



POWER QUALITY IMPROVEMENT USING SHUNT ACTIVE POWER FILTER WITH dq0 THEORY

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Abstract--- This paper presents a comprehensive analysis and mitigation of harmonics in a grid-connected solar photovoltaic (PV) system with a voltage source inverter (VSI) and a current source inverter (CSI) at the load side. The load consists of a three-phase rectifier, a three-phase induction motor, and a three-phase unbalanced load. The system's harmonic distortion is mitigated using the DQ (Direct-Quadrature) methodology. The proposed approach effectively transforms the time-domain signals into the DQ domain, enabling the identification and compensation of harmonics. Simulation results demonstrate the efficacy of the proposed method in reducing total harmonic distortion (THD) and improving the overall power quality of the system. The findings of this research contribute to the development of more efficient and reliable grid-connected PV systems.

Keywords--- Solar PV system, Voltage Source Inverter, Current Source Inverter, DQ methodology, Harmonic mitigation, Power quality.

I. INTRODUCTION

Power quality refers to the state of voltage and current in an electrical system, evaluated based on factors such as voltage stability, supply reliability, and waveform conformity to an ideal sine wave [15]. Poor power quality can result in substantial financial losses, including equipment damage, production downtime, service interruptions, and increased maintenance costs. Additionally, inefficiencies caused by poor power quality can elevate energy consumption, leading to higher operational expenses [9].

Several disturbances contribute to power quality issues, including voltage fluctuations (such as sags, swells, and transients), harmonic distortion, frequency deviations, and phase imbalance [17]. To address these challenges, various international standards have been established, such as IEEE 519, IEEE 1159, the IEC 61000 series, and EN 50160, which define acceptable voltage and current limits to prevent equipment failures, malfunctions, and safety hazards [8]. Ensuring compliance with these regulations is critical, especially as industrial and infrastructure development continues to advance,

emphasizing the growing need for effective power quality assessment and improvement [25].

II. LITERATURE REVIEW

Electric power quality refers to an electrical system's ability to deliver energy to a load in a way that allows the user to utilize it effectively. This often involves ensuring proper voltage regulation, maintaining the rated frequency, and preserving a sinusoidal waveform without any momentary interruptions [10]. The IEEE defines power quality as the characteristics of the electricity supplied to a system that enable the proper functioning of electrical equipment, including factors such as voltage stability, frequency consistency, and waveform integrity. It also involves minimizing disturbances like harmonics, transients, and interruptions [17].

Power quality disturbances, such as voltage sags, swells, transients, harmonic distortion, frequency deviations, and phase imbalances, arise from various underlying causes and typically exhibit distinct symptoms based on the nature of the problem. Among these, harmonic distortion is a significant concern, arising from non-linear loads such as modern electronic devices that disturb the smooth sinusoidal waveform characteristic of alternating current systems. As per IEEE Std 519-2022, harmonics are sinusoidal voltages or currents at frequencies that are integer multiples of the fundamental power system frequency, which can distort the electrical waveform and impact system performance [1][4]. To quantify the extent of harmonic distortion, Total Harmonic Distortion (THD) serves as a critical metric, offering insights into waveform deviations by comparing the magnitudes of harmonic frequencies to the fundamental [2][3]. THD, expressed as a ratio or percentage, quantifies the level of harmonic distortion in a system. A higher THD value signifies greater distortion, which can reduce efficiency and lead to operational challenges. It is calculated by determining the root mean square of the harmonic components in relation to the fundamental frequency, providing a deeper analysis of the system's power quality.

THD Formula

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \dots + I_n^2}}{I_1}$$

Where:

I_1 is the amplitude of the fundamental current.

$I_2, I_3, I_4, \dots, I_n$ are the amplitudes of the harmonic components of current at frequencies $2f, 3f, 4f, \dots, nf$ respectively.

The international standards IEC 61000.3.6 and IEEE 519 set guidelines for acceptable levels of harmonic voltages in power systems. According to these standards, Total Harmonic Distortion (THD) limits for current and voltage are generally specified within the range of 5% to 8% for total harmonic current, while individual harmonic components are typically required to remain at or below 6%. These thresholds are critical for maintaining power quality and ensuring the efficient operation of electrical systems.

