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A New Strategy for Power Management in Multisource Microgrid System with MPPT Algorithm

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Abstract- — Distributed Generators (DG) embody a multi-source microgrid amalgamated within a unified framework. These DGs are meticulously designed to calibrate voltage, current, and frequency in accordance with the load terminal's observed power demand. Constructing an optimal control paradigm for these systems amplifies their functional efficacy. This study simulates a DG control architecture within MATLAB/Simulink, integrating photovoltaic (PV) arrays, a proton-exchange membrane fuel cell (PEMFC), and an ultra-capacitor to ensure a steady and dependable output for the grid. The PV component within this configuration utilizes a Maximum Power Point Tracking (MPPT) mechanism, which optimizes power transmission to the grid. To address PV's inherent variability, an ultra-capacitor and PEMFC are employed, ensuring stable output. Here, the ultra-capacitor counterbalances the PEMFC's thermodynamic fluctuations, enhancing reliability. A power-electronics-based interfacing circuit, paired with advanced control configurations, upholds power quality by regulating the grid's voltage and frequency within permissible thresholds.

Keywords: Controller, Distributed generation, Photovoltaic cell, PEMFC-UC.

INTRODUCTION

The rising global temperatures, paired with an intensifying demand for energy to maintain societal quality of life, have prompted a shift toward expanding electric power generation. This growth has led to both innovations and environmental considerations within power generation, distribution, and consumption—ultimately paving the way for sustainable energy technologies. However, as traditional energy sources diminish and fossil fuel costs, including coal, oil, gas, and nuclear materials, escalate, renewable energy alternatives are increasingly prioritized.

Among renewable sources, Photovoltaic (PV) technology has emerged as a predominant contributor due to its clean energy output, minimal emissions, and relatively low manufacturing costs. Photovoltaic cells, however, only operate at peak efficiency when calibrated to an optimal voltage and current threshold, necessitating precise power tracking. Numerous tracking algorithms have been explored, differing by sensor count, operational speed, cost, complexity, and implementation. The Perturb and Observe (P&O) technique, known for its simplicity and affordability, is often preferred in lower-cost implementations. Given the unpredictability of solar irradiation and the sporadic nature of sunlight, system performance can be further optimized by integrating PV systems with additional energy sources.

The fuel cell, a pioneering energy source, stands out as a complementary partner for PV in hybrid systems. Among the types of fuel cells, the Proton Exchange Membrane Fuel Cell (PEMFC) is widely utilized due to its silent operation at relatively low temperatures, high power density, solid electrolyte composition, and robust attributes such as stable power-to-weight ratios, rapid start-up, extended lifespan, low corrosion, and zero gas emissions. In conditions of reduced solar irradiation, the fuel cell supplements energy demand. To address the fuel cell's transient limitations arising from its slower electrochemical response, hybridizing with an ultracapacitor offers a solution.

The ultracapacitor mitigates fluctuations by absorbing power surges that arise from abrupt load changes or inconsistencies in PV output. When the PV-FC hybrid system's energy generation does not meet demand, the ultracapacitor discharges to stabilize the load. It recharges during excess generation periods, thereby storing energy for future needs. Ultracapacitors outperform traditional batteries by responding swiftly to load shifts, providing high power density, reducing fuel cell size and costs, and extending operational life. Figure 1 illustrates various power management strategies suitable for grid-connected Distributed Generators (DGs) based on their configuration models and load requirements.

