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ISSN 2249-3352 (P) 2278-0505 (E)
Cosmos Impact Factor-5.86

Fuel Cell Based Hybrid Electric Vehicle System Multi Input Bidirectional DC to DC Converter

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Abstract

The adoption of electric vehicles (EVs) has significantly increased over the past decade due to growing awareness and advancements in technology. While battery-operated EVs have been the primary choice due to their simple design, alternative energy sources have also been explored. Among these, fuel cells offer a promising solution with near-zero emissions, low operating pressure, and moderate temperature. Various converter topologies and control strategies have been developed to efficiently manage energy transfer from proton exchange membrane (PEM) fuel cells, which are a preferred choice for EV applications. This paper introduces a modified multi-input DC-DC converter that integrates both a fuel cell and a battery to supply power to a brushless DC (BLDC) motor. An artificial neural network (ANN)-based controller is employed for real-time power distribution, optimizing fuel cell and battery operation. The proposed system is analyzed

using ANN-driven maximum power point tracking (MPPT) techniques with Wolf optimization-based. Simulation results confirm that the proposed topology with ANN control enhances energy efficiency and dynamic response, making it a viable solution for electric vehicle applications.

Introduction:

In recent years, passenger car efficiency has improved significantly, owing to stringent global regulations on fuel efficiency, emissions, and CO_2 reduction. These regulations have imposed high standards on manufacturers, which continue to pose challenges. Consequently, the recent economic crisis, rising oil prices, and greenhouse gas (GHG) reduction policies have accelerated a shift in transportation trends, resulting in substantial gains in fuel efficiency [1]. Battery Electric Vehicles (BEVs) emerged as a promising alternative to conventional transport models due to their excellent dynamic response. However, BEVs face significant limitations, such as short discharge durations and long recharging times, rendering them unsuitable for many users under current technological constraints [2].

Fuel Cell Electric Vehicles (FCEVs) have been proposed as another near-zero emission solution, operating at lower pressures and temperatures [3]. Despite their reliability, fuel cells suffer from drawbacks including low transient response, reduced efficiency, and high production costs [4]. Additionally, their development at a large scale is hindered by issues like high CO emissions and extensive cooling requirements [5].

As a compromise, Hybrid Electric Vehicles (HEVs) have been introduced, integrating both battery and fuel cell sources to deliver the required output power. These systems offer improved dynamic response, higher energy density, and enhanced efficiency [6]. HEVs utilize power electronic converters to regulate and stabilize power from variable sources. Figure 1 presents a hybrid structure based on a common DC bus. The evolution of electric and hybrid vehicles has significantly increased the demand for advanced power electronic converters, controllers, and electric drives [7].