Power Filter:

Harmonic filters are specialized electrical circuits designed to reduce distortion and interference in electrical currents and voltages caused by harmonic frequencies. These filters play a crucial role in maintaining power quality and are categorized into three main types: passive, active, and hybrid filters. Passive filters utilize components like resistors, capacitors, and inductors to either redirect unwanted harmonic components or block them by creating a high-impedance path. In contrast, active filters employ power electronic devices and advanced control techniques to supply the harmonic current needed by the load, ensuring that only clean current is drawn.[7]

Passive Power Filter:

Passive power filters are widely used to mitigate power system harmonics due to their effectiveness and simplicity [28]. These filters come in various topologies, each with unique frequency response characteristics [21-22]. Comprising passive components like resistors, capacitors, and inductors, passive filters selectively allow or block specific frequencies based on their inherent impedance properties [18]. Unlike active filters, passive filters don't require external power sources or amplifiers [27]. Capacitors and inductors exhibit inverse impedance behavior at higher frequencies, enabling the design of low-pass, high-pass, band-pass, and band-stop filters [12]. Passive filters are extensively employed in audio systems, communication networks, and power circuits, valuing their simplicity, reliability, and efficiency.[22]

Active Power Filter:

Traditionally, passive filters have been used for harmonic improvement due to less cost [13]. The performance of passive filters is often unsatisfactory due to fluctuations in load and operating conditions. As a result, active power filters have emerged as a more effective solution for mitigating harmonics. One of the primary advantages of active filters over passive filters is their ability to adapt to changing loads and harmonic variations.[20] Additionally, a single active filter can compensate for multiple harmonic components while also

addressing other power quality issues, such as flicker, voltage sags, and swells [1-4]

Series Active Power Filter

A Voltage Source Inverter (VSI) plays a crucial role in a Series Active Power Filter (SAPF) by generating a Pulse Width Modulation (PWM) output. This output allows the filter to inject a compensating voltage in series between the power source and the load, effectively mitigating harmonic distortions in the electrical system. The generation of this reference voltage is based on a current control strategy, wherein the series compensator identifies and extracts the harmonic and reactive components of the load current to achieve effective compensation [26].

The Series Active Power Filter (SAPF) is connected in series within the power distribution network and primarily serves to protect sensitive loads from various voltage disturbances such as sags, swells, and transients.

Unlike shunt active filters, which are designed to correct current waveform distortions, the series active filter primarily compensates for voltage anomalies. It achieves this by injecting a controlled compensating voltage, effectively neutralizing fluctuations and distortions present in the supply voltage. This approach ensures a clean and stable voltage supply, making SAPFs highly beneficial in environments where voltage stability is critical, such as industrial automation, medical equipment, and precision manufacturing.

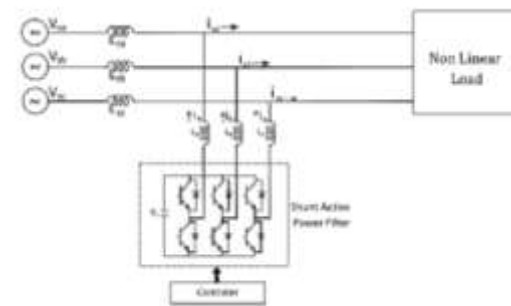


Fig.1 Shunt Active Power Filter

Shunt Active Power Filter:

A Shunt Active Power Filter (APF) is a power electronic device used for mitigating the harmonic currents from nonlinear loads [19]

A **Shunt Active Power Filter (SAPF)** is a power electronic device used to improve power quality by reducing harmonic distortion, compensating for reactive power, and enhancing system stability. It achieves this by injecting compensating currents into the system based on real-time load current and voltage measurements. Key components of SAPFs include power electronic switches, a DC-link capacitor, current and voltage sensors, and a control unit [26]. SAPFs are implemented using different inverter topologies such as Voltage Source Inverter (VSI)-based, Current Source Inverter (CSI)-based, and Multilevel Inverter-based configurations.

SAPFs offer several benefits, including effective harmonic suppression, improved power factor, reduced Total Harmonic Distortion (THD), and compact design, making them essential for modern power systems. However, challenges such as high costs, complex control strategies, switching losses, and

Fig.2 Solar source with P&O MPPT and Boost converter

electromagnetic interference. To optimize SAPF performance, various control strategies have been developed. These include Instantaneous Reactive Power (p-q) Theory for real-time harmonic detection [3], Synchronous Reference Frame (SRF) Theory for improved harmonic compensation [23], Adaptive Filtering Techniques for dynamic response [11], and Model Predictive Control (MPC) for real-time optimization [24].

