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(Research Article)

Design and simulation of an IoT-enabled Bi-directional energy meter for grid-connected photovoltaic systems

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Abstract

This study addresses the limitations of conventional unidirectional energy meters in grid-connected solar photovoltaic (PV) systems, which are unable to accurately account for bidirectional power flow in modern prosumer environments. Existing approaches often treat energy metering, grid synchronization, and system monitoring as separate functionalities, resulting in limited integration and reduced effectiveness in smart grid applications. This research presents the design and simulation of a three-phase, grid-connected bi-directional energy metering system developed within the MATLAB/Simulink environment. The proposed framework integrates a PV generation model, a grid-synchronized inverter employing phase-locked loop (PLL) control, and an LCL filter for harmonic mitigation. A computational metering algorithm based on instantaneous power theory is implemented to distinguish and accumulate imported and exported energy in real time. Simulation studies were conducted under dynamic operating conditions involving transitions between net-import and net-export modes. Results demonstrate that the system accurately tracks bidirectional energy flow, correctly registering energy exchange across both operating states while maintaining stable system response during power flow reversals. The model also exhibits effective transient behavior, with fast stabilization following changes in load and generation conditions. The results provide a validated baseline for further development of intelligent metering systems and support the advancement of smart grid–compatible energy management solutions.

Keywords: Bi-directional energy metering; Grid-connected photovoltaic system; Three-phase systems; Instantaneous power theory; Phase-locked loop (PLL); MATLAB/Simulink; Smart grid

1. Introduction

The increasing deployment of grid-connected solar photovoltaic (PV) systems has significantly transformed conventional power distribution networks by enabling bidirectional energy flow between consumers and the utility grid. In such systems, consumers operate as prosumers, simultaneously consuming and exporting electrical energy, thereby supporting net-metering schemes based on the difference between imported and exported energy [1], [2]. Accurate measurement of this bidirectional energy exchange is therefore essential for fair billing and effective energy management.

However, conventional energy meters are designed for unidirectional power flow and are unable to distinguish between energy imported from and exported to the grid. This limitation leads to inaccurate energy accounting and restricts the effective implementation of net-metering policies [3]. In addition, the dynamic nature of PV generation introduces frequent transitions between import and export modes, requiring reliable system synchronization and robust energy measurement under varying operating conditions [4].

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Existing smart metering solutions primarily focus on data acquisition and communication, with limited integration of real-time computational metering and system-level validation. Furthermore, many studies treat energy metering, grid synchronization, and power conditioning as separate components, resulting in fragmented system architectures [5].

This study presents the design and simulation of a three-phase, grid-connected bi-directional energy metering system using MATLAB/Simulink. The proposed framework integrates PV generation, grid synchronization using a phase-locked loop (PLL), harmonic filtering through an LCL filter, and a computational metering algorithm based on instantaneous power theory. The developed model provides a unified simulation environment for accurate tracking of bidirectional energy flow and evaluation of system performance under dynamic operating conditions.

2. Literature review

Review on the relevant literature on bi-directional energy meter is here presented. The transition from conventional unidirectional grids to distributed energy systems has led to the development of bi-directional energy meters capable of measuring both imported and exported power. Early studies, such as Maharaja et al. [6], demonstrated the feasibility of low-cost microcontroller-based net meters for domestic PV applications. Similarly, Rahman et al. [1] developed a hardware-based bi-directional meter using phase difference detection between voltage and current signals to determine power flow direction. While these approaches confirm the practicality of bidirectional metering, they are often limited by low sampling accuracy, restricted testing conditions, and lack of scalability for complex grid-connected systems.

2.1. Smart Metering and IOT Integration

Recent advancements in smart metering focus on integrating communication technologies for real-time monitoring and control. Bera et al. [7] proposed energy-efficient smart metering architectures for improved data transmission within smart grids, while Saleem et al. [5] demonstrated IoT-enabled systems capable of remote energy monitoring and load management. These systems enhance visibility and control but often prioritize communication over accurate real-time computational metering. In many cases, the metering logic is treated as a secondary function, resulting in limited validation of energy accounting accuracy under dynamic operating conditions.

