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Modelling of a Bi-directional Converter System for Sustainable Microgrid Integration

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Abstract: **This paper presents the modeling and simulation of a bi-directional converter system designed for efficient energy exchange between a solar-powered microgrid and the national grid. The system enables two-way power flow, exporting surplus energy from distributed generation to the grid and importing power during low-generation periods while maintaining voltage and frequency stability. Using MATLAB/Simulink, the converter was modelled with integrated control features including a Proportional–Integral (PI) regulator for voltage and current control, and a Phase-Locked Loop (PLL) for grid synchronization. The system performance was analyzed under varying solar irradiance and load conditions to evaluate its stability, conversion efficiency, and harmonic distortion. Simulation results demonstrated that the converter sustained a stable DC link voltage of 380 V with deviations below 2%, achieved a peak efficiency of 95.8%, and maintained a Total Harmonic Distortion (THD) of less than 3.5%. These findings confirm that bi-directional converters are essential for** enhancing **microgrid reliability, energy efficiency,** and tariff accuracy **when integrated with bi-directional metering. The proposed model provides a practical foundation for intelligent renewable energy management and supports the development of sustainable distributed power systems.**

Keywords: **Bi-directional converter, microgrid integration, MATLAB/Simulink, renewable energy, power flow control, grid synchronization, energy efficiency, harmonic distortion.**

I. INTRODUCTION

The transition to renewable-based microgrids requires efficient power electronic interfaces that allow seamless energy exchange between distributed generators and the main grid. One such interface is the bi-directional converter system, which regulates power flow in both directions, exporting surplus renewable energy to the grid and importing power during periods of low generation (Sreelatha et al., 2024; Tricarico, 2020). In hybrid systems that combine solar PV generation, battery energy storage, and grid support, the converter must maintain synchronization of voltage, frequency, and phase angles while minimizing conversion losses and harmonic distortions (Bakeer et al., 2024). The key challenge lies in ensuring real-time stability during fluctuating solar input and variable load conditions (Panchanathan et al., 2023).

In this study, a bi-directional converter model was developed as part of a sustainable solar-powered microgrid framework designed for a 20-unit residential estate. The converter acts as the intermediary between DC sources (solar PV, batteries) and the AC grid, enabling both grid import and export through controlled switching mechanisms. MATLAB/Simulink was used to model converter dynamics, control parameters, and system performance under variable load and solar conditions. The objective is to develop a functional and validated model that ensures efficient energy conversion, maintains grid compatibility, and supports accurate metering in smart microgrid applications (Kabeyi & Olanrewaju, 2023; Xu et al., 2024).

II. METHODOLOGY

A. Design Method

The essential device for grid-connected microgrids requires a bi-directional energy meter that precisely measures incoming and outgoing electrical power. A bi-directional meter serves two purposes by analyzing grid-supplied power consumption and monitoring the export of surplus power. Renewable energy-based microgrids require precise energy metering, as they experience fluctuations in solar irradiance, and people use electricity from both the national grid and on-site solar PV during the daytime.

