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A Novel Hybrid Control Approach for Microgrid Systems Based on UAPF: Controlling Power Flow and Active Power Line Conditioner

Jay M.Pawar , S.S.Hadpe , Dr.S.S.Khule, V.R.Aranke

Department of Electrical Engineering, Matoshri College of Engineering and Research Centre, Nashik, India

ABSTRACT: The growing worldwide popularity of renewable energy, especially from solar sources, emphasizes the need of advanced management systems for improving power generating efficiency. Solar energy production is intermittent, resulting in power supply changes that may create voltage and frequency instability within the microgrid. Power flow management techniques are required to balance variable generation with load demand and ensure system stability. To enhance the foregoing, the microgrid system is implemented by integrating external sources into the UAPF's DC connection. A hybrid control technique is provided to estimate the reference characteristics and generate switching signals for improved power quality and efficient power flow management. As a result, the converters function as active filters for PQ improvement and power converters for grid-feeding, grid-supporting, and grid-forming configurations in microgrid operations. A conventional grid-connected hybrid microgrid with one ac microgrid and one dc microgrid is used as the study system. The system with the suggested control method is simulated using MATLAB/Simulink and verified in the experimental setup under different modes.

KEYWORDS: Microgrids, renewable energy sources, power quality, batteries, active filters, power quality, power flow management, hybrid power systems, voltage control, and power system stability;

I. INTRODUCTION

A photovoltaic (PV)-based hybrid microgrid is required to capture clean, renewable energy in a more dependable and efficient way [1]. Individually, sunlight sources are discontinuous and weather-dependent, resulting in periods of little or no power output. By integrating both energy sources in a hybrid microgrid, the system can adjust for their variability—solar output during the day often peaks at night or during overcast circumstances. This complimentary nature increases the total energy accessibility and stability of the system. Furthermore, a hybrid microgrid minimizes dependency on fossil fuels, lowers emissions of greenhouse gases, and promotes sustainable energy, particularly in distant or off-grid places. It also permits localized power production, which reduces transmission losses and improves energy security. Power flow regulation is critical in a photovoltaic (PV)-based hybrid microgrid to guarantee efficient, stable, and dependable operation [2]. Because renewable energy sources such as solar are intermittent and variable, the produced electricity changes often, resulting in supply-demand mismatches. Effective power flow management helps to manage these oscillations by managing power distribution among the microgrid's multiple sources, loads, and storage systems. It provides voltage and frequency stability, minimizes line and equipment overloads, and maximizes energy efficiency. Furthermore, in a hybrid system, power flow management is critical for coordinating PV sources' contributions, allowing for smooth integration, minimizing reliance on backup systems, and improving the microgrid's overall resilience and performance.

The total efficiency of the hybrid microgrid may be considerably enhanced by intelligently controlling the power flow between diverse sources, loads, and storage devices, lowering energy losses and optimizing the use of clean energy resources. As a result, effective power flow regulation is not only desirable, but also essential for the successful deployment and operation of PV-based hybrid microgrids.

An Active Power Line Conditioner (APLC) is an essential component of the Unified Active Power Filter (UAPF) arrangement in a PV-based hybrid microgrid. Because of its intermittent and non-linear nature, the integration of renewable energy sources causes power quality challenges such as voltage fluctuations, harmonics, and unbalanced loads. The APFC in a UAPF system is in charge of minimizing these concerns by actively filtering out harmonics, adjusting for reactive power, and balancing load currents. It provides a clean and reliable power supply to connected

loads by preserving sinusoidal voltage and current waveforms. This improves the overall efficiency, dependability, and longevity of microgrid components. Furthermore, the APLC allows bidirectional power flow and adaptive response, making it perfect for controlling variable power injections from PV sources, resulting in better power quality and stability of the grid in hybrid microgrids.

II. LITERATURE SURVEY

Despite the variable supply of renewable energy sources, control methods in PV hybrid microgrids are essential for ensuring regular and efficient operation. This is the case even if the supply of renewable energy sources might change. Artificial intelligence-based control, hierarchical control, droop control, and model predictive control are the broad categories that are used to classify these systems.

Primary, secondary, and tertiary are the three levels that are often included in hierarchical management schemes [3]. It is the responsibility of primary control to manage the rapid inner loops that are responsible for regulating the voltage and current of individual sources. The secondary control system is responsible for regulating power sharing and adjusting for voltage and frequency abnormalities that are caused by the main control system. Control at the tertiary level gives economic dispatch and optimal power flow the highest priority at the system level.

