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Enhancing Power Quality in ON-Grid Systems with PV-STATCOM for Reactive Power Compensation

Journal of Electrical Systems

Abstract: - This research investigates the integration of an Artificial Neural Network (ANN) controlled boost inverter into a solar photovoltaic (PV) system connected to the utility grid. The boost inverter, equipped with a Static Synchronous Compensator (STATCOM), ensures stable grid voltage and enhances power quality. The ANN controller fine-tunes the DC-AC conversion process of the boost inverter in real-time, ensuring efficient operation under varying PV output and grid conditions. The system's performance was evaluated through simulations, demonstrating its ability to efficiently manage PV power generation and correct reactive power in local loads, thereby enhancing system reliability and grid stability.

Keywords: Artificial Neural Network, harmonics, nonlinear load, power quality, switching devices

INTRODUCTION

In today's world, the utility sector is increasingly concerned with power quality issues. Electric power quality refers to maintaining the rated magnitude and frequency of electricity, ensuring a sinusoidal power distribution in bus voltage. It's crucial for the energy supplied to customers to be uninterrupted for reliability. However, a significant portion of power consumption comes from reactive loads like fans and pumps. These loads draw lagging power factor currents, which increase feeder losses and reduce the active power flow capability of the distribution system, ultimately affecting the voltage profile.

Moreover, with fossil fuel sources depleting rapidly, there's a growing necessity to shift towards renewable energy sources. Renewable energy systems offer numerous advantages over conventional ones. They are clean, pollution-free, eco-friendly, and do not emit greenhouse gases or pose health hazards. Among renewable energy sources, solar energy holds the greatest potential. Even a small fraction of solar energy could significantly contribute to our energy needs. Solar energy, along with other renewable sources, can be directly or indirectly converted into various forms of energy, including heat and electricity, which can then be utilized by mankind. Therefore, focusing on renewable energy sources like solar power can not only address power quality issues but also mitigate environmental concerns associated with conventional energy sources.

Power electronics devices have revolutionized the power system, enhancing its reliability and quality. With the advancement in semiconductor technologies, power electronics devices have become ubiquitous in controlling active and reactive power flow in the power system.

These devices offer unmatched flexibility and control, catering to both transmission and distribution sides of the power grid. Among various power quality concerns, managing active and reactive power transfer to and from the grid demands special attention.

To address this, power electronics-based FACTS (Flexible Alternating Current Transmission System) devices have been developed. These devices provide enhanced knowledge and control over power systems, offering rapid power swing damping and allowing power transmission lines to operate securely close to their thermal limits.

Traditionally, capacitor banks were used for reactive power control in power grids. However, with the introduction of power electronics-based FACTS devices, STATCOM (Static Synchronous Compensator) has

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gained prominence. STATCOMs offer superior reactive power control capabilities, providing more effective management of power system dynamics.

METHODOLOGY

In a solar PV system connected to the utility grid, the boost inverter serves as a crucial component, converting DC electricity from the PV array into AC power suitable for the grid. Integrated within the boost inverter is the STATCOM (Static Synchronous Compensator), which plays a vital role in stabilizing grid voltage and preventing power quality issues such as dips, spikes, and harmonic distortion. By regulating reactive power flow, the STATCOM ensures smooth grid operation, enhancing its reliability and efficiency.

Additionally, the boost inverter is controlled by an Artificial Neural Network (ANN) controller, which fine-tunes the DC-AC conversion process. Trained using a back propagation method, the ANN controller makes real-time adjustments based on changes in both the PV array's output and the grid conditions. This dynamic control system not only ensures efficient conversion but also enhances grid stability and reliability, ultimately improving the overall performance of the solar PV system connected to the utility grid.