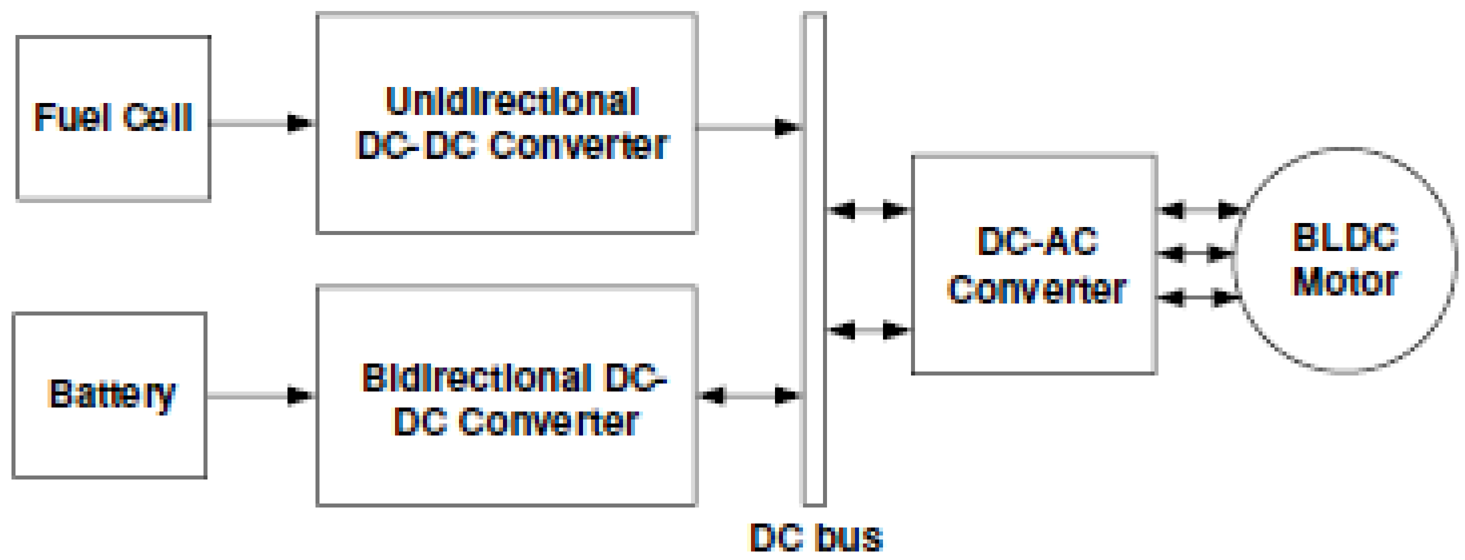

Fig.1. Block Diagram of proposed DC-DC converter

Traditionally, large electric motors demand high voltage and low current. Two-stage inverters were used for small AC motors, while multilevel inverters have been adopted for large induction motors to reduce conduction losses and operate with lower voltage sources [8]. The introduction of Brushless DC (BLDC) motors further expanded the use of DC-DC converters and inverters in Electric Vehicles [9]. Bidirectional converters have also been developed to harness regenerative braking energy for battery charging. Several topologies have been proposed to enhance braking energy utilization [10– 12].

A key research area is the development of intelligent control strategies for converters. Maximum Power Point Tracking (MPPT) techniques are employed to extract optimal power from input sources such as solar PV and fuel cells [13– 15]. In recent advancements, Artificial Neural Network (ANN)-based controllers have shown great potential in improving the dynamic performance and robustness of BLDC motor drives, particularly under varying load and input conditions. These intelligent controllers are capable of self-tuning and learning from system behavior, thereby outperforming traditional control techniques in terms of accuracy and response time.

This paper introduces a novel powertrain topology that integrates a fuel cell and battery system via a single bidirectional DC-DC converter, controlled through a hybrid approach involving both Incremental Conductance (IC) and Grey Wolf Optimization (GWO) MPPT algorithms. Additionally, an ANN-based controller is implemented for efficient control of the BLDC motor, ensuring precise torque and speed regulation, even during abrupt load changes. The proposed configuration not only reduces the number of switches, passive components, and control circuitry compared to conventional designs, but also maximizes power delivery, enhances system efficiency, and ensures reliable performance across various driving conditions.

2.0 Modeling and operation of proposed system

The proposed system is divided into three main sections: the Input Section, the Controller Section, and the Load Section. In the input section, a Fuel Cell and a Battery are employed as the primary and secondary energy sources, respectively. The fuel cell serves as the main power supply, while the battery supplements the load only when the fuel cell output is insufficient or unavailable. Each energy source is regulated by its own dedicated switch for flexible and controlled operation.

A bidirectional DC-DC converter is utilized to manage energy flow between the sources and the load. This converter operates in two distinct modes: boost mode during forward motoring and buck mode during regenerative braking. In boost mode, the converter steps up the voltage to meet the load demand; in buck mode, it steps down the voltage to store regenerative energy back into the battery. Figure 3 illustrates the proposed topology, where a Brushless DC (BLDC) motor is connected via a three-phase inverter circuit for high-efficiency motor drive control.

