Assessing the Integration of Large-Scale Solar PV to a Nine-Bus Power System

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Abstract. Solar energy has numerous promising features which also includes CO$_2$ reduction. The adoption of large-scale solar PV ensures that demand can be satisfied by utilising renewable energy and reduces the dependency on the conventional non-renewable energy resources. Bringing this energy to widespread consumers requires transmission medium. However, controlling and bringing the harvested energy to the homes and industries is a task which needs attention. According to the various researches, it is deduced that the implementation of large-scale solar PV will have a marked effect on the grid which may lead to instability. The main obstacle to implementation is the distribution and transmission of energy to the recipients. In this study, the efforts are put to design the large-scale solar PV suitable for Malaysia using Pvsyst designing algorithm and the designed LSS PV is studied in a power system analysis tool to analyse the potential difference variation in different buses when connected to the nine-bus power system. Three solar PV models were selected based on their efficiency; among them two best PV model were obtained by conducting PVsyst simulation. The power output respect to time obtained from the simulation is used as inputs for conducting steady state stability analysis on nine bus power system to understand the voltage fluctuations when the LSSPV is integrated to the power system.

1. Introduction

With an aim to shift from fossils to zero-carbon energy generation by 2050, solar energy is evident to provide the needs for this resolution [1]. The rapid development of solar photovoltaic and cost declination has contributed to the deployment of solar PV in many countries [2]. An extensive system consisting of many PV modules and the power generated from it is fed to a power system network comprising of various electrical and electronic equipment’s, this whole system is a centralised system known as large-scale solar PV system. Large-scale centralised grid-connected PV system is a primary focus of this study, even though there are still many parameters which are expected to have a significant effect on the power grid [3]. Solar photovoltaic energy extraction is based on the phenomenon of the photovoltaic effect. This free energy is mostly available during daytime as evident due to the sun, and at the same time, the likely peak demand is more during this time. Hence extracting this energy for our use would reduce conventional generation in huge numbers [4]. Another important aspect of large-scale solar PV is the extraction of energy available in abundance in an earthly plane. With the enormous advantages of solar PV, there are still limitations that need to be solved. The new challenges and technical concerns are being discussed in the following sections which addresses the impact of large-scale PV systems on the power grid.
1.1 Solar Variation
Solar variability due to irradiance and temperature, as a fact, does not offer a constant generation for the desired duration. Another critical factor for the intermittency of PV generation is the shading effect caused by the clouds [5, 6]. This factor is one of the challenges for the large-scale solar PV where the cloud cover affects the dynamic change in generation output which leads to the sudden load change in the power system.

1.2 Economic Dispatch
Economic dispatch refers to switching on or off of the different types of generators to match with the load, and the result is an economical operation saving fuel and resources [7]. Conventional AGC cannot handle the specific problems of economic dispatch for the Solar PV due to variable nature of output generation [7-9]. For a solution, proposing an algorithm for optimal economic dispatch and unit commitment of PV generation [8]. It involves forecasting the PV generation and then committing conventional generators and storages also importing from other tie-lines. Hence, thorough monitoring and control are required. A study by the U.S. for determining the stability and performance of high penetration solar PV on power system network was performed where they discovered that the individual PV units should have a good performance for a large-scale PV system for the stability perspective. Deducing that economic dispatch and unit commitment is also one of the factors that influence the power system network [10].

