European Journal of Energy Research
Vol 5 | Issue 4 | July 2025
ISSN 2736-5506

RESEARCH ARTICLE

The Dynamic Modeling of a Grid-Connected Photovoltaic Setup using MATLAB/Simulink

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ABSTRACT

Development of renewable-based energy systems is developed to retail photovoltaic systems into electrical networks. By building a grid connected photovoltaic system in MATLAB/Simulink, the system behavior during environmental variations and changing the grid conditions can easily be analyzed by researchers. This study evaluates a grid-tied photovoltaic (PV) system in Lahore's urban environmental conditions, leveraging MATLAB/Simulink modeling. The system incorporates high-efficiency Jinko Solar Maxpower panels, a boost converter, and a Growatt inverter, achieving a stable 12 kW output with control like Incremental Conductance Maximum Power Point Tracking (MPPT). This paper pre rent a system dynamic model and simulation in Simulink. The system has no battery. So, all solar produced power is sent to connected load and local grid.

Keywords: Grid-tied photovoltaic system, MATLAB/Simulink, MPPT DC-dc boost converter, solar energy.

Submitted: April 15, 2025

Published: July 12, 2025

10.24018/ejenergy.2025.5.4.167

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1. Introduction

The transition from fossil fuel to renewable energy is a very crucial requirement in sustainable development, rather critical at times when global energy landscapes are changing rapidly [1]. Grid-connected solar inverters are instrumental devices for making possible the adoption of solar energy in the energy supply infrastructures in urban areas [2]; for instance, they have an interesting future in cities like Lahore. The demand for energy will have continued to move higher and higher into the roof; hence such ones also become ever important. Assessing the solar energy source potential of Lahore includes an evaluation of the energy demand profile of the city, infrastructure ableness, and all-weather parameters affecting the performance of photovoltaic (PV) systems. This makes it easy for solar energy capturing for solar power generation, as the city enjoys generally well-known sunshine for most of the year with relatively high intensity and stable quantity. However, temperature differences, dust accumulation, and other environmental determinants call for customized designs of PV systems. Joining grid-tied solar inverters to Lahore's energy network would present a great opportunity for reshaping the energy framework of the city. These systems can make possible the smooth interfacing of solar power with the grid while providing for a reliable energy supply solution. The aim of this research will be to fill the gap between this theory and application by direct on-field examinations of such a system in various urban settings. Simultaneously, they will manage peak load demands while lessening the dependency on other traditional energy sources. Therefore, grid-connected solar inverters can contribute tremendously to energy resilience and thus the long-term stability of Lahore.

2. Literature Review

Many reviews have undertaken the energy evaluation of grid-connected photovoltaic (PV) systems through simulation with innumerable software. According to Benaissa *et al*. [3], the PV system's energy evaluation was done in detail over MATLAB/Simulink. The MATLAB model consisted of a boost converter and DC-AC inverter (VSC) through which electrical energy was fed into the grid. The example used is two 100 kW solar arrays, a boost converter, and a three-level inverter at the grid side. An elaborate solar cell model accounting for ambient temperature and irradiance along with an MPPT algorithm was implemented in further nonmathematical simulations. The results were obtained to demonstrate the effect of irradiance on the system and confirmed the ability of their controller to effectively manage the power transfer with respect to the grid.

Similarly, Kumar and Padma [4] modeled and simulated the residential PV plant utilizing 170-W modules of Mitsubishi. They studied I-V, P-V, and P-I characteristics based on a single-diode equivalent model and implemented a Perturb and Observe MPPT scheme using MATLAB/Simulink. The focus of the study was to have a clearer perspective on the vigorous performance and energy yield of the system under differing operational states. Then Rout and Bhattrai [5] carried out performance assessment of a grid-tied PV system of 1 kW capacity. Historical environmental data were used by the authors to develop a mathematical model for power output analysis and operational constraints identification while proposing strategies for the mitigation of the constraints in various situations. Tina and Selsa [6] exhibited a single-phase model of a grid connected inverter. The model consisted of the inverter, SPWM mechanism, control strategy, PLL, and filter elements. The authors declared that their model permits the independent control of active and reactive power and ensures voltage regulation at the PCC. Experimental and numerical validation confirmed the inverter stability and efficiency.