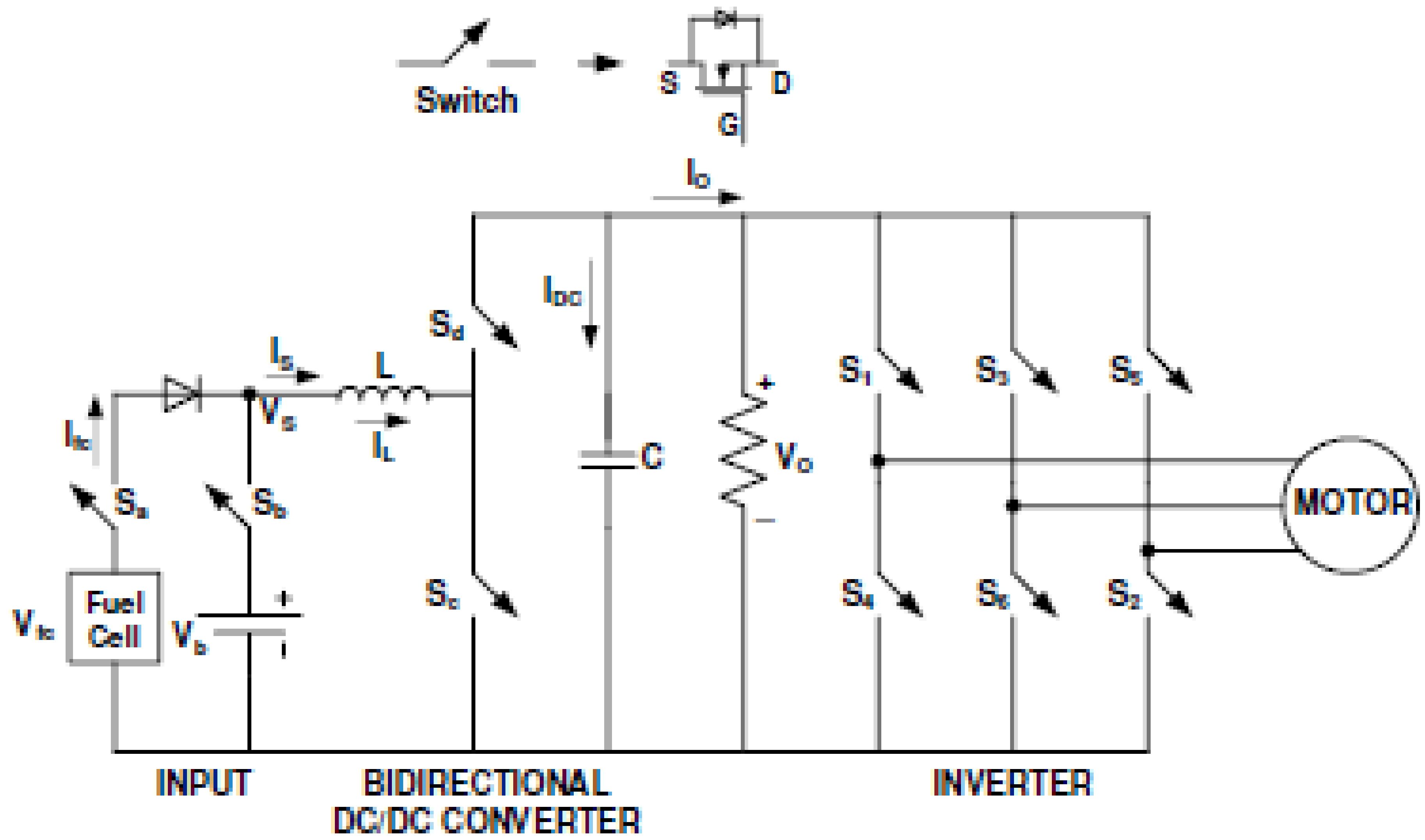

Figure 2 demonstrates the operational modes of the bidirectional converter:

- Boost Mode (Forward Operation): As shown in Figure 2, when switch Sc is closed, the input source charges the inductor L. In the next phase, illustrated in Figure 2, switch Sd is closed, allowing the stored energy in the inductor and the input source to simultaneously power the load. The output voltage in this mode is the sum of the input voltage and the voltage across the inductor.

- Braking Mode (Reverse Operation): During braking, the back EMF generated by the BLDC motor exceeds the supply voltage. In this case, as shown in Figure 2, the inductor charges in the reverse direction through switch Sd. When switch Sc is closed in this reverse or buck mode, the inductor discharges in the opposite direction, and the energy is fed back to charge the battery efficiently.

This bidirectional converter-based architecture enables efficient power management and energy recovery during deceleration. When combined with intelligent control strategies, such as MPPT algorithms and ANN-based BLDC motor controllers, the proposed system achieves high dynamic performance, energy efficiency, and reliability.

Fuel Cell Modeling Topology with Mathematical Implementations

Fuel cells are electrochemical devices that convert chemical energy directly into electrical energy with high efficiency and low emissions. In electric and hybrid electric vehicle systems, the Proton Exchange Membrane Fuel Cell (PEMFC) is commonly used due to its low operating temperature, fast start-up, and suitability for automotive applications.

The modeling of a fuel cell system is essential for analyzing its dynamic behavior, designing controllers, and integrating it effectively into hybrid topologies. The model includes the electrical, chemical, and thermodynamic characteristics, as well as the losses involved during energy conversion.

3.1 Fuel Cell

Using electrochemical reactions, a fuel cell converts chemical energy to electrical energy and generates heat. Various models were presented in literature to explain the characteristics and output parameters of a PEM fuel cell. Amphlett, et al. model [16] has been taken into consideration in this paper. Total output voltage of a single cell difference between thermodynamic voltage EN and the losses due to activation (R*act*), diffusion (R*co*) and ohmic resistance (R*ohm*).

$$V_{FU,i} = E_{N,i} - \gamma_{act,i} - \gamma_{co,i} - \gamma_{om,i}$$

The cells are connected in series to generate a fuel cell with the output voltage and current specified. As mentioned the total output voltage of a pair of cells is the sum of the voltages
of the individual cells.

$$V_{FU} = \Sigma V_{FU,}$$

The total losses are calculated by using

$$\gamma_{act} = \delta_a + \delta_b T_{FU} + \delta_c T_{FU} \ln(C_{ox}) + \delta_d T_{FU} \ln(I_{FU})$$

Where δa to δd are the parametric coefficients used to control the output voltage of fuel cell.

Voltage loss due to ohmic resistance of a fuel cell can be calculated using

$\gamma_{om} = I_{FU}\,(R_M + R_C)$

Where RC is the contact resistance due to electron flow and RM is the resistance of the membrane.

