iJRASET
International Journal For Research in Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 11 Issue: IX Month of publication: September 2023

DOI: https://doi.org/10.22214/ijraset.2023.55646

SAPF based on ANN-Second Order Generalized Integrator for Harmonic Absorption

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***Abstract:** The purpose of this study is to provide a photovoltaic (PV)-based generation system that is coupled with a shunt active power filter (SAPF) in order to effectively compensate for reactive power and mitigate harmonics. The Solar Active Power Filter is made up of a DC link capacitor, a voltage source inverter (VSI), and a solar production system. With the assistance of an active power filter, the current harmonics that are brought on by nonlinear loads are capable of being significantly decreased. The artificial neural network is presented as a solution for both the generation of the reference current and the regulation of SAPF. Calculating the reference source current for SAPF requires the use of the Second Order Generalized Integrator (SOGI), which is coupled with an Artificial Neural Network (ANN) controller. ANN is also notable for its high compatibility with digital implementation, control performance, and blazingly quick dynamic reaction times. The created controller is validated with the assistance of MATLAB simulations in order to demonstrate the efficacy and superior concert of the proposed methodology.*
***Keyword:** ANN – Artificial Neural Network, SAPF – Shunt Active Power Filter, VSI – Voltage Source Inverter, PV – Photovoltaic, SOGI - Second Order Generalized Integrator, THD – Total Harmonic Distortion*

I. INTRODUCTION

It is a lucrative company that has long been a focus of academic study and practice guidelines to ensure that consumers in every region of the world have access to reliable energy sources. The employment of nonlinear loads in industrial settings contributes to the worsening of harmonic pollution and the quality of the electricity [1]. A breakdown in even a single component of the electrical grid can have negative and far-reaching repercussions for the entire system due to the grid's highly interconnected architecture. Harmonics in electrical current and methods for their reduction have emerged as key concerns for a growing number of businesses over the past few years. Because of the excessive nonlinear loads, the lifespan of the equipment is decreased, and the quality of the power is decreased as well. In order to improve the reliability of the power supply, industrial facilities are installing power factor improvement devices. Instead of using reactors for this purpose, capacitors are employed since reactors would generate harmonic distortion and resonance in the electrical system. Capacitors are used instead. In addition, the current that is pulled by nonlinear loads is not precisely sinusoidal. This is due to the fact that the waveform of the current deviates from that of a sine wave, which causes distortions in the waveforms of the voltage. It is the harmonics that are responsible for the malfunctioning of electronic equipment, the overloading of capacitors, the overheating of power transformers, the increased heating impact on