Enhanced Power Management in PV-Fuel Cell Systems Using Super capacitor Integration

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Abstract: The continuous rise in global energy demand, coupled with growing environmental concerns, has significantly boosted the adoption of renewable energy sources over the past decade. Energy options such as solar, wind, and hydro have gained widespread acceptance due to their clean, emission-free nature and their abundance. Advancements in semiconductor technologies have facilitated the development and commercialization of photovoltaic (PV) cells, positioning PV systems as a viable alternative energy solution. However, as the use of PV systems expands, their impact on the power grid becomes increasingly significant. Issues such as harmonic distortion and grid stability challenges arise, necessitating compliance with technical standards to ensure power quality. This includes the regulation of harmonic currents, which is especially important when large-scale PV installations are connected to the grid, as they can lead to severe disturbances. Similarly, modern wind farms rely heavily on power electronic components. These devices, while essential, contribute to harmonic emissions. The widespread deployment of static power converters—such as rectifiers and switched-mode power supplies—further aggravates the situation by introducing harmonic currents into the distribution network. These harmonics can distort voltages and currents, ultimately affecting the stable and efficient operation of the entire power system.

Keywords*: Solar PV system, Fuel Cell, Hybrid system*

I. INTRODUCTION

The sun serves as the primary source of nearly all energy utilized on Earth. Solar panels are created by assembling multiple photovoltaic (PV) cells. The term "photo" refers to light, while "voltaic" relates to the generation of electricity. Photovoltaic technology enables the production of electrical energy from light. A typical PV cell consists of two layers of semiconductor material—one positively charged and the other negatively charged. When sunlight strikes the semiconductor surface, the electric field formed at the junction between the two layers initiates a flow of electricity. The greater the sunlight intensity, the higher the electricity output.

Table 1 Growth of Solar Power in India

State	MW as of March 2021	MW as of March 2022	MW as of Jan 2023
Tamil Nadu	148.52	1061.82	1590.97
Rajasthan	942.10	1269.93	1317.64
Gujarat	1000.05	1119.17	1159.76

PV panels come in different shapes and types for various applications. Some are designed as solar tiles that can replace conventional roofing tiles, offering ease of installation. The light absorbed by the panels is transformed into clean, renewable electricity. Since PV systems have no moving parts, the process is completely silent. The electricity they produce is in the form of direct current (DC). However, the solar energy potential depends largely on geographic location. For instance, as shown in Table 1, Tamil Nadu ranks as the leading state in solar power generation within India.

II. FUELL CELL SYSTEM

Traditionally, energy storage systems based on batteries and capacitors are used to supply power during load demand and fault conditions. Batteries are commonly used due to their low cost and are often paired with capacitors. However, this setup has certain limitations. Batteries cannot be recharged endlessly and tend to have a limited lifespan. Additionally, to maintain a suitable energy-to-volume ratio, capacitors are needed for each battery unit, which increases the overall system cost.

In this study, a fuel cell system integrated with an ultra-capacitor is proposed. Fuel cell technology is gaining attention in the modern engineering landscape due to its ability to efficiently distribute power through electrochemical reactions. Energy produced from hydrogen or similar fuels offers high efficiency and minimal emissions. Moreover, this combined system performs well under dynamic load conditions such as acceleration, braking, and during power fluctuations.

III. SUPER CAPACITOR (SC)

Supercapacitors operate similarly to secondary batteries in terms of energy storage and delivery, but the underlying method of storing energy is fundamentally different. Unlike batteries, which generate electric charge through chemical reactions, supercapacitors store energy in the form of electrostatic charge. This direct storage method allows them to charge and discharge much more rapidly than batteries of the same size. However, their energy density is significantly lower—typically 10 to 20 times less than that of conventional batteries, as highlighted in the studies by Surewaard and Tiller.