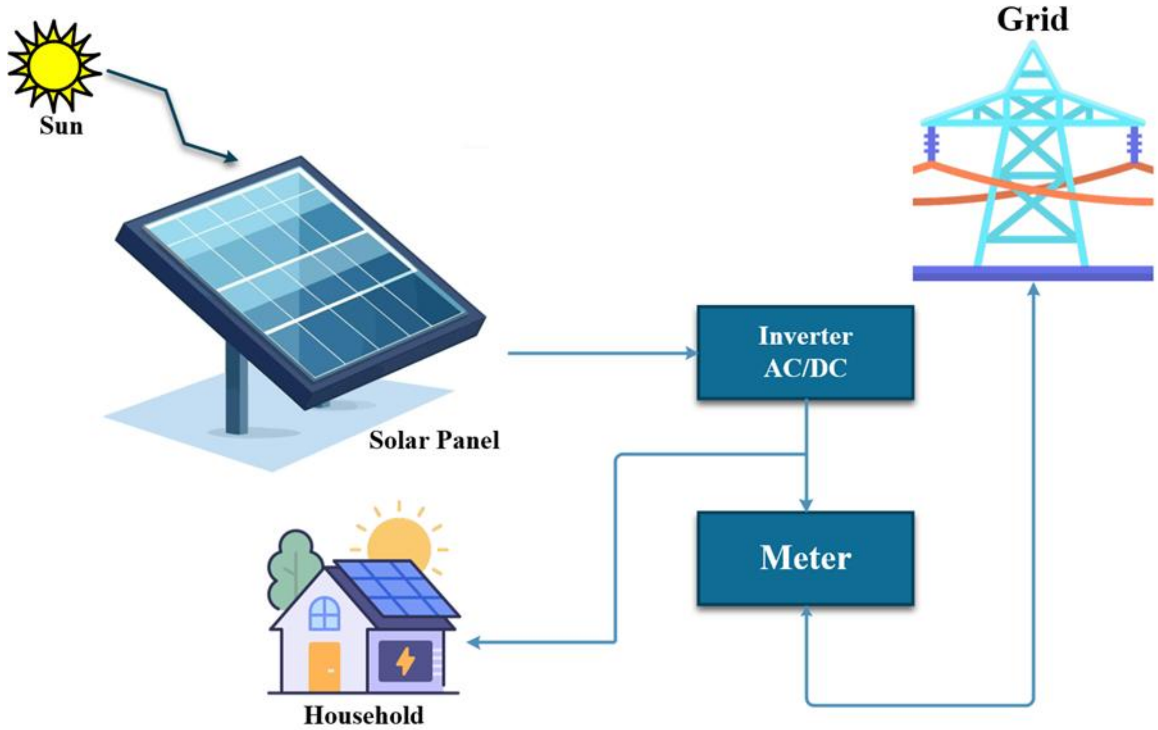

Fig. 1: Conceptual architecture of a grid-connected solar microgrid using a bi-directional converter.

Figure 1 illustrates the architecture of a bi-directional energy metering system where solar panels generate electricity from sunlight, supplying power to both the household and the utility grid. The inverter converts the solar DC power to AC. At the same time, the bi-directional meter tracks energy flow in both directions, monitoring energy consumed by the home and excess energy sent back to the grid.

B. Modelling of the Bi-Directional Metering for Energy Monitoring and Billing

The modeling process combined power electronics simulation**,** control design, and energy flow analysis. The major system components are described below.

C. System Components

1. PV (Photovoltaic) panel
2. Inverter
3. Bidirectional Meter
4. Utility Grid
5. To Workspace (output or data collection block)

