Enhancing Power Quality: Integration of Series Active Power Filter And PV System for Optimal Performance

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Abstract **-** This study delves into the integration of a Series Active Filter (SAF) and Photovoltaic (PV) system to elevate power quality (PQ). Employing MATLAB/Simulink simulations, the research attains heightened voltage compensation and regulation capabilities. The investigation thoroughly evaluates the system's reactions to voltage fluctuations, including sags, swells, and dips. Notably, the study demonstrates the SAF's remarkable efficacy in enhancing PQ. This comprehensive exploration significantly contributes to addressing industrial voltage apprehensions, offering innovative solutions for optimized PQ.

Keywords **-** Photovoltaic System, Power Quality Enhancement, Series Active Filter (SAF), Voltage Compensation, Voltage Fluctuations.

I. INTRODUCTION

One of the main problems with the contemporary electrical distribution system is power quality (PQ). Voltage unbalance, voltage swell and sag, and partial or complete loss of one or more phases can all be used to examine the PQ [1,2]. The main factor contributing to the voltage imbalance is the uneven distribution of single-phase loads, which may alter continually throughout a three-phase system [3]. Harmonics, nonlinear loads, grid switching, variations in load demand, and electrical faults are factors that can induce voltage sags, swells, and dips in the power system [4,5].

Unwanted consequences including flicker voltage distortion, poor power factor, electromagnetic interference, etc., might result from this sag/swell and nonlinearities. These disruptions might have negative effects for domestic consumers and industry, ranging from system failure to complete plant shutdown. Unwanted consequences including flicker voltage distortion, poor power factor, electromagnetic interference, etc., might result from this sag/swell and nonlinearities. These disruptions might have negative effects for domestic consumers and industry, ranging from system failure to complete plant shutdown [6].

The functionality of the system can deteriorate to the extent of causing complete shutdowns of industrial plants. Currently, research is making significant progress in addressing various aspects of active power filters, including their design, computation, operation, and initiation. Among these, the series active power conditioner, which has evolved through advancements in power electronics technology, stands out as a versatile solution for mitigating and rectifying PQ issues such as voltage fluctuations and harmonics [7].

Power electronics and power system engineers have focused on the growing significance of harmonic pollution inside power networks, driving them to develop flexible and adaptable solutions for resolving PQ challenges.

Voltage sags, swells, and dips can effectively be mitigated through the utilization of a three-phase Series Active Filter (SAF), which regulates voltage levels to attain the desired parameters [7,8]. This study showcases the design and simulation of such a three-phase SAF, specifically tailored for unbalanced voltage compensation, employing a PV system as an integral component.

II. CONFIGURATION SYSTEM

The fundamental principle of a SAF revolves around generating a voltage waveform with precise frequency and magnitude [10]. This waveform is strategically applied to counteract and eliminate imbalances or distortions present in the supply voltage. Making ensuring the voltage at the load terminals precisely matches the intended waveform is the ultimate objective [11].

Fig. 1 depicts the conceptual design of a three-phase, three-wire SAF integrated into a power system that supplies an R-L load. The SAPF configuration consists of a three-leg Voltage Source Inverter (VSI) operated under voltage control, serving as the SAF component. Positioned between the supply and load terminals, the series filter is established through the utilization of three single-phase transformers. These transformers are arranged in a star configuration, connected across the inverter, and linked in series with the supply lines.

These transformers serve a dual purpose: first, they enable the injection of corrective voltage by the series filter; second, they effectively function as filters, attenuating the switching-related ripple originating from the SAF. This combined functionality enhances the overall performance of the SAPF system, contributing to the mitigation of PQ issues and ensuring the desired voltage and current waveforms at the load terminals [12].

