Quantification of Voltage Profiles Intermittency for Small-Scale Solar Photovoltaic System under Different Loading Conditions

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Abstract- The recent rapid uptake of solar photovoltaic system in Malaysia has introduced new challenges to the operation of the power grid, particularly on the voltage profile of distribution networks. An intermittent nature of the voltage fluctuation that caused by solar output remain as important topic as how these rapid voltage changes will affect the operation of the network. Hence, this paper presents a quantification of voltage profiles intermittency for small-scale solar photovoltaic system under different loading conditions. Actual field measurements have been performed for both high and low loading conditions. Mainly two parameters have been analysed for this work, namely voltage profile and solar power output. An intermittency quantity of voltage profile during solar generation for day time is higher than night time, which indicates high intermittent in solar irradiance causing rapid fluctuation in solar generation. Furthermore, increased voltage magnitude was observed during the low load condition. The high voltage intermittency caused by rapid fluctuation of solar output and voltage rise during low load giving a negative effect on distribution network. It is expected that grid-connected battery energy storage system could serve as the potential solution to alleviate both solar intermittency and voltage raise issues.

Keywords Renewable energy; solar photovoltaic; voltage profile intermittency; solar output fluctuation; voltage rise.

1. Introduction

Renewable Energy (RE) sector has shown rapid growth in Malaysia. Annual demand Feed-in Tariff (FiT) quota especially the solar photovoltaic (PV) category had far exceeded the supply allocated, which is a good sign as the country has become more receptive to the RE sector recently. It is reported that solar PV has contributed the largest share of installed RE capacity at 354.03 MW (67.04%) to the cumulative RE capacity that has achieved commercial operations. In order to encourage greater adoption of the solar PV systems, the Authority was tasked as the implementing agency to spearhead and execute the Net Energy Metering (NEM) scheme. NEM scheme is ideally suitable to complement the current FiT and Large Scale Solar (LSS) schemes. Furthermore, the Authority has announced to enhanced the NEM concept, which took effect on 2nd January 2019 and the expectation is for an improved take up rate of the NEM post 2018 [1-2].

The recent rapid uptake of solar photovoltaic (PV) system in Malaysia has introduced new challenges to the operation of the power grid, particularly on the voltage profile of distribution networks where most of the PV system were connected. Along with the increase of PV system in power network, voltage stability of the distribution system has been severely affected [3]. A case study in Malaysia for voltage fluctuation and flicker emissions caused by PV system has been address in paper [4]. With cloudy weather condition of Malaysia, high fluctuation in solar irradiance due to overpassing clouds shadows making solar PV power output to be very intermittent, which causes the voltage at the point of connection to be fluctuating sharply and frequently, hence generate a large number of voltage fluctuation to the low voltage distribution network [5-7]. The rapid and frequent fluctuation could affect the existing power grid if large amount of solar PV system were installed in the network [8]. In addition, these intermittent source along with demand variation has caused several negative effects on distribution systems such as reverse power flow, power fluctuation, voltage rise and poor power quality [9-10].

It is well understood that the reverse power flow from the PV system will cause voltage rise in the network. Nevertheless, the intermittent nature of the voltage fluctuation that caused by solar output remain as important topic as how these rapid voltage changes will affect the operation of the network. For example, increased of transformer tap changer operation, malfunction of sensitive manufacturing tools, and etc. Therefore, it is important to quantify the voltage profile intermittency under actual weather conditions in Malaysia. The results can be used to inform the relevant parties to as how the solar PV system in Malaysia will impact the quality of supply, particularly to those industries that require high level of power quality. Hence, this paper aims to quantify the voltage profiles intermittency for small-scale solar photovoltaic system under different loading condition. The next section of the paper described the set up for small-scale grid-connected solar PV system and measurement method, followed by the result and discussion. Finally, the paper is concluded with major findings of this work.