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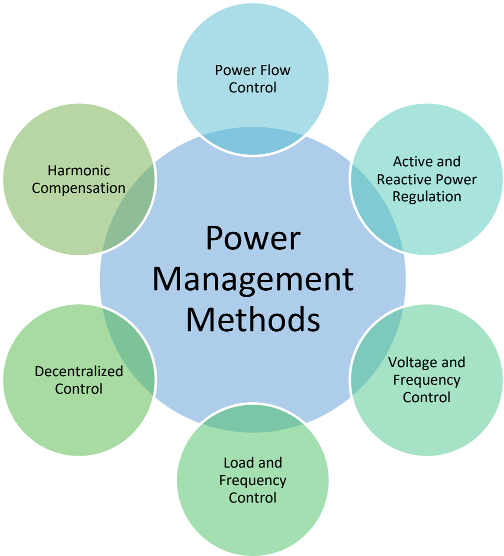

Fig.1 Power Management Strategy in DG

III. PV-FC-UC SYSTEM

The focal point here is to emulate the PV-FC-UC configuration within the MATLAB/Simulink environment. Each Distributed Generation (DG) source is interconnected to the DC-Link through an independent DC-DC converter. This integrated DG system interfaces with the grid by means of an inverter, where grid voltage and frequency are meticulously regulated via suitable control mechanisms. The schematic representation of this grid-interfaced hybrid DG is depicted in Figure 2.

The dynamic modelling of this hybrid DG is simulated in MATLAB / Simulink. This hybrid distributed generation is coupled to the grid to deliver quality power to the utility through properly designed controller action and power electronic interfacing devices.

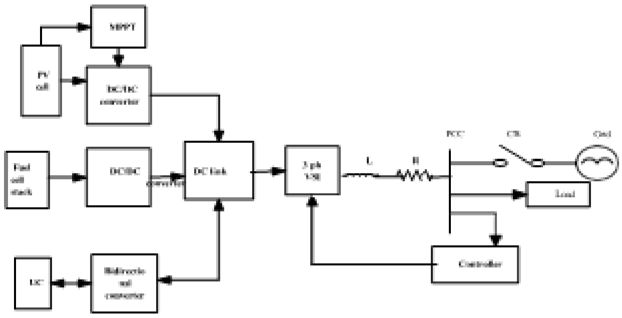

Fig. 2. Hybrid DG to grid connection.

Description of solar cell modelling

Solar cells are typically semiconductor devices built on p-n junctions that emit electrons when exposed to sunlight, generating an electric current [6]. Their behavior can be modeled using a single-diode framework [7]-[9], in which a current source and a diode operate in parallel, as illustrated in the equivalent circuit diagram (Figure 2). The performance of a photovoltaic (PV) cell depends not only on solar irradiance and cell temperature but also on specific panel parameters. Analysis of the I-V and P-V characteristics of solar cells reveals that they achieve optimal efficiency at a precise operating point. Consequently, diverse methods for maximum power point tracking (MPPT) under varying irradiance and temperature conditions are documented in literature. The perturb-and-observe (PO) MPPT algorithm is widely employed due to its straightforward implementation. This paper examines the application of the PO MPPT approach, chosen for its implementation simplicity, to identify the peak power, as represented in the flowchart in Figure 3 [10].

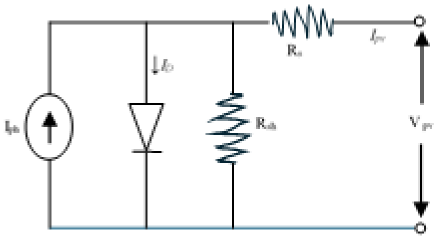

Fig. 3. Electrical equivalent representation of an ideal photovoltaic cell.

The solar module photon current is given by (1),

$$h = c + (-298) * / 1000 \quad (1)$$

Module reverse saturation current (2),

$$I_{rs} = \frac{I_{SC}}{\left[exp\left(\frac{qv_{OC}}{N_S KPAT}\right) - 1\right]} \quad (2)$$

The saturation current Io is represented as in (3),

$$I_O = I_{rs}\left[\frac{T^3}{T_r^3}\right] exp\left[q * \frac{E_{go}}{BK}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right] \quad (3)$$

The output current (4),

$$I_{PV} = N_P * I_{PV} - N_P * I_O\left[exp\left\{\frac{q*(V_{PV}+I_{PV}*R_S)}{N_S AKT}\right\} - 1\right] \quad (4)$$