2.2. Grid Synchronization and Power Quality Considerations

The integration of PV systems into the grid introduces challenges related to synchronization and power quality. Phase-Locked Loop (PLL) techniques are widely used to ensure proper alignment between inverter output and grid voltage, thereby enabling stable power exchange [3]. Additionally, harmonic distortions introduced by power electronic converters are commonly mitigated using LCL filters, which provide improved attenuation of switching harmonics compared to conventional filtering approaches [4]. Although these studies effectively address grid stability and power quality, they often treat metering and control systems as separate entities, limiting the evaluation of their combined performance.

2.3. Integrated Smart Grid Energy Systems

Several studies have explored the broader concept of smart grid integration, including energy sharing, demand-side management, and real-time monitoring [8], [9]. However, existing research typically focuses on individual components such as metering hardware, communication systems, or control strategies in isolation. Limited work has been conducted on developing a unified framework that integrates bi-directional energy measurement, grid-connected PV dynamics, and real-time computational logic within a single simulation environment.

In particular, many existing implementations rely on hardware prototypes without comprehensive system-level validation, or simulation studies that do not incorporate accurate metering algorithms for bidirectional energy accounting. This creates a gap in the development of fully integrated and validated models suitable for modern prosumer-based energy systems.

This study addresses the identified gap by developing a MATLAB/Simulink-based simulation framework that combines three-phase PV generation, grid synchronization, harmonic filtering, and a computational bi-directional metering algorithm within a unified model. This approach enables a more comprehensive evaluation of system performance under dynamic operating conditions.

3. Methodology

This section details the design and modeling of the proposed bi-directional energy metering system. The methodology encompasses the architectural design of the grid-connected photovoltaic system, the control strategies for power conversion and grid synchronization, and the algorithmic development for the bi-directional energy calculation, all of which are modeled and simulated using the MATLAB/Simulink environment.

3.1. Design and Simulation Framework

A model-based design (MBD) approach was adopted to develop the proposed system within the MATLAB/Simulink environment. The system consists of a three-phase, grid-connected photovoltaic (PV) source integrated with a bi-directional energy metering algorithm.

The complete simulation framework comprises four main subsystems: the PV generation unit, a three-phase inverter, a grid synchronization and filtering stage, and a computational energy metering block. The overall architecture of the system is presented in Figure 1, where all subsystems are integrated within a closed-loop simulation environment to replicate real operating conditions.