Diffusion loss occurs due to diffusion of Hydrogen and Oxygen ions and described as,

$\gamma_{co} = (1 - J_{FU}/J_{max})$

3.2 Boost Converter

Boost converter is the circuit used to transfer DC voltage from Source to load with a boosted value. A boost converter is either an isolated circuit or a non-isolated circuit. The practical model of the Boost converter

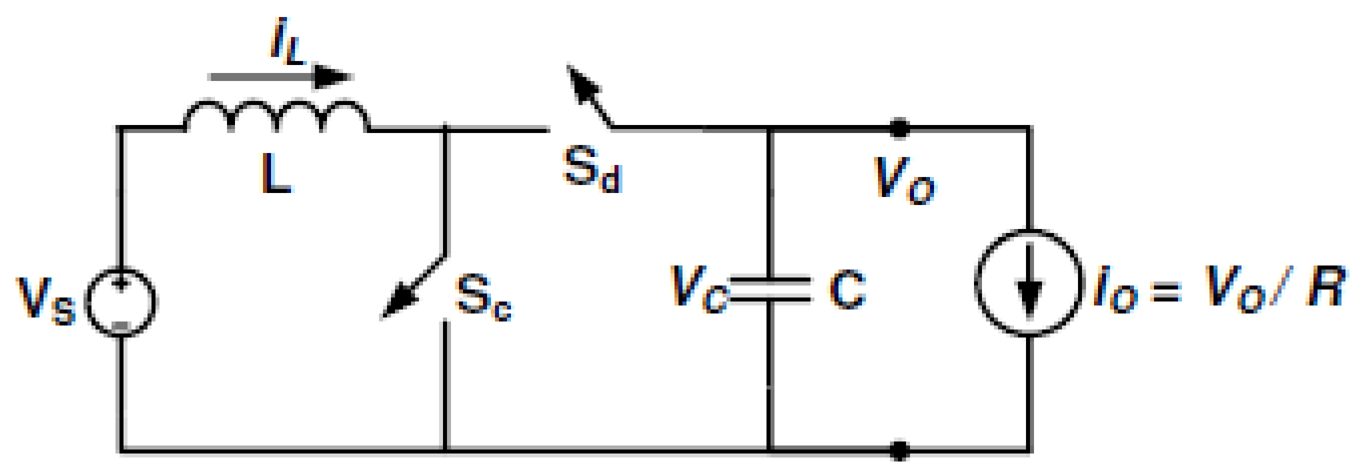

Fig.5. Figure Practical Boost Converter

The duty cycle ‘ D’ of the boost converter is calculated using the following equations,

Duty cycle D = T_{ON}

$T = 1 - V_s\, V_o$

Output Voltage $V_o = (1- D)$

Where $V_S = S_a . V_{fc} + S_b .$, Sa = Sb = 0 or 1.

The maximum value of load current (i0) and the change in load current value (ΔIo) is given by,

$I_0 = (1- D).R\,\Delta I$

$_0 = V_s\, DT\, L$

From equations (7)-(10) the dynamic equation of the DC boost converter based Li-ion charging method,

$$\begin{bmatrix} \dot{i_L} \\ \dot{V_O} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{(1-D)}{L} \\ \frac{(1-D)}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_O \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} [V_S] + \begin{bmatrix} 0 \\ -\frac{1}{C} \end{bmatrix} [i_O]$$

$$\begin{bmatrix} V_O \\ i_O \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} i_L \\ V_O \end{bmatrix}$$

3.3 Brushless DC (BLDC) Motor

Brushless DC (BLDC) Motor or Permanent Magnet synchronous motor is similar to other electrical motors that convert electrical energy into mechanical energy. This motor uses a three phase AC supply to operate, which requires a three phase converter.

Per phase voltage equation of the BLDC motor is given by,

$$V_S = R I_a + L \frac{d i_a}{d t} + E_b$$

Where, R = Stator resistance per phase, L = Stator
Inductance per phase, Eb – Back EMF and Ia – armature current.

4. Control Strategy

The presented circuit has been analysed with incremental conductance tracking and Grey Wolf algorithm based tracking methods to find the maximum power point. The duty cycle calculation using MPPT techniques. The optimal duty cycle for maximum power is calculated using the MPPT techniques and the load is operated at maximum power.

