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ASSESSMENT OF STRING INVERTERS FOR LARGE-SCALE SOLAR POWER PLANT IN MALAYSIA'S

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Abstract: Tremendous promotion and growth of Large-Scale Solar Photovoltaic (LSSPV) Power Plant in Malaysia increase the reliability and potentiality of the system in having efficient monitoring, operation and maintenance for the plants. Through the Ministry of Energy, Science and Technology, the government aims to increase the renewable energy in its generation mix in 2025 by 20% and intends to reduce its greenhouse gas (GHG) emission intensity per unit of gross domestic product (GDP) to 45% by 2030. This was followed by the Energy Commission (EC) announcement of 500 MW LSSPV power plants in Malaysia, slated for commercial operation in 2021. Thus, proper monitoring and respectable power generation are crucial to optimising LSSPV for grid interconnection. This paper presents the assessment of string inverters configuration and analysis models to recommend an optimised configuration for maximum harvested power generation in the LSSPV power plant in Malaysia. An analysis of string invert configuration is carried out based on real data measurements of electric generation of a 50 MW LSSPV power plant at the Kuala Ketil site. The test verified that the configuration string inverters offer a reliable outcome for the grid code test (GCT). Besides, the string inverters provide a potential approach to maximising power generation at different climate conditions, thus, reducing the workforce for the operation and maintenance activities. The string system endeavours a feasibility implementation on the suitability of effective configurations for LSSPV in Malaysia without often shutting down the plant generations due to any defect or damage of PV modules.

Keywords: String inverters, LSSPV, GCT, photovoltaic, GHG.

Introduction

Due to increased demand for energy resources, renewable energy has been widely used due to its eco-friendly to the environment. Currently, solar power technology is developing very fast in the world, with a total installed grid-tied solar power capacity of 99.1 GW in 2017 (Phap & Hang, 2019), in which the United States, China, Germany and Japan were the largest installed power capacity in the world. Since June 2011, Malaysia Renewable Energy (RE) Act 2011 was gazette with the introduced Feed-in Tariff (FIT) scheme. Some 1.6% collection scheme from public electricity bills as RE projects development supporting the scheme, which is encouraged by the Sustainable Energy Development Authority (SEDA) (Tan *et al*., 2018). Many programs have been held in Malaysia and the large-scale solar photovoltaic plant (LSSPV) is one of the popular programs introduced by the public since April 2016 with a 1 GW deployment goal. To achieve this goal, a good type of inverter must be installed. Inverters are a critical part of solar PV systems since they convert from DC to AC and thus, transmit the electricity to the utility grid with the support of the maximum power point tracking (MPPT) controller. Several inverters such as central inverters, string inverters and micro-inverters. This paper presents the effectiveness and benefits of string inverters especially in LSSPV plants which are met in criteria including the monitoring tasks, initial investment cost, electricity sales price or subsidy schemes, initial performance ratio, mounting or space constraints, maintenance and repair requirements, the future availability of spare parts and operational availability (Kröger-Vodde *et al*., 2010).

String inverter integrated with Maximum Power Point Tracking (MPPT), where the solar panel string can be connected directly through the inverter without using a DC cable container box. The system is more flexible than other inverters regardless of whether the solar module strings move in many directions, the angle of tilt and several solar panels (Phap & Hang, 2019). For safety factors, a string inverter must have anti-islanding protection, meaning it must automatically stop power flow when the grid goes down (Nwaigwe *et al*., 2019). If the inverter failed, it did not affect the whole solar power plant because the inverter's capacity was not large. This small string inverter can reduce the installation cost because there is no need to use a crane and too many workers for the installation process. The string inverter is extremely easy to manage for maintenance. If a string inverter is failed, the inverter will be replaced with a new one and the replacement can be done at the solar power plant site, which is difficult from the central inverter, where need a height cost to replace a new one and it also very complex due to use of specialised equipment and need of many workers. An intelligent wireless monitoring control system has been installed into the inverter design, where the Supervisory Control and Data Acquisition (SCADA) string inverter system becomes more modern and convenient and can remove too many communication cables in the system.

String inverters also own centralised and micro-inverter at lower cost and optimal MPPT control features were caused by the string diodes of centralised inverters or individual MPPT of micro-inverter not existing in string inverter structure (Kabalci *et al*., 2015). The multi-string inverter is one of the upgrades from the string inverter, which consists of more MPPT where it can resolve the limitation of string input voltage which is allowed to be high enough while the input power and several string connections to the dc-dc converter are limited (Čorba *et al*., 2012). The string and multi-string inverters provide effective cost and power energy conversion systems. Research by Phap and Hang (2019) identified that the selection of plant is important due to the cost and the superior grid functionality where the author suggests that the string inverter could be applied for a solar farm located in a shading area and irregular topography area such as mountain because of the flexibility operation function of MPPT tracker and lightweight. Even though a central inverter is commonly used in a European solar power plant, a string inverter offers an alternative of cost and effective operation and maintenance for small up to large-scale solar power, particularly in Malaysia.

