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Testing guidelines for connection of solar photovoltaic farm to distribution grid: The Malaysian experience

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Summary

Solar photovoltaic technology is intermittent in nature and employs power converters for grid-interconnection, which can bring stability and power quality (PQ) issues to the power grid. Therefore, a set of testing guidelines is required to assure that solar plants comply with the grid and inverter requirements. As such, this article presents comprehensive testing guidelines for the interconnection of solar systems into Malaysian power grid, including inverter and PQ tests. The test points, conditions, parameters and acceptable limits for both tests are discussed in detail. This article also presents the results of a case study in which the testing guidelines were applied to examine the PQ of an actual grid-connected solar photovoltaic plant in Malaysia and to assess the performance of the smart inverter used in the tested solar system. The testing outcomes, which were recorded by a PQ analyser, showed that the tested solar system was in compliance with all the requirements stipulated in the testing guidelines. The findings presented in this article will help relevant parties to understand these solar testing guidelines and serve to promote the wide deployment of solar technology towards a clean and sustainable future.

KEYWORDS

inverters, photovoltaic systems, power quality, renewable energy sources, testing guidelines

1 | INTRODUCTION

Renewable energy (RE) refers to energy generated from non-depleting indigenous resources, such as sunlight, wind, tide and geothermal heat.[1,2] In the energy sector, the generation of electricity from renewable resources has received a huge amount of attention worldwide.[3-5] The primary reason for this is because RE is based on clean resources that produce no or insignificant amounts of waste products and pollutants.[6] Hence, RE can reduce carbon footprint and has

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Abbreviations: AC, alternating current; DC, direct current; DL, distribution licensee; ECA, electrical contractors association; FiAH, feed-in approval holder; FiT, feed-in tariff; LSS, large-scale solar; LV, low voltage; MV, medium voltage; NEM, net energy metering; PCC, point of common coupling; PF, power factor; Plt, long-term flicker; PPA, power purchase agreements; PQ, power quality; Pst, short-term flicker; PV, photovoltaic; RE, renewable energy; RMS, root-mean-square; SAPVIA, south african photovoltaic industry association; SEDA, sustainable energy development authority; THDI, total harmonics current distortion; THDV, total harmonics voltage distortion.

minimal impact on the natural environment.[7-9] RE also has the potential to realize energy sustainability since this resource is naturally replenished.[10] Thus, RE serves as an excellent countermeasure to concerns about fossil fuel reserves and their global price fluctuations.[11-14] Furthermore, the overall operational cost of RE is low as the resources are natural in origin and RE facilities generally require less maintenance than conventional generators.[15,16]

1.1 | RE in Malaysia

In Malaysia, various strategic efforts have been made to promote and develop the RE industry. In 2009, the National RE Policy and Action Plan was initiated to enhance the utilisation of RE resources to contribute to the security of the electricity supply and sustainable socioeconomic development.[17] This RE policy considers the aspects of energy, industry and environment in outlining a balanced roadmap for the advancement of the nation's RE sector. The five key objectives of this policy are: (a) to increase the contribution of RE in the national power generation mix, (b) to facilitate the growth of the RE industry, (c) to ensure reasonable RE generation costs, (d) to conserve the environment for future generations and finally, (e) to enhance awareness of the role and importance of RE.[17,18] To achieve these policy objectives, an action plan with strategic thrusts was proposed and implemented.[17] Figure 1 shows a schematic of the action plan adopted to achieve a successful National RE Policy. With proper implementation of the National RE Policy and Action Plan, RE can contribute up to 11.5 GW or 36% of the total peak electricity demand capacity in the national power generation mix by 2050.[17,18]

Various RE resources are found in Malaysia, including but not limited to solar power, mini-hydro power, biomass wastes from agro-based and farming industries, biogas, solid wastes, wind energy, and geothermal energy. Table 1 presents the advantages and disadvantages of different RE resources.[19-22] It is difficult to perform a direct comparison among all of the RE resources because each has its own specific strength and weakness. Furthermore, the selection of RE resource also heavily depends on the geographic locations. Overall, solar photovoltaic (PV) technology seems to be the most promising renewable option among the available resources with the reasons as follows:

- Solar PV is the most abundant RE resources available and the solar irradiance is basically free to harness.
- From the environmental perspective, solar PV is a nonpolluting energy source where some of the RE resources (biomass, biogas, and geothermal) do emit pollution.
- Solar PV technology pays off in long run despite high upfront costs. The solar PV systems generally last very long and this RE resource has relatively low operating and maintenance costs.
- Solar PV can be installed or mounted on existing building and roof, which can save space and land use. On the other hand, wind turbine and hydroelectric dam require large physical installation space.
- Unlike biomass and biogas technologies where the sources must be transported to the plant, solar PV has minimal transportation costs.

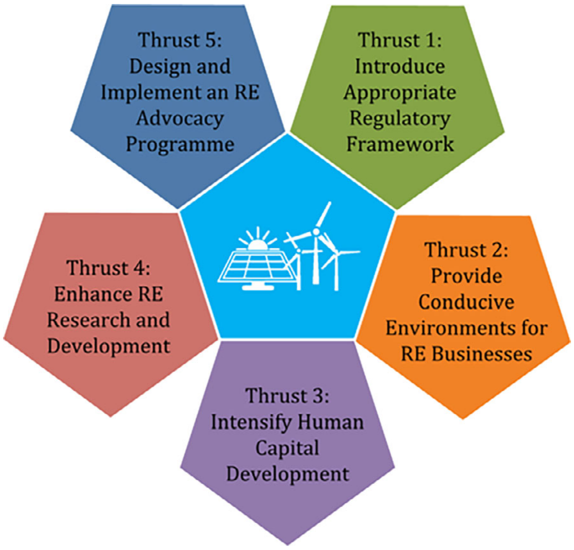


FIGURE 1 Five strategic thrusts for the realisation of National Renewable Energy Policy[17]

TABLE 1 Advantages and disadvantages of main RE technologies[19-22]

RE Types	Advantages	Disadvantages
Solar PV	• Free and non-polluting energy source • Most abundant energy source available • Low usage cost in long-term since systems last very long • Low maintenance cost • Can be installed on existing building and roof	• High initial investment cost • Dependent on weather or intermittent • Supplemental energy may be required during low solar irradiance period
Wind energy	• Free and non-polluting energy source • Little disruption of ecosystems • Relatively high output power	• High initial investment and maintenance cost • Output is dependent on wind speed, which is not feasible for all geographic locations • Require large physical installation space
Biomass/ biogas	• Abundant supply • Engines can be easily converted to run on bio-fuels	• Emits pollution • Uses some fossil fuels in conversion • Source must be near usage to cut transportation costs
Hydroelectric	• No emissions • Output power can be regulated to meet demand	• Hydropower dams are expensive to build • Disruption of ecosystems by changing the environment in the dam area • Not feasible for all geographic locations and dams may be affected by drought
Geothermal	• Efficient energy source • Relatively low emissions • Low usage cost after the initial investment	• High initial investment cost • Not feasible for all geographic locations and source could eventually be depleted

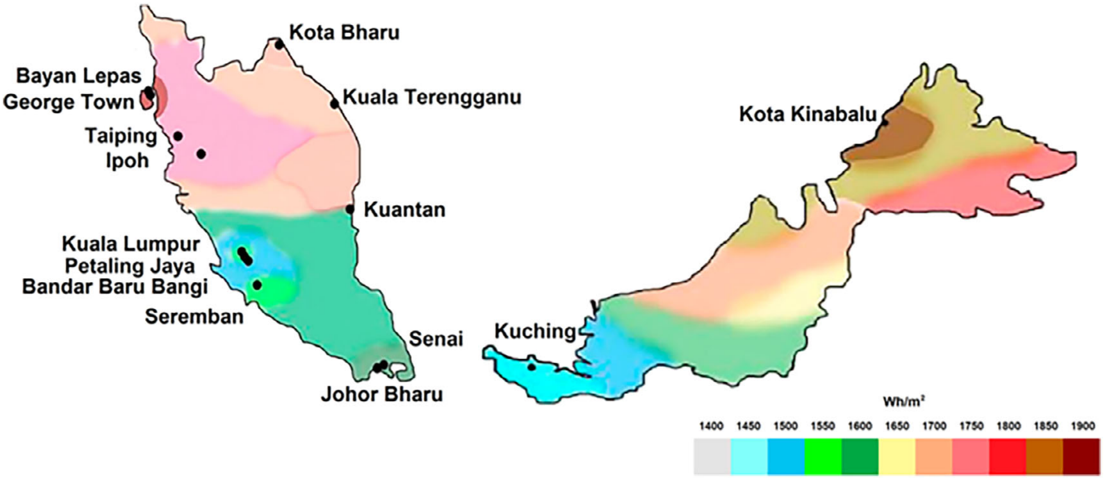


FIGURE 2 Solar irradiance levels in Malaysia with highest recorded at 1900 watt-hours per square metre[18]

In Malaysia, studies in References 19 and 20 have identified that solar PV is the main RE resource with the highest potential to meet the energy demand, despite the intermittency nature of this technology. The main reason is due to the geographical advantage of Malaysia, which receives direct sunlight for the entire year. The solar irradiance levels in Malaysia can reach as high as 1900 watt-hours per square meter, as shown in Figure 2.[18] The intermittency issue of solar PV can also be solved by the implementation of energy storages in the power grid.[23-25] On the other hand, the potential of wind energy in Malaysia was also investigated in References 22, 26, and 27. Similar to solar PV which is an intermittent source, the output of wind energy strongly depends on the wind speed. The studies revealed that the possible wind turbine options are small and medium scale turbines due to low wind speed in Malaysia, which is less than 6 m/s.[22,26] As such, the potential of solar PV technology outweighs wind energy in Malaysia. This claim is also supported by the national RE goal. Figure 3 shows the national RE goals in Malaysia, with targets projected to the year

