Under-Voltage Load Shedding Scheme Based on Voltage Stability Index for Distribution Network

N. A. Yusof, H. Mokhlis, M. Karimi, J. A. Laghari, H. A. Illias, N. M. Sapari
Department of Electrical Engineering
Faculty of Engineering, University of Malaya,
50603, Kuala Lumpur, Malaysia

Keywords- Under-Voltage Load Shedding; Distributed Generation; Voltage Stability; Load Shedding; Islanding.

Abstract- **In a power system, voltage stability problem usually happen due to excess of electricity demand and deficiency of power generation. To avoid voltage instability, under-voltage load shedding can be a last option to remove buses with instable voltage in a power system. However, the knowledge of location of the load to be shed is important so that the optimum number of load shed may be attainable without the possibility of over or under voltage, to happen. Voltage stability index is a reliable indicator to detect loads condition. This paper proposes an under-voltage load shedding scheme with voltage stability index approach. A distribution network energized by two DGs had been modeled in PSCAD software to test the proposed under voltage load shedding scheme. The distribution system is energized by utility grid, a mini hydro generator and a PV solar system. Case studies with islanding and a sudden change in PV power deliver have been conducted to demonstrate the effectiveness of the load shedding scheme. The results show that the proposed method is an excellent approach in order to implement a successful load shedding scheme.**

I. INTRODUCTION

Distributed generation (DG) is small-scale technologies to generate electricity close to the end users of power. DG technologies often consist of modular and renewable energy generators, and offer a number of potential benefits. In many cases, distributed generators can provide lower-cost electricity, higher power reliability and security with fewer environmental consequences than traditional power generators. One of a well-known DG commercially used in most countries is photovoltaic (PV) generation.

PV is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect. PV is a clean and efficient renewable energy that can help to prevent power system from black out. However, many studies involving PV generation were conducted by incorporating with anti-islanding relay [1, 2, 3]. These studies show that when distribution network encounter a disturbance that prevents the electric utility to supply power into the distribution network, PV generations will be disconnected from the network. However, the disconnection of PV generation in case of islanding is uneconomical.

Disturbance in distribution networks may trigger severe consequences. When a disturbance causes a progressive and uncontrollable decrease in voltage level, the system is in a voltage instability condition [4]. It is important for the system to act fast to restore the system stability. This has motivated researchers to develop recovery techniques to mitigate the risk of blackouts due to voltage instability.

Under voltage load shedding (UVLS) is a solution to the voltage stability challenges faced by electric utilities [5]. Research has proved that UVLS is an effective counter-measure against voltage collapse [6]. When a system is not able to maintain its generation and transmission schedule due to voltage instability, voltage collapse can happen. Through the bus voltages, voltage instability can be investigated. Voltage instability has become severe as the power system become more complex and therefore the voltage problems become a great concern [7, 8, 9, 10]. Furthermore, it has been investigated that most power outages happened in most countries was due to the voltage instability [11].

II. VOLTAGE STABILITY

In [12], voltage stability is defined as “the ability of a system to maintain voltage so that when load admittance is increased, load power will increase and so that both power and voltage are controllable”. Voltage stability analysis has become more important as a result of insufficient reactive resources in bulk transmission systems. The objective of voltage stability analysis is to identify the weak regions in terms of reactive power deficiency and determine the critical contingencies and voltage stability margins for various power transfers within regions. In recent literature, many voltage stability and voltage collapse prediction methods have been presented [4, 10, 12].

A. Fast Voltage Stability Index

A novel fast voltage stability index (FVSI) [8,13] simplified from a pre-developed voltage stability index [14] referred to a line initiated from the voltage quadratic equation at the sending end of a representation of a 2-bus system. The line index in the system in which the value is near to 1.00 indicates that the line has reached its instability limit. It could cause sudden voltage drop to the corresponding bus caused by the reactive load variation [13]. Mathematically,

$$FVSI = \frac{4Z_{ij}^{2}Q_r}{V_s^2 x_{ij}} \tag{1}$$

Where, FVSI = Fast voltage stability index
V_s = Sending voltage
Z_{ij} = Impedance of the line *i-j*
Q_r = Reactive load at receiving end
X_{ij} = reactance of the line *i-j*

According to the above equation, the line that has the nearest value of FVSI to 1.0 is the weakest line. When the value of FVSI becomes 1.0 or more, the particular line is unstable. One of the buses that connected to the line will experience a sudden voltage drop, and this event will lead to the system's collapse.

