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Power Efficiency Analysis based on Lightning Effect on Large-Scale Solar Photovoltaic System

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ABSTRACT

Currently, a large-scale solar photovoltaic (LSSPV) has become one of the fastest developments of electrical generation power for Malaysian Renewable Energy. However, lightning strikes are common in Malaysia due to its geographical position and tropical climate, especially in the open space of large-scale site power plants. This paper discussed the scientific basis and key assumptions that should be included in the layout of a lightning protection scheme in a large-scale solar photovoltaic installation. The framework proposal aims to ensure compliance with standards and guidelines, mitigating the risk of significantly induced currents in the LSSPV power plant. A 2.5 MW solar PV farm system was modelled using MATLAB software for assessing a solar PV farm's electrical performance under various lightning current waveforms and lightning magnitude currents. These lightning strikes will impact photovoltaic modules, thus deteriorating the system's ratio generation. The effects of lightning current on LSSPV were accessed based on simulation work in MATLAB Simulink. The induced current protection scheme covered rating selection and collecting data on lightning that may hit the modules or arrays. This data was then analysed according to the standard guidelines to ascertain the most effective protection measures for the 50MW PV farm within the LSSPV system. Minimising the maintenance and replacement cost of equipment is possible. The performance of a 2.5MW solar PV power plant with a grid connection was evaluated. A maximum and minimum power output of 2.47MW and 522.50kW, respectively, were observed. However, when the lightning impulsive current is included through the system, the power output decrease to 407.33kW due to the high magnitude induced.

1. Introduction

Electricity has become increasingly crucial in daily life. Electricity is becoming increasingly important for growing electrical energy-developing industries [1]. Previous research on lightning protection of PV systems has attracted much attention [2]. As a result of the increased likelihood of

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such systems being hit by lightning, several studies have been undertaken on lightning and photovoltaics [3]. Three different categories of PV systems can be installed: Residential (Residential), Commercial (Private/Industrial) and Solar Farm. Previous simulation studies and hardware implementations show lightning damage to the PV system installations. Exposure to lightning impulse voltages causes several types of electrical degradation [2,4]. In addition, the direct lightning strike on the PV panel also caused the high magnitude lightning impulse current [5-7], reducing the effectiveness of the PV module or even damaging the modules.

Green buildings help the construction industry meet energy and water efficiency standards, reduce natural resource use, and improve health and the environment. Green building rating tools such as Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), and Green Mark evaluate and identify buildings that meet certain green requirements. Malaysia, on the other hand, uses GBI as a standard requirement for green buildings. The criteria included in the standards are energy Efficiency, Indoor Environmental Quality, Sustainable Site Planning & Management, Water Efficiency, and Innovation [8].

Solar collectors, which can be perceived as specialised heat exchangers, transform solar radiation energy into internal energy transported through a medium. The solar collector is the primary component of a solar system. It absorbs solar radiation from the sun, transforms it into heat, and transfers it to a liquid moving through the collector, with 60% effective heat conversion. Solar collectors are frequently installed at an angle rather than horizontally to increase the intercepted radiation and decrease reflection and cosine losses [9]. A high-performance heat exchanger with excellent heat transfer efficiency can reduce costs, materials, and energy usage. The performance factor, defined as the ratio of the relative effect of change in heat transfer rate to change in friction factor, can be used to assess the effectiveness of heat transfer enhancement [10-12].

Conventionally, LSSPVs are not fully secured from lightning strikes. The PV systems can be susceptible to unbecoming lightning damage, impairing the building's electrical and electronic components or the PV system. These potential accidents will disrupt their normal operation. The potential Return of Investment from solar power generation will be adversely affected too. However, implementing a Lightning Protection System (LPS) could mitigate the cost of PV system maintenance.

This work aims to present the scientific background and the essential assumptions that must be introduced when designing lightning protection systems (induced current) in photovoltaic systems. Besides that, the article also summarised the LPS criteria based on the standards and guidelines.

2. Methodology

2.1 Modelling 2.5MW LSSPV Power Plant

Figure 1 shows the 2.5MW Solar PV system Block Diagram without Lightning Protection Scheme. Currently, the solar PV system study was modelled in MATLAB, consisting primarily of a PV array model, a boost converter, a three-phase inverter with (IGBT), and an LCL filter. The photovoltaic array icon in MATLAB was designed to generate 2.5 MW from 10 series-connected modules per string consisting of 660 parallel strings.

