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# Implementation of String Inverters for 50 MW Large Scale Solar Power Plant in Malaysia

Mohd Najib Mohd Hussain[1,2], Irfanudin Nor Anwar[3], Mashitah Mohd Hussain[4], Nor Adni Mat Leh[5] and Intan Rahayu Ibrahim[6]
[1,3,5,6]*College of Engineering, School of Engineering, University Teknologi MARA, Cawangan Pulau Pinang, 13500 Permatang Pauh, Pulau Pinang, Malaysia,*
[2]*Solar Research Institute, University Teknologi MARA, 45400 Shah Alam, Malaysia,*
[4]*College of Engineering, School of Engineering, University Teknologi MARA, Cawangan Pasir Gudang, 81750 Pasir Gudang, Malaysia*
**corresponding author: [1]najibmh@uitm.edu.my*

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**ABSTRACT**

*The growth of large-scale solar photovoltaic (LSSPV) power plant site development in Malaysia has increased the demand for the reliability and potentiality of the system in achieving efficient monitoring, operation, and maintenance for the plants. A configuration of string inverters is applied in a 50 MW large-scale solar photovoltaic installation because of its flexibility and scalable technological advancements. This installation demonstrates that the plant can optimise the power output and monitor the performance of the system up to the string level with a cost-efficient implementation. The output from each photovoltaic (PV) string provides a guarantee of better maximum power point tracking (MPPT) capability. Instead of having shorter DC wires compared to the central inverter, this system offers the potentiality of monitoring the solar PV module at a string level, which also affords scalability for future expansion. The tests conducted verify that the string inverter configuration serves as a reliable outcome for grid code test (GCT) requirements. Furthermore, the string inverters provide a potential approach to achieving maximum power generation in different climate conditions, thus reducing the need for manpower in operation and maintenance activities. The string system offers a feasible implementation of effective configurations and decarbonisation for LSSPV in Malaysia without frequent shutdowns of plant generation due to defects or damage to PV equipment and modules.*

**Keywords:** *string inverters; LSSPV; GCT; photovoltaic; GHG.*

## 1. INTRODUCTION

Nowadays, decarbonisation has become a vital process associated with sustainability and climate change. Energy decarbonisation plays an important role in shifting the entire energy generation system to prevent carbon emissions from entering the atmosphere. One solution is to install a large number of solar photovoltaic systems as a large-scale renewable energy resource, which is also considered environmentally friendly. In 2017, most large-scale solar photovoltaic plants (LSSPV) globally installed employed grid-tied solar power capacity of 99.1 GW [1], with the United States, China, Germany, and Japan having the largest power capacity in the world. In Malaysia, the Renewable Energy (RE) Act of 2011 was gazetted with the introduction of the Feed-in Tariff (FIT) scheme. Several collection schemes, amounting to 1.6% of public electricity bills, are encouraged by the Sustainable Energy Development Authority (SEDA) to support RE project development [2]. To achieve this goal, it is essential to install

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the right type of inverter as part of a crucial balancing system for solar PV power plants. Inverters play a critical role in solar PV systems as they convert DC energy generated by solar PV modules into grid AC interconnection. The most prominent inverters widely used include central inverters, string inverters, and micro-inverters. The effectiveness and benefits of string inverters, especially in LSSPV plants, are crucial to meet system criteria, including monitoring tasks, initial investment costs, electricity sales prices or subsidy schemes, initial performance ratio, mounting or space constraints, maintenance and repair requirements, the future availability of spare parts, and operational availability. This is because the failure rate of the PV module within each PV string depends on the inverter approach in the system [3]. The analysis of the contributions of string inverters and some related grid code tests in LSSPV plants will be the main outcomes presented to demonstrate the benefits of using string inverter configurations for the successful operation of LSSPV plants in Malaysia.

A string inverter typically integrated with maximum power point tracking (MPPT) is used to efficiently harvest the maximum power from the sunlight. This system is more flexible than other inverters regardless of the solar module strings moving in many directions, the angle of tilt, and several solar panels. For safety factors, a string inverter must have anti-islanding protection, meaning it must automatically stop power flow when the grid goes down [4]. If the inverter fails, it does not affect the whole solar power plant because the capacity of the inverter is not large. Using this small string inverter can reduce the cost of installation 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 fails, 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 which needs a high cost to replace with a new one and is 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) system of string inverters become more modern and convenient and can also remove too many communication cables in the system.

