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# Power Quality Impacts of PV Systems Integration on Petroleum Development Oman (PDO) - Mina Al-Fahal (MAF) Distribution Network

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**Abstract.** The importance of solar photovoltaic (PV) systems has grown significantly with the continuous development of the solar cells industry over the past years. However, studying the potential impacts of solar PV systems on the distribution network has recently become an important topic with high attention. This paper presents an overview of the potential power quality impacts of solar PV systems integration on the Petroleum Development Oman (PDO) - Mina Al-Fahal (MAF) Distribution Network under different weather conditions. The investigations was performed using measurements. It was found that the measured voltage unbalance and Total Harmonics Distortion (THD) levels were within the limits stated by the Omani and international distribution codes. Furthermore, the evaluation of voltage flickers showed some violations of the limits specified by the distribution code requiring closer system monitoring.

**Key words.** Power Quality, PV Systems, Distribution Network.

## 1. Introduction

Power quality is known as the power grid's capability to generate a clean and stable power flow. The power flow should have a pure sinusoidal waveform and it should sustain within specified voltage, and frequency limit. In the IEEE glossary, power quality is recognized as "the idea of powering and grounding sensitive devices in an issue that is appropriate to the activity equipment operations" [1]. In distribution networks, low power quality is the major critical issue as the solar PV system comprises of DC source and electronic equipment, which can indeed be the origin of some power quality issues such as flickers, harmonics and voltage unbalance [2-4]. Different works carried out on grid-connected solar PV system presented in [5, 6] to assess the solar PV effect including voltage profile, harmonics and other power quality issues. Previous works have shown that solar PV installations have positively affected the distribution system. This paper studies the impacts of grid-connected solar PV system related on power quality including voltage unbalance, flickers, and harmonics.

Intermittency is the ordinary behavior of the solar PV system output. The rapid variation of the solar PV power outputs may generate voltage fluctuation; hence, voltage flickers may appear in the system. In addition, harmonic distortions can be generated from nonlinear equipment such as inverters.

The remaining parts of the paper are organized as follows: Section 2 addresses literature review on the impacts of PV systems on power quality. Section 3 presents PDO-MAF PV system data. Measurements and performance evaluation are presented in Section 4. Finally, conclusions are provided in Section 5.

## 2. Impacts of PV System on Power Quality

Power quality is known as the power grid's capability to generate a clean and stable power flow. The voltage signal should be a clean sinusoidal waveform and it should be maintained within specified voltage and frequency limits. In the IEEE glossary, power quality is recognized as "the idea of powering and grounding sensitive devices in an issue that is appropriate to the activity equipment operations" [7]. The main power quality problems are expressed with reference to voltage, frequency, and interruptions [8-10]. Different measure works carried out on grid-connected solar PV system presented in [11, 12] to assess the solar PV effects including voltage profile, harmonics and other power quality indices. In general, the results have shown that solar PV systems have a positive impact on distribution systems. In [13], the authors presented the calculated values versus the standards limits. The impacts of PV systems on power quality depend on the grid stiffness and the used inverter.

### *A. Voltage Unbalance*

The power system is comprised of three phases that convey three voltage and current waveforms. Preferably, these waveforms are alike in magnitude with a phase shift of 120° from each other. Unbalance happens in the event that one or both conditions are not satisfied. Single-phase loading is the main cause for an unbalanced operation mainly in distribution systems [8,14]. Commonly, unbalance in power systems shows up as voltage asymmetry, current asymmetry, or instantaneous voltage and current asymmetry. The presence of voltage negative sequence component increases the unbalance of the line currents [8, 10, 14-16]. There are two causes for voltage unbalance: 1) the structural asymmetry of equipment; 2) the voltage drops in the system caused by current unbalance. The unbalanced load is the major reason of current unbalance. The unbalanced load is mostly resulted from three items: large single phase loads, inadequate spreading of single phase loads, and faults [8, 10, 14-16]. The most common quantification index of voltage unbalance is the Voltage Unbalance Factor VUF [25]. The International Electro-technical Commission (IEC) definition of VUF is known as the voltage component relation of the negative sequence $V_1$ to the positive sequence $V_2$ of the three-phase voltage signal as shown in equation 1 [8, 10, 14-16]:

$$\%VUF = \frac{V_1}{V_2} \times 100\% \tag{1}$$

Positive sequence element contains of three phases identical in magnitude with 120° phase shifted from each other using phase sequence (abc). Negative sequence elements comprise of three phases identical in magnitude with 120° phase shifted from each using opposite phase sequence (acb). Zero sequence elements comprise of three phasors that are equal in magnitude with no phase change [8, 10, 14-16]. The IEC standards, (the IEC 1000-3-x series) [17], specify the upper limit of the UVF to be 2% for low voltage and medium voltage systems and 1% for high voltage networks. In terms of the instantaneous value, the upper limit is 4% [8, 10, 14-16].

Oman grid [18] and distribution codes [19] express unbalance limit as the voltage component ratio of the negative sequence to the positive-sequence as 1.0% except during abnormal conditions in which a limit of 2.0% is allowed.

Table I. Voltage Unbalance Ratio Limits

| Standard | Unbalance Ratio | |
|---|---|---|
| Oman Distribution Code | 1.0% | 2.0% abnormal conditions |
| IEC 1000-3-x | 2% for LV and MV | 1% for HV |

A voltage unbalance happens in the electrical system once the line voltage or phase shift between them differ [8]. In [20], a voltage unbalance sensitivity study of grid-connected PV systems was presented using a stochastic evaluation. The authors in [21] found that VUF values are higher at the receiving end of the feeder than at the sending end. A rise in voltage unbalance can cause malfunction of some controlling equipment; therefore, can reduce their lifetime. Moreover, with grid-connected solar PV systems, networks become active by exporting and importing power from and to the grid. Rapid fluctuations in solar irradiation subject to the passing of clouds may result in voltage fluctuations/unbalance problems as discussed in [22].

*B. Flicker*

In IEEE 100-1977 [23], Flicker is defined as "the influence of brightness or color fluctuating, happening at the time the frequency of detected fluctuation ranges from a few hertz to the fusion frequency of images". Flicker is a result of voltage fluctuations. These can be evaluated by measurements using a flicker meter that fulfills the specifications provided in IEC-61000-4-15 [24].

To measure the flicker severity, two indices are used in which P stands for Perceptibility: the short-term ($P_{st}$) and the log-term ($P_{lt}$) severity indices. The short term flicker severity index ($P_{st}$) is assessed under short period of 10 minutes and the long term flicker severity index ($P_{lt}$) is assessed under long period of 2 hours of the evaluation period consuming 12 parts of consecutive 10 minutes $P_{st}$ values [25].

$$P_{lt} = \sqrt[3]{\frac{\sum_{i=1}^{12} p_{st}^3}{12}} \tag{6}$$

The standard value is identified as $P_{st}$ = 1. When there is more than one flicker source, the total flicker severity is found by addition of the irritating factors initiated by each source.

$$P_{st} = \sqrt[3]{\sum_i P_{sti}^3} \tag{6}$$

Flicker levels are influenced by two factors: network impedance and load current fluctuation. IEC 61000 3-7 [26] offers voltage fluctuations standard specification to the system operators, owners and engineers who are accountable for supplying electricity to the consumer. The related IEC standard has been adopted by IEEE.

The Oman grid code used for high voltage networks specifies that "the level of voltage oscillations at a point of connection shall follow the limits specified in IEC 61000-3-7 [26], with $P_{st}$ of 0.8 unit and $P_{lt}$ of 0.6 unit".

In [27], the flickers were studied considering PV output variability and high ramp rates. It is vital to consider the impacts of different solar irradiations scenarios on network voltage variation [28].