2. Research Method

The Faculty of Electrical Engineering, UTeM has installed grid-connected solar PV systems with four different module technologies at different locations in free standing installation method. Each of the systems is equipped with three units of 2kW single-phase inverter. Total solar PV capacity for each systems is 23.88kW as shown in Table 1. In addition, the output of these four PV systems are terminating at the Point of Common Coupling (PCC) as shown in Fig.1. It is important to note that the connection of the 12 single-phase inverters to the main grid was arranged in the balance manner. Any imbalance occurred in the system is caused by external factors such as a temperature, shading, module mismatch, weather conditions and etc.

Table 1. Solar PV array capacity

System	PV array capacity (kW_p)
Mono-crystalline	6.12
Poly-crystalline	5.88
Thin-film	6.24
Heterojunction	5.64
Total	23.88

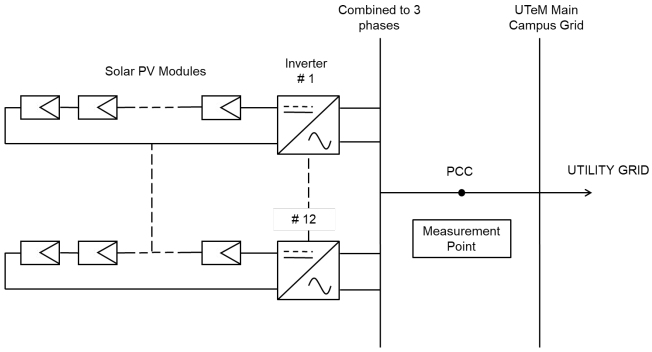

Fig. 1. Schematic diagram for the solar PV system at UTeM

Field of measurement in this work were taken at PCC. The measurement device that has been installed at this PCC is SIEMENS SENTRON PAC4200 energy power meter. From this measurement device, two main parameters are considered in this work for quantifying the voltage profiles intermittency under different loading condition, namely voltage and active power (solar power output). In this paper, voltage profile intermittency (V_i) is defined as the change of voltage magnitude (v) by one-minute time (t), which data are measured consecutively based on the solar PV power output conditions as following equations.

$$V_i\,(t) = v^t - v^{t-1} \tag{1}$$

After calculated all the term in (1), the result will be given value as

$$\begin{cases} \left| v^t - v^{t-1} \right| > 0, \; V_i\,(t) = 1 \\ v^t - vt\text{-}1 \;\; = 0, \; V_i\,(t) = 0 \end{cases} \tag{2}$$

Total quantity of voltage profile intermittency (Q_v) can be obtained by sum up all in (1) according to value given in (2) as following equation

$$Q_v = \sum_{t=2}^{n} V_i\,(t) \tag{3}$$

Furthermore, two periods with significant difference in load profile are considered in this work, which is weekday (high load) and weekend (low load), as it is a working day and off day for UTeM. An example of the load profile for weekday and weekend at UTeM main campus in 30-minutes resolution is shown in Fig.2. The total maximum demand for the whole campus in weekday and weekend is 4.41MW and 1.34MW, respectively, which maximum demand in weekday increases 69.61% (3.07kW) from weekend. The 69.61% substantial gap between those two period can be considered as difference energy demand due to people's activities. Social practices have characteristics which determined the way energy demand comes about [11]. As discussed earlier, since the total capacity for four distributed solar PV output is approximately 24kWp, which represents approximately 0.5% of the UTeM peak demand.