Technology and Structure of String Inverters

Figure 1 shows the arrangement of the string inverter configuration. This scheme connects several PV modules on the DC side to form a string. The output from each string is converted into an AC power through a separate individual inverter. Therefore, separated MPPTs are applied to each PV string. Besides, the scheme is allowed to obtain high voltage via the reduction of mismatching and partial shading losses. The string converter reduces the version of the centralised converter by their plug and

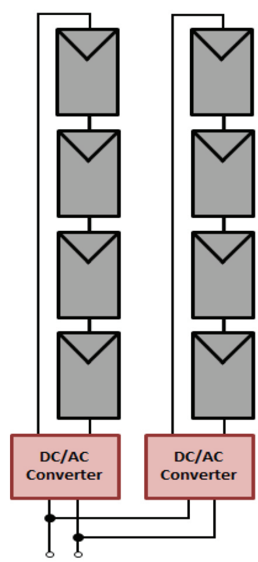

Figure 1: String configuration scheme

plays opportunity but may increase the cost of converter parts and provide an efficient tuning method for MPPT (Mohd Zakki *et al*., 2018).

In Malaysia, string inverter scheme has been proven with their established reliability, accessibility and high efficiency, especially for LSSPV power plant. A typical comprehensive configuration of string inverters for the LSSPV system until grid interconnection is shown in Figure 2. One of Malaysia's recently large-scale solar power plants that employ the string inverters system is installed at 50 MW Kuala Ketil, Kedah Darul Aman. This plant utilised 1,200 units of a string inverter, which was severally rated at 42 kW for DC-level conversion from PV arrays into AC conversion of 50.4 MW.

This scheme improves grid management and safety functions by enhancing power control features, providing dedicated data and addressing any serial arc fault circuit interruption up to string PV modules configuration.

In addition, string inverters installed in common locations or rooms can facilitate the ease of maintenance and troubleshooting processes. This is a serious benefit in places with extremely hot climates. String inverters are currently cheaper than micro-inverters and only need one string per installation while for micro-inverters, all PV modules need the inverter. While one of the key benefits of string inverters over central inverters is that if there is any defect of strings, an individual unit can easily be swapped out rather than requiring trained operation and maintenance staffing to perform an in-site repairing process. This also contributes to fewer years of payback compared with other configurations of inverters especially for large-scale implementation (Gazis *et al*., 2013).

Table 1 summarises the characteristic performance comparison between central, string and multi-string inverter topologies referring to the nomenclature of H for high, L for low and M for medium. These findings performance is categorised into four characteristics: The general characteristic, power losses, power quality and cost of the topologies. From Table 1, the overall performance of the string inverter lead in all categories as a prominent inverter that must be considered widely used in large-scale solar power plants, especially in Malaysian climatological conditions.

The general characteristic has low robustness but is high in other aspects that can still be considered good. For power loss, the string inverter has low performance in losses compared to the central and string inverter due to higher mismatching losses from an array module configuration. The switching losses are also considered a concern since the performance might affect the output generation, particularly when there are problems with inverters in a central or multi-string inverter connection. The central inverters have very high losses because

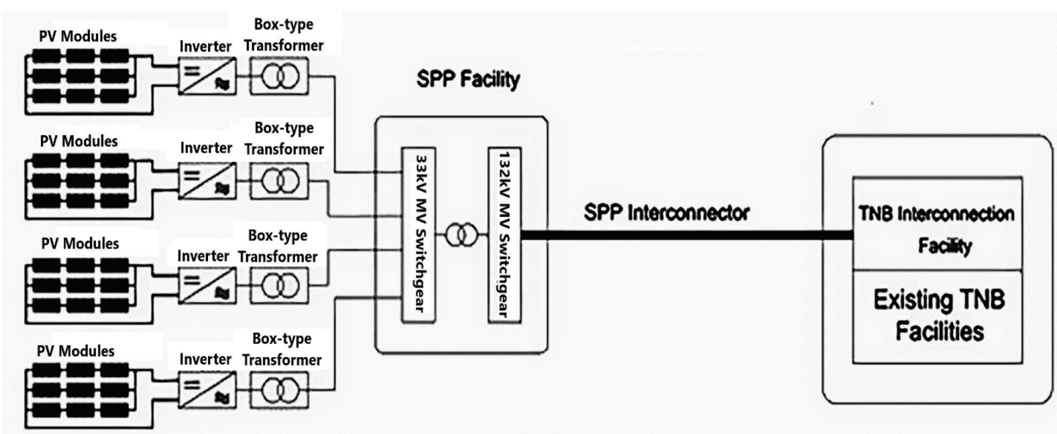

Figure 2: Comprehensive LSSPV configuration using string inverters

Table 1: Comparison performance between the inverter topologies

		Central	String	Multistring
General characteristic	Reliability	L	H	M
	Robustness	H	L	M
	Flexibility	L	H	M
	MPPT efficiency	L	H	M
Power losses	Mismatching	H	L	L
	Switching	H	L	M
	AC power losses	L	M	M
	DC power losses	H	L	M
Power quality	AC voltage variation	L	H	M
	DC voltage variation	H-H	M	H
	Voltage balance	H	M	L
Cost	Installation cost	M	H	M
	DC cable	H	L	M
	AC cable	H	M	M
	Maintenance	L	M	H

of the string connected in parallel. In terms of cost, string inverters need a lower cost than the central inverter installation for DC and AC cables is higher than a string inverter connection.