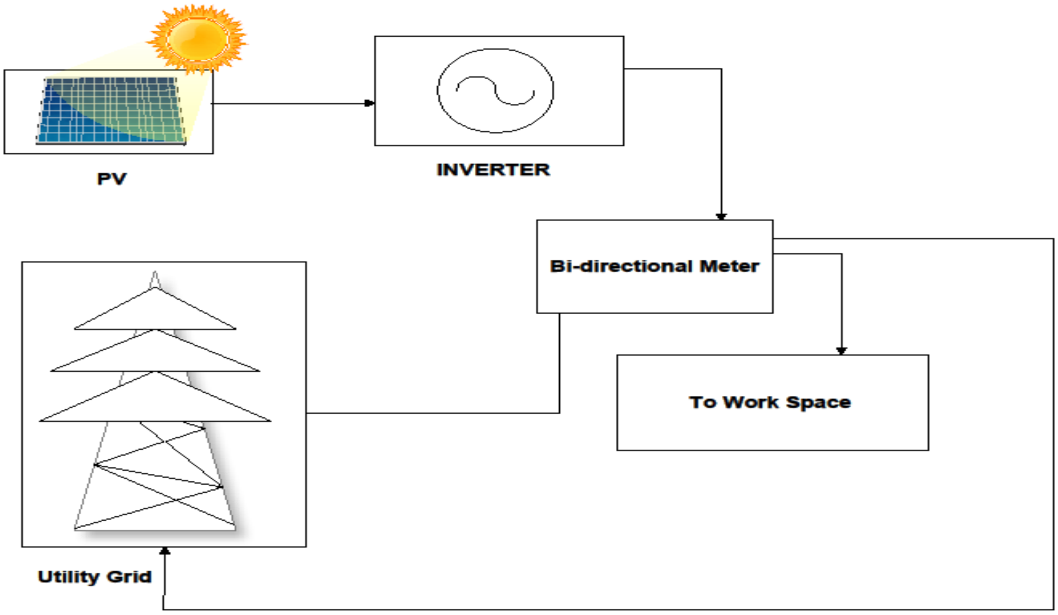

Fig. 2: Block diagram Model of the Bi-directional Metering System

The Simulink model in Figure 2 represents a bi-directional energy metering system within a grid-connected solar microgrid. In this setup, the solar PV array generates DC power from sunlight, which is converted to AC by the inverter for household consumption and interaction with the utility grid. The load block models the estate's energy usage, while the grid block represents the national supply that provides power when solar generation is insufficient. At the point of common coupling, a bi-directional meter measures imported energy (E_imp) from the grid when demand exceeds solar output, and exported energy (E_exp) when surplus solar power is fed back into the grid. These measurements are processed by the billing and tariff calculation subsystem, which applies net metering, time-of-use pricing, or dynamic tariffs, ensuring accurate billing by charging for imported energy and crediting exported energy.

D. Mathematical Model of the Bi-directional Metering System

A bi-directional energy metering system was modelled to accurately record both imported energy (E_{imp}) and exported energy (E_{Exp}) between the grid and the local microgrid. The net energy consumption was computed as:

$$E_{net} = E_{imp} - E_{exp} \quad (1)$$

Three tariff models were applied within the simulation framework:

1. Net Metering, where exported energy offsets imported energy one-to-one:

$$E_{bill} = max(0, E_{imp} - E_{exp}) \quad (2)$$

If $E_{exp} > E_{imp}$, the surplus energy is credited to the user's account or carried forward to future billing cycles.

2. Feed-in Tariff (FIT)**,** in which exported energy is credited at a lower fixed rate than imported energy costs.

3. Dynamic Pricing, where tariffs vary in real-time based on grid demand:

$$C_{bill} = (E_{imp,peak} \times P_{peak}) + (E_{imp,offpeak} \times P_{offpeak}) \quad (3)$$

where P_{peak} and $P_{offpeak}$ are the respective electricity rates for peak and off-peak hours. The simulation was executed over a 24-hour daily cycle, capturing system performance under varying solar irradiance and load conditions.

III. RESULTS AND DISCUSSION

The graph in Figure 3 illustrates the simulated daily operation of the bi-directional energy metering system in the evaluated microgrid. In the early hours, before sunrise, all household demand is met by importing electricity from the grid. As solar irradiance increases in the morning, PV generation rises and gradually offsets grid imports until, by late morning, generation matches the load. Around midday, PV output peaks and exceeds household demand, leading to significant energy exports back to the grid. This surplus period continues through early afternoon before tapering off as solar production declines. By evening, PV generation drops to zero, and the household resumes importing all its energy needs from the grid. The evaluation results confirm that the bi-directional meter accurately tracks both imported and exported energy, enabling precise calculation of net consumption, billable energy, and credits according to the applied tariff models.