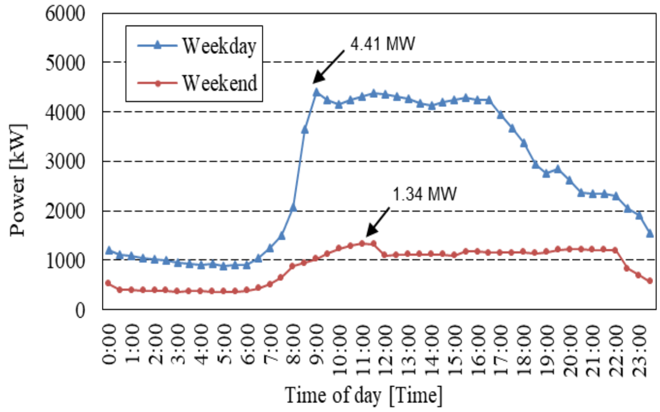

Fig. 2. An example of load profile at UTeM main campus on weekday and weekend

3. Results and Discussions

Actual voltage profiles in one-minute time resolution recorded for 2 months (September 2018 and October 2018) are presented in Fig.3 and Fig.4, respectively. More specifically, the measurement data for 8 days were selected randomly from each weekday and weekend within the 2 months. Based on above data, in view of voltage profile comparison between weekday and weekend, no significant difference was observed even though the loading on weekend is much lower than on weekday.

Further case study has been conducted by analysing the relation between voltage and PV power output. Fig.5 and Fig.6 show the actual voltage and active power in one-minute time resolution recorded on 3rd September 2018 (high load) and 1st September 2018 (low load) with solar generation, respectively. The active power is referring to solar generation, which indicates as negative load since it is injecting power from consumer (UTeM) side to existing grid. In addition, the figures show high occurrence of intermittence during solar generation caused by large amount of moving clouds, which represent in general the cloudy weather condition of Malaysia.

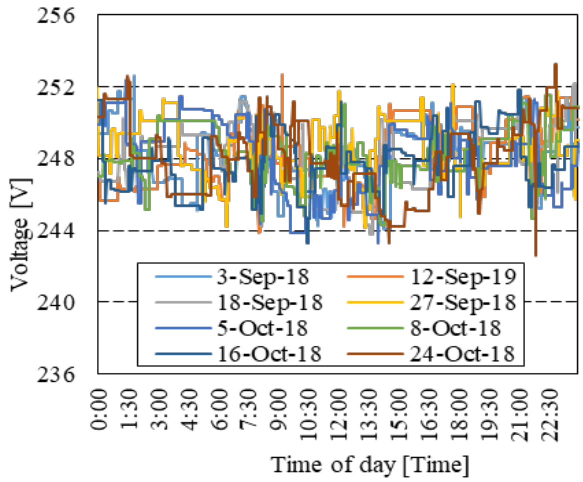

Fig. 3. Actual voltage profile under high load (weekday) for 2 months

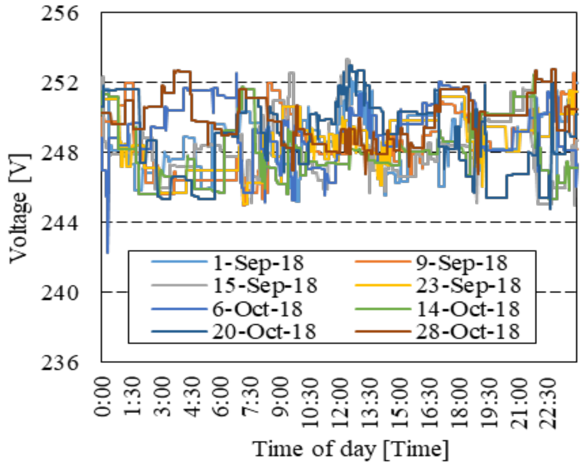

Fig. 4. Actual voltage profile under high load (weekend) for 2 months

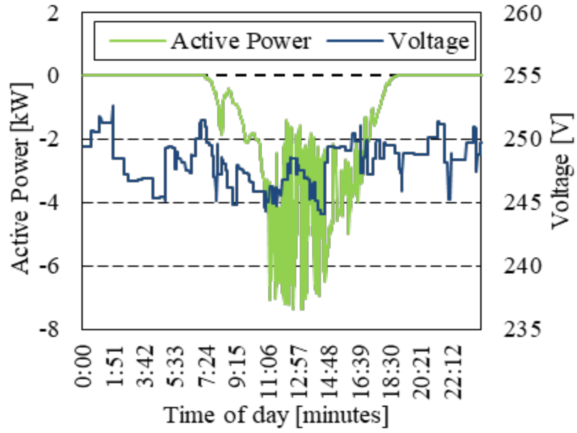

Fig. 5. Actual voltage and active power profile under high load (weekday)