Molina and Espejo [7] PVSET 1.0 is a MATLAB/Simulink-based simulation tool developed to evaluate the working and dynamic characteristics of grid-integrated PV systems. Their work provided important insight into how PV systems behave under various grid scenarios.

AbdelHady [8] build a MATLAB/Simulink model of a 91 kW PV installation fully integrated under a microgrid with all set-ups at the National Water Research Center in Egypt to compare the performance of such systems in low- and high-voltage grid conditions under various scenarios and thus investigate the economic feasibility of such systems. Iqbal *et al*. [9] modeled standalone a PV generator for providing energy to a typical rural house in Pakistan. They sized a 5.8 kW PV array, eight batteries, and a 1.4 kW inverter by deriving hourly load data using BEopt and by using HOMER Pro. The results from MATLAB/Simulink were used to justify the ability of the system to meet the rural energy demand. This paper presents an analysis of Xie *et al*. [10], who addressed the problem of voltage control in grid connected PV systems via proposed nonlinear controller schemes based on Lyapunov theory and finite-time convergence, aiming at controlling the reactive power and regulating the DC link voltage. The approach's performance was demonstrated to be superior to traditional PI controllers, especially during disturbances concerning irradiance changes and grid faults. Gulzar *et al*. [11] gave yet another innovative idea by creating a converter-less control system for a combined usage of PV, wind, fuel cell, and batteries. It was found that without this invention, inventory costs would be cut by eliminating the PV inverter. This study [12] designed and simulated power electronics controllers for grid-connected PV arrays with MPPT capability. The author compared open- and closed-loop control strategies within Simulink, clearly proving the efficiency of the suggested controller in power delivery stabilization.

Further, Gulzar *et al*. [13] researched improving PV system control when rapidly varied weather conditions were present. AI-based optimization was applied to tune a sliding mode controller to enhance voltage stability and reduce the chance of overvoltage. Their finite-time sliding mode MPPT controller was said to perform excellently based on transient and steady-state conditions.

The study by Mahmood *et al*. [14] concentrated on the fault tolerance and stability aspects of such PV/-fuel cell hybrid systems considering a MIMO controller designed for MPPT and voltage regulation purposes. It was observed from MATLAB/Simulink simulations that voltage stability was improved and harmonic distortion reduced. Zebet *et al*. [15] determined a Fuzzy-PI controller model that regulates DC voltage in a single-phase grid-connected PV system with a capacity of 3 kW. This design helped minimize ripple at the input side and voltage fluctuation, as well as reduced the requirement in DC capacitor sizing, therefore strengthening the robustness of the system. Habib *et al*. [16] presented an optimized plan and predictive control strategy for a hybrid system of wind, diesel, battery storage, and converters applied in a remote village in Pakistan, including optimal component sizing, SOC-based battery management, and MPC for output voltage stabilization and reduced harmonic distortion. Battery depth of discharge (DOD) was considered in [17] for four technologies such as lead-acid, lithium-ion, vanadium redox, and nickel-iron at different cement plants in Pakistan. The study in [18] assessed the promising feasibility of hybrid energy solutions in cement factories. Batteries play a very significant role in energy storage; thus, proper health diagnoses were highlighted to be essential for longevity and savings in cost [19].

A comprehensive review pertaining to hybrid microgrid development, which included an analysis of the energy sources, system demands, and modeling strategies, was provided in [20]. It also assessed economic and environmental metrics through a detailed case study. The current paper adds to the work already done in this field, presenting a dynamic Simulink model of a grid-tied PV system. The system will include high-efficiency solar panels, boost converter, and grid tie inverter to maximize energy delivery.

