Under Voltage Load Shedding Scheme for Islanded Distribution System based on Voltage Stability Indices

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Abstract— When a power generation system fails, load needs to be shed to overcome the instability of the power system. As this is a very significant problem, to overcome that many researchers have proposed different load shedding schemes. In this paper, a load shedding scheme called Under Voltage Load Shedding (UVLS) is proposed. To simulate the event of insufficient power supply, islanded distribution system is implemented in 22 bus system using distributed generation (DG) solar system. The performance of two different voltage stability indices for the load shedding scheme is analysed.

Keywords—under voltage load shedding scheme; voltage stability index; islanded distribution system; distributed generation.

I. Introduction

These days the power generators are working up to their limits, due to continuous demand of more and more energy. Operations in such conditions endangers the whole system to shut down and makes the voltage supply unstable. When the voltage instability happens, it can cause severe problems in the transmission lines due to the large different of power generation and the demand. If the instability is not recovered quickly it will cause a blackout which will harm a lot of key operation in any area. Voltage instability may occur in the event of islanded distribution network where the main power grid fails leaving only load demand and distributed generations (DGs) in the network system. However, a lot of the studies show that the require disconnection to avoid further system failure [1] due to imbalance of power transmission. However, it is such a loss to not have the distributed generation to be used in the islanded distribution state. Thus, it is significant that the islanded operation system to be further researched so that the renewable energy is not wasted during islanding operation. As the main power grid fails, and the islanded operation starts, the voltage and frequency of the system becomes very unstable because the generation and demand has a big indifference. When that event occurs, the voltage and frequency of the system decrease very quickly making the whole system unstable. At that moment, certain of the load need to be shed to stabilize the system. The conventional solution of load shedding scheme is to predetermine the load to be shed based on the power consumed by the consumers [2]. This solution is not efficient since the critical and non-critical loads are not considered. Researchers had been proposed different types of load shedding schemes which can be categorized into Under-Frequency Load Shedding (UFLS) and Under Voltage Load Shedding (UVLS) scheme. UFLS determines which loads needs to be shed based on frequency drop while UVLS protects the system from complete failure based on voltage instability. However, only UVLS will be focused in this paper.

[3] incorporating logic relay design into the UVLS to improve voltage profile. However, the method was simulated in MATLAB which does not consider a real time simulation which reflect an actual condition. UVLS with uncertainty modeling using information gap decision theory (IGDT) technique was proposed by [4] to improve the inaccuracy of the parameters due to the mismatch betweeen simulation model and actual physical model. The results show the effectiveness and robustness but the complexity of the algorithm may affect the time consumption.

A new UVLS based on voltage stability indices for islanded distribution system is proposed by [1] to avoid the system blackouts. However, there was no frequency reference considered in the simulation. [5] proposed load shedding scheme based on rate of change of frequency (ROCOF) to estimate the power imbalance and voltage stability to prioritize the load to be shed. The results show that the proposed scheme not only stabilise the system frequency but also the voltage magnitude of the buses. A novel algorithm of smart-direct load control (S-DLC) for load shedding is proposed by [6] to minimize power outages in sudden grid load changes and reduce the peak-to-average ratio. The algorithm utilizes forecasting and shedding using Internet of Things (IoT) to provide real-time control load and generates daily schedule for customers. However, the priority of load to be shed was not considered. The researchers in [7] proposed an optimal load shedding scheme based on backtracking search algorithm (BSA). A constraint multi-objective function considering linear static voltage stability margin (VSM) and load curtailment was formulated. However, the algorithm was simulated in MATLAB which has less feature compared to PSCAD.

In [8], the loads are ranked based on the criterion called Outage Sensitivity Index (OSI) considering the loading rate of line, the apparent power of the line prone to outage, and the voltage magnitude. However, the efficiency of proposed approach is validated on transmission line test system instead of distribution network which has higher probability of islanding. The objective of this paper is to design a load shedding scheme based on stability indices to avoid the system collapse during islanding. A solar distributed generation (DG) is integrated into the network to simulate the islanding event. The next section outlines the concept design of UVLS, formulation of stability indices and test system used, section III elaborate the modelling of the solar DG, UVLS and load controller in PSCAD, section IV discuss on the result and analysis and section V conclude the results obtained.

