Advances in Nonlinear Variational Inequalities
ISSN: 1092-910X
Vol 28 No. 3s (2025)

Active Filter Based Harmonics Mitigation in Grid-Connected PV Systems

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Article History:

Received: *07-10-2024*

Revised: *29-11-2024*

Accepted: *08-12-2024*

Abstract :
One essential component of human advancement is energy. Fossil fuels have been the primary energy source for many centuries, but as businesses and society grow, so does the demand for energy resources. However, fossil fuels produce emissions of greenhouse gases that cause climate change in addition to being depletable. Therefore, humanity must hasten the shift to a low-carbon economy due to the predictable rise in energy consumption and the depletion of fossil fuels, which necessitates the search for clean and renewable alternative energies. These consist of solar, geothermal, biomass, wind, and hydropower. Our planet's cleanest and most plentiful energy source is solar energy, which is also limitless.

Solar energy, with its immense potential, is now a major subject of intense research and swift advancement, particularly in recent years. Rooftop photovoltaic (PV) systems are arising as a popular replacement for electricity generation. Installing and connecting PV systems to the electrical grid is now simpler thanks to advancements in power electronic devices. Nonetheless, ensuring power quality is essential when integrating PV systems with the power grid. Among power quality issues, harmonics pose a substantial difficulty because of the reliance on various power electronic components in PV systems.

This paper focuses on designing and evaluating the performance of a rooftop solar system connected to power grid in a solar-rich location, using simulation tools to address harmonic mitigation. By successfully reducing harmonics in the grid-connected PV system, it seeks to improve power quality.

Keywords: Harmonics, Solar PV System, Active Filter, Grid, Power Quality.

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1. Introduction

Among the various renewable energy sources, solar power stands out as one of the most prominent. With abundant solar potential available throughout the year, a substantial number of solar power stations have been constructed throughout the nation. Solar power offers a remarkable ability to generate clean, non-polluting, and cost-free electrical energy. Its efficiency and sustainability have inspired nations worldwide to set ambitious targets for expanding solar energy installations.

In order to complement or replace traditional energy sources, many nations have included sizable solar power capacity into their main electrical grids. One of two primary methods is used by solar power plants to function:

1. Photovoltaic (PV) Systems : These systems utilize solar panels, which can be installed on rooftops or mounted on the ground, to directly convert sunlight into electricity.

2. Concentrated Solar Power (CSP): These systems, often referred to as concentrated solar thermal plants, which uses the thermal energy of the sun to generate steam, which runs the turbines and then use to turn that steam into electricity.

Photovoltaic (PV) systems have witnessed significant growth in recent years. These installations are increasingly being integrated with the electrical grid, aiming to become a vital component of the overall electricity generation mix.

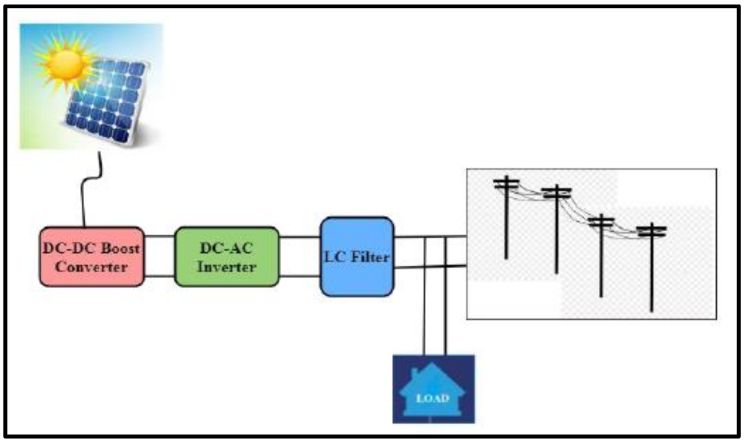

Fig. 1 : Basic grid-connected photovoltaic scheme design

2. Problem statement :

The integration of a photovoltaic (PV) system with the electrical grid, becomes a valuable asset to modern society. However, the integration of large-scale PV systems introduces several power quality challenges. On one hand, substantial power generation through grid-connected PV systems maximizes the employment of solar energy resources. However, it drives new requirements for innovation in system design, operation protocols, safety measures, and other technical parameters.