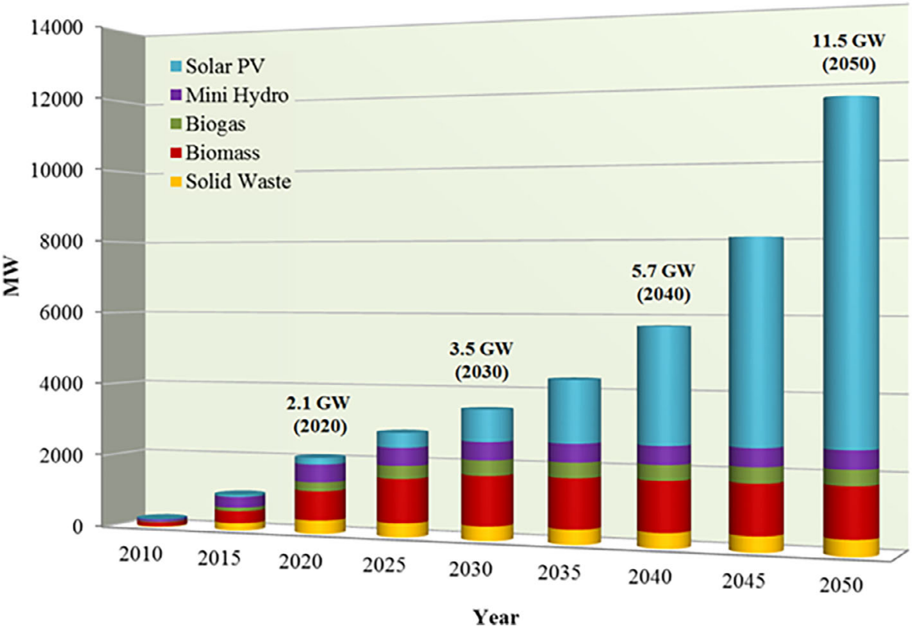


FIGURE 3 National RE goals in Malaysia with solar PV projected as the main RE resource by the year 2050[17,18]

2050.[17,18] It is noticeable that solar PV resource is anticipated to have a higher take-up rate compared to the other RE technologies. Hence, this article will focus on the development of solar PV system in Malaysia.

The parliamentary approval of the Renewable Energy Act in 2011 served as a catalyst for the implementation of a unique tariff system for RE generation, as well as to ensure the entry of privately operated RE generation in the Malaysian electricity grid.[28] This tariff system, known as the Feed-in Tariff (FiT), requires the Distribution Licensee (DL) to purchase electricity produced from renewable resources from a Feed-in Approval Holder (FiAH).[29] A fixed premium rate is payable for each unit of RE sold to a DL for a specific duration. The FiT rate differs for different renewable resources and installed capacities and the duration is based on the characteristics of the renewable resources and technologies. For instance, the duration is 16 years for biomass and biogas resources, whereas it is 21 years for small hydropower and solar PV technologies.[29,30]

In 2016, the Large-Scale Solar (LSS) and Net Energy Metering (NEM) programmes were implemented in Malaysia.[31-33] Both programmes promote the deployment of solar PV technology since the global cost of solar PV systems has continued to fall significantly each year. LSS refers to any solar PV system with a minimum power rating of 1 MW_{AC} up to a maximum of 50 MW_{AC} that is connected to either a transmission or distribution system in Peninsular Malaysia, Sabah or Labuan.[31] Since the scale of an LSS facility is large, the generated electricity is sold to wholesale utility buyers rather than end-use consumers. The target capacity for the LSS programme is 1000 MW_{AC} by 2020, with an annual capacity capped at 200 MW_{AC} for Peninsular Malaysia and at 50 MW_{AC} for Sabah from 2017 until 2020.[31]

The concept of the NEM programme is that the energy produced from solar PV systems will be consumed first and any surplus will be transferred and sold to the DL at the prevailing displaced cost prescribed by the Energy Commission.[32,33] The received credit may be used to offset part of the electricity bill. The NEM programme is applicable to all domestic, commercial and industrial sectors that have solar PV systems installed on available rooftops or car porches within their own premises. The NEM programme is an ideal complement to the FiT and LSS programmes. Malaysia will be executing its 500 MW_{AC} target capacity under the NEM programme from 2016 until 2020 with an annual 100 MW_{AC} capacity limit in Peninsular Malaysia and Sabah.[32,33]

1.2 | Related Literature of Solar PV System

Many researches and developments have been conducted to improve the solar technology. One of the popular solar research areas is the system planning of solar farm. Researchers from the Washington State University proposed a pre-engineered algorithm to help user to properly size the solar system's components to optimize the performance of the overall PV system.[34] Proper sizing and allocation guidelines of the PV system were also presented to achieve better system efficiency and to reduce shading effect. In Reference 35, the authors proposed a Boolean map of locations to determine the suitable installation points for large-scale solar farms to meet the climate change target in the UK. Furthermore, an improved grounding framework for a solar farm was proposed in Reference 36 to enhance the system safety and protection. The grounding framework was designed to interconnect the grounding grids of the substation, PV panels and inverters to achieve a healthier ground potential.

Another important solar research area is the installation of solar PV system. Appropriate installation procedures are important to ensure the system reliability and personnel safety. The Electrical Contractors Association (ECA) in the UK has published an installation guideline for appropriate solar PV installation on building.[37] This guideline provides recommendations, such as installation procedures, safe workplace practices, system standards and regulations. Similarly, South African Photovoltaic Industry Association (SAPVIA) introduced a PV installation guide to educate solar installers with the knowledge to install the PV panels, inverters and storages.[38]

In the literature, studies were also conducted to assess the operation of solar farms. For example in reference,[39] the performance monitoring was conducted on the solar farm installed at Moshoeshoe Airport. Various system parameters were accessed throughout the PV system operation and immediate maintenances were performed if problem was detected. This practice has significantly improved the overall performance of the solar farm. Moreover, the authors in reference[40] investigated the performance comparison between two large-scale solar farms in Western Australia, where one of them employed solar trackers while the other one was without it. The findings showed that significant technical and economical benefits were attained by employing solar tracker in large-scale solar farm. In Reference 41, an operational scheme was designed to manage the solar generation in Lombok Island. This scheme minimised the system's overall operational cost by managing the energy dispatch from the solar farm to reduce the burden of fossil fuel plants.

The implementation of policy to encourage solar PV integration into the power network is also a popular research scope. Recently, the Spanish government has enforced a building code that requires all new buildings to install PV panels.[42] The minimum PV capacity required depends on the climate zone, size and purpose of these buildings. In the UK, the development of solar industry also receives strong supports from the government. A solar-specific Power Purchase Agreements (PPA) has been established to manage the electricity pricing between the power utilities and solar farm developers. Moreover, the UK government also places an obligation to all energy suppliers to source a certain portion of their energy generation using renewable resources.[43]

In Malaysia, the solar PV industry had gained tremendous traction. Bakhtyar et al[44] reviewed the FiT policy for solar generation in Malaysia. The advantages and disadvantages of the policy were presented, and recommendations were also provided to the local power utility and developers. Research in Wong et al[45] investigated the impact of intermittent generation of solar PV on the voltage fluctuation problem in the distribution grid. In this research, appropriate solution was proposed to regulate the quality of the power grid voltage.

1.3 | Research Gap and Paper Contributions

In the literature, researches mainly focused on the planning, installation, operation and policy development of the solar PV system. Nevertheless, the research scope of testing the functionality of a solar farm is very limited. The performance testing of the PV system is crucial as this can help the power utility and developer to understand if the solar farm operates as intended and meet the requirements of the power grid code. Therefore, this has led to the need for the development and validation of a set of unifying testing guidelines to ensure a smooth, reliable and safe transition for the incorporation of solar PV power into the grid.

This article presents inclusive testing guidelines for the integration of solar PV technology in the Malaysian power grid. The testing guidelines comprise inverter and power quality (PQ) tests. The inverter test provides a crucial measure of the performance and practicality of the tested solar inverter in meeting stringent requirements for the implementation of a grid-connected PV system. The objective of the PQ test is to ensure that the grid-connected PV system has minimal negative impact on power grid reliability. Moreover, these testing guidelines were employed to examine the PQ and inverter performances of an actual solar farm in Malaysia. The main contributions of this article are summarised as follows:

- Comprehensive Inverter Test was performed to investigate the power factor, harmonics, voltage fluctuation, flicker, DC current injection, anti-islanding, and steady-state voltage at medium voltage (MV) of solar inverters.
- Inclusive PQ Test was conducted to assess the voltage profile, current profile, harmonics, voltage flicker, and voltage unbalance at the point of common coupling (PCC) of the actual PV system.

- The PV system with the tested inverters was proven to be able to provide reliable solar power generation into the Malaysian power grid by complying with all the stipulated requirements and conditions of the testing guidelines.

2 | TESTING GUIDELINES FOR SOLAR PV INTERCONNECTION INTO MALAYSIAN POWER GRID

Solar panels are available in various types, such as mono-crystalline, poly-crystalline, and thin-film types.[46-48] A solar PV system is generally constructed with multiple modules connected in series and parallel to acquire the required output voltage and capacity. Since solar PV technology uses sunlight to generate output power in DC form, the PV system is connected to inverters to convert DC power into AC power before connecting to the power grid.[49,50] Dedicated transformers are usually employed to step up the output voltage of the PV system to an appropriate level and power cables may be installed prior to the interconnection point.

Generally, a PV generation plant can be connected to the power grid using central inverter or string inverter.[51,52] Both inverters have different connection framework, which can affect the costing, installation, operation and maintenance procedure of the system. For PV plant using central inverter, many groups of PV panels will be connected in parallel and tied to the central inverter before integrating into the power grid.[53] The rated capacity of central inverter is usually large, which results in higher cost. However, the benefit of PV system using central inverter is less complicated to build and operate. On the other hand, PV system using string inverters requires multiple inverters to convert DC power generated by small group of PV panels into AC power.[54] These AC power can be tapped together and fed into the power grid. This system requires more distributed space for string inverters mounting. Nevertheless, plant operational issues, such as cloud shading or panel failure, has lesser impact to the overall system.

When connected to the power grid, a PV system can function as a distributed generator that supports the main generation systems by supplying power into the grid. Nevertheless, caution must be taken with respect to the possible effects of the PV system on the power grid. With a higher penetration of PV in the generation mix, significant grid stability issue may arise. For instance, as an intermittent energy source, the inconsistent power generated by solar PV technology can cause significant voltage fluctuation.[55-60] The use of inverters in PV systems also introduces harmonics to the connected power grid, which can damage nearby sensitive equipment.[61-65] In comparison to conventional networks, in which power is transmitted from generation plants at a higher voltage level to the point of consumption at lower voltage levels, PV sources connected near the distribution loads may cause reverse power flow and voltage rise issues.[66-69]

Due to the potential implications associated with PV systems, it is crucial that compliance tests be conducted to assess the suitability of PV systems before their integration into the power grid. These commonly executed compliance tests are the inverter and PQ tests. Figure 4 shows the single-line diagram of a typical solar PV interconnection to the Malaysian power grid with appropriate location points for performing these two tests focus on the development of solar PV system in Malaysia.