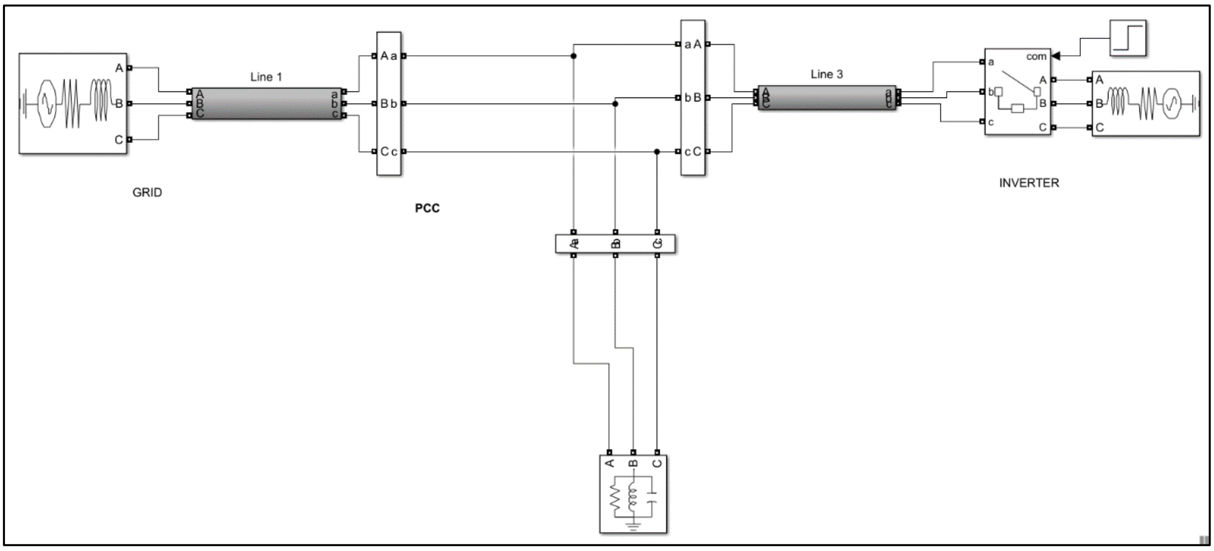

Figure 1 Top-level Simulink model showing PV array, inverter, grid interface, synchronisation unit, and metering block

3.2. System Modelling

This section outlines the development of the simulation model in MATLAB/Simulink. It provides an overview of the mathematical modeling and functional configuration of each subsystem, ensuring a high-fidelity representation of the grid-connected PV system for accurate bi-directional metering analysis

3.2.1. Photovoltaic (PV) Modelling

The PV system was modelled to represent the nonlinear current-voltage characteristics of solar cells, where output current is dependent on irradiance and temperature. The PV array serves as the primary DC energy source for the system. The generated power is expressed as:

$P_{PV} = V_{PV} \cdot I_{PV}$ ...(1)

To ensure optimal power extraction, a Maximum Power Point Tracking (MPPT) algorithm based on the Perturb and Observe (P&O) method was implemented [3].

3.2.2. Three-Phase Inverter and Grid Synchronization

The DC output from the PV system was converted to AC using a three-phase voltage source inverter (VSI). The inverter enables bidirectional power exchange between the PV system and the utility grid depending on system conditions.

For a balanced three-phase system, the active power is given by:

$$P = \sqrt{3} V_L I_L \cos\phi \qquad ...(2)$$

where, V_L is the line voltage, I_L is the line current and ϕ is the phase angle

The interaction between the PV system, inverter, and grid is illustrated in Figure 2.

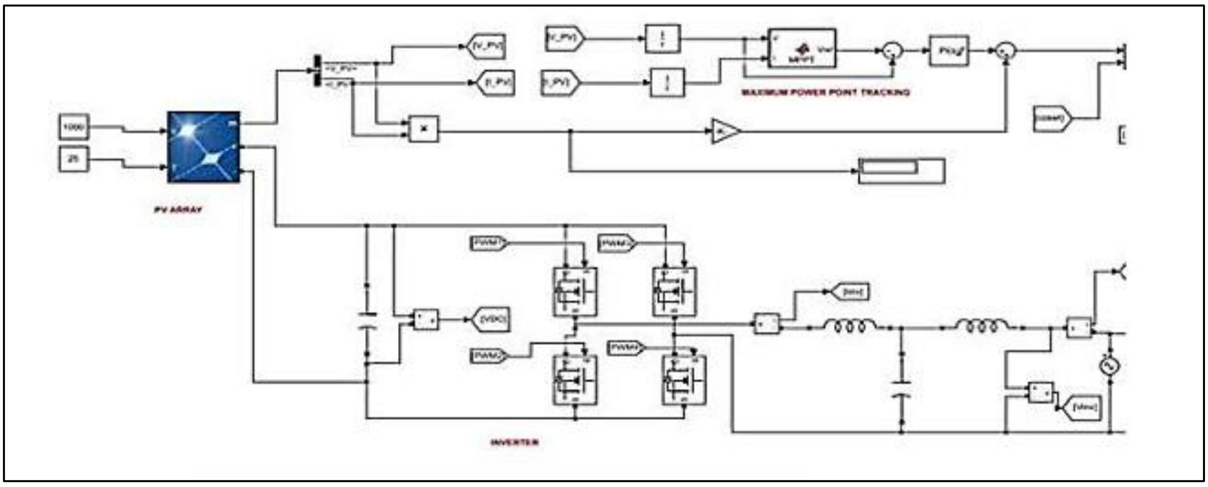

Figure 2 Block diagram showing PV array, DC-AC inverter, LCL filter, and grid connection.