String inverters also operates as a central micro-inverter which provides a lower cost of maintenance and optimal MPPT control features due to the integration of the string diodes. Whereas a centralised inverter or individual MPPT micro-inverters did not offer these capabilities in the overall PV structures [5]. A multi-string inverter is an advanced string inverter approach which consists of more than one MPPTs. It can resolve the limitation of string input voltage to deliver high string voltage and able to accommodate with several number of identical DC-DC converter for maintaining a better performance ratio (PR) of the system [6-7]. The string and multi-string inverter configurations as shown in Figure 1 and Figure 2 provide effective cost and power energy conversion systems. Research in [1] identified that the selection of plant is important due to the cost and the superior grid functionality where the author suggests the string inverter could be applied for solar farms located in shading areas and irregular topography areas such as mountains because of the flexibility operation function of MPPT tracker and lightweight. Even though a central inverter is commonly used in solar power plants in Europe, a string inverter offers an alternative of cost and effective operation and maintenance from small up to large-scale solar power, particularly in Malaysia.

Among the grid code test (GCT) conditions, the ramp rate and reactive power capability are crucial tests that fulfil GCT pass requirements for the total commissioning of the large-scale solar PV plant. The results will indicate the successful implementation of new grid generation

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to limit the ramp-rate (RR) behaviour of PVs, allowing the grid resources to manage power fluctuations if any occur. Additionally, the plant should provide the capability to generate reactive power to the grid if required, and this is tested using a string inverter configuration in the 50 MW LSSPV plant. Furthermore, the implementation of inverters in string configurations also provides several benefits, which are verified by the results obtained in the plant.

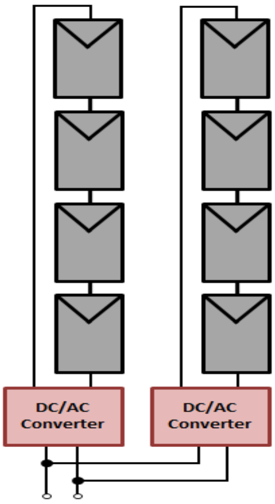

Figure 1: String configuration

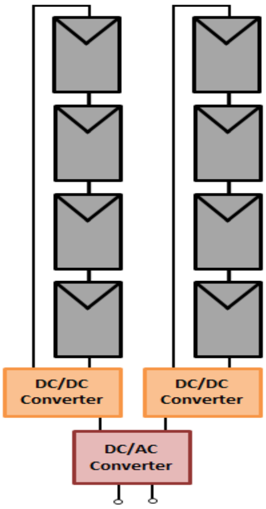

Figure 2: Multiple string configuration

## 2. TECHNOLOGY AND STRUCTURE OF STRING INVERTERS

Figure 3 shows the arrangement of seven (7) strings of PV modules into a string inverter of eight (8) MPPT configurations. In this scheme, several PV modules are connected in series 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-play opportunity but may increase the cost of converter parts and provide an efficient tuning method for MPPT [8].

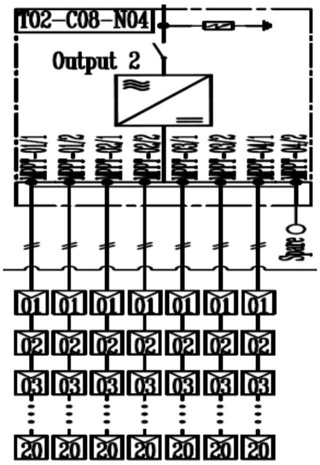

Figure 3: String configuration scheme into single string inverter

Most LSSPV development in Malaysia employed string inverter schemes since the configuration has been proven with their established reliability, accessibility and high efficiency, especially for a power plant. A comprehensive typical configuration of string inverters for LSSPV systems until grid interconnection is shown in Figure 4. An example of a large-scale solar power plant in Malaysia which employs the system of string inverters is installed at 50 MW. This plant utilised 1200 units of string inverter which severally rated at 42 kW for DC level conversion from PV arrays into AC conversion of 50.4 MW.