2.1 | Inverter test

The objective of the inverter test is to assess the impact of the inverter output on the power grid and thus ascertain its suitability for use in Malaysia, as well as to determine whether the inverters meet the output parameters listed by the manufacturers. The inverter test includes testing of the power factor, harmonics, voltage fluctuation, flicker, DC current injection, anti-islanding and steady-state voltage at medium voltage. These tests must be conducted during the period prescribed for each test, during which the inverter output must vary between 10% and 50% of the rated output. The inverter test must be conducted by a competent party designated by the Sustainable Energy Development Authority (SEDA) Malaysia whilst adhering to the provisions of all relevant laws and regulations. A full report of the inverter test results must be submitted directly to SEDA Malaysia by the competent party.

2.2 | PQ test

The PQ test is conducted to ensure that the interconnection of the PV system has no detrimental impact on the operation of the power grid. The PQ test is conducted by a competent party appointed by the power utility. Initially, background measurements are obtained at the PCC to ascertain the existing PQ prior to commissioning. These same

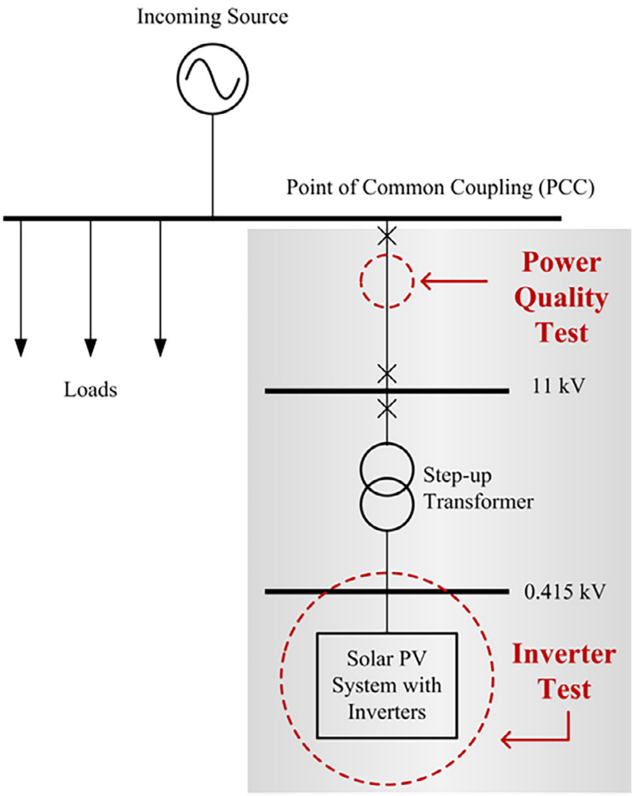


FIGURE 4 Single-line diagram of a typical solar PV interconnection to the Malaysian power grid with location points for conducting inverter and PQ tests

measurements are repeated after commissioning to identify any PQ issues arising from the connection of the PV system. Specifically, PQ monitoring is performed for 7 days prior to plant energising and for another 7 days after plant energising. The measurements considered in the PQ test include the voltage profile, current profile, harmonics, voltage flicker and voltage unbalance.

3 | SPECIFIC CRITERIA OF THE INVERTER TEST

In this section, the details of each test included in the inverter test for a grid-connected solar PV system are discussed. The test points, test conditions and permissible limit of each test are also presented.

3.1 | Power factor test

Power factor is defined as the ratio between the applied active (real) power and the apparent power.[70] A solar inverter operates within a certain power factor range to meet the power grid requirements, for which two conditions must hold. First, the power factor of the inverter should have greater than 0.85 lagging when the inverter output is approximately 10% of the rated power. Second, the power factor of the PV inverter should exceed 0.9 lagging when the inverter output is approximately half of the rated power. In the power factor test, the test points vary based on the inverter configuration. For central inverters, the test points are at output terminal of each inverter, whereas for string-configured inverters, the test point is at the common output point of a group of inverters. When an inverter is being tested, all other inverters on both the input and output sides must be switched off to ensure that accurate results are attained. The test data are recorded for a period of at least six daylight hours using appropriate recording tools.

3.2 | Harmonics test

Harmonics occur when a sinusoidal component of a periodic wave has a frequency that is an integral multiple of the fundamental frequency at which the supply system is designed to operate, which is 50 Hz for the Malaysian power grid.[71-73] The test points and test conditions for the harmonics test are similar to those of the power factor test presented in Section 3.1. For central inverters, a test point is located at each of the PV inverter output terminals. For string inverters, the test point is located at the common output point of a group of PV inverters. The test condition for the harmonics test is that all other inverters are switched off, except the one that is being tested. These test data are also recorded for at least six daylight hours using appropriate recording tools. The PV inverter must comply with the acceptable limits of the maximum Total Harmonics Current Distortion (THDI) and the individual current harmonics defined in IEC 61727-2003.[74] The maximum THDI must be less than or equal to 5% of no more than 50% of the rated inverter output. The permissible limit for the individual current harmonics of no more than 50% of the rated inverter output, is presented in Table 2.[74]

3.3 | Voltage fluctuation test

Voltage fluctuation occurs regularly due to the intermittent nature of solar PV and is detrimental to the operation of the power grid.[75] Therefore, a voltage fluctuation test of the PV inverter is conducted prior to the grid connection.[76] A practical allowable limit for voltage fluctuation is 6% from the maximum to minimum of the biggest fluctuation during the test period. Again, the test point depends on the inverter type. For the string inverter, the suggested test point is at the common output point of a group of inverters. For central inverters, test points are located at each inverter output terminal. The test condition is also based on the inverter configuration. For central inverters, all other inverters on both the input and output sides are switched off during the test, except for the one being tested. For the string inverter, all main switch boards are switched off, except for the one being tested. The voltage fluctuation test is conducted for at least 2 hours during the mid-day (from 12 noon to 2 PM) at one-second intervals. A plot of the root-mean-square (RMS) line voltages against time is produced for each central inverter or group of string inverters.

3.4 | Flicker test

Flicker is a PQ issue that can be explained as being like the visual unsteadiness induced by a light stimulus in which the luminance distribution fluctuates with time.[77] Flicker is usually caused by rapidly changing loads. For the flicker test, the test point is located at the LV PCC or the LV side of the PV step-up transformer. During the test, both the short-term flicker (Pst) and long-term flicker (Plt) are monitored, with the Pst and Plt recorded for 10 minutes and 2 hours, respectively. The PQ analyser can be utilised to record flicker data by setting it to the flicker mode. The acceptable limit for the flicker test is that it should not exceed the boundary defined by the maximum borderline irritation limits, which are less than 1 for Pst and less than 0.8 for Plt.[78]

3.5 | DC current injection test

The DC current injection should be less than 1% of the rated output current from the inverter for each phase.[79] The test points for this test are located at the output terminals of each inverter for central inverters and at the common output point of a group of inverters for string inverters. During the DC current injection test on a particular PV inverter, all

TABLE 2 Current distortion limits set in IEC 61727-2003[74]

	Distortion limit (%)
Odd harmonics	
3-9	<4.0
11-15	<2.0
17-21	<1.5
23-33	<0.6
Even harmonics	
2-8	<1.0
10-32	<0.5

other PV inverters must be switched off. The maximum output of the inverter being tested must be 50% of the rated inverter output and the current clamps used for measurement should be set to DC mode.

3.6 | Anti-islanding test

The anti-islanding test is conducted on the PV inverter for the purposes of both system and personnel safety.[80] This test is conducted at each inverter output terminal for central inverters and at the common output point of a group of inverters for string inverters. All other inverters must be switched off during testing of each individual inverter. Additionally, the inverter being tested is first switched off to record the disconnection time and switched on to record the reconnection time. In Malaysia, the anti-islanding test must comply with several power grid requirements. In the event of loss of grid supply, the maximum disconnection time is set to 0.6 seconds. When the grid supply is restored, the minimum reconnection time for PV inverters is 5 minutes for medium voltage and 2 minutes for low voltage (LV) networks. If the PV inverter cannot meet the reconnection time requirement, a timer relay must be installed.

3.7 | Steady-state voltage measurement of medium voltage

This test is performed at the developer's MV side and is conducted for a minimum of 6 daylight hours at 1-minute intervals. The acceptable limit for this test is one that ensures that the maximum voltage fluctuation is within ±5% of the nominal voltage.

4 | SPECIFIC CRITERIA OF THE PQ TEST

This section presents the aspects of each test performed in the PQ test prior to the interconnection of the solar PV system into the power grid. The acceptable limits for each test in the PQ test are provided. The PQ test ensures that the grid-connected PV system does no harm to the power grid. All the tests must be performed immediately before and after the commissioning of the PV system to identify any PQ issues that might be introduced by the solar plant.