3.2.3. Grid Synchronization using Phase-Locked Loop (PLL)

To ensure proper synchronization between the inverter output and the grid, a Phase-Locked Loop (PLL) was implemented. The PLL continuously tracks the grid phase angle and frequency, ensuring stable power exchange [3].

The estimated phase angle is given by:

$$\theta(t) = \int \omega(t) dt \qquad ...(3)$$

where, ω is the grid angular frequency

This synchronization mechanism is critical for accurate power flow direction detection and system stability.

3.2.4. Harmonic Filtering using LCL Filter

An LCL filter was used to reduce harmonic distortions introduced by inverter switching. The filter improves power quality by attenuating high-frequency harmonics before power is injected into the grid [4].

The resonance frequency of the LCL filter is expressed as:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{L_1+L_2}{L_1 L_2 C}} \qquad ...(4)$$

where, L_1, L_2 are inductances, and C is the filter capacitance

3.3. Bi-Directional Energy Metering Algorithm

The core of the system is the computational metering algorithm based on instantaneous power theory. The instantaneous power is calculated as:

$$p(t) = v(t) \cdot i(t) \qquad ...(5)$$

The direction of power flow is determined from the sign of $p(t)$: if $p(t) > 0$ it means energy import (grid to load) and if $p(t) < 0$, it signifies energy export (PV to grid).

The total energy is obtained by integrating power over time:

$$E = \int p(t)dt \qquad \text{...(6)}$$

To improve measurement accuracy, RMS values of voltage and current are also evaluated as:

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T v^2(t)dt} \qquad \text{...(7)}$$

$$I_{rms} = \sqrt{\frac{1}{T}\int_0^T i^2(t)dt} \qquad \text{...(8)}$$

The implementation of the metering logic is illustrated in Figure 3.

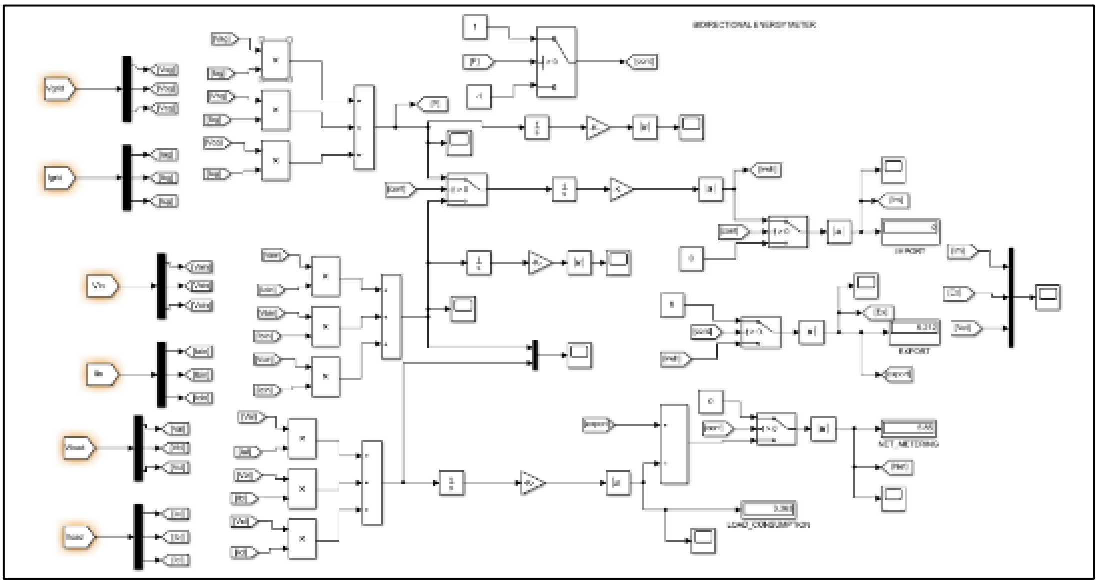

Figure 3 Computational block showing voltage and current measurement, power calculation, sign detection, and energy accumulation.

