EEET ECOLOGICAL ENGINEERING
& ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology 2024, 25(4), 220–234
https://doi.org/10.12912/27197050/185934
ISSN 2719-7050, License CC-BY 4.0

Received: 2024.02.21
Accepted: 2024.03.21
Published: 2024.04.01

Performance Evaluation and Economic Analysis of a Grid-Connected Solar Power Plant: A Case Study of Engreen Sarishabari Solar Plant Ltd. in Bangladesh

Riad Mollik Babu[1*], Enamul Basher[1]

[1] Department of Electrical and Electronic Engineering, University of Asia Pacific, 74/A Green Rd, Dhaka 1205, Bangladesh

* Corresponding author's e-mail: riadmallickbabu@gmail.com

ABSTRACT

As the global quest for sustainable energy solutions intensifies, the role of solar power plants in meeting energy demands while mitigating environmental impact becomes increasingly vital. This study focuses on the performance evaluation and economic analysis of Engreen Sarishabari Solar Plant Ltd., a 3.3 MW grid-connected photovoltaic (PV) power plant located in Sarishabari, Jamalpur, Bangladesh. A thorough evaluation of the solar power plant's performance ratio was carried out using the PVsyst software and data supplied by plant authorities. Moreover, a mathematical model was developed to analyze energy output variations, while grid stability post-integration of PV into the distribution feeder was examined under diverse conditions, including load and irradiance variations, as well as different short-circuit fault scenarios. The findings reveal that the annual performance ratio of the solar power plant stands at approximately 71%, with an average annual energy production of 3132 MWh. With a payback period of 10.1 years and an energy generating cost per kWh of 0.1132 USD, the installation cost came to 6,740,853 USD. This research not only provides valuable insights into the operational efficiency and economic viability of the Engreen Sarishabari Solar Plant Ltd. but also contributes to the broader discourse on the integration of solar energy into the grid infrastructure of Bangladesh, offering practical implications for policymakers, energy stakeholders, and investors striving towards a sustainable energy future.

Keywords: solar power plant, performance evaluation, economic analysis, grid integration, bangladesh, sustainability.

INTRODUCTION

Energy serves as the cornerstone for human survival and progress, playing a pivotal role in a nation's economic growth and security (Mondol et al., 2010). Without the effective utilization of energy, no country can hope to advance and sustain its development. An imbalance between energy demand and supply can significantly disrupt a nation's functionality, particularly in developing regions (Gulagi et al., 2017). As society transitions from modern to ultramodern, there is a notable escalation in global energy demand (Bagalini et al., 2019) , which stands as a primary driver behind global energy challenges and is anticipated to surge nearly fivefold by 2100 (Asif et al., 2007) With technological advancements, increasing demand, and sometimes excessive usage of electrical and electronic devices, our energy consumption continues to rise incessantly (Halder et al.,2015; Ahmed et al., 2014). Fossil fuels such as natural gas, coal, and petroleum are commonly recognized energy sources (Grammelis et al., 2016), predominantly utilized for electricity generation (Ahiduzzaman et al., 2011). Approximately three-quarters of the world's energy comes from fossil fuels, contributing significantly to greenhouse gas emissions (Yüksel, 2008; Altabatabaie et al., 2022). Moreover, projections suggest that global fossil fuel reserves will be completely exhausted within a few decades, indicating their finite nature and escalating costs

(Shezan et al., 2017). Considering the global energy crisis, Bangladesh is transitioning towards renewable energy sources to partially fulfill their energy requirements (Mohazzem et al., 2024). Moreover, Bangladesh's commitment to renewable energy is evident in its ambitious targets, aiming for 40% renewable energy in electricity generation by 2041, with solar energy expected to constitute a significant portion (Mahmud et al., 2021). This would lead to a renewable energy capacity of 16 GW (representing 30% of the total) by 2031, and a renewable energy capacity of 40 GW (representing 40% of the total) by 2041 (Wing 2023). At present, renewable sources make up 3.7% of the overall energy composition, with solar energy representing over 75% (equivalent to 2.8% of the total energy mix) (IEPMP 2023). The state gives precedence to the utilization of power derived from renewable sources rather than non-renewable sources. Government officials have planned several solar projects with a total capacity exceeding 3 GW in the future years (Koons, 2023).

Bangladesh boasts favorable geographic conditions, experiencing daily solar radiation ranging from 4 to 6.54–6.5 kWh/m^2 and an average annual sunshine duration of 1,900 kWh/m^2 (Lipu et al., 2013). Recognizing this abundant solar potential, the National Renewable Energy Laboratory estimates Bangladesh's solar capacity at a staggering 240,000 MW, requiring just 1.5 percent of its total land area (Teske et al., 2019). Such statistics underscore the pivotal role solar energy can play in addressing Bangladesh's mounting energy needs.

Because of the advantageous geographical location combined with other facilities, the payback year, which is a key indicator of the solar photovoltaic (PV) system's economic feasibility, is competitive compared to neighboring countries (Inan, 2022). The payback period for grid-connected photovoltaic installations in Bangladesh spans from 6.4 to 13.1 years. Shamim et al. (2022) discovered that employing a net metering strategy with solar PV in a grid-connected system yielded a payback period of 6.4 years over a 20-year lifespan. In a separate study, Mondal and Islam (2009) conducted a techno-economic feasibility analysis for a 500 kW grid-connected solar PV system, revealing an equity payback period of approximately 13.1 years. Additionally, Hasanuzzaman et al. (2022) investigated the economic impacts of PV power generation in Bangladesh. Their findings indicated that over a 21-year period, a 1 kWp system could lead to a reduction of US $4495.856 in total energy costs and a decrease of 0.198 per kWh in the cost of energy.

The payback period for grid-connected photovoltaic installations in Sri Lanka may range from roughly 2 to 5 years, contingent on variables such as system size, energy consumption, and configuration. In a comprehensive techno-economic evaluation of a 1 MW grid-connected system yielded a payback period of approximately 5 years (Archishman et al., 2017). Another investigation focused on residential solar photovoltaics, illustrating that for homes consuming over 300 kWh/month, the payback period could be as short as 2 years and 9 months (Rasul et al., 2022).

Photovoltaic installations in India have been extensively studied for their performance and feasibility. For instance, Sharma et al. (2023) conducted an analysis on a 13 kWp rooftop grid-connected solar photovoltaic system situated at Siksha 'O' Anusandhan, Bhubaneswar. This system demonstrated an annual electricity supply to the grid of 17.79 MWh, a final yield of 3.80 h/d, and a performance ratio of 0.82. Similarly, Singh and Rizwan (2022) investigated the impact of dust accumulation on a 5 kW photovoltaic system installed on the rooftop of a laboratory at Delhi Technological University. They compared the performance analysis results of the practical system with PVsyst software results. Additionally, Nitin Goyal et al. (2027) evaluated the performance of a PV power plant located at SKIT, Jaipur, under composite climate conditions, revealing a final yield of 4.5 kWh/kWp/day and a money payback period of 4.3 years. Moreover, (Saxena et al., 2023) scrutinized the viability of mounting solar PV plants in various cities across India, noting a performance ratio ranging between 70% and 80%, a capacity utilization factor of 19–21%, and an estimated energy output of 170 MWh annually at all sites (Komal et al., 2022).

The environmental and economic feasibility of photovoltaic installations is evident in Pakistan (Zafor er al., 2018). One study simulated a photovoltaic system in a remote location in Pakistan and found that it generated more electricity than the demand, with an energy payback time of 7.4 years and a reduction in greenhouse gas emissions (Muhammad et al., 2023). Ahmad et al. (2022) explored the techno-economic viability of grid-connected solar photovoltaic power plants for the manufacturing SME sector in Punjab, discovering that the payback period in Sargodha was the shortest at 7.7 years. Moreover, Awais et al. (2023) simulated a photovoltaic system in a remote location in Pakistan, determining an energy payback time of 7.4 years.