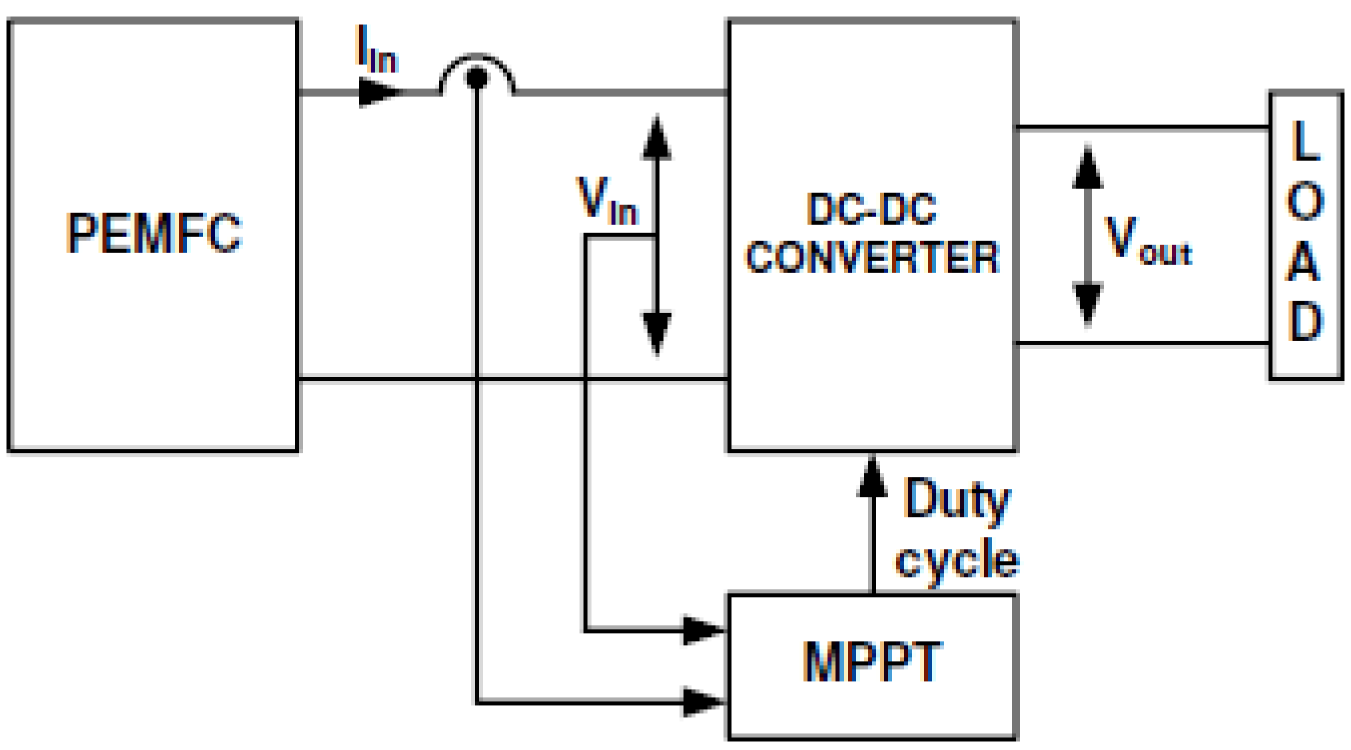

Fig.7. Block Diagram of proposed circuit with MPPT Controller

Simulation result

The proposed topology has been simulated using the MATLAB/Simulink environment. Table 1 outlines the design parameters used for the simulation. Figure 10 presents the input parameters for the fuel cell, including fuel flow rate, utilization, consumption, and efficiency. The simulation results indicate that the fuel cell operates at an efficiency of approximately 65%, with a fuel utilization rate of about 90%.

Conclusion

The detailed mathematical modeling of the fuel cell provides an analytical foundation for dynamic simulations and controller design in hybrid electric vehicles. It allows accurate prediction of voltage, current, efficiency, and fuel consumption under varying load and environmental conditions. When integrated with intelligent controllers and MPPT techniques, the model can be used to optimize fuel cell performance and prolong

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ISSN 2249-3352 (P) 2278-0505 (E)
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operational lifespan