The purpose of a boost converter is to switch rising from a changing solar panel voltage to a consistent DC voltage. It employs voltage feedback to maintain a steady output voltage. Then, by using the IGBT, the DC output is changed into an AC output. These Sinusoidal Pulse Width Modulation (SPWM) is used to generate the IGBT firing pulses approach, which compares A triangular carrier wave modulated by three sinusoidal modulating waves.

To allow LSS to be connected to the Transmission Network, it must have a capacity of at least 30 $MW_{ac.}$ These must be approved by the Commission at one Interconnection Point (Point of Common

Coupling, PCC), as demonstrated in Figure 1. The connection can be made at any point along the Grid System to enable the export of power produced by the transmission-connected LSS. Nevertheless, it depends on the acceptable power output from a transmission-connected LSS [13].

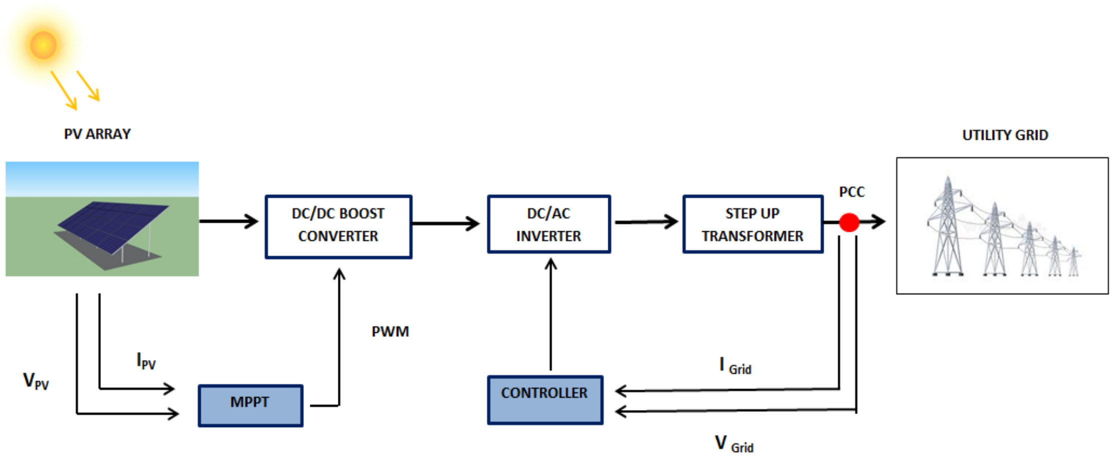

Fig. 1. 2.5MW solar farm system block diagram

Figure 2 shows the PV system's steady-state circuit. PV panels are connected to IGBT as inverters to change DC to AC. LC filter is used to smooth the AC waveform. Three-phase parallel RL load is connected to the test circuit for drawing current. The scope is used to see the output.

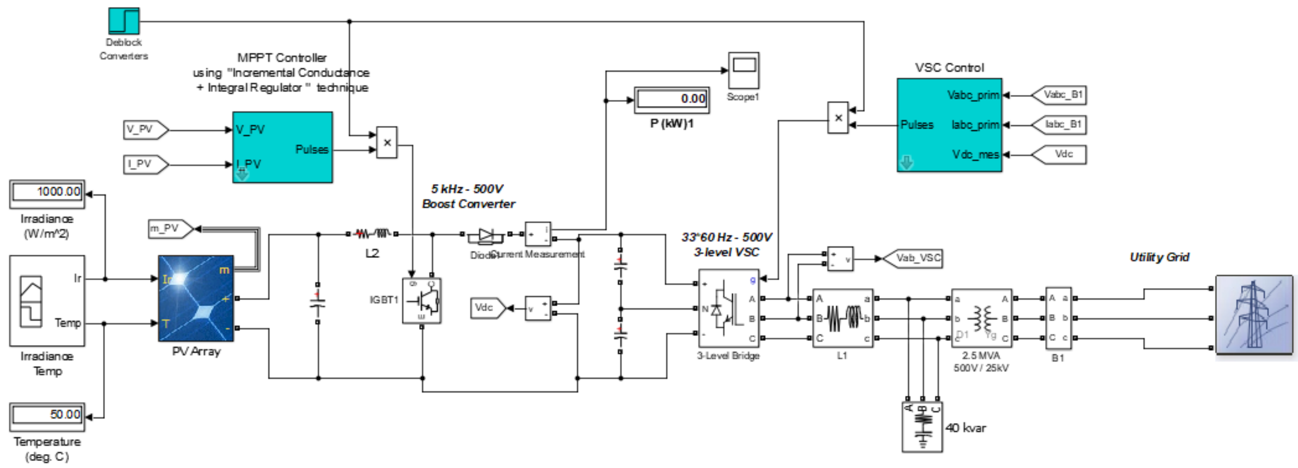

Fig. 2. Test case: steady-state circuit of the PV system

Table 1 shows the parameter of this test case used.