Where,

Vpv PV output voltage (V)
Ipv current (A)
T Temperature (operating) in Kelvin
Tr The PV module referenced temperature (298 K)
Io The PV saturation current (A)
Iph The PV module
A, B Ideality factor (1.6)
K Boltzmann constant
Q electron charge
RS is PV series resistance (Ω)
ISC PV module short circuit current

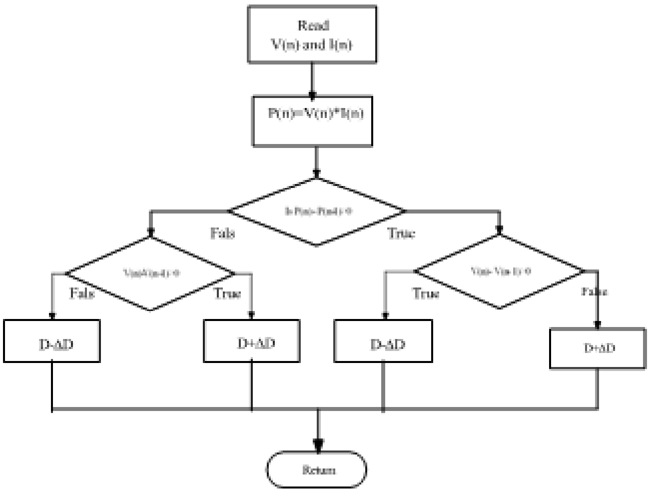

Fig. 4. Perturb and observe method flow chart.

Description of PEMFC Modelling

Proton exchange membrane fuel cells (PEMFCs) operate at modest temperatures, utilizing a polymeric membrane as their electrolyte and drawing hydrogen gas as a fuel source. Atmospheric oxygen serves as an oxidizing agent. Within the cell, hydrogen gas flows into the anode, while oxygen is introduced at the cathode. The hydrogen molecules disassociate, releasing protons (H^+) and electrons (e^-). The H^+ ions are channeled across the electrolyte toward the cathode, while the electrons journey through an external circuit, creating a direct current (DC) flow. At the cathode, these protons and electrons combine oxygen molecules, producing water as a secondary byproduct and releasing thermal energy in the process [11]. A solitary PEMFC typically generates a low DC output, close to 1 V, which can be amplified by linking multiple cells in a series-parallel configuration to construct a fuel cell stack [12].

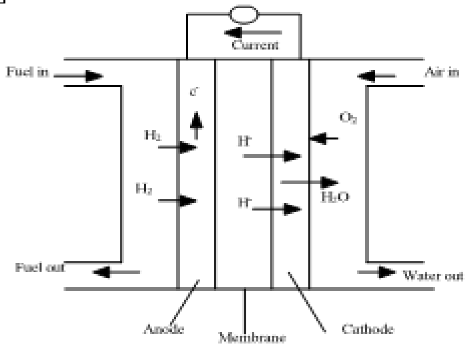

Fig. 5. Working of PEM fuel cell.

The PEMFC response is shown in (5) and (6). Figure 4 shows the PEMFC mathematical formulation.

$$H_2 \rightarrow 2H^+ + 2e^- \quad (5)$$

$$2H^+ + {}^1/_2\, O_2 + 2e^- \rightarrow H_2O + heat + electric \quad (6)$$

The energy released is (7),

EQ 7

Where 〖Δg〗 ^u Gibbs free energy change at standard pressure, R universal gas constant, T_FC is PEM temperature, P_(O_2) and P_(H_2) are gas pressures.

PEM fuel cell open circuit voltage E is expressed by (8),

$$E = -\frac{\Delta g}{2F} \quad (8)$$

Where F is Faraday's Constant.