II. Concept Design

A. Under Voltage Load Shedding Scheme

Under voltage load shedding scheme (UVLS) is employed to maintain the stability of the system. In order to maintain the stability of the system, the voltage and frequency of the network must be kept within the acceptable limits. The scheme remove selected non vital load of the system so that the network can still be operated for the vital load which is better than having a total blackout due to insufficient power supply. Figure 1 shows the block diagram of UVLS.

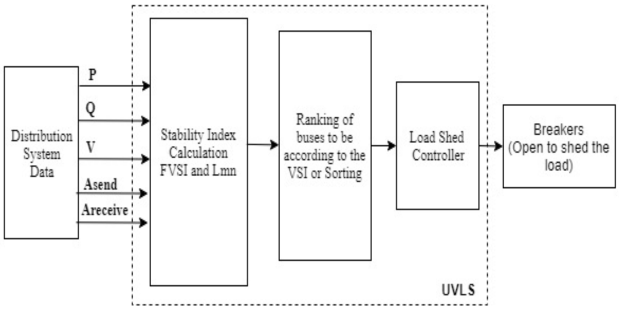

Fig. 1. The block diagram of UVLS design process

The scheme starts by collecting the data of real and reactive load power, *P* and *Q*, bus voltage, *V*, sending and receiving end angle, *Asend* and *Areceive*. Then, the data are used to calculate the stability index to determine the ranking of the bus on which load to be shed. The sorted load bus is transferred to the load shed controller in order to send signal to the circuit of the selected bus to be opened when imbalance of power between supply and demand is detected in the system. The imbalance of the system network is determined by Eq. (1) below:

$$\Delta P = (P_{grid} + P_{DG}) - P_{load} \quad (1)$$

Where ΔP is the power mismatch, P_{grid} is the power supply by main grid, P_{DG} is the power supply by solar DG, and P_{load} is the power consumed. In order to rank the load to be shed, two stability indices are considered as follows:

1) Fast Voltage Stability Index

The Fast Voltage Stability Index (FVSI) proposed by (Musirin and Rahman, 2002) is as follows:

$$\text{FVSI} = \frac{4Z^2 Q_j}{V_i^2 X_{ij}} \quad (2)$$

Where Z is the line impedance, Q_j is the reactive power at receiving end, V_i is the sending end voltage, and X_{ij} is the line reactance. The bus voltage is considered near to collapse when the value of FVSI close to 1.0.

2) Line Stability Index

The line stability index (LSI) proposed by [9] is as follows:

$$L_{mn} = \frac{4X_{ij}Q_j}{(V_i \sin(\theta - \delta))^2} \quad (3)$$

Where X_{ij} is the reactance of the line *i-j*, Q_j is the reactive load at receiving end, V_i is sending voltage, θ is the angle of line impedance and δ is the angle difference between sending and receiving voltage. The line is considered critical or weak if the value of LSI near to 1.0. Considering both stability indices in Eq. (1) and (2), the details of UVLS process is summarised in a flowchart as shown below in Figure 2.

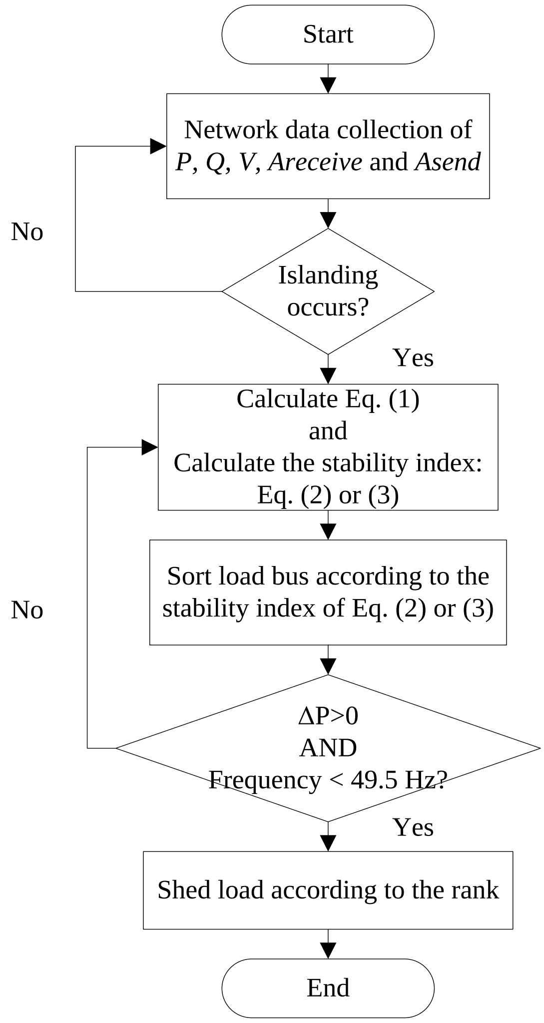

Fig. 2. Flowchart of UVLS

The steps of the process are as follows:

- The distribution network is connected to a main grid supply and solar DGs.
- Then, the main grid is disconnected from the system to simulate the islanding. This cause the bus voltage becomes unstable.
- The two stability indices are measured for each bus.
- If the system is unbalanced where $\Delta P > 0$ based on Eq. (1) and the frequency drop is below than 49.5 Hz, the weak bus load is shed according to ranked load by the stability indices.

- The load is continuously shed until $\Delta P = 0$ which indicating that the supply is equal to load or supply is sufficient for the system.

B. Modelling of Distribution Network

A test system of 22 bus of actual network from [5] is modelled and simulated using PSCAD software as shown in Figure 3. There are 20 loads connected to 20 bus independently, while Bus 3 connected to solar DG and Bus 10 connected to main grid. All distribution lines in the system is modelled using nominal pi network. The test system is operated at 11 kV.

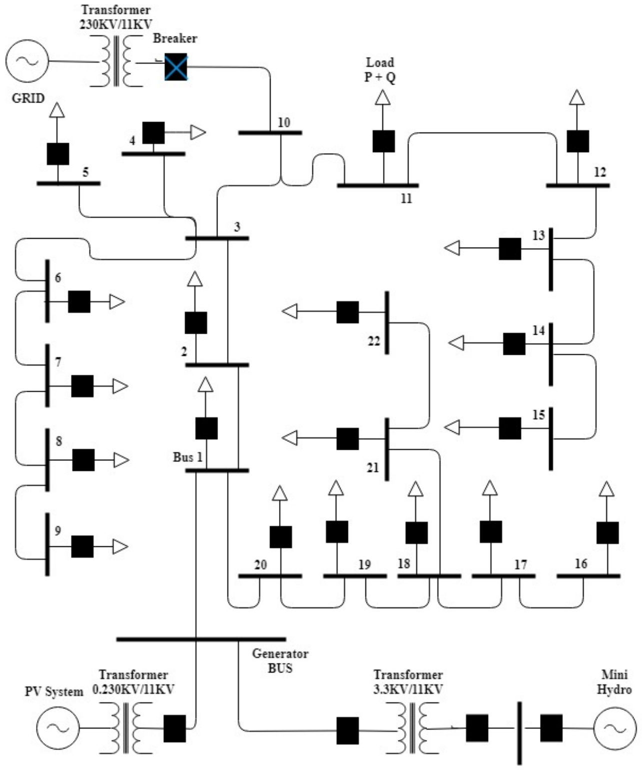

Fig. 3. Test system of 22 bus network

There are three types of load considered in the network system which are vital, semi-vital and non-vital as shown in Table 1. However, only non-vital load will be considered for load shedding to simplify the algorithm.

TABLE I. LOAD CATEGORY OF TEST SYSTEM

Bus	Load category	Bus	Load category
1	Non-vital	13	Non-vital
2	Non-vital	14	Semi-vital
4	Non-vital	15	Non-vital
5	Non-vital	16	Semi-vital
6	Vital	17	Semi-vital
7	Vital	18	Non-vital
8	Vital	19	Semi-vital
9	Semi-vital	20	Semi-vital
11	Non-vital	21	Semi-vital
12	Non-vital	22	Non-vital

III. Final Design And System Implementation

A. Modelling of solar DG

The solar DG used in the UVLS scheme comprises of photovoltaic array, DC-DC converter, a three-phase bridge inverter, and Maximum Power Point Tracking (MPPT). The PV generation model used in the test system is shown in Figure 4.