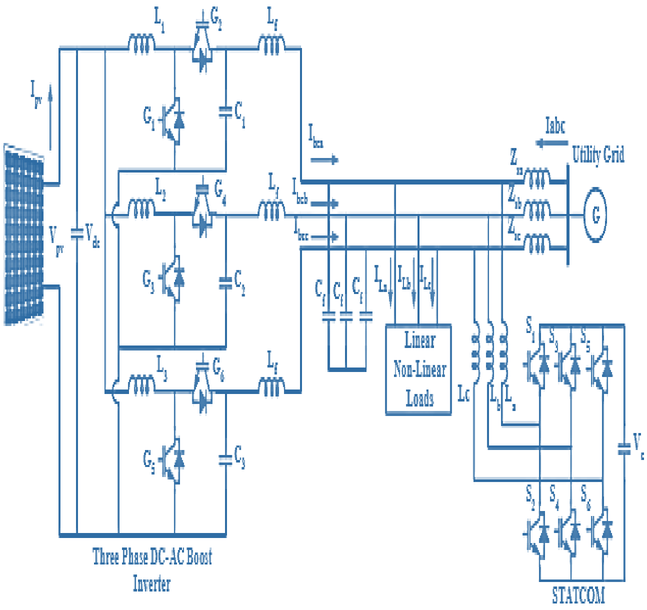

Figure 1. Proposed System

Design Considerations for PV Arrays

When constructing a solar PV system, the arrangement of the PV panels can significantly impact its performance. Solar PV panels can be connected in either series or parallel configurations. When connected in series, the terminal voltage of the array increases. This means that the voltages of individual panels are added together, resulting in a higher overall voltage for the array.

On the other hand, when connected in parallel, the current rating of the system increases. This means that the currents of individual panels are added together, resulting in a higher overall current for the array. In this specific case, each solar PV panel is rated at 225.30 watts, with a maximum power point voltage of 30 volts, an open circuit voltage of 38.2 volts, a short circuit current of 8.74 amperes, and a maximum power point current of 8.73 amperes. The configuration of the solar PV array mentioned consists of ten PV panels in a series configuration and forty-seven in a parallel configuration. This results in an overall rating of 32.923 kW for the solar PV array.

The full power point current is 323.54 A, and the maximum power point voltage is 325 V. The PV panel voltage at the open circuit is 375 V, and the PV current at the short circuit is 123.2 A.

Bidirectional DC-DC Buck Boost Converter

In a bidirectional DC-DC converter, like the one shown in Figure 2, switches S1 and S2 play a crucial role in determining whether the converter operates in buck (step-down) or boost (step-up) mode. Let's take a closer look at how switches S1 and S2 swap modes in both circumstances:

Buck (Step-Down) Operation:

- During buck operation, switch S1 is turned ON, while switch S2 is turned OFF.
- When S1 is ON, it allows current to flow from the input to the output, reducing the voltage to a lower level.
- Switching S2 OFF ensures that there is no reverse flow of current.

Boost (Step-Up) Operation:

- In boost mode, switch S2 is turned ON, while switch S1 is turned OFF.
- With S2 ON, energy from the input is stored in the inductor, and when S2 turns OFF, the inductor discharges its stored energy to the output.
- By turning S1 OFF, reverse current flow is prevented.

The bidirectional converter switches between these modes by controlling the states of S1 and S2. This switching allows the converter to either step up or step down the input voltage as required.

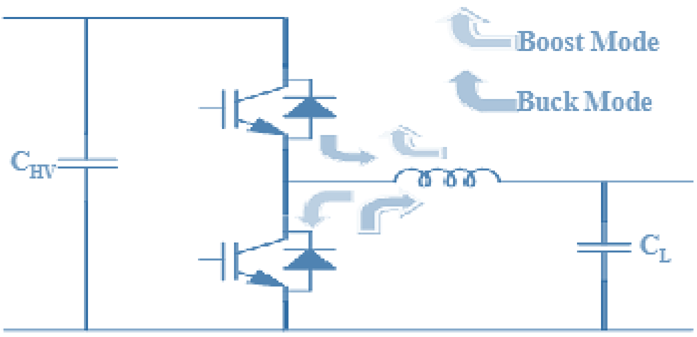

Figure 2. Buck and Boost Modes of a Hard-Switching Bidirectional DC/DC Converter

Bidirectional Three-Phase DC-AC Boost Inverter

Three-phase DC-AC boost inverter comprising three series-connected bidirectional boost converters. Each boost converter utilizes a DC-biased sinusoidal waveform with an adjustable duty cycle to generate a unipolar voltage exceeding the input DC voltage. One of the key advantages of this configuration is its ability to generate a three-phase AC output voltage using just six switches and a few additional passive elements, which is notably higher than the input DC voltage.

In Figure 3, the results are depicted after subtracting the DC offset (Vdc) from the outputs of two boost converters. At this stage, only the AC components remain, simplifying the output to solely AC.

