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Hybrid Energy System Simulation and Modelling Incorporating Wind, Solar, Battery and Fuel Cell Power

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Abstract: *Improving grid-interfaced hybrid generation systems' power transmission capabilities is the primary goal of this work. This hybrid system typically combines wind and solar energy sources. This research suggests the idea of maximum power tracking strategies to obtain the maximum and consistent output power from these renewable energy sources at any given moment. Direct Current (DC) to DC boost converter control is the primary function of this maximum power point tracking controller. Lastly, MatLab/Simulink simulation is used to observe the performance of this hybrid system based on Maximum Power Point Tracking (MPPT).*

Keywords: *Solar power, wind/photovoltaic, battery, and fuel cell hybrid generation, simulation and modelling, microhydropower, and renewable energy.*

I. INTRODUCTION

It is common knowledge that the world's fossil fuel supplies are rapidly depleting. Today's energy needs are mostly met by fossil fuels and nuclear power facilities. Only a small portion comes from renewable energy sources including geothermal, biomass, solar, wind, and others. The lack of fuel will be serious in the not-too-distant future. According to the energy conservation rules, energy can only be changed from one form to another; it cannot be created or destroyed. Preserving energy reserves and increasing energy efficiency are the main areas of current research. Additionally, research has been done on how to construct reliable and study systems for using non-traditional energy sources. Both of them are abundant sources of renewable energy. Sunlight is regarded as a vital resource since direct solar intensities in many tropical and temperate countries exceed 1000w/m². A solar cell system uses sunlight to create electricity. Grouped cells are the components that make up panels and modules. Due to its many advantages, such as low maintenance costs, high reliability, ease of allocation, and no fuel prices, as well as the fact that there are no moving parts, solar cell production is growing in popularity as a renewable energy source. Wind energy is converted into usable electrical power by wind turbines. When it comes to powering new buildings, onshore wind is frequently more cost-effective than offshore wind. Small onshore wind turbines provide electricity to remote places. When used, wind energy is clean, renewable, requires little space, and emits no greenhouse gases. The consequences on the environment are often less severe than those of other power sources. Although wind power fluctuates significantly over shorter periods of time, it is largely consistent throughout the year. A region's grid will need to be modified as wind power increases because mechanical wind turbine models that use synchronous generators will make conventional energy more challenging. When the wind turbine is rotating, the wind will not differ significantly from the surrounding air. The value of this can be raised for real-time implementation.

II. SYSTEM MODELING AND PROBLEM STATEMENT

This work suggests modelling and simulating solar and wind power systems independently, then merging them for the transformer's output AC load in the manner described below:

A. Solar Power System

Solar cell technology is used to turn sunlight into electricity. The most crucial part of the solar cell system is thought to be the solar cell itself. Modules or panels are made up of cells grouped collectively. Many panels can be combined to make large solar arrays. Arrays are solar panels or collections of panels with several cells connected in parallel, series, or both. Most people are interested in modelling solar cell panels or commercial solar cell technology [4]. Our solar PV array module has a 15KW rating.

The average PV cell generates less than 0.4 to 0.5 watts at 400to500mAand1V,hencethecellsonamodulemustbeconnectedin series-parallel configuration to generatesufficienthighpower.Aphotovoltaicarrayisanelectricallyconnectedgroupofsolarmodules that use series and parallel circuits to generate the required current and voltage. [5] [6] To supply the necessary output power, PV modules are then connected in a series-parallel configuration.

A circuit consisting of a diode and a parallel current source can be used to mimic a solar cell. The cell's I through V characteristics are determined by the diode. The amount of solar radiation that reaches the cell is directly connected to the current source output. [7]

The Shockley equation, which describes the relationship between voltage and current in a solar cell, states that the open circuit voltage grows logarithmically.[8].

$$I = I_{pv} - I_o [\exp(qU/kT) - 1]$$

$$U = kTq \ln (1 - I_{pv} / I_o)$$

Where:

photovoltaic current (I_{pv}) Diode saturation current (I_o) and elementary charge (q) are equal to 1.6021×10^{19} As. U = voltage of the solar cell

k =Boltzmannconstant(1.3806×10^{23} J/K) T =Thetemperatureofthereferencesolar cell.