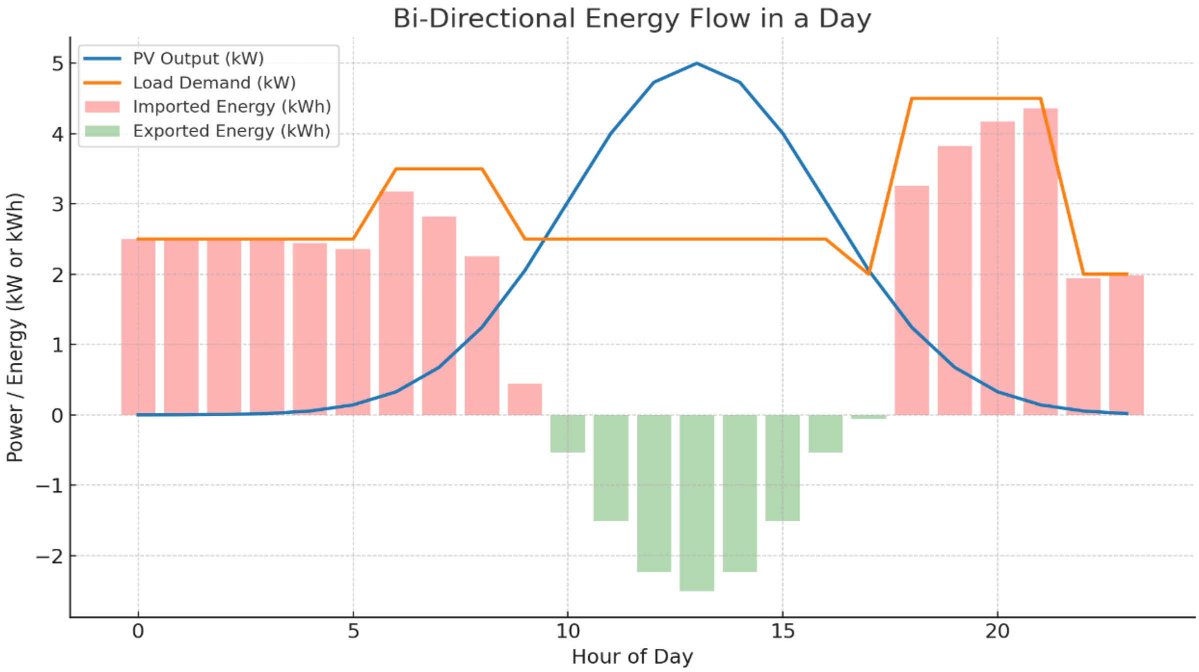

Fig. 3: Bi-directional Energy Flow in a Day

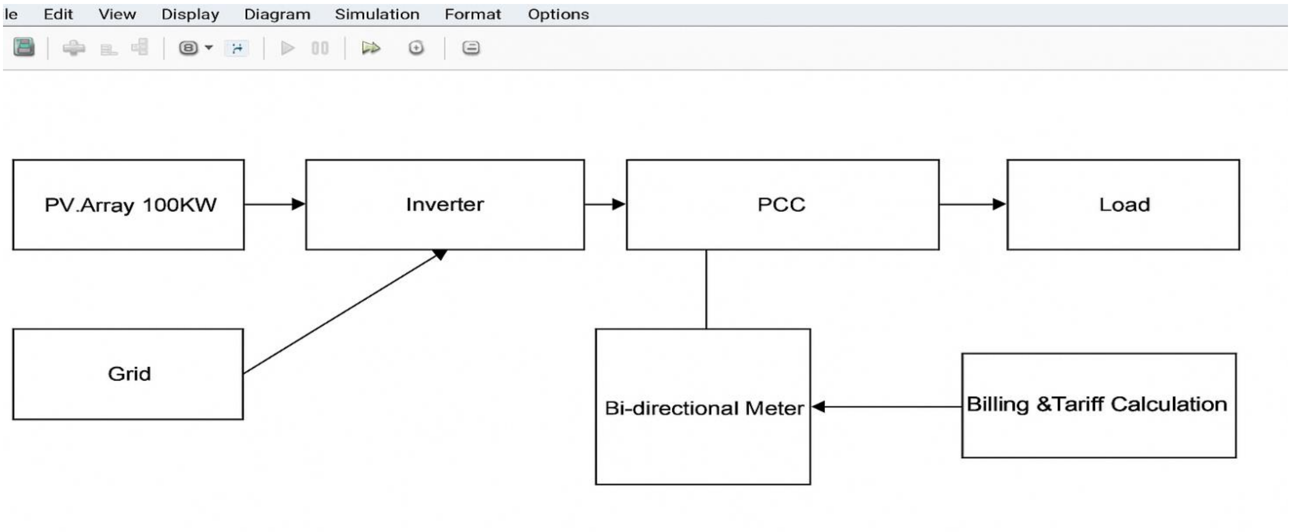

Fig.4: Model for the Bi-directional Energy System

The diagram in Figure 4 shows how a 100-kW solar PV system works in a grid-connected setup. Power generated by the PV array goes to the inverter, which converts the DC output into AC. This AC power passes through the point of common coupling (PCC), where it can either supply