3. Site Description

The research area selected is a domestic house in Lahore, Pakistan. The coordinates for the location are 31.482982 and latitude 74.3156. The image of an area from Google Map is shown in Fig. 1. With ample rooftop area the optometry conditions are perfect for solar energy systems. The geographical position in model town Lahore is favorable for achieving maximum solar irradiance throughout the year, greatly increasing the efficiency and production from the PV system. The modular approach improves

Fig. 1. Site location.

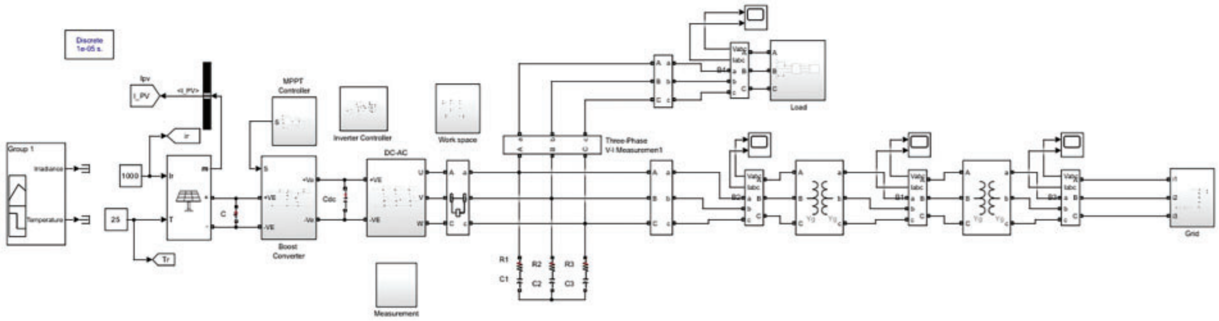

Fig. 2. Overall structure of model implemented on simulink.

TABLE I: Technical Specification of PV System

Type	Rating
Max Power (Pmax)	540 W
Open Circuit Voltage (Voc)	49.2 VDC
Max Power Voltage (Vmp)	40.70 VDC
Short Circuit Current (Isc)	13.85 A
Max Power Current (Imp)	13.27 A
Module efficiency	20.94%
Power Tolerance	0%–3%
Temp Coefficient of Isc (α_Isc)	0.048%°C
Temp Coefficient of Voc (β_Isc)	−0.28%°C
Temp Coefficient of Pmax (γ_Isc)	−0.35%°C

flexibility by allowing in-depth examination of each component's impact on performance. This model is based on the conditions of Lahore and applies climate-related parameters of the region.

3.1. Model Description

The Simulink model has already been implemented on a house under study. The researchers also used Homer Pro for techno-economic analysis. Fig. 2 illustrates the grid-connected photovoltaic (PV) system designed in this paper, with the addition of Jinko Solar panels for efficient conversion of solar energy. The PV array is made to control at an optimal voltage of 48 V, which is stringently regulated by a Maximum Power Point Tracking (MPPT) controller for maximum performance at varying irradiance levels. A boost converter boosts the PV output to 400 V, providing ideal conditions for grid synchronization through voltage amplification. For the convenience of integration with the electrical grid, the system is based on a Growatt MOD 11KTL3-X, an 11-kW pure sine wave hybrid inverter. Designed for 230 VAC, 50 Hz operation, the inverter matches the local utility supply standards for stable energy conversion. Compared to conventional hybrid systems, this arrangement is devoid of battery storage and injects the generated energy directly into the grid. Engineered for stability and efficiency, the system responds dynamically to changes in the environment, such as irradiance and temperature variations, with stable operation. Through its advanced control functionality, it delivers precise control of energy flow, optimizing sustainable energy management and grid interaction.