Currently, the payback period for grid-connected photovoltaic installations in Bhutan faces financial challenges, primarily due to the relatively high cost of PV energy generation in comparison to the average cost of hydropower generation (Yangchen et al., 2015). For instance, a proposed system intended for a library building in Bhutan exhibits a payback period that extends beyond the project's lifespan and generates a negative net cash flow (Xuan et al., 2022). Moreover, the existing subsidized electricity tariff structure in Bhutan does not render the implementation of such systems financially feasible (Simón-Martín et al., 2012).

Since 2017, there has been a significant increase in both investment and research and development (R&D) efforts in the field of solar energy in Bangladesh (Hossain et al., 2021; Riad, 2023). The significant rise in investments has prompted a concentrated emphasis on research related to enhancing efficiency and optimizing operations in the solar energy industry (Abdulrazak et al., 2021). Research and development bodies, encompassing both corporate and academic institutions, are engaging in an extensive investigation of multiple variables. These variables include crucial elements such as the duration of sunshine, angles of radiation, temperature, humidity, wind patterns, specific coordinates of position, types of solar panels, and efficiency of inverters (Karim et al., 2019). This increased examination demonstrates a dedication to comprehending and improving the efficiency of solar energy systems within the particular circumstances of Bangladesh. An in-depth examination of these various elements is crucial for improving the design, implementation, and functioning of solar power installations.The partnership between research and development organizations and academic institutions highlights the increasing recognition of the need of customizing solar energy solutions to the specific environmental circumstances and needs of the area (Baky et al., 2017). In this study, a techno-economic assessment of the photovoltaic (PV) system is conducted to determine its levelized cost of energy (LCOE), payback time, and other key indicators to ascertain profitability. Annual energy production for the solar power plant is estimated, and a mathematical model is developed to predict annual energy production by varying solar irradiance levels. Additionally, a grid impact analysis is performed to assess the effects of integrating a significant volume of PV into the grid, considering load variation, irradiation fluctuation, and conducting short-circuit analysis to ensure grid stability and reliability.

METHODOLOGY

To comprehensively evaluate the performance and economic viability of the Engreen Sarishabari Solar Plant Ltd., we employed a hybrid methodology integrating simulation techniques and software analysis. This approach enabled us to delve into the intricacies of the solar photovoltaic system, ensuring a robust evaluation of its operational efficiency and economic feasibility.

Firstly, we replicated the key components of a typical solar PV plant, including photovoltaic panels and inverters, to conduct simulations tailored to the specific characteristics of the Engreen Sarishabari Solar Plant. These simulations provided insights into the system's performance under varying environmental conditions and operational parameters. For economic analysis, we gathered crucial data from plant officials, including total installation costs, taxes, inflation rates, and other pertinent factors. We obtained vital parameters including radiation values, average temperature, wind speed, and humidity by entering the coordinates of the chosen region. The careful procedure employed in PVSyst established the foundation for a thorough assessment of the solar power plant's performance and efficiency, considering actual environmental conditions. After completing the design phase, we calculated monthly energy production data for the power plant, utilizing its installed capacity of 3.3 MW, and determined the average performance ratio (PR) of the facility. PVSyst software played a crucial role in analyzing both overall electricity generation and the payback period, offering valuable insights into the economic feasibility and return on investment of the plant.

In the final stage of our study, we conducted a grid impact analysis to assess the plant's interaction with the electricity grid. This involved developing a system model with grid connections using SIMULINK, a powerful simulation platform. We meticulously studied different types of fault conditions to evaluate the plant's resilience and its impact on grid stability, ensuring a comprehensive understanding of its operational dynamics within the broader energy infrastructure. By integrating simulation techniques, software analysis, and empirical data, our methodology enabled a thorough evaluation of the Engreen Sarishabari Solar Plant Ltd., offering valuable insights into its performance, economic viability, and grid integration capabilities.

Design of the solar PV system

Table 1 presents data regarding the orientation of the PV array. A manual solar tracker system has been incorporated into the solar PV system, enabling adjustments to optimize sunlight capture. During summer, the tilt angle is set at 5º, while in winter, it is adjusted to 24º. Table 2 provides a concise overview of key photovoltaic components utilized in the solar PV system, including solar panels, inverters, and AC junction boxes. These components, meticulously selected for their quality and performance, underscore the robustness and efficiency of the system design. Table 3 offers a snapshot of the solar PV system's key specifications. It delineates vital parameters such as the installed capacity, module configuration details including nominal power and total number, as well as inverter specifications including nominal power and quantity. Table 4 presents a breakdown of the costs associated with the solar PV project. It itemizes the quantity, unit cost, and total cost in USD for various components and expenses involved in the project. Additionally, it provides details of annual operating costs in BDT, including staff salary, lease payment, and maintenance expenses. The solar PV system comprises 11,580 installed solar modules and 123 inverters. However, accounting for potential damage and unforeseen events, a total of 12,200 solar modules and 125 inverters were purchased. The exchange rate was 1 USD to around 80 Taka at that time. After analyzing the data and converting the Bangladeshi Taka to US Dollars, the total cost of installing the plant was 6,740,853 USD. Operating expenses are being covered in Bangladeshi currency.

Table 1. Orientation of PV array

Tilt angle	Summer tilt 5°
	Winter (October, November December, January, February, March) tilt 24°
Azimuth	180°

Table 2. Details of the PV components

PV Component	Model Name	Manufacturer
Solar panel	Sunmodule plus sw 285 mono	Solarworld
Inverter	Sunny Tripower STP 25000TL-30	SMA Solar Technology AG
AC junction box	PVXLS	Henan Senyuan Electronic Co.

Table 3. Design details of the PV plant

Installed capacity	3000 kWh
Module nom. power (Wp)	285
Total number of modules	11580
Nominal (STC)	3300 kWp
Modules	579 string × 20 In series
Inverter AC nom. power	25.0 kW
Number of inverters	123
Inverter AC total power	3075 kW

Table 4. Installation and operating cost

Item	Quantity	Unit cost (USD)	Total cost (USD)
Solar PV modules	12,200	328	4,001,600
Support structures for modules			455,537
Inverters	125	4057	507,125
Transformers	3	6493	136,661
Computers, software, cables, and measurement tools			501,090
Field leveling			455,537
Civil construction including a residential building and warehouse			182,214
Labor cost			182,214
Fence, cameras, and thunder protection			318,875
Power plant installation			6,740,853
Annual operating cost (BDT)			
Staff salary	5,000,000		
Lease payment	1,000,000		
Maintenance	500,000		

RESULTS AND DISCUSSION

The performance evaluation and economic analysis were conducted using PVsyst software, which yielded results slightly different from the actual data collected from the plant officials. In our simulation model, the annual average energy production is calculated at 3132 MW, whereas the plant officials anticipate a figure of 3300 MW. Consequently, minor discrepancies exist in the projected payback period. While the plant officials expect a payback period of 10 years, our simulation results indicate a slightly higher figure of 10.1 years.

Performance evaluation and economic analysis

Table 5 provides valuable insights into the operational efficiency and economic feasibility of the Engreen Sarishabari Solar Plant. The plant showed an impressive use of solar energy resources. This performance ratio is in line with industry benchmarks and highlights the plant's efficiency in turning solar energy into electricity. The economic analysis showed positive results about the plant's financial feasibility. The Engreen Sarishabari Solar Plant has a favorable payback period, indicating a satisfactory return on investment. The cost of the energy produced highlights the plant's competitiveness in the energy market.