B. Wind Power System

Harvesting wind energy involves physically connecting a rotor with two or more blades to an electrical generator. The power coefficient's maximum theoretical value is 0.55. It is affected by pitch angle and tip speed ratio (TSR). Pitch angle is the angle at which the blades of a turbine align with its longitudinal axis. TSR is the rotor's linear speed in relation to wind speed. TSR, or tip speed ratio.

$$\lambda = \omega * R / v_w \tag{3}$$

Where:

the tip speed is denoted by λ

Turbine rotor speed (rad/s) is represented by the ratio ω .

R is the turbine blade's radius in meters. Wind speed (m/s) is denoted by v_w .

The wind energy converter model is developed based on the following assumption:

- Less friction;
- Static wind flow;
- Longitudinal wind flow without shear;
- Rotational free flow;
- Incompressible wind flow ($\rho = 1.22 \text{ kg/m}^3$)
- The wind flows freely around the wind energy converter.

The greatest physically convertible wind energy may be found using a theoretical model that is independent of the technical specifications of the wind energy converter and the presumptions made. There is a lot of energy in a moving mass of air. This energy comes from air movement caused by a pressure gradient on the planet's surface. Wind turbines are used to create electricity using this energy [12][13].

The wind converter's maximum power value, which is determined by the air masses' kinetic energy, is given by the following equation: $P_{max} = (8/27) * A \rho v^3$ (4)

The following formula can be used to calculate the hypothetical electricity represented by a percentage of incident air flow: $P_{max} = (8/27) * A \rho v^3$

$$P_{wind} = 0.5 A \rho v^3$$

$$P_{max} = P_{wind} \cdot C_p \tag{5}$$

Synchronous and induction generators are two types of electric generators. The following formula is used to determine the wind's mechanical power:

$$P = 0.5 \rho A C_p(\lambda, \beta) v^3 \quad (6)$$

Where:

ρ stands for air density.

$C_p(\lambda, \beta)$ is the rotor swept area A . The function of the power coefficient. The ratio of tip speed to λ β is the pitch angle. V - wind speed. It is inefficient to set up a freestanding power system because the PMSG is utilized in this wind power system instead of an induction generator, which requires a leading voltage to stimulate it. This is often accomplished by connecting the induction machine to the grid. The rotor and magnetic field rotate at the same speed in a synchronous system because the magnetic field is produced by a permanent magnet that is fixed to the shaft. Through the magnet mechanism, electricity is induced into the stationary armature [14]. The wind system has a 60 KW rating.

III. LITERATURE REVIEW

Hybrid energy systems (HES) that integrate wind, solar, battery storage, and fuel cell technologies have emerged as a promising solution for sustainable and reliable power generation, especially in remote or off-grid areas. The variability and intermittency of renewable sources such as wind and solar necessitate the incorporation of energy storage systems like batteries and fuel cells to ensure stable and continuous power supply. Simulation and modelling play a crucial role in designing, optimizing, and evaluating the performance of such complex systems. Various software tools have been employed for this purpose, including HOMER, MATLAB/Simulink, TRNSYS, and PSCAD. HOMER is particularly popular for techno-economic analysis and optimal sizing, while MATLAB/Simulink is widely used for dynamic modelling and control strategy development. Researchers such as Lambert et al. (2006) and Rajkumar et al. (2013) have demonstrated the use of these tools in simulating solar-wind-fuel cell systems to assess their feasibility and reliability. Advanced modelling techniques, including probabilistic approaches and artificial intelligence (AI)-based optimization methods like genetic algorithms and particle swarm optimization, have also been applied to manage the stochastic nature of renewable sources and to fine-tune system configurations. Recent studies have further explored the integration of hydrogen storage with fuel cells to extend backup duration and improve sustainability. Challenges such as system control complexity, economic viability, and hydrogen handling remain areas of active research. Nonetheless, the growing capabilities of simulation tools and real-time energy management systems indicate a strong potential for hybrid systems to play a central role in future energy infrastructure.