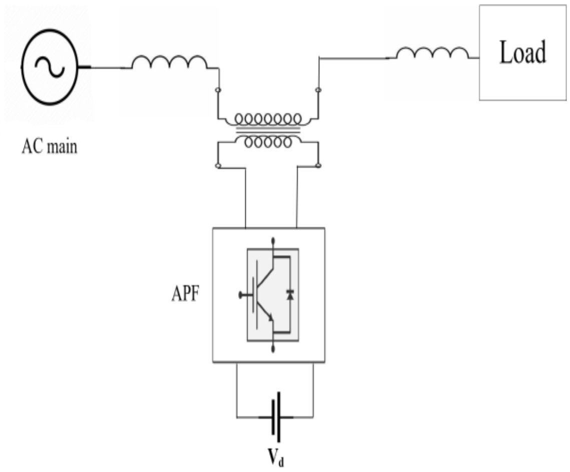

Fig. 1. Block diagram of the series APF

The SAF offers the capability to rectify issues associated with the supply voltage [13]. By introducing a voltage in series with the line, it achieves a voltage at the load terminal that is devoid of distortions [14]. The series inverter within the SAPF can be mathematically represented by the following equation:

$$V_{inj} = V_L - V_S \tag{1}$$

Where;
V_{inj} = Injection Voltage
V_L = Load Voltage
V_S = Supply Voltage

III. FILTER SIMULATION MODEL OF SERIES ACTIVE

The SAF assumes the form of a voltage-controlled VSI [15]. This VSI configuration is seamlessly interconnected in series with a dedicated series injection transformer. SAF serve as indispensable tools for mitigating issues stemming from voltage irregularities and distortions.

An algorithm is created to control the series filters efficiently. This method guides the series filter to inject voltages that are carefully calculated to counteract and eliminate the distortions and imbalances present in the supply voltages [11]. This synchronization harmoniously produces voltages at the point where the power is shared , making them balanced and smooth, just like sinusoidal waves, and with the intended strength [16].

Since the supply voltage often comes with imbalances or distortions, we introduce something called a phase-locked loop (PLL) to make sure it perfectly matches the supply's rhythm. This PLL uses three-phase distorted or unbalanced supply voltages to create two sets of orthogonal unit vectors.

To regulate the operation of series filters, a controlled approach is employed. This involves directing the series filter to introduce voltages that effectively counteract any distortions or imbalances existing in the supply voltage [17]. This corrective action results in the achievement of precisely balanced and sinusoidal voltages at the Point of Common Coupling (PCC), meeting the desired amplitude criteria. In simpler terms, The desired voltage at the load terminals is produced by the combined action of the supply voltage and the injected series filter voltage.

Given the inherent unbalance and distortion in the supply voltage, the synchronization with the supply is accomplished using a PLL. This PLL system takes in distorted or unbalanced three-phase supply voltages as inputs and generates two orthogonal unit vectors (sin θ, cos θ). To enhance the effectiveness of this process, the sensed supply voltage is multiplied by an appropriate gain before being fed into the PLL. The in-phase sine and cosine outputs produced by the PLL are then employed to calculate the three unit vectors of the supply voltage, each phase-displaced by 120°using eq. (2).

$$\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} * \begin{bmatrix} \sin\theta \\ \cos\theta \end{bmatrix} \tag{2}$$

The three-phase reference PCC voltages are obtained from eq. (3) by multiplying the calculated three in-phase unit vectors by the intended peak value of the PCC phase voltage (Vref).

$$\begin{bmatrix} V\text{desired\_}a \\ V\text{desired\_}b \\ V\text{desired\_}c \end{bmatrix} = [\text{Vref}] * \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} \tag{3}$$

Together with the measured three-phase PCC voltages, the voltages determined by equation (3) are then supplied into the hysteresis controller. The hysteresis controller's output manifests as switching signals, which in turn command the operation of the six switches within the VSI of the SAF [18]. The hysteresis controller's coordinated action guarantees that the voltage at the PCC matches the intended sinusoidal reference voltage. Consequently, the ripple filter-assisted voltage injection across the series transformer successfully offsets the supply voltage's harmonics and imbalances. In essence, this corrective action serves to nullify the undesirable effects in the supply voltage, contributing to improved PQ.

