Harmonic Distortion and Voltage Imbalance Study of Photovoltaic Power Plant Connected to the Malaysian Grid

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***Abstract*—This paper presents power quality analysis on the effects of large-scale photovoltaic power plant (PVPP) connected to the distribution system of Malaysian grid. For this purpose, the PVPP system with a capacity of 1.5 MW is connected to the medium voltage level of the distribution network through a single-stage voltage source inverter (VSI). Power quality issues at connection point such as current and voltage harmonics distortion and voltage imbalance have been studied based on the standard requirements especially Malaysian standards at different levels of solar irradiation. This analysis is very useful to help researchers and grid operators to study the effects of power quality problems concerning grid-connected PVPP. It can be clearly seen from the measured results that the harmonic distortion and voltage imbalance of the proposed PVPP can meet the Malaysian distribution grid code and national grid standard requirements.**

***Index Terms*—Grid-connected PV System; Harmonics; Photovoltaic Power Plant; Power Quality; Voltage Imbalance.**

I. INTRODUCTION

The increase in power demand and depletion of traditional power plants due to the high cost and limitation of fossil fuel sources, increasing global warming, and the rising of the percentage of use as well as implementation of sustainable energy sources in the generation mix has encouraged to connect renewable energy sources to utility grid for power generation. Therefore, recently, there is a rising interest in the installation and integration of renewable energy systems to medium and low voltage distribution network. Among the renewable energy sources available, the use of photovoltaic power plants which is safe, clean, highly reliable, and available in abundance from the sun's source of energy has rapidly increased all over the world [1, 2]. Figure 1 shows that there is a gradual increase of PV system installed globally from 2010 to 2014 by about 30 GW or more per year. Over the last year, the installation of PV plants has increased to 227 GW, which is higher than 2014 by around 50 GW [3].

Photovoltaic power plants connected distribution network can improve the operation of the power system by enhancing the voltage profile as well as by reducing the distribution feeders' energy losses, operating and maintenance costs in addition to reducing electricity bills and the loading of transformer tap changers during peak hours [4]. However, and because of the significant increase of PVPPs integration to the power grid, low power quality issues such as voltage and current harmonics, voltage imbalance, and power factor at the Point of Common Coupling (PCC) can impose some adverse effects to the distribution system, especially to nearby loads. For instance, power electronics inverters of large-scale PV system can insert inherent current harmonics to the associated bus and consequently pollute the power quality of nearby power systems and connected loads [5]. Therefore, it is very important to apply strict power quality regulations concerning the penetration of distribution energy generators which are imposed by either national Grid Codes (GCs) or international standard requirements such as IEEE standards [6] and IEC standards [7]. In Malaysia, due to the tropical climate and government's incentives to install PV system, the national electric grid in Peninsular Malaysia has issued the standard guideline on grid-connected PV system [8, 9].

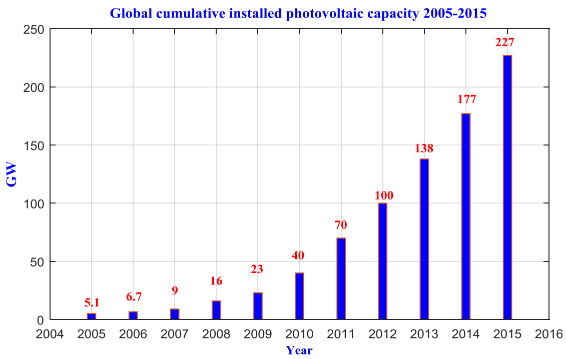

Figure 1: Global cumulative installed solar PV capacity 2005-2015

Since it is well-known that most traditional power systems are designed in a manner where generating stations are far away from the load centers and therefore utilize the transmission and distribution network as pathways. The normal operation of conventional power systems does not contain generation plants in the distribution system or in the customer's side of the network. Nevertheless, the integration of PVPPs in distribution systems changes the normal operation of power systems and poses a few problems on the quality of the power system [5, 10, 11]. Therefore, power quality issues such as harmonics and voltage imbalance analysis of installing large-scale PVPPs connected grid on the performance of the electric network is important. This evaluation is necessary since it can give possible solution for potential operation issues that PVPPs can bring about to the other components in distribution networks. In the literature, many power quality issues have been highlighted such as power factor characteristics, voltage flicker, voltage sag, voltage and frequency fluctuations, and islanding [4, 5, 12-