the load or feed into the grid if there's excess energy. The bi-directional meter monitors energy flow in both directions, tracking how much power is imported from or exported to the grid. That data is then used in the billing and tariff calculation block to determine energy costs or credits.

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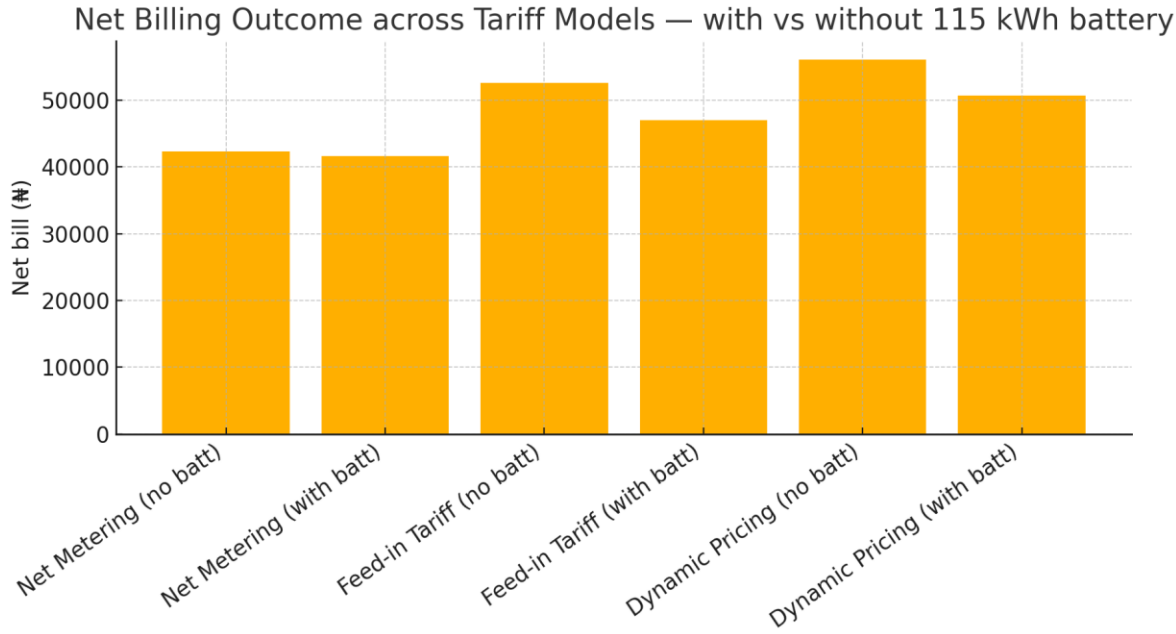

Fig.5: Bi-directional Energy Flow in a Day (100Kw PV-Sunny)