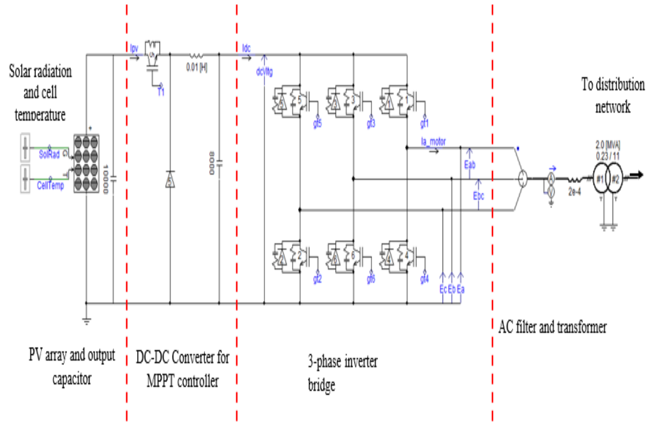

Fig. 4. Solar DG Model in PSCAD

The PV model is according to Standard Test Conditions (STC). STC is a condition where a module is consistently checked in a laboratory with intensity of irradiance of 1000 W/m2, AM1.5 solar spectrum reference and module temperature of 25±20C [10].

B. Modelling of UVLS using PSCAD

To simulate the islanding event and load shedding scheme in the power system network, a sequence block is arranged in PSCAD as in Figure 5. Sequence block determines which breaker of the bus to be opened at the appointed time. The simulation starts by closing the circuit breakers of main grid and solar DGs to supplying the power into the system. After 3.5s, which when the system is at stable frequency, the main grid circuit breaker is opened to simulate the islanding event.

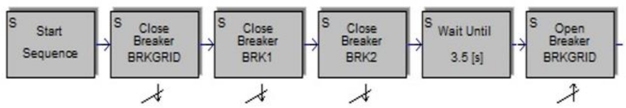

Fig. 5. Sequence block of UVLS Modelling

When islanding occurs, the frequency is monitored to decide on whether the load is required to be shed. For UVLS, the algorithm is written in PSCAD using component block as shown in Figure 6. There are three component blocks used for the process which are data collection block, stability index block, and sorting block.

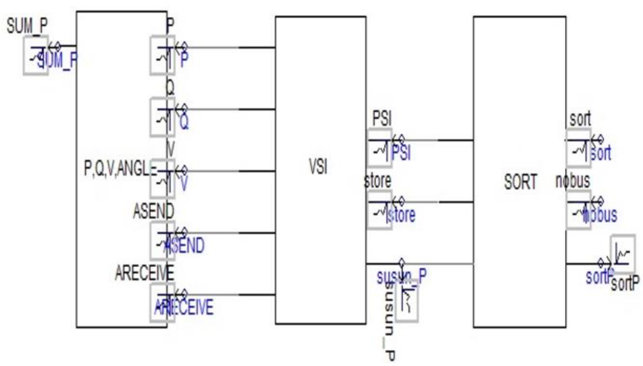

Fig. 6. Combination of data, stability index and sorting block component

C. *Modelling of Load Shed Controller*

The load ranking from the sorting block becomes the input for the block of load shed controller as shown in Figure 7. The controller monitors all the bus voltages where the voltage must be between 0.95 pu to 1.05 pu. At the same time, the power mismatch of Eq. (1) and frequency drop are also being monitored. As the error of the voltage deviates from ±0.5% error and satisfying the condition of power mismatch and frequency drop, the load shed controller is activated to shed the load based on the sorted load previously.

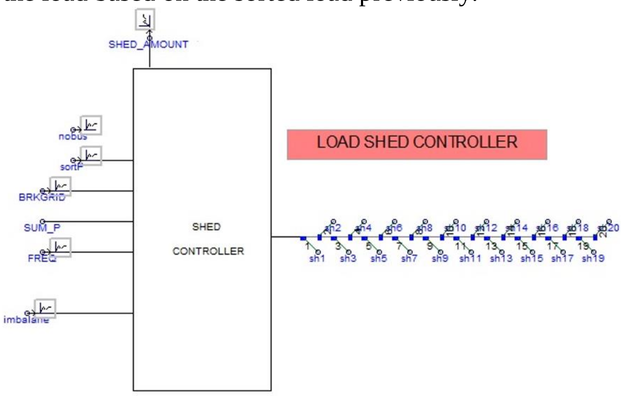

Fig. 7. Load shed controller component block

The load shed controller works by sending the signal to the circuit breaker of the selected load to be opened. Each circuit breaker of the load has its own signal which indicated by *sh1* to *sh20*. It will continuously monitoring the imbalance of power, voltage and frequency drop to avoid the unbalanced system of the network.

IV. Results and Discussion

A. *Solar DG Analysis*

The solar DG must generate power in order to compensate the loss of main grid. This test is to analyse the behaviour of the solar DG before and after islanding. Figure 8(a) and (b) shows the power and voltage generated by solar DG. It can be seen that the solar DG is generating around 0.6 MW at 1.0 pu. The drop of voltage and power around 3.5s are due to islanding or disconnection of main grid.