IV. SOLAR, WIND, BATTERY AND FUEL CELL POWER SYSTEM SIMULATION

The wind turbine is the most crucial component of wind power systems. Wind turbines use aerodynamically constructed blades to catch wind energy and convert it into rotating mechanical power. Frequently, three blades are used. The rotating component of an electric generator absorbs this mechanical energy and converts it into electrical energy. A solar photovoltaic array is used in solar systems. Simulating rechargeable and fuel cell power systems entails building computer-based representations and mathematical models to examine how these energy sources function in various scenarios. The electrochemical processes, the state of charge, voltage behaviour, temperature impacts, and degradation over time are the main topics of simulations in batteries. The electrochemical processes that turn the oxygen and hydrogen into electricity are modelled via simulations for fuel cells, taking into account variables like system efficiency, water and heat management, and gas flow dynamics. Without the need for expensive physical prototypes, these simulations assist engineers in performance prediction, design optimization, control strategy testing, and battery or fuel cell integration into larger systems such as electric vehicles or renewable energy grids. Simulations offer insights into system response, energy efficiency, and durability by varying parameters like load demand, temperature, and operating conditions. This aids in improved design and practical implementation.

The following is the complete Simulink design model:

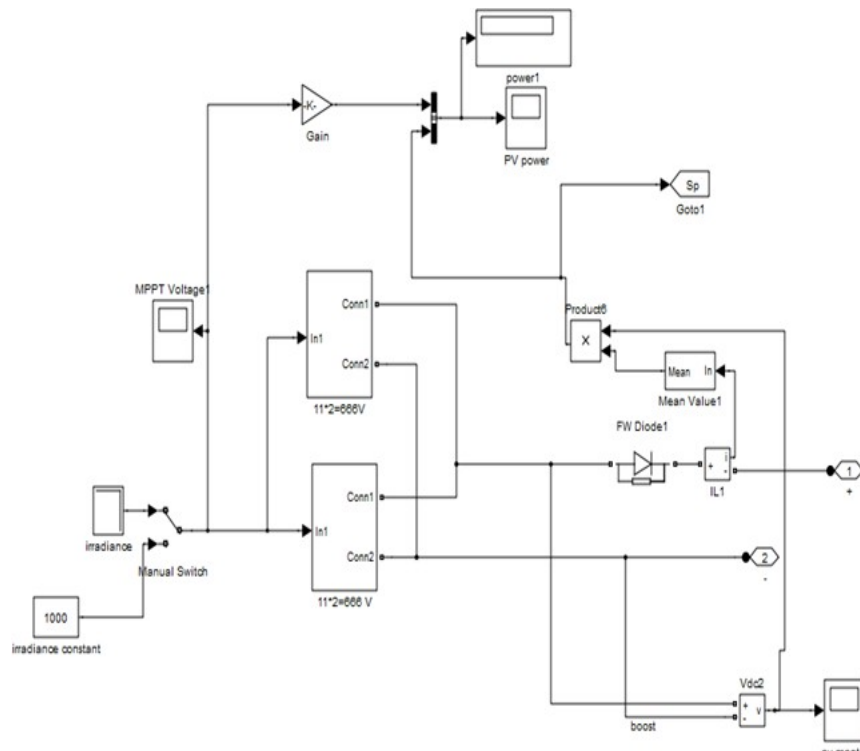


Figure-1: SimulinkDiagramofSolarpowersystem.

