# Assessment of voltage and current quality indices of grid connected solar PV plants against international standards

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***Abstract* — The renewable energy based power generation is increasingly gaining attention with the technological advances and global climatic concerns. Among different type of the renewable energy sources solar photovoltaic (PV) become the most prominent renewable energy source. As solar PV is connected to the all voltage levels in a power system, the intermittency and variability of solar PV output may raise the issues in stability of the system. It was identified that in order to minimize the impact of intermittent distributed generators like solar PV, they should comply with distribution codes/guidelines which are introduced by utilities/standardization bodies. However with the penetration level of PV is increasing utilities have fears about adequacy of distribution codes/guidelines. This research communication presents a performance assessment of grid connected solar PV plants against a number of distribution codes/guidelines using the real time measurements of five sites in Malaysia. The measurement of RMS voltage, Total Harmonic Voltage Distortion, Total Harmonic Current Distortion, Voltage Unbalance, and Voltage Flicker of the grid connected PV plants were taken into consideration. The results shows that PV systems considered comply with all the essential requirements of the international standards.**

***Keywords— solar power, Distribution codes, test results, compliance to international standards***

## I. INTRODUCTION

Global initiatives have paved the way of shifting from fossil fuel based electrical energy generation to greener alternatives. Many European countries, America, and China invested heavily on renewables thus creating critical markets for them and triggered the early technological advances [1]. Growing emphasis on mitigating climate change further contributed to building up the momentum.

Among different renewable energy technologies, solar photovoltaic (PV) gathered momentum in recent years. The global total PV capacity as at the end of 2017 was 404 GWdc. Solar PV is connected to all voltage levels. Large and medium scale plants in MW range are connected to transmission and distribution voltages and rooftop kW scale plants are connected to the low voltage networks. When a medium scale PV plant is connected to the power grid, it functions as a distributed generator that assists the main generation system by supplying power into the grid. Nevertheless, caution has to be taken on the possible effects of PV system upon the power grid. With higher penetration of PV in the generation mix, significant grid stability issues may arise. For instance, solar PV is an intermittent energy source, where inconsistent power generation can cause a significant voltage fluctuation [2],[3],[4],[5],[6]. The use of inverters in PV systems also introduces harmonics to the connected power grid, which can damage nearby sensitive equipment [7],[8]. In comparison to the conventional network, where power is transmitted from a higher voltage level in generation plants to the point of consumption at lower voltage levels, the PV sources can be connected near the distribution loads that may cause reverse power flow and voltage rise issues [9],[10],[11],[12]. Therefore utilities are causes about high penetration of renewables, especially distributed generation.

In order to limit possible impacts to the distribution networks, PV plants should abide by the distribution codes/guidelines imposed by the utilities. These distribution codes/guidelines are mainly based on the international standards such as IEEE1547 [13], IEEE 519 [14], G59 [15], and IEC 61000-3-6: 2008 [16]. Even though some distribution codes are not explicitly specifying these standards, the limits specify there are comparable with the limits specified in the standards. Even though these standards and distribution codes/guidelines are well documented, according to the best of authors' knowledge there are no studies to make judgements such as whether the existing distribution codes/guidelines are more stringent thus hinders the uptake of PV or whether they are more lenient thus creating adverse impact to the network to which they are connected. Therefore in this paper, an attempt was taken to critically evaluate real measurements taken from a few PV plants in Malaysia against the commonly referred standards in distribution codes. This work could feed into active revisions of existing standards. For example on 26th April 2018, IEEE announced the publication and availability of IEEE 1547-2018 - Standard for Interconnection and Interoperability of Distributed Energy Resources (DER) with Associated Electric Power Systems Interfaces.

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## II. International Standards

In order to highlight whether solar PV additions worsen the distribution grids, some commonly used international standards applicable to PV connections at distribution voltage levels were reviewed. The general requirements, voltage related limits and power quality related limits of these standards are given in Tables I, II and III respectively.