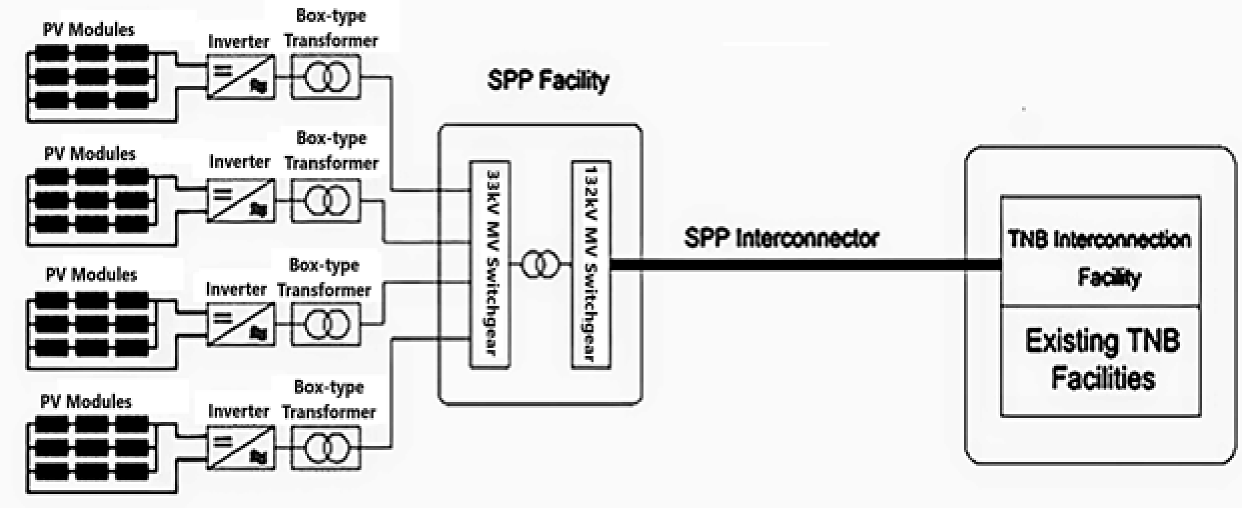

Figure 4: Comprehensive LSSPV configuration using string inverters

This scheme offers a solution for improving grid management and safety functions by enhancing power control features, providing dedicated data, and also being able to address any serial arc fault circuit interruption up to string PV module configuration.

In addition, string inverters, which are installed in a common location or room, can facilitate the ease of maintenance and troubleshooting process. This is a significant benefit in places with extremely hot climates. In terms of cost, when compared with micro-inverters, string inverters are currently cheaper and only require one string per installation, whereas for microinverters,

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all PV modules need an inverter. One of the key benefits of string inverters over central inverters is that if there are any defects in strings, an individual unit can easily be swapped out rather than requiring trained operation and maintenance staff to perform an on-site repair process. This also contributes to a shorter payback period compared with other configurations of inverters, especially for large-scale implementation [9].

The overall configuration of string inverters is shown in Figure 5. It is evident that for irregular site topography, the string inverters provide better performance on sites and minimise string mismatches. In the event of a failure, the availability of string inverter-based systems has minimal impact on total generation since the system can easily be replaced without an overall shutdown.