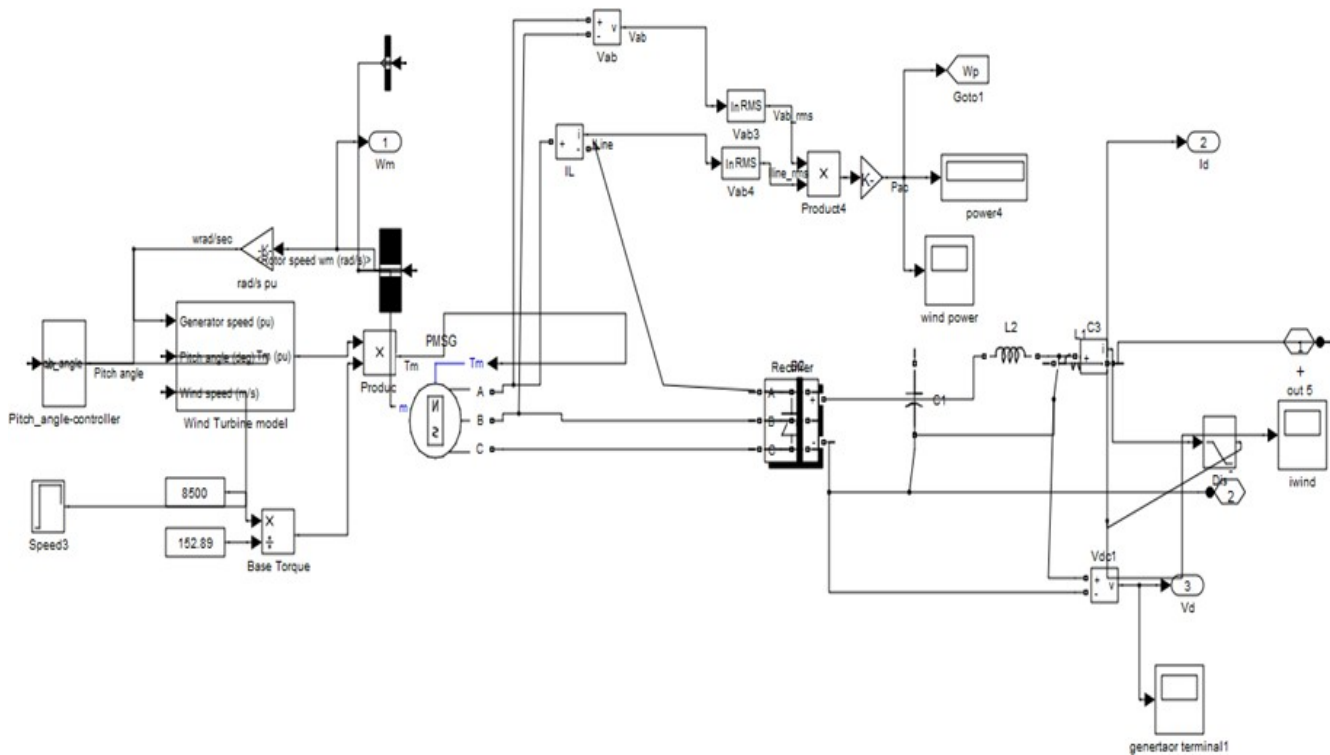


FIGURE2:Simulinkdiagramofwindpowersystem

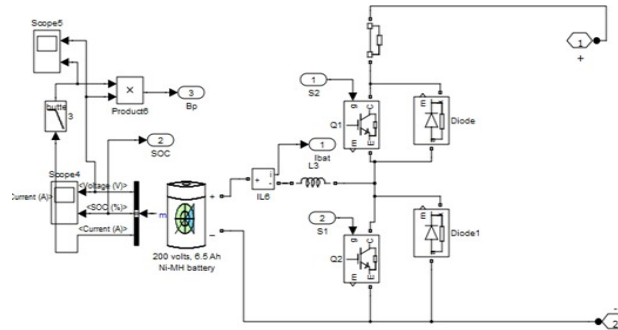


FIGURE3:SimulinkdiagramofBattery

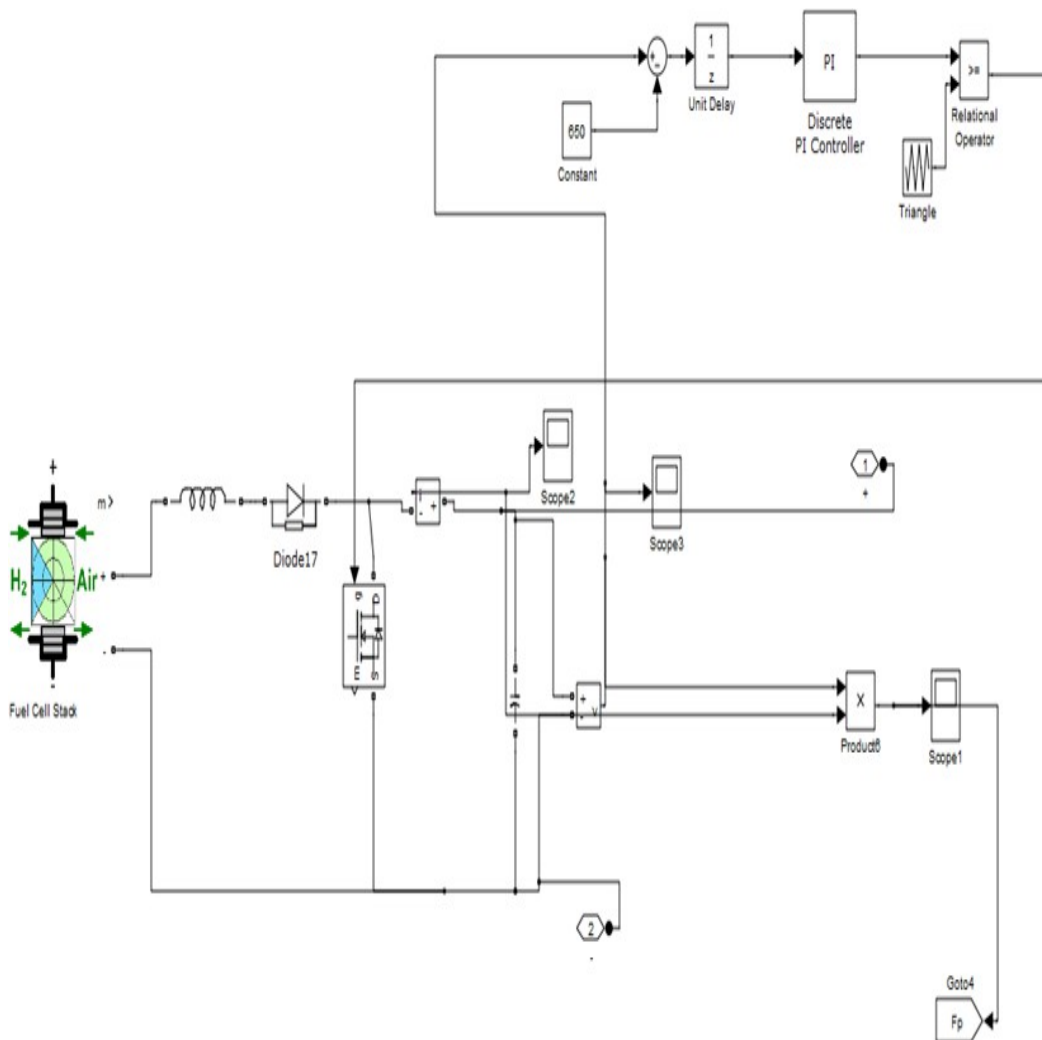


Figure-4: : SimulinkDiagramoffuelcellpowersystem

The Simulink model of a solar power system, comprising a PV array, boost converter, and MPPT, is displayed in Figure 1.

The wind power Simulink model, which includes wind turbine simulation, PMSG, rectifier, and Dc-Dc boost converter, is displayed in Figure 2.

The Simulink model of a battery which includes a bidirectional switch in figure 3.

The Simulink model of a fuel cell which includes PI controllers, diode and unit delay in fig 4.

The Simulink model which shows the overall power system like solar, wind, battery and fuel cells shown in fig 5.