Table 1
Parameters used in steady state test case circuit

Block/Component name	Parameter
Irradiance	1000w/m
Temperature	25°C
Capacitor, C1	100 µF
Inductance filter, L	5mH
Capacitor filter, C	100 µF
Three-phase parallel RL load	Vn= 500V, Fn = 50Hz, P = 2.5MW PQL = 40kar

Table 2 shows the Technical Specifications of Topsun TS-S238TA1.

Table 2
Technical specifications of Topsun TS-S238TA1

Cell Type	Monocrystalline Silicon
Number of cells per module (Ncell)	60
Maximum Power (W)	238.0118
Open circuit voltage Voc (V)	36.53
Voltage at maximum power point Vmp (V)	29.53
Temperature coefficient of Voc (%/deg.C)	-0.34399
Short-circuit current Isc (A)	8.58
Current at maximum power point Imp (A)	8.06
Temperature coefficient of Isc (%/deg.C)	0.05

Figure 3 shows the power output from the 2.5 MW Solar PV systems. The results show that 522.50kW.

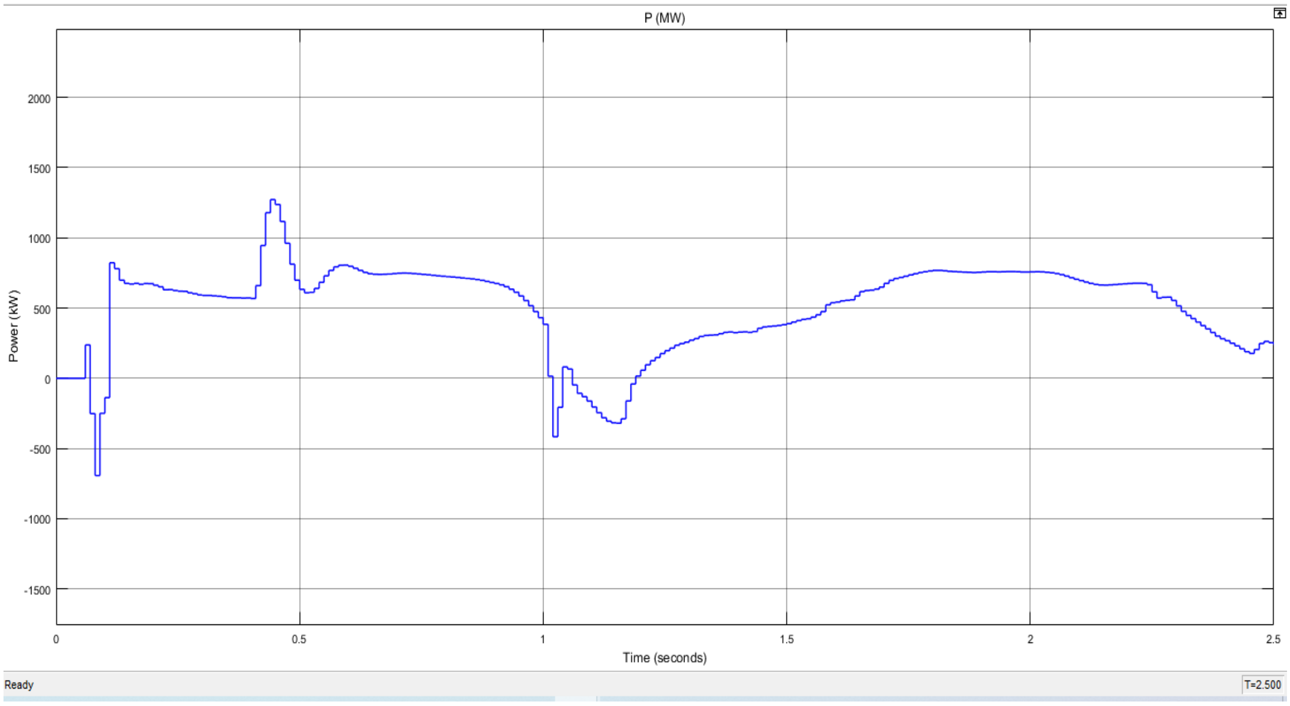

Fig. 3. Power output from solar PV system

While Figure 4 shows the output waveform of the PV panel. From t=0 to t=2.5 seconds, The boost converter's duty cycle is fixed (D= 0.5). The PV array power output is 522.50 kW. At t=2.5 seconds, the MPPT is 0. When the duty cycle is D=0.5, Maximum power (2.47 