III. Proposed Methodology

This research is conducted using UVLS solely. The system's stability approach will be used in the scheme through stability indices. These indices can be used to reveal either critical bus or the stability of each line connected with two buses in a power system

Before performing a load shedding scheme, the loads had been categorized into three types; (1) non vital, (2) semi vital and (3) vital loads. Vital loads are the important customers that cannot afford any loss of electricity such as hospitals. Therefore in this proposed scheme, the non vital loads will be shed first followed by semi vital loads. Stability index had been chosen to be the indicator of any load bus' condition. Fig. 1 shows the test system comprises of a distribution network, a utility grid, a PV and a mini hydro generation. The network used in this research is a part of utility TNB at Batang Kali, Selangor. The distribution network consists of 30 buses, 27 lumped loads, and a mini hydro generator with a PV based DG. Both DGs are operated at 11kV voltage level. The DGs were connected to two different buses in the distribution network.

A controller receives the data from the distribution network. The data are active power, reactive power, resistance, reactance, impedance of the line involving the sending voltage from each bus, and angles used in stability index calculation. The controller continuously monitor whether islanding event has occurred or not.

When islanding occurs, the controller will calculate the value of FVSI of each bus. After this, the controller monitor if there is some events happen such as overload or sudden change of PV generation. If there is no additional event happens, the controller will rank the buses according to the highest value of FVSI. The loads that have the highest FVSI will be placed at the top of stability index list. The arranged list with the highest stability index at the top is called load ranking.

All loads have been categorized according to their priority. The vital loads will not choose to be shed regardless its FVSI values. In the load ranking, the non vital loads are the loads that will be shed first. After all non vital loads are shed; semi vital loads will be shed.

After the loads were shed, the values of the voltage of each bus are again monitored. According to Arief et al. [15], the voltage must not drop below 0.85 p.u. If the voltages drop below 0.85 p.u, the calculation of FVSI process will repeat and some more loads are shed until all bus voltages are above 0.85p.u. Proposed load shedding scheme is completed when all of the bus voltages are in steady state within the range of 0.85 to 1.00 p.u.

Although this method only monitoring the bus voltages and perform load shedding based on voltage stability, however, it is expected that the stability of the distribution system would be maintained, too.