Primarily, integrating a PV system to the power grid alters the topological structure and flow pathways within the grid. Simultaneously, it exposes the power quality delivered to consumers to the effects of PV system performance. Poor power quality can lead to financial losses and inconvenience for consumers. Additionally, substandard power quality can cause grid equipment to overheat and operate outside their intended conditions, potentially resulting in significant damage.

The integration of PV systems with active power networks raises notable power quality concerns, including harmonics, voltage sags and swells, voltage interruptions, under-voltage, over-voltage, reactive power imbalances, and frequency variations. Addressing these issues is crucial for ensuring reliable and efficient grid operation.

One of the biggest obstacles to the operation of grid-connected photovoltaic systems is harmonics. To address this issue, various techniques are employed to mitigate their effects. The term THD (Total Harmonic Distortion) is frequently used to quantify the distortion of an alternating current or voltage waveform, which is referred to as harmonics. The Total Harmonic Distortion (THD) is defined as the ratio of the magnitude of the fundamental component to the square root of the sum of the squares of the magnitudes of all harmonic components. The fundamental component, which is usually the largest component and, in the case of electricity systems, the system's frequency (e.g., 50Hz or 60Hz), is the major frequency of importance.

3. Objectives :

The primary goal is to assess and mitigate harmonics in accordance with IEEE standards and the specific limits of the site under consideration. To reduce harmonic distortion, a Selective Active Filter (SAF) is employed. An Active Filter (AF) enhances power quality by injecting a current or voltage that is identical in magnitude but opposite in phase to the distortion present in the network, effectively cancelling out the harmful effects of the original distortion.

At the core of the active filter is the controller, which plays a vital part in optimizing the filter's performance and stability. The Synchronous Reference Frame (SRF) theory, a time-domain approach, is employed for harmonic extraction. Additionally, the DC link voltage is controlled using a fuzzy controller, ensuring proper operation. To generate the necessary control signals, a Hysteresis Current Controller is applied, producing the pulses that drive the filter’s corrective actions.

This paper focuses on the following objectives:

- Analyzing the grid-integrated PV plant of the selected site.
- Modeling the site in MATLAB for simulation and analysis.
- Investigating the occurrence of harmonics resulting from PV system integration with the grid.
- Mitigating the harmonics using a Selective Active Filter (SAF).

4. Proposed Methodology

This paper's primary goal is to improve the quality of a grid connected PV system by reducing the impact of harmonics. The primary aim is to assess and reduce the harmonics at the considered site in compliance with IEEE standards and limits. To minimize harmonic content, an Active Power Filter (APF) is employed. An APF improves power quality by injecting current or voltage distortions that are equal in magnitude but opposite in phase to the existing distortions, effectively cancelling their impact. To specifically address current harmonics, a Shunt Active Filter (SAF) type APF is used.

The Shunt Active Filter (SAF) utilizes power electronic (PE) devices to generate harmonic components that are opposite in phase, making up for the harmonics that are produced by the nonlinear loads. The harmonic filter consists of two main components: the power converter and the control unit. The control unit regulates the injection of compensating harmonics into the electrical network based on the calculated harmonic content.

The filter continuously monitors the harmonics in the system and generates opposing harmonic currents to cancel out the unwanted harmonics at the source. This creates a feedback loop, ensuring that the source supplies a pure waveform to the loads, thus improving the overall power quality.