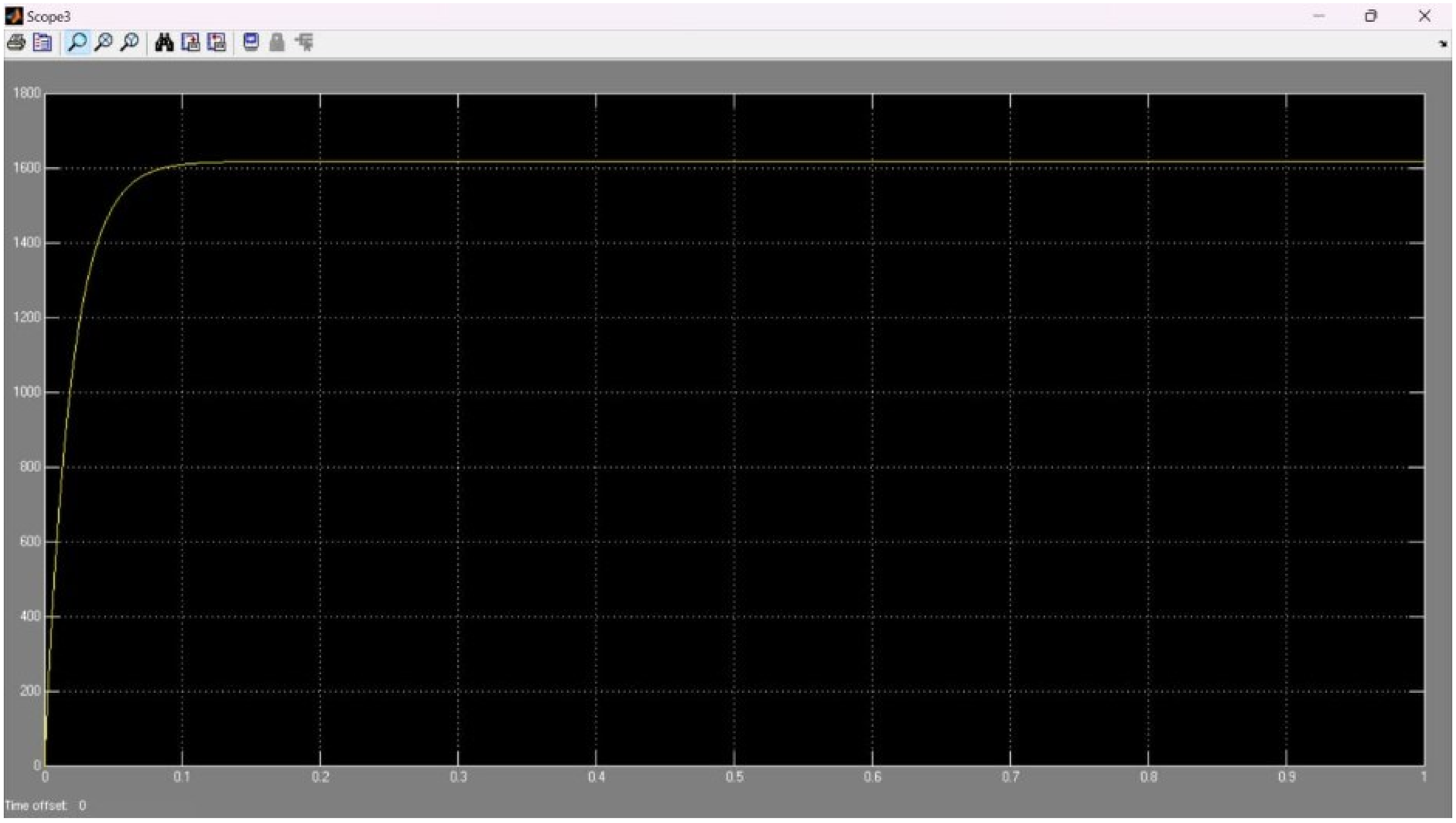

fig 1: Output Curve at IC MPPT

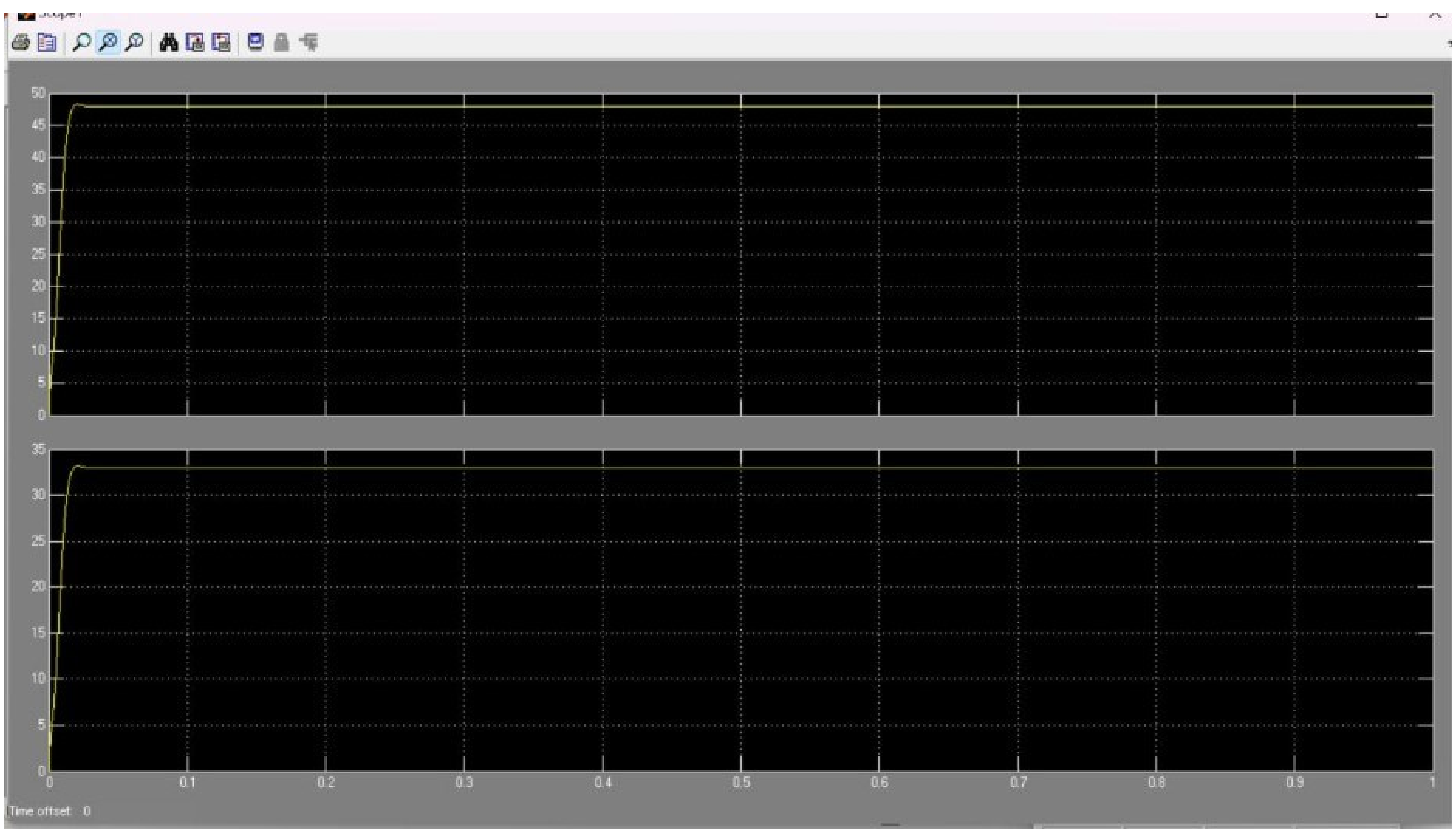