Table 5. Economic and performance analysis

Produced energy	3132 MWh/year
Specific production	949 kWh/kWp/year
Cost of produced energy	0.1132 USD/kWh
Feed in tariff	0.18970 USD/kWh
Electricity sale	11,882,808 USD
Payback period	10.1 years
Return on investment	92.3 %
Cumulative profit	4,526,693 USD
Performance ratio	0.71

Grid impact analysis

This section entails an examination of the plant's performance and its influence on the grid under various circumstances, such as dynamic weather, load fluctuations, and diverse fault states. Initially, this presentation showcases the complete configuration and the resulting consequences in typical circumstances.

The analysis of the grid impact is conducted by means of simulation, with the simulation system being developed using MATLAB. The depicted system, as seen in Figure 1, comprises a solar photovoltaic module with a capacity of 3.3 MW, operating under an average irradiance level of 700 W/m^2 at a temperature of 25 ^{0}C. Phase lock loop (PLL) systems were employed to develop an inverter capable of converting the direct current (DC) power generated by solar photovoltaic systems into alternating current (AC). The inverter output of 415 V is linked to a 0.4 kV/33 kV transformer. The step-up transformer is linked to a transformer with a voltage ratio of 33 kV/11 kV. Subsequently, the three-phase line originating from the step-down transformer is connected to the grid. The location where the connection is established between the supply of the photovoltaic plant and the electrical grid is referred to as the point of common coupling, commonly abbreviated

Figure 2 illustrates various metrics under normal conditions. These include a power frequency of 50 Hz at the point of common coupling (PCC), a power factor of roughly 9.6, PV generation of

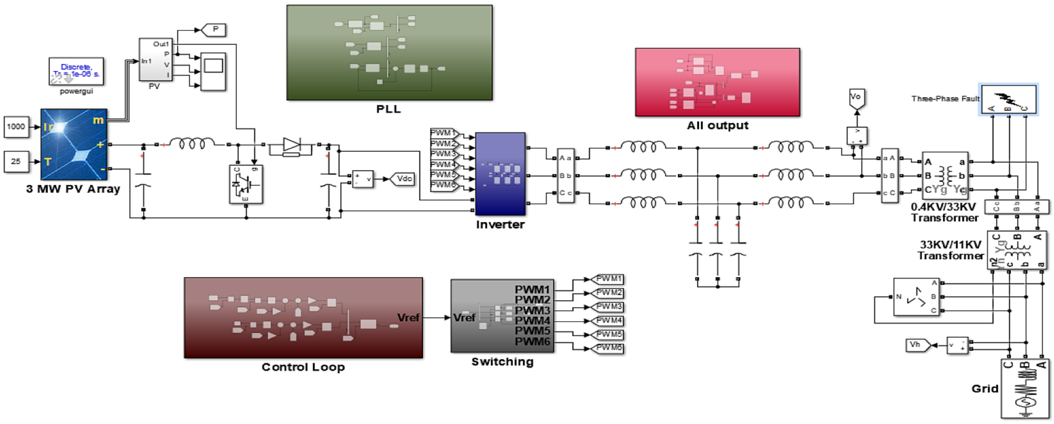


Figure 1. System implementation in simulating software.

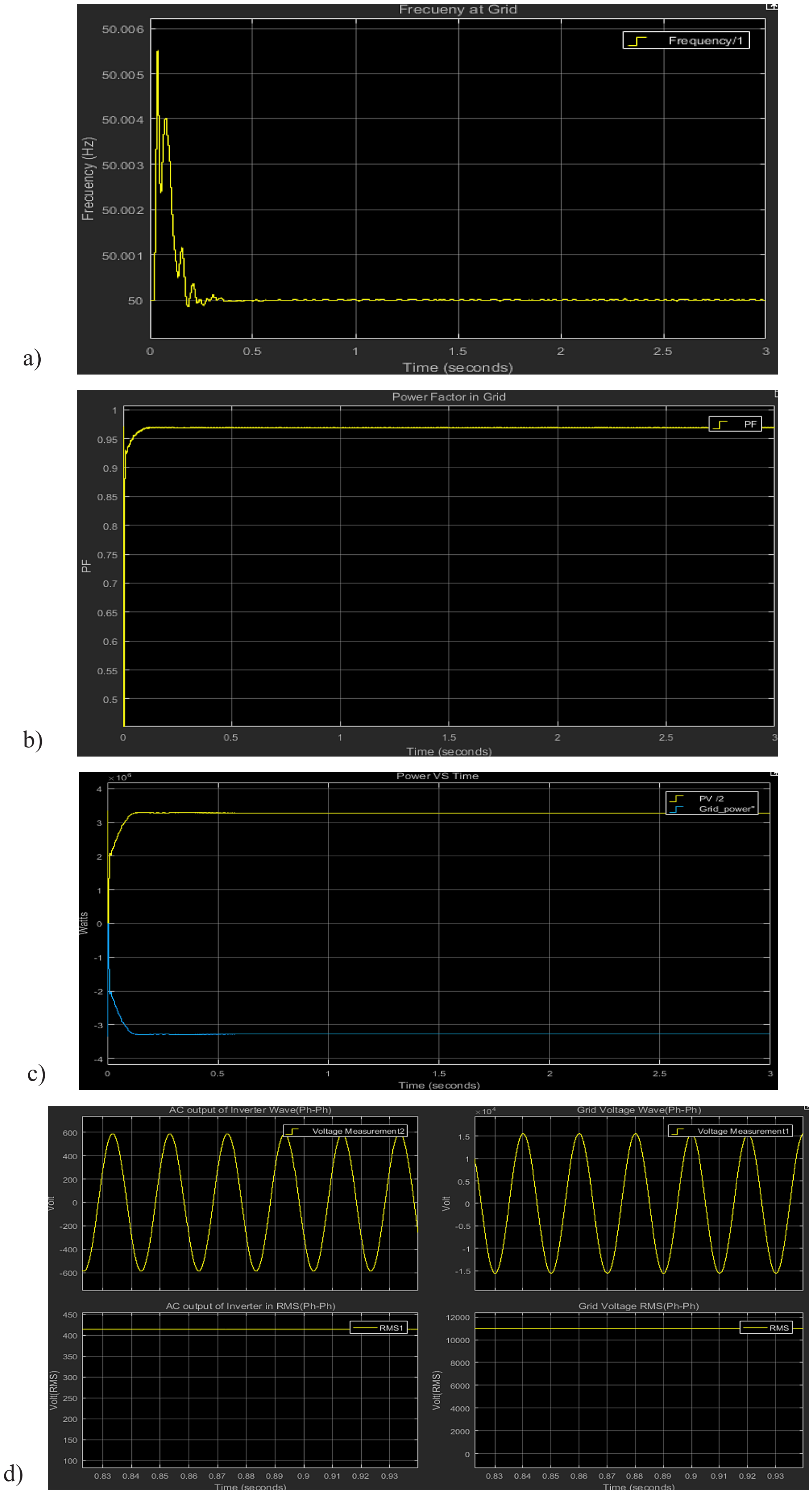


Figure 2. (a) Frequency at PCC, (b) power factor at PCC, (c) power sharing between PV and grid in normal condition, (d) line voltage at PCC and grid and RMS value of voltage at PCC and grid

around 3.3 MW, and an RMS voltage value of 415 V after the AC inverter. The voltage at the PCC following the transformation from 0.415 kV to 33 kV and subsequently from 33 kV to 11 kV is 11 kV in terms of its root mean square (RMS) value. Consequently, it is content to establish a connection with the power supply and electrical grid. Energy is sent to the grid.