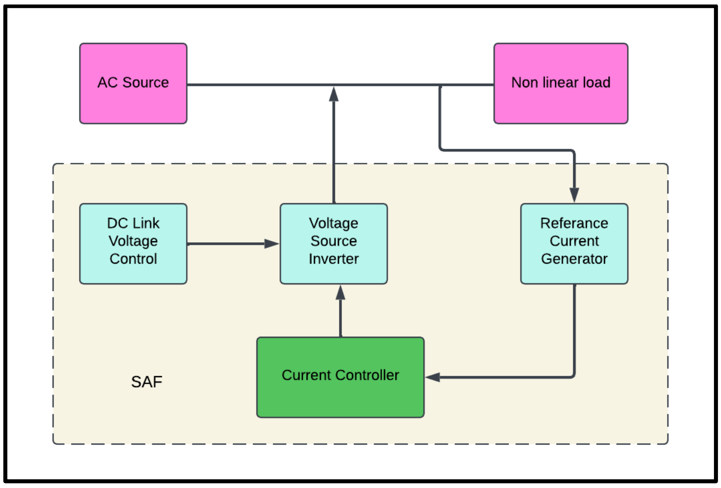

Fig. 2 SAF Controller Block

Figure 3 illustrates the simplified design of a Shunt Active Filter (SAF). In this setup, the DC side of the Voltage Source Inverter (VSI) is connected to an energy storage capacitor, while the AC side of the VSI is linked to the AC buses via an inductor. These buses provide power to commercial, industrial, and household loads, including nonlinear loads that can introduce harmonics.

The SAF operates in a closed-loop mode, where the inverter switching is controlled to actively shape the current waveform. The coupling or interface inductor is essential to making sure that the inverter follows the reference currents, which helps synchronize the source current to be in-phase with the input sinusoidal supply. As a result, the SAF injects the required harmonic components, ensuring that the current supplied by the source remains in-phase with the fundamental current component, thereby improving the overall power quality.

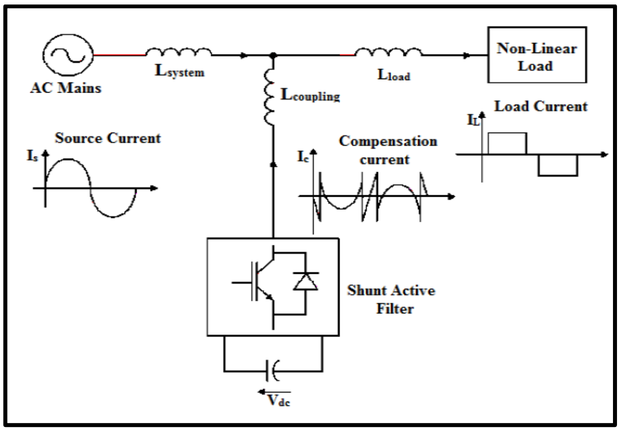

Fig. 3 Basic illustration of SAF

150KW ROOFTOP PV SYSTEM WITH GRID CONNECTION

Self-production of electrical energy can be made possible by installing a photovoltaic solar system on the roof top of a structure. Simultaneously, the PV system can reinforce the electrical grid by supplying additional energy, particularly during sunny and warm periods. During such times, solar power generation is at its peak due to higher solar irradiance, while the demand on the electricity grid also increases because of the widespread use of air-conditioning systems. This dual benefit helps reduce the environmental and ecological impacts associated with traditional energy production. For a PV system to be viable, however, there must be a consistent and reliable supply of sunlight throughout the year. India, with its abundant solar energy resources, offers significant potential for photovoltaic generation on a large scale.

Rooftop photovoltaic (PV) systems are becoming more popular as an alternative method of electricity generation. The available roof area can be effectively utilized to reduce electricity bills, making it a viable solution for both commercial and residential buildings. Governments are also offering incentives such as subsidies and other support measures to encourage the installation of rooftop PV systems. The use of power electronic devices has significantly simplified the installation process. Yet, harmonics pose a significant issue that must be managed during both the installation and operation of grid connected PV systems, owing to their dependence on power electronics.

This study focuses on a commercial building situated in Mumbai, Maharashtra, India. Electrical power in Mumbai is supplied by providers such as Maharashtra state Electricity Board, Tata Electric Power and Adani Electricity. The PV system under analysis is installed on the rooftop of this commercial building.

PV modules, grid-connection devices, and a power conditioning unit with solar inverters are the components of a typical grid connected Photovoltaic system. This configuration ensures the optimal use of power produced by solar energy, as it eliminates storage-related losses. Under ideal circumstances, a grid-connected solar system distributes excess power back to the service grid after meeting the consumption requirements of the associated load. This extra power can be efficiently used by the grid, unlike in standalone systems where surplus energy is either stored in batteries or goes to waste. This feature of the grid-connected system optimizes the utilization of the energy produced, making it a more efficient and sustainable solution.