MW) is obtained. From t=0 seconds to t=0.5 seconds, the PV array is tested under standard conditions (25 degrees Celsius, 1000 W/m2). Duty cycle, D constant at 0.5. PV voltage = 2300 V and mean power = 2.47 MW is predicted from PV module specifications. From t=0.5 seconds to t=1.5 seconds, the sun's irradiance is reduced from 1000 W/m2 to 250 W/m^2. As can be seen, this type of MPPT controller only tracks maximum power while irradiance remains constant. From t=1.5 seconds to t=2.0 seconds, when the irradiance remains constant and equal to 250 W/m^2, the duty cycle D varies between 0 and 1. Corresponding PV voltage and power are V_PV= 2300V and Pmean =2.155MW. From t=2.0 seconds to t=2.5 seconds, solar irradiance is restored to 1000 W/m^2, and then the temperature varies between 50 degrees

Celsius and 0 degrees Celsius. The PV output power is measured at the lowest temperature to observe the effect of temperature.

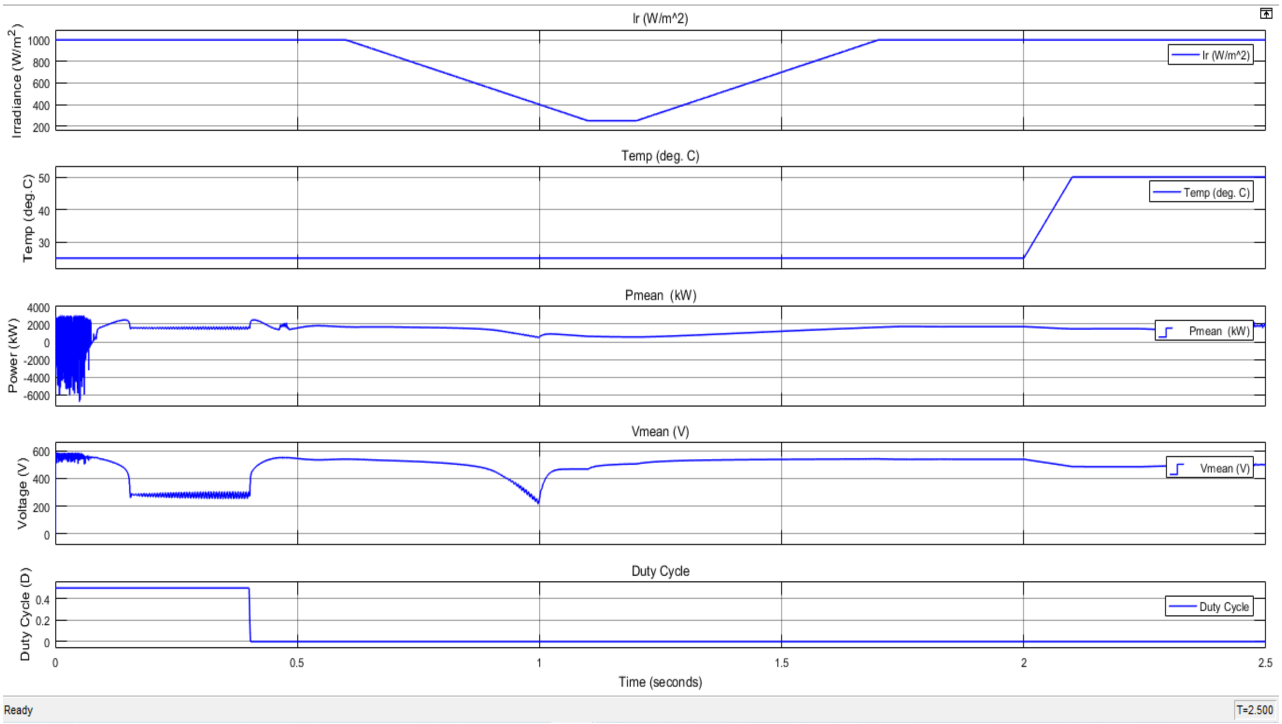

Fig. 4. Output waveform of PV panel

2.2 Previous Study of Lightning on PV System

As a result of significant advantages to the country, The advancement of solar PV systems has been gradually growing in the future [8,9].