Monitoring and Evaluation

String inverters are equipped with Smart logger apparatus as the data collector, which requires a monitoring system to run the data including inverter, box type transformer and meteorological parameters dataset. The data are transferred into the supervisory control and data acquisition (SCADA) system through fibre optic cables as shown in Figure 3. The string inverters communicate with the Smart logger through the power line communication (PLC). The signal from the Smart logger is then communicated to SCADA through a switch by an optical cable. Therefore, the SCADA monitoring system can observe the data up to the string level of the LSSPV plant.

The concept of string connected inverter for LSSPV was developed based on the geotechnical inspection report. Due to the hilly and uneven terrain, a string inverter configuration was preferred for optimal power generation from sunlight and module layout. A string inverter also provides optimum harnessing of the PV power for maximum conversion to AC power. With multi-MPPTs of the string inverters, the efficiency of the inverter can be increased in multiple operational environments such as during shading, different string module output power at a respective tilt angle.

Other advantages of string inverters over central inverters are that when there are defects of PV modules, inverters, or related performance issues, an individual or respective unit can be easily swapped out rather than requiring site repairing or partially shutting down the operation. Each string inverter consists of four MPPT with eight inputs as shown in Figure 4. As part of the protection system, the inverter is built with a DC and AC surge protection device (SPD) including with filtering circuit.

Site Tests and Results

Before connecting to the grid-connected, inverter site tests are conducted to access the impact of the string inverter output on the grid. This is to ensure the suitability of the inverter

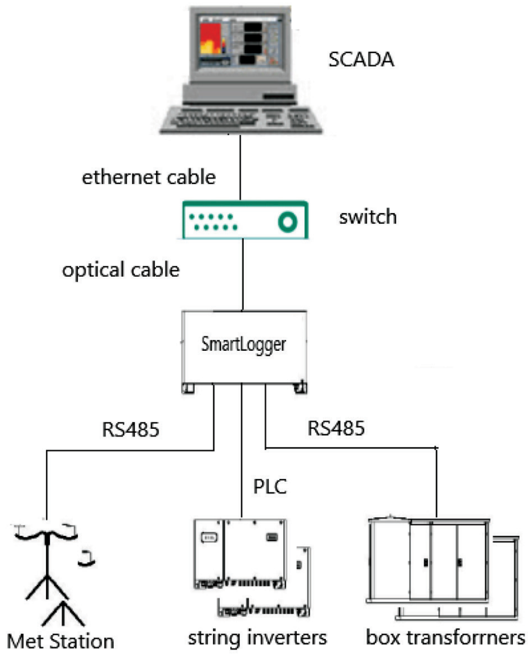

Figure 3: SCADA monitoring system from the string inverters

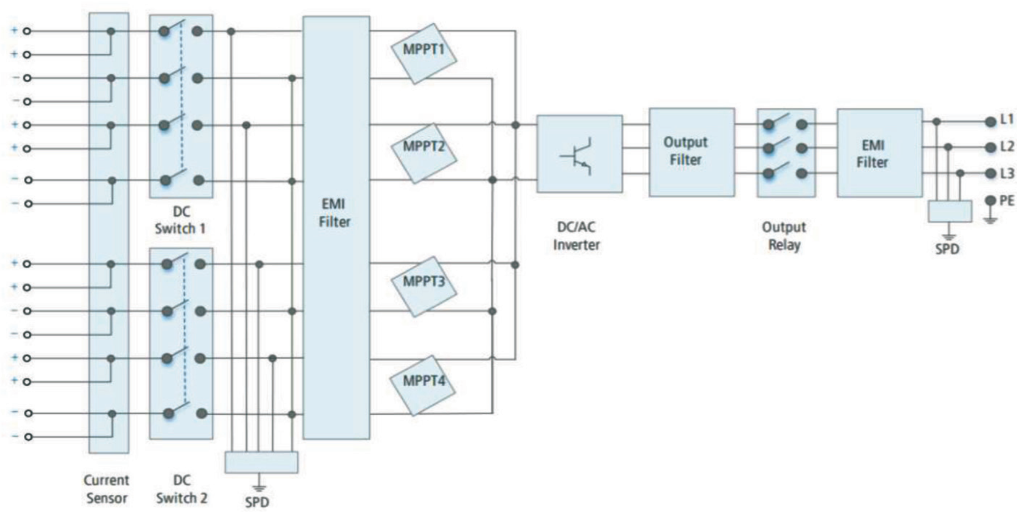

Figure 4: Circuit diagram of the string inverters

to meet the output parameters requirement in Malaysian environments. The test is conducted at varying inverter output, at least 10% to 50% of the rated output. This string inverters site test is based on the following tests for a selected zone (total zone in site location is 25 number of zones):

(1) Power Factor Test
(2) Harmonics Test
(3) Voltage Fluctuation Test
(4) Flicker Test
(5) DC Current Injection Test
(6) Steady State Voltage Measurement at Medium Voltage Test

The main objective of this selection inverter site test is to assess the impact of total string inverters output into grid interconnection. This will ensure that the system is suitable for implementation in Malaysia's standard conditions and thus meet the output parameters given by manufacturers. The tests are carried out during the period prescribed for each test.

To meet the requirement of the inverter site test under the Grid Code Test (GCT), the power factor (PF) need to be greater than 0.85 when the inverter output is approximately 10% of the rated power while the PF is required to be greater than 0.9 when the inverter output is at 50% of rated power. The recorded data for the daylight of real power and power factor at 33 kV box transformer are severally shown in Figures 5 (a) and (b). From the recorded data, for 10% inverter output, the measured PF is 0.99 while during inverter output at 50% rate, the measured PF is 0.98. Therefore, both measurements are within the acceptable limit for the string inverters to operate in voltage control mode for grid interconnection.