3.1.1. PV Array

The Jinko Solar high-efficiency monocrystalline solar modules are being used in this research. Each of these modules has a max power output of 540 W with a module efficiency of 20.94%. The main electrical characteristics are the open-circuit voltage (Voc), which is 49.2 V, short-circuit current (Isc) values as high as 13.85 A, max power voltage (Vmp) of 40.7 V, and max power current (Imp) of 13.27 A (refer to Table I for particulars).

3.1.2. DC-DC Converter

The configuration for the simulation critically calls for the modeling of a DC-DC converter with the inverter system. While the inverter has its own DC-DC converter, to emulate the operation and dynamic behavior of the real system closely, a boost converter has been modeled in Simulink. The boost converter plays a key role in the simulation of power transfer from the PV array to the inverter while regulating an output voltage of 476 V. Thus, the model adds a greater degree of realism to the simulation and also provides a platform for a thorough examination of the converter's efficiency and its subsequent impact on system performance. Further, the constraint for maximum power point tracking (MPPT) requires must be in place so that the performance of the DC-DC converter inside the PV system is maximized. The MPPT control scheme shown in Fig. 3 is realized through the Incremental Conductance method combined with an Integral Regulator.

The Incremental Conductance (IC) method is actively capable of dynamical changing the operating point of a PV system to achieve max power. It can follow continuously changing power and voltage to keep aligned with the MPP on the power-voltage (P-V) curve. Under the rapidly changing state of irradiance and temperature, this technique has proved very effective due to its rapid and accurate response. This method gives power voltage characteristics according to which the slope of power concerning voltage becomes equal to zero for maximal power point. The firing system compares the incremental conductance ($\Delta I/\Delta V$) and instantaneous conductance (I/V), adjusting the operating point till $\Delta I/\Delta V$ equals negative I/V, indicating the optimal point IC=0.

Use of the Integral Regulator adds to tracking accuracy and stability of the system under the MPPT approach. The essence of the regulator is to reduce the error in steady state through the accumulation of the difference of actual conductance and target conductance with time. Consequently, this will entail rendering power extraction

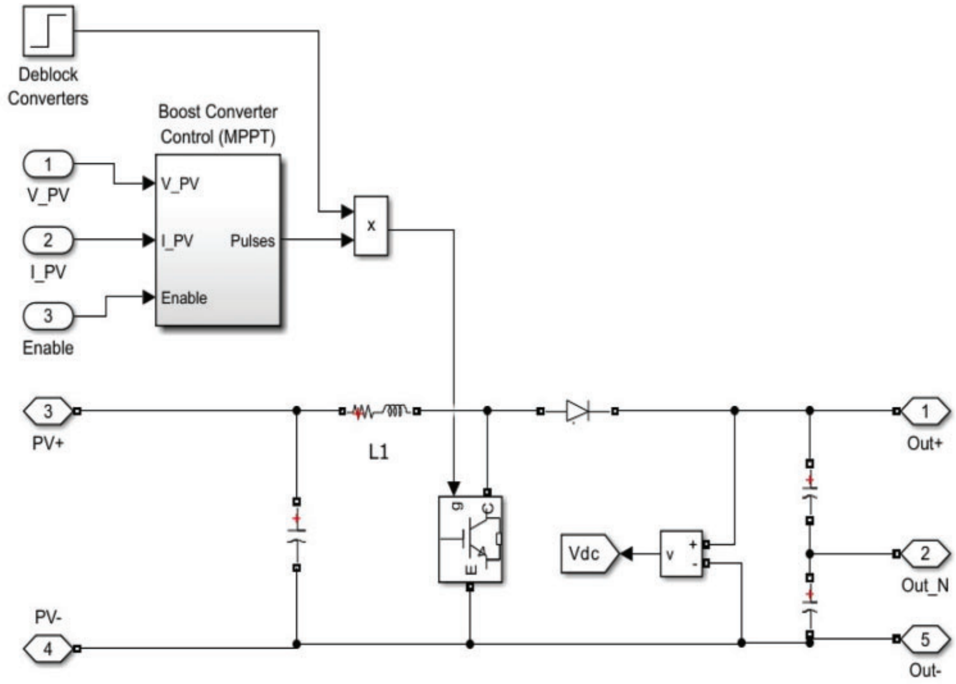

Fig. 3. MPPT converter simulink model.