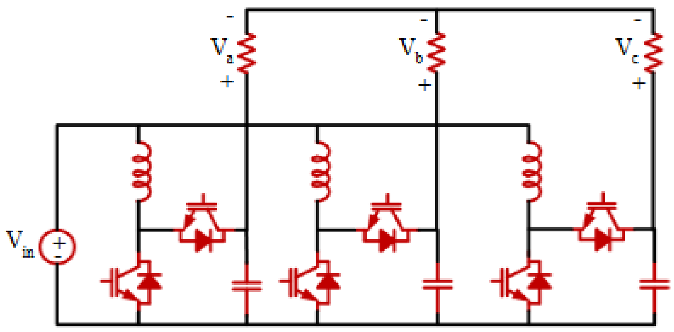

Figure 3. Three-Phase Boost Inverter Design

OPTIMIZED CONTROL STRATEGY FOR DC-AC BOOST INVERTER USING ARTIFICIAL NEURAL NETWORKS

The DC-AC boost inverter is controlled by an Artificial Neural Network (ANN) trained to maintain a balanced voltage across the DC link capacitor. The ANN receives input in the form of the difference between the reference voltage (375V) and the actual voltage (Vdc), along with the associated error. Based on this input, the ANN predicts the output, which is the loss component of the current, serving as the target data.

To achieve this, a 100-layer deep network is employed, which is trained using Leven berg-Marquardt back propagation. The MATLAB/Simulink model of the ANN is designed to regulate the capacitor voltage, ensuring that it stays within desired limits.

In Figure 4, we can observe the MATLAB/Simulink model of the ANN, which generates the reference DC voltage. The system compares this reference voltage with the actual source voltage, ensuring that the shunt converter receives the appropriate switching pulses for regulation.

Additionally, Figure 5 illustrates the comparison between the reference voltage generated by the ANN control system and the actual source voltage. This comparison results in the shunt converter receiving the necessary switching pulses.