14]. Harmonics study for two-stage PVPP connected utility grid using PSCAD model had been done in [15] based on IEEE Std 519-1992. It can be concluded that Total Harmonic Distortion (THD) depends on its interface with the utility system as well as the size of PV plants. Another study proposed in [16] studied the THD according to the IEC standards to show the impact of different loads to current and voltage THD. On the other hand, a view attempt is yet to be made to study the effect of voltage imbalance regarding PV system penetration. For instance, the power quality study that is proposed in [17] and [18] for small size PV system which only addressed voltage imbalance problem, but it is not sufficiently investigated. The main aim of this paper is to accurately analyze the effects of installing large-scale PVPP station on current and voltage harmonic distortion and voltage imbalance of distribution networks. The PVPP model connected into Malaysian distribution side is used to analyze these power quality issues based on the Malaysian standard requirements at the different level of irradiation. The simulation results show that the THD and voltage imbalance are modified and degrades to the standard defined level.

II. Modeling of The PV Power System

The schematic diagram of Figure 2 shows the power stage of the grid-connected three phase single-stage PV system modeled in this study. It includes the PV array, Maximum Power Point Tracking (MPPT) technique without boosting stage is used to extract maximum available power from the PV array, and the dc-link capacitors that connects to the output terminal of the PV array. In addition, three-phase VSI with its control, RL filter which is connected to the low voltage ac grid, and set up transformer-connected distribution side of the Malaysian grid [9, 11, 19].

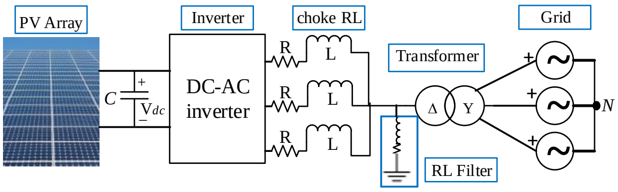

Figure 2: Schematic diagram of the single-stage PVPP system

The inverter is the most important part of Grid-Connected Photovoltaic Power Plants (GCPPPs). In this study, a self-commutated inverter VSI is used in the proposed design to execute the power conversion and control optimization purposes. The inverter control frame consists of all the basic control requirements for grid-connected PV system. This control system adopts double loops Pulse Width Modulation (PWM) control mode. It consists of an inner current loop and outer voltage loop. The typical Proportional-Integral (PI) controllers are utilized to regulate the grid current and the dc-link voltage [20]. A PVPP with peak output power of 1.5 MW is connected to Malaysian distribution system model and an inverter control has been fully described in an earlier paper written by the authors [9]. In this study, the focus will be on enhancing some power quality issues regarding the connection of PVPP to the distribution network according to the standard requirements especially Malaysian grid (TNB) technical regulation concerning the penetration of PV system to medium and low voltage distribution system of the national grid [8].

III. Harmonic Distortion

Harmonic distortion in an electrical power system is a serious power quality problem. It is described as a distortion of the normal electrical voltage or current waveform and is then adjusted from the original shape or characteristics. Generally, harmonic distortion is caused by rectifiers, non-linear loads, power converters, transformers, and rotating machines [4]. As it is well known that PV system consists of different power-electronic devices that produce distortion, and inverters that consider the main part in GCPPP are no exception. Two of the most important characteristics of the PV inverters-connected grid are the efficiency and the electricity supply quality. Therefore, the electricity supply quality can be studied from the current and voltage total harmonic distortion. The total harmonic distortion (THD) is utilized to measure the presence of harmonics in a power system. The THD for a voltage or current waveform is a measurement of the harmonic distortion present and is defined as the ratio of the sum of all magnitudes of voltage or current harmonic components to the voltage or current magnitude of the fundamental frequency. It can be calculated using the following expression [16, 21]:

$$THD = \frac{\sqrt{\sum_{n=2}^{k} h_n^2}}{h_1} \tag{1}$$

where $h_2, h_3, \ldots, h_n$ denote the effective value of the harmonics for the orders $1,2,3,\ldots,k$ while h_1 is the fundamental component. The n and k represent the harmonic order and last harmonic series, respectively. It is worth mentioning that if the wave is an ideal sinusoidal wave, the total harmonic distortion is zero. Furthermore, more particular measures for the quantitative analysis of the components, either the voltage distortion or the current distortion in percentage can also be expressed for a more exact view using the following equations, respectively [21]:

$$V_{THD}\% = \frac{\sqrt{|V_2|^2 + |V_3|^2 + |V_4|^2 + \ldots}}{|V_1|} \times 100\% \tag{2}$$

$$I_{THD}\% = \frac{\sqrt{|I_2|^2 + |I_3|^2 + |I_4|^2 + \ldots}}{|I_1|} \times 100\% \tag{3}$$

For the inverter of GCPPP, the output voltage is synchronized with the grid voltage signal whilst the current waveform should be sinusoidal and as ideal as possible. Therefore, the integration of PVPPs to the grid must comply with these standards to regulate the effects of THD on the utility grid. One such international standard is IEEE Std 519-1992, IEEE 1547 Stds., IEC standards, as well as Malaysian national grid standards, are amongst the standards related to power quality, especially THD [6-8, 10, 22]. All these standards mentioned that the inverters should operate at PCC with current total harmonic distortion not exceeding 5%. Malaysian grid also requires that I_{THD} shall be less than 5% at a rated inverter output in PCC and the individual harmonics should be limited to the limits listed in Table 1 [8]. In this study, these values will be considered as reference.

Table 1
Current Distortion Limits

The Harmonics		Distortion limit
Odd	3-9	< 4%
	11-15	< 2%
	17-21	< 1.5%
	23-33	< 0.6%
Even	2-8	< 1.0%
	10-32	< 0.5%

Regarding voltage distortion, IEEE Standard 519-1992 indicates that voltage distortion at PCC is limited to 3% for individual harmonic content and only 5% for voltage bus rated 2.3 - 69 kV, as illustrated in Table 2. It is recommended that the voltage distortion of the system should be lower than 2.5% before a distributed generator such as PV is integrated with the system [22]. The TNB Malaysian grid technical regulation and Malaysian distribution grid code require that voltage distortion for all distribution generator connected utility company unless abnormal conditions prevail, shall not exceed: (a): at 33kV, 22kV, 11kV and 6.6 kV: a THD of 6.5%. (b): at 400V and below, a THD of 5% [8, 23]. Therefore, these values will be used as reference in this study.

Table 2
Voltage Distortion Limits

Voltage Harmonic Distortion in % at PCC		
Bus Voltage	Individual Voltage Distortion (%)	Total Voltage Distortion (V_{THD} %)
2.3-69 kV	3	5
69-161 kV	1.5	2.5
>161 kV	1	1.5

IV. Voltage Imbalance

Voltage imbalance is defined as the ratio of the negative sequence voltage component to the positive sequence voltage component [8, 24]. Voltage imbalance occurs when the three-phase voltage varies in magnitude and/or in the normal 120º phase difference [25]. According to IEEE standards, the recommended practice for monitoring electric power quality is the percentage voltage imbalance factor (VUF %). The true definition in many of different standards of VUF % is given by the following equation [17, 24]:

$$VUF\ (\%) = \frac{V^-}{V^+} \times 100 \tag{4}$$

where V^+ and V^- are the positive and negative sequence of the voltage and can be calculated in the three-phase system as expressed in (5) and (6), respectively.

$$V^+ = \frac{1}{3}(V_a + aV_b + a^2V_c) \tag{5}$$

$$V^- = \frac{1}{3}(V_a + a^2V_b + aV_c) \tag{6}$$

where a is the operator that shifts the vector counter-clockwise at an angle of 120 degrees, while a^2 fulfills a phase shift by 240 degrees counter-clockwise.