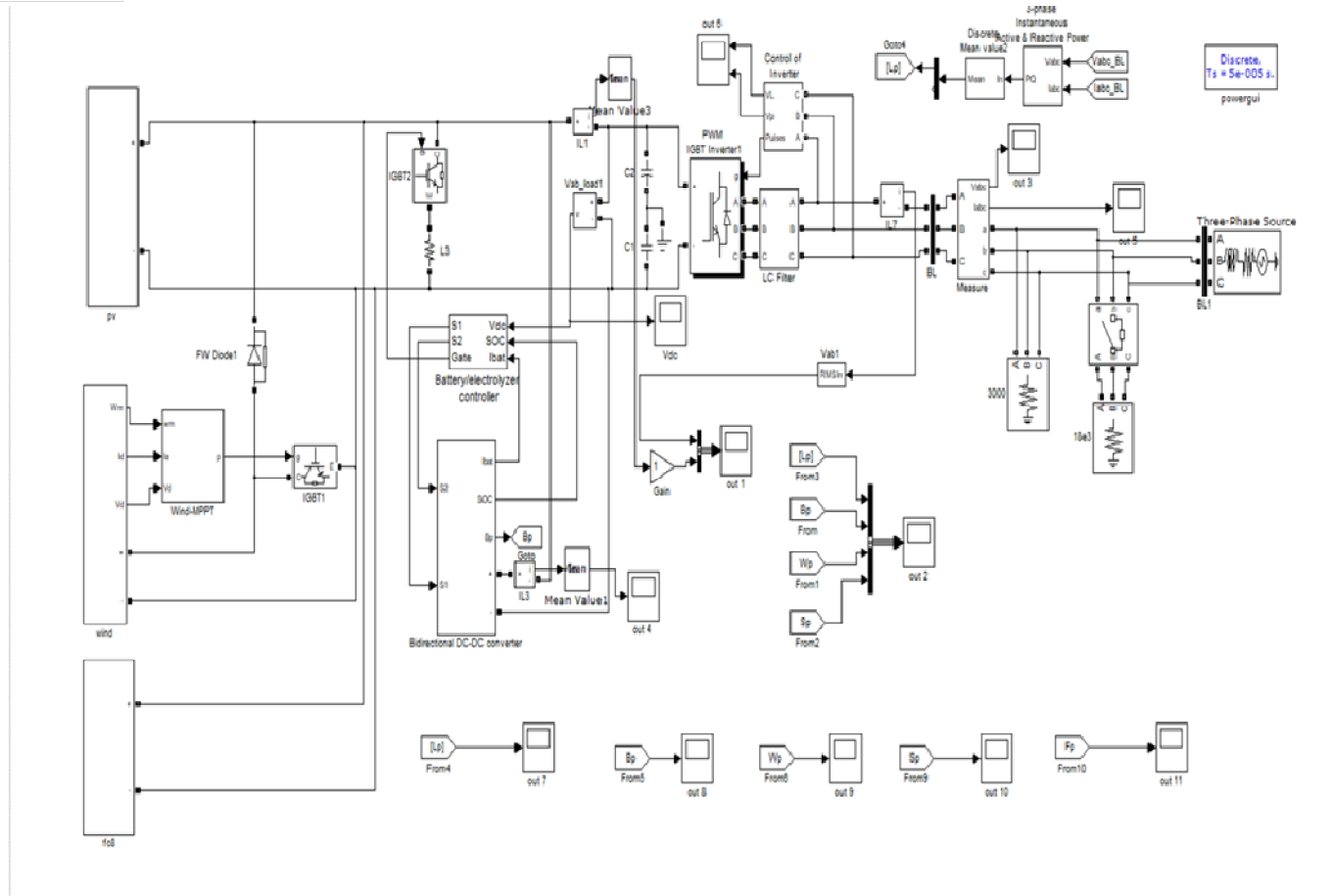


Figure-5: Simulink Diagram of solar, wind, battery and fuel cell hybrid system.

The boost converter, which is used for solar systems, is designed to raise the DC voltage from a fluctuating solar panel to a higher, constant value. It also uses voltage feedback to keep the wind generator's output voltage constant, so that at lower wind speeds, the voltage is lower and at higher wind speeds, it is higher. Due to their intrinsic unpredictability, these sources' power output varies with the weather and the time of day. However, because boost converters can handle a broad range of input voltages, and the energy generated by both sources can be fully utilized. Changes in energy generation can lead to variations in voltage levels. Boost converters assist connected loads in receiving a consistent and reliable power supply by stabilizing the output voltage. The voltage generated by solar panels and wind turbines might not always be sufficient for the load or batteries. Boost converters can be used to adjust voltage levels to meet the specific needs of the system.

V. RESULTS AND DISCUSSION

The hybrid photovoltaic-wind system with an AC load is the focus of the study. Each source is adapted to the local climate, taking into account factors like radiation and wind speed. A current as well as voltage sensor is also required for each of these in order to ensure that the optimum amount of electricity produced is maintained in spite of environmental changes. The system's independence is ensured by these two sources in conjunction with an AC load. Compared to typical systems that only use one source, the hybrid system uses two linked sources, which results in a higher effective rate.

The simulation findings demonstrate the robust performance of the proposed solar and wind combined energy source across a variety of operating conditions. The dynamic modelling and analysis emphasize the system's ability to seamlessly integrate and benefit from the complementary features of solar and wind resources. The enhanced stability and dependability of power generation observed with protective schemes indicates a considerable improvement in the overall performance of the hybrid system.

Figure 6 displays the solar power system's output, including the system's voltage, current, and diode current.

Figure 7 illustrates the output of wind power systems using a permanent magnet synchronous generator (PMSG) coupled to wind turbines.

Figure 8 shows the output of the fuel cell.

Figure 9 displays the power output of a battery power with SOC (state of charge) and out power including time.

Figure 10 displays the output of overall power output from the solar, wind, battery etc.