Designing an SAPF requires careful selection of filter ratings, optimization of the DC-link capacitor, management of switching frequency, refinement of control algorithms, and EMI mitigation. These filters are widely used in industrial and commercial power systems, renewable energy applications, EV charging stations, and smart distribution networks.

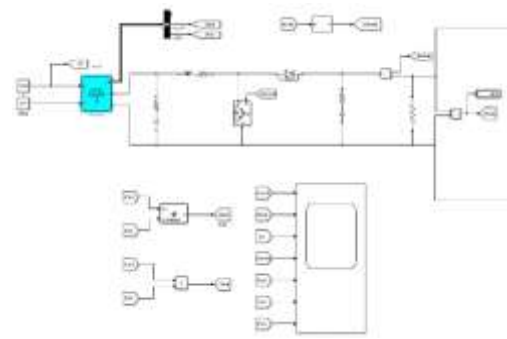


Fig.7 Current and voltage waveform of source side

III.PROBLEM IDENTIFICATION

This MATLAB simulation explores the operational dynamics of a solar-powered electrical distribution system, featuring a photovoltaic source and three distinct loads: an unbalanced three-phase load, a three-phase rectifier, and a three-phase induction motor. The system's performance is scrutinized to identify potential challenges and limitations arising from the integration of nonlinear loads, which can lead to power quality issues, including harmonic distortion, power factor deterioration, voltage instability, and thermal overloading, ultimately affecting system reliability and efficiency.

The proliferation of nonlinear loads in residential and industrial environments is causing significant power quality issues due to distorted current waveforms. Devices like computers and variable frequency drives produce high-crest-factor pulse waveforms, leading to power quality problems, device malfunctions, lighting flicker, and premature equipment failure. Effective control and mitigation strategies are essential to maintaining power quality, as nonlinear loads can introduce harmonic distortion, power factor degradation, voltage instability, and increased thermal loading, highlighting the need for advanced solutions to ensure reliable and efficient electricity distribution.

