Supercapacitor-Assisted Hybrid Renewable Energy System: Integration of PV and Fuel Cell Technologies

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Abstract: ***Most of the world's energy needs are currently met by fossil fuels, but these sources pose significant environmental concerns and are not viable in the long term. On the other hand, solar photovoltaic (PV) power, though renewable, suffers from variability—its output can drop suddenly due to factors like unexpected cloud cover or fog. This fluctuation creates challenges when integrating PV systems with conventional power generation, which typically lacks the flexibility to adjust output quickly. Moreover, bringing additional traditional generators online is not an immediate process, as it involves startup delays.***

Since photovoltaic (PV) systems can only generate power during daylight hours, the electricity demand during nighttime must be fulfilled using conventional energy sources. This limitation leads to a dependency between power generation infrastructure and generation scheduling. To address the challenges posed by this variability, integrating energy storage systems becomes essential. These storage units help align the intermittent nature of renewable sources with the fluctuating power demand. In order to tackle these environmental and operational challenges effectively, a hybrid energy system comprising PV panels, fuel cells, and a supercapacitor-based battery storage solution is proposed.

Key Words: Solar Cells, Fuel Cell, Green Energy.

1. INTRODUCTION

With the continuous increase in global energy demand, the focus is gradually shifting toward renewable energy sources. Among them, solar energy stands out as one of the most mature and widely used technologies. However, solar power is inherently variable and its output fluctuates due to factors such as weather conditions, geographic location, time of day, and seasonal variations, making it challenging to match with changing load requirements. To address this issue, this study incorporates a fuel cell system supported by an ultra-capacitor. Fuel cells are gaining significant attention in modern engineering applications due to their ability to efficiently deliver power through electrochemical processes.

The power generated from hydrogen or the fuels is highly efficient and has a low emission rate. The above system is familiar to load conditions which include acceleration, breaking periods and distortion periods.

2. DESIGNING OF PV WITH MPPT MODEL

The process of converting solar energy into electricity through photovoltaic (PV) cells involves two fundamental stages. Initially, incident sunlight is absorbed, generating electron-hole pairs within the semiconductor material. These charge carriers are then separated by the internal electric field of the device — electrons are directed toward the negative terminal, while holes move toward the positive terminal. Supercapacitors, similar to secondary batteries, are used for energy storage and delivery. However, their mechanism of storing charge significantly differs from that of batteries. While batteries rely on chemical reactions to generate electrical energy, supercapacitors store energy electrostatically, in the form of static charge. This direct form of storage enables them to charge and discharge much more rapidly than conventional batteries of equivalent size. Nevertheless, their energy remains lower than that of batteries, typically ranging between 10% to 20% of a comparable battery. The PV system integrated with Maximum Power Point Tracking (MPPT) is illustrated in Figure 1.

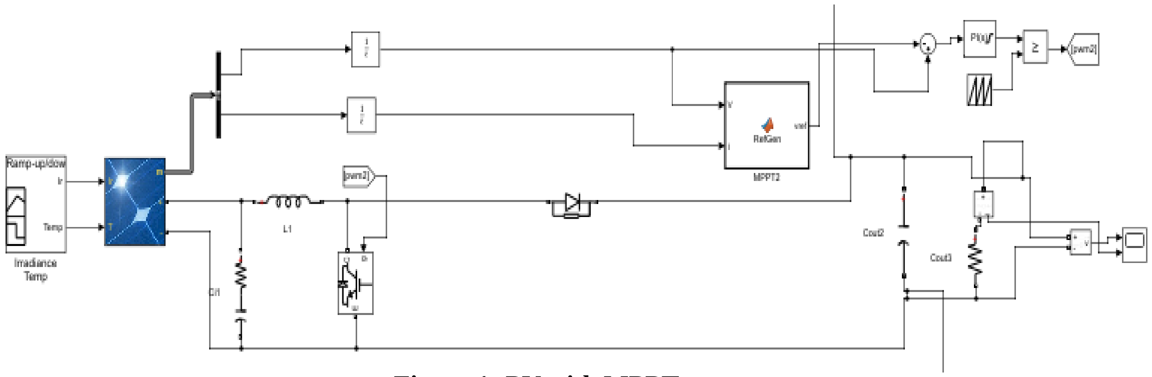

Figure 1: PV with MPPT

3. PROPOSED MODEL

The proposed system introduces power management strategies for a grid-connected hybrid energy generation setup capable of flexible power transfer. This configuration is designed to maximize the effective use of renewable sources such as photovoltaic and wind energy. To achieve this, an adaptive Maximum Power Point Tracking (MPPT) algorithm will be implemented in combination with the conventional perturb and observe (P&O) technique.This study primarily investigates the performance of fuel-cell-driven interleaved converter topologies, aiming to identify the most suitable conversion scheme for the Proton Exchange Membrane Fuel Cell (PEMFC). The research also focuses on enhancing the system's transient response by minimizing voltage fluctuations on both input and output sides, as well as regulating current surges at the fuel cell and load terminals. Additionally, this work seeks to improve the voltage gain characteristics of DC-DC converters applied in PV cells, fuel cells, and supercapacitor-based energy systems.