This is a normal visualization of system performance in normal conditions. This section examines the effects of dynamic weather and various symmetric and unsymmetric fault states on the system. We will manipulate the irradiance and induce line-to-ground faults in the system to get the desired scenarios. The value of irradiance is not kept constant due to dynamic weather. So, we are analyzing this by changing the value of irradiance inputs to the solar PV array. The result of the variation in irradiance is exhibited in Figure 3. Where the solar irradiance is varied from 1000 W/m^2 to 500 W/m^2 at time = 0.8 s, then 500 W/m^2 to 800 W/m^2 at time = 1.5 s, and finally from 800 W/m^2 to 1000 W/m^2 at time 2 s again.

According to Figure 3, it is observed that the supply of solar plants drops from 3.3 MW to 1.65 MW at 0.8 s when solar irradiance is varied from 1000 W/m^2 to 500 W/m^2 and the frequency of the PCC falls from 50 Hz to 49.99 Hz for a few moments. The power factor also drops from 0.96 to 0.90 (approximate) at the same time, and a spike is seen up to 0.8 at 0.8 s. The same amount of power produced from the PV plant goes to the grid. Then power generation increases from 1.65 MW to 2.64 MW at 1.5 s when solar irradiance is varied from 500 W/m^2 to 800 W/m^2 and the frequency of the PCC increases from 50 Hz to 50.01 Hz for a few moments, then the power factor also increases from 0.90 to 0.95 at that time. At last, power generation returns to 3.3 MW at 2 s when solar irradiance is varied from 800 W/m^2 to 1000 W/m^2. The frequency also increases for a short period, from 50 Hz to 50.006 Hz, and the power factor returns to 0.96.

Impact on line-ground short circuit

To analyze the short circuit effect, line-ground short circuit is created for a short period from 1 s to 2 s in our system, and the result of this event is visible in Figure 4. So, power sharing, frequency, power factor, and voltage are visible in the a, b, c, and d parts of Figure 4.

Figure 4 shows us that during the fault period from 1 s to 2 s, when a fault occurs after the 0.4 kV/33 kV transformer is connected to the 33 kV/11 kV, a distortion exists in the load supply. That's why a distortion also goes to the PCC (point of common coupling) connected to the grid, as exhibited in Figure 4a.

Another impact is seen in Figure 4b, where a spike appears in the frequency up to 49.6 Hz from the balanced level of 50 Hz at 1.0 s, and again, it has changed between 50.3 and 49.7 Hz from 50 Hz at 2.0 s for a few moments. A significant impact is the power factor in Figure 4c, which fluctuates from 0.99 to approximately 0 from 1 s to 2 s. And after removing the fault, the power factor and power could not return to a stable position because of losing power synchronization. In Figure 4d, the inverter voltage, and its RMS value (on the left) of the PCC are seen, and the line voltage and its RMS value (on the right) are also seen. Because a fault occurs in one phase, the RMS value drops from 415 V to 235 V. But the grid voltage has continued at its normal level.

Impact on line-line-ground short circuit

To analyze the short circuit effect, a double line-ground short circuit is created for a short period from 1.0 s to 2.0 s in our system, and the result of this event is visible in Figure 5. So, power sharing, frequency, power factor, and voltage are visible in the a, b, c, and d parts of Figure 5.

Figure 5 shows us that during the fault period from 1.0 s to 2.0 s, when a fault occurs after the 0.4 kV/33 kV transformer is connected to the 33 kV/11 kV, a distortion exists in the load supply. That's why a distortion also goes to the PCC (point of common coupling) connected to the grid, and a noise also appears in the supply of the PV plant at Figure 5a.

Another impact is seen in Figure 5b, where a spike appears in the frequency up to 49.6 Hz from the balanced level of 50 Hz at 1.0 s, and again, it has changed between 50.35 and 49.65 Hz from 50 Hz at 2.0 s for a few moments. A significant impact is the power factor in Figure 5c, which fluctuates from 1 to approximately 0 from 1 s to 2 s. But from 1.2 s to 1.8 s, the value of pf fluctuates from 1 to -1. It could not return to a stable position after removing the fault.

In Figure 5d, the inverter voltage, and its RMS value (on the left) of the PCC are seen, and the line voltage and its RMS value (on the

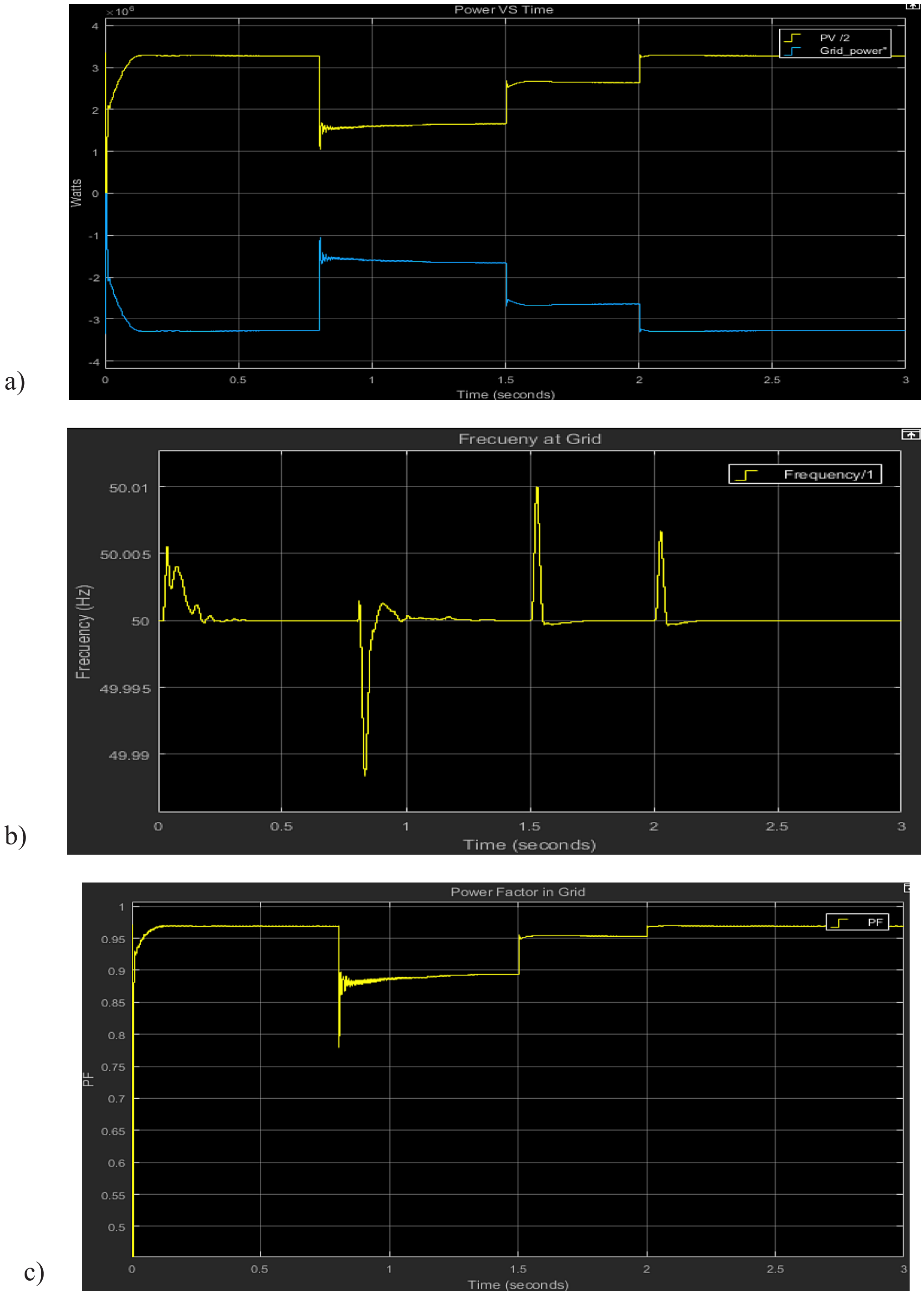


Figure 3. (a) power sharing between PV and grid in irradiation variation, (b) frequency at PCC (c) power factor during irradiation variation

right) are also seen. Because a fault occurs in two phases, its RMS value drops from 415 V to 10 V approximately. But the grid voltage has continued at its normal level.