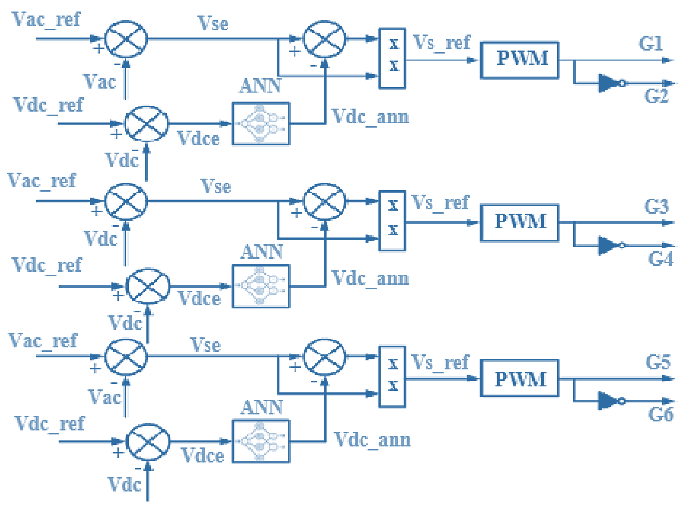

Figure 4. DC-AC boost inverter system control design

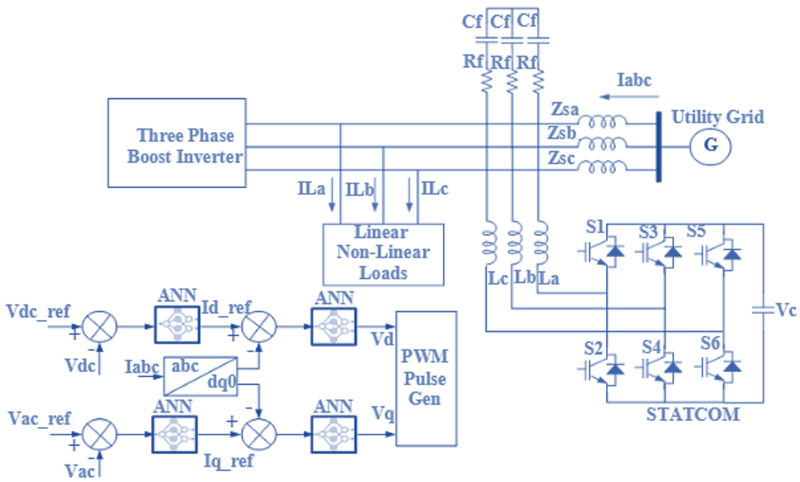

Figure 5. D-STATCOM topology for carrier-based control

Exploring Artificial Neural Networks

Artificial Neural Networks (ANN) are computer systems designed to replicate the functionality of biological neural networks. Comprising input, hidden, and output layers, ANNs process data in a manner similar to the human brain. Operational data is received from the input layer, processed in the hidden layer using weighted connections, and the results are stored in the output layer.

One popular ANN approach is the feed-forward error back propagation network, which adjusts the weights of connections to correct output errors. A specific technique, Leven berg-Marquardt Back propagation (LMBP), enhances training convergence by adjusting weights based on derivatives. This research utilizes ANN, particularly LMBP, to generate voltage and current standards, promising improved accuracy and efficiency in electronic systems.

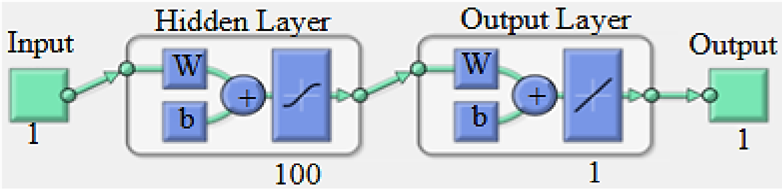

Figure 6. Integrating Artificial Neural Networks into DC-AC Boost Inverter and Shunt Converter Designs

RESULT AND DISCUSSION

A simulation was conducted to assess the effectiveness of a proposed control strategy for managing the energy generated by a photovoltaic (PV) array and correcting reactive power in local loads. The simulation, which takes 0.8 seconds to complete, was performed under varying solar irradiance conditions, with the sun's irradiance dropping from 1000W/m^2 to 500W/m^2 in 0.5 seconds. The control system operates with a sample time of 100 µs across the board, including in the phase-locked loop (PLL) synchronization unit, voltage controllers, and current controllers. The boost and voltage-source converter (VSC) converter pulse generators employ a 1 µs sample period to ensure clean pulse width modulation (PWM) waveforms. The switching frequency of the insulated-gate bipolar transistor (IGBT) has been set at 10 kilohertz.

At maximum solar irradiance, the PV array can generate up to 10,137 kW of power. However, when the solar irradiance drops by half in one second, the active power output from the PV array decreases to 8.32 kW. Figures 13 and 14 illustrate that after stabilizing the system, the PV modules' active power production follows a smooth curve, indicating the correct operation of the PV array model and DC-AC boost inverter. During the period when solar irradiation is at its strongest (0.2s to 0.5s), the VSC produces its maximum active power, meeting the local area's dynamic electricity demand (8.74 kW). Any excess active power is returned to the grid during this time. Additionally, the control approach efficiently adjusts local load reactive power, as evidenced by the VSC producing nearly enough reactive power to meet local load requirements (2.167 KVAR).

However, when solar irradiance decreases, the VSC's output drops to 50% of its maximum active and reactive power between 0.5s and 0.8s, falling below local load needs. Although there is a slight shift in the production of reactive power, it is clear that the system takes more than 0.2s to achieve a steady state. Between 0.2s and 0.5s, the DC link voltage remains constant. However, the DC connection voltage fluctuates significantly as solar irradiance decreases at 0.5 seconds.

To stabilize this voltage deviation, an Artificial Neural Network (ANN) control mechanism takes about 0.2 seconds. While effective, further improvements in control performance are desirable. When solar irradiance is high, the Point of Common Coupling (PCC) maintains the voltage at the required level. However, as solar irradiance drops, the PCC voltage hardly increases, suggesting a relatively quick transition between stable states. Voltage curves in a three-phase system are smoother than current curves. When solar irradiance is high, it may be possible to maintain constant current, but as solar radiation decreases, less power is available. Therefore, the control algorithm should be improved to better adjust to changes in sunlight, which is the only variable to be adjusted.