TABLE I. General requirements

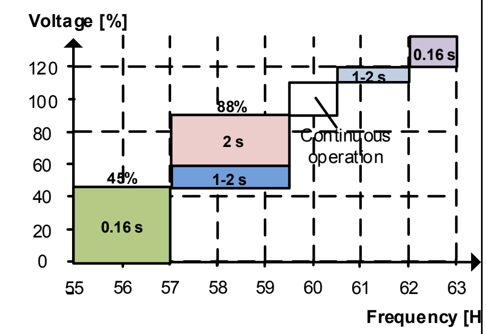
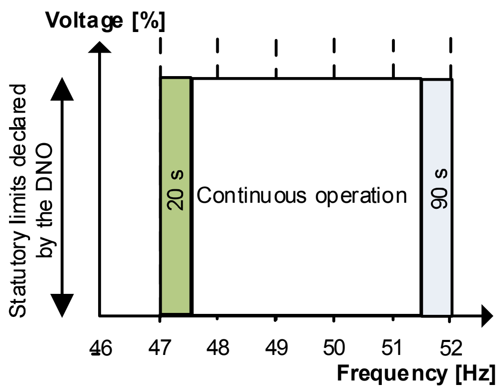
| | **IEEE1547** | **G59 (mainly applicable in the UK)** |
|---|---|---|
| Applicability | DR technologies of aggregate capacity of 10 MVA or less that are interconnected at typical primary or secondary distribution voltage. | Embedded Generating Plant sites with outputs less than 5MW and connected at system voltages less than 20kV. |
| Voltage and frequency range of operation |  <br>Clearance times are given inside each box |   |
| Voltage regulation | • DR operators shall be required for the DR to actively participate to regulate the voltage by changes of real and reactive power. | • Where it is agreed that the Generation Plant should operate in voltage control mode the Generating Plant will have a specific role to control the Distribution System voltage. |
| EPS grounding | • Shall not cause over voltages that exceed the rating of the equipment connected to the Area EPS and shall not disrupt the coordination of the ground-fault protection on the Area EPS. | • Shall satisfy the requirements of the Distribution Code.<br>• Shall be designed, installed, tested and maintained in accordance with ENA TS 41-24, BS7354 and BS7430. |
| Monitoring provisions | • Each DR unit of 250 kVA or more or DR aggregate of 250 kVA or more at a single PCC shall have provisions for monitoring its connection status, real power output, reactive power output, and voltage at the point of DR connection. | Not specified |
| Limitation of dc injection | • The DR and its interconnection system shall not inject dc current greater than 0.5% of the full rated output current at the point of DR connection. | • The limit for DC injection is less than 0.25% of the AC rating per Generating Unit. |
| Islanding | • DR interconnection system shall detect the island and cease to energize the Area EPS within two seconds of the formation of an island.<br>• If the DR is intended to supply power only to its own local EPS and not to the area EPS across the PCC, reverse power relays may be installed at the PCC to operate isolating devices | • Suitable equipment will need to be installed to detect that an island situation has occurred and an inter tripping scheme is preferred to provide absolute discrimination at the time of the event.<br>• If islanding is permitted (with the agreement of DNO), supplies to customers are maintained within statutory limits and Distribution Systems are earthed at all times. |

TABLE II. Voltage changes, voltage fluctuations and flicker

| | IEEE1547 | G59 |
|---|---|---|
| Limitation of flicker - | Pst (short-term flicker severity)<br>• less than or equal to 1 for a PCC at the secondary distribution voltage<br>• less than or equal to 0.9 for a PCC at the primary distribution voltage | Pst severity is less than or equal to 1 as specified in the Engineering Recommendation P28 |
| Unbalanced voltages | Not specified | • Should be no greater than 1.3% for systems with a nominal voltage below 33kV, or 1% for other systems with a nominal voltage no greater than 132kV.<br>• Should not exceed 2% when assessed over any one minute period. |
| Step Voltage Change caused by the connection and disconnection of Generating Plant | Not specified | • ± 3% for infrequent planned switching events or outages<br>• ±10% for unplanned outages such faults. |

TABLE III. Harmonics

| | IEEE 519 | IEC 61000-3-6: 2008 |
|---|---|---|
| Applicability | Guidance in the design of power systems with nonlinear loads. The limits set are for steady-state operation and are recommended for "worst case" conditions. | The connection of distorting installations to MV, HV and EHV public power systems |
| Total Harmonic distortion (THD) | THD = 5 % | THD = 8 % for long-term effects |
| Individual harmonic distortion | For different $I_{SC}/I_L$ values (where $I_{SC}$ is the maximum short-circuit current at PCC and $I_L$ is the maximum demand load current at PCC), the maximum harmonic current distortion in percent of $I_L$ is specified. | The maximum harmonic current distortion in percent of $I_L$ is specified. |

## III. Measurements

The following tests were carried out to check the performance of a number of PV plants with respect to the standards reviewed in the previous section. Fluke 435 Power Quality Analyzer was used for all the tests. To obtain voltage and current measurements the Fluke was connected to the outgoing feeder control panel of the solar plant; i.e. on the 11 kV side of the collector transformer.