4. MODELLING OF HYBRID SYSTEM

Since photovoltaic (PV) systems generate power only during daylight hours, meeting energy demand during nighttime necessitates the use of conventional energy sources. This dependency results in a closely linked relationship between installed generation capacity and scheduling strategies. To effectively address the associated environmental and operational challenges, a hybrid energy system integrating PV panels, fuel cells, and a supercapacitor-based energy storage unit is proposed. A general schematic of the proposed system is illustrated in Fig. 2.

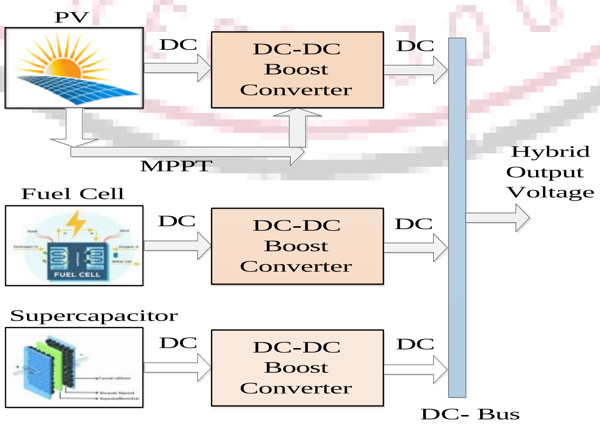

Figure 2: General representation of Hybrid System

5. DESIGNING OF FUEL CELL MODEL

Combustion of fossil fuels for power generation results in the emission of oxides of sulphur, nitrogen and carbon and particulates, which causes health hazards and global warming. The depletion of fossil fuels and climate change due to pollutants has motivated the research and development of more efficient and cleaner alternate energy sources. Simulation model of fuel cell shown in figure 3. along with a DC-DC boost converter. The other alternate energy sources are wind, solar, geothermal etc. The intermittent nature of wind and solar energy warrants the need for alternate energy sources which can supply continuously.

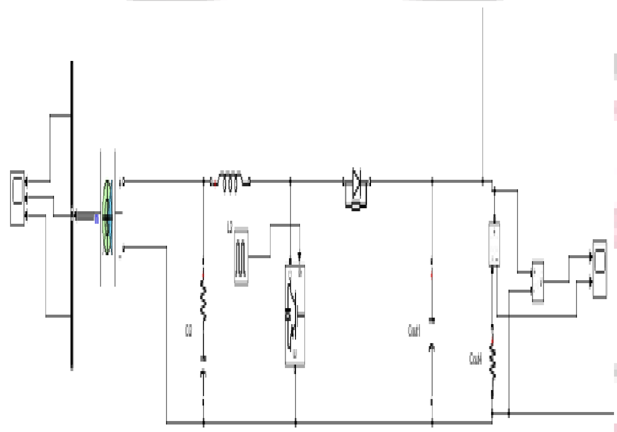

Figure 3: Simulation Model of Fuel Cell

The Current- Voltage (I-V) characteristic can be described by the Shockley solar cell equation given as;

$$ID = Iph - Io\ (eqV/KT-1) \qquad [1]$$

Where, q is the electron charge, V is the voltage at the terminal, k is the Boltzmann constant, T is the absolute temperature, Io is the diode saturation current and Iph is the photo generated current. The I-V and P-V characteristic of solar cell is shown in Figure 4. In the ideal case, the short circuit current Isc is equal to the photo-generated current Iph, and the open circuit voltage VOC is given by