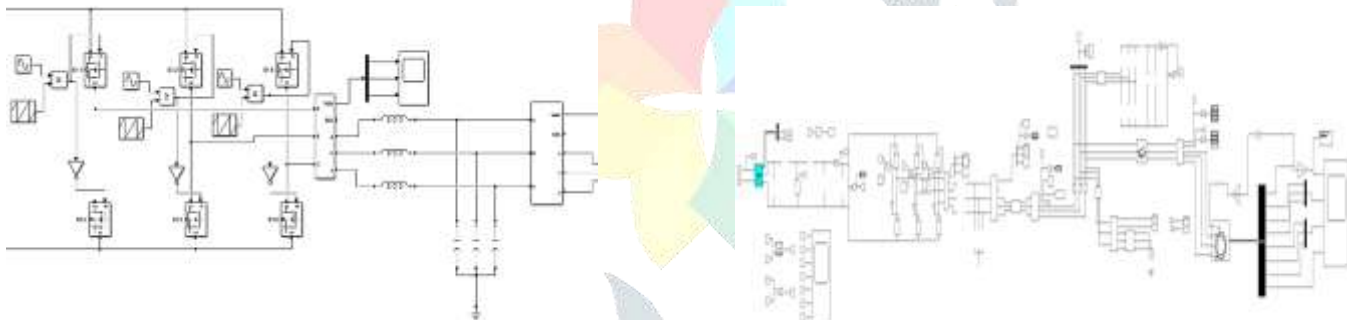


Fig.3 Three phase Inverter with SPWM and three phase LC filter

Fig.6 Simulation

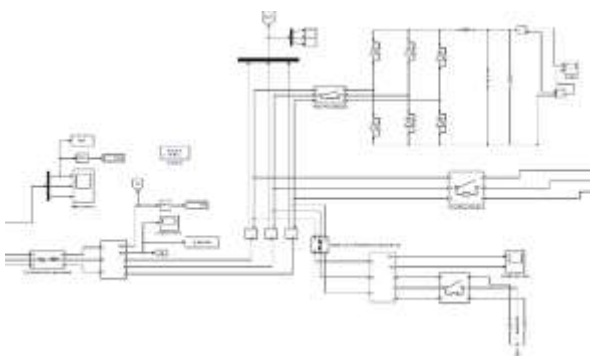
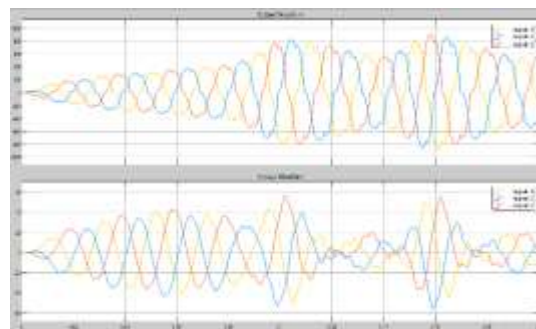


Fig.4 Rectifier and three phase unbalanced load

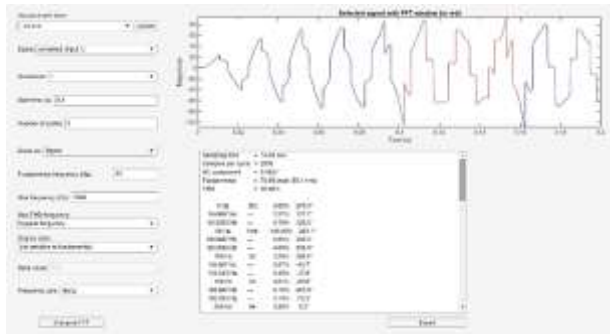


Fig.8 FFT Analysis of Source side current

The FFT analysis of the source current waveform indicates substantial total harmonic distortion (THD), primarily attributed to nonlinear loads. Harmonic distortion is a well-known cause of power quality degradation, resulting in adverse effects on electrical systems, including increased energy losses, decreased system efficiency, and compromised equipment lifespan. Furthermore, harmonics can lead to capacitor overheating, transformer degradation, motor vibration, and power factor degradation, emphasizing the need for effective harmonic mitigation strategies to ensure reliable and efficient electrical system operation.

IV. PROPOSED METHODOLOGY

The implementation of a Shunt Active Power Filter (SAPF) based on dq-theory necessitates an intricate approach encompassing signal processing, control strategy design, and real-time execution. This methodology delineates the essential procedural framework and computational paradigms instrumental in achieving optimal harmonic mitigation and reactive power compensation.

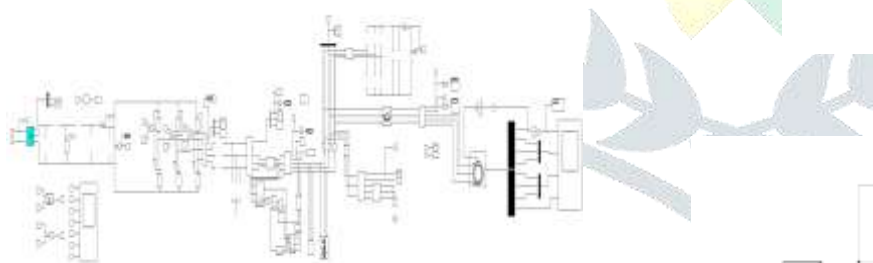


Fig.9 Simulation with dq0

This figure illustrates the graphical representation of the transformation from the abc stationary reference frame to the synchronous reference frame, converting coordinates from a three-phase abc stationary system to the dq0 rotating coordinate system [6]. In a three-phase system, currents and voltages fluctuate sinusoidally over time, making direct harmonic extraction challenging. DQ Theory facilitates this transformation by converting time-varying signals into a rotating reference frame, where fundamental components appear as DC values and harmonic components manifest as AC ripples, thereby simplifying harmonic filtering and improving reactive power compensation.

The three-phase system (**ABC frame**) is transformed into the DQ frame using **Park's Transformation**, given by:

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin\omega t & \sin(\omega t - \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \\ \cos\omega t & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

Where:

DQ Theory [Synchronous Reference Frame]

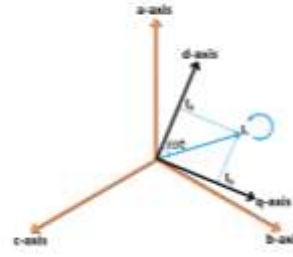


Fig.10 DQ Theory Synchronous Reference Frame

- i_a, i_b, i_c are the phase currents.
- i_d, i_q are the transformed DQ components.
- i_0 is the zero-sequence component (neglected in

balanced systems).