### A. Power Quality (PQ) Test

PQ tests to ascertain voltage profile, current profile, harmonics, voltage flicker, and voltage unbalance were conducted. Initially, background measurements were done at the PCC to ascertain the existing quality of power prior to commissioning. Same measurements were repeated after commissioning to identify any PQ issue due to the connection of PV system. Measurements were taken few days before plant energization and for another few days after plant energization.

### B. Steady-State Voltage Measurement of Medium Voltage

This test was performed at the developer's MV side. The test was conducted for a minimum of six daylight hours at one minute interval.

## IV. Results and Discussion

### A. Measurement sites

Measurements were taken from the sites shown in Table IV.

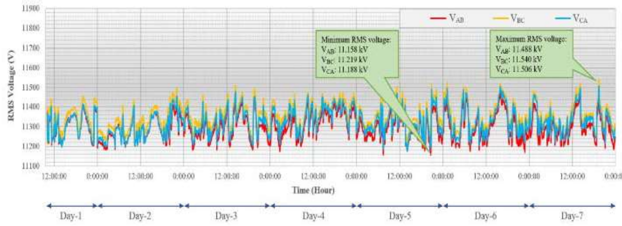
TABLE IV. Measurement Sites

| Site Number | Site Name | Plant capacity | Voltage to which the plant is connected |
|---|---|---|---|
| 1 | PE F.Y. Food Processing | 1 MWp | 11 kV |
| 2 | P/E Puchong Gateway No.4 | | |
| 3 | P/E Kraftangan Ewa | | |
| 4 | P/E Puchong Gateway No.2 | | |
| 5 | P/E Amkawood Kg Selamat | | |
| 6 | SSU HI-Essence | | |

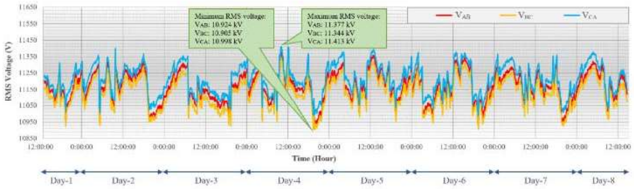
### B. RMS voltage

The RMS voltages at the PCC of the Puchong Gateway before plant commissioning and after plant energization are shown in Fig. 1 (a) and (b). The voltage measurement was taken for approximately seven days at five minutes interval. Using such time series measurements, the maximum and minimum voltage that was reported during the measurement period were obtained. The plot shown in Fig. 2 indicates the maximum and minimum voltage level of all the sites given in Table IV. These voltages are well within the limits specified in Table I.

Further, TNB Technical Guidebook on Grid-Interconnection of PV plant to LV and MV Networks [17], and the Malaysian Distribution Code for Peninsular Malaysia, Sabah & F.T. Labuan [18] demand voltage to be within the limits of ± 5% of nominal voltage of 11 kV; i.e. from 0.95 pu to 1.05 pu. As can be seen from Fig. 2 all sites comply with this requirement.

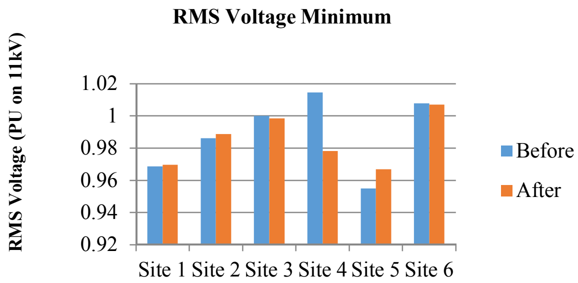


*(a)* . Before PV plant commissioning



(b). After PV plant commissioning.