Figure 5 illustrates the amounts of RE created due to the FiT system in Malaysia. There are four eligible renewable resources under the FiT scheme: biogas, biomass, small hydropower and solar PV. Solar PV has the highest contribution and is expected to be developed rapidly in Malaysia in the future. Mostly the system was installed in a wide open area, and there will be a high risk of being struck by lightning, particularly in lightning-prone areas.

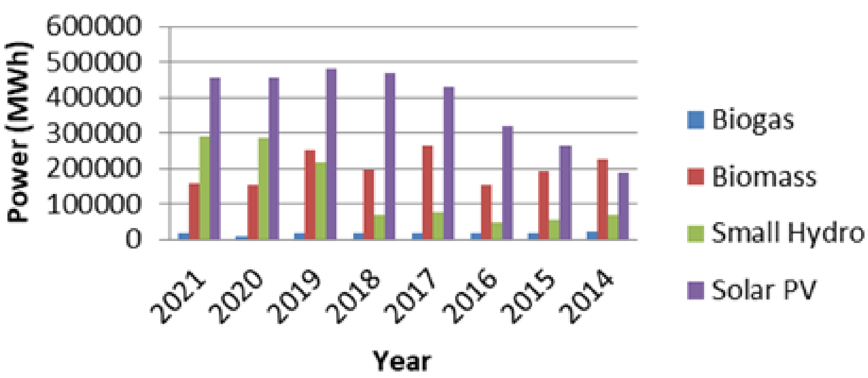

Fig. 5. Annual Power Generation (MWh) of Commissioned RE Installations [14]

Previous research studies investigated the implications of solar PV modules or systems energised by lightning. The results indicated that a sudden lightning hit would cause damage to the PV modules or systems. As can be seen from the result, a lightning strike or an energetic load could be the main causes of the deterioration of the electrical properties, resulting in near-zero output power. Depending on the location, design, and application of a PV system, a productive lightning protection solution (LPS) is required.

The studies were focused on direct lightning that hit the PV panel. It shows that the surface discharge occurs when a frame is grounded, which might help prevent direct lightning hits on PV panels [5]. Besides, the affected PV was triggered when a bolt of lightning struck. The indirect lightning strikes caused the discard of a high voltage between the cables and the cells induced that will disrupt panels. These caused no power output from panels [12].

2.3 Induced Current Protection System

By analysing the data from three utility-scale repair logs of PV systems greater than 10 MW, researchers discovered some instances of PV module bypass diode failures during or following close lightning strikes. The string to which it was connected in the PV module was not powered because the bypass diode was in a short circuit condition. These caused the failure of a PV module. The bypass diodes in the module would be used to channel the current produced by the PV cells were shorted. The junction box's string monitor recorded a low-power fault, frequently necessitating the replacement of the whole PV module [13]. The current is induced because the wire between modules has a bigger loop area than the PV modules. Installing the PV module's conductive frame reduces the magnitudes of the module's induced currents. Because these PV modules lack a conductive frame, their EMI susceptibility should be investigated further.

2.4 Type of Lightning Protection System

Lighting Protection System (LPS) carries the tasks to avoid physical destruction of design and dangers to life. Therefore, LPS is an integral component in PV systems in the light of the severe damages that lightning strikes could cause. Because of the wide field of PV arrays, they are constantly at risk of being struck by lightning [14].

In order to reduce the likelihood of errors and interruptions caused by direct lightning strikes, an external LPS must be used in PV systems. When lightning strikes appear near the PV array, overvoltage and overcurrent may cause damage to PV array installations. Therefore, it is critical to install overvoltage protection. The external lightning protection system should intercept the step line with an air-termination device, initiate the lightning current protection in the direction of the earth transfer the lightning current to the ground through a down conductor and an earthing system. However, it is only covered in the area with this lightning protection. Outside the area, The PV panel could still experience damage [15].

Several experimental and theoretical studies have been conducted, with most of them focusing on analysing the surge impedance of towers, primarily electric power transmission line towers. They proposed some engineering designs to evaluate the potential increase at the lightning point. Recently proposed models include

i. models made up of many lossless transmission lines [10-12]
ii. models of multistory towers [18]
iii. non-uniform line models [19]

iv. frequency-dependent models [20]. Most previously discussed, existing works primarily focused on increasing the high-voltage power transmission line tower's highest potential. The tower base currents are not given special consideration. Because of the preceding conclusion, they cannot be used in the current study.

Earlier methods of characterising impedance attempted to use a step response activation or reactivity with a constantly increasing front. The response of the tower is clearly affected by the frequency range of the excitation. It behaved more like an antenna at high frequencies, led by transmission line actions. As the frequency is lowered, a capacitive-inductive and inductive-resistive response can be observed [15].