Impact on line-line-line-ground short circuit

To analyze the short circuit effect, line-line-line-ground short circuit is created for a short period from 1 s to 2 s in our system, and the result of this event is visible in Figure 6. Power sharing, frequency, power factor, and voltage are visible in the a, b, c, and d parts of Figure 6.

Figure 6 shows us that during the fault period from 1.0 s to 2.0 s, when a fault occurs after the 0.4 kV/33 kV transformer is connected to the 33 kV/11 kV, the line is disconnected from the supply as three phases are shorted to ground. That's why a

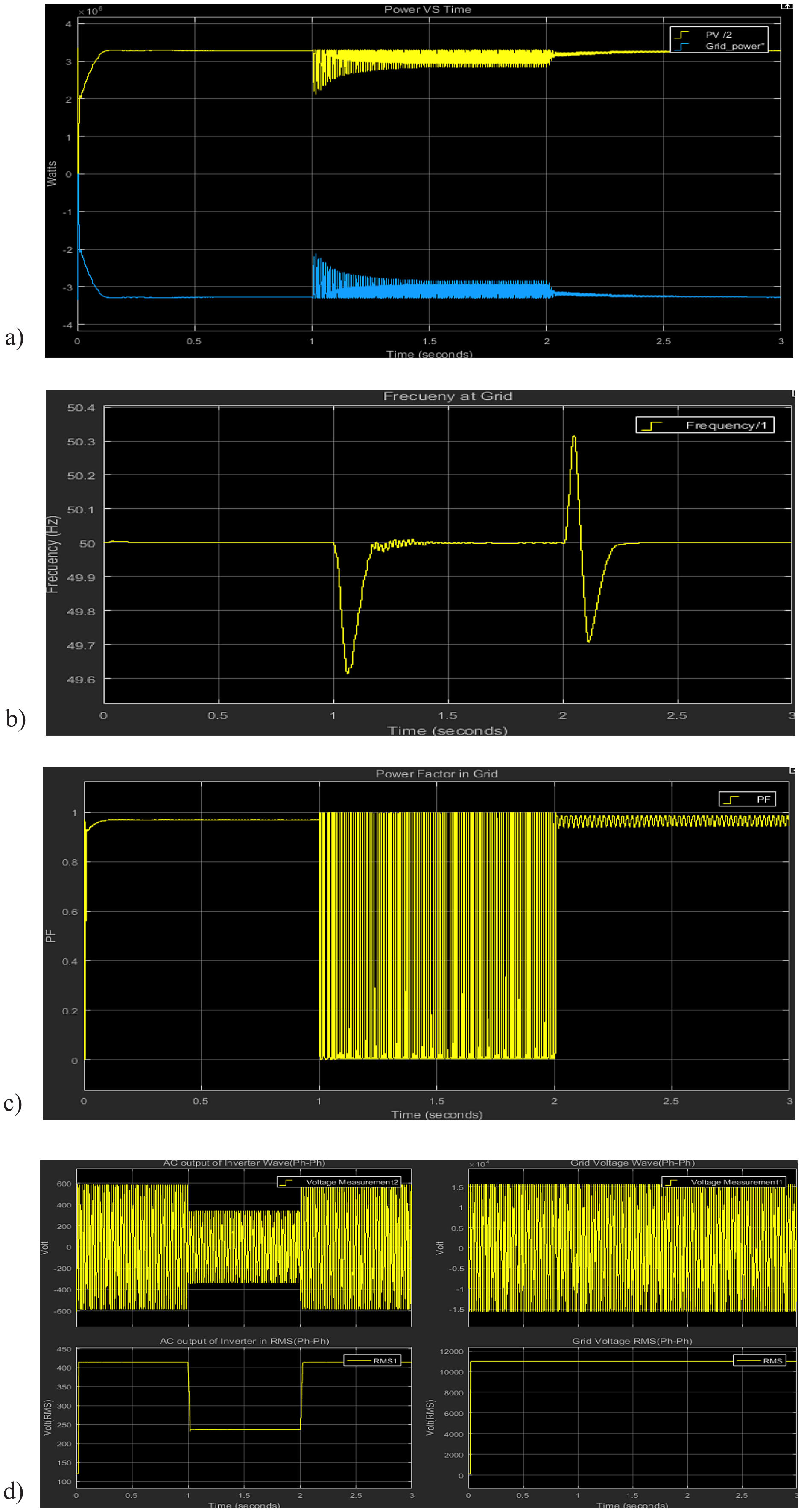


Figure 4. (a) power sharing between PV and grid in L-G short circuit, (b) frequency at PCC during L-G short circuit (c) Power factor at PCC during L-G short circuit, (d) phase voltage and RMS value at PCC Line voltage and RMS value at grid