Actual voltage is given by (9),

$$V_{FC} = E - V_{active} - V_{con} - V_\Omega \quad (9)$$

Activation voltage drop V_active can be given by (10),

$$V_{active} = V_0 - V_a(1 - e^{-c^i}) \quad (10)$$

The initial voltage drops $V0$ manifests at zero current density, directly influenced by fuel cell temperature, water vapor pressure, and the pressure within the cathode. The active voltage V active shifts in relation to i the current density and is further modulated by $C1$, the activation voltage constant. The concentration voltage decline V con V con emerges due to the oxygen presence and water movement, as articulated by equation (11).

$$V_{con} = i(C_2\frac{i}{i_{max}})C_1 \quad (11)$$

C2 varies with FC temperature, water saturation and pressure of oxygen and C3 is voltage constant at saturation. The resistive loss because of the defects in cathode and anode resistance manufacturing VΩ is given in (12),

$$V_\Omega = R_\Omega i \quad (12)$$

The resistance of the membrane RΩ depends on membrane specific conductivity σm as well as thickness tm and is given as,

$$V_{\Omega} = R_{\Omega} i \quad (13)$$

tm and σm are membrane thickness and specific conductivity respectively.

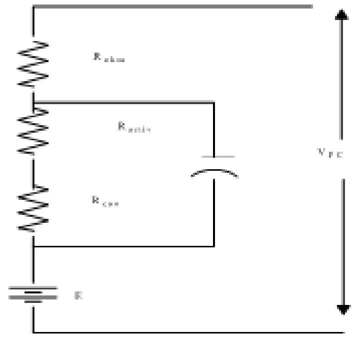

Fig. 6. Equivalent of PEMFC (electric circuit).

Description of UC Modelling

Ultra-capacitors are elector-chemical capacitors, (super-capacitors), have low series resistance (ESR) and high-power density and. Ultra capacitors exhibit large charging-discharging capacity with high efficiency [14]. The electrical model of UC has a capacitor in parallel with a resistor and the combination is in series with a series resistor. The series resistor signifies the charging/discharging process and parallel resistor is to represent the self-discharging losses in fig. 6. The UC simulation is in MATLAB/ Simulink.

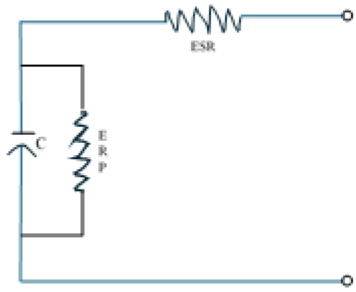

Fig. 7. Ultra-capacitor (electric equivalent).

Power Conditioning for the hybrid system,

The discrete energy sources are connected to a unified DC bus via specialized DC-to-DC converters, as illustrated in Figure 6. Both the PV array and FC stack are interfaced using individual DC/DC boost converters, which amplify their output voltage to the required DC link level. Meanwhile, the ultra-capacitor interfaces with the DC link through a bidirectional DC-to-DC converter; this device operates in boost mode to elevate voltage during discharge, and in buck mode when surplus energy from the hybrid source recharges the capacitor [15]. The P&O MPPT algorithm adjusts the duty ratio of the PV DC-DC converter's switches, based on the differential between the DC link voltage and the target reference voltage.

This error signal enters the PI controller, generating PWM pulses with the appropriate duty ratio for the DC-to-DC converter switches to maintain the reference voltage. To filter out the harmonics emerging at the inverter's output, an LC filter is applied [16]. The voltage source inverter not only delivers active power to the grid but also mitigates harmonics and supplies reactive power to the load at the PCC. Additionally, the inverter's power angle is carefully controlled to stabilize the DC link voltage.

Active-Power compensation is by managing the inverter angle and modulation index.