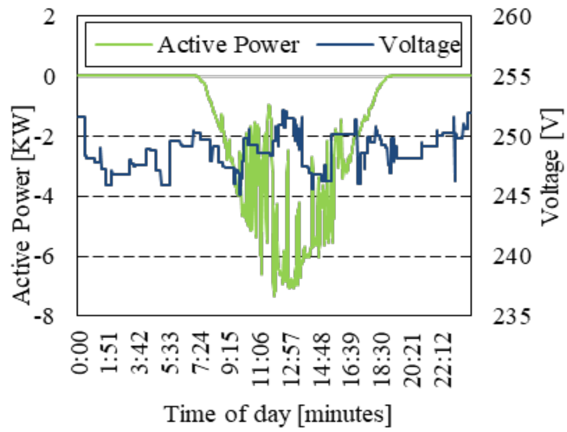

Fig. 6. Actual voltage and active power profile under high load (weekend)

Day with maximum and minimum PV power output within two months (September 2019 until October 2019) are presented in Fig.7 (23th October 2019) and Fig.8 (22nd October 2019), which total output was 6746.66 kW and 2877.09 kW, respectively. As the irradiance and temperature are main factors that affect the performance of PV power output, it shows that most of the day was cloudy during minimum output.

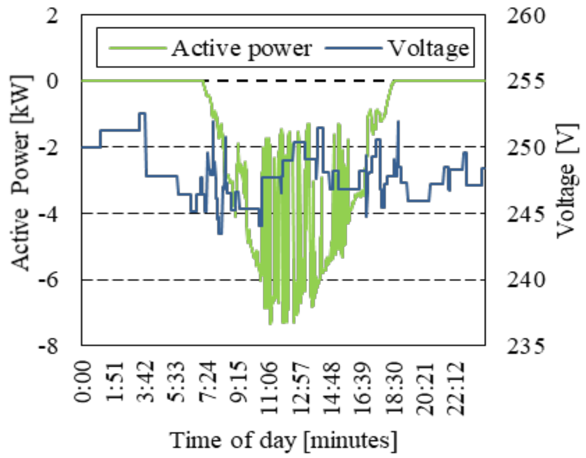

Fig. 7. Maximum PV power output

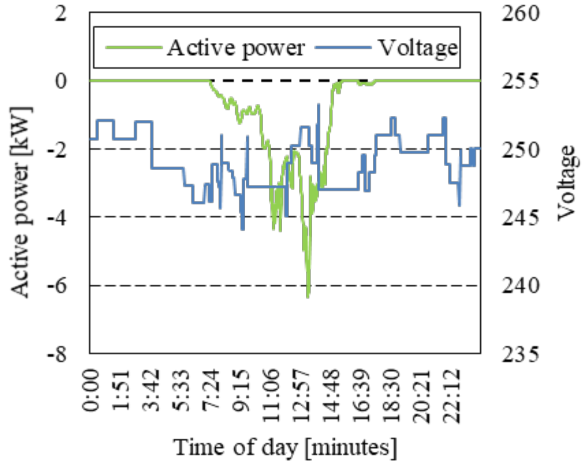

Fig. 8. Minimum PV power output

Voltage profile intermittency based on solar PV power output has been quantified as shown in Table 2. From this table, it is noticed that the intermittency quantity of voltage during solar generation for day time is higher than night time, which indicates higher voltage fluctuation during day time. High fluctuation in solar irradiance causing high intermittent in solar generation. This rapid intermittent of solar generation causing voltage magnitude to change frequently [4]. This is confirmed by recorded data in Fig. 5 until Fig. 8, which voltage intermittency quantity is higher during the day time.