According to [24] and [7], the allowed limit for voltage imbalance should not exceed 2% in medium and low voltage networks. On the other hands, according to the Malaysian distribution GC [23] and TNB grid technical regulation [8], the limits for voltage imbalance are based on the United Kingdom Energy Networks Association Engineering Recommendation P29 which limits the whole voltage imbalance of the network to be 2% and 1.3% at the load point. Other than the abnormal operations, the Malaysian distribution grid code requires the voltage imbalance at the steady state not to exceed 1% [23]. In this study, these limits will be considered as a reference.

V. Results and Discussion

To investigate the power quality issues that occur in the GCPPP such as harmonics and voltage unbalance, a large-scale PVPP connected to Malaysian distribution grid is simulated using Matlab/Simulink as described in section II. As mentioned above, it is recommended that the THD at the PCC should comply with the standard requirements especially Malaysian standards [8, 23]. PCC is known as the point at which the utility grid and the PV power station is connected and being utilized widely in the business as a reference to the connection point. In this PVPP Simulink model, PCC lies between the transformer and the power grid. The output of the PV system should have low THD levels either for current or voltage to guarantee that no adverse impacts are caused to other equipment connected to the grid. In order to calculate the THD, the Fast Fourier Transform (FFT) tool in Simulink was used to record the THD of the output voltage and current waveform with the fundamental frequency at 50 Hz.

Figure 3 and Figure 4 show the THD of the current and voltage at PCC measured at STC (G=1000 W/m^2, T=25 Cº). It can be observed from the figures that the THD of current and voltage (I_{THD} and V_{THD}) waveform are oscillating around 9.2% and 2.8%, respectively. It is evident that the I_{THD} is higher than the 5% limit, whilst the V_{THD} is lower than the 5% limit, established by the previously discussed standard. Even after using three-level voltage source inverter and an efficient current control [9], the I_{THD} still higher than these limits. Thus, to solve this issue, proper RL filter in the PV inverter had been used. The carrier frequency of the PWM is remaining the same with 2000 Hz. Therefore, the values of RL filter parameters used for calculation of harmonics suppression are 1.25Ω and 0.1 mH, respectively at switching frequency (f_c) equal to 2000 Hz, based on the following equation:

$$f_c = \frac{\omega_c}{2\pi} = \frac{R}{2\pi L} Hz \tag{7}$$

The effectiveness of this method is shown in Figure 5 and Figure 6 in which the I_{THD} and V_{THD} have been decreased to lower values of 0.74% and 0.15%, respectively, which are much lower than the value of the 5% limit. Figure 7 illustrates the three-phase current waveform of the PVPP at PCC. When compare the sub-plot of this figure, in the time domain, it is evident that before using filtering the distortion was high and clear as shown in part (a), while in part (b), it can be observed that the shape of the current waveform is smoother than waveform in part (a) due to using proper RL filter and increasing the PWM carrier frequency. As a result, the FFT results show that the waveforms (Figure 5 & Figure 6) after filtering have less THD and meet the desired limit than before filtering case (Figure 3 & Figure 4).