The PSIT inverter receives the solar unit's output and converts the DC electricity produced into AC. After synchronization, the AC power is then fed into the state grid. To ensure safety and protect the grid, the system is equipped with a protection mechanism. In the event of poor grid conditions—such as grid failure or when the voltage drops too low or rises too high— to safeguard against harm to the system or the state grid, the photovoltaic system will be instantly cut off from it.

A 150kW segment of the PV system has been modelled and simulated using MATLAB Simulink. The PV module utilized in the Simulink model is described in completely in Table 1.

The power-voltage (P-V) and current-voltage (I -V) curves are shown in Figure 4 and Figure 5, respectively, for a module of the designed PV system. These graphs illustrate the PV system's performance by showing the relationship between voltage, current, and power under various operating situations.

Table 1: Specifications of PV-Module

Electrical Characteristics	
Module Type	Sun Power-SPR-305WHT
Open Circuit Voltage (Voc)	65.5 Volts
Maximum Operating Voltage (Vmp)	55.8 Volts
Short Circuit Current (Isc)	5.69 Amp
Maximum Operating Current (Imp)	5.48 Amp
No of cells/module	96
Maximum Power in STC (Pmax)	302 Wp
Nser	5
Npar	32

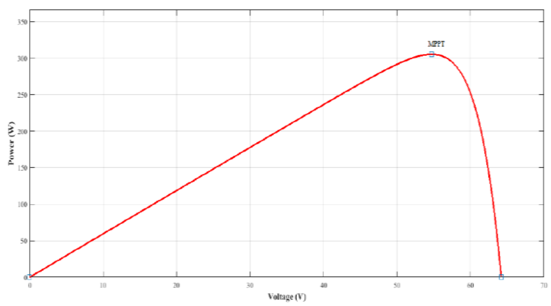

Fig. 4 I-V curve of SPR-305 Module

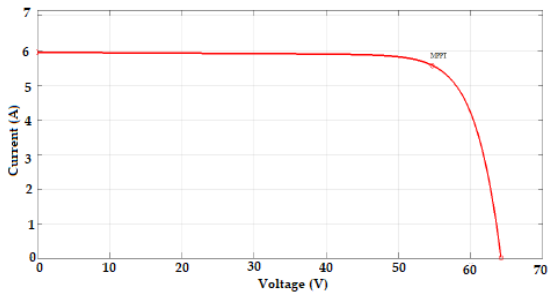

Fig. 5 : P-V curve of SPR-305 Module

The PV system produces output in direct current (DC) form. Figures 6 and 7 illustrate the current and voltage waveforms of the DC output, respectively. These DC outputs are then converted to AC through the inverter, and the resulting AC waveforms are depicted in Figures 8 and 9, showing the transformed current and voltage waveforms after the inversion process. This conversion process enables the PV system to deliver power to the power grid in the form of AC, which is compatible with the grid requirements.