1.3 Power System Challenges
Similar investigations were conducted for determining the challenges of integrating large-scale solar PV to the power system network, in which the questions to be answered were mainly the variation in PV output generation, lack of inertia and uninstalling the conventional synchronous generators which helped in providing reactive power. The possible answers and solutions were found to be, improving dispatch strategy, adopting spinning reserve, maintaining the voltage and frequency level in the power system and providing inertial stability [11]. As explained earlier, with variation in several parameters such as irradiance, wind and temperature. This will cause the generation profile of PV to vary. Keeping that in mind, an algorithm based on probabilistic power flow method (PPF) was developed which accounts conventional power generation which is used to cover the unbalance of the load-supply mismatch caused due to the variation of PV. However, it was found to have some drawbacks such as voltage and frequency fluctuations. [5, 11, 12]. It has been seen from the above reviews, the amount of penetration level required for sustaining the stability of the transmission system through a combination of conventional generation. A study from Denmark provides renewable energy mix including other renewable technologies with the conventional generation to solve the same problems [13]. Other power system challenges involve reverse power flow, fluctuations in voltage level and steady-state response which requires protection. Hence, electric power inverters consist of protection capabilities such as protection against overcurrent, undercurrent and frequency stability; and protection against unintentional islanding [14-16]. Upcoming inverters are required to provide the above protections and some other new functions such as regulation of voltage, power curtailment, ramp-rate control and smart protection; whose research is still in progress [14]. Another important function that is required is the reactive power injection. An analysis came up with an RPI-APC algorithm for voltage regulation [16]. The voltage fluctuations due to dynamic changes in PV generation mitigation came up with two techniques that are, unity power factor control and automatic voltage control methods. However, the application of unity control method was limited to small-scale PV systems [17, 18].

2. Grid Code Requirements and Load Flow Analysis
Large-scale solar PV possess challenges regarding connecting it to the power system network; hence grid codes are essential for perfect integration of the PV system to the power grid [24]. Grid codes need to be updated that supports and adopt the variable renewable energy technology. The following grid codes are endorsed for 30 - 50 MW, capacity transmission network, connected large-scale solar PV plant by energy commission. For any symmetrical or unsymmetrical faults, the PV power plant
should be connected to the transmission line, and it should withstand the failure is cleared. According to CC6.4.15.2 of grid code for Peninsular Malaysia 2016 states that for any symmetrical or unsymmetrical faults, the solar PV power plant should be connected to the transmission line for at least 150ms. After the fault occurs, the transmission voltage should be back to 90% of its nominal voltage within 1.5 seconds.

The standard voltage limits for 500, 275 and 132 KV voltage levels are ±5%. According to CC6.2.3 of grid code for Peninsular Malaysia 2016 states that the nominal power system frequency should be 50 Hz and should be within limits 49.5 Hz to 50.5 Hz except for exceptional circumstances. For extraordinary circumstances, the limits are 47.0 Hz to 52.0 Hz. It is necessary that the active power control match with the solar energy variation and the grid code requirements. Hence, the PV plant should have an active power control for the change in system frequency. The below limits shown in the graph from the code CC 6.4.2.3 lies from 47.0 Hz to 52.0 Hz. The code states, active power control should be independent of system frequency lying between 47.0 Hz – 50.5 Hz. After 50.5 Hz the active power follows the droop setting set by the grid system operator, which is a drop in active power to 40% of rated MW at 52.0 Hz. Another constraint which falls under active power control is the power gradient or ramp rate limit. This is an essential factor which sets the value for increasing or decreasing the active power; its units are MW/min. PV plant should be able to control the power within a ramp rate of 15% of the rated capacity per minute.

Connecting a Solar PV plant to a grid requires control of the voltage which further involves two fundamental challenges. First, the voltage should be maintained within a dead band prescribed by the grid system operator; second, the PV plant must fulfil the capability curve specified by the grid system operator. Voltage regulation and reactive power control are some of the methods for controlling the voltage [15]. Malaysia grid code employs voltage and power factor control. CC 6.4.2.1 of grid code for Peninsular Malaysia 2016 mentions that the power plant must supply the rated output within the power factor limits of 0.85 lagging to 0.95 leading. According to voltage variation stated earlier, the power plant should provide the reactive power within the range of ±10% of the rated voltage. The grid code for Peninsular Malaysia 2016 does not clarify the reactive power requirement for dynamic operating conditions. Load flow analysis or load flow studies is essential in determining voltage, current and power factor at various points of a standard operating power system network this helps in developing the power system that is tolerable to effects due to installation and interconnection of new transmission lines, power plants, new loads and even variable generation sources. Consider a four-bus system and bus 1 be the slack bus, so computation starts for bus 2.