Fig. 1. RMS voltage profile



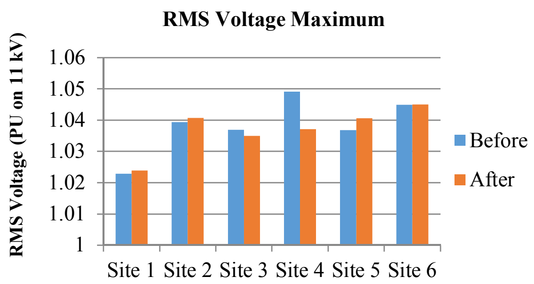




Fig. 2. Maximum and minimum voltage of six sites

## *C. Total Harmonic Voltage Distortion*

Total Harmonics Voltage Distortion (THDV) levels before and after energizing the PV system for all the sites are given in Fig 3. The acceptable THDV limit is 5% as stipulated in IEEE 519 and 6.5%, as stipulated in the Malaysian Distribution Code. The maximum values recorded in all six sites are much less than the limits.

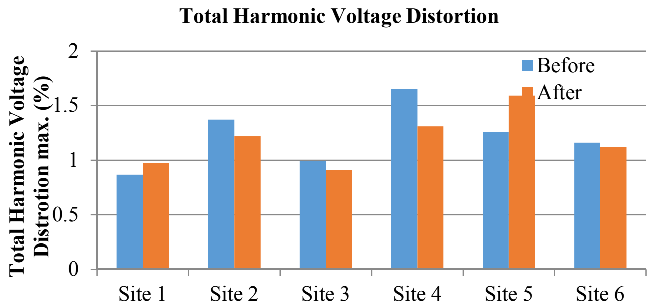



Fig. 3. Maximum recorded value of the Total Harmonic Voltage Distortion

## *D. Total Harmonic Current Distortion*

The Total Harmonics Current Distortion (THDI) levels after energizing the PV system for all the sites are given in Fig 4. The acceptable THDI limit is 5% as stipulated in the Malaysian Distribution Code. The maximum values recorded in all six sites are less than the limits. However THDI reaches 5% in site 2.

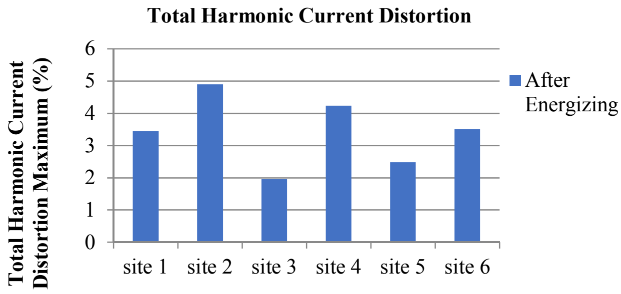
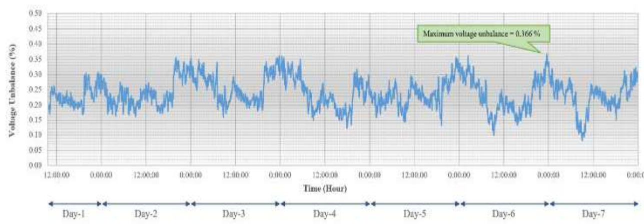


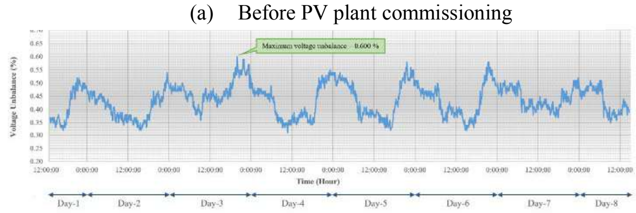

Fig. 4. Maximum recorded value of the Total Harmonic Current Distortion

## *E. Voltage Unbalance*

Fig. 5(a) shows the voltage unbalance profile for seven days before energizing the Puchong Gateway plant. The maximum voltage unbalance recorded was 0.366%. Meanwhile, the voltage unbalance profile after energizing the PV plant is depicted in Fig. 5(b). The maximum voltage unbalance measured during this period seemed to increase slightly to 0.6%.



(a) Before PV plant commissioning



(b) After PV plant commissioning

Fig. 5. Voltage unbalance profile

The voltage unbalance % before and after energizing the PV system for all the sites are given in Fig 6. The acceptable voltage unbalance % limit is 1.3% as stipulated in G59 and 1%, as stipulated in the Malaysian Distribution Code.
The maximum values recorded in all six sites are much less than the limits.