TABLE II: Technical Specification of Inverter

Type	Rating
Output power	12100VA/1100W
Voltage	230/400 VAC
Frequency limit	50Hz/60Hz
PV voltage limit	140-1000 dc V
PV I_{sc}	16 dc A∗2
Max input current	13 dc A∗2
Max output current	18.3 ac A
Operating temp	–25°C – +60°C

from the array consistent and precise when environmental changes occur. The equation for the Integral Regulator can be written as (1):

$$I_{Reg} = I_{Reg} + k_i \cdot error \tag{1}$$

where *I_Reg* is the integral term, *k_i* is the integral gain, *error* is the difference between the actual conductance and the conductance at the maximum power point.

3.1.3. Inverter

The proposed system uses a Growatt pure sine wave hybrid inverter, specifically designed for residential and small commercial PV systems. This single-phase string inverter offers a maximum output power. It can handle a maximum input current of 26 A and supports an input voltage range between 140 V to 1000V as shown in Table II.

The inverter includes dual DC connections and can accommodate power from a PV generator, with a nominal and maximum AC output power. It operates within an AC voltage range of 180 V to 270 V and is compatible with a 1∼NPE 220/230 V grid connection.

In this respect, WLAN, Ethernet LAN, Modbus TCP SunSpec, and USB ports have been deployed on the inverter for data logging and firmware updates. This is accomplished with regulated air cooling and an insignificant consumption of less than 1 W when in standby during the night. The inverter also offers three operational modes: stand-alone operation (with battery backup in isolation

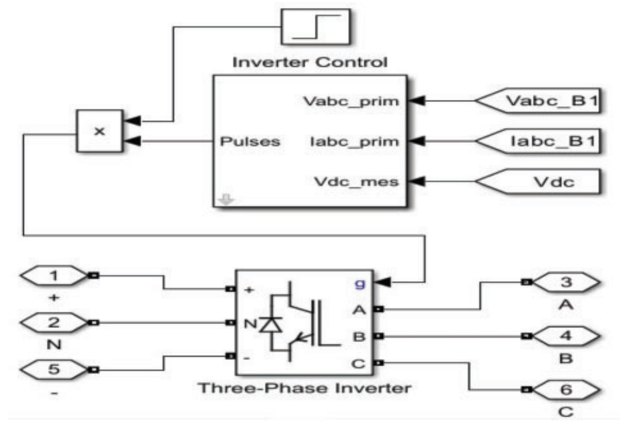

Fig. 4. Control block of inverter in simulink.

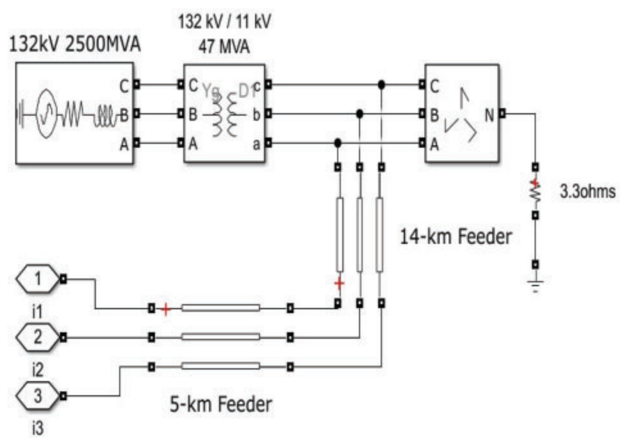

Fig. 5. Grid system model.

from the utility), grid tied (where it operates with solar panels and the utility grid), and hybrid mode (where it operates with both battery backup and utility supply). The control block of an inverter system is shown in Fig. 4. Smart load management is further enhanced through dual outputs, where one output can be allocated to non-critical loads that can be automatically disconnected to save battery power during the night. However, this value was not considered in this study.