For the harmonic test, the maximum total harmonic distortion (THD) of the current is measured to be less than or equal to 5% at not more than 50% rated inverter output. Meanwhile, the individual harmonics need to be limited to 50% of the rated inverter output based on current distortion limits provided by IEC 61727-2003 in Table 2. Figure 6 displays

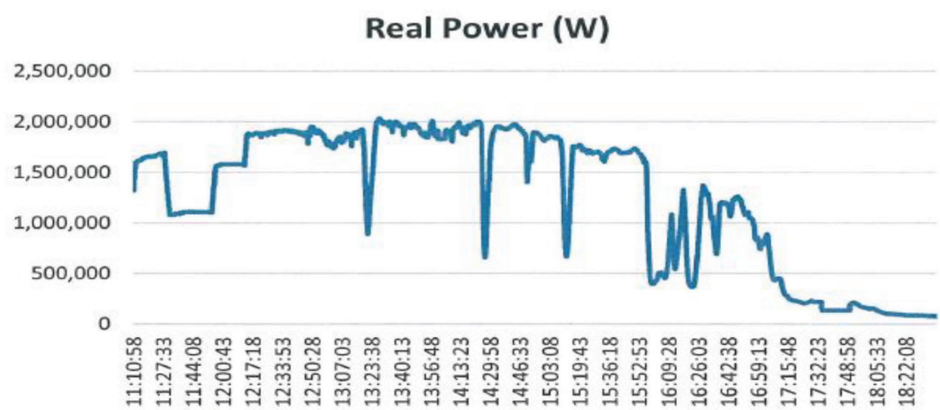

Figure 5 (a): Recorded data for real power

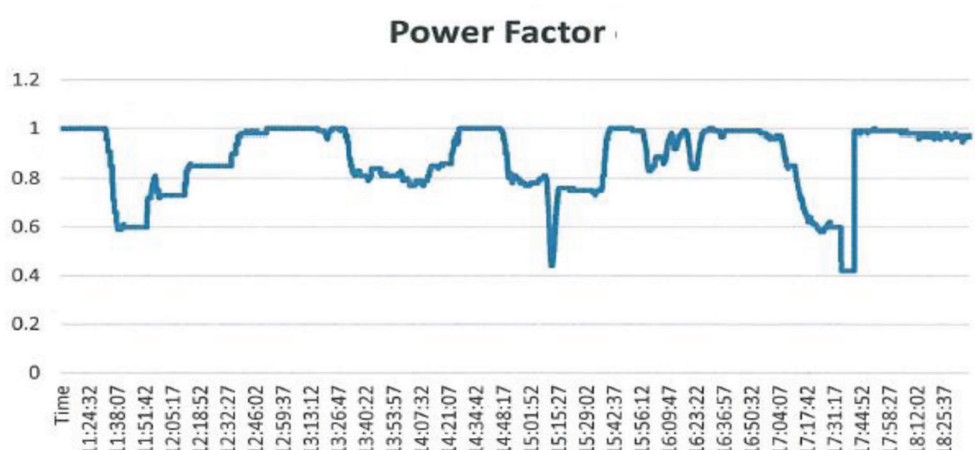

Figure 5 (b): Recorded data for power factor the THD of current and individual current harmonics. The plotted THD graph for L1, L2 and L3 show that all the odd and even harmonics from string inverters are within the acceptable distortion limit for harmonics requirement.

Voltage fluctuation test condition for string inverter is implemented by switching off all other main switchboards except the one under test. The test is conducted for at least two hours at midday (12.00 pm to 2.00 pm) at one-second intervals. The test shows that the maximum voltage fluctuation allowed is 6% from maximum to minimum of the highest fluctuation during the test period within the acceptable limit, as shown in Figure 7. All the line voltages are in phase for RMS voltage fluctuation.

The flicker test is conducted at the LV point of common coupling (PCC), followed by the test condition of monitoring the short-time flicker (Pst) within 10 minutes and the long-time flicker (Plt) within two hours. The acceptable limit criteria to pass the test should not exceed the limits defined by the maximum borderline irritation limits of Pst and Plt to be less than 1.0 and 0.8. Figures 8 (a) and (b) represent the inverter test's short-term and long-term flicker severity. The measured flicker for the period, Pst for each phase of L1, L2 and L3 are 0.52 while the flicker for Plt for each phase of L1, L2 and L3 are 0.31. All the measured flicker index is within the acceptable limit for string inverters to be connected with the PCC location.