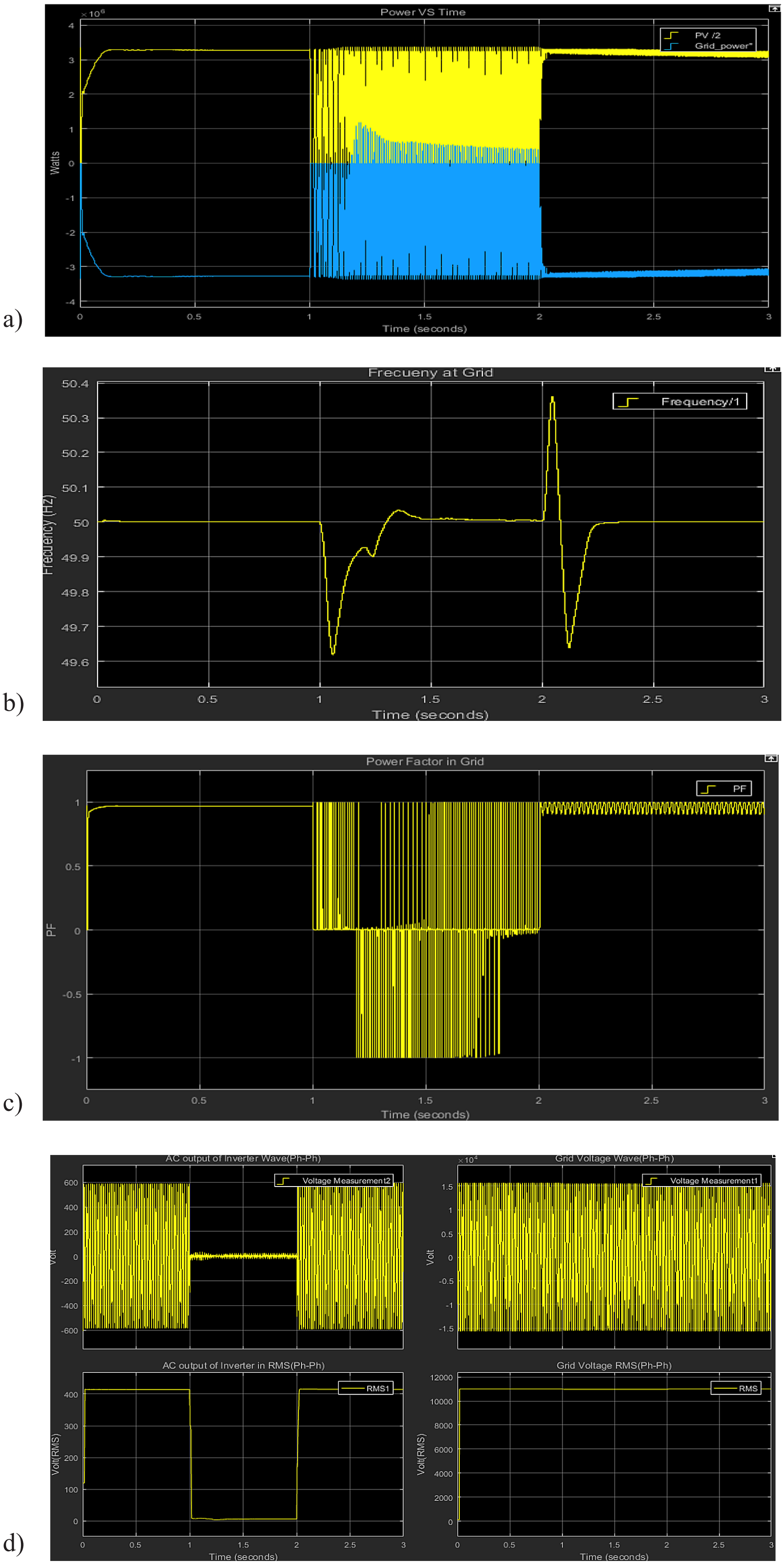


Figure 5. (a) power sharing between PV and grid in L-L-G short circuit, (b) frequency at PCC during L-L-G short circuit, (c) power factor at PCC during L-L-G, (d) phase voltage and RMS value at PCC Line voltage and RMS value at

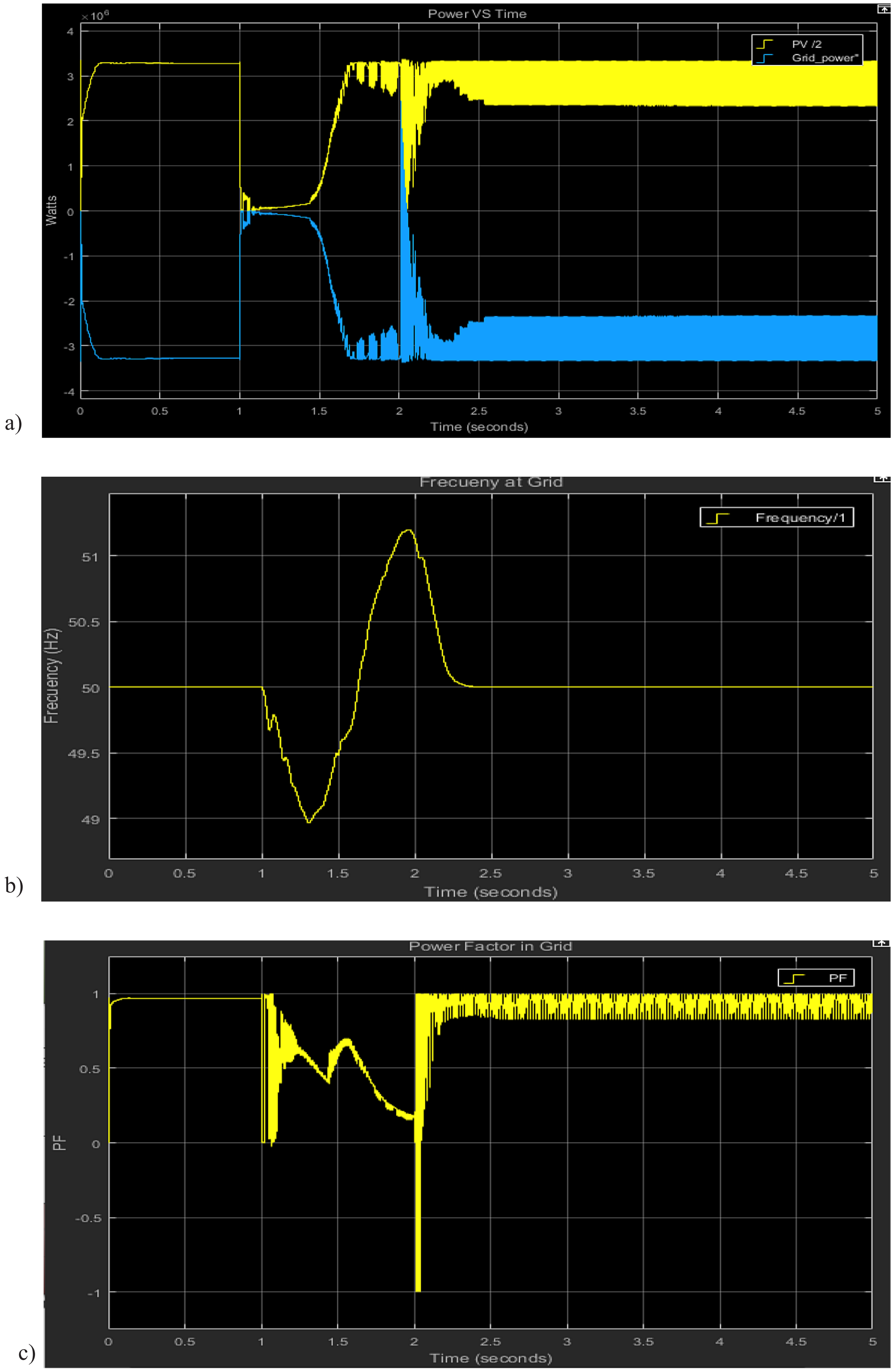
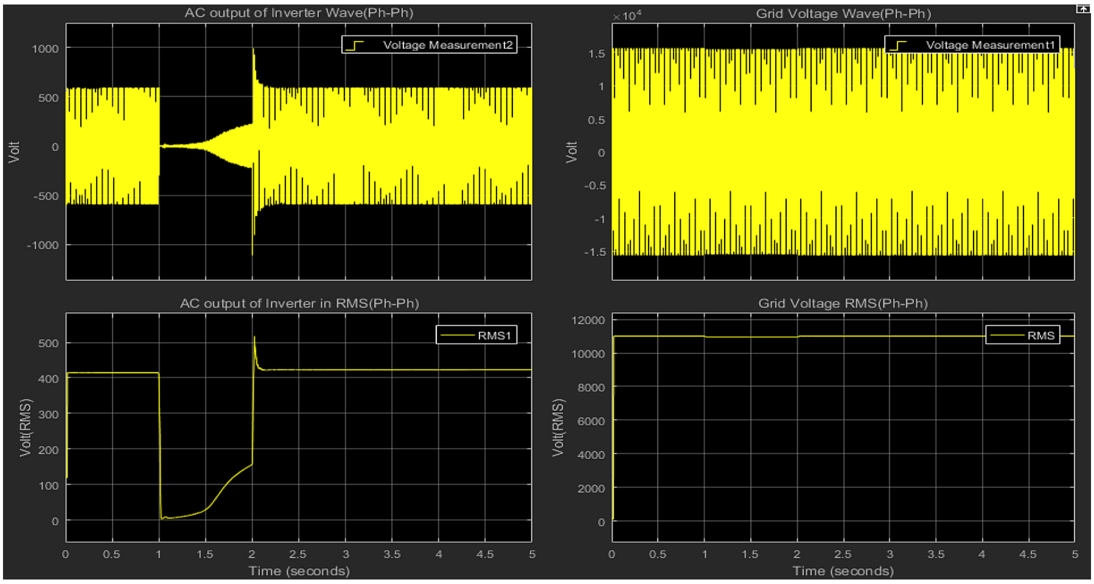