The proposed system introduces power control strategies for a grid-connected hybrid energy generation setup that supports flexible power transfer. This hybrid configuration enables optimal use of naturally available renewable sources such as wind and solar (photovoltaic) energy. To achieve this, an adaptive Maximum Power Point Tracking (MPPT) technique, combined with the conventional perturb and observe method, will be implemented. This study primarily evaluates the performance of various interleaved converter topologies when powered by a Fuel Cell, with a particular focus on identifying the most efficient conversion technique for a Proton Exchange Membrane Fuel Cell (PEMFC). The research further targets enhanced transient response, minimizing voltage spikes at both input and load ends, and effectively managing current fluctuations on the fuel cell and load sides. Additionally, the study aims to enhance the voltage gain of the DC-DC converters employed in PV, fuel cell, and super capacitor-based systems.

IV. MODELLING OF HYBRID SYSTEM

Since photovoltaic (PV) systems generate power only during daylight hours, meeting energy demands during nighttime requires support from conventional energy sources. This dependency highlights the need for coordinated generation planning and scheduling, creating a complementary relationship between existing energy generation and load requirements. To address various environmental challenges, the development of a hybrid energy system becomes essential—one that integrates PV panels, fuel cells, and super capacitors as part of a battery energy storage solution. A general illustration of this system is provided in Fig. 1.

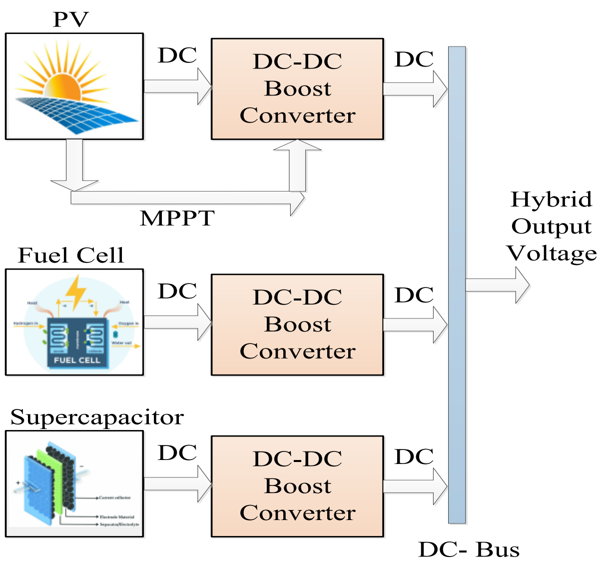

Figure 1: General representation of Hybrid System

V. PROBLEM FORMULATION

The hybrid energy system integrates both wind and photovoltaic (PV) sources. Wind energy, which originates from the kinetic motion of atmospheric air, is harnessed using components like wind turbines, generators, and AC/DC converters. The wind turbine, coupled with a Permanent Magnet Synchronous Generator (PMSG), converts mechanical rotation into electrical energy. To ensure efficient extraction of energy, a Maximum Power Point (MPP) tracking technique is applied. The AC voltage produced is then converted into DC using an AC-DC converter. Similarly, solar energy—an abundant natural resource—is utilized by PV modules to generate electrical power. With the implementation of appropriate technologies suited to specific geographic areas, a significant amount of solar energy can be harvested. Like the wind system, the PV setup also employs an MPP tracking method to extract the highest possible power output. A DC-DC converter is used to raise the generated DC voltage to the required level. Numerous studies have explored strategies for maximizing power extraction from both wind and solar sources. However, the development and implementation of an adaptive hybrid controller for MPPT are still in their early stages. Therefore, there is a growing need for a control strategy that effectively integrates the strengths of both solar and wind MPPT logic. This research proposes a hybrid renewable energy system connected to the grid through a common DC link, combining the outputs from both wind and solar sources. Traditional methods have been used to control power delivery to match load demand, but this work aims to enhance such approaches with an adaptive hybrid control mechanism.