One of the most common decentralized approaches, known as droop control [4], imitates the behavior of synchronous generators. This allows scattered generators to share active and reactive power based on variations in frequency and voltage, respectively. When it comes to microgrids, modified droop control systems are often used in order to enhance performance and address specific problems.

Model Predictive Control (MPC) [5] is a technique that makes use of a system model in order to anticipate future behavior and optimize control operations over a predetermined time horizon. This technique takes into consideration a variety of constraints and objectives, including controlling voltage and ensuring power balance.

Adaptive and intelligent control solutions are provided by artificial intelligence (AI)-based control [6], which includes techniques such as fuzzy logic, neural networks, and genetic algorithms. These control solutions are particularly effective in dealing with the uncertainties and nonlinearities that are associated with renewable energy sources and load variations. It is becoming more common for advanced photovoltaic microgrid systems to make use of hybrid control approaches, which combine the advantages of a number of different technologies.

An enhanced hybrid control approach is presented by M. Golla and colleagues [7] for a microgrid system that is based on a universal active power filter (UAPF) and has an active power line conditioner. The only thing that conventional UAPF does is increase power quality (PQ), and it does so by using more power. One of the consequences of this is that the utilization factor of the converter and its power handling capacities in the system are reduced. An integrated universal active power filter (UAPF) for renewable energy was proposed by M. Golla and colleagues [8] for the microgrid system. This filter would allow for the connection of other renewable energy sources, such as solar and battery storage systems, to the UAPF's direct current (DC) link. The microgrid system that has been recommended makes use of a centralized microgrid controller (CMC) in order to enhance the quality of the electricity and efficiently manage the flow of power. In their paper [9], M. Golla and colleagues describe an improved control approach for a hybrid AC/DC microgrid system that is based on a multifunctional unified active power filter (UAPF). This system incorporates both AC/DC sources and loads via the use of a UAPF. The control approach of the converters makes it possible to achieve increased power quality (PQ) via the use of flexible bidirectional power flows. Through the use of a modified unified interphase power controller (UIPC), M. Zolfaghari and colleagues [10] provide a unique method for the management of power flow in grid-connected hybrid microgrids that are coupled to alternating current and direct current microgrids. A. Verma and colleagues [11] present a modified hybrid unified multi-input multi-output system for microgrid optimization. This system offers an all-weather synchronized solution by integrating multi-located PV nanoarrays and single-phase grid supply as multi-input sources for AC-DC multi-output loads with a bi-directional battery management system. The system is designed to optimize the microgrid.

The AC-DC hybrid microgrid was first presented by L. Kou and colleagues [12] with the intention of facilitating unified monitoring and control of energy flow from various units, including energy storage stations,

distributed solar systems, AC/DC loads, and other units. In order to enhance frequency responsiveness, K. Baral and colleagues [13] proposed a hybrid microgrid system (h-MG) that makes use of a unique marine predator algorithm (MPA) and an upgraded fuzzy PID with filter (FPIDF). A power quality (PQ) enhancement approach was developed by C. Sanjenbam and colleagues [14] for a freestanding system that was powered by a battery and a self-excited induction generator (SEIG) as the source of supply. The Southeast Energy Integration Group (SEIG), which is driven by a hydro turbine, is the primary source of electricity for this independent system. It is essential to use Maximum Power Point Tracking (MPPT) strategies in order to improve the efficiency of hybrid renewable energy systems. These strategies aim to maximize the amount of power extracted from sources that are subject to fluctuations. Adaptive Neuro-Fuzzy Inference System (ANFIS) and Fuzzy Logic Control (FLC) are two of the solutions that have been proposed by M. Saqib et al. [15]. Both of these strategies have shown significant promise in terms of enhancing Maximum Power Point Tracking (MPPT) for solar energy systems. For the purpose of estimating load current and grid voltage sequence components, G. Modi et al. [16] present a novel harmonic decoupling network that is based on a fourth-order generalized integrator. These components are used in order to include DSTATCOM capability into a microgrid that consists of a solar photovoltaic array, battery energy storage, and a wind generator that is based on synchronous reluctance generators.