The DC injection test is measured at a common output point from each string configuration for string inverters. As a passing criterion, this DC injection needs to be less than 1% of the rated output current from the inverter for each phase. The test is conducted by switching off all other inverters except the one under test and the maximum output of the

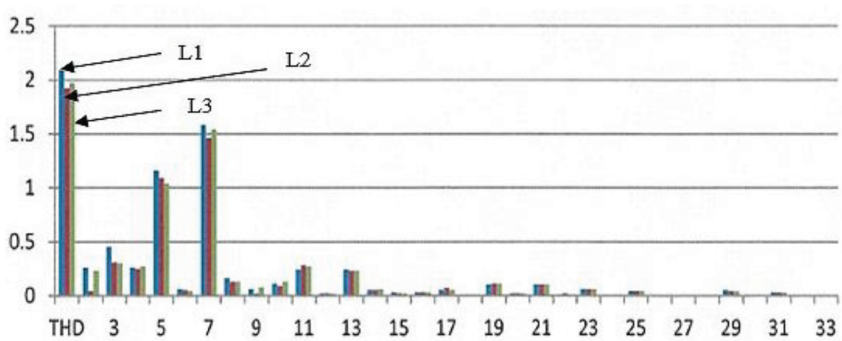

Figure 6: THD current harmonics

Table 2: Current distortion limits

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

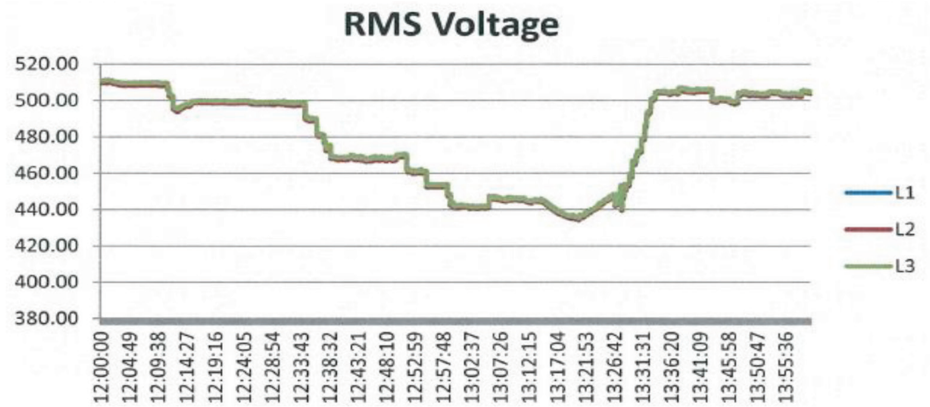

Figure 7: RMS voltage fluctuation

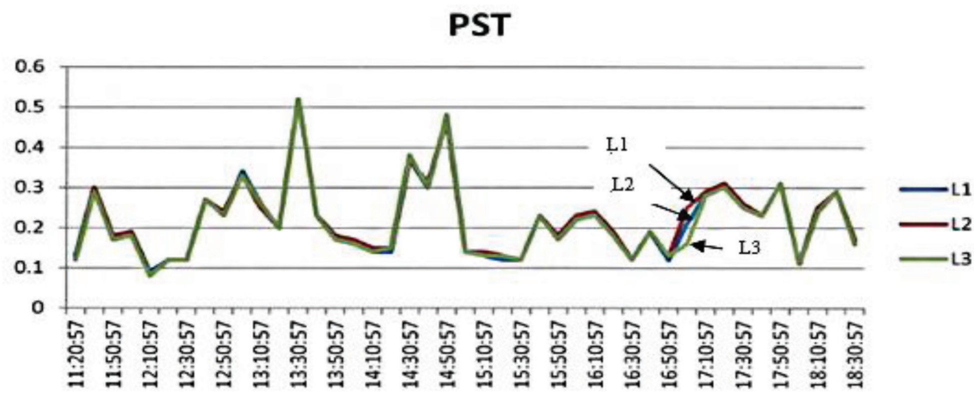

Figure 8 (a): PST flicker severity

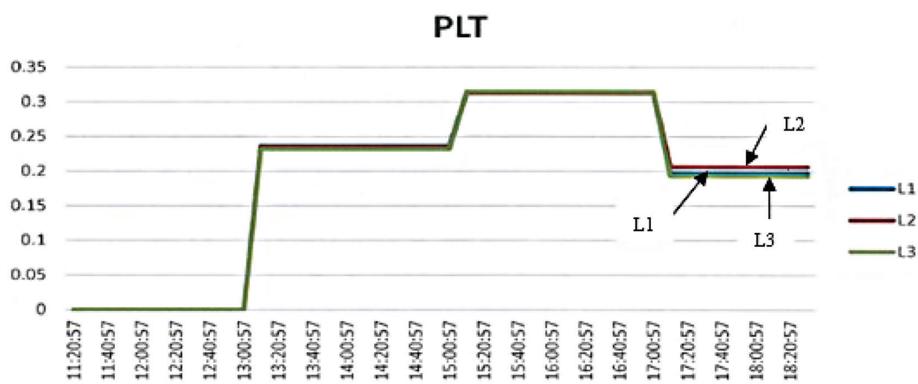

Figure 8 (b): PLT flicker severity

inverter shall be at 50% of the rated output. The test shows that the measured current injection in phase with each other and less than 1% of the rated output current from the inverter of each phase. The current injection for L1 is 0.45% whereas the current injection for L2 and L3 is measured at 0.43%.

The steady-state voltage measurement of medium voltage is measured at the medium voltage side (33 kV) by monitoring the test for a minimum of six-day light hours at one-minute intervals. The acceptable limit for maximum voltage fluctuation allowed is ±10% of nominal based on medium voltage equipment rating. The steady-state voltage fluctuation of each phase is shown in Figure 9, specifically at maximum during the noon period. The line voltages L1, L2 and L3 are observed to be within the equipment rating, where the limits are ±10% nominal.