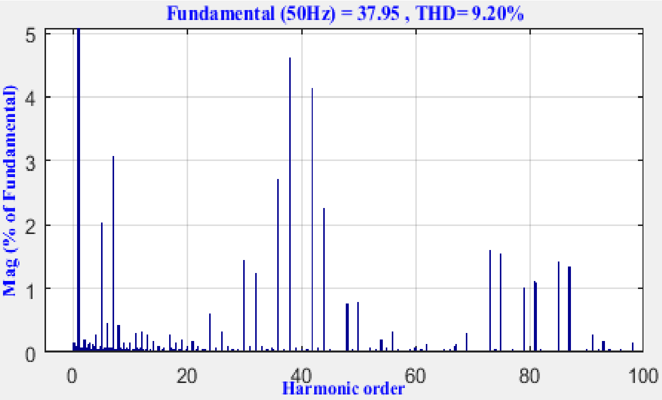

Figure 3: THD level of the current waveform at STC before filtering

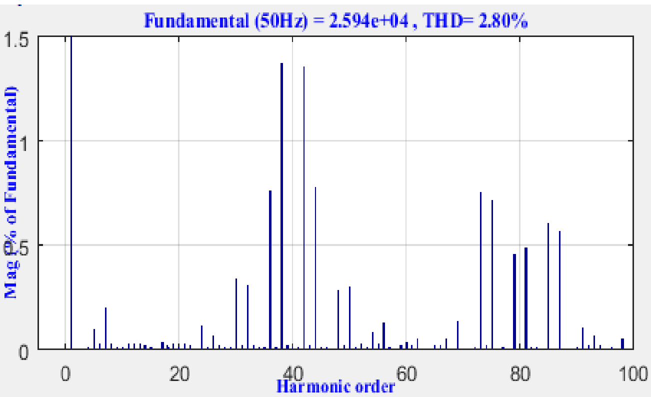

Figure 4: THD level of the voltage waveform at STC before filtering

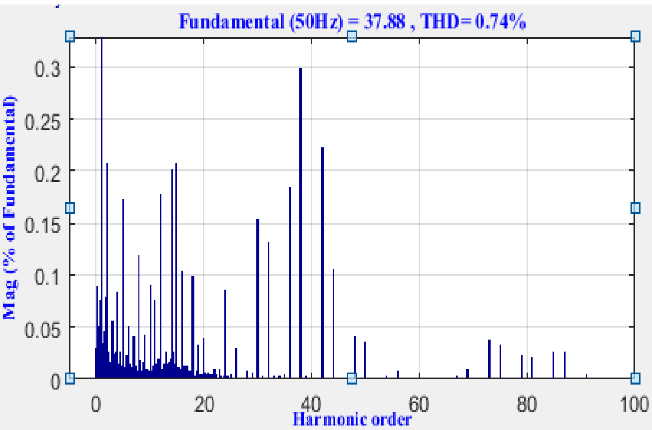

Figure 5: THD level of the current waveform at STC after filtering

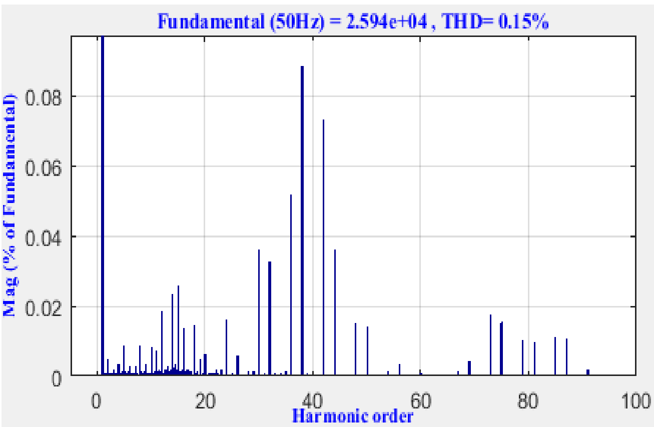

Figure 6: THD level of the voltage waveform at STC after filtering

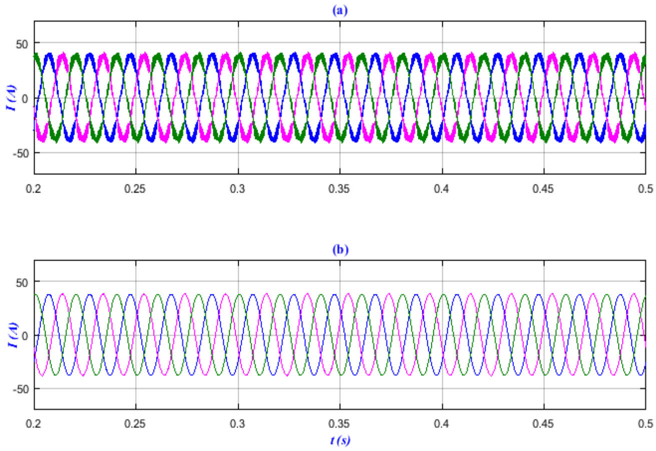

Figure 7: The three-phase waveform of the current at PCC; (a) before using RL filter and (b) after the implementation of RL filter

In order to test THD of proposed PVPP connected Malaysian grid under different levels of solar irradiation, the I_{THD} and V_{THD} values of the PVPP at PCC were illustrated at 500W/m^2 irradiation values as shown in Figure 8 and Figure 9, respectively. It is shown in Figure 8 that by decreasing the solar irradiation value to 500W/m^2, the I_{THD} values were increasing. On the other hand, as shown in Figure 9, there is a small noticeable effect of decreasing solar irradiation on the V_{THD} value which remains almost constant as compared to Figure 6. Therefore, one could conclude that the I_{THD} analysis is more significant than the V_{THD} analysis in the case of GCPPP operating under different solar irradiation. In addition, the GCPPP injects more current harmonics into the utility grid when operating under low solar irradiation than at high irradiation values. In conclusion, it can be observed that as the solar irradiation increases, the THD reduces and vice versa. This occurs because of that the THD tends to increases, when the modulation index (*m*) decreases, however, the THD is minimum with modulation index equal to one (*m*=1) [26]. Therefore, in the case of irradiation decreased to 500W/m^2, the THD is increased as compared with 1000W/m^2 because the generated current and voltage is lower than the rated value, and this means the modulation index is less than one. To illustrate the effectiveness of the proposed method for individual harmonics, the value of each current harmonic in Figure 5 and Figure 8 is compared to the range given in Table 1, and the value of each individual voltage harmonic in Figure 6 and Figure 9 is compared to the range given in Table 2. It was found that none of the individual harmonics violates the specified limits.