III. METHODOLOGY

A Unified Active Power Filter (UAPF)-based microgrid in a PV system is critical for improving power quality and reliability in dispersed generating networks. In this arrangement, the UAPF combines series and shunt active filters to address a broad variety of power quality concerns, including voltage sags/swells, harmonics, and reactive power imbalances. When coupled to a photovoltaic (PV) source, the system not only provides clean, renewable energy, but it also guarantees that the electricity sent to the grid or local loads is steady and meets acceptable quality standards. The UAPF's shunt section adjusts for load current harmonics and maintains the correct power factor, and the series part protects sensitive loads from voltage fluctuations. The UAPF also stabilizes the DC-link voltage, which is required for the converters to operate continuously and to provide efficient power conditioning. Overall, introducing a UAPF into a PV-based microgrid improves energy efficiency, system stability, and grid code compliance.

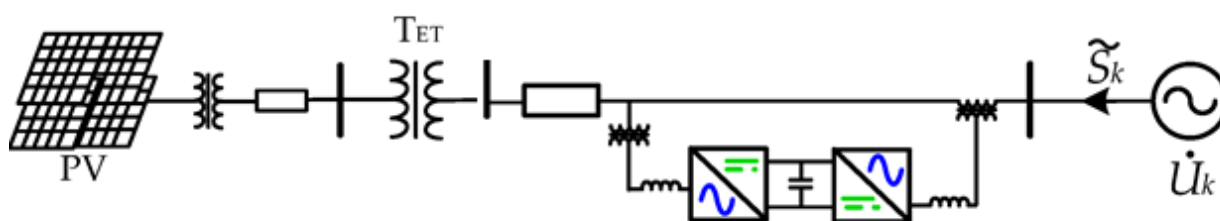


Fig 1: Line Diagram of UAPF-Based Microgrid

Unified Active Power Filter (UAPF) Modelling:

The Unified Active Power Filter (UAPF) is an electrical component that combines both series and shunt active power filters in order to compensate for issues with power quality such as voltage sags/swells, harmonic distortion, imbalanced loads, and reactive power demands in power systems, particularly in renewable energy-based microgrids such as wind-PV.

The UAPF consists of two major parts:

- Shunt Active Power Filter (SAPF): Connected in parallel to the load. It injects compensating currents to eliminate load current harmonics, improve power factor, and balance load currents.
- Series Active Power Filter (SEAPF): Coupled in series with the power supply. It adjusts for voltage harmonics, sags, swells, and unbalanced loads. Both are regulated by a single DC-link capacitor, which serves as an energy storage device to enable bidirectional power transmission.

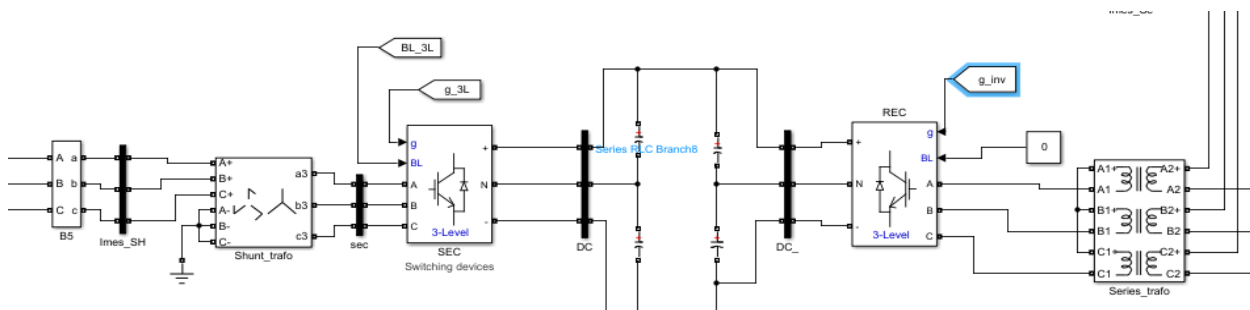


Fig 2: Shunt and Series Filter Modelling

c) Shunt Filter Modelling

The current dynamics of the shunt filter may be expressed using the synchronous reference frame (SRF) or dq transformation as follows:

$$L_f \left(\frac{di_f}{dt} \right) + R_f i_f = V_{dc} - V_{load} \quad (1)$$

Where:

L_f and R_f are the filter inductance and resistance

i_f is the filter current

V_{dc} is the converter-side voltage

 V_{load} is the load voltage

The control goal is to monitor the reference current resulting from power quality correction schemes.