4.1 | RMS voltage

After energising the solar PV system, the RMS voltage must be within ±5% of the nominal voltage stipulated in The Malaysian Distribution Code for Peninsular Malaysia, Sabah & F.T. Labuan[81] and in the TNB Technical Guidebook on Grid-Interconnection of Photovoltaic Power Generation System for LV and MV Networks.[78]

4.2 | Total harmonics voltage distortion

Total harmonics voltage distortion (THDV) is defined as a departure from the sinusoidal shape of the AC-voltage waveform caused by the addition of one or more harmonics to the fundamental frequency and is the square root of the sum of the squares of all the harmonics expressed as a percentage of the magnitude of the fundamental frequency. The THDV levels before and after energising the solar PV system must be within 6.5%, as stipulated in The Malaysian Distribution Code for Peninsular Malaysia, Sabah & F.T. Labuan.[81]

4.3 | Voltage flicker

Voltage flicker can be categorized to short term and long term, denoted as Pst and Plt, correspondingly. The Pst and Plt readings of voltage flicker in a PV system should be below 0.9 and 0.7, respectively, as stipulated in the TNB Technical Guidebook on Grid-Interconnection of Photovoltaic Power Generation System to LV and MV Networks[78] and The Malaysian Distribution Code for Peninsular Malaysia, Sabah & F.T. Labuan.[81]

4.4 | Voltage unbalance

Voltage unbalance can be expressed as the ratio of the negative-sequence voltage component to the positive-sequence voltage component. The recorded measurements of the voltage unbalance must be within 1%, as per The Malaysian Distribution Code for Peninsular Malaysia, Sabah & F.T. Labuan[81] and within 2%, as per the TNB Technical Guidebook on Grid-Interconnection of Photovoltaic Power Generation System to LV and MV Networks.[78]

4.5 | Total harmonics current distortion

Total harmonics current distortion (THDI) is described as a departure from the sinusoidal shape of the AC-current waveform, which arises from the addition of one or more harmonics to the fundamental frequency and is the square root of the sum of the squares of all the harmonics expressed as a percentage of the magnitude of the fundamental frequency. The THDI levels introduced by the PV system must be within 5%, as stipulated in the TNB Technical Guidebook on Grid-Interconnection of Photovoltaic Power Generation System to LV and MV Networks[78] and The Malaysian Distribution Code for Peninsular Malaysia, Sabah & F.T. Labuan.[81]

5 | PRACTICAL CASE STUDY

This section presents the technical analysis of the testing guideline outcomes of an actual solar PV system implemented in the Malaysian power grid. The solar PV system has a peak capacity of 2 MW_p and uses the smart string inverters (Huawei SUN2000-33KTL).[82] A Fluke 435 Power Quality Analyzer was utilized to obtain the power grid measurements and PQ parameters. The test results for both the inverter and PQ tests are presented and discussed. To guarantee that the solar PV system operates reliably in the Malaysian power distribution grid, the test outcomes must comply with all the stipulated conditions and requirements presented in Sections 3 and 4, which are summarised in Figure 5.

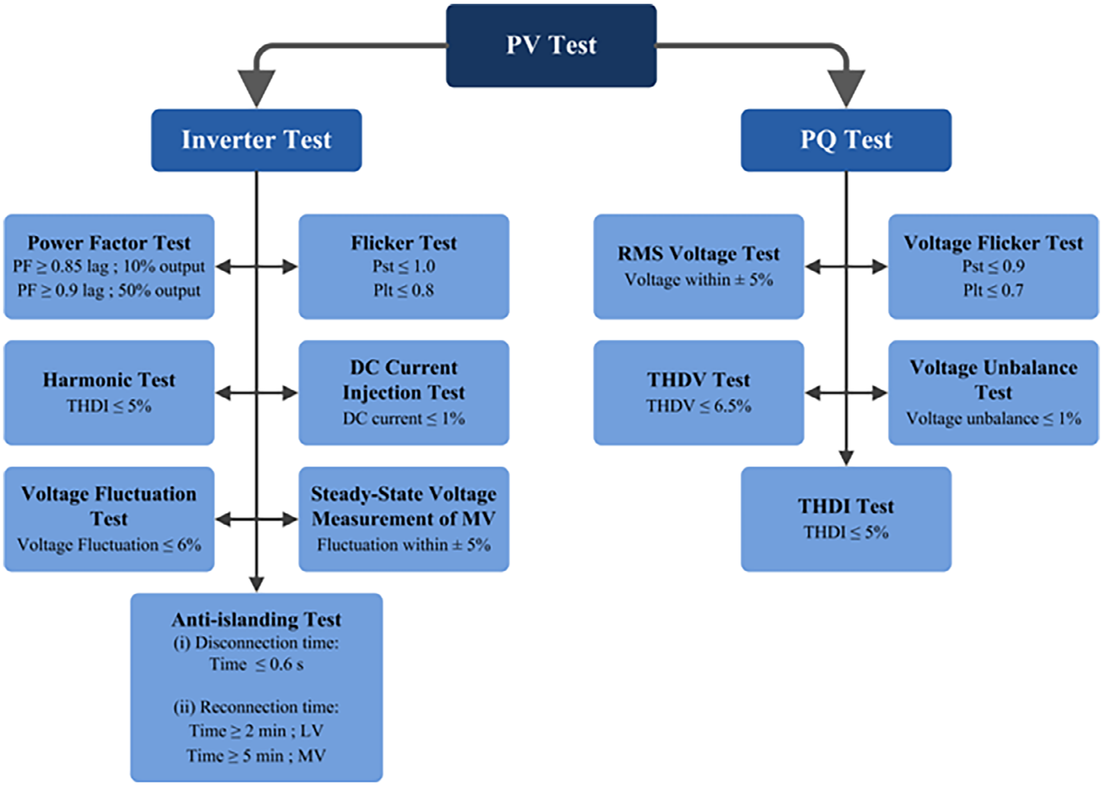


FIGURE 5 Summary of inverter and PQ tests with stipulated conditions and requirements

5.1 | Results and discussion of inverter test

Figure 6 shows a plotted graph of the results of the power factor test performed on a string inverter. The test condition did display compliancy as the monitoring was conducted for more than 6 daylight hours. The power factor of the tested inverter was required to exceed 0.85 and 0.9 lagging when the inverter output was approximately 10% and 50% of the rated power, respectively. Figure 6 shows that the measured power factor of the inverter was close to unity in both situations and met the stipulated limits.

Current harmonics test was also performed on the string inverter and the results are presented in Figure 7. During the inverter operation, the measured maximum THDI for each phase was not more than 5% at less than 50% of the rated inverter output. As shown in Figure 7, the solar PV inverter was also compliant with respect to the limits of individual current harmonics, as stipulated in IEC 61727-2003.[74] All the harmonics requirements were met.

Voltage fluctuation test was performed on the same string inverter, for which the test point was at the common output point of the group of inverters being tested. This test was conducted for 2 hours during mid-day at 1-second

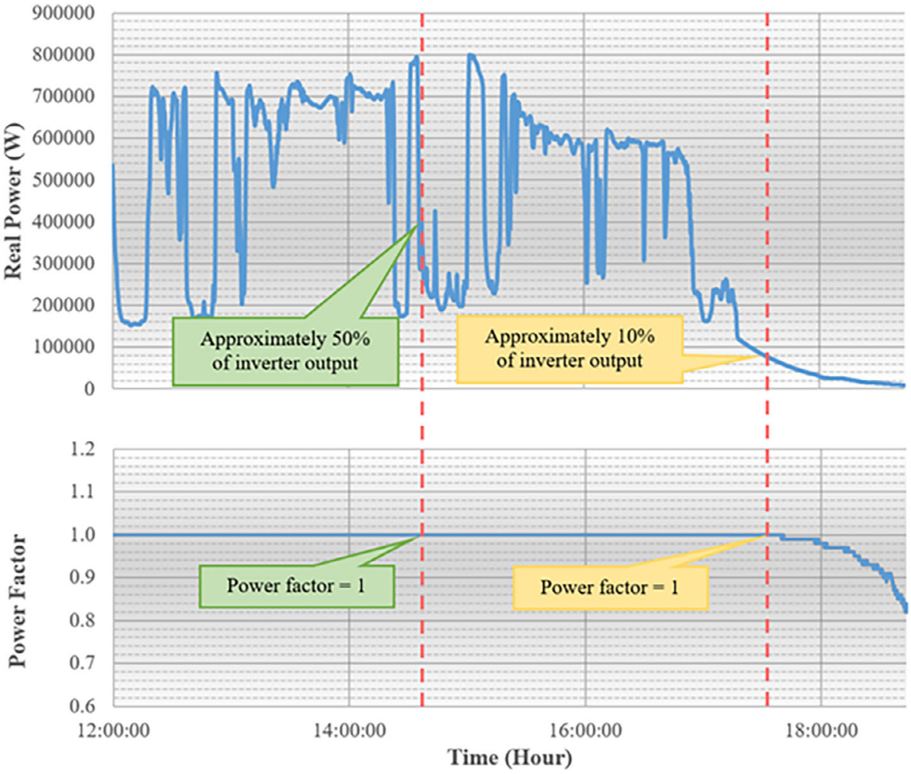


FIGURE 6 Monitored waveforms of power factor test with recorded results close to unity power factor

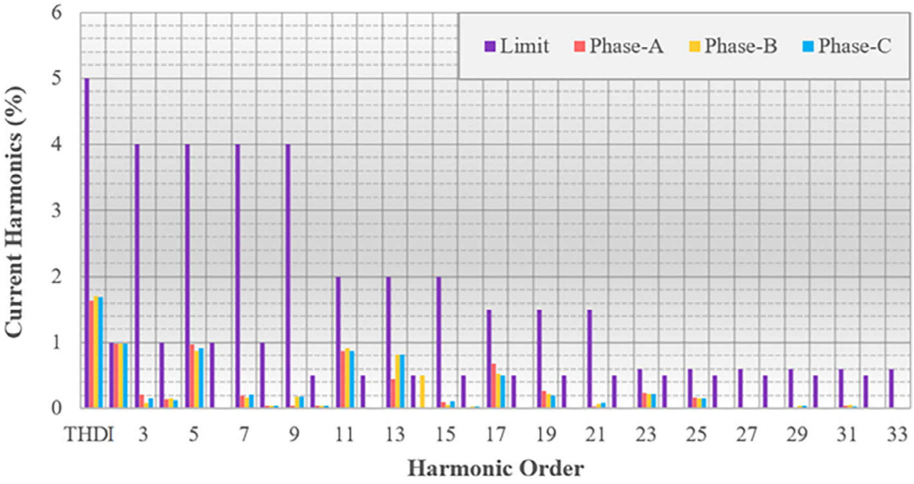


FIGURE 7 Current harmonics test results of PV inverter in compliance to IEC 61727-2003[74]

intervals, which complied with the test requirement. Figure 8 shows a plot of the RMS line voltages against time of the tested inverter. The maximum voltage fluctuation measured during the test period was 2.5%, which was well within the allowable 6% limit.