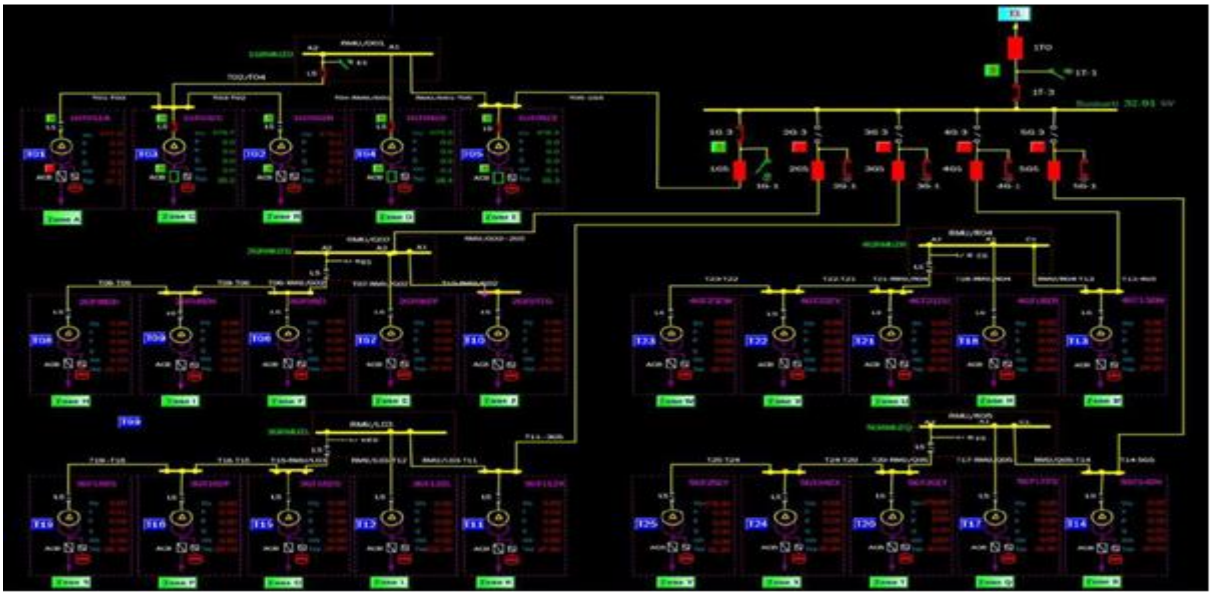


Figure 5: Overall string inverters configuration for 50MW LSSPV plant

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, including the general characteristic, power losses, power quality, and cost of the topologies. From the table, the overall performance of the string inverter leads in all categories as a prominent inverter that needs to be considered for widespread use 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. In terms of power loss, the string inverter exhibits lower losses compared to both the central and string inverters due to higher mismatching losses from an array module configuration. Switching losses are also a concern since they might affect performance, especially when there are issues with inverters in a central or multi-string inverter connection. Central inverters have very high losses because of the strings connected in parallel. Regarding cost, string inverters have a lower cost than central inverters, as the installation for DC and AC cables is higher for a central inverter connection. The total financial losses, based on initial costs, repair costs, and financial losses due to downtime for system recovery, also indicate the potential of string inverters to become reliable systems for solar PV plant generation [10].

Table 1: Comparison of performance between the inverter topologies

| | | Central | String | Multistring |
|---|---|---|---|---|
| eneral Characteristics | 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 |

## 3. MONITORING AND EVALUATION

A string inverter is equipped with a smart logger apparatus as a data collector, which is acquired for the monitoring system to record the data, including inverter, box-type transformer, and meteorological parameters dataset. The data is transferred to the supervisory control and data acquisition (SCADA) system through fiber-optic cables, as shown in Figure 6. The string inverters communicate with the smart logger through power line communication (PLC). The signal from the smart logger is then relayed to SCADA through a switch via an optical cable. Therefore, the SCADA monitoring system can observe the data up to the string level of the LSSPV plant. The string inverter with smart logger interfacing provides opportunities to view them in a human-machine interface (HMI), as shown in Figure 7.

The concept of string-connected inverters 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 the inclusion of multi-MPPTs of the string inverters, the efficiency of the inverter can be increased in multiple operational environments, such as during shading and different string module output power at respective tilt angles. Another advantage of string inverters over central inverters is that when there are any defects in the PV module, inverters, or related performance issues, an individual or respective unit can be easily swapped out rather than requiring site repairs or partial shutdowns. Each string inverter consists of 4 MPPTs with 8 inputs, as shown in Figure 4.