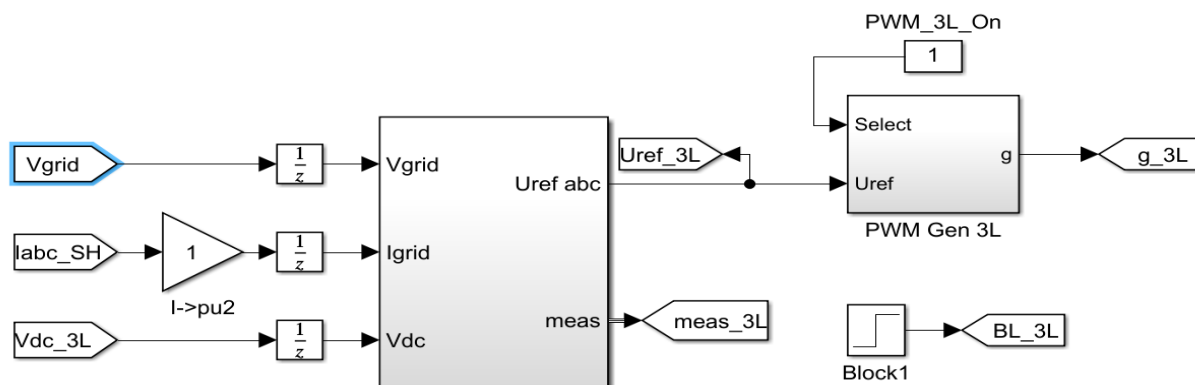


Fig 3: Shunt Controller

d) Series Filter Modelling

The series filter injects a compensating voltage, V_{inj} such that the load perceives a clean voltage. The equation that governs it is:

$$L_s \left(\frac{di_s}{dt} \right) + R_s i_s = V_{source} - V_{load} \quad (2)$$

Where:

L_s and R_s are the series filter parameters

i_s is the source current

V_{source} is the grid-side voltage

V_{load} is the voltage delivered to the load



The Fig 5 depicts a microgrid's active power output (P in kW) during a 2.5-second period. The red line illustrates that the power output fluctuates significantly during the first phase, with values quickly swinging from negative to positive, indicating instability or transients caused by starting circumstances, fast load changes, and PV source variability.

Around the 0.5 to 1.0 second mark, the power continues to vary but exhibits damping oscillations, suggesting that the suggested control system is starting to regulate the output. After around 1.0 second, the power output enters a continuous ramp-up phase, peaking at 1.8 seconds and then stabilizing around 65-70 kW toward the conclusion of the window.

This pattern represents the dynamic behavior of a regulated PV microgrid system, in which active power line conditioners regulate and stabilize output despite input fluctuations. The final stabilization displays effective power management, which is critical for sustaining power quality and satisfying load needs in microgrids.