Figure 6 (a) power sharing between PV and grid in L-L-L-G short circuit, (b) frequency at PCC during L-L-L-G short, (c) power factor at PCC during L-L-L-G, (d) phase voltage and RMS value at PCC Line voltage and RMS value at



d)

Figure 6. Cont. (d) phase voltage and RMS value at PCC Line voltage and RMS value at

distortion in power has remained during this fault period, and after removing the fault, the distortion exists in power as the 3-phase line was shorted and needs to be synchronized before connecting again, as shown in Figure 6a. Another impact is seen in Figure 6b, where the frequency has been dropped to 49 Hz from the balanced level of 50 Hz at 1 s, and again, it has risen to 51 Hz during the fault period. However, the frequency would continue to rise until the fault was removed. A significant impact is the power factor in Figure 6c, which is changed randomly from 1 s to 2 s. After this fault period, the PF continued with a distortion as the line connected to the grid without synchronization.

In Figure 6d, the inverter voltage, and its RMS value (on the left) of the PCC are seen, and the line voltage and its RMS value (on the right) are also seen. Because a fault occurs in three phases to ground, the RMS value of it drops from 415 V to approximately 0 V. But the voltage level continues to rise exponentially with respect to time during this fault period, and within 1 s, it rises up to 150 V (rms) from zero. However, after removing the fault, the voltage continues at its normal value after creating a spike. We also observe a tiny change in grid voltage at this time. The grid impact analysis provided valuable insights into the Engreen Sarishabari Solar Plant's interaction with the electricity grid under various conditions. Simulation results depicted the plant's behavior during dynamic weather fluctuations and fault scenarios, shedding light on its resilience and contribution to grid stability. Under normal operating conditions, the plant exhibited stable performance, with a power frequency maintained at 50 Hz and a power factor of approximately 0.96. However, during periods of irradiance variation, slight fluctuations in power output and frequency were observed, although within acceptable limits. Furthermore, fault scenarios, including line-ground (L-G) and line-line-ground (L-L-G) short circuits, were analyzed to assess the plant's response and impact on grid stability. The results showed temporary disruptions in power output, frequency, and power factor during fault periods, emphasizing the importance of implementing protective measures and grid integration strategies to ensure uninterrupted power supply and grid resilience. Overall, the results of the performance evaluation and grid impact analysis underscore the effectiveness and reliability of the Engreen Sarishabari Solar Plant. By combining operational efficiency with economic viability and grid integration capabilities, the plant emerges as a promising model for sustainable energy development in Bangladesh, contributing to the country's renewable energy targets and environmental objectives.

CONCLUSIONS

The Engreen Sarishabari Solar Plant is a symbol of advancement in Bangladesh's renewable energy industry, serving as the country's first solar power plant connected to the national grid. The project, first driven by the vision of investors and engineers, has evolved into a pioneering success, sparking enthusiasm and financial support in the rapidly growing solar energy industry. The plant's outstanding performance, highlighted by a significant return on investment and a rapid payback period, confirms its effectiveness and economic feasibility. Our software simulation has resulted in outstanding outcomes, with an annual generation of 3,132 MWh and an energy yield of 959 kWh/kWp/year. However, actual data provided by plant officials surpasses these projections, boasting an average annual electricity generation of 3,300 MWh, indicative of an even higher energy yield. Anticipating a 10-year payback period and a return on investment of approximately 105%, the plant stands competitively against solar PV installations in neighboring countries. Moreover, the technological and financial model of the solar PV system meticulously accounts for policy, regulatory, and physical constraints, ensuring a holistic approach to sustainability and profitability.

Moreover, the solar PV plant's performance under various conditions was analyzed using a grid impact analysis. The plant's response to fault scenarios, including line-ground and line-line-ground short circuits, showed temporary disruptions in power output, frequency, and power factor during fault periods. Line-ground faults cause distortion in the load supply and impact the point of common coupling (PCC). The frequency fluctuates from 49.6 Hz to 50.3 Hz, and the power factor drops from 99 to nearly 0 during fault periods. After removing the fault, power synchronization is lost, and the inverter voltage and line voltage drop due to a fault in one phase, while grid voltage remains normal.

The impact of line-line-ground short circuits was evaluated by simulating a double line-ground short circuit from 1.0 s to 2.0 s within the system. This results in distortion in the load supply, noise in the PV plant supply, and a spike in frequency. The power factor fluctuates from 1 to approximately 0 from 1 s to 2 s but cannot return to a stable position after removing the fault. The inverter voltage and line voltage also show significant impacts, with the RMS value dropping from 415 V to 10 V due to the fault occurring in two phases. Similarly, the effects of line-line-ground short circuits were assessed through a fault occurring from 1 s to 2 s. The system shows power sharing, frequency, power factor, and voltage changes during the fault period. The fault occurs when a transformer is connected to the supply, causing a distortion in power. The frequency drops to 49 Hz and then rises to 51 Hz but remains constant until the fault is removed. The power factor changes randomly from 1s to 2 s, and the inverter voltage and line voltage also show changes. After removing the fault, the voltage remains at its normal value. These findings highlight the importance of implementing protective measures and grid integration strategies to ensure uninterrupted power supply and grid resilience.

The insights gleaned from this grid impact analysis are pivotal for enhancing the integration of solar power plants into the electricity grid. By understanding the plant's behavior under diverse operating conditions, stakeholders can implement measures to optimize grid operation and planning, thereby bolstering grid resilience and reliability. In the future, the incorporation of intelligent storage systems shows potential for improving the stability of power grids and maximizing the economic feasibility of solar energy. Subsequent research endeavors could investigate the economic viability of these systems, thereby facilitating enhanced sustainability and resilience in Bangladesh's power industry.

Acknowledgements

We would like to express our sincere gratitude to Mr. Motaharul Islam, Operation Engineer at Engreen Sarishabari Solar Plant Ltd., for his invaluable assistance and support throughout the course of this research project. Mr. Islam provided us with essential data and insights into the operation and performance of the grid-connected solar PV system being studied. His expertise and willingness to share knowledge greatly enriched our understanding and contributed to the success of this research endeavor. We are also grateful to the management team at Engreen Sarishabari Solar Plant Ltd. for granting us access to the solar PV system and facilitating the data collection process. Additionally, we extend our appreciation to all individuals who contributed, directly or indirectly, to this research.