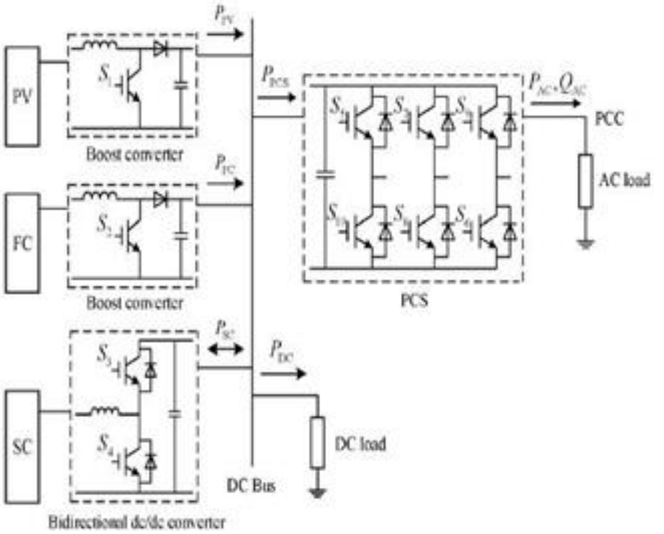

Fig. 8. Power conditioning system for PV/FC/UC [17].

III. POWER MANAGEMENT AND CONTROL STRATEGY FOR PV/PEMF/UC

The output from the DC-to-DC converter is transmitted through the integrated DC bus, linking it to the DC/AC converter by using precise gate signals [18]. To achieve optimal load power PO delivery, a meticulous converter control approach is employed. Seamless integration with the grid necessitates control over both active and reactive power, requiring careful regulation of voltage and frequency to maintain grid standards. This is managed through minor adjustments to the voltage phase and amplitude, respectively [19].

The hybrid distributed generation (DG) system maintains voltage consistency at the point of common coupling (PCC) and facilitates power injection into the grid. Should the load demand surpass the power supplied by DG, the grid compensates by delivering the additional power required [20]. When the photovoltaic (PV) system generates surplus energy beyond the load's demand, the excess power is directed toward charging the ultracapacitor (UC). Conversely, when PV output falls short of load requirements, the load is supported by the proton exchange membrane fuel cell (PEMFC) in conjunction with PV, supplemented as needed by the UC. Beyond merely covering additional demand, the UC counteracts the slower response of the PEMFC's thermodynamic properties.

Given the fuel cell's inability to respond immediately to rapid load fluctuations, the UC stabilizes any energy imbalance during both startup and transient load conditions [21]. Figure 8 illustrates the control strategy employed for orchestrating the power management across the PV, PEMFC, and UC, optimizing their collective functionality and ensuring sustained reliability in variable demand scenarios [22-24].

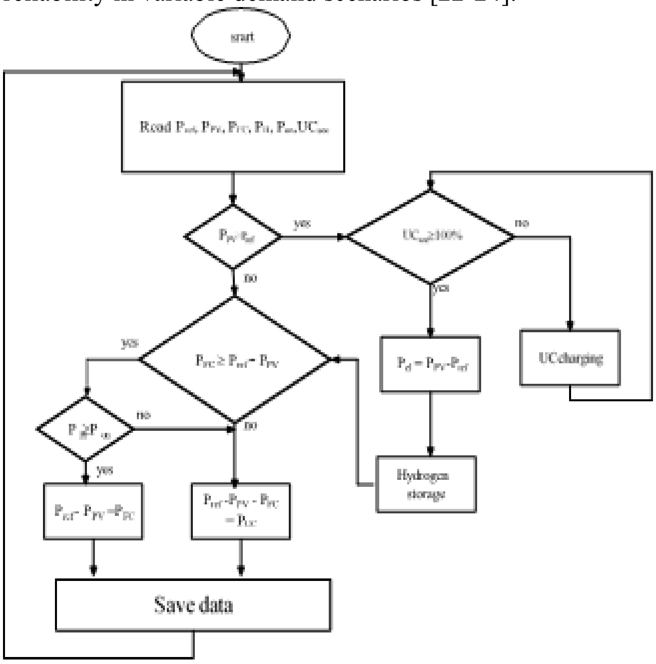

Fig. 9. Control Strategy used in Main Controller.

The DG PWM inverter regulates the injected current by the DG. Fig. 9 controller where the PI controller operates in dq frame of reference in (15) and (16). For the reference frame by PLL. At the grid reference voltage and frequency, power is delivered from the current controller to the inverter. PWM control technique is used for inverter switching operation.