The performance of string inverters for the plant is verified through the I-V characteristics of the PV modules, which are remotely monitored through each string inverter. Figure 10 (a) indicates the simulation of the I-V curve operating at the normal condition from the ideal solar cell equation. Applying string inverters for LSSPV plant, the abnormal or faulty string can be monitored closely through the I-V curve as shown in Figure 10 (b). During inspection test observation, the curve shows small dust on the lowest side of PV modules in the circle. At the same time, Figure 10 (c) exemplifies the effect of current mismatch on the PV string due to the inconsistency of the PV module current.

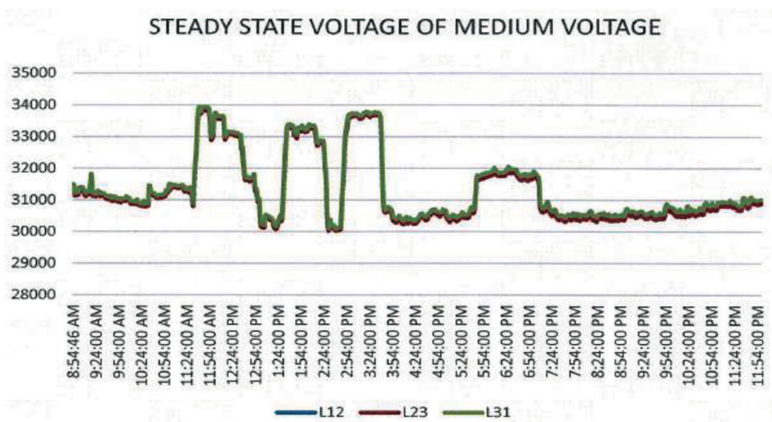

Figure 9: Steady-state voltage trajectories

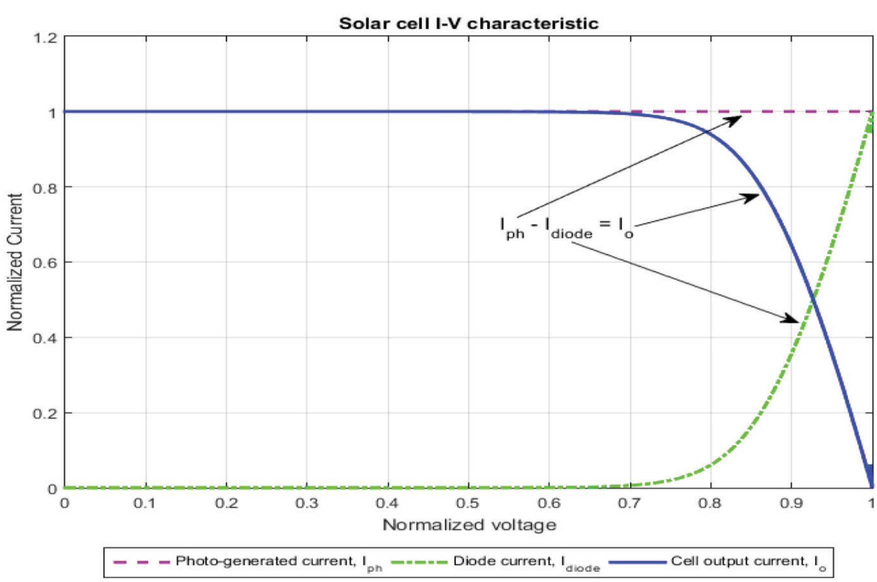

Figure 10 (a): I-V curve for normal operating of PV module

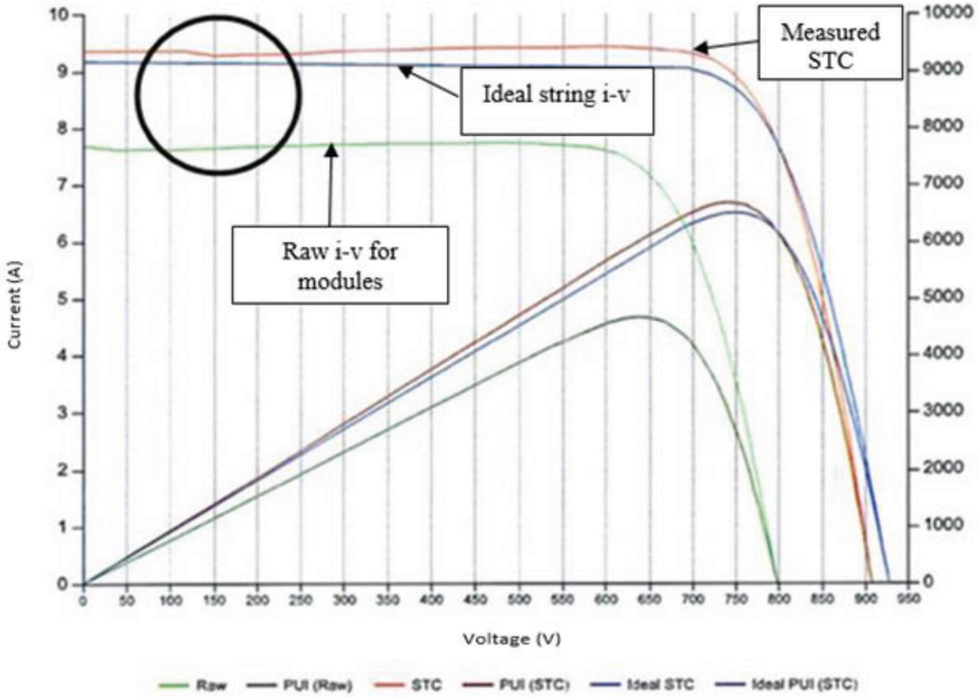

Figure 10 (b): Effect of small dust on the PV module

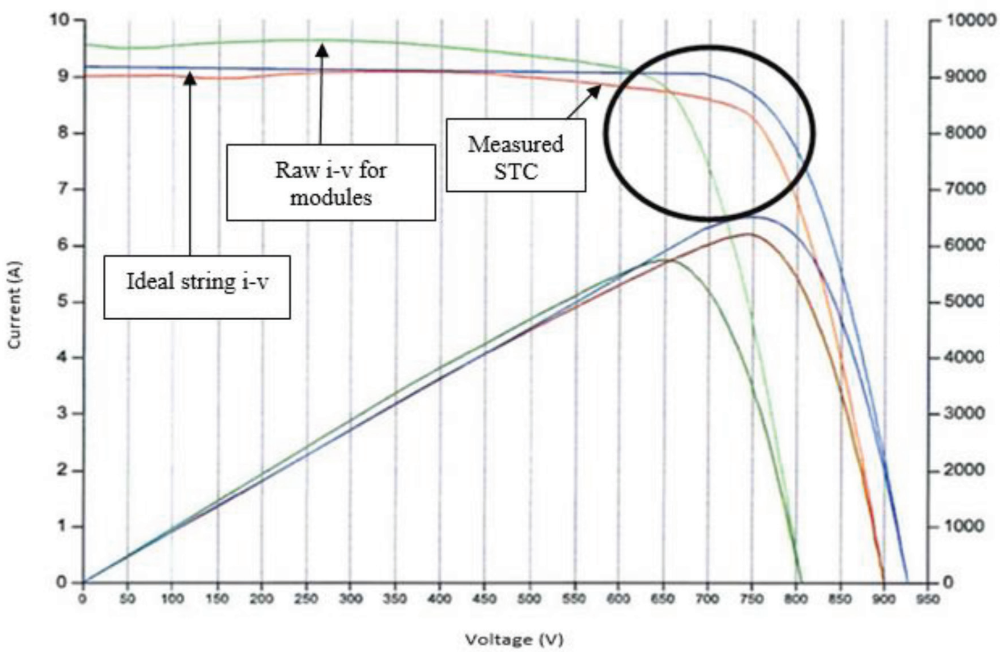

Figure 10 (c): Effect of current mismatch on the PV string

From the IV curve of each string, the plant can monitor, troubleshoot and conduct maintenance for respective defect string modules only without interrupting the normal operation of other PV string generation. This process can optimise the plant generation at a maximum level compared with a central inverter, which must shut down a large PV array configuration for maintenance and replacement work.

Besides, a string inverters system also provides an appropriate reactive (Var) power to assist the plant in successfully passing the reactive power capability of grid code test where the solar power park meets the 0.85 pf lagging and 0.95 pf leading at 90% of reporting condition (45 MW) for test 1 and test 5 based on Malaysian Grid Code requirement of Solar Power Park as shown in Figure 11.

The implementation of string inverters in the plant enhances the capacity of power generated at more than 50 MW during a sunny day weather condition for the valuation date, as shown in Figure 12. By regression method, the plant can deliver a generation of 51.32 MW under the proposed value of MW.

Conclusion

The analysis through inverter site tests conducted up to string configuration of large-scale solar PV power plant proved that the string inverters can provide an optimum energy conversion at desired plant capacity. Based on Malaysian cloudy weather, which tends to harvest different solar irradiance spots in a large-scale area, string inverter is a prime solution chosen as DC to AC conversion for maximum harvested energy.