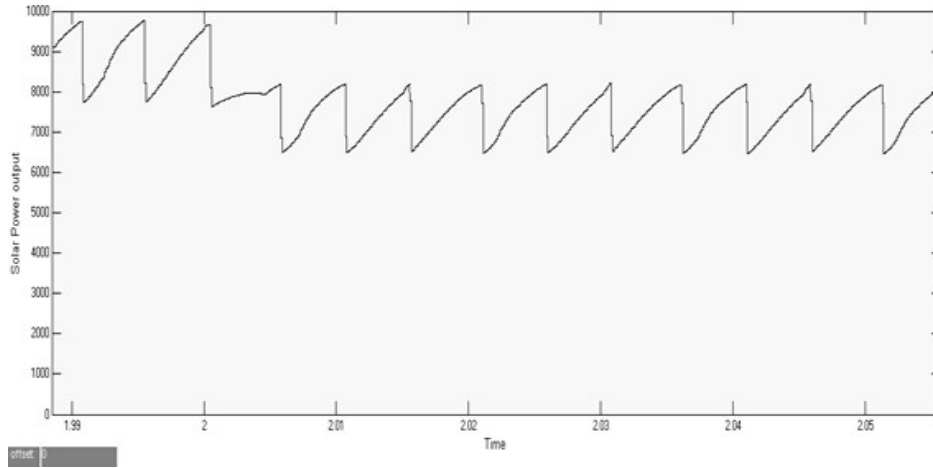


Figure 6: Solar system output.