For more details, voltage profile is plotted according to maximum-minimum arrangement of active power as shown in Fig.9 and Fig.10 for high load and lower load, respectively. For the solar generation, these figures show maximum 7.37 kW (high load) and 7.34 kW (low load). Based on these figures, two important characteristics of voltage profile are observed as listed below;

1. Intermittent of voltage profile during solar generation is higher compared to no solar generation under both load profile. As discussed earlier, high intermittent of voltage profile is caused by rapid fluctuation of solar generation. This can be confirmed with the difference in voltage profile intermittency based on PV power output condition.
2. At nearest maximum point of solar generation, the voltage magnitude for low load is higher than high load. It can be noticed from Fig.10 (low load) that most of the voltage magnitude is higher than 250V at first 70 from maximum of solar generation. In contrary, Fig.9 (high load) shows all voltage magnitude is lower than 249V for the same period. It is considered that, low net load during solar generation caused a slight increase in the voltage magnitude. In overall view during solar generation (day time), the number of occurrence for voltage magnitude during low load condition is about 66% higher than the average voltage magnitude with no solar generation (248V), while about 40% during high load condition.

The high intermittent of voltage profile caused by rapid fluctuation of solar output and voltage rise during low load are giving negative effect on distribution system, which is unfavourable in the utility point of view. It is expected that grid-connected Battery Energy Storage System (BESS) could serve as the potential solution to alleviate both the solar intermittency and voltage raise issues. BESS can also provide flexible energy management solution while maintaining the grid quality and reliability [12-18].

Table 2. Quantification of voltage profile intermittency based on solar PV power output conditions

PV Power Output Conditions		Voltage intermittency quantity	Average Voltage Magnitude [V]
High load with solar generation	Day	82	247.60
	Night	55	248.72
Low load with solar generation	Day	71	248.90
	Night	46	248.60
Day with maximum power output	Day	58	247.66
	Night	15	248.40
Day with minimum power output	Day	40	248.31
	Night	18	249.72
Day with no solar generation	Day	31	247.54
	Night	26	249.15

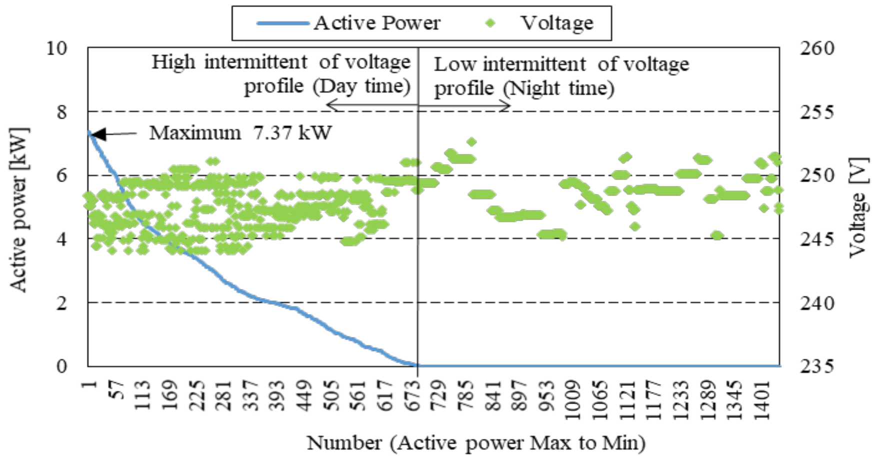

Fig. 9. PV power output from maximum to minimum and voltage profile (high load) with solar generation