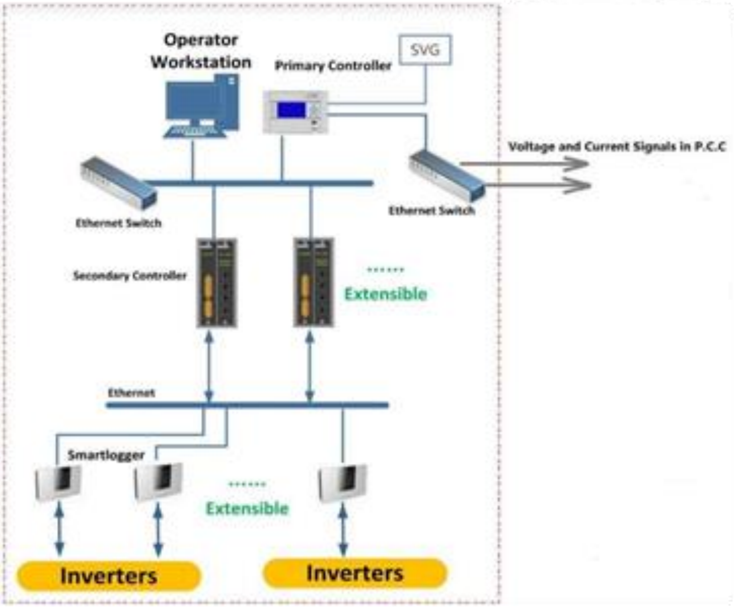


Figure 6: SCADA monitoring system from the string inverters

Figure 7: String inverter HMI facilities

## 4. SITE TESTS AND RESULTS

The performance of string inverters to increase energy production for the plant is verified through the ramp rate (RR) test procedure as shown in Figure 8. The test shows that the sample has a normal ramp rate since it can increase the output during normal operation as a normal start-up criterion. The string inverter can achieve ramp-up (U1) from the shutdown of (D1) for less than 15% of the required registered capacity per minute at 7.5 MW/min as sample shown in Figure 8. The string inverter also demonstrates the ability to restart until 100% of 50 MW without any adverse behaviour and resume full delivery of energy within 12 minutes upon reclosing of the solar power plant interconnection.

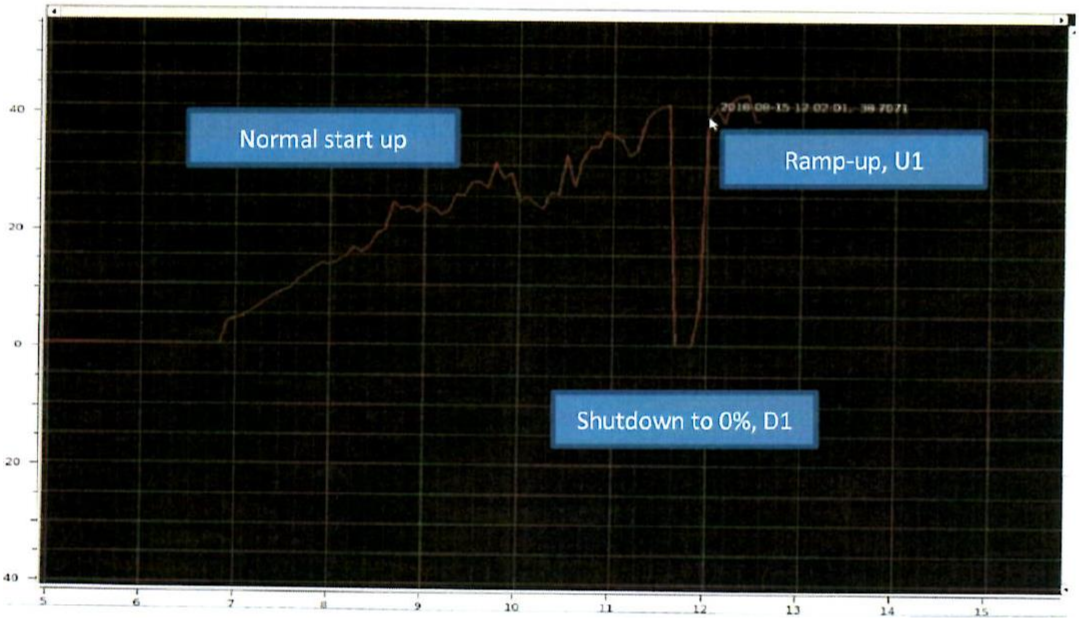
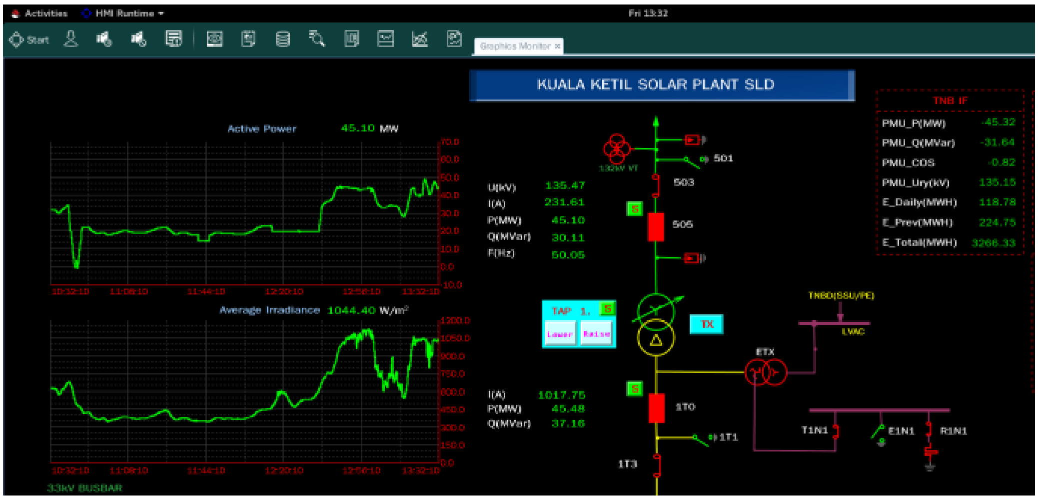