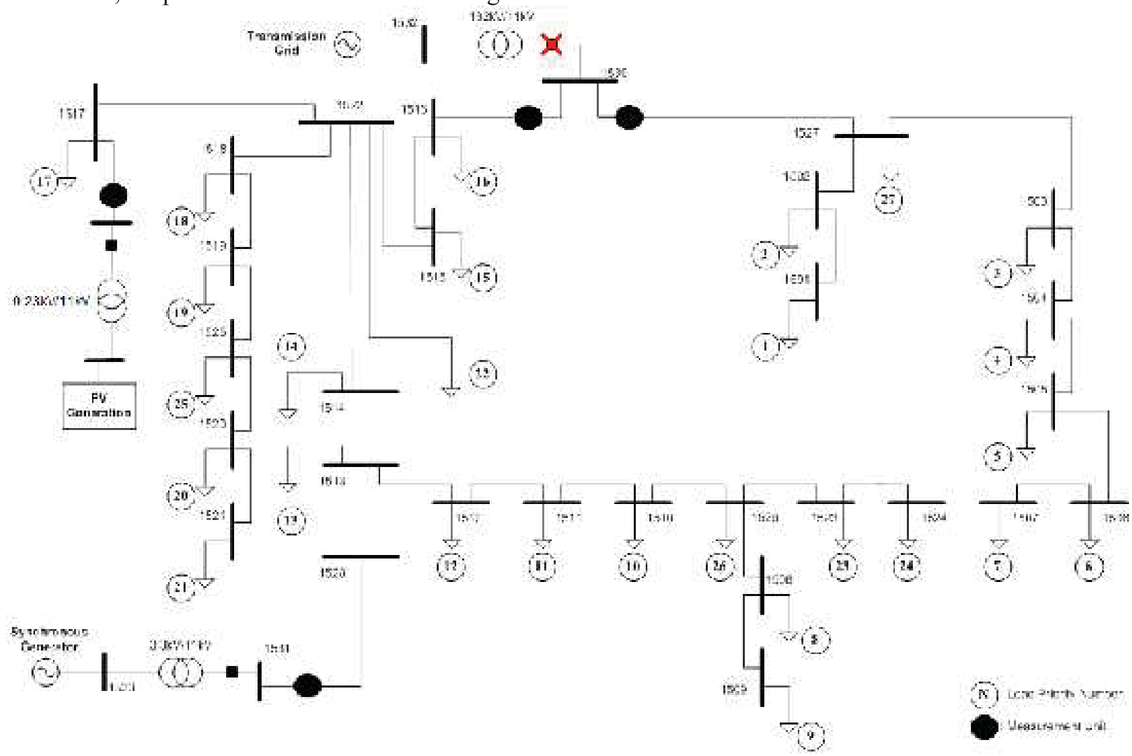

Fig. 1. Test System

IV. Results and Discussions

In order to prove the effectiveness of the UVLS scheme, two case studies had been conducted to test the proposed scheme. All related parameter's responses are presented in the next sections. The case studies are as follows:

1) Case 1: Islanding
2) Case 2: Change of power in PV based DG

A. Case 1: Islanding

In this case, the islanding was simulated at t = 3s. After islanding, the bus numbers were arranged according to their FVSI values as in Table I.

At t = 3s, as seen in Fig. 2 (magnified version in Fig. 3), a slight drop of voltages occurred. The lowest voltage drop however went down only until 0.93357 p.u at bus 4. It had taken time of 0.5s for the voltages to recover back to 1.0 p.u in steady state. This is an acceptable result since it was not dropped lower than 0.9 p.u.

From Table I, five most unstable buses are bus 4, 12, 10, 15 and 25 because they were ranked as the highest in the load ranking. Therefore, according to the proposed UVLS scheme, these buses' loads were shed. The power supplied by DGs and Grid is shown in Fig.4 and their magnitudes are shown in Table II. After load shedding, the DGs had been delivering enough power of 2.45 MW for the remaining loads which was 2.40MW as shown in Fig.5

TABLE I
Load Ranking for Case 1

Bus no.	**FVSI**	**Load category**
4	0.95258	Non-vital
12	0.85819	Non-vital
10	0.84063	Non-vital
15	0.76237	Non-vital
25	0.72908	Non-vital
24	0.65868	Non-vital
22	0.62604	Non-vital
18	0.61811	Non-vital
26	0.57130	Non-vital
16	0.55586	Non-vital
11	0.51934	Non-vital
3	0.50413	Non-vital
23	0.48905	Non-vital
2	0.40060	Non-vital
19	0.38809	Non-vital
1	0.38655	Non-vital
13	0.30000	Non-vital
14	0.76086	Semi-vital
9	0.64806	Semi-vital
20	0.59853	Semi-vital
5	0.46521	Semi-vital
6	0.41881	Semi-vital
8	0.34174	Semi-vital
21	0.22548	Semi-vital

TABLE II
Active Power Response in Case 1

Power (MW)	Before islanding	After islanding
P_{grid}	1.10	0.00
P_{dg}	2.25	2.45
P_{load}	3.25	2.40