REFERENCES

1. Abdulrazak, L.F., Islam, A., Hossain, M.B. 2021. Towards energy sustainability: Bangladesh perspectives. Energy Strategy Reviews, 38, 100738.
2. Ahiduzzaman, M.D., Islam, A.S. 2011. Greenhouse gas emission and renewable energy sources for sustainable development in Bangladesh. Renewable and Sustainable Energy Reviews, 15(9), 4659–4666.
3. Ahmad, M., Khattak, A., Kashif Janjua, A., Alahmadi, A.A., Salman Khan, M., Ullah, N. 2022. Techno-economic feasibility analyses of grid-connected solar photovoltaic power plants for small scale industries of Punjab, Pakistan. Frontiers in Energy Research, 10, 1028310.
4. Ahmed, S., Islam, M.T., Karim, M.A., Karim, N.M. 2014. Exploitation of renewable energy for sustainable development and overcoming power crisis in Bangladesh. Renewable Energy, 72, 223–235.
5. Al-tabatabaie, K.F., Hossain, M.B., Islam, M.K., Awual, M.R., TowfiqulIslam, A.R.M., Hossain, M.A., ... Islam, A. 2022. Taking strides towards decarbonization: The viewpoint of Bangladesh. Energy Strategy Reviews, 44, 100948.
6. Asif, M., Muneer, T. 2007. Energy supply, its demand and security issues for developed and emerging economies. Renewable and sustainable energy reviews, 11(7), 1388–1413.
7. Baky, M.A.H., Rahman, M.M., Islam, A.S. 2017. Development of renewable energy sector in Bangladesh: Current status and future potentials. Renewable and Sustainable Energy Reviews, 73, 1184–1197.
8. Bose, A., Rajan, K.R., Abeyweera, R., Rathnakumara, J., Senanayake, N.S., Wicramarathna, T., Jayasuriya, J. 2017. Sustainable Power for Carbon Neutral Operation: A Feasibility Study for Printing Industry in Sri Lanka. SLEMA Journal, 20(1–2). doi:10.4038/SLEMAJ.V20I1-2.7.
9. Grammelis, P., Margaritis, N., Karampinis, E. 2016. Solid fuel types for energy generation: Coal and fossil carbon-derivative solid fuels. In: Fuel Flexible Energy Generation, Woodhead Publishing, 29–58.
10. Gulagi, A., Choudhary, P., Bogdanov, D., Breyer, C. 2017. Electricity system based on 100% renewable energy for India and SAARC. PLoS One, 12(7), e0180611.
11. Halder, P.K., Paul, N., Joardder, M.U., Sarker, M. 2015. Energy scarcity and potential of renewable energy in Bangladesh. Renewable and Sustainable Energy Reviews, 51, 1636–1649.
12. Hossain, S., Rahman, M.M. 2021. Solar energy prospects in Bangladesh: Target and current status. Energy and Power Engineering, 13(8), 322–332.
13. Inan At. 2022. Solar Power Plant Efficiency and Economically Analysis in Different Regional Climate for Selected Cities in Turkey. https://dergipark.org.tr/en/pub/jeps/issue/74081/1177913.
14. Integrated Energy and Power Master Plan (IEPMP). 2023. http://www.powerdivision.gov.bd
15. Singh K., Rizwan M. 2022. Performance Analysis of Solar PV Modules with Dust Accumulation for Indian Scenario. doi:10.1109/PIICON56320.2022.10045127.
16. Koons E. 2023. Solar Energy in Bangladesh: Current Status and Future. Energy Tracker Asia. https://energytracker.asia/solar-energy-in-bangladesh-current-status-and-future/.
17. Lipu M.S., Uddin M.S., Miah M.A. 2013. A feasibility study of solar-wind-diesel hybrid system in rural and remote areas of Bangladesh. International journal of Renewable energy research. 22; 3(4), 892–900.
18. M.M.H. Shamim, S.M. Silmee and M.M. Sikder. 2022. Design and Techno-economic Analysis of a Grid-connected Solar Photovoltaic System in Bangladesh. In: Second International Conference on Advances in Electrical, Computing, Communication and Sustainable Technologies, 1–6. doi:10.1109/ICAECT54875.2022.9808078.
19. de Simón-Martín, M., Díaz-Mediavilla M., Alonso-Tristán C., García-Calderón T., Rodríguez-Amigo C. 2012. Grid connected pv systems: energy payback time analysis. In: 5th International Conference on Sustainable Energy and Environmental Protection, 174–179. doi:10.13140/2.1.5180.6089
20. Mahmud H., Roy J. 2021. Barriers to overcome in accelerating renewable energy penetration in Bangladesh. Sustainability, 13(14), 7694.
21. Mondal M.A.H, Islam A.K.M.S. 2009. Techno-economic feasibility of grid connected solar PV system in Bangladesh. In: 1st International Conference on the Developements in Renewable Energy Technology, IEEE. doi:10.1109/ICDRET.2009.5454241.
22. Mohazzem Hossain, S., Biswas S., Raihan Uddin M. 2024. Sustainable energy transition in Bangladesh: Challenges and pathways for the future. Engineering Reports, 6(1), e12752.
23. Mondal, M.A.H., Denich M. 2010. Assessment of renewable energy resources potential for electricity generation in Bangladesh. Renewable and Sustainable Energy Reviews, 14(8), 2401–2413.
24. Awais M., Farooq M., Seung R., Ahn K., Gwak J., Kihwan K, Ahn S., Eo Y.-J. 2023. Assessment for the installation of a solar PV system in Pakistan for a sustainable environmental and economic development. Mehran University Research Journal of Engineering and Technology. doi:10.22581/muet1982.2302.05
25. Rasul M.J., de Alwis N., Kolhe M.L. 2022. Cost-Benefit and Short-Term Power Flow Analysis of Grid

Integrated Residential Photovoltaic-Battery Energy System. In: Control of Smart Buildings: An Integration to Grid and Local Energy Communities. Singapore: Springer Nature Singapore, 251–270.

26. Sharma R., Goel S., Lenka S.R. 2023. Pragmatic analysis of solar photovoltaic system design in an institutional building in eastern India. Frontiers in Energy Research. doi:10.3389/fenrg.2023.943207
27. Babu R.M. 2023. Empowering Sustainability: A comprehensive analysis of Sarishabari Engreen Solar Power Plant – Bangladesh's pioneering grid-connected solar endeavor. International Research Journal of Engineering and Technology. 10(12), 915–924.
28. Saxena A.K., Saxena S., Sudhakar K. 2021. Energy, economic and environmental performance assessment of a grid-tied rooftop system in different cities of India based on 3E analysis. Clean energy, 5(2), 288–301.
29. Shezan S.K.A., Ping H.W. 2017. Techno-economic and feasibility analysis of a hybrid PV-wind-biomass-diesel energy system for sustainable development at offshore areas in Bangladesh. Current Alternative Energy, 1(1), 20–32.
30. Sumita, Goyal N., N. Soni, Khurana M., Gupta M., Madhukar K. 2017. Performance Assessment of Solar PV Power Plant with Pvsyst Simulation Tool. Indian Scientific Journal of Research in Engineering and Management. doi:10.55041/ijsrem18911.
31. Teske S., Morris T., Nagrath K. 2019. 100% Renewable energy for Bangladesh – access to renewable energy for all within one generation. Report prepared by ISF for Coastal Development Partnership (CDP Bangladesh; Bread for the World).
32. Bagalini V., Zhao B.Y., Wang R.Z., Desideri U. 2019. Solar PV-Battery-Electric Grid-Based Energy System for Residential Applications: System Configuration and Viability. Research. doi:10.34133/2019/3838603.
33. Wing L.A. 2023. Solar Energy Landscape of Bangladesh. Light Castle Partners. https://www.lightcastlebd.com/insights/2023/03/solar-energy-landscape-of-bangladesh.
34. Ngo X.C., Do N.Y. 2022. The impact of electrical energy consumption on the payback period of a rooftop grid-connected photovoltaic system: A case study from Vietnam. International Journal of Renewable Energy Development. doi:10.14710/ijred.2022.42981
35. Dolkar Y., Jamtsho D., Adhikari R., Wangdi T., Dorji S., Lhendup T., Lhamo P. 2015. System Design and Performance Analysis of a Grid-Tied Solar PV Power System in Bhutan. doi:10.1109/CICT.2015.55
36. Yüksel I. 2008. Global warming and renewable energy sources for sustainable development in Turkey. Renewable Energy, 33(4), 802–812.
37. Zafar U., Rashid T.U., Khosa A.A., Khalil, M.S., Rashid, M. 2018. An overview of implemented renewable energy policy of Pakistan. Renewable and Sustainable Energy Reviews, 82, 654–665.