3.1.4. Grid Modeling

A grid connected PV system model is precisely built to mimic Lahore's power distribution network as shown in Fig. 5.

4. Result and Discussion

The comprehensive working evaluation of the photovoltaic (PV) grid-connected system highlighted its efficiency and robustness across varying environmental conditions. The system components include Jinko Solar JKM540M-72HL4-V panels and Growatt PV Grid Inverter MOD 11KTL3-X, which has a boost converter and MPPT.

The solar panels demonstrated an optimal power output of approximately 11 kW under peak sunlight conditions, with an efficiency of around 17.37%. The PV panels give high performance despite fluctuations in solar irradiance and ambient temperature, maintaining efficiency even under partial shading and cloud cover. The advanced cell technology and anti-reflective coating optimized light absorption, particularly in low-light conditions during early mornings and late afternoons.

The system parameters included a PV input voltage of 48 V with an MPPT voltage also set at 48 V, ensuring that the array operated at its maximum efficiency. The boost converter played a pivotal role in elevating the DC voltage to 350 V, which was subsequently converted to a 220 V AC supply through the inverter for grid integration. The combined efficiency of these components ensured reliable energy transfer and minimized power losses.

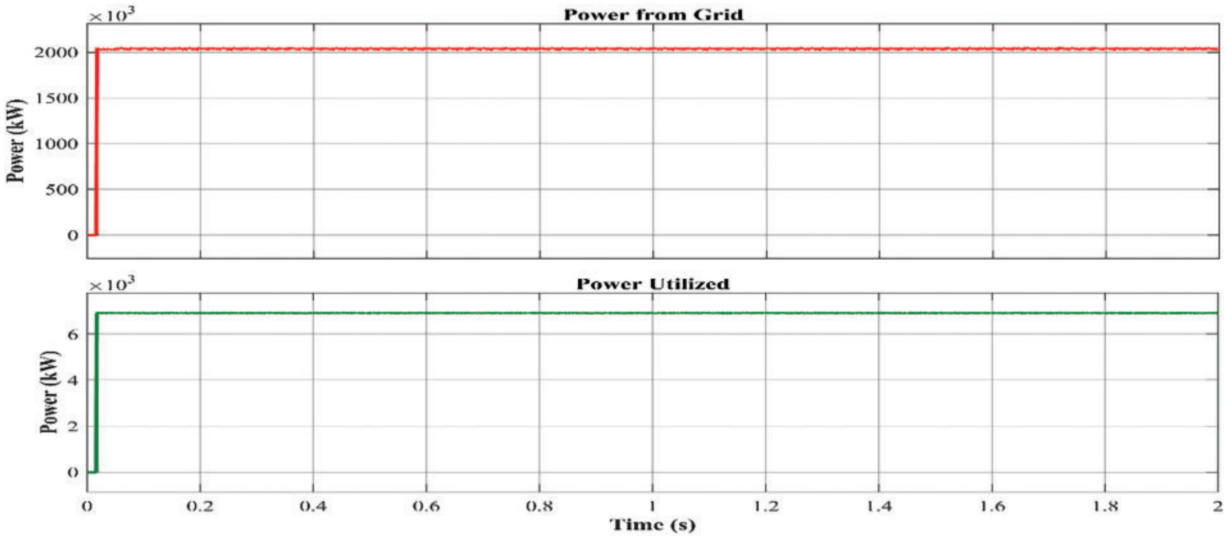

Fig. 6. Grid power and load consumption.