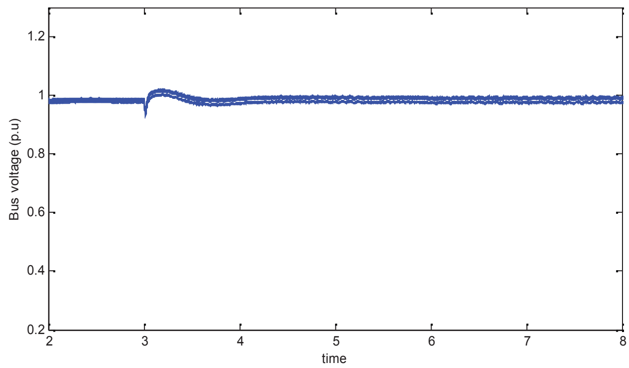

Fig. 2. 27 bus voltages in case 1

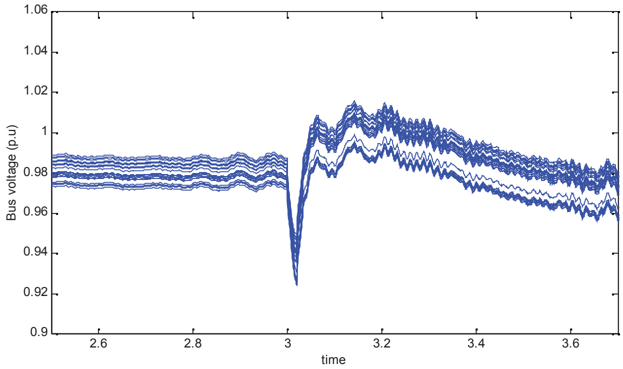

Fig. 3. Zoom-in of bus voltages at t = 3s

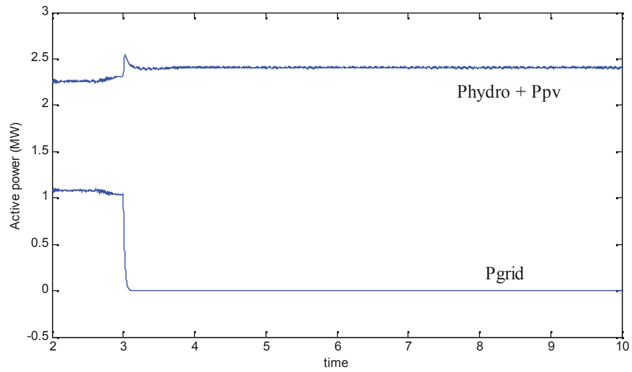

Fig. 4. Total generation power for case 1

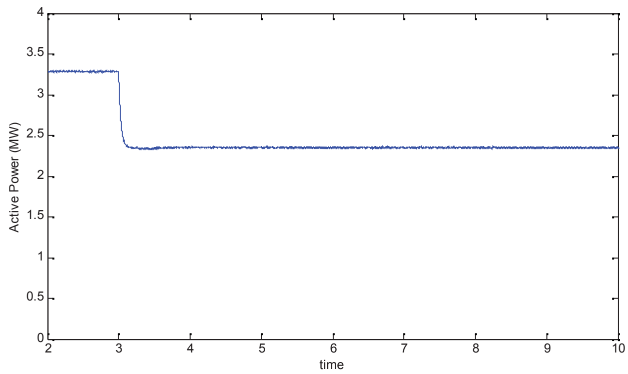

Fig. 5. Total load power for case 1

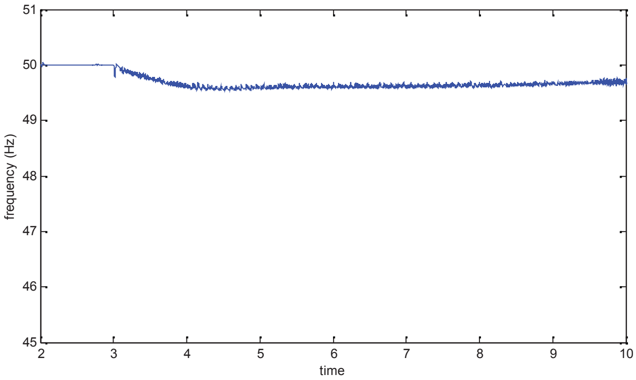

Fig. 6. Frequency response for case 1

From Fig. 6, it can be noticed that the frequency dropped after the islanding but still remains in the acceptable range, which is 49.5Hz. This result in agreement with the expected result is showing that the proposed UVLS scheme has performed load shedding correctly.

B. Case 2: Change of power in PV based DG

This case is simulated because the PV generation can change its power generation any time since it depends on the ambient temperature and irradiance of the sunlight. When weather is changing, the power deliver by PV will change too. In this case, intentionally, the power of PV generation is decreased by 25% from its original value 2 seconds after islanding occurred. Table III is the FVSI values for case 2 at *t*=3s and *t*=5s. New values of FVSI were calculated by the UVLS controller in order to make a new load ranking.

TABLE III
FVSI VALUES AFTER ISLANDING AND DECREMENT OF PV GENERATION

t = 3s (islanding)		
Bus no.	**FVSI**	**Load category**
4	0.95258	Non-vital
12	0.85819	Non-vital
10	0.84063	Non-vital
15	0.76237	Non-vital
25	0.72908	Non-vital
24	0.65868	Non-vital
22	0.62604	Non-vital
18	0.61811	Non-vital
26	0.57130	Non-vital
16	0.55586	Non-vital
11	0.51934	Non-vital
***t* = 5s (Ppv decreasing)**		
Bus no.	**FVSI**	**Load category**
24	0.65868	Non-vital
22	0.62604	Non-vital
18	0.61811	Non-vital
26	0.57130	Non-vital
16	0.55586	Non-vital
11	0.51934	Non-vital
3	0.50413	Non-vital
23	0.48905	Non-vital
2	0.40060	Non-vital
19	0.38809	Non-vital
1	0.38655	Non-vital