Figures 9 and 10 show the respective Pst and Plt waveforms of the inverter flicker test. The measurements were taken at the LV side of the step-up transformer of the PV plant. The Pst was monitored every 10 minutes, whereas the Plt was recorded every 2 hours. The overall test period lasted longer than six daylight hours. The acceptable limits for

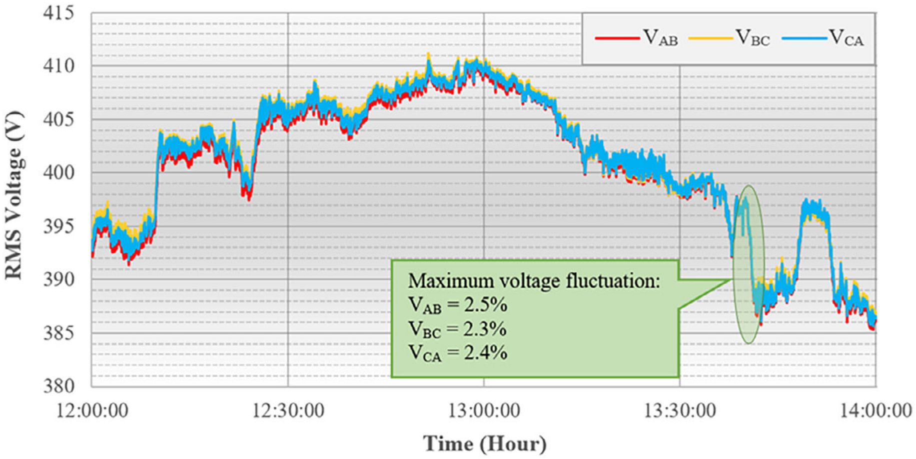


FIGURE 8 Voltage fluctuation test waveforms of PV inverter with maximum fluctuation recorded at 2.5%

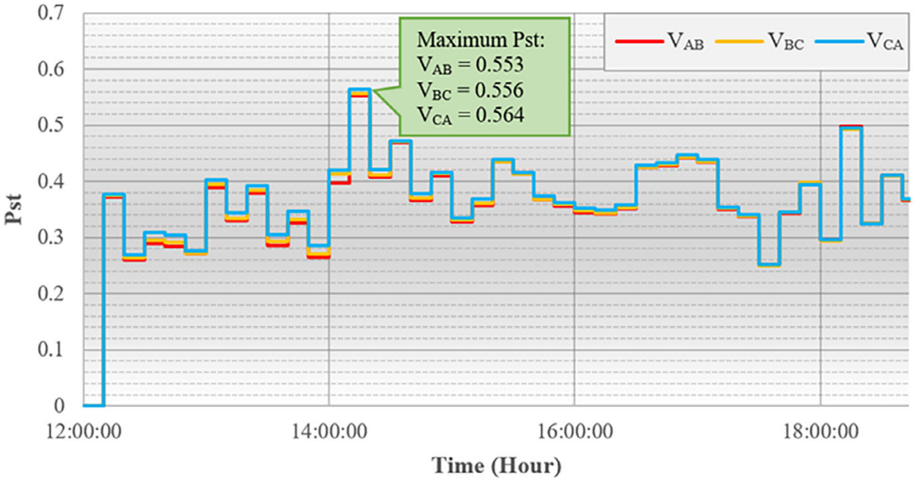


FIGURE 9 Pst results of inverter flicker test with recorded indices were within the allowable limits

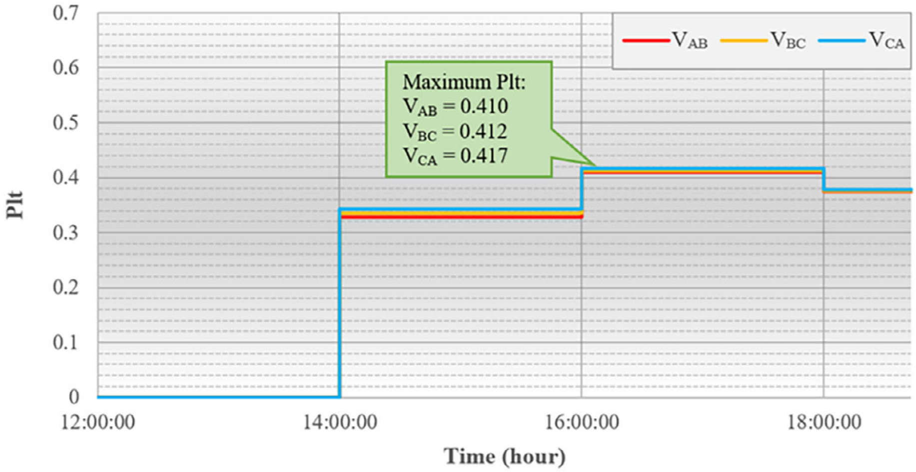


FIGURE 10 Plt results of inverter flicker test with recorded indices were within the permissible limits

the flicker test, as presented in Section 3.4, are that the Pst should be less than 1 and the Plt less than 0.8, based on the maximum borderline irritation limits. The results in Figure 9 show that the maximum Pst values recorded for each line voltage were 0.553, 0.556 and 0.564. On the other hand, Figure 10 shows that the maximum Plt values measured at each line voltage were 0.410, 0.412 and 0.417. As such, all the monitored flicker indices were well within the limits.

Next, a DC current injection test was performed on the PV inverter and the test data was recorded by setting the current clamp of the PQ analyser to DC mode. The maximum DC current injection at each phase was obtained by observation and the results were 0.15%, 0.09% and 0.21%. Hence, the DC current injection was within the 1% limit.

An anti-islanding test was also conducted on the inverter. To do so, the inverter to be tested was first switched off to record the disconnection time and then switched on to monitor the reconnection time. The allowable disconnection time should be within 0.6 seconds, whereas the minimum reconnection time is 5 minutes for MV networks and 2 minutes for LV networks. Figure 11 depicts the anti-islanding test results for the PV inverter. When the grid supply was interrupted, the inverter was successfully disconnected after 0.5 seconds and no current was supplied by the PV inverter during this period. Then, the power grid supply was restored. The inverter was reconnected to the system after 5 minutes and 7 seconds. Both the disconnection and the reconnection time of PV inverter during grid supply interruption and restoration complied with the stipulated limits.

Steady-state voltage measurements were obtained at the MV side of the PV plant, as presented in Figure 12. This test was performed for more than six daylight hours at one-minute intervals. The results showed that the recorded maximum voltage fluctuation was approximately 2%, which occurred at around 14:30 in the afternoon. Since the allowable maximum voltage fluctuation is ±5% of the nominal voltage, the measured results were well within the permissible limits.

In a nutshell, all the sub-tests components of the inverter test were successfully conducted and the recorded results complied with the respective stipulated limits. Therefore, the tested inverter was deemed to be suitable for use in the grid-connected PV system in Malaysia.

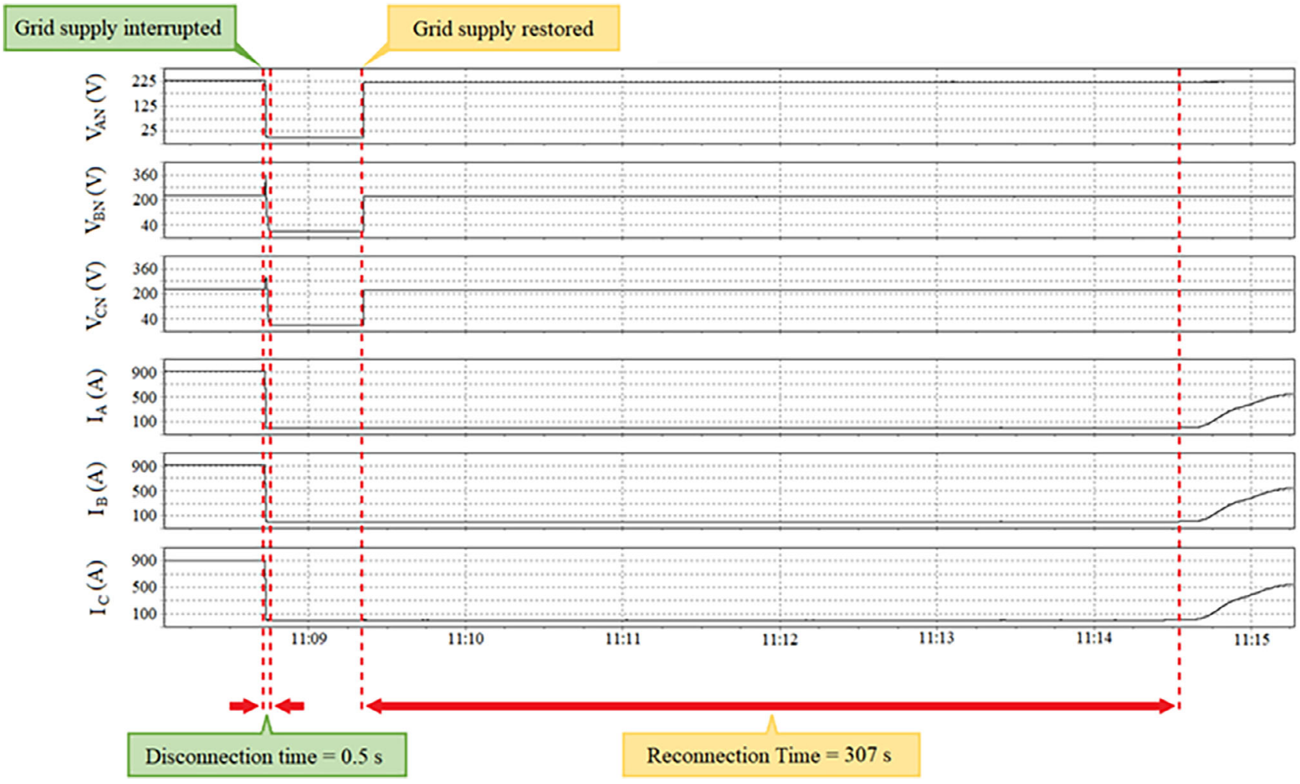


FIGURE 11 Anti-islanding test waveforms of PV inverter with the disconnection and reconnection times were complied with the allowable limits