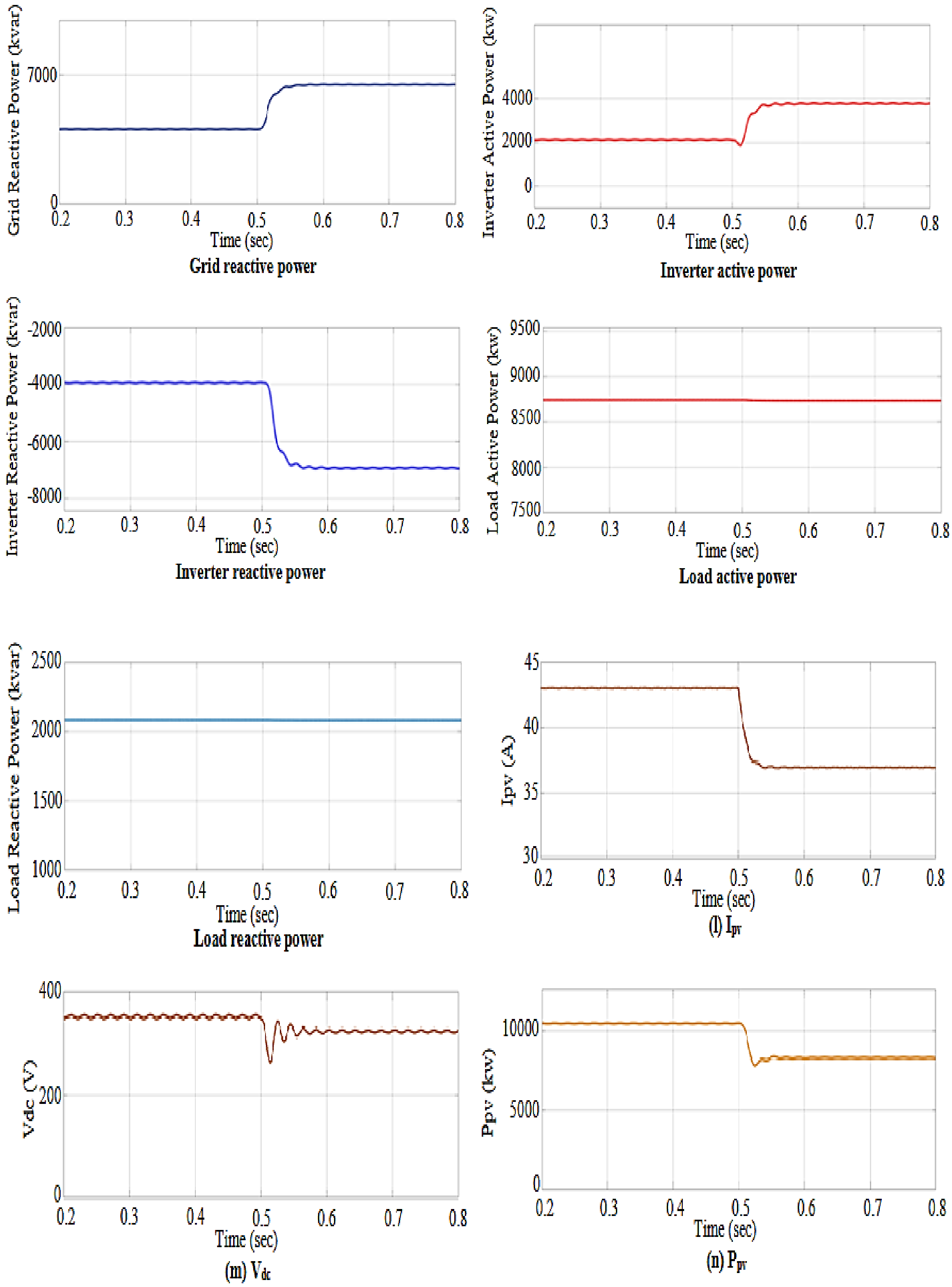

Figure 7. Performance Analysis of PV-Connected DC-AC Boost Inverter Excluding STATCOM Functionality