The part right after the islanding is the same as in case 1. However, at t = 5s, the PV decreasing its power delivers by 25% making the UVLS controller to shed more loads. The voltages were dropped slightly and then recovering back to 1.0 p.u after 0.25s. Loads were shed more because the total Pdg at t = 5s insufficient to fully energized the distribution network; hence some loads were needed to be shed. According to Table III, at t = 5s, bus 24, 22, 18 and 26 were at the top of the load ranking. About 30% of the loads were shed to stabilize the system. The loads were sheds one by one until bus voltages restored back to 1.0 p.u.
The voltage graph for this case is shown in Fig. 7 where the voltages dropped slightly after t = 5s, and after that recovering back to its original value. Bus 24, 22, 18 and 26 were the bus that carries the shed loads. Power responses for this case are presented in Fig. 8 and 9.

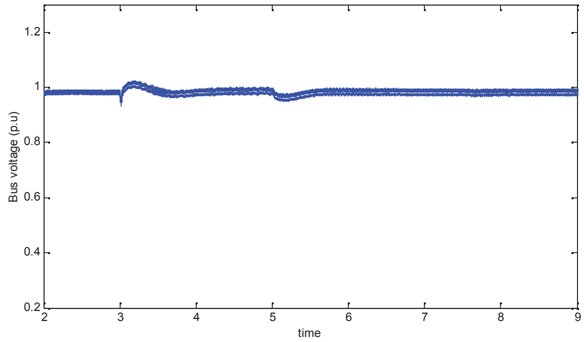

Fig. 7. Bus voltages for case 2

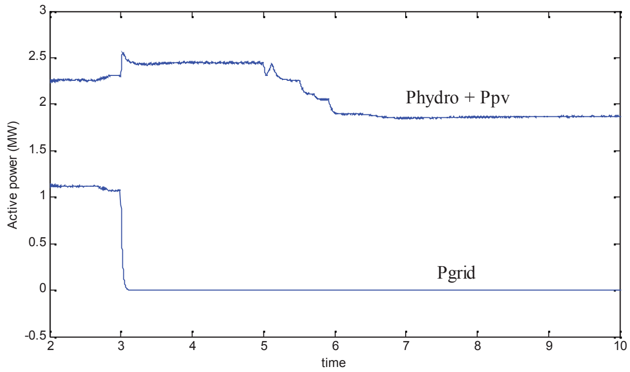

Fig. 8. Total power generation response for case 2

Simpler explanation for the active power magnitudes are shown in Table IV.

TABLE IV
Power Values for case 2

Power (MW)	Before islanding	After islanding	After t = 5s
P_{dg}	2.25	2.40	1.87
P_{grid}	1.13	0.00	0.00
P_{load}	3.30	2.35	1.80

After 30% of the loads were shed since PV decreased its generation, the DGs were still able to deliver 1.87 MW into the distribution network that was remained with 1.80 MW loads. In Fig. 9, it is noticed that the frequency at t = 5s was slightly dropped from 49.3 Hz until 49.1 Hz, and then it was gradually recover back to 50Hz. The frequency was satisfactorily returned to its original value, proving that the proposed UVLS scheme is a successful.