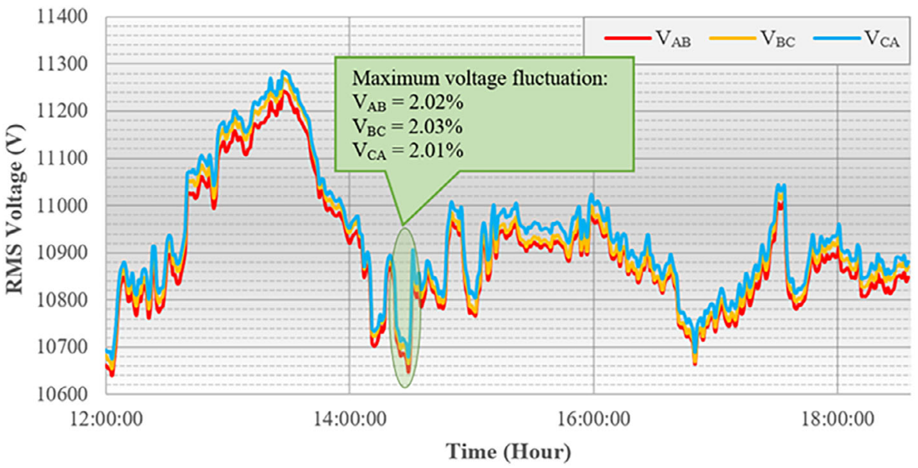


FIGURE 12 Steady-state voltage measurements of MV for PV inverter

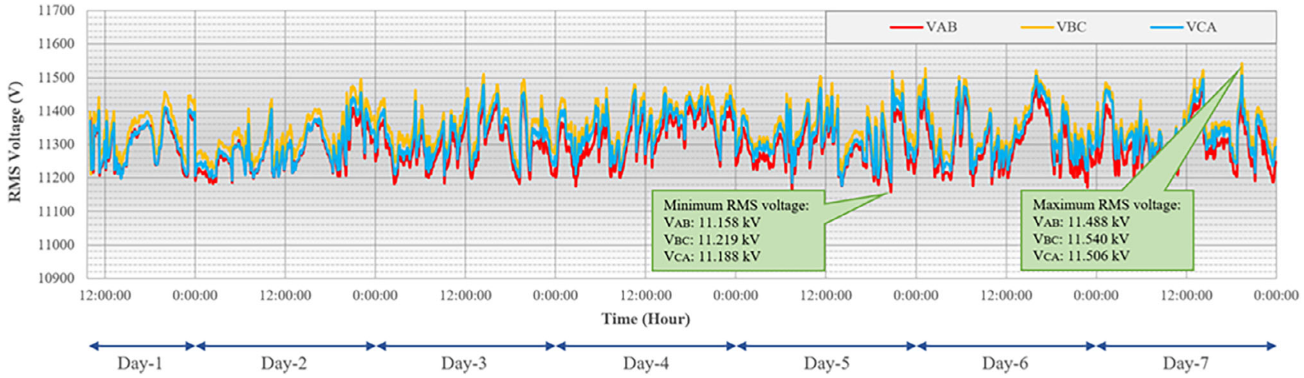


FIGURE 13 RMS voltage profiles before PV plant commissioning with minimum voltage measured at 11.159 kV and maximum voltage recorded at 11.540 kV

5.2 | Results and discussion of PQ test

The PQ test was performed on a 2 MW_p solar PV system to ensure that the PV system was compliant with all the stipulated requirements and conditions in the testing guidelines. This test was conducted for 7 days prior to plant commissioning as well as 7 days after plant energising. The first test is essentially a background study of the power grid, whereas the latter determines the power grid conditions after interconnection with the PV system. In addition, a comparative analysis was performed using the on-site PQ data obtained throughout the monitoring period to highlight any PQ problems introduced by the integration of the PV system.

The RMS voltage was initially analysed at the PCC of the grid-connected PV system. Figure 13 shows the RMS voltage waveforms at the PCC before plant commissioning and Figure 14 shows those after plant energising. Voltage measurements were taken for approximately 7 days at 5-minute intervals. The allowable RMS voltage was within ±5% of the nominal voltage of 11 kV, which are 10.45 and 11.55 kV. As shown in Figure 13, the minimum and maximum RMS voltage values obtained prior to plant energising were 11.158 and 11.540 kV, respectively. On the other hand, Figure 14 shows that the minimum and the maximum RMS voltage values recorded after plant commissioning were 10.905 and 11.413 kV, respectively. Therefore, the RMS voltages before and after energising the solar PV plant were within the limits of ±5% of nominal voltage of 11 kV, as stipulated in the TNB Technical Guidebook on Grid-Interconnection of Photovoltaic Power Generation System to LV and MV Networks[78] and The Malaysian Distribution Code for Peninsular Malaysia, Sabah & F.T. Labuan.[81]

In addition to the RMS voltage, investigation was also conducted on the THDV levels before and after energising the PV system. The acceptable THDV limit is 6.5%, as stipulated in the Malaysian Distribution Code.[81] Figures 15 and 16 illustrate the THDV levels before and after plant commissioning. The THDV levels at 11 kV before and after energising the solar PV plant were less than 2%, well within the 6.5% limit. Hence, the THDV requirements were met.

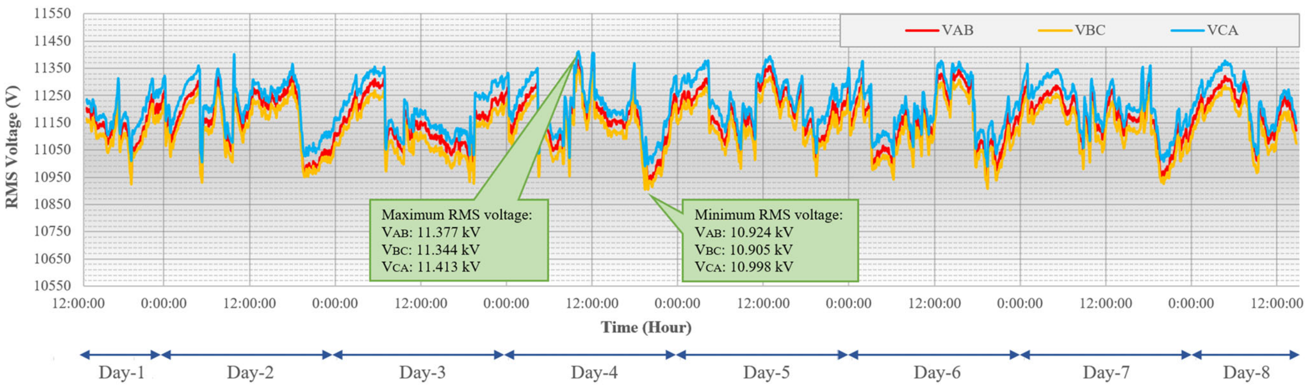


FIGURE 14 RMS voltage profiles after PV plant commissioning with minimum voltage measured at 10.905 kV and maximum voltage recorded at 11.413 kV

FIGURE 15 THDV profiles before PV plant commissioning with results recorded were less than 2%

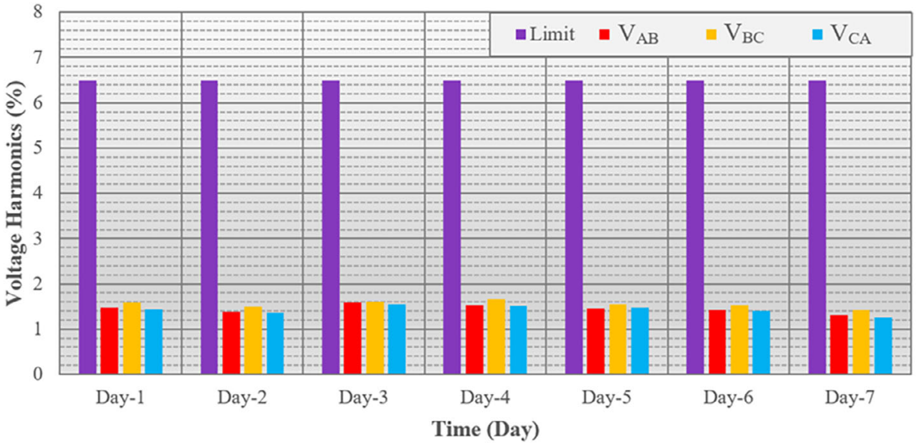
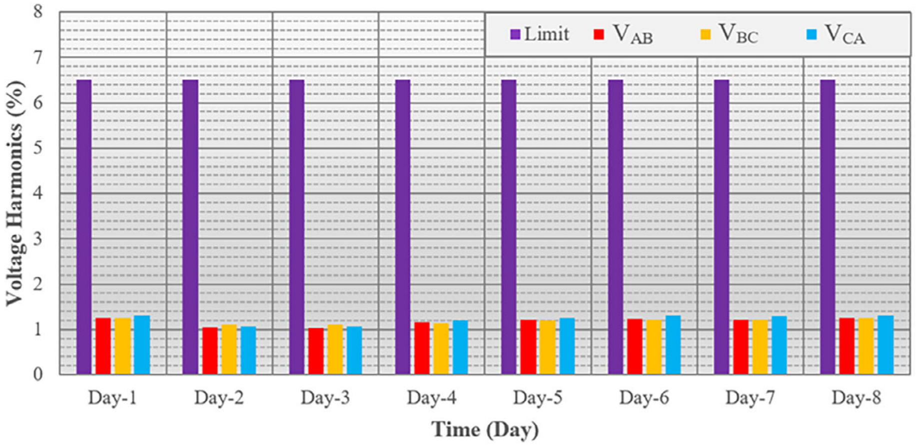
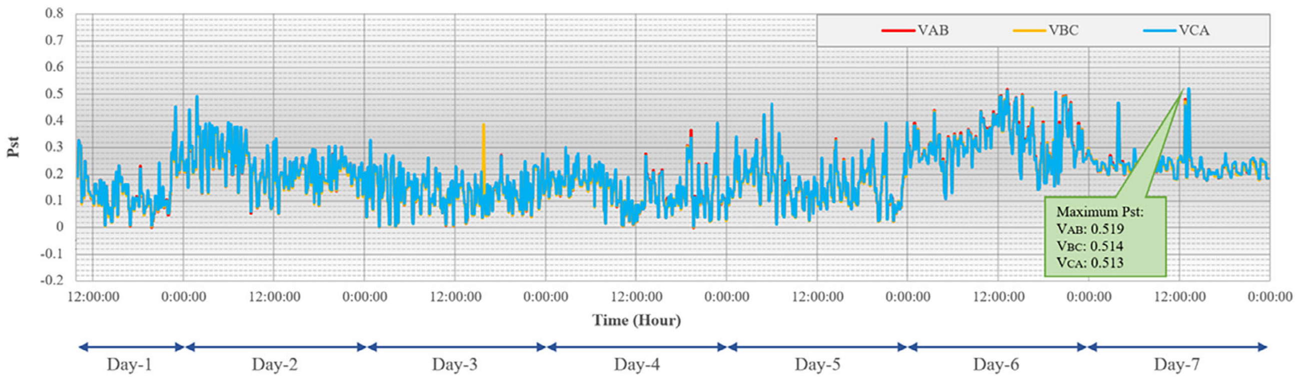


FIGURE 16 THDV profiles after PV plant commissioning with results recorded were within 2%