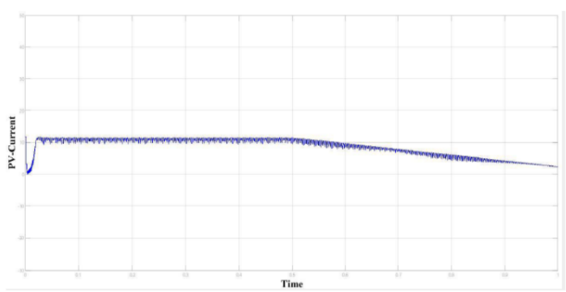

Fig. 6 : PV-System Output Current Waveform

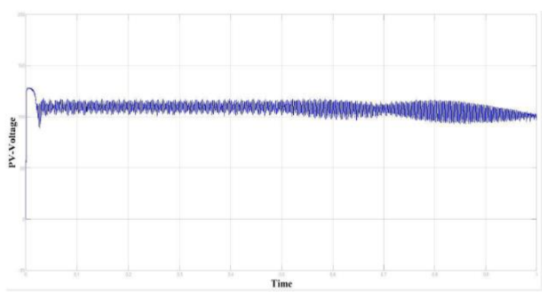

Fig. 7 : PV-System Output Voltage waveform

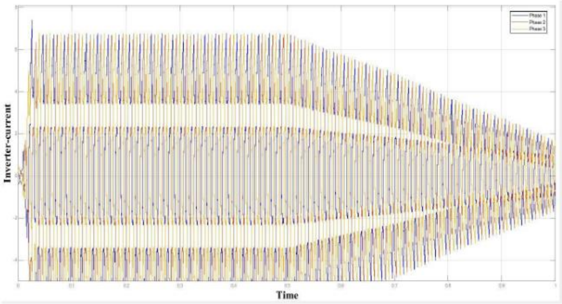

Fig. 8 : The inverter's output current waveform

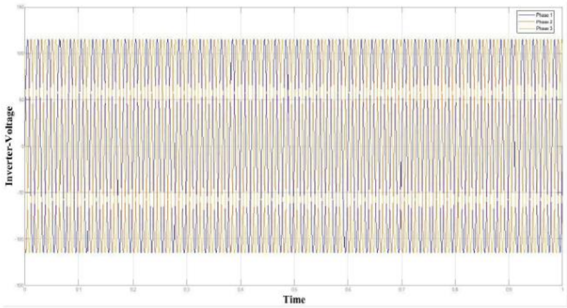

Fig. 9 : The inverter's output voltage waveform

5. Simulation Model for Grid-connected PV-System

Figure 10 illustrates a replica of the subsection of the studied PV Grid-Connected System. The model includes a 50-kW photovoltaic array, which generates DC output. The P&O (Perturb and Observe) technique is used to track the optimum power point for effective energy creation in order to maximize this output.

The generated DC power is then given to a boost converter, which adjusts the voltage and current to the required levels. After that, a three-phase inverter receives the boost converter's output & transforms the DC power into the necessary three phase AC supply. This alternating current (AC) output is then supplied to the utility grid through the Point of Common Coupling (PCC). Since harmonics might have an impact on how the PV system and the grid operate, harmonic analysis is done at the PCC to ensure the quality of the power being supplied. This analysis helps in identifying any distortions and ensures that the power quality remains within acceptable limits.