Figure 8: Sample of ramp rate test for string inverter

For reactive power capability as part of the standard requirement for the LSSPV plant, a string inverter system offers an appropriate reactive ($V_{ar}$) power to assist the plant in successfully passing the reactive power capability of the grid code test. The solar power park should meet the 0.85 pf lagging and 0.95 pf leading at 90% of the reporting condition for at least 45 MW, based on the Malaysian Grid Code requirement for the LSSPV power plant. Test 1 was conducted between 1.32 pm to 1.43 pm to achieve a 45 MW lagging power, as shown in Figure 9 and Figure 10, while Figure 11 and Figure 12 illustrate the achievement of peak power of 45 MW leading between 1.05 pm to 1.15 pm.



Active Power 45.10 MW
Average Irradiance 1044.40 W/m²

U(kV) 135.47
I(A) 231.61
P(MW) 45.10
Q(MVar) 30.11
F(Hz) 50.05

I(A) 1017.75
P(MW) 45.48
Q(MVar) 37.16

PMU_P(MW) -45.32
PMU_Q(MVar) -31.64
PMU_COS -0.82
PMU_Ury(kV) 135.15
E_Daily(MWH) 118.78
E_Prev(MWH) 224.75
E_Total(MWH) 3266.33

Figure 9: Start time at 1.32 pm (lagging)

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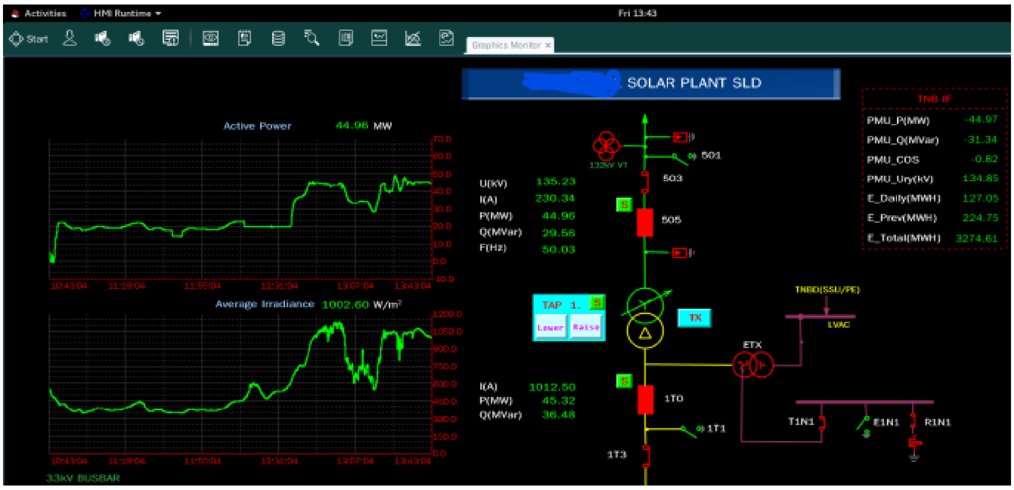