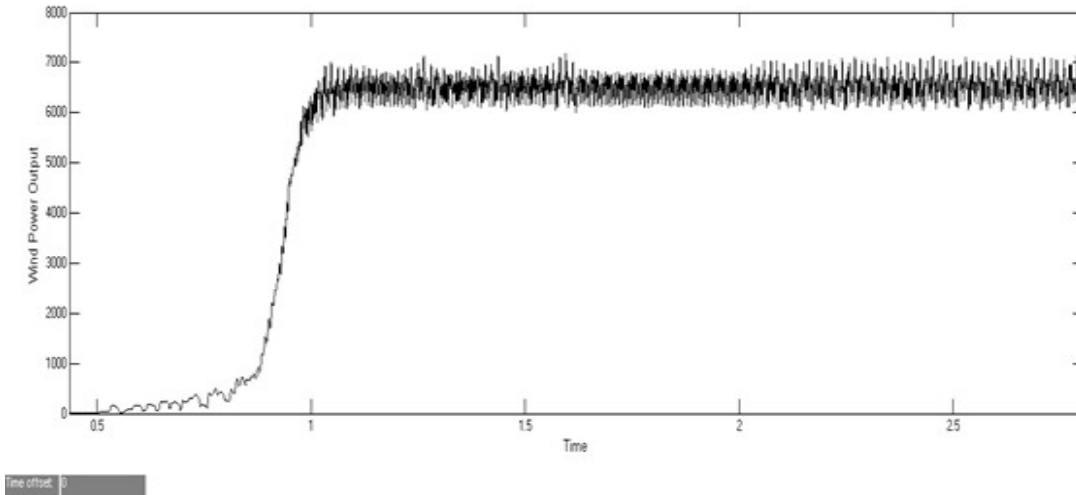


Figure 7: Wind Power output

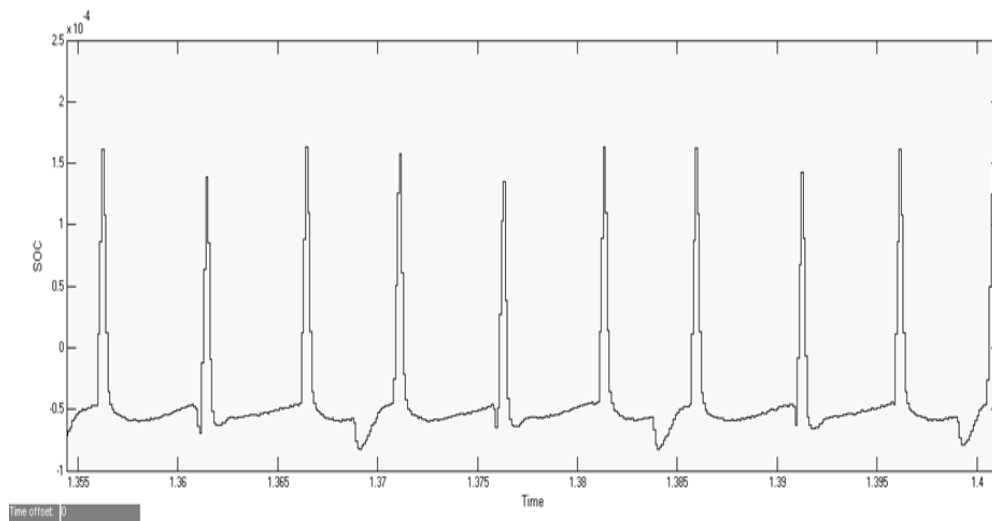


Figure-8: Fuel cell output

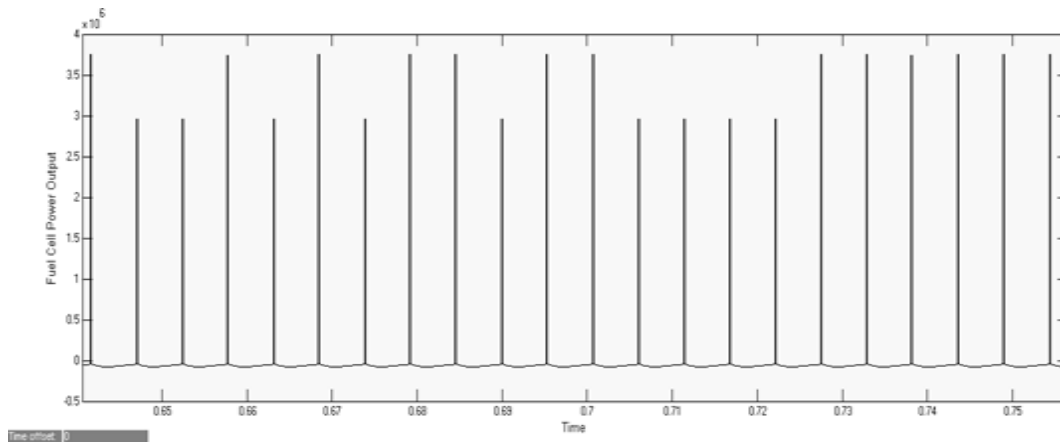


Figure9-BatteryOutput

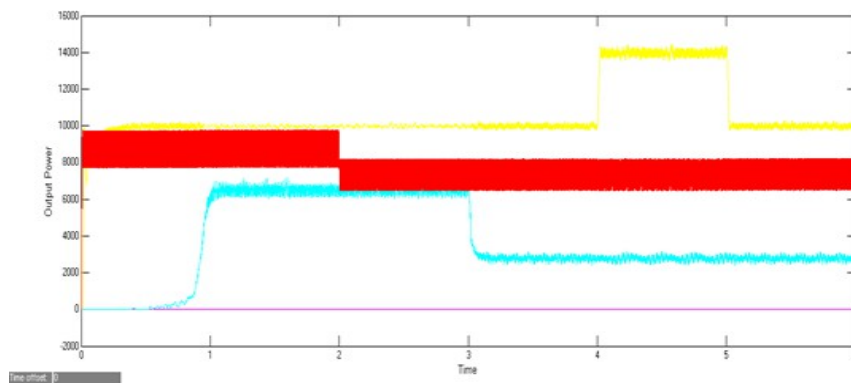


Figure-10:OutputsofLoadpower, WindandSolar power

VI. CONCLUSIONS

The new control method for PV-WIND-SMES systems based on fuzzy logic control (FLC) has been proposed in this paper. The proposed FLC method maintains higher reliability of the SMES device by taking into account its state of charge (SOC). Additionally, the proposed controller eliminates the fluctuated nature of the PV generation and wind generation through local load management. Additionally, the proposed FLC method maintains a longer lifetime of the DC link capacitors by avoiding high operating voltages due to deep charge and discharge operations. The output from solar and wind systems is converted into AC power output using an inverter, and a circuit breaker is disconnected in the allotted time. The hybrid system is adjusted to provide the maximum output power under all operating conditions in order to fulfill the load. In order to satisfy the load, the battery supports the wind or solar system. It can operate simultaneously for the same load.

V. ACKNOWLEDGMENT

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