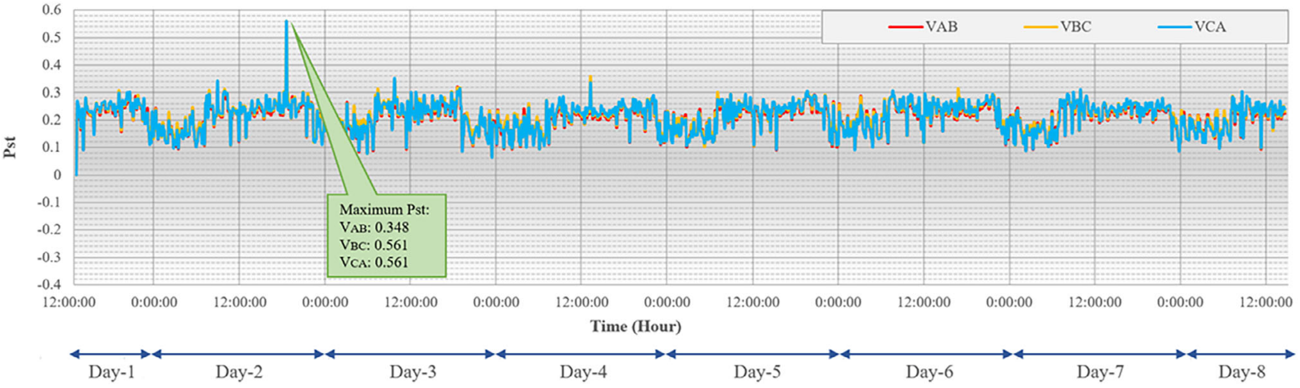


Voltage flicker, as explained above, is generally classified either Pst or Plt. With reference to reference 78 and reference 81, the Pst and Plt readings of a PV system must be below 0.9 and 0.7, respectively. Figures 17 and 18 show the Pst values before and after plant commissioning and Figures 19 and 20 shows the Plt values before and after plant energising, respectively. For the Pst results, the maximum recorded values before energising the PV plant were 0.519, 0.514 and 0.513 for each line, whereas the values obtained after plant energising were 0.348, 0.561 and 0.561 for each line. These short-term voltage flicker indices were below the limit of 0.9. The recorded maximum Plt values for each line before and after plant commissioning were 0.627, 0.640 and 0.577 (before) and 0.331, 0.335 and 0.332 (after). Hence, the long-term voltage flicker indices were well within the permissible limit of 0.7.



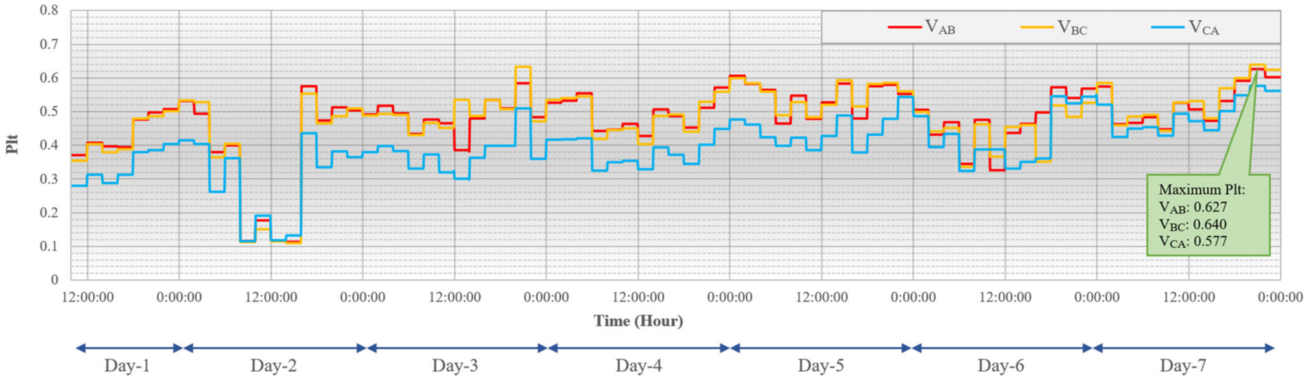
Maximum Pst:
VAB: 0.519
VBC: 0.514
VCA: 0.513

FIGURE 17 Pst profiles before PV plant commissioning with maximum Pst recorded at 0.519, 0.514 and 0.513 for each line



Maximum Pst:
VAB: 0.348
VBC: 0.561
VCA: 0.561

FIGURE 18 Pst profiles after PV plant commissioning with maximum Pst recorded at 0.348, 0.561 and 0.561 for each line



Maximum Plt:
V_{AB}: 0.627
V_{BC}: 0.640
V_{CA}: 0.577

FIGURE 19 Plt profiles before PV plant commissioning with maximum Plt recorded at 0.627, 0.640 and 0.577 for each line

Figure 21 shows the voltage unbalance profile for the 7 days before energising the solar plant, for which the maximum voltage unbalance recorded was 0.366%. The voltage unbalance profile after energising the PV plant is shown in Figure 22, in which the maximum voltage unbalance measured during this period increased slightly to 0.6%. Nevertheless, all the recorded voltage unbalance measurements were within the 1% limit, as stipulated by The Malaysian Distribution Code.[81] These results also complied with the 2% limit stipulated in the TNB Technical Guidebook on Grid-Interconnection of Photovoltaic Power Generation System to LV and MV Networks.[78] As stated above, the THDI introduced by the PV system must be within a 5% limit.[78,81] Figures 23 and 24 illustrate the THDI profiles before and after PV plant commissioning. Throughout the recording period, the measured THDI levels did not violate the permissible limit of 5%.

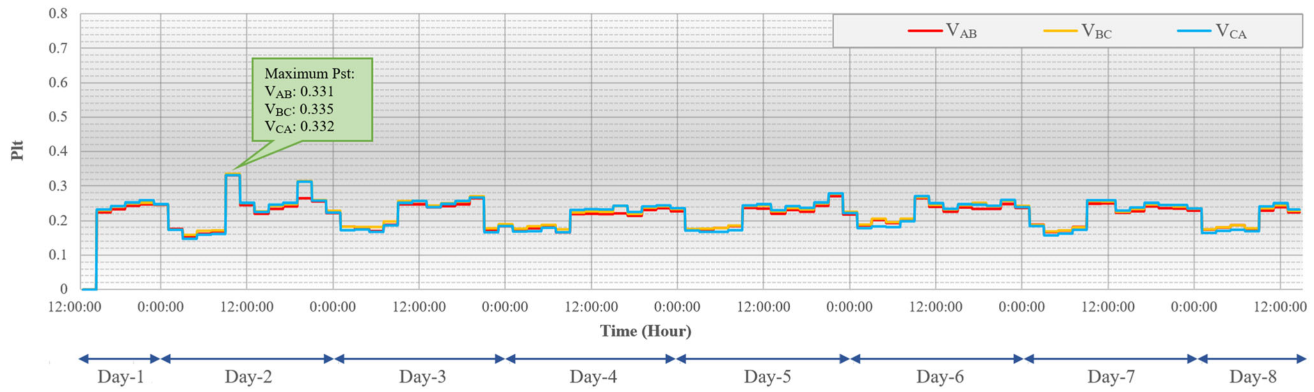


FIGURE 20 Plt profiles after PV plant commissioning with maximum Plt recorded at 0.331, 0.335 and 0.332 for each line

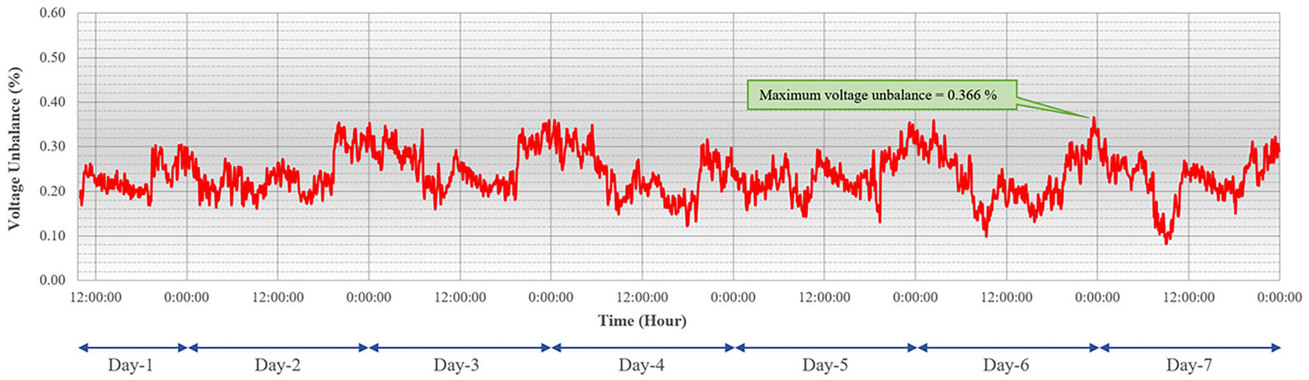


FIGURE 21 Voltage unbalance profiles before PV plant commissioning with maximum voltage unbalance recorded at 0.366%

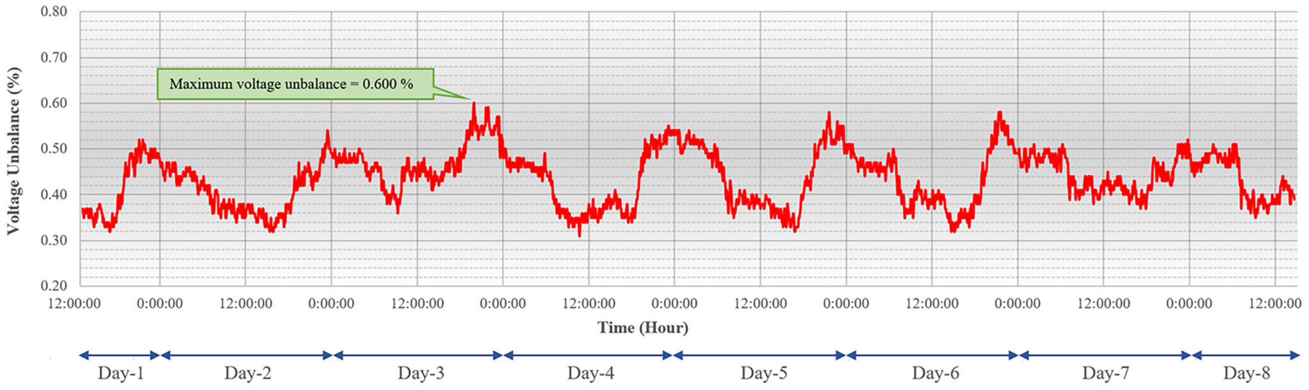


FIGURE 22 Voltage unbalance profiles after PV plant commissioning with maximum voltage unbalance recorded at 0.6%

In short, the tested solar PV plant complied with all the stipulated limits of the PQ test. Hence, it can be concluded that the interconnection of this PV system will not have any significant impact on the operation of the power grid. Table 3 summarizes the result comparison of inverter and PQ tests.