IV. INTEGRATION OF PV WITH SAF

A) Modeling of Photovoltaic Systems

Two primary electrical components may be used to model a solar panel: a diode and an ideal current source connected in parallel. This modeling is predicated on how the solar cell's PN junction functions [19, 20].

A PV cell's equivalent circuit is made up of a diode and an ideal current connected in parallel. The cell is subjected to actual radiation G and temperature T conditions.

Thus, the output voltage, V pv, current generated by a solar cell, I pv, can be expressed as follows:

$$I_{PV} = I_{Ph} - I_{d0}\left[esp\left(\frac{q}{nKT}V_{do}\right) - 1\right] - \left(V_{do}\frac{V_{PV}+R_S I_{PV}}{R_{Sh}}\right) \quad (4)$$

$$V_{PV} = V_{do} - R_S I_{PV} \tag{5}$$

B) Maximum Power Point and MPPT Technique

PV cells' sensitivity to changes in irradiance has a major impact on their energy production [21]. As a result of the fluctuating solar irradiance and temperature conditions, monitoring the PV cells' full power availability at all times becomes crucial. This is achieved by using the Maximum Power Point Tracking (MPPT) approach to appropriately operate a boost converter [22]. The basic idea behind this tracking technique is to use incremental conductance (INC) algorithms to maximize the power that the PV panels can produce.

C) Incremental Conductance Algorithm

One technique utilized in MPPT systems for photovoltaic (PV) power generation is the INC algorithm [23]. It seeks to dynamically modify the PV system's operating point in order to optimize power output under a range of temperature and irradiance circumstances [24].

The steps of the INC algorithm are summarized as follows:

- Assess the PV system's voltage (V) and current (I).
- Utilizing the voltage and current readings, compute the INC (dP/dV).

- Examine the INC in comparison to the reference conductivity.

Modify the voltage a little bit:

- Lower the voltage if the INC exceeds the reference.
- Raise the voltage if the INC is less than the reference.

This iterative process continues until the system reaches the MPPT, where the INC matches the reference conductance.

This illustration showcases the practical implementation of the INC algorithm within a PV system, connected to a boost converter, as depicted in Fig. 2. As explained in Section B, the algorithm dynamically modifies the system's operating point to maximize power production across a range of temperature and irradiance circumstances. The figure visually demonstrates the role of the MPPT technique in harnessing maximum energy from the PV panels.

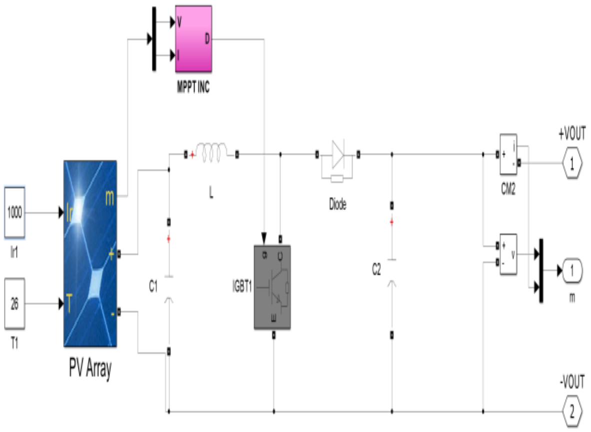

Fig. 2. Integration of PV with Boost Converter using the Incremental Conductance (INC).

V. RESULTS AND DISCUSSION

The three phase source of supplying 230 V, 50Hz to a non-linear load of thyristor converter fed RL (R = 150 Ω, L = 20 mH) is considerfor simulation analysis Fig. 3.

The simulation has been performed under unbalanced source supplying to non-linear load Fig. 4.