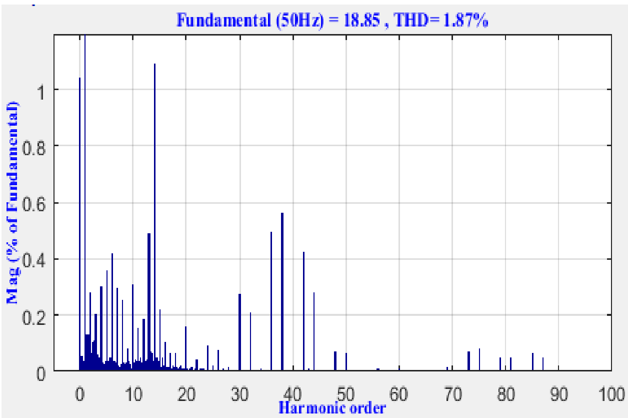

Figure 8: THD level of the current waveform at 500 W/m^2 solar irradiation

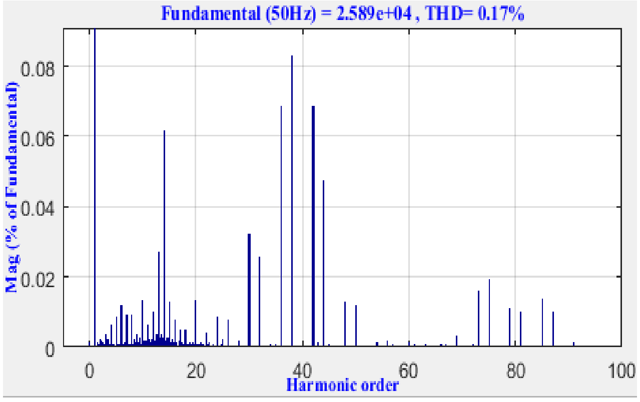

Figure 9: THD level of the voltage waveform at 500 W/m^2 solar irradiation

Voltage imbalance mostly occurs at the low voltage distribution level especially at the user end and therefore it is more common in the individual customer load due to the imbalance of phase load [27]. Despite the fact that voltages are well balanced at the supply side, the voltage at customers' level can turn out to be unequal due to the unequal impedance of the system, incorrect distribution of single-phase loads by the three phases of the system, or large quantities of single phase transformers [17, 27, 28]. As a result, these issues are out of the scope of this study and it is the responsibility of distribution system operator to overcome this problem by rearranging or distributing the residential loads equally among the three-phase distribution feeders [25], or by installing Dynamic Voltage Restorer (DVR) for better outcomes [29]. Therefore, in this study, the voltage imbalance problem will be focused and tested at the PCC to ensure that no imbalance three phase voltage is injected into the distribution system. The standard mentioned above requires VUF% to remain under 2% whilst at the abnormal operations, the Malaysian distribution grid code requires the voltage imbalance at the steady state not to exceed 1%. Figure10 illustrates that the VUF % at STC is 0.2%, whereas, at a low level of irradiation (500 W/m^2), the corresponding value is 0.16%. It is evident that the VUF % in both cases is much less than the standard limits.

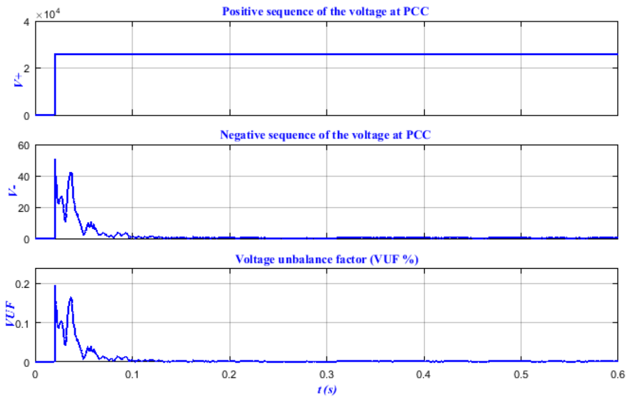

Figure 10: Voltage unbalance factor of the PVPP-connected grid at STC

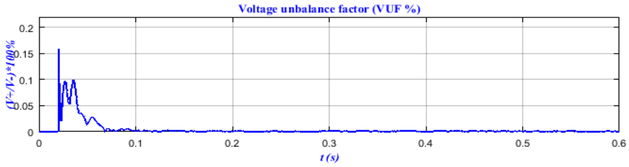

Figure 11: Voltage imbalance factor of the PVPP-connected grid at 500 W/m^2

VI. CONCLUSION

This paper presents an analysis and investigation of the possible effects of large-scale PVPP connected Malaysian utility grid on power quality issues such as harmonics distortion and voltage unbalance in distribution systems under different levels of solar irradiance. The Malaysian standard of distribution grid code and TNB technical regulation concerning the penetration of PV system into medium and low voltage have been used as a reference in this study. THD of the current and voltage at PCC has been decreased within the standard limits by using proper inverter filter and PWM carrier frequency. The effect of solar irradiation to THD is an inverse relationship in which the increase of solar irradiation cause decreasing in the THD either of current or voltage waveform. On the other hand, the relation between voltage unbalances and solar irradiation is a direct relationship in which as the irradiation increased the voltage unbalance factor is increased and vice versa. It can be concluded from the results that the power quality problem of the studied PVPP such as voltage unbalance and total demand distortion at PCC can meet the Malaysian standards and operate within the required limits.

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