fig 2: Output Current and Voltage Of Fuel Cell Stack

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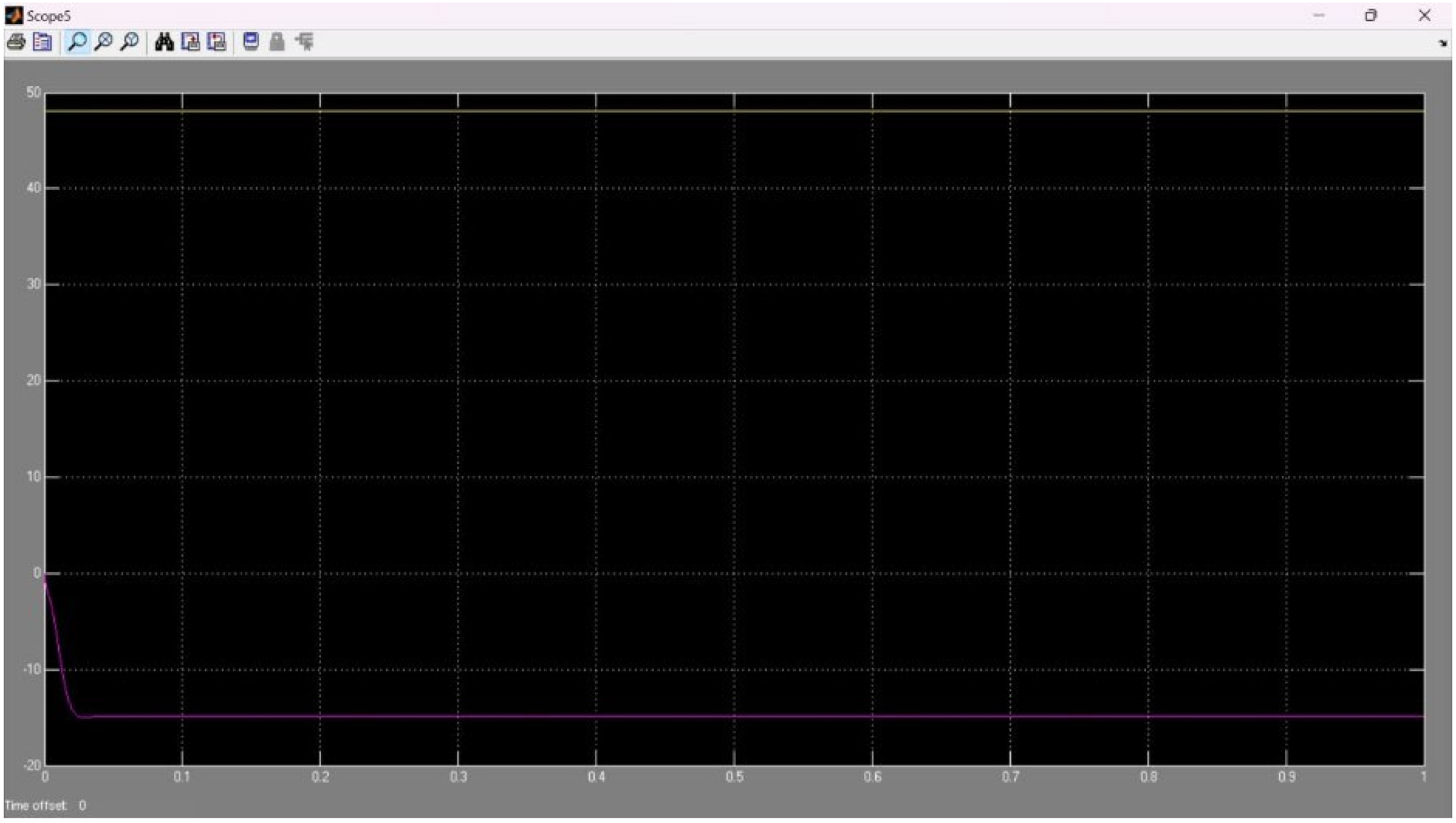