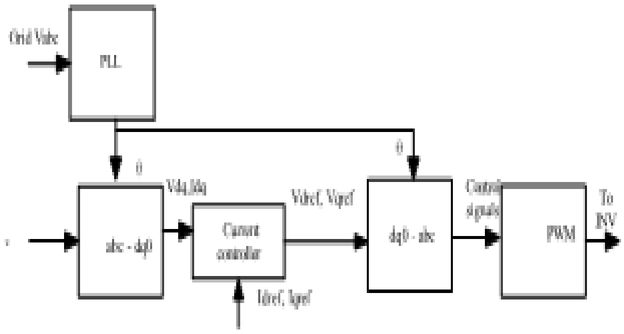

Fig. 10. Block diagram of the current controller.

IV. RESULTS AND DISCUSSIONS

In the MATLAB/Simulink environment, the PV, PEMFC, and UC systems are meticulously modelled. This hybrid distributed generation unit connects seamlessly to the grid, guided by a precise controller mechanism and a dynamic power management scheme. The simulation proceeds with the PV system operating under stable conditions at 25°C and irradiance of 1000 W/m². Figure 10 illustrates the DC link's output voltage, maintained consistently at a steady level. Through the controller's intervention, the modulation index remains confined within the optimal operational range. Figure 11 presents the inverter's output voltage, stabilized to align precisely with grid standards.

This configuration interfaces directly with the grid, as illustrated in Figures 12 and 13, where the current distribution and power contribution from various sources to the grid are displayed. It is evident that in the absence of photovoltaic (PV) output, the ultra-capacitor independently sustains the load requirements until the fuel cell adjusts to accommodate load fluctuations. At the 0.6-second mark, an escalation in PV power output prompts a corresponding reduction in the fuel cell's power generation to meet the lowered load demand.

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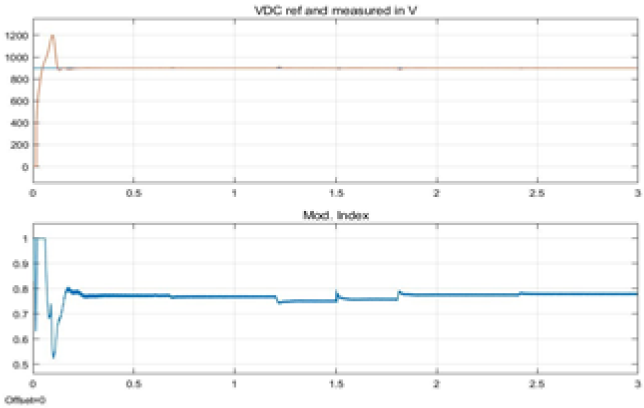

Fig. 11. Output at the DC link.

For every fluctuation in PV output, the ultra-capacitor's role is to swiftly mitigate transients by reacting instantaneously to variations, a necessity due to the inherently gradual response rate of the fuel cell's thermodynamic processes. As shown in Figure 14, the controller's action is explicit in maintaining a stable grid voltage and in delivering consistent power to both the grid

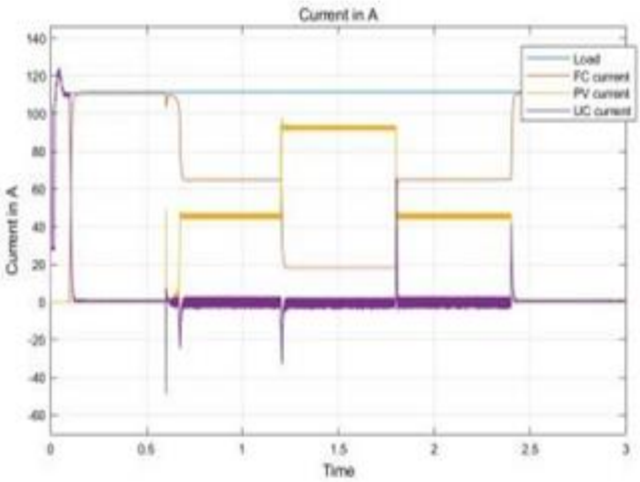

Fig. 12. Current contribution at different load.