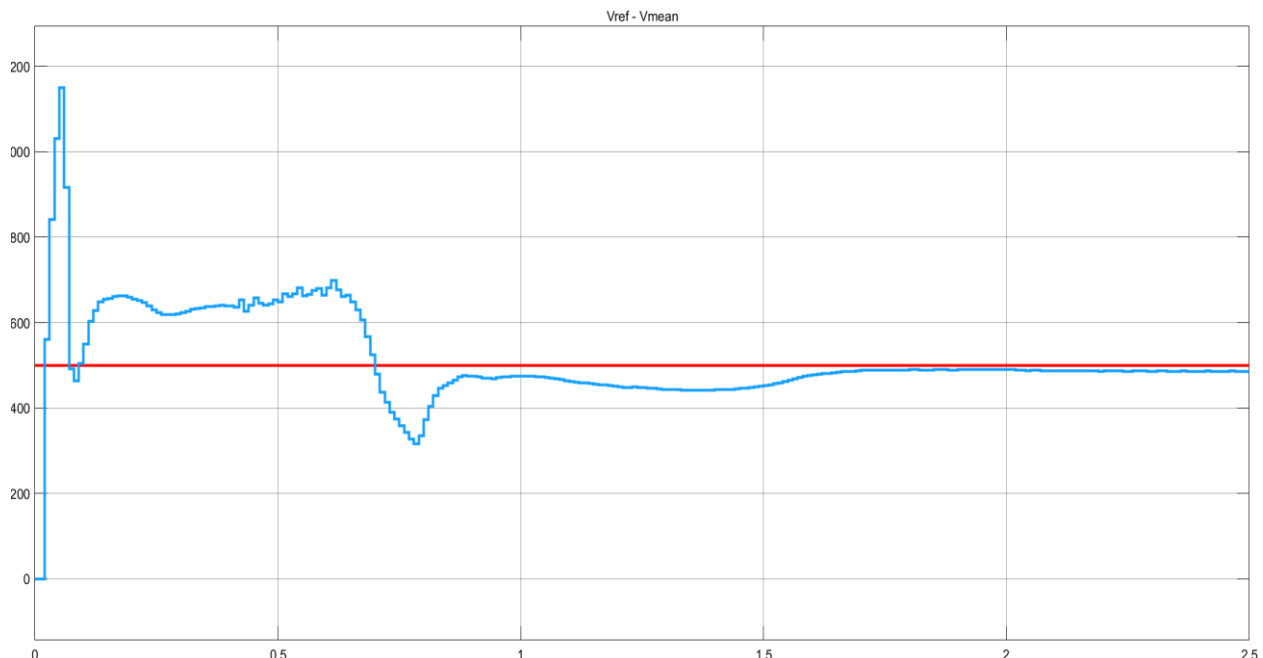


Fig 6: Proposed and reference Voltage

The figure depicts the DC-link voltage control behavior in a PV microgrid using a Unified Active Power Filter (UAPF) technology. The red line shows the reference voltage, which is set at a constant desirable level of roughly 500 V. The blue line represents the actual measured DC-link voltage over time. The system first encounters a considerable voltage overshoot, which is most likely caused by startup transients or a quick input of electricity from renewable sources. The voltage then oscillates and drops, particularly between 0.3 and 1.0 seconds, which might be caused by load disturbances or source switching (for example, PV fluctuations). Despite these swings, the controller strives to fix the problem, and after about 1.5 seconds, the real voltage stabilizes and approaches the reference value. This answer demonstrates the efficacy of the UAPF's DC-link voltage management mechanism, which is normally managed by a controller, in maintaining voltage stability. Proper control of this DC-link is crucial for the dependable functioning of the series and shunt converters in the UAPF, providing smooth adjustment of power quality concerns including harmonics, voltage sags, and reactive power imbalance.

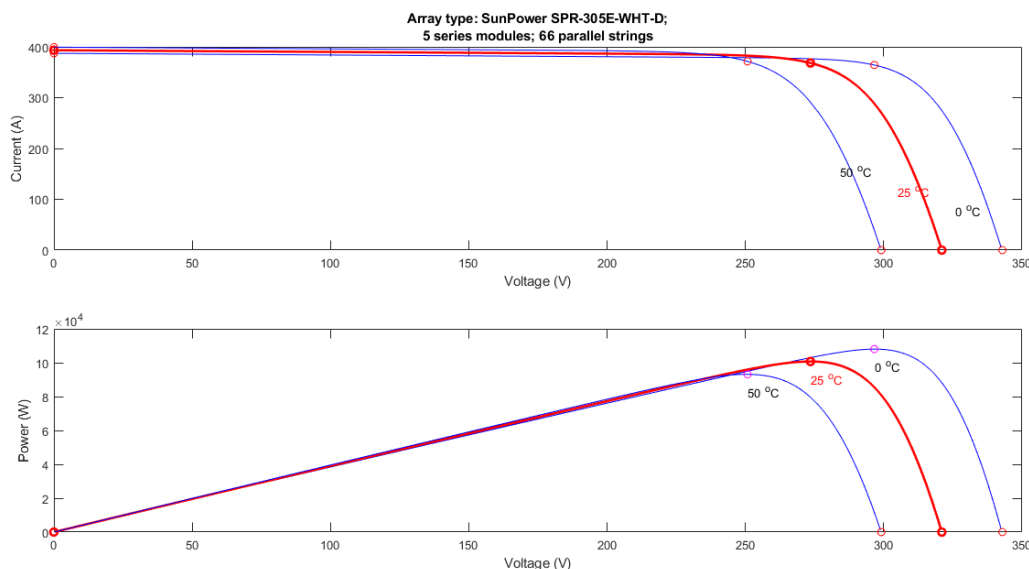


Fig 7: PV Characteristics

V. CONCLUSION

Because renewable energy sources such as solar are intermittent and variable, the produced electricity changes often, resulting in supply-demand mismatches. Effective power flow management helps to manage these oscillations by managing power distribution among the microgrid's multiple sources, loads, and storage systems. The addition of a Unified Active electricity Filter (UAPF) to a PV-based microgrid improves the system's capacity to provide clean, reliable, and high-quality electricity. The UAPF successfully tackles typical power quality challenges in renewable energy systems by integrating the characteristics of both series and shunt converters. It guarantees that the DC-link voltage is properly regulated and that the PV source remains synchronized with the utility grid or local loads. As a consequence, the microgrid's overall dependability, efficiency, and performance have significantly increased. The UAPF not only helps the photovoltaic system run smoothly, but it also assures grid compliance, making it an important part of the move to smarter, more sustainable energy systems.

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