- ωt is the phase angle obtained using a **Phase-Locked Loop (PLL)** to ensure synchronization with the supply voltage.

This reference is turning in a synchronous constant speed with the three-phase voltage [29][5] The above equation is expanded in embedded system blocks as shown in fig.

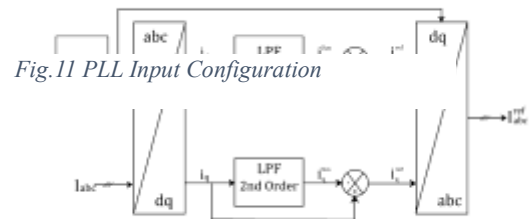
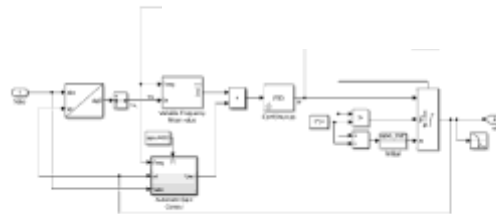


Fig.11 PLL Input Configuration



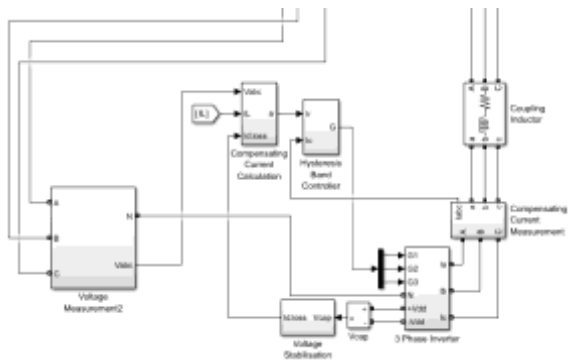


Fig.12 dq0 simulation

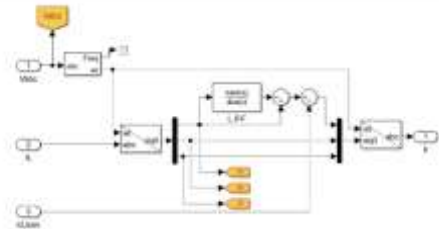


Fig.13 Compensating current calculation

When nonlinear loads are present, the actual load current in the dq frame (i_d and i_q) becomes distorted due to the generated current harmonics, leading to a revised load current expression as follows:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} i_d^{fund} + i_d^{hrm} \\ i_q^{fund} + i_q^{hrm} \end{bmatrix}$$

Where:

- i_d^{fund} and i_q^{fund} are the fundamental (DC) components.
- i_d^{hrm} and i_q^{hrm} are the harmonic (AC) components.

Once the currents are transformed into the DQ domain, a Low-Pass Filter (LPF) is applied to separate the fundamental component from the harmonics. Since the fundamental component is DC-like, an LPF efficiently removes high-frequency harmonics, leaving only the desired fundamental current. The filter used for this purpose is a second order Butterworth-typed LPF with a cutting frequency of 10 Hz. This type of filter is accepted as the best “all-rounder” filter which provides fast dynamic response with acceptable filtering performance [16].

To generate the reference currents that the SAPF must inject, the fundamental components extracted from the LPF are subtracted from the original DQ currents:

$$\begin{aligned} i_d^{ref} &= i_d - i_d^{fund} \\ i_q^{ref} &= i_q - i_q^{fund} \end{aligned}$$

Fig.14 Block diagram of reference current calculation

Where:

- i_d^{ref} and i_q^{ref} represent the **harmonic and unwanted reactive current components** that need compensation.
- These reference currents dictate how much current the SAPF must inject to cancel out harmonics and maintain power quality.