3. Methodology
3.1 Site Selection and Land Availability
The significant part of a large-scale solar PV system is the determination of a location that is most suitable, as this gives the strength to LSS PV contribution towards the energy harvesting. The location for LSS PV is selected based on four reasons, namely, land availability, energy yield, energy consumption and transmission losses. Large-scale solar PV development plan by the Malaysian government is initiated and the projects are distributed among the bidders and to design an LSS PV system and conduct the power system analysis, it is wiser to select the locations prescribed by Malaysian government which are held under their control. Government has made an effort to deploy solar PV farm of capacity up to 50 Megawatts, which is still a low capacity deployment due to the fact, the government can utilize solar energy which is available in abundance in Malaysia in order to reduce fossil fuels energy generation. However, various factors need to be considered, and among them, power system stability is a major concern. Perak and Kedah are the two dominant states which contribute 20 and 19 percent respectively of the total Malaysia estimated capacity. Thereby, it is understood that these states have an abundance of land availability for LSS PV.
3.2 Energy Yield and Consumption

It is vital to know the amount of energy that can be harvested in different states. Labuan and Sabah are at the top among all the states in terms of irradiation value having irradiation levels of around 5.65 KWh/m$^2$/day and the lowest in Johor state of about 4.6 KWh/m$^2$/day. Data for electricity consumption by state is not available. Therefore, the load demand was estimated using population factor. With an understanding that population is directly proportional to consumption neglecting other factors, undertaking this analysis. Based on this assumption, Selangor has the highest electricity consumption of about 19.9% followed by Sabah at 12% and the lowest at Labuan of 0.3%.

3.3 Transmission Losses

It is crucial that the energy harvested is transported to short distances; this is because the transmission lines have an impedance which increases with an increase in transmission line length. This impedance contributes to power losses within the line. Other essential factors that contribute are skin effect and corona loss for long transmission lines. Hence it is required to keep the lines as short as possible. Among all the factors considered, transmission loss is kept at highest priority to reduce losses. Thereby, Selangor which has a high population density and energy consumption and can provide short distance transmission compared to other states is a selection. Although land availability is scarce, the government has allocated land of a capacity of 50 MW which is in the high capacity placement range, and irradiation levels are satisfying which is around 5.04 KWh/m$^2$/day. Hence, the analysis proceeds further with the selection of Selangor as the location of LSS PV deployment.

3.4 Designs

Design 1 consists of the combination of SunPower PV module and SMA inverter. With an annual degradation of 0.25%, the energy production at a 25$^{th}$ year would be 93.75% of the total capacity which is 46.2 MW$_{ac}$. Hence, inverter capacity is based on the 25$^{th}$ year capacity to fully utilise the inverter till the LSS PV system lifetime. Design 2 consists of the combination of Suntech module and SMA inverter. With an annual degradation of 0.7%, the energy production at a 25$^{th}$ year is 80.7% of the total capacity that would be 40.34 MW$_{ac}$. Design 3 consists of the combination of First Solar module and SMA inverter. With an annual degradation of 0.5%, the energy production at a 25$^{th}$ year is 86% of the total capacity, that would be 43 MW$_{ac}$.

3.5 Power System Analysis

It is difficult to extract the real data of Malaysian grid, and at the same time, the data would be confidential. Hence a test system derived by IEEE is taken for testing the solar PV systems with its generation profile. The average generation profile during December is used for the load flow analysis based on the reason that December had most of the rainfall in Malaysia, which led to most of the cloud coverage which might have an adverse effect on generation and system voltage. Hence, analysing on this profile is decided. With the analysis results, the primary focus is the deviation of the voltage level in the buses when Solar PV is connected. The analysis is done for the integration of the LSS to every bus except the generation buses. Noting that the solar PV plant needs to be stepped up to 320 KV using a transformer of the desired rating to connect it to the grid. IEEE 9 bus system has been taken for this analysis for its convergence to the result. Figure 1 shows the IEEE 9 bus system with its data. It is an equivalent network of Western System Coordinating Council (WSCC). The analysis is done for integration of Solar PV to buses 4 to 9.
4. Result and Discussion