The illustrations featured in Fig. 4 and Fig. 7 visually depict the responses of source, filter-injected, and load voltages during a source voltage sag. These figures also showcase the voltage behavior of the source, filter injection, and load during a source voltage drop and surge.

The figures, namely Fig. 5 and Fig. 6, illustrate the behavior of source voltage during a voltage SAG, accompanied by harmonic THD analysis. Additionally, Fig. 8 provides insight into the source voltage response, along with harmonic THD analysis, during a voltage drop and surge. Furthermore, Fig. 9 portrays the response of load voltage with harmonic THD analysis in the context of voltage drop and surge scenarios. These figures collectively contribute to a comprehensive understanding of the system's voltage dynamics and harmonics under various conditions.

The discussion of results for a SAF during a voltage sag is noteworthy. When we introduced a voltage sag of 0.2 seconds in the source voltage, the SAF responded by injecting a compensating voltage. This action effectively stabilized the load voltage despite the initial voltage sag. This outcome underscores the efficacy of the SAF in mitigating voltage disturbances and highlights its crucial role in enhancing power supply quality.

The same scenario applies when applying a voltage drop and voltage surge to the source voltage. The SAF compensates for these voltage fluctuations, thereby stabilizing the load voltage. This outcome underscores the effectiveness of the SAF in mitigating both voltage drops and voltage surges, reaffirming its vital role in enhancing power supply quality.

The Total Harmonic Distortion (THD) has been notably improved, remaining at 1.07% during the voltage sag and 1.37 %during the voltage drop and surge in the load voltage. These values are well below the international norm of 5%. In the source voltage, the THD levels are 9.88% and 8% for the voltage drop and surge, respectively.

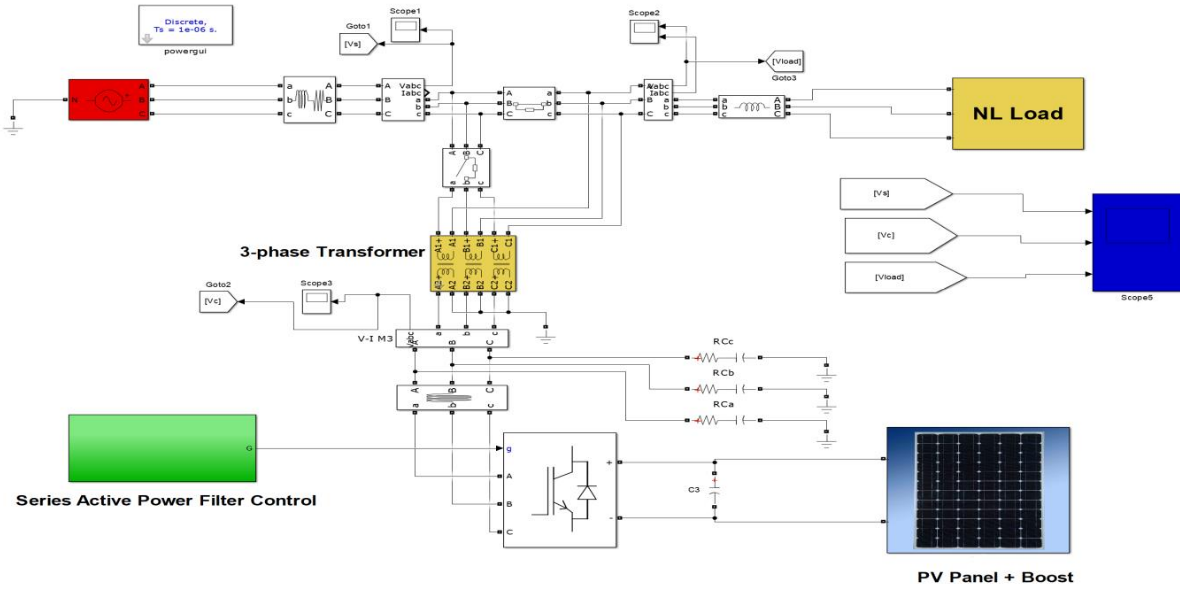

Fig. 3. Integration of Three-Phase SAPF with PV into MATLAB Model of Three-Phase AC System.