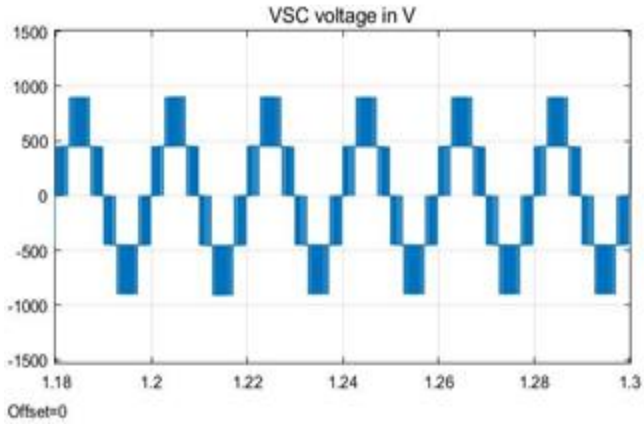

Fig. 13. Inverter output voltage

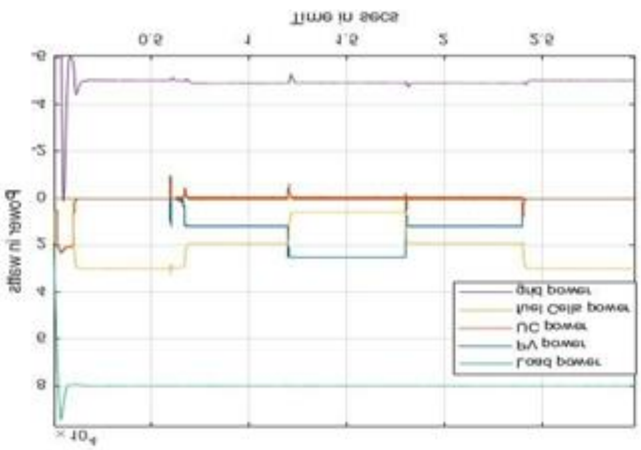

Fig. 14. Power from DG to grid.

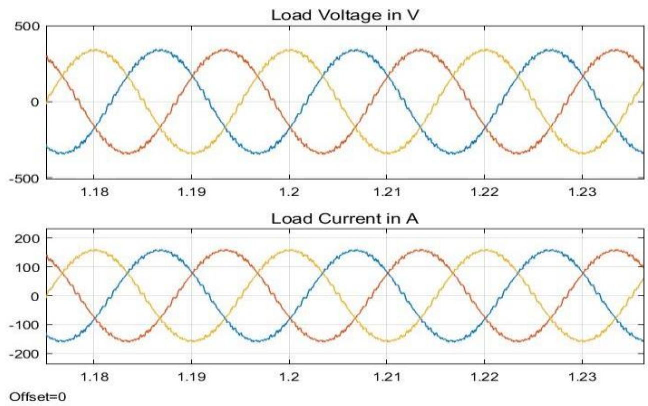

Fig. 15. Grid voltage and grid current.

V. CONCLUSIONS

Using PV-PEMFC-UC on the MATLAB/Simulink platform, a hybrid DG system is envisioned for integration into a grid-connected application. MPPT algorithm is incorporated into the design to maximize the photovoltaic (PV) unit's power extraction. The main purpose of the UC is to help manage power fluctuations by giving the PV system additional support during times of peak load. Consequently, this design improves the hybrid DG system's capacity to smooth loads. Additionally, the built model effectively satisfies power requirements in a range of load situations. In situations where the PV module's power output is insufficient, the PEMFC is introduced to meet the energy needs. The efficiency of the suggested model under various load scenarios inside the rid architecture is confirmed by the experimental results.

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