Table II. Oman Grid and Distribution Codes and IEC 61000 3-7 Flickers planning indicative values

| Indices | MV from 1 kV to 35 kV | HV & EHV more than 35 kV |
|---|---|---|
| $P_{st}$ | 0.9 | 0.8 |
| $P_{lt}$ | 0.7 | 0.6 |

*C. Harmonics Distortion*

Harmonics are caused by nonlinear loads that consumes a non-sinusoidal current. Therefore, the presence of harmonics is an indication of the quality of the sinusoidal current and voltage waveforms. Harmonics are quantified using the Total Harmonic Distortion (THD). The IEEE 519-2014 [29] expresses the THD as "the relation of the root mean square harmonic element, considering up to 50th order of harmonic elements, without inter harmonics, stated as a percent of the fundamental". Inverters are essential devices in grid-connected solar PV systems, and they are accountable for the quality of power supplied into the grid. Additionally, inverters produce harmonics into the system in the presence of nonlinear loads, during DC to AC conversion. On the other hand, current harmonics are also a major cause of voltage harmonics as it causes extra system losses and reduce life cycle of transformers [29-32].

IEEE standard 519 specifies the THD limits for both the current and the voltage signals. The IEEE standard 519-2014 [29] "Recommended Practices and Requirements for Harmonic control in Electrical Power Systems" specifies the limit of harmonic voltage and current at the PCC between the customer and grid. The upper limit recognized by this standard is 5% for the voltage and current harmonic distortion. The limit for the maximum specific harmonic element must be 3% for voltage less than 69kV.

The European standard EN 61727 (IEC 61727) "PV system Characteristics of utility interface" has identified more preventive limits for voltage and current THD. The limits specified for $THD_V$ is 2% and for $THD_I$ is 5%. The maximum for individual voltage harmonic is as well limited to less than 1% as shown Table III.

Based on the European standard EN50160 (IEC 50160) [33], which is implemented by almost European Grid Codes, "Voltage characteristics of electricity supplied by public distribution system", the limit for THD must be less than 8% involving up to 40$^{th}$ harmonic order.

Alike to the IEC standards, the Omani grid [18] and distribution codes [19] don't identify any limit on the current distortion. The Omani codes specify that the THD must be less than 2% and for individual harmonic is less than 1.5% for transmission networks of 132kV and above. Similarly, the distribution code identifies that the maximum THD limit on systems below 66kV must be less than 2% and individual harmonic is less than 1.5%. For 415 V low voltage line, the THD limit is up to 2.5%.

Table III. Harmonic Distortion Limits based on EN 61727

| Individual Harmonic magnitude (%) | $THD_V$ **(%)** | $THD_I$**%** |
|---|---|---|
| < 1 % | 2% | 5% |

Table IV. Voltage THD Limits based on Oman Distribution Code

| Voltage Level | Individual harmonic magnitude (%) | $THD_V$ (%) |
|---|---|---|
| Low voltage (415 V) | — | 2.5 |
| Distribution level (11, 33, 66 kV) | 1.5 | 2 |
| Transmission level (132, 220 kV) | 1.5 | 2 |
| Transmission level (5 kV) | 1 | 1.5 |

Table V: Voltage THD limits according to IEEE 519-2014

| PCC voltage | Individual harmonic magnitude (%) | THD (%) |
|---|---|---|
| $V \leq 1$ kV | 5 | 8 |
| $1 < V \leq 69$ kV | 3 | 5 |
| $69 < V \leq 161$ kV | 1.5 | 2.5 |
| $V > 161$ kV | 1 | 1.5 |

The authors in [34] concluded that the integration of PV systems and the presence of nonlinear loads lead to severe effect on system THD levels. Various installations of solar PV systems in several locations may result in rising the THD levels in the distribution system [35, 36]. This result is due to converters that emits high frequency currents during normal operation. If these currents are not filtered out properly, they can affect the power quality and generate Electromagnetic Interference (EMI) with other electrical and electronic equipment. Accordingly, having properly designed filters is essential for the PV systems [37]. In [38], experimentations were made on a solar PV system to investigate the impacts of solar irradiance variations on the distorted waveform. Utilities manage the THD at the end user connection point to be within the limits specified in IEEE 519-2014 [39]. In [40], the authors highlighted that harmonic distortion in distribution system is caused by nonlinear loads such as Compact Fluorescent Lamps (CFL), televisions, computers, variable speed drives, DC drives and other loads.