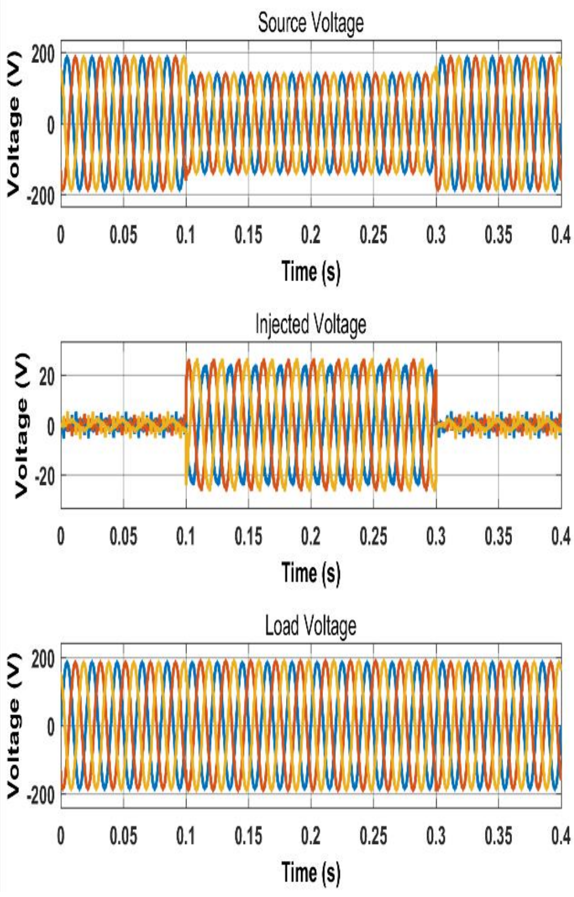

Fig. 4. Response of Source, Filter-Injected, and Load Voltages during Source Voltage Sag