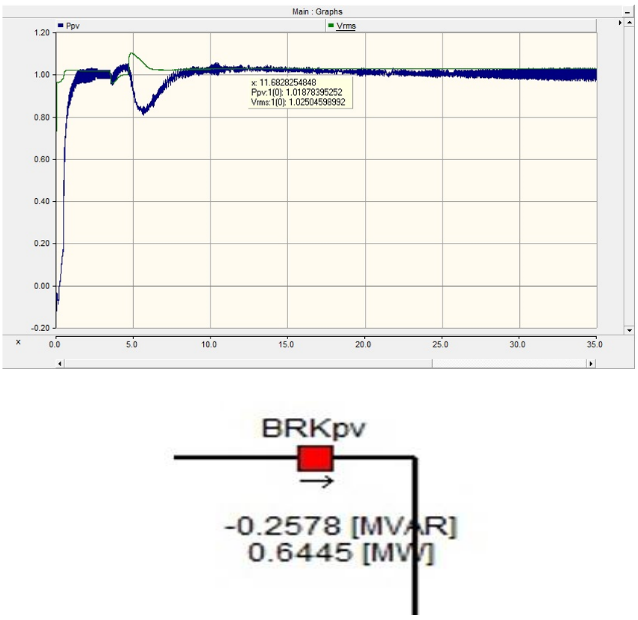

Fig. 8. Graph and meter of DG output

B. *Voltage Profile Test*

In order to prove the UVLS is successful or able to stabilise the system, all the bus voltages are monitored before and after the islanding. However, to simplify the analysis, the result at Bus 7 is discussed. Basically the result pattern of Bus 7 is similar to all other 21 buses. Figure 9 and 10 show the difference of voltage profile at Bus 7 for algorithm using FVSI and Lmn respectively. Both graphs in Figure 9 and 10 show the voltage drop right after islanding event takes place at 3.5s. It can observed from Figure 9 and 10 that the minimum value of voltage drop is only at 0.90 pu. However, Figure 9 shows that the voltage gets stable with 0.96 pu. while Figure 10 shows that the voltage overshoots more than 1.09 pu at 4.7s before getting stable with 1.0 pu. These results show that UVLS with Lmn index is better than FVSI since the voltage profile gets stable within the acceptable limit of ±0.5%.

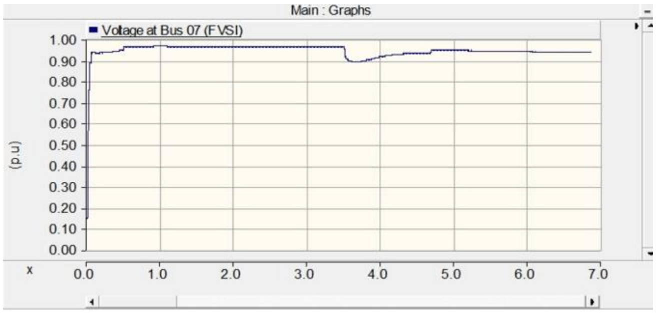

Fig. 9. Voltage Profile of UVLS with FVSI

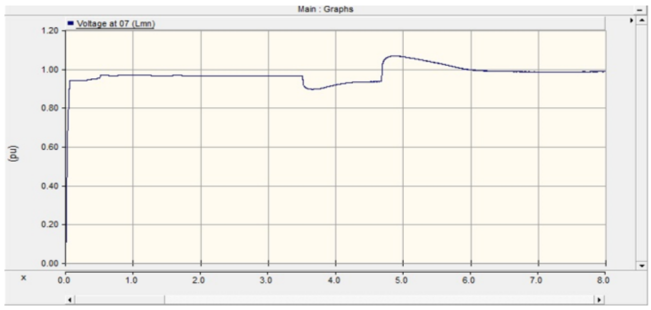

Fig. 10. Voltage Profile of UVLS with Lmn index

C. *Stability Indices Test*

After the islanding takes place at 3.5s, both FVSI and Lmn index are calculated for all the buses. Both indices give the value near or equal to 1.0 indicate that the bus is unstable and 0.0 value to indicate that bus is stable. Table II and III show the indices values of both FVSI and Lmn index respectively before and after islanding for all buses. The rank bus is sorted according the stability indices values.