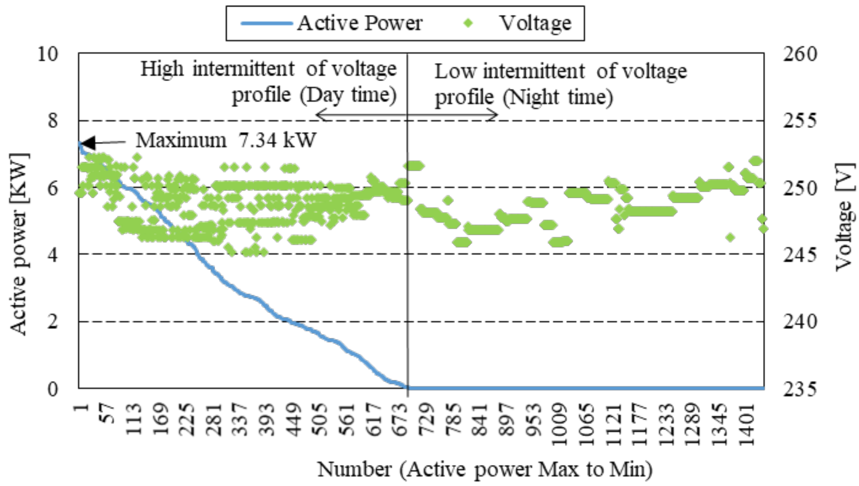

Fig. 10. PV power output from maximum to minimum and voltage profile (low load) with solar generation

An additional experiment has been conducted to investigate the influence of load on voltage profile intermittency in order to confirm the above result and consideration. (Fig.9 and Fig.10). Since high demand for UTeM as shown in Fig.2 is occurred on day time during weekday, the inverters for Line 1 on each system was turned off for one day full (24 hours) on weekday. By this method, solar PV power output was not

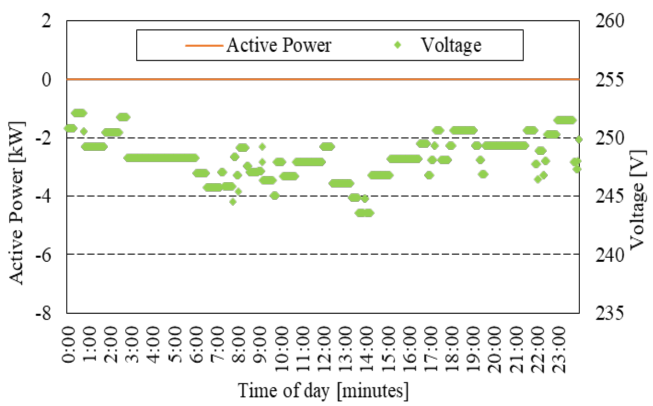

Fig. 10. Actual voltage and active power profile with no solar generation

injected to the grid, which allowed only grid connected to the load. As a result, actual voltage and active power profile in one-minute time resolution recorded on 28th February 2019 with no solar generation is presented in Fig.11. From this Fig. 10. PV power output from figure, it is noticed that the voltage profile intermittency is almost stable throughout the day. In addition, there is no significant difference of voltage profile intermittency between day and night time as shown in Table 2. Thus, the load did not influence the voltage profile intermittency, which confirmed the above result and consideration.

4. Conclusion

This paper presents quantification of voltage profile intermittency for small-scale solar PV system under different loading condition. Two main parameters have been analyzed in order to quantify the voltage profile intermittency, namely voltage profile and solar power output. Based on analyzed data, high intermittent of voltage profile occurred during day time for both high and low load condition, which indicates rapid fluctuation in solar irradiance causing high intermittent in solar generation. Furthermore, increased voltage magnitude was observed during low load condition. It is considered that, low net load during solar generation caused a slight increase in the voltage magnitude. High intermittency of voltage profile and voltage rise during low load are giving negative effect on distribution network. Thus, a grid-connected Battery Energy Storage System (BESS) has been considered as a potential solution to alleviate those issues.

Acknowledgements

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