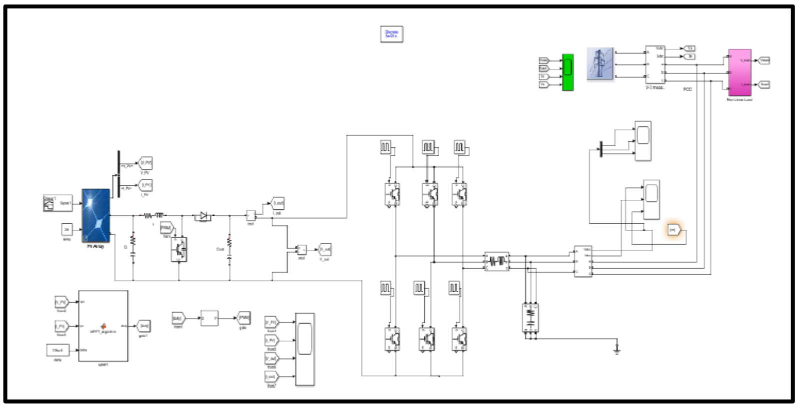

Fig. 10 : Simulation Model of considered site

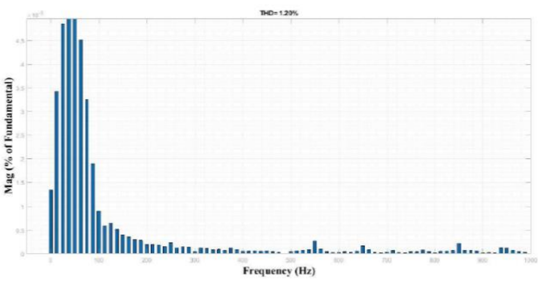

Fig. 11 : THD analysis of Voltage at PCC

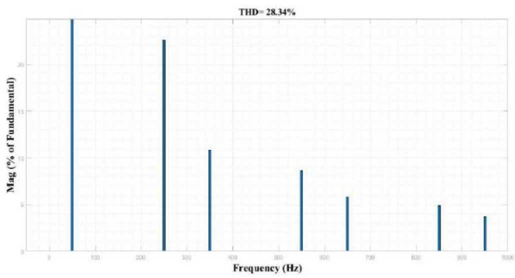

Fig. 12 : THD analysis of Current at PCC

The THD (Total Harmonic Distortion) of current and voltage was utilised to perform the harmonic analysis. The 3-phase voltage waveform was found to be nearly sinusoidal, and the THD analysis revealed that the voltage THD is 1.20% (as shown in Figure 11), which is within the acceptable limits set by IEEE. Therefore, no correction is necessary for the voltage waveform.

However, when examining the current distortion, it was observed that the three phase current waveform is non-sinusoidal (as indicated in Figure 11). The THD evaluation of the current revealed a THD of 28.34% (as depicted in Figure 12), which indicates significant harmonic distortion.

These results highlight the need for a device to mitigate the current harmonics. Active Filters (AFs) are an effective solution to compensate for these harmonics. Since there are only current harmonics, the overall power quality is improved, and the current distortion is reduced by using a Shunt Active Filter (SAF).

SAF Implementation for Grid connected PV System for Harmonic Mitigation

A Shunt Active Filter (SAF) was used to correct for the current distortion because the system detects current harmonics. Figure 13 illustrates the simulation model incorporating the SAF to mitigate these harmonics.

To confirm the efficacy of the suggested controllers and control schemes, extensive simulations were run in MATLAB, and the comprehensive results are displayed. These simulations provide important information on how well the SAF works to lower current harmonics and improve the grid connected PV system's overall power quality.

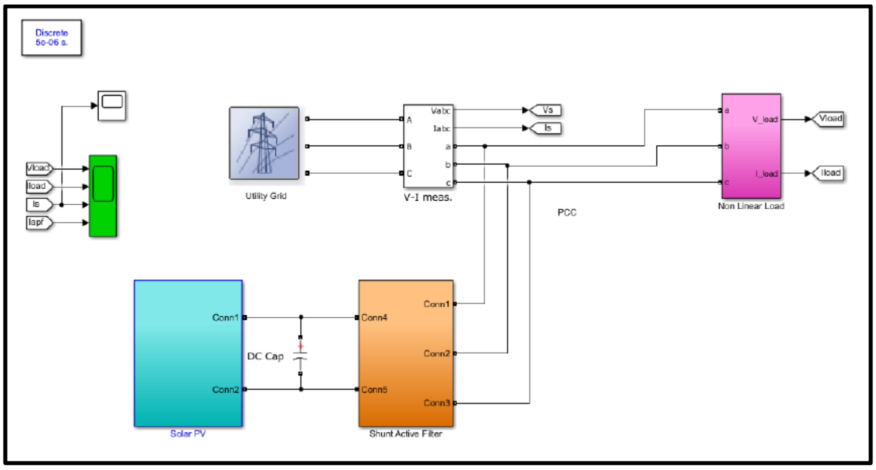

Fig. 13 : Grid Connected PV System Simulation Model with SAF

6. Harmonic Analysis at PCC

The SAF (Shunt Active Filter) is applied to reduce the harmonics within the IEEE limits, and various controllers have been designed for this purpose. After applying the SAF to the PV grid-connected system, the harmonic analysis at the Point of Common Coupling (PCC) is shown in this section. Different controllers are employed in the SAF, and their effectiveness in mitigating harmonics is analyzed.

Figures 14 and 15 show the Total Harmonic Distortion (THDi) analysis with different controllers. These figures illustrate the impact of various control strategies on the current harmonics. The details of the controllers and their performance in reducing THDi are provided below, demonstrating how the SAF improves the power quality at the PCC.