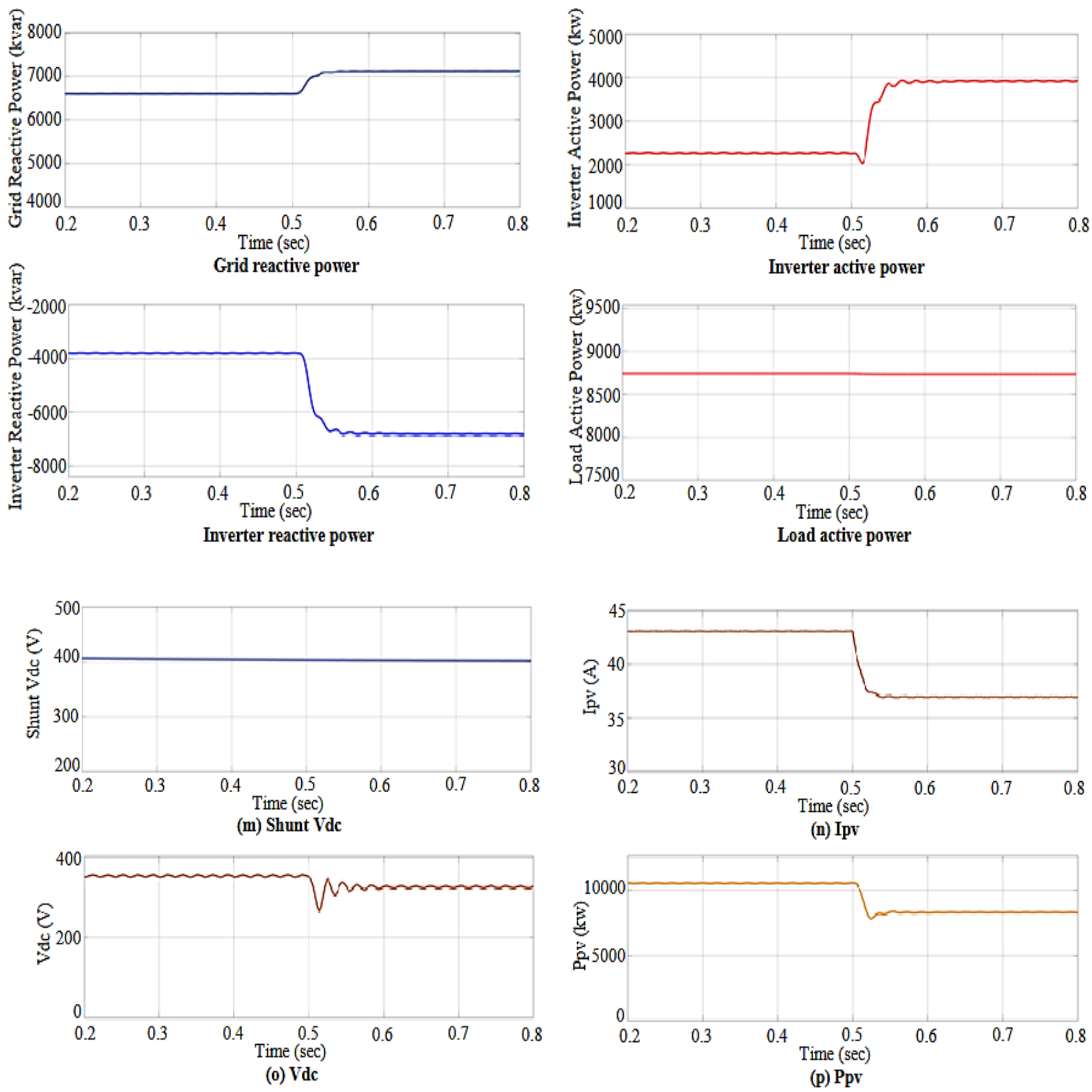

Figure 8. STATCOM Integration in PV-Connected DC-AC Boost Inverter

Conclusion

The proposed control strategy, employing an Artificial Neural Network (ANN) controlled boost inverter integrated with a photovoltaic (PV) system, demonstrates efficient management of PV power generation and correction of reactive power in local loads. Simulation results indicate the system's ability to stabilize grid voltage, enhance power quality, and ensure efficient operation under varying solar irradiance conditions. The ANN controller effectively regulates the DC-AC conversion process of the boost inverter in real-time, contributing to improved system reliability and grid stability. However, further improvements in control performance are desirable to better adapt to rapid changes in solar irradiance and ensure smoother transitions between stable states. Overall, the integrated system shows promise in enhancing the performance of solar PV systems connected to the utility grid.

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