TABLE II. Rank of Load Based on FVSI for Both Before and After Islanding

Bus	FVSI	
	Before islanding	**After islanding**
18	0.9457	0.4095
1	0.5230	0
11	0.2607	0
22	0.1967	0.1289
13	0.1827	0.1567
4	0.1240	0.1245
12	0.0980	0.0823
15	0.0672	0.0667
5	0.0632	0.0635
2	0.0446	0.0449

Focusing on five priority bus for the load to be shed, it can be observed that Bus 18, 1, 11, 22, and 13 are selected according to FVSI while Bus 1, 18, 11, 4 and 12 are selected according to Lmn. After the loads have been shed, it is observed the stability indices values approaching 0.0 for both FVSI and Lmn after islanding. This shows that the UVLS successfully stabilise the bus system. However, comparing between FVSI and Lmn, four buses reach to 0.0 values for Lmn while only 2 buses reach to 0.0 values for FVSI. This indicates that the load shed selection by Lmn achieve better stability as compared to FVSI.

TABLE III. RANK OF LOAD BASED ON LMN FOR BOTH BEFORE AND AFTER ISLANDING

Bus	Lmn	
	Before islanding	**After islanding**
1	0.4218	0
18	0.4095	0
11	0.2618	0
4	0.2038	0
12	0.1567	0.0845
13	0.1438	0.1607
22	0.1289	0.1309
15	0.0667	0.0683
5	0.0649	0.0688
2	0.0379	0.0385

D. *Frequency Response Test*

Figure 11 and 12 show the frequency responses of FVSI and Lmn respectively. It is observed that the frequency of both UVLS with FVSI and Lmn drop at 3.5s when the islading event occurs. In Figure 11, it shows that the frequency shoot up to 50.10 Hz and reduce to stability of 50 Hz at 25s. However, in Figure 12, the frequency shoot up to 5.55 Hz before reduce to stabilty of 50 Hz at 30s. The results show that the frequency response of the system is better for UVLS with FVSI as compared to Lmn since the frequecy gets stable at shorter time.

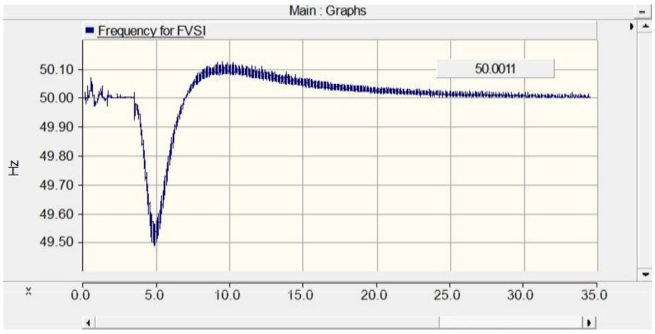

Fig. 11. Frequency response of UVLS with FVSI

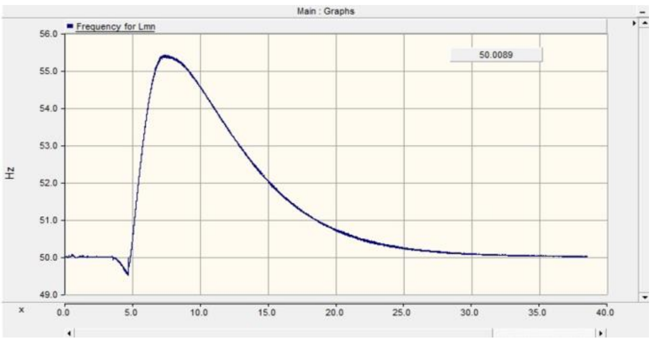

Fig. 12. Frequency response using Lmn in PSCAD

V. CONCLUSION

This paper aim to develop a viable load shedding scheme based on stability voltage indices. A 22 bus distribution network integrated with main grid and solar DG is modelled in PSCAD for a test system. The performance of the UVLS are studied based on two stability indices of FVSI and Lmn. The simulated UVLS successfully stabilized the voltage and frequency after islanding. Comparison between two stability indices are studied based on voltage profile, indices values and frequency response. Based on the results obtained, it shows that UVLS with Lmn is better than UVLS with FVSI in terms of voltage profile and indices values. However, a slightly unfavourable result for UVLS with Lmn found for frequency response compared to UVLS with FVSI. Hence, the deficiency of UVLS with Lmn in terms of frequency responses can be improved in future.

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