3.4. Simulation Scenarios and Performance Evaluation

The system was evaluated under dynamic operating conditions to simulate realistic grid-connected PV behavior. These scenarios include transitions between energy import and export by varying load demand and PV generation levels.

Performance evaluation was based on the following criteria:

- Accuracy of bidirectional energy measurement,
- Correct detection of power flow direction,
- Stability during power flow transitions, and
- Transient response to sudden changes in load or generation

4. Results and discussion

This section presents and discusses the performance of the proposed bi-directional energy metering system under different operating conditions. Particular attention is given to the system's ability to accurately track import and export energy, maintain stability during mode transitions, and respond effectively to transient changes in generation and load demand.

4.1. System response under the Bi-Directional Operation

The performance of the proposed system was evaluated under dynamic operating conditions involving transitions between energy import and export modes. These conditions were simulated by varying the PV generation and load demand within the system.

As shown in Figure 4, the system initially operates in import mode, where energy is drawn from the grid due to insufficient PV generation. At a defined transition point, the import energy accumulation stops, indicating a shift in system operation.

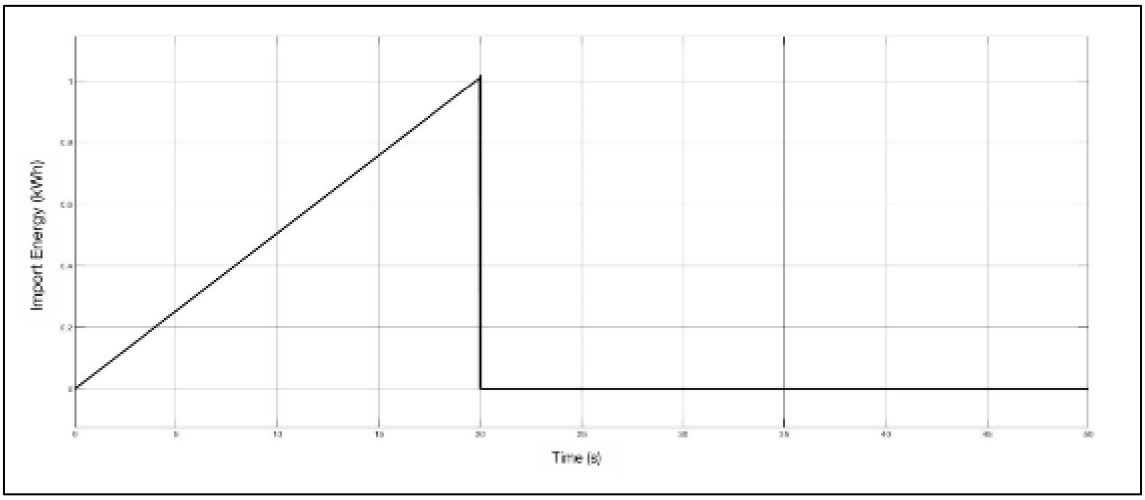

Figure 4 Time-domain profile of cumulative imported energy illustrating steady energy accumulation under utility-dominant operating conditions.

From Figure 4, the linear increase in imported energy confirms stable energy consumption from the grid. The abrupt flattening of the curve indicates a transition point where grid import ceases, demonstrating correct detection of operating mode changes by the metering system.

4.2. Accuracy of energy measurements

The accumulated energy values for both import and export modes were obtained by integrating the instantaneous power over time. The combined energy profiles are presented in Figure 5.