fig 3: Battery Voltage and Charging Current at IC MPPT

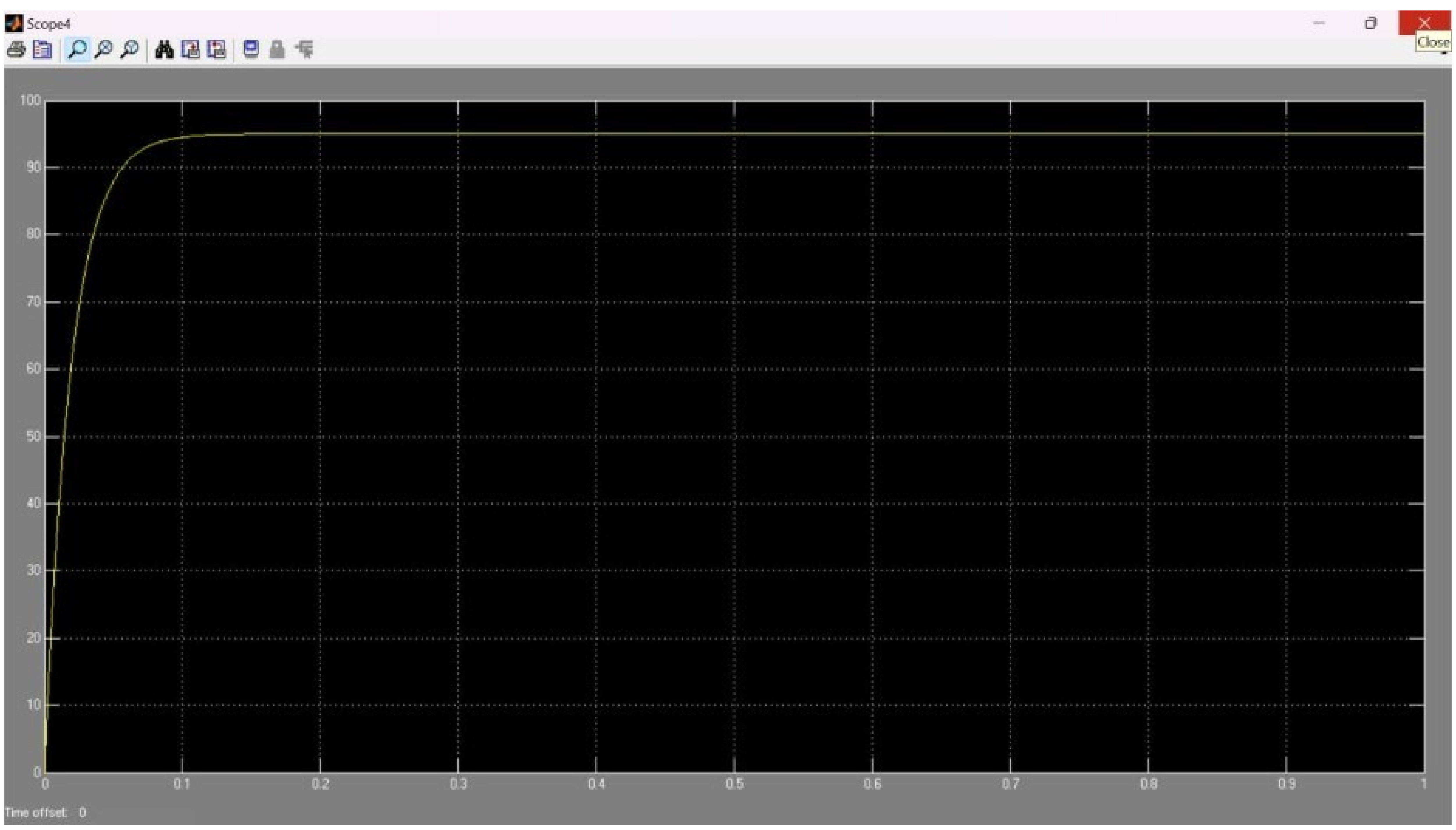

fig 4: Output Voltage Converter at IC MPPT

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