The intrinsic nature of biofluid resources is closely related to their thermo-physical and chemical characteristics of converting biomass waste and by-products into useful energy carriers. Evaluation of the development of biofluids production processes is necessary to lay the ground for potential applications such as providing suitable feedstocks, constructing suitable power generation systems, generating techno-economic values, and preserving environmental impacts. Because of the improvement in heat transfers, it has been found that biofluids can be used as heat transfer fluids in many thermal applications. Thermal electronics cooling applications can be made more energy-efficient and compact using biofluids in heat-exchanging devices like solar thermal collectors, micro and macro heat channels, heat engines, and thermal electronics [21].

The current LPS are the Franklin air terminal LPS and the streamer emission air terminal protection system. The protection radius in the ESE system appears to be smaller than the other method, indicating a difference between the two methods. The grounding systems of the two systems differ when using this smaller amount, which leads to a higher actual lightning arrester installation cost. In addition, the simulation revealed that the lighting consequences of the Franklin rod type were greater than those of the ESE rod type. The ESE lightning protection system was chosen to be installed in the PV power plant [22].

2.5 The Recommendation of LPS Standards for PV Systems

Table 3 recommends standards for photovoltaic systems, such as solar panels, electrical installations and lightning protection systems. A well-designed LPS with a well-placed PV panel come up with great power generation efficiency while reducing the risk of lightning. The implementation of the PV system and PV panel arrangement should be considered while designing an external LPS considered.

Table 3
The standards for reference recommended for LSSPV systems

Standards	Description
IEC 62305 [23]	Protection against lightning • Part 1 – General lightning • Part 2 – Risk management • Part 3 – Physical damage to structures and life hazards • Part 4 – Electrical and electronic systems within structures
MS 1837 [24]	Installation of grid-connected PV system
IEC 62561[25]	Lightning protection system components (LPSC) • Part 1 – Requirements for connection components • Part 2 – Requirements for conductors and earth electrodes • Part 3 – Requirements for isolating spark gaps (ISG) • Part 4 – Requirements for fasteners

	• Part 5 – Requirements for earth electrode inspection housings and electrode seals • Part 6 – Requirements for lightning strike counters (LSC) • Part 7 – Requirements for earth enhancing compound
IEC 60364 [26]	Electrical installations of buildings • Part 7–712: Requirements for special installations or locations – PV power supply systems • Part 4–44: Protection for safety – Protection against voltage disturbances and electromagnetic disturbances • Part 5–53: Selection and erection of electrical equipment – Earthing arrangements, protective conductors and protective bonding conductors
EN 50110–1 [27]	Operation of electrical installations
IEC 60904–2 [28]	PV devices, Requirements for reference solar device
IEC 62446 [29]	Grid-connected PV systems

2.6 Policy, Standards, Barriers and Issues in Solar PV Systems

The (SEDA) was established under Act 726 in 2011 to promote further RE in Malaysia, including administering and managing the FiT and NET [14]. The FiT allows electricity to be fed into the grid from indigenous RE sources and sold to power utilities at fixed premium prices and specific durations. Solar PV has the highest contribution and is expected to be developed rapidly in Malaysia in the future. The NEM (launched in 2016) scheme is a billing mechanism that allows eligible consumers who generate electricity from solar energy to get credits for the extra electricity fed to the grid [30].

2.7 Electromagnetic Induction Due to Lightning

A strong magnetic field is generated due to this surge current associated with the lightning discharge. A current is more likely to be induced as a result of the presence of large loop areas in the inter-module wiring than in the PV modules themselves [31,32]. PV panels are particularly vulnerable to lightning damage because they are exposed to the sky. Thus, components such as panels, DC lines, inverters, and other plant equipment are prone to damage. The induced voltage phenomenon, its characteristics, and its effects on a large-scale solar power plant were investigated using a properly designed lightning protection system to minimise this effect.

Utilising the Finite Difference Time Domain (FDTD) method, the Virtual Surge Test Lab (VSTL) tool measures the electromagnetic field and the induced voltage in various locations throughout the plant. Different electromagnetic interference characteristics are examined in relation to soil resistance, lightning time, and lightning locations [33].

3. Results

3.1 The Lightning Effects on LSSPV

Figure 6 depicts the lightning impulse model produced during the simulation. It simulates an impulsive transient-induced lightning strike near a transmission line. The model fed a 10 kW resistive and 10 kVar inductive loads by a 0.4 kV, 1 MVA, 50 Hz three-phase source block.