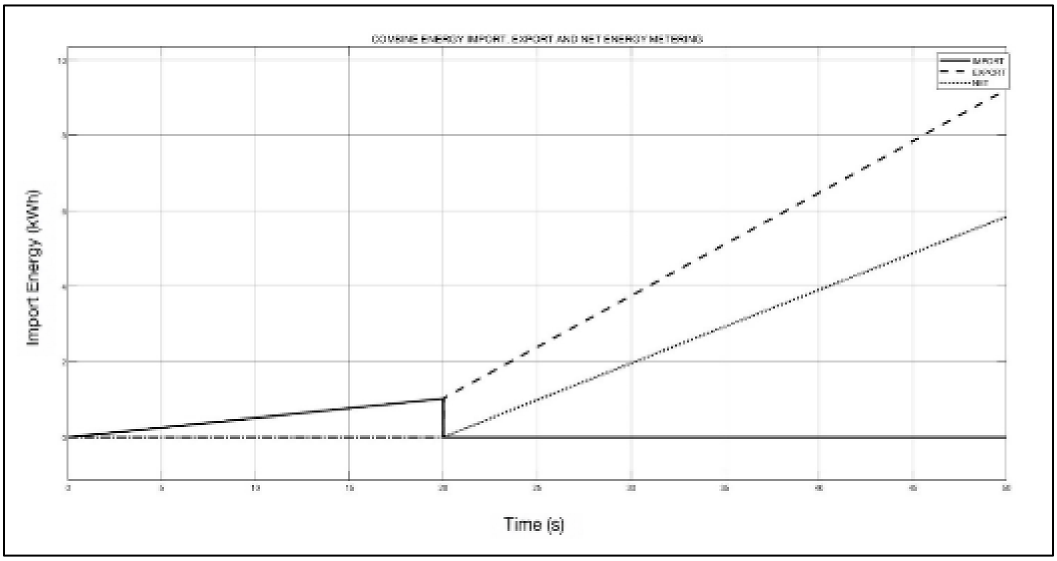

Figure 5 Combined energy metering profile showing cumulative import, export, and net energy variation for bidirectional power flow analysis.

As illustrated in Figure 5, the system initially accumulates import energy, followed by a steady increase in export energy after the transition point. The net energy curve reflects the difference between the two, confirming accurate implementation of net metering. The consistency between the energy curves demonstrates that the system correctly separates and accumulates imported and exported energy without overlap or error.

4.3. Transient Response and System Stability

The transient behavior of the system during transition from import to export mode is further illustrated in Figure 6.