After reference currents are generated in the DQ frame, they must be converted back into the ABC (three-phase) frame to control the SAPF inverter. This is done using Inverse Park’s Transformation, which reconstructs the three-phase reference currents ($i_a^{ref}, i_b^{ref}, i_c^{ref}$) from the d-axis and q-axis components.

$$\begin{bmatrix} i_a^{ref} \\ i_b^{ref} \\ i_c^{ref} \end{bmatrix} = \begin{bmatrix} \sin\omega t & \cos\omega t & 1 \\ \sin(\omega t - \frac{2\pi}{3}) & \cos(\omega t - \frac{2\pi}{3}) & 1 \\ \sin(\omega t + \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} i_d^{ref} \\ i_q^{ref} \\ i_0 \end{bmatrix}$$

Where:

- i_d^{ref} and i_q^{ref} are the reference direct-axis and quadrature-axis currents.
- i_0 is the zero-sequence component, usually zero in a balanced system.
- ωt is the phase angle obtained from the Phase-Locked Loop (PLL).
- $i_a^{ref}, i_b^{ref}, i_c^{ref}$ are the three-phase reference currents that the SAPF must inject to compensate harmonics and reactive power.

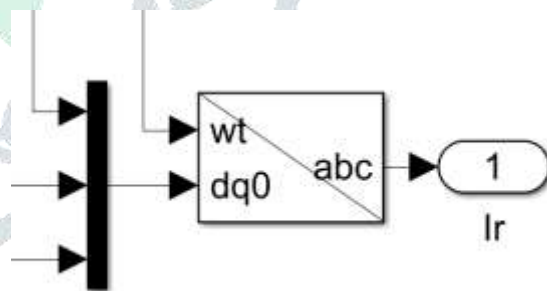


Fig.15 Inverse Park's Transformation

The inverse transformation converts the reference direct-axis (i_d^{ref}) and quadrature-axis (i_q^{ref}) currents back into three-phase form (i_a^{ref}, i_b^{ref} and i_c^{ref}). The actual value of current in the system is then compared with this reference value in the hysteresis controller to generate the PWM pulse required to control the operation of VSI and generate the compensating current to be injected in the system. This ensures that the SAPF accurately tracks the reference current and effectively compensates for harmonics and reactive power.

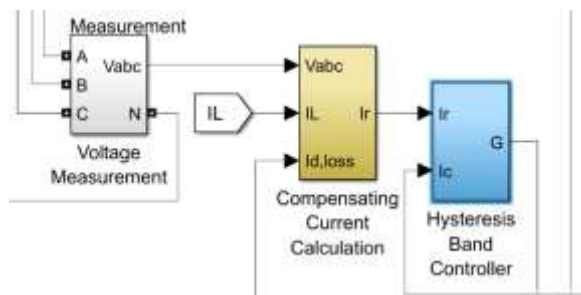
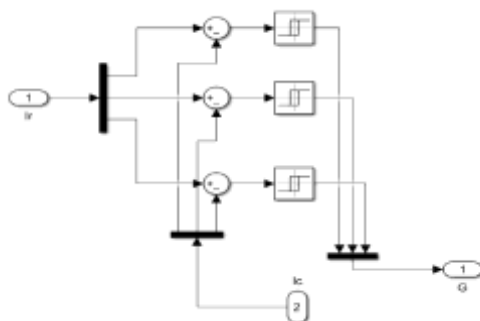


Fig.19 Comparative Analysis of simulation without SAPF and with SAPF

Fig.16 Input Configuration of Hysteresis Band Controller



After using SAPF, the THD was reduced to 5.06%.

Following is the comparative analysis of Source Current without dq0 theory and with dq0 theory:-

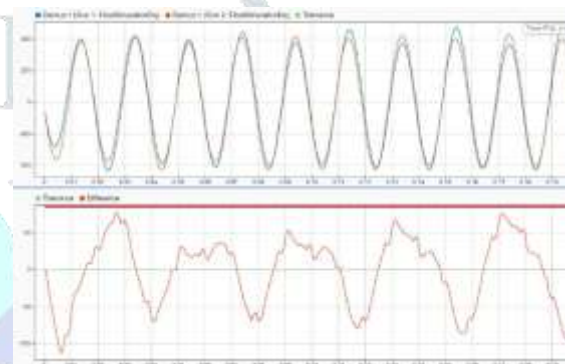
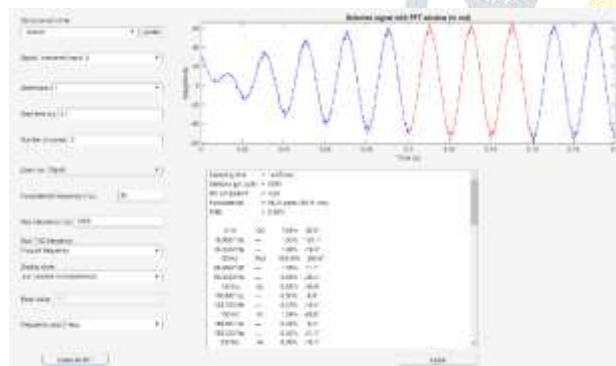