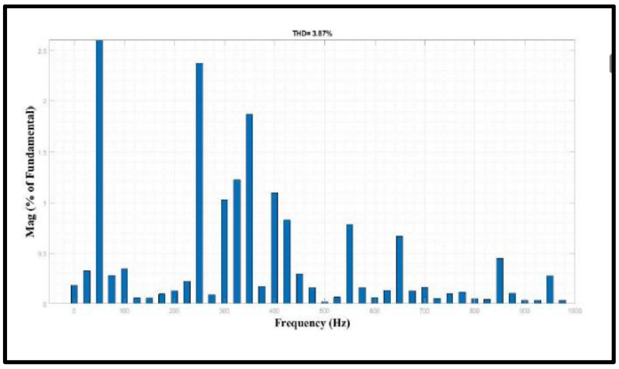

Figure 14 : THDi at PCC with PI-PQ based SAF

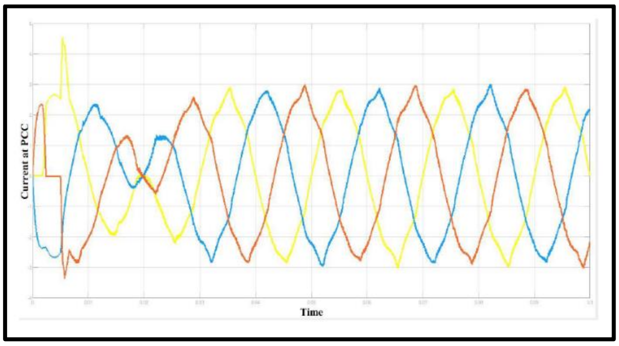

Fig. 15 : 3phase Current-waveform at PCC with PI-PQ based SAF

The production of electricity using renewable energy sources in India is growing rapidly, leading to an increase in power-quality issues when such systems are integrated with the power grid. The primary goal of this study is to eliminate harmonics at the Point of Common Coupling (PCC) while connecting a PV system to the grid. The research specifically investigates the impact of a Shunt Active Filter (SAF) on reducing harmonics at the PCC for a subsection of a rooftop PV grid-connected system located in Mumbai.

As detailed in the previous chapters, simulation models have been developed for this specific part of the considered site using the MATLAB software tool. The usefulness of SAF in reducing current harmonics and enhancing the overall power quality at the PCC for the chosen PV system is thoroughly examined in this research.

Table 2 shows the THDi measurements at PCC for different cases of SAF.

TABLE 2 THDi MEASUREMENTS AT PCC

<table>
<tr><th>S No</th><th colspan="2">Grid-connected PV-system Design</th><th>THDi</th></tr>
<tr><td>1</td><td colspan="2">Without SAF</td><td>27.96</td></tr>
<tr><td>2</td><td rowspan="2">With SAF</td><td>PI-dq</td><td>3.78</td></tr>
<tr><td>3</td><td>PI-pq</td><td>3.67</td></tr>
</table>

TABLE 3 THD VALUES FOR CURRENT AND VOLTAGE AT PCC

S No	THD at PCC	Without SAF	With SAF
1	THDv	1.18	1.19
2	THDi	28.04	2.90

7. CONCLUSION

The three-phase Shunt Active Filter (SAF) efficiently lowers current harmonics in a photovoltaic system connected to the grid. The SAF has been designed using various controller technique configurations, and the results demonstrate that the compensation process, which applies SRF/DQ theory for reference current extraction and controls the SAF's dc-link voltage capacitor using Fuzzy Logic Control (FLC), provides the best results in reducing current harmonics.

The SAF is implemented using a PWM-current-controlled VSI (Voltage Source Inverter), and the Hysteresis Current Control (HCC) approach is used to create the switching signals. The results indicate that the SAF successfully compensates for current harmonics, reducing them to a much lower level. Specifically, THD of the current is reduced to 2.90% when using the Fuzzy-Dq based SAF, compared to other controller configurations.

The voltage harmonics are already within the IEEE limits, with a THD of 1.19%, meaning no further compensation is required. When the SAF is connected to the system, the voltage harmonics remain unchanged, as confirmed by the results in Table 3.

In conclusion, the integration of the SAF reduces the current THD (THDi) from 28.04% (without SAF) to 2.90%, significantly improving the power quality of the PV system connected to the grid.

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