[redacted] SOLAR PLANT SLD

Active Power 44.96 MW

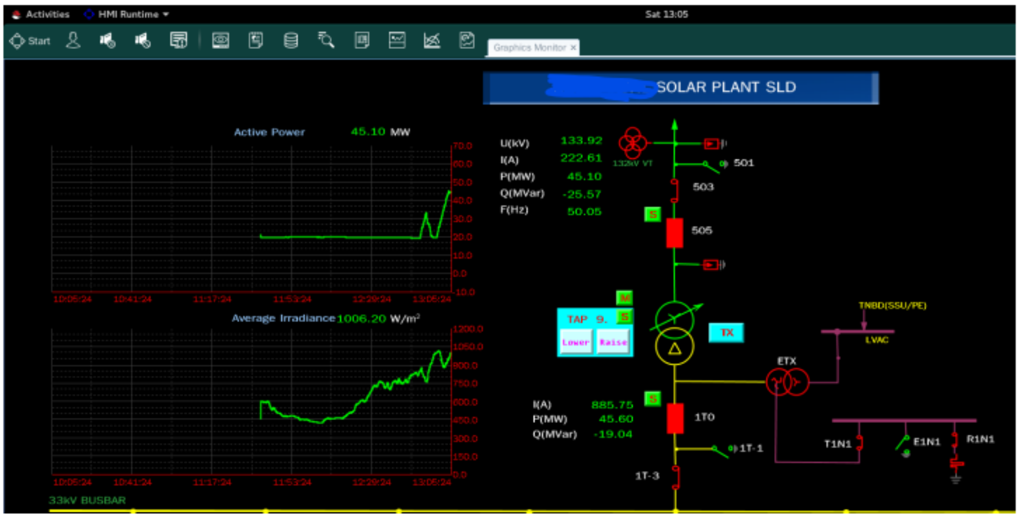
Average Irradiance 1002.60 W/m²

U(kV) 135.23
I(A) 230.34
P(MW) 44.96
Q(MVar) 29.56
F(Hz) 50.03

I(A) 1012.50
P(MW) 45.32
Q(MVar) 36.48

PMU_P(MW) -44.97
PMU_Q(MVar) -31.34
PMU_COS -0.82
PMU_Ury(kV) 134.85
E_Daily(MWH) 127.05
E_Prev(MWH) 224.75
E_Total(MWH) 3274.61

Figure 10: End time at 1.43 pm (lagging)