Fig.17 Pulse Width Modulation (PWM) Signal Generation

V.RESULT

The FFT analysis of the system after integrating the Shunt active power filter with dq0 theory is presented below:-



A THD of 5.06% indicates that the shunt active power filter has effectively reduced the harmonic distortion in the system. This reduction in THD can be attributed to the filter's ability to inject compensating currents that cancel out the harmonic components.

Fig.18 Source Current waveform and THD after implementing SAPF

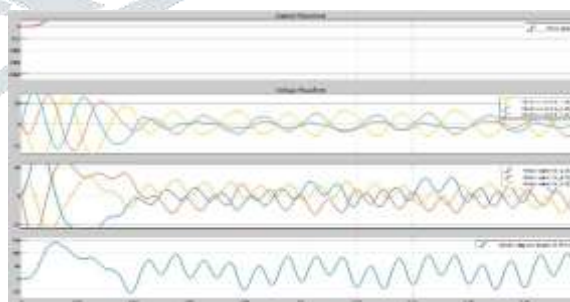


Fig.20 Graph of Induction Motor

The graph represents the performance characteristics of three-phase induction motor (Asynchronous Machine), focusing on rotor speed, stator and rotor currents, and electromagnetic torque. The rotor speed stabilizes over time, while the stator and rotor currents exhibit sinusoidal waveforms with minor distortions. The electromagnetic torque waveform shows reduced oscillations, minimizing torque ripples and improving mechanical stability. These results confirm that the SAPF effectively mitigates harmonics, enhances power quality, and

ensures efficient motor operation with reduced losses and vibrations.

Comparison of THD in Simulation

Without SAPF

Sampling time	=	1e-05 sec.	
Samples per cycle	=	2000	
DC component	=	0.4827	
Fundamental	=	70.85 peak (50.1 rms)	
THD	=	35.86%	
0 Hz	DC	0.68%	270.0°
16.6667 Hz	--	1.27%	127.7°
33.3333 Hz	--	0.79%	129.5°
50 Hz	Fnd	100.00%	263.1°
66.6667 Hz	--	9.82%	205.9°
83.3333 Hz	--	4.65%	232.4°
100 Hz	h2	1.29%	268.8°
116.667 Hz	--	0.57%	-40.7°
133.333 Hz	--	0.49%	-17.8°
150 Hz	h3	0.61%	-28.8°
166.667 Hz	--	0.10%	257.9°
183.333 Hz	--	1.10%	73.3°
200 Hz	h4	3.58%	0.2°

With SAPF

Sampling time	=	1e-05 sec.	
Samples per cycle	=	2000	
DC component	=	4.32	
Fundamental	=	55.31 peak (38.11 rms)	
THD	=	5.05%	
0 Hz	DC	7.81%	90.0°
16.6667 Hz	--	1.53%	124.1°
33.3333 Hz	--	1.09%	-19.3°
50 Hz	Fnd	100.00%	262.6°
66.6667 Hz	--	1.95%	11.1°
83.3333 Hz	--	0.65%	-32.4°
100 Hz	h2	0.81%	-43.9°
116.667 Hz	--	0.50%	-8.6°
133.333 Hz	--	0.45%	-15.4°
150 Hz	h3	1.24%	-59.8°
166.667 Hz	--	0.39%	6.3°
183.333 Hz	--	0.30%	-31.1°
200 Hz	h4	0.39%	-19.1°

CONCLUSION

This research has demonstrated that the DQ theory-based approach for Shunt Active Power Filters (SAPF) is an effective solution for mitigating current harmonics, compensating reactive power, and correcting load imbalances. By converting three-phase currents into the synchronous reference frame, this method ensures precise and real-time harmonic compensation, leading to enhanced power quality and adherence to international standards. The study validates the practicality and reliability of implementing SAPF using DQ theory in industrial and commercial applications. Furthermore, its role in improving system stability, minimizing energy losses, and optimizing power distribution highlights its significance in modern power networks. Future work may explore advanced control strategies, real-time implementation enhancements, and the integration of artificial intelligence for further performance improvements.

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