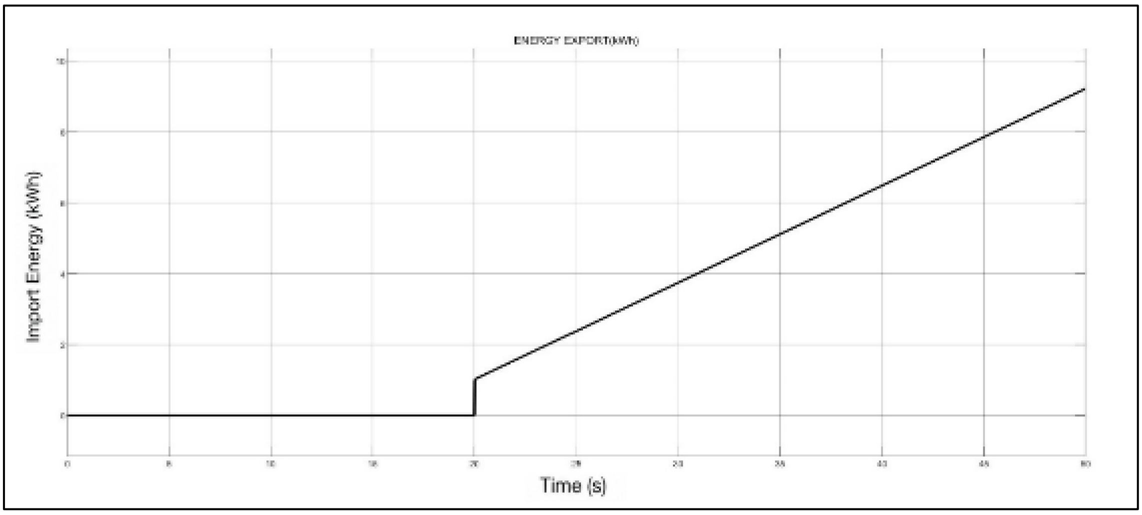

Figure 6 Time-domain profile of cumulative exported energy showing initiation and growth of energy export following transition to PV-dominant operation.

As shown in Figure 6, the export energy remains zero during the initial period and begins to increase only after the transition point. This confirms that the system correctly detects the reversal of power flow direction. The smooth transition without oscillation or delay indicates that the metering algorithm operates reliably under changing operating conditions.

4.4. System Response Under Grid Disturbance

To evaluate system robustness, the response under grid disturbance conditions was analyzed, as shown in Figure 7.

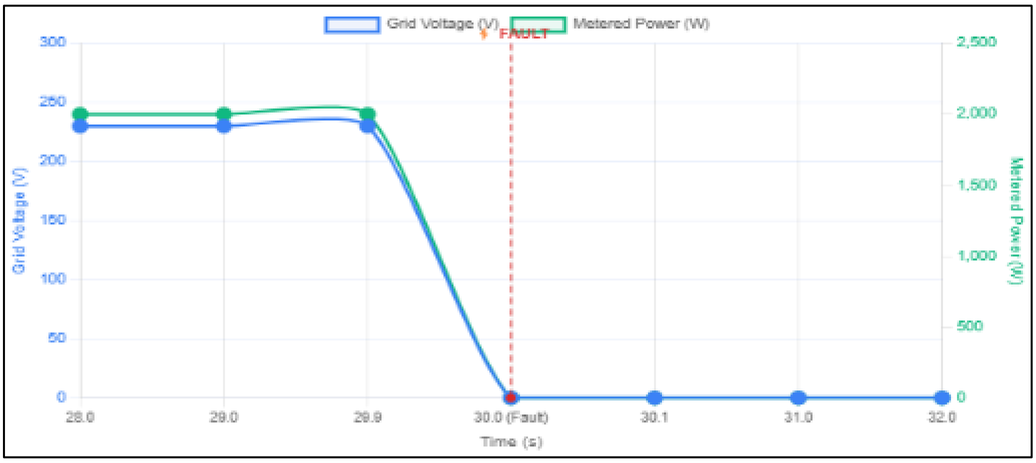

Figure 7 System response under grid disturbance showing voltage collapse and corresponding variation in metered power.

As observed in Figure 7, a sudden drop in grid voltage occurs at the fault point, accompanied by a corresponding reduction in metered power. The system responds immediately without introducing erroneous energy accumulation. This demonstrates that the metering system maintains accuracy and stability even under abnormal grid conditions.

5. Summary and conclusion

This study presented the design and simulation of a three-phase, grid-connected bi-directional energy metering system developed in the MATLAB/Simulink environment. The proposed framework integrates PV generation, grid synchronization using a phase-locked loop (PLL), harmonic filtering through an LCL filter, and a computational metering algorithm based on instantaneous power theory.

The results confirm that the proposed system provides accurate and stable measurement of bidirectional energy flow in a three-phase grid-connected PV system. The system successfully differentiates between import and export conditions and maintains correct energy accumulation across operating modes.

The combined energy profile further validates the implementation of net metering, while the system response under disturbance conditions demonstrates robustness and reliability. Future work should focus on hardware implementation for real-time validation, integration of IoT-based monitoring systems, and incorporation of advanced control and fault detection strategies to enhance system performance under practical operating conditions.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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