6 | CHALLENGES AND FUTURE RESEARCH DIRECTIONS

This section presents the major barriers and future research directions of solar PV system.

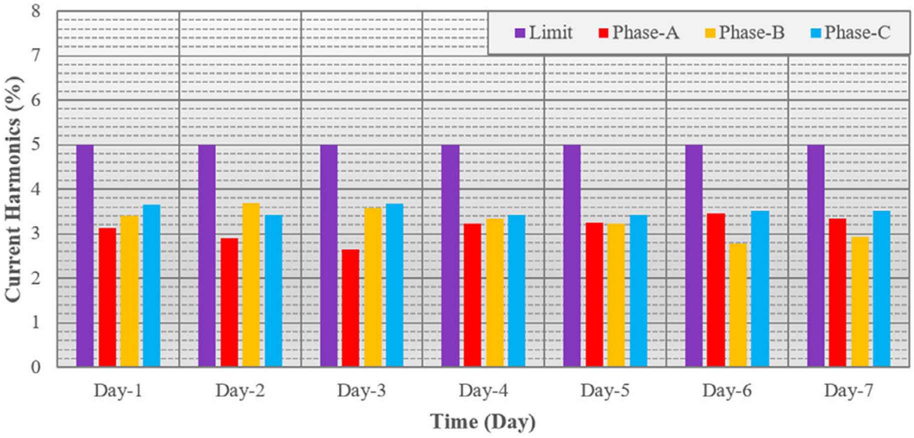


FIGURE 23 THDI profiles before PV plant commissioning with all results measured were within stipulated limits of 5%

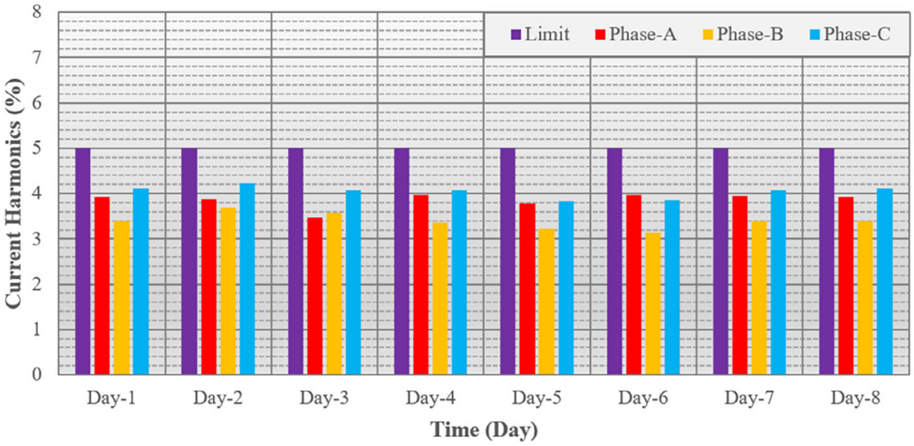


FIGURE 24 THDI profiles after PV plant commissioning with all results measured were within stipulated limits of 5%

6.1 | Challenges

For a wider take-up of PV technology, there are some limitations need to be addressed for the current solar industry, which are listed as follows:

- Inefficient PV panels: Although the price of PV panel has dropped significantly in the past few years, solar PV is still considered as an expensive technology to be implemented. The reason is because the efficiency of PV panel is generally ranges from 10% to 20%, which is relatively low compared to the conventional fuel combustion turbine generation plant.[83,84] Hence, a large-scale solar farm is needed to generate a practical amount of power supply. Researchers and engineers are working to improve this issue. For instance, a sun-tracking PV panel is one of the new technologies that is invented to help the PV panel in capturing the irradiance at an accurate angle, which results in system efficiency improvement.[85,86]
- Intermittent generation: Solar PV technology is a highly intermittent energy source because the electricity generation depends on the irradiance of sunlight, which fluctuates based on the weather condition.[87,88] This issue is especially challenging in Malaysia because of the clouds and high rainfall rate throughout the year. The intermittent solar energy can lead to grid voltage fluctuation and flickers problems.[45] As a result, the power grid operator needs to monitor the real-time and day-ahead system operations from time to time to ensure the balance between grid supply and demand is achieved.
- The need of energy storages for support: One of the common solution to alleviate intermittent solar generation is by installing energy storages.[89] Energy storages can store the excessive energy generated from PV and save it for later use. These storages can also supply stored energy when the solar generation is low.[90,91] In other words, energy storages help to balance the supply and demand in power grid with a high penetration level of solar PV technology. Moreover, energy storages can act as a complementary component to maximize

TABLE 3 Result comparison of inverter and PQ tests

PV Tests	Sub-tests	Stipulated Limits	Remarks	Compliance
Inverter test	Power factor	PF ≥ 0.85 lagging for 10% output; PF ≥ 0.90 lagging for 50% output	Inverter PF was close to unity.	Yes
	Harmonics	THDI ≤ 5%	THDI for each phase was not more than 5% and within individual current harmonics limit.	Yes
	Voltage fluctuation	Voltage fluctuation ≤ 6%	Maximum voltage fluctuation measured was 2.5%.	Yes
	Flicker	Pst ≤1.0; Plt ≤ 0.8	Maximum Pst recorded for each phase were 0.553, 0.556 and 0.564. Maximum Plt recorded for each phase were 0.410, 0.412 and 0.417.	Yes
	DC current injection	DC current ≤ 1%	For each phase, maximum DC current injection obtained were 0.15%, 0.09% and 0.21%.	Yes
	Anti-islanding	Disconnection time ≤ 0.6 s; Reconnection time ≥ 2 min for LV; Reconnection time ≥ 5 min for MV	For MV, disconnection time recorded was 0.5 second while reconnection time measured was 307 seconds.	Yes
	Steady-state voltage measurement of MV	Voltage fluctuation within ±5%	Maximum voltage fluctuation recorded was around 2%.	Yes
PQ test	RMS voltage	Voltage within ±5%	Before commissioning, RMS voltages recorded were 11.158 kV (min) and 11.540 kV (max). After commissioning, RMS voltages recorded were 10.905 kV (min) and 11.413 kV (max).	Yes
	THDV	THDV ≤ 6.5%	THDV recorded were less than 2% before and after plant commissioning.	Yes
	Voltage flicker	Pst ≤ 0.9; Plt ≤ 0.7	Before plant commissioning, maximum Pst and Plt recorded for each phase were 0.519, 0.514, 0.513 and 0.627, 0.640, 0.577, respectively. After plant commissioning, maximum Pst and Plt recorded for each phase were 0.348, 0.561, 0.561 and 0.331, 0.335, 0.332, respectively.	Yes
	Voltage unbalance	Voltage unbalance ≤ 1%	Before plant commissioning, maximum voltage unbalance recorded was 0.366%. After plant commissioning, maximum voltage unbalance recorded was 0.6%.	Yes
	THDI	THDI ≤ 5%	THDI recorded were less than 4.5% before and after plant commissioning.	Yes

the integration of PV resources and lead to a sustainable power grid.[92] Nevertheless, energy storage technology is relatively expensive and a massive amount of energy storage capacity is required to achieve the aforementioned purposes.[93]

- Potential attack risks: A solar farm is usually connected near to the power distribution loads to reduce system losses. This situation increases the intrusion and attack risks because the solar farm is much easier to be accessed by the public.[94] Moreover, researches has been performed to investigate the cyber-attack risk of solar PV system. In Reference 95, an investigation was performed to assess the impacts when the control parameters of the solar PV system were hacked by the attackers. The results revealed that severe system interruptions occurred when the PV system was under attack.

6.2 | Future research directions

This section presents some future research directions for a better deployment of solar PV technology, which are listed as follows:

- Governments and power utilities are interested in adopting solar generation into the power generation mix for its environmental benefits. Nevertheless, the low power conversion efficiency of solar PV panels has limited its potential for full deployment. Therefore, more researches should be conducted to search for a breakthrough in solar materials with high power conversion efficiency.
- For grid-connected solar PV system, inappropriate sizing and allocation of solar farm will cause a poor overall system performance. Improper system planning will result in a waste of time and resources. Hence, future researches should focus on appropriate planning of sizing and allocation of the solar system in the power grid to maximize the potentials of solar energy.
- Energy storage is an element that can help solving the intermittent generation from PV panels. However, achieving this objective requires a smart energy management system to control the amount of energy and duration required to charge/discharge the storage. Therefore, a future research direction is to design a real-time energy management algorithm that can appropriately manage the supply-demand balance among grid supply, solar generation, energy storages and loads.
- From the perspective of cyber security, there are various potential cyber attacks and risks involved in the information security, data privacy and data integrity in PV system communication. Hence, security assessment of communication protocols should be investigated and appropriate measures should be implemented for a secure operation in solar PV system.

7 | CONCLUSIONS

This article comprehensively presents the complete testing guidelines for the PV inverter performance and the PQ impacts of the PV system on the power grid. The testing guidelines include two compliance tests, which are inverter and PQ tests. The test points, test conditions and permissible limits for each test were discussed. The inverter test is conducted to evaluate the power factor of the PV inverter, along with its harmonics, voltage fluctuation, flicker, DC current injection, anti-islanding and steady-state voltage at MV. The PQ test is conducted to obtain the voltage profile, current profile, harmonics, voltage flicker and voltage unbalance at the PCC of the PV system to identify any PQ issues introduced by the system to the power grid. All the tests listed in the testing guidelines were executed on an actual 2 $\mathrm{MW_p}$ (peak) solar PV system in the Malaysian power grid that employs string-type smart inverters. The results revealed that the tested PV system complied with all the stipulated requirements of the inverter and PQ tests. Hence, the PV system can be operated reliably without posing any hazards to the Malaysian power grid. These testing guidelines will also serve as a catalyst for the effective deployment of the solar PV industry.

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