From the three designs, Sunpower and first solar have good performance while Suntech lacks behind. Both, Sunpower and First Solar generate around 80 GWh/year for the first year having an almost similar capacity factor of 18%. Generation by Suntech is 78 GWh/year for the first year and has a capacity factor of 17.9%. As a Solar tracker is installed, the curve in the generation profile of all the three designs forms a broader curve, increasing generation between 08:00 to 11:00 and 17:00 to 20:00.

Maximum generation for all the three designs is obtained during March. Among Sunpower and First Solar, First Solar is comparatively economical, but the technology of First Solar is CdTe which is more hazardous to the environment compared to Sunpower’s technology of mono-silicon. On the other hand, Sunpower takes less space compared to First Solar.

The load flow analysis for integrating all the three LSS PV to IEEE nine-bus power system shows similar response as the magnitude of energy injected ranges between $41 \text{ MW}_{ac}$ to $47 \text{ MW}_{ac}$. Hence, there is not much difference. When the LSS PV is integrated to IEEE nine bus system at bus 4, it can be observed that there is very slight fluctuation in voltage stability in the buses, there is mostly increase in voltage. However, the fluctuations are not too large and are within limits. When the LSS PV is connected to bus 5, the voltage fluctuations are increased, and the voltage increase is observed in bus 5, higher compared to other buses. However, the deviations are not too extreme. Hence, compensation devices can be used at bus 5 to suppress the fluctuations. The LSS PV penetration into bus 6 results in the same behaviors of integration to bus 5, but the voltage increase is observed in bus 6. Large scale solar integration into bus 7 led to voltage drops, and buses 4, 5 and 6 are mostly affected. Hence, more reactive power compensation or other compensator banks are required compared to the previous scenarios. When bus 8 is integrated with LSS PV, voltage drops are observed in buses 4, 5 and 6; voltage increase in bus 8. Therefore, different types of compensators are required both reactive power injection and extraction. LSS PV integration to bus 9 shows similar behaviour as to the integration of LSS to bus 7. Hence, the same solutions are required for this scenario. The stability of the system reduces in the order of LSS PV integration to the buses. Hence, integrating the LSS PV to bus 4 is more stable, and integration to bus 8 is worst. Here,
steady state stability of the IEEE nine-bus power system is studied and its adverse effects and solutions.

![Energy injected into the grid by three LSS PVs](image)

**Figure 2.** Energy injected into the grid by three LSS PVs

5. Conclusion
Sunpower and First Solar produces almost the same amount of energy. Sunpower has better performance compared to the first solar. Though CdTe technology being hazardous to the environment especially during decommissioning, it can be dealt with by taking precautions and continuous monitoring during its lifetime. It is advisable to opt for First Solar considering based on economic factors. With the help of load flow analysis, different scenarios were discovered in which the potential difference variation in the buses varied from the integration of large-scale solar photovoltaic systems to different buses. It has been observed the affect on power system network due to integration at various locations and variation in magnitude of the LSS PV. An optimal bus for integration of LSS is determined which gives a stable power system. However, in real time integration of LSS PV to the grid is not pre-determined, i.e., the connection could be at any bus, at that moment this analysis gives the effects on the power system and the requirements to compensate the problem. Hence, determining of compensation devices like capacitor banks, synchronous machines, flywheels and other reactive power injection methods is made accessible to place it at the right position or bus. With the latest inverter technology of reactive power injection by SMA inverters, it will help solve this problem much faster. This analysis further helps in designing or adjusting a vast power system network for large-scale solar integration and other such renewable energy integration. It also helps in the microgrid and smart grid designing for stable operation of the power network.

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