For measurement, at 0.4 kV buses, there were real-time data waveform scopes. The lightning block is attached to the feeder line to induce an impulsive transient. The long transmission line type was selected as the transmission line. The test case’s parameters include a 120 kV parameter, a 50

Hz system frequency, and a 6 km transmission line coupled to a 2 MW load and 2 km that connected to a load of 30 MW.

The typical lightning impulse characteristic is 1.2/50 s, implying that the impulse reaches its peak at 1.2 s and then begins to decline to 50% at 50 µs time.

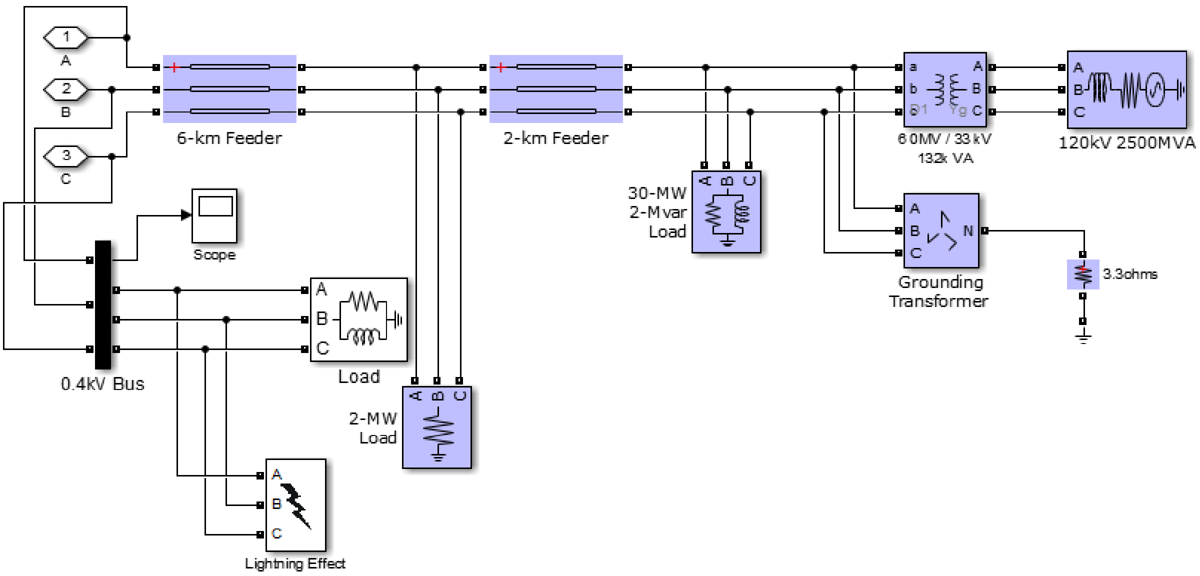

Fig. 6. Lightning impulsive transient model

Figure 7 depicts the waveform obtained using a scope sampled at 1 MHz.