$$VOC = (KT/q)\ln(1+ Iph/Io) \qquad [2]$$

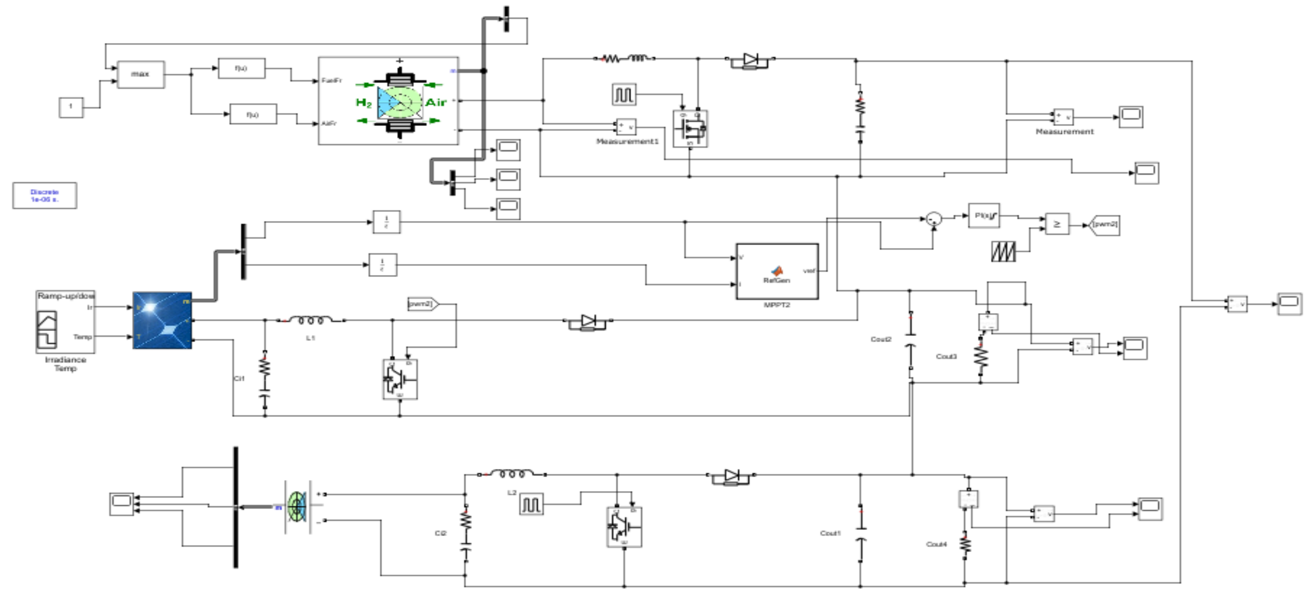

Figure 4: Simulation model of Hybrid System

T[illegible] el cells, other renewable energy sources include wind, solar, and geothermal energy. However, the inconsistent availability of wind and solar power emphasizes the importance of alternative energy systems capable of delivering continuous power. Hydrogen and hydrogen-rich compounds emerge as promising clean fuels due to their high energy content. Unlike conventional carbon-based combustion processes, hydrogen can be utilized electrochemically, resulting in zero pollutant emissions and improved energy efficiency.

6. DESIGNING OF SUPERCAPACITOR MODEL

Recent development in capacitor has given rise to a concept supercapacitor, which has got higher life than many other storage devices. Supercapacitor gives faradic capacitance value and hence it is referred as supercapacitor. Simulation model of supercapacitor is shown in Figure 4.

7. SIMULATION RESULTS

This work simulates at a 100 KW power rating and use a PV module as 47 parallel and 10 series connected string at specific module. Also, specified 300 maximum dc output voltage. Graph plot of current and power with respect to voltage shown in Figure 5.

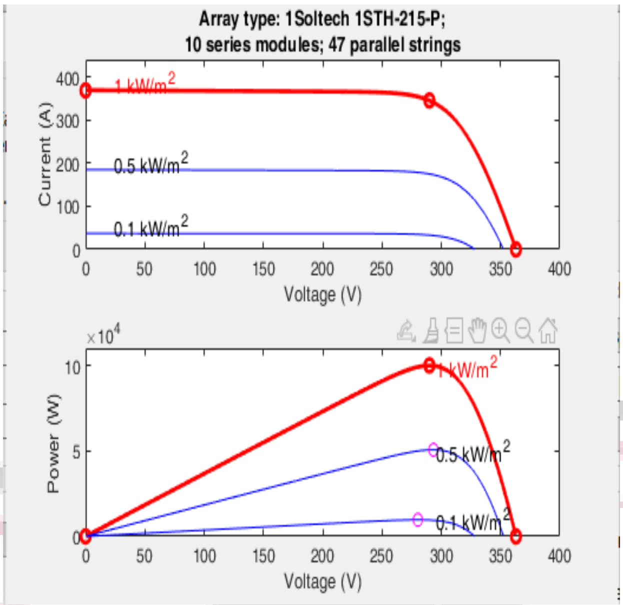

Figure 5: Graph plot of current and power

This high voltage ripple can damage a system and reduces the efficiency also increases the losses of the system. DC voltage of the PV output shown in Figure 6