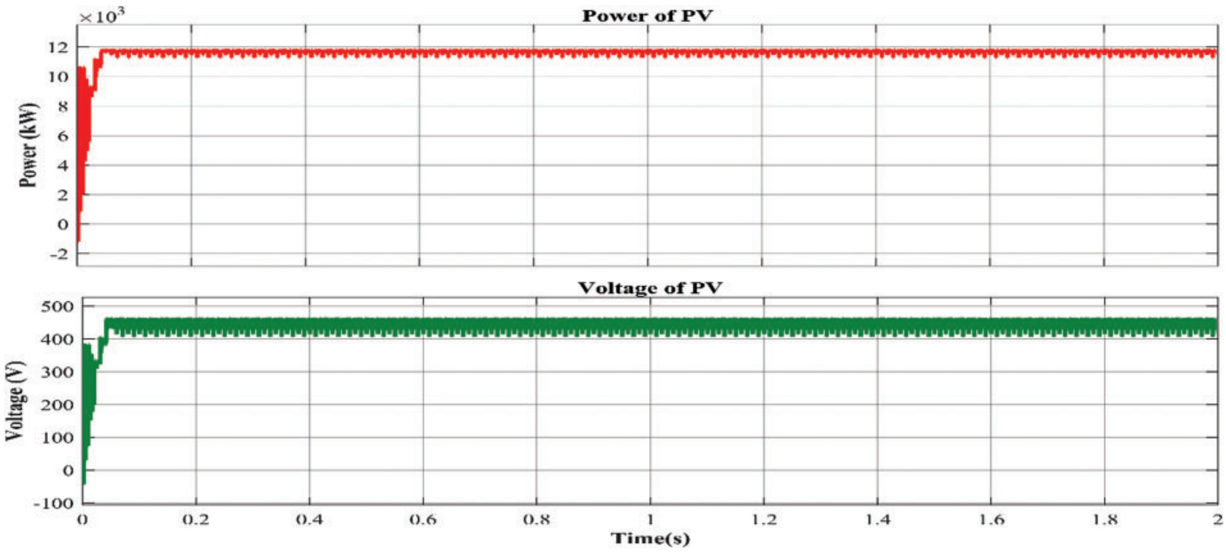

Fig. 7. PV result.

The boost converter efficiently elevated the PV output to the required 406 V, supporting a stable AC output from the inverter. This voltage boost was crucial in optimizing power transfer to the grid, as illustrated in Fig. 6. The combination of the MPPT controller and the boost converter also minimized voltage ripples, enhancing overall system efficiency and extending the lifespan of the PV installation.

The inverter's rapid response to grid voltage and frequency fluctuations maintained a stable output of up to 12 kW, even under variable grid conditions. The PV power output was closely linked to solar irradiance levels, with the system demonstrating efficient energy harvesting. This capability ensures that the system can support grid stability during peak solar generation.

The PV voltage remained stable at around 460 V, showcasing the MPPT controller's effectiveness in optimizing voltage levels for maximum power extraction as shown in Fig 7.

Solar irradiance quickly reached 1000 W/m^2, directly correlating with increased PV power output. This illustrates the system's efficient response to changes in solar input, ensuring consistent energy supply. The integration of PV generation and grid connection facilitated smooth energy management:

The grid power flow stabilized at around 11kW after initial fluctuations, demonstrating the effective use of the grid to balance excess generation with load demand.

The load power consumption was maintained at approximately 7.10 kW, indicating that the system successfully met high demand while optimizing power flow between the PV array, and the grid.

Overall, this system represents an effective solution for integrating renewable energy into the grid.

5. Conclusion

The modeled grid-connected PV system indeed had excellent efficiency, reliability and adaptability, and thus is a solution for a sustainable energy integration in urban environments. Efficient implementation of a Maximum Power Point Tracking (MPPT) controlled boost converter, and a high efficiency inverter have been achieved to yield maximum power extraction and minimal energy loss, to improve system performance. It is found that the design proposed in the study is practically applicable to the residential and commercial sectors, especially in cities like Lahore which need its adoption to address the power shortages. The findings set a solid ground for PV developments and reaffirm solar energy.

Conflict of Interest

The authors declare that they do not have any conflict of interest.

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