[redacted] SOLAR PLANT SLD

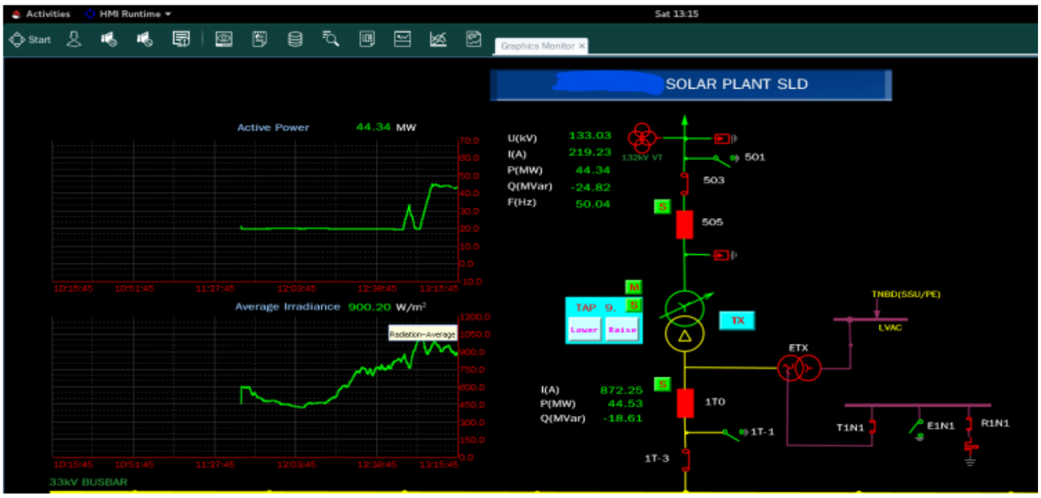
Active Power 45.10 MW

Average Irradiance 1006.20 W/m²

U(kV) 133.92
I(A) 222.61
P(MW) 45.10
Q(MVar) -25.57
F(Hz) 50.05

I(A) 885.75
P(MW) 45.60
Q(MVar) -19.04

Figure 11: Start time at 1.05 pm (leading)



[redacted] SOLAR PLANT SLD

Active Power 44.34 MW

Average Irradiance 900.20 W/m²

U(kV) 133.03
I(A) 219.23
P(MW) 44.34
Q(MVar) -24.82
F(Hz) 50.04

I(A) 872.25
P(MW) 44.53
Q(MVar) -18.61

Figure 12: End time at 1.15 pm (leading)

The samples for three (3) days of active power, as recorded for registered capacity achievement in Figure 10, also indicate that the string inverters can enhance the plant's power capacity to generate more than 50 MW during sunny weather conditions when necessary. Through the regression method, the plant can deliver a generation of 51.32 MW under the proposed value of MW since each inverter is supported by related $kV_{ar}$ generation to the plant system.

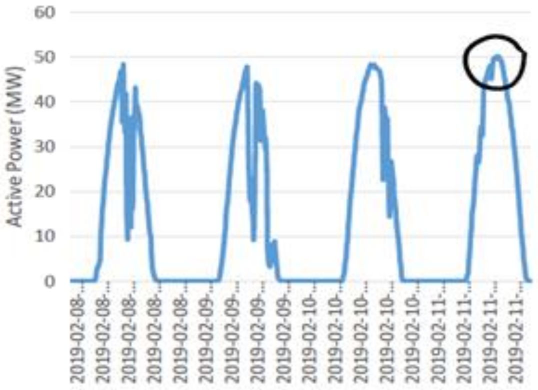


Figure 10: Daily active power recorded for establishing capacity test

## 5. CONCLUSION

From the inverter site test conducted up to the string configuration of a large-scale solar PV power plant, it is proven that the string inverters can provide an optimal conversion of energy at the desired plant capacity. Based on Malaysian cloudy weather which tends to harvest different solar irradiance in a large-scale area, a string inverter is a prime solution to be chosen as DC to AC conversion for maximum harvested energy. The rate at which the inverter can increase the plant energy production is proven that the ramp rate (RR) is less than 15% of registered capacity requirements and can restart with full delivery of energy within 12 minutes after reclosing the system. The results from the grid code test observed that this configuration fulfils the requirement of the grid code test requirement to hit at least twice 50 MW generation for establishing capacity test with the assistance of $V_{ar}$ of the string inverters at 90% of power condition.

The reactive power capability test at 45 MW lagging and leading has met the required criteria, with a variation in real power recorded for the duration being less than 2% due to irradiance change. The string inverters also provide a valuable solution and cost-effectiveness for the benefits of operation and maintenance activities. All the PV modules can be remotely monitored through a string inverter for a 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 a higher MW per day. Therefore, in the Malaysian irregular site topology and uncertainty of cloudy phenomena, a string inverter offers the best solution for harvesting maximum energy generation for the grid-interconnection system.

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## CONFLICT OF INTEREST

The authors declare no conflict of interest regarding the publication of this paper.

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