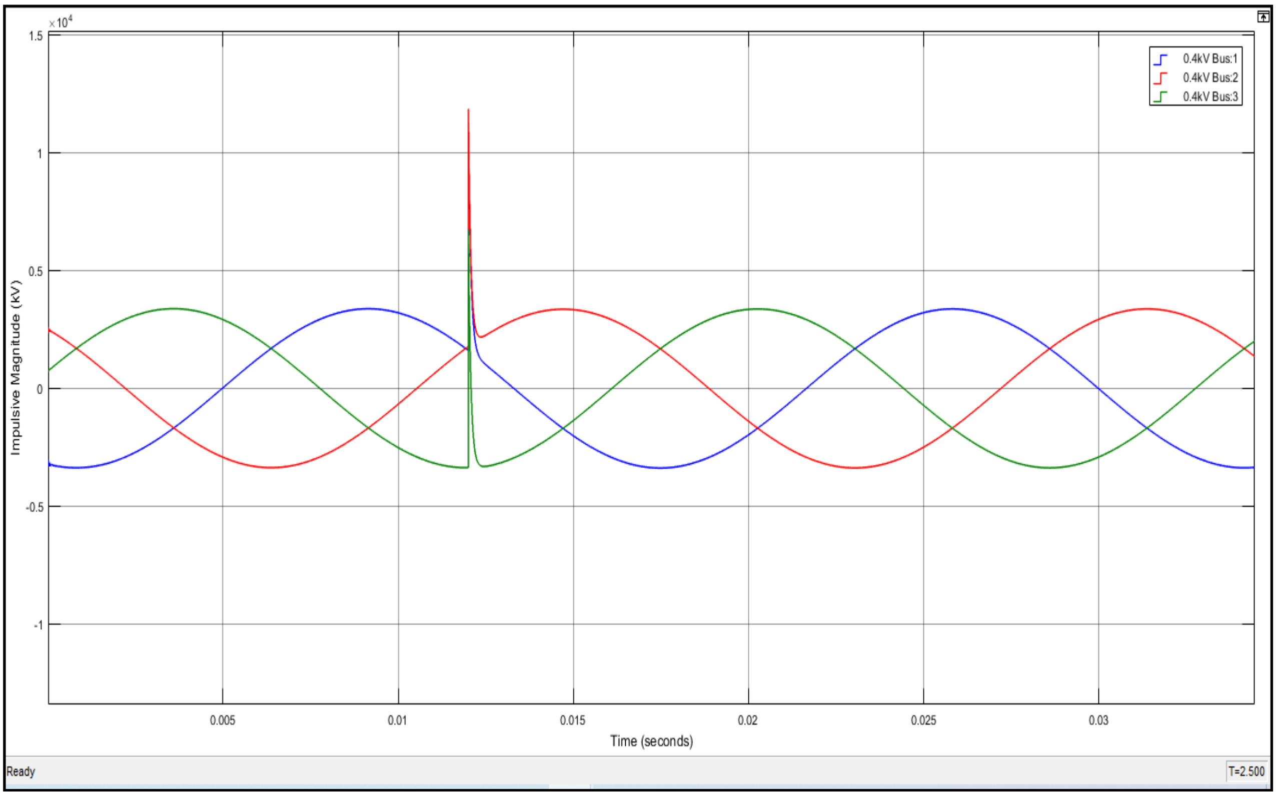

Fig. 7. Output of lightning impulsive transient

The results show in Table 4. The result demonstrated the time when lightning strikes disrupted the system. For 0.012 seconds, test instances were simulated.

For impulse magnitude, 10 kV was set, which starts at 0.012 seconds. Thus, the coupling network was set at 10 Ω and 1 µH. The impulsive transient waveform for all three phases simulation is shown in Figure 6. The function of coupling network impedance is to assess the proximity of the size of the impulsive transient magnitude induced in the waveform by the lightning discharge to the transmission line. The coupling network's decreased impedance indicates that lightning is approaching the transmission line.

Table 4 shows that Phase 2 has the highest impulsive transient, and Phase 3 has the lowest impulsive transient. The voltage loss is caused by transmission line cable impedance. These results show that the model is close to the 1.2/50s lightning impulse characteristic as defined by the standard.

Table 4
Output results in Lightning Impulsive Transient

Time sample (s)	Impulsive Magnitude (V) – Phase 1 (Blue)	Impulsive Magnitude (V) – Phase 2 (Red)	Impulsive Magnitude (V) – Phase 3 (Green)
0	-3625	-3368	-3369
0.012	11670	11850	6707
0.0125	1766	2564	-2213

i. For Phase 1 (Blue), the impulse increase from -3625 V (0 seconds) to the peak magnitude of 11670 V (0.012 seconds), then decreases to 1766 V (0.0125).
ii. For Phase 2 (Red), the impulse increase from -3368 V (0 seconds) to the peak magnitude of 11850 V (0.012 seconds), then decreases to 2564 V (0.0125).
iii. For Phase 3 (Green), the impulse increase from -3369 V (0 seconds) to the peak magnitude of 6707 V (0.012 seconds), then decreases to -2213 V (0.0125).

4. Conclusions

This study discussed the issues and assumptions related to LPS for PV systems. The performance of a 2.5 MW solar PV power plant with a grid connection was evaluated. A peak and minimum power output of 2.47 MW and 522.50 kW, respectively, were observed. However, when the lightning impulsive current is included through the system, the power output decreases to 268.12 kW due to the high magnitude induced. A summary of solar PV systems and earlier investigations by other academics has been collated. The risk and possible protection from a lightning stroke must be considered for the LPS's effective design. The ignorance of protection costs system damage, resulting in a loss of investment return for both the private and solar system investor. The correct protective measures must fulfil the criteria of the regulations in order to offer adequate lightning protection and increase the PV operation's lifespan. As a result, the recommended standards in Table 3 would be an excellent source of information and references for planning the optimum LPS for solar PV system installation. This paper discussed the outcomes of the power efficiency of LSSPV that will implement in the LPS. Protecting critical structures and implementing needed protection measures must be determined in terms of risk, with complete risk management. The power efficiency before applying the lightning effect was 21.15%. In comparison, the power efficiency after applying the lightning effect was 10.86%.

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