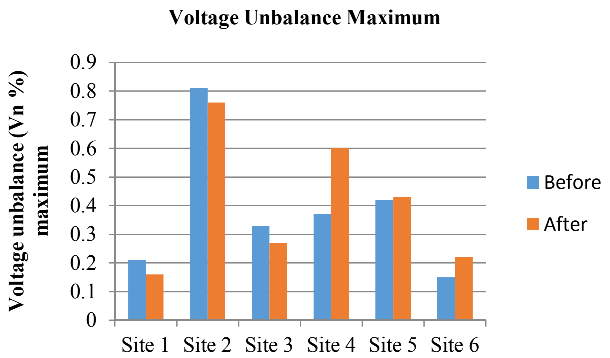
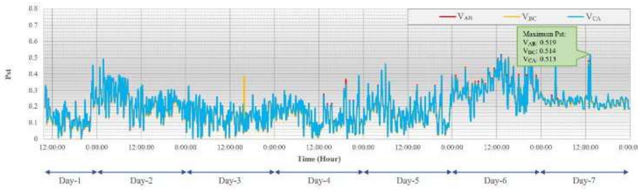


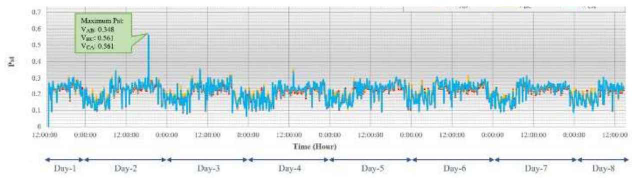

Fig. 6. Maximum recorded value of the % unbalance

### F. Voltage Flicker

Figs. 7(a) and (b) depict the $P_{st}$ before and after plant commissioning. As for $P_{st}$ results, the maximum recorded data before energizing the PV plant were 0.519, 0.514, and 0.513 for each line, whereas the collected data after plant energization were 0.348, 0.561, and 0.561 for each line. The recorded maximum Plt values for each line before and after plant commissioning were 0.627, 0.640, and 0.577 (before), as well as 0.331, 0.335, and 0.332 (after).



(a) Before PV plant commissioning



(b) After PV plant commissioning
Fig. 7. $P_{st}$ profile

The $P_{st}$ and $P_{lt}$ before and after energizing the PV system for all the sites are given in Fig. 8. The acceptable limit is 1.0 as stipulated in IEEE 1547 and G59. As stipulated in the Malaysian Distribution Code, $P_{st}$ and $P_{lt}$ limits are 0.9 and 0.7. The maximum values recorded in all six sites are less than the limits.

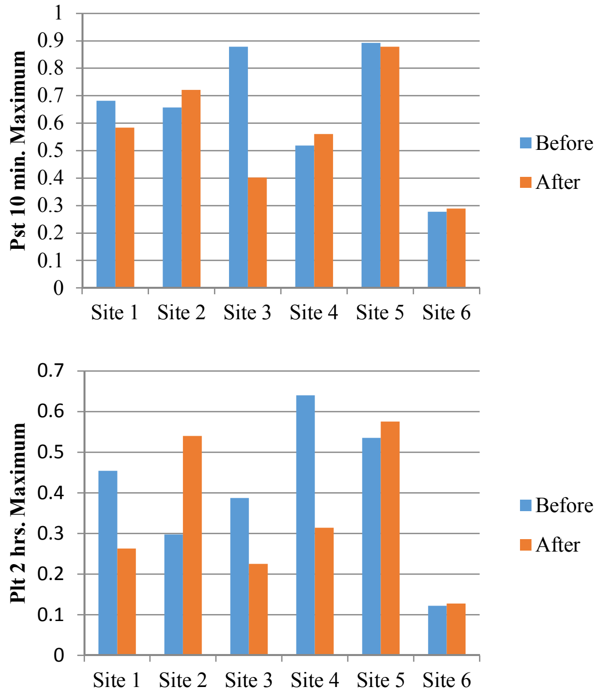



Fig. 8. Voltage Flicker $P_{st}$ & $P_{lt}$

## V. CONCLUSIONS

The measurements taken from a few distribution generation sites in Malaysia against commonly used international standards and Malaysian distribution codes were compared. The PQ parameters such as voltage profile, current profile, harmonics, voltage flicker, and voltage unbalance at PCC of the PV system were obtained to detect any PQ issues due to the injection of PV into the power grid. The results showed that the tested PV systems comply with all the stipulated requirements of the international standards. Further, often it is seen that PV addition reduces the PQ related quantities in distribution networks.

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