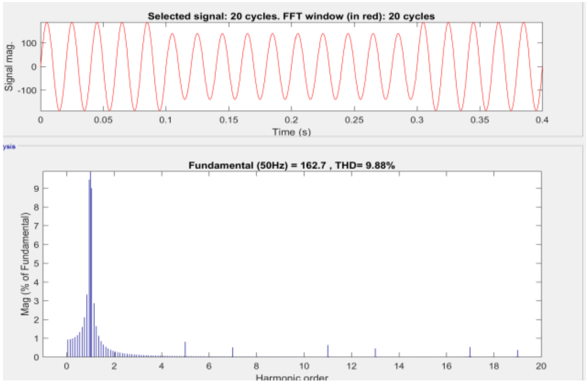

Fig. 5. Source Voltage Behavior and Harmonic THD Analysis during Voltage Sag

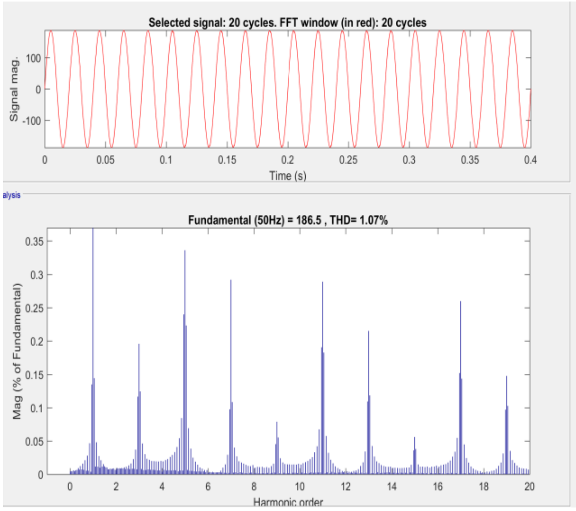

Fig. 6. Load Voltage Response and Source Voltage Harmonic THD during Voltage Sag

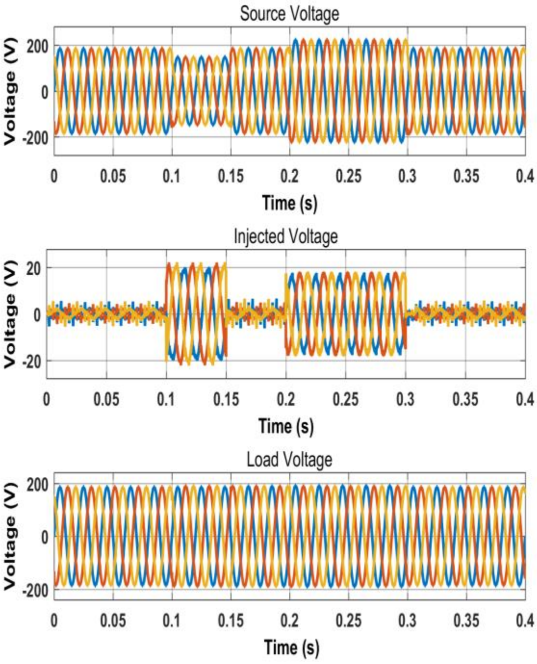

Fig. 7. Voltage Behavior of Source, Filter Injection, and Load during Source Voltage Drop and Surge

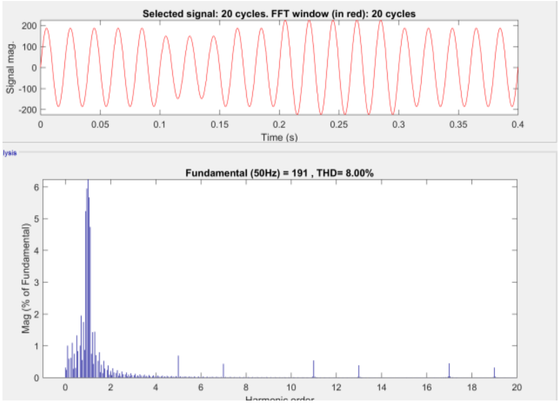

Fig. 8. Source Voltage Response with Harmonic THD Analysis during Voltage Drop and Surge

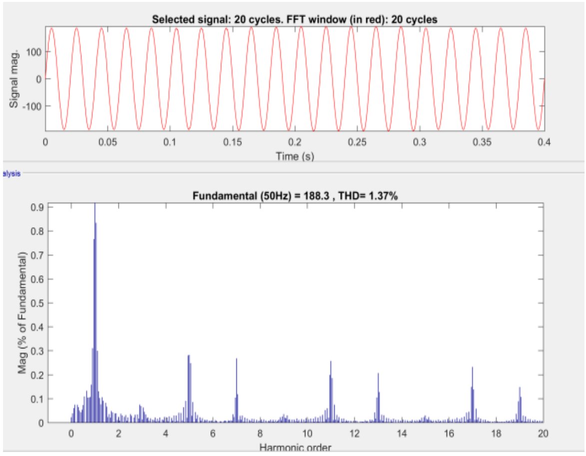

Fig. 9. Load Voltage Response with Harmonic THD Analysis during Voltage Drop and Surge.

VI. CONCLUSION

The present research shows the integration of a SAF and PV system proves highly effective in mitigating voltage disturbances, stabilizing load voltage, and reducing THD in electrical distribution systems.

The SAPF's compensation mechanism plays a key role in achieving balanced and sinusoidal voltage profiles, addressing transient and sustained PQ challenges, and enhancing energy supply reliability. This study offers a practical solution applicable to various contexts, advancing power system optimization and dependability.

VII. ACKNOWLEDGMENT

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