From Figure 5, it can be observed that the net bill is consistently lower when the 115-kWh lithium-ion battery is included, regardless of the tariff model applied. Under Net Metering, the reduction is modest because exported energy already receives the same retail rate, so storing surplus in the battery instead of exporting it provides only a small additional financial benefit. In contrast, under the Feed-in Tariff (FIT) model, where exports are credited at a much lower rate than imports are charged, the battery shows a more noticeable reduction in net bill. This is because the battery stores surplus midday solar energy that would otherwise be sold cheaply to the grid, and later discharges it to offset more expensive evening imports. The Dynamic Pricing scenario shows the greatest relative benefit from the battery. Here, the battery can charge when electricity is effectively "cheap" (from the PV system during midday) and discharge during the evening peak period, when grid import rates are highest (₦120/kWh). This peak-shaving effect reduces the customer's high-price purchases from the utility, resulting in a significantly lower net bill compared to operating without storage. Overall, the graph highlights how the economic value of battery storage is strongly influenced by the chosen tariff structure**,** with the largest savings occurring in pricing schemes that penalise peak-hour imports or pay less for exported energy.

Table 1: Power Exchange Table (imports from grid vs exports to grid), for each tariff and the two cases (no battery / with 115 kWh battery).

Tariff	**Battery**	**Imported (kWh)**	**Exported (kWh)**	**Customer pays utility (₦)**	**Utility pays customer (₦)**	**Net (₦)**
Net Metering	No battery	860.30	255.67	60,220.84	17,896.75	**42,324.10**
Net Metering	With a 115-kWh battery	729.38	134.45	51,056.64	9,411.39	**41,645.25**
Feed-in Tariff (FIT)	No battery	860.30	255.67	60,220.84	7,670.03	**52,550.81**
Feed-in Tariff (FIT)	With a 115-kWh battery	729.38	134.45	51,056.64	4,033.45	**47,023.19**
Dynamic Pricing	No battery	860.30	255.67	73,998.35	17,896.75	**56,101.60**
Dynamic Pricing	With a 115-kWh battery	729.38	134.45	60,067.98	9,411.39	**50,656.59**

Table 1 presents the breakdown of energy imports from the grid, exports to the grid, and the corresponding monetary flows between the customer and the utility for the three tariff models, both without and with the 115-kWh battery installed. From the table, it is clear that including the battery consistently reduces grid imports and total exports, as more midday surplus energy is stored and later used to meet evening demand. Under Net Metering, the change in the net bill is minimal because exported energy already earns the same rate as imports, making battery storage less financially impactful. In the Feed-in Tariff case, the battery produces a more substantial reduction in net bill, since it helps avoid selling surplus energy at the lower FIT rate and instead offsets higher-priced imports. The Dynamic Pricing model shows the largest financial benefit, as the battery shifts consumption away from peak-price periods, greatly reducing high-cost imports. Overall, the results in Table 4.5 demonstrate that the financial value of battery storage depends strongly on the tariff structure, with the highest savings realized under pricing schemes that have low export compensation or steep peak-hour charges.

IV. CONCLUSION

This study successfully modeled and simulated a bi-directional converter system as a critical component of sustainable microgrid integration with the national grid. The MATLAB/Simulink-based model accurately represented the interaction between solar photovoltaic generation, local loads, and grid supply through a controlled bidirectional power flow mechanism. The converter demonstrated efficient energy conversion, achieving a peak efficiency of 95.8% while maintaining voltage and frequency deviations within ±5%. The simulation results confirmed the system’s capability to operate effectively in both grid-to-load and load-to-grid modes, with stable power exchange and minimal harmonic distortion. The integration of the PI control loop and Phase-Locked Loop (PLL) synchronization ensured smooth switching, improved transient response, and reduced waveform distortion. Overall, the developed model provides a foundation for enhancing power quality, grid reliability, and economic transparency in renewable energy systems. Its integration with bi-directional metering supports fair billing through accurate import–export tracking and enables the implementation of net metering and dynamic pricing strategies. The proposed system can be further expanded by incorporating real-time data acquisition and intelligent energy management algorithms for adaptive control in larger distributed generation networks. This research contributes to ongoing efforts toward achieving stable, efficient, and intelligent renewable-based microgrids that can support the transition to a sustainable power ecosystem.

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