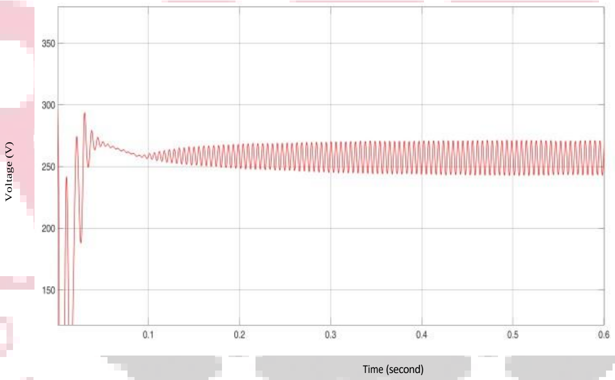

Figure 6: PV output DC voltage with 50V ripple

8. SIMULATION RESULTS FOR HYBRID HIGH VOLTAGE DC OUTPUT

To achieve high-voltage output for renewable energy generation or battery-based energy storage systems, multiple modules need to be interconnected in a hybrid configuration. This arrangement enables the generation of a higher DC voltage. The resulting output voltage of the proposed hybrid system is illustrated in Figure 7.

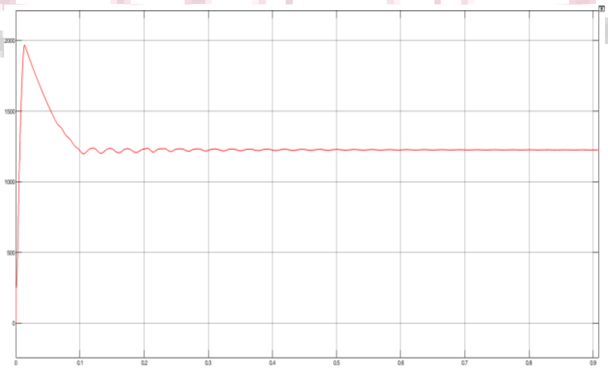

Figure 7: Hybrid high voltage DC output

By the validation of all the simulation results in MATLAB/Simulink justified the performance of the solar panel, fuel cell and supercapacitor as a hybrid system and also battery energy storage system.

CONCLUSION

Renewable energy sources have become central to meeting the world's growing energy demands, with photovoltaic (PV) systems, fuel cells, and supercapacitors standing out as key technologies. Solar panels convert sunlight into electrical energy through the photovoltaic effect. However, when directly connected to a load, these panels do not necessarily operate at their optimal efficiency or maximum power point (MPP). To overcome this, Maximum Power Point Tracking (MPPT) techniques are employed. MPPT is an electronic control strategy that dynamically adjusts the duty cycle of a DC-DC converter to ensure the extraction of the maximum possible power from the solar array. In stand-alone solar systems, energy storage becomes essential. While conventional batteries are commonly used for this purpose, they come with limitations—particularly their inability to handle pulsed or sudden high-power loads without experiencing deep discharge, which can significantly reduce their lifespan. Fuel cells offer an alternative solution by converting stored chemical energy directly into electrical energy through electrochemical reactions. Unlike combustion-based systems, fuel cells operate efficiently and cleanly using fuels such as hydrogen, methane, or gasoline. Functionally similar to batteries, they generate electricity through the conversion of chemical energy, but unlike batteries, they continue to produce power as long as fuel is supplied.

In contrast to batteries, fuel cells generate electricity using external sources of fuel (supplied at the anode) and oxidants (introduced at the cathode), which react in the presence of an electrolyte. During operation, the reactants are continuously fed into the cell, and the by-products are expelled, while the electrolyte remains stationary within the system. As long as the input flow of reactants is maintained, the fuel cell can operate continuously. Supercapacitors (SCs) function as advanced energy storage systems that fill the performance gap between traditional capacitors and batteries. They offer higher energy storage capacity than conventional capacitors and can deliver greater power output compared to batteries. Their key advantages include rapid charge-discharge capability, high cycle life, and long-term operational stability, making them highly suitable for modern energy storage applications. SCs are already in use across a range of systems—either in hybrid configurations alongside batteries or as standalone energy storage units. Commercially, porous carbon materials are commonly employed for SC electrodes due to their excellent electrical conductivity and high surface area.

Simulation and modeling performed in MATLAB/Simulink validate the effective integration and operation of a hybrid system consisting of solar panels, fuel cells, and supercapacitors. The results further confirm the system's viability as an alternative or complement to traditional battery-based energy storage solutions.

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