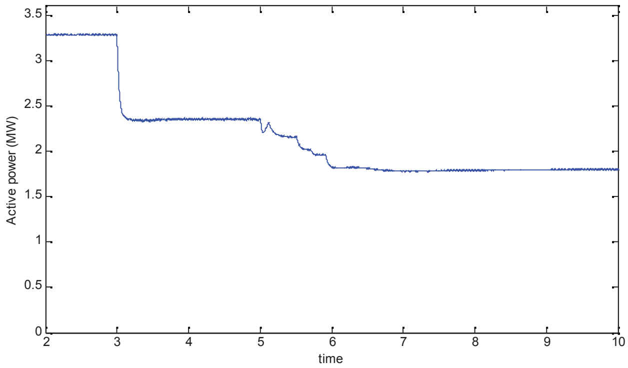

Fig. 9. Total load power response for case 2

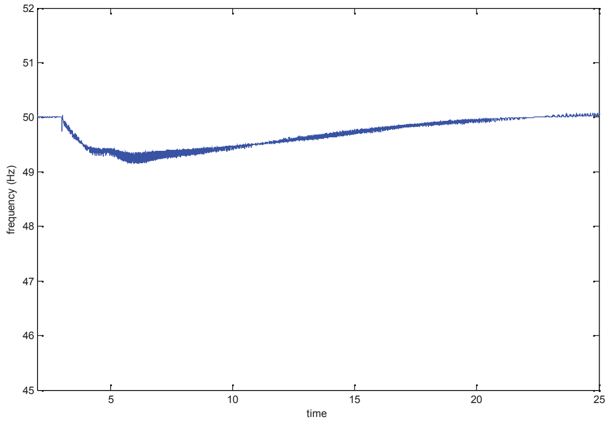

Fig. 10. Frequency response for case 2

V. Conclusion

A lot of studies of PV generation in distribution network were included anti-islanding relay, however they suggested that disconnecting PV generation from the network when islanding happens. This research had conducted a feasibility study using PV generation as one of the DG to deliver active power to the loads even after islanding. Results show that the proposed UVLS scheme is successful in order to avoid a total black out in a distribution network. Two case studies had been simulated successfully and proved that stability index is an excellent approach to implement an UVLS scheme. The PV also does not need anti-islanding relay so that PV can energize the distribution network. Thus, reliability of power supply is also increased.

Acknowledgment

This work was supported by University of Malaya, Kuala Lumpur, Malaysia under E-science Fund research Grant (Grant code: SF005-2013).

References

[1] Xu, M., R.V. Melnik, and U. Borup, *Modeling anti-islanding protection devices for photovoltaic systems.* Renewable energy, 2004. **29**(15): p. 2195-2216.

[2] Ye, Z., et al., *Study and development of anti-islanding control for grid-connected inverters*. 2004: National Renewable Energy Laboratory.

[3] Smith, G., P. Onions, and D. Infield. *Predicting islanding operation of grid connected PV inverters*. in *Electric Power Applications, IEE Proceedings-*. 2000. IET.

[4] Reis, C. and F. Barbosa. *A Comparison of Voltage Stability Indices*. in *Electrotechnical Conference, 2006. MELECON 2006. IEEE Mediterranean*. 2006. IEEE.

[5] Taylor, C.W., *Concepts of undervoltage load shedding for voltage stability*. IEEE Transactions on Power Delivery, 1992. **7**(2): p. 480-488.

[6] Arief, A., et al., *Under voltage load shedding in power systems with wind turbine-driven doubly fed induction generators.* Electric Power Systems Research, 2013. **96**: p. 91-100.

[7] Ladhani, S.S. and W. Rosehart. *Under voltage load shedding for voltage stability overview of concepts and principles*. in *Power Engineering Society General Meeting, 2004. IEEE*. 2004. IEEE.

[8] Verayiah, R., et al. *Under Voltage Load Shedding (UVLS) study for 746 test bus system*. in *Energy and Environment, 2009. ICEE 2009. 3rd IEEE.International Conference*. 2009.

[9] Zahidi, R., et al. *Study of static voltage stability index as an indicator for Under Voltage Load Shedding schemes*. in *Energy and Environment, 2009. ICEE 2009. 3rd IEEE International Conference on*. 2009.

[10] Amraee, T., et al., *An enhanced under-voltage load-shedding scheme to provide voltage stability.* Electric power systems research, 2007. **77**(8): p. 1038-1046.

[11] Laghari, J., et al., *Application of computational intelligence techniques for load shedding in power systems: A review.* Energy Conversion and Management, 2013. **75**: p. 130-140.

[12] Wiszniewski, A., *New criteria of voltage stability margin for the purpose of load shedding.* IEEE Transactions on Power Delivery, 2007. **22**(3): p. 1367-1371.

[13] Musirin, I. and T.K. Abdul Rahman. *Novel fast voltage stability index (FVSI) for voltage stability analysis in power transmission system*. in *Research and Development, 2002. SCOReD 2002. IEEE Student Conference on*. 2002.

[14] Lof, P.-A., et al., *Fast calculation of a voltage stability index.* IEEE Transactions on Power Systems, 1992. **7**(1): p. 54-64.

[15] Arief, A., et al. *Under voltage load shedding design with modal analysis approach*. in *Advances in Power System Control, Operation and Management (APSCOM 2009), 8th International Conference on*. 2009. IET.