1103.

[6] J. D. Crabtree, Y. Dickson, L. Kerford, and A. Wright. (2001). Methods to accommodate embedded generation without degrading network voltage regulation. [Online]. Available: webarchive.nationalarchives.gov.uk/+/http://www.berr.gov.uk/files/file15129.pdf

[7] T. Tran-Quoc, Rami, E. Monnot, A. Almeida, N. Hadjsaid, and C. Kieny. (2007). Intelligent voltage control in distribution network with distributed generation. *CIGRE/CIRED*. [Online]. Available: http://www.cired.be/CIRED07/pdfs/CIRED2007_0727_paper.pdf

[8] D. N. Gaonkar and G. N. Pillai, “Fuzzy logic based coordinated voltage regulation method for distribution system with multiple

synchronous generators," in *Proc. IEEE PES Transmission and Distribution Conference and Exposition*, 2010, p. 1–5.

[9] A. E. Kiprakis and A. R. Wallace, "Maximising energy capture from distributed generators in weak networks," *IEE Proc. - Generation, Transmission and Distribution*, vol. 151, no. 5, pp. 611, 2004.

[10] P. Kou, D. Liang, and L. Gao, "Distributed EMPC of multiple microgrids for coordinated stochastic energy management," *Applied Energy*, vol. 185, pp. 939-952, 2017.

[11] P. Balram, L. A. Tuan, and O. Carlson, "Comparative study of MPC based coordinated voltage control in LV distribution systems with photovoltaics and battery storage," *Electrical Power and Energy Systems*, vol. 95, pp. 227-238, 2018.

[12] C. Huang, S. Weng, D. Yue, S. Deng, J. Xie, and H. Ge, "Distributed coorperative control of energy storage units in microgrid based on multi-agent consensus method," *Electrical Power and Energy Systems*, vol. 147, pp. 213-223, 2017.

[13] T. Hosseinimehr, A. Ghosh, and F. Shahnia, "Cooperative control of battery energy storage systems in microgrids," *Electrical Power and Energy Systems*, vol. 87, pp. 109-120, 2017.

[14] M. L. Kothari and J. C. Patra, "Design of STATCOM controllers with energy storage system for stability and power quality improvements," in *Proc. 37th Annual North American Power Symposium*, 2005, pp. 260-266.

[15] M. F. Rahmat and M. M. Ghazaly, "Performance comparison between PID and fuzzy logic controller in position control system of DC servomotor," *Jurnal Teknologi*, vol. 45, no. D, pp. 1–17, 2006.

[16] N. Essam and A. B. Khalid, "Comparison between conventional and fuzzy logic PID Controllers for controlling DC motors," *Int. Journal of Computer Science Issues*, vol. 7, no. 5, pp. 128–134, 2010.

[17] L. Guo, J. Y. Hung, and R. M. Nelms, "Comparative evaluation of sliding mode fuzzy controller and PID controller for a boost converter," *Electric Power Systems Research*, no. 1, pp. 99–106, 2011.

[18] A. K. Gaurav, "Comparison between conventional PID and fuzzy logic controller for liquid flow control: Performance evaluation of fuzzy logic and PID Controller by using MATLAB/Simulink," *Int. Journal of Innovative Technology and Exploring Engineering*, vol. 1, no. 1, pp. 84–88, 2012.

[19] R. Caldon, M. Coppo, and R. Turri, "Distributed voltage control strategy for LV networks with inverter-interfaced generators," *Electric Power Systems Research*, vol. 107, pp. 85–92, 2014.

**Jianhui Wong** received her B.Eng. (Hons), MSc. Eng. and Ph.D. Eng. (Electrical) from Universiti Tunku Abdul Rahman (UTAR). She is attached to the Department of Electrical and Electronic Engineering, UTAR as an Assistant Professor & affiliated with the Electrical Engineering Technical Division of The Institution of Engineers Malaysia (IEM) and Board of Engineers Malaysia. Dr. Wong Jianhui has 8 years of research experiences. To date, she has actively involved as the Principle and Co-researcher in the research projects receiving a total amount of RM 2.2 Million. Her research interests including the areas on Power System Study, Energy Management and Smart Grid. Prior joining Universiti Tunku Abdul Rahman as a Lecturer, she has been working as an electrical consultant for building services. In view of her academic path, she has experiences in lecturing electrical related subjects including power systems and power protection

**Yun Seng Lim** pursued his undergraduate studies in Electrical and Electronic Engineering at the University of Manchester Institute of Science and Technology (UMIST), United Kingdom, in 1998. With his 1st class degree in the B.Eng. (Hons), Lim was awarded the Overseas Research Scheme to do his Ph.D. at UMIST in the area of power system from 1998 to 2001. Lim started his academic career at Universiti Tunku Abdul Rahman (UTAR) in 2005 after working in the UK in an engineering consulting firm for 2 years. He is Professional Engineer with Practising Certificate and CEng registered with the Board of Engineer Malaysia and UK Engineering Council respectively. He is the full member of the Institution of Engineering and Technology (IET), Institution of Engineers Malaysia (IEM), senior member of IEEE, and Fellow of ASEAN Academy of Engineering and Technology (AAET) and the Associate Fellow of Academic Science Malaysia.