## 3. System Data

The Petroleum Development Oman (PDO) commissioned Phase I and Phase II of the Mina Al-Fahal (MAF) Solar Car Park Project in January 2018 and December 2020 respectively. The total project installed capacity is expected 8.852 MWp with a total coverage area of 34,600 m². The PDO-MAF solar PV power is used to supply power to PDO offices and buildings. The plant area of Phase I and II is divided into five blocks: Bait Al-Bushra Area (BAB), Bait Mina Al-Fahal Main Area (BMF Main), Bait Mina Al-Fahal overflow Area (BMF overflow), PDO Training Center (HLD) and Bait Saih Al-Maleh (BSM). The locations of PDO-MAF solar car park projects are shown in Fig. 1.


Fig. 1. Phases I & II PDO-MAF Solar Car Park Project Locations

The PDO-MAF Solar PV car park is located at longitude 58.52º E, latitude 23.63º N and at a height of 10 m above sea level. This location has a high level of solar irradiation throughout the year as presented in Fig. 2.


Fig. 2. PDO MAF PV System Location

The Phase I project includes 81 inverters and 969 strings while Phase II project includes 36 inverters and 414 strings with total installed capacity of 8.8 MWp. Fig. 3 shows the conceptual diagram of the Solar Car Park Project which includes 12 strings connected in parallel to a single inverter via DC combiner box. Each string includes 20 solar panels connected in a series. Each inverter connects the PV array to a Low Voltage (LV) switchgear. The LV switchgear is connected to the Medium Voltage (MV) PDO-MAF distribution system through a 415/11kV step-up transformer.

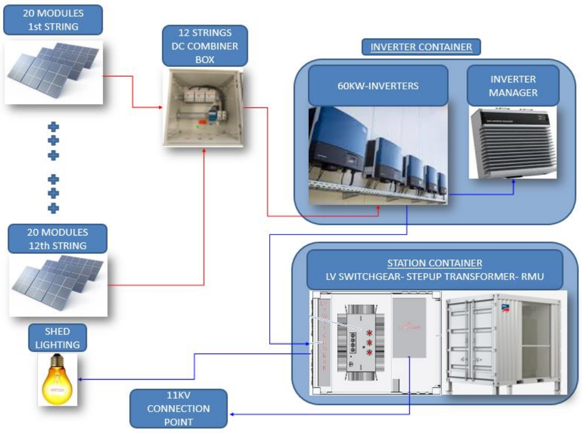


Fig. 3. Conceptual Diagram of Phase 1 of the PDO-MAF Solar Car Park Project

The impact of PV systems on power quality parameters based on real system measurement for PDO solar PV system including flicker, voltage unbalance and harmonics, are considered. A Power Network Analyzer “Unilyzer-900” [41] is installed in existing PV system for power quality measurements. A typical clear sky power output for PDO-MAF Solar PV system at BAB is shown in Fig. 4.

Listed below are some examples of Unilyzer-900 measured parameters:

- Unbalance
- Flicker levels
- Harmonics
- Sags and swells
- Voltage (and current) variations
- Transients

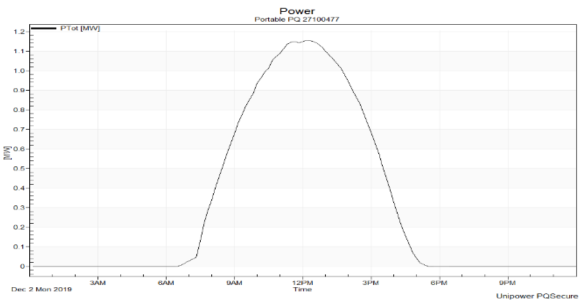


Fig. 4. Unilyzer-900 Typical Clear Sky Power Output for PDO MAF Solar PV system at BAB