Renewable energy sources, when integrated with a microgrid, play a vital role in incorporating Distributed Energy Resources (DERs), Energy Storage Systems (ESS), and both AC/DC loads. These systems can function either independently (in islanded mode) or while connected to the main grid. The ESS typically comprises batteries and supercapacitors. Due to unpredictable changes in load demand, fluctuations in instantaneous power can disrupt the smooth functioning of the microgrid. Hence, incorporating an ESS ensures the system remains reliable, stable, and secure. Green energy generated from renewable sources contributes to reducing environmental pollution. In this study, a hybrid model combining PV and wind energy systems is developed. The energy generated from these two sources is supplied to the grid. To interface renewable systems with the grid, an inverter is essential. Additionally, a controller is required to seamlessly switch between the Maximum Power Point Tracking (MPPT) mode and a voltage regulation mode, ensuring that the DC bus voltage remains unaffected. Effective system monitoring is crucial to maintain energy balance between different storage units. This helps prevent issues such as high Depth of Discharge (DOD) and low State of Charge (SOC) in the battery, thereby enhancing overall system efficiency and battery lifespan.

VI. DESIGNING OF PV WITH MPPT MODEL

A DC-DC boost converter is employed to maintain a stable output voltage in grid-connected photovoltaic (PV) systems. Its main function is to elevate the varying voltage generated by solar panels to a higher, constant DC voltage level. To ensure voltage stability, the converter uses a voltage feedback mechanism. At the core of this control setup is a microcontroller, which continuously monitors the system and generates pulse-width modulation (PWM) signals to manage the switching of power electronic components within the boost converter. This configuration allows the boost converter to interface directly with a grid-tied inverter, making it suitable for applications where photovoltaic systems are integrated with the electrical grid.

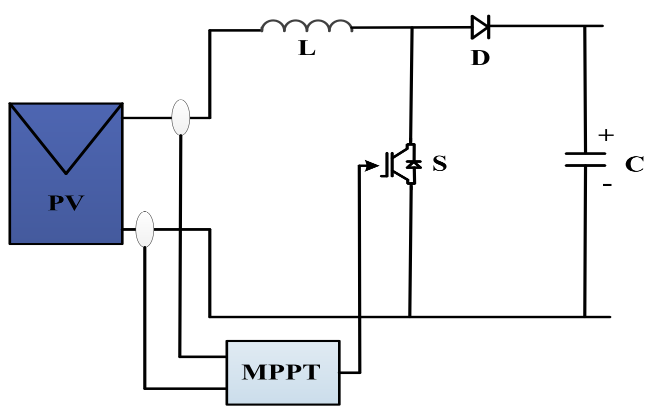

Figure 2: DC-DC boost converter with MPPT tracking

The boost converter acts as a medium for power transfer, facilitating both the absorption and delivery of energy from a solar panel to a grid-connected inverter. This energy transfer process is carried out through the coordinated operation of four main components: an inductor, an electronic switch, a diode, and an output capacitor. The typical circuit configuration of a boost converter is illustrated in Figure 2. Energy absorption and injection take place within a switching cycle. In simple terms, the average output voltage is determined by how long the switch remains on or off during each cycle. When the switching frequency is kept constant, modifying the duration of the switch’s on and off states is known as pulse-width modulation (PWM). The switching duty cycle, denoted as k, is defined as the ratio of the switch's on-time to the total switching period. Depending on the duration of energy transfer relative to the switching time, the converter operates in one of two modes: Continuous Conduction Mode (CCM) or Discontinuous Conduction Mode (DCM).

VII. CONCLUSION

A significant portion of the world’s energy demand is increasingly being fulfilled by renewable sources, with solar energy, fuel cells, and supercapacitors being among the most prominent. Solar panels convert sunlight into electrical energy through the photovoltaic effect. However, when directly connected to a load, these panels do not always function at their highest efficiency or at their Maximum Power Point (MPP). To ensure optimal energy extraction, a technique known as Maximum Power Point Tracking (MPPT) is employed. This method electronically adjusts the duty cycle of a DC-DC converter to continuously maintain operation at the panel's MPP. In standalone systems, where solar panels operate independently from the grid, an energy storage component—typically a conventional battery—is required to store excess energy and provide backup when sunlight is unavailable.

Conflict of Interest: The corresponding author, on behalf of second author, confirms that there are no conflicts of interest to disclose.

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