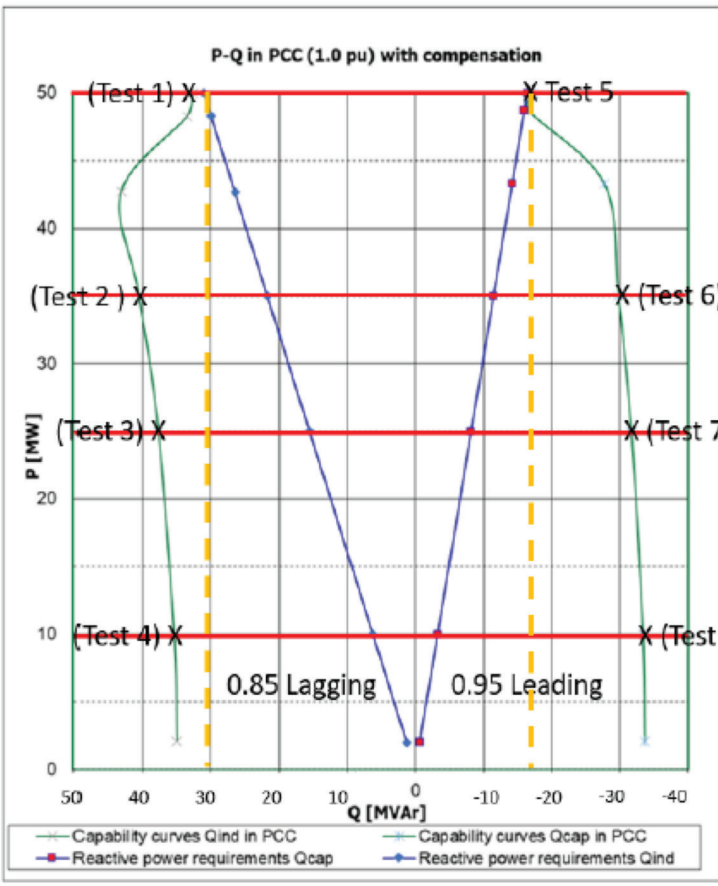

Figure 11: Reactive power capability test

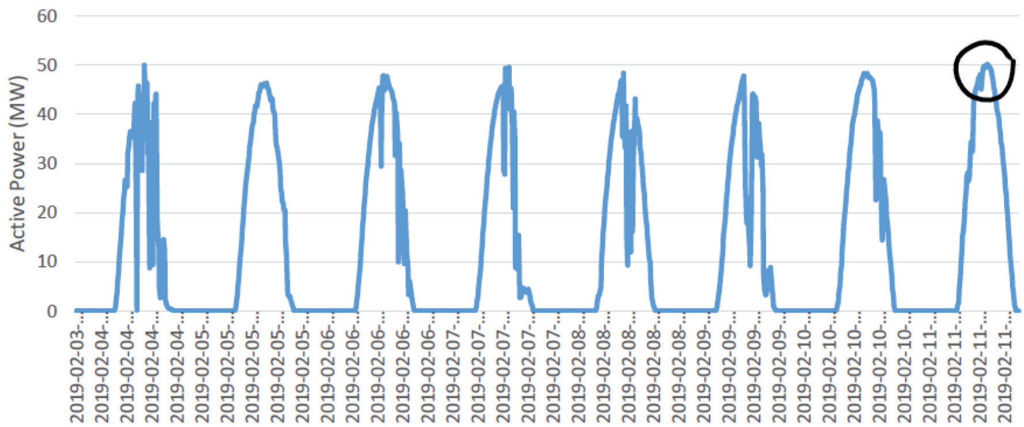

Figure 12: Daily active power recorded for establishing capacity test

The results from the grid code test observed that this configuration fulfils the grid code test requirement and establishes capacity test at 50 MW of proposed generation with the assistance of Var of the string inverters. The string inverters also provide a valuable solution and cost-effectiveness for the benefits of operation and maintenance activities. Since all the PV modules can be remotely monitored through a string inverter for fast response and action taken to maximise the power generation from the plant without shutting down the PV generation for any replacement of damaged PV modules. This will enhance and optimise the plant for generating electricity at higher MW daily. Thus, the solar power plant generates maximum energy capacity into the grid interconnection system.

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References

Čorba, Z. J., Katić, V. A., Dumnić, B. P., & Milićević, D. M. (2012). In-grid solar-to-electrical energy conversion system modeling and testing. *Thermal Science*, *16*(SUPPL. 1). https://doi.org/10.2298/TSCI120224069C

Gazis, F. S., Vokas, G. A., Katsimardou, I. J., & Kaldelis, J. K. (2013). Micro inverters for PV plants compared to the ordinary string or central inverters. *The Conference for International Synergy in Energy, Environment, Tourism and Contribution of Information Technology in Science, Economy, Society and Education*. https://www.researchgate.net/publication/271515745_Micro_inverters_for_PV_plants_compared_to_the_ordinary_string_or_central_inverters

Kabalci, E., Kabalci, Y., Canbaz, R., & Gokkus, G. (2015). Single phase multilevel string inverter for solar applications. *2015 International Conference on Renewable Energy Research and Applications, ICRERA 2015*, 109-114. https://doi.org/10.1109/ICRERA.2015.7418459

Kröger-Vodde, A., Armbruster, A., Hadek, V., & Heydenreich, W. (2010). Distributed vs. central inverters - a comparison of monitored PV systems. In the *25th European*

Photovoltaic Solar Energy Conference and Exhibition. https://www.researchgate.net/publication/265333024_Distributed_vs_Central_Inverters_-_A_Comparison_of_Monitored_PV_Systems

Mohd Zakki, M. I., Mohd Hussain, M. N., & Seroji, N. (2018). Implementation of particle swarm optimization for tuning of PID controller in Arduino Nano for Solar MPPT System. *International Journal of Electrical and Electronic Systems Research (JEESR)*, *13*(11), 1-8.

Nwaigwe, K. N., Mutabilwa, P., & Dintwa, E. (2019). An overview of solar power (PV systems) integration into electricity grids. *Materials Science for Energy Technologies*, *2*(3), 629-633. https://doi.org/10.1016/j.mset.2019.07.002

Phap, V. M., & Hang, L. T. T. (2019). Comparison of central inverter and string inverter for solar power plant: Case study in Vietnam. *Journal of Nuclear Engineering & Technology*, *9*(3), 11-23. https://doi.org/10.37591/JONET.V9I3.3538

Tan, P. H., Saedon, A., Suwannarat, A., Naengnoy, M., & Gan, C. K. (2018). Inverter selection impact to large scale solar photovoltaic power plant layout in Malaysia. *Proceedings of Symposium on Electrical, Mechatronics and Applied Science 2018*, 109-110. http://seda.gov.my