## 4. Measurement and Evaluation

The performance evaluation is captured by the real time field measurement collected from power quality analyzers connected at the PDO solar PV system. The study explored the impact of solar PV integration on power quality under varying solar irradiation levels with different scenarios as follows:

- *Case – I: Clear Sky (Day time)*
- *Case – 2: Cloudy Sky (Day time)*
- *Case –3: Partial Cloudy Sky (Day time)*
- *Case –4: No Solar PV (Nighttime)*

*A. Voltage Unbalance*

Fig. 5 displays a comparative graph of voltage unbalance impacts with grid-connected solar PV system under several weather conditions; a sunny day, a cloudy day, a partial cloudy day and no PV case during night-time.

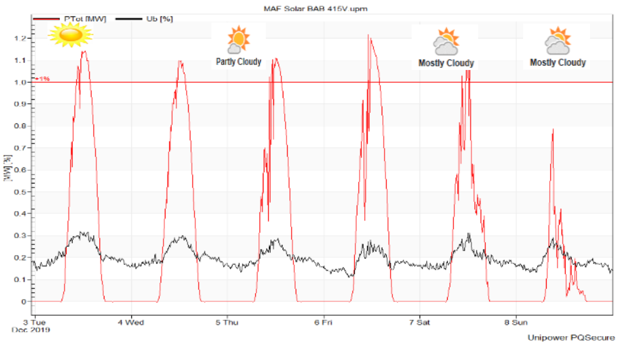


Fig. 5. A Comparative Plot of Voltage Unbalance Impacts with Grid-connected solar PV Integration under several Weather Conditions

In general, the solar PV system had a minor impact on the voltage unbalance. It is also noticed that the voltage unbalance is varying with solar irradiation and demand. Hence, the voltage unbalance remains within the limit specified by the Omani standard.

*B. Voltage Flicker*

Fast fluctuations of solar irradiation due to passing clouds can result in significant variations in solar PV power output that can cause voltage variations at the PV system interconnection point [42]. The quick ramp up/down of solar PV power may raise the number of unwanted operations of transformer tap changers resulting in reducing the lifetime of devices. The comparative plots of flicker levels under several weather conditions are illustrated in Fig. 6 and Fig. 7.

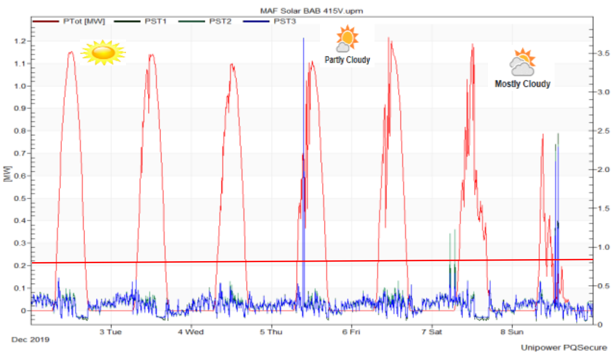


Fig. 6. A Comparative Plot of Short-term Flicker Severity index (**$P_{st}$**) with Solar PV Integration under several Weather Conditions

It is observed that the impacts of PDO solar MAF PV system on flicker is not definite. Infrequent spikes were observed during a daytime for both partially and cloudy days as well as during nighttime. The flicker severity index could be due to different reasons including network operations, load variations and solar PV system output variations. It is worth mentioning that, during the measurement time, $P_{st}$ and $P_{lt}$ indices were within the standard limit, except for a few incidences. It is worth noting that PDO MAF system is stiff and has a high short circuits level. This results in reducing the negative impacts of power output variations on flicker levels.

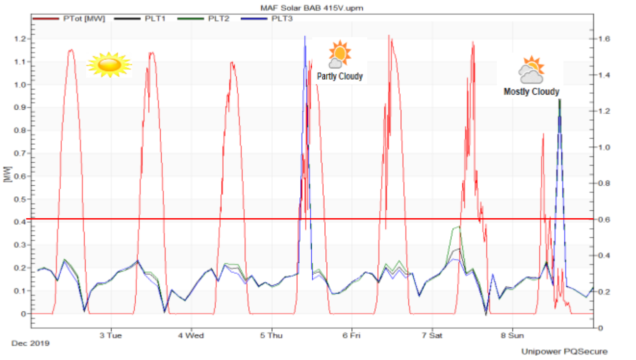


Fig. 7. A Comparative Plot of Long-term Flicker Severity index (**$P_{lt}$**) with Solar PV Integration under several Weather Conditions

*C. Harmonics*

The harmonics analysis is essential with grid-connected solar PV systems for various operating situations as the harmonics distortions from solar PV system are varied by changing solar irradiation conditions. In this study, variations of solar PV system due to a cloud cover were evaluated and the impacts on Total Harmonic Distortion (THD) during different weather conditions were studied.

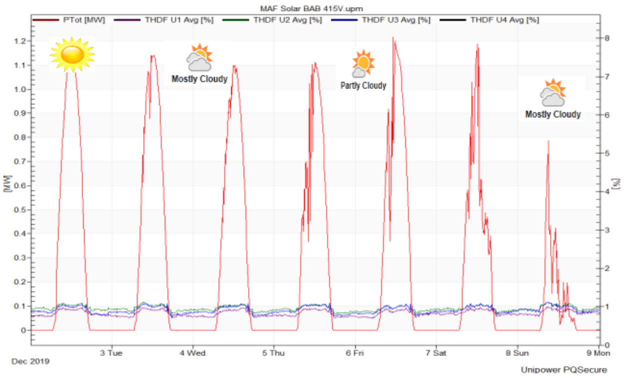


Fig. 8. A Comparative Plot of the Impact of Voltage THD with Solar PV System Integration

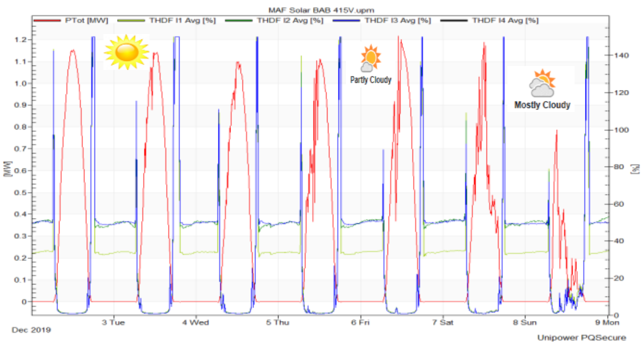


Fig. 9. A Comparative Plot of the Impact of Current THD with Solar PV System Integration

The results showed that the voltage THD evaluated level is independent from the solar PV power generation. Additionally, harmonics measurements revealed that during the early and last hours of inverters operation, high levels of current harmonics were observed due to the fundamental current being small after sunrise and before sunset. A comparative plot shown in Fig. 8 and Fig. 9 demonstrate the impact of THD with integration of solar PV system for various weather conditions such clear day, cloudy day, partial cloudy day and no PV during at nighttime. It is worth noting that there is no THD limit violation was observed due to the use of appropriate filter integrated with the inverters.

## 5. Conclusions

This paper presented a comprehensive discussion into the grid-connected solar PV system measured power quality issues of voltage unbalance, flicker and harmonics distortions under various weather and solar irradiation conditions. Power quality measurements revealed that the voltage unbalance and the THD levels were sustained within the ranges established by the standard with and without the solar PV system. The current THD had an inverse relationship with solar PV output as a result of the fundamental current being small at sunrise and sunset.

On cloudy days, the solar irradiation changes swiftly resulting in significant variations in generated output power of PVs causing the voltage at the PCC to fluctuate. There were few instances in which flicker levels limits were violated. However, these violations might be attributed to different flicker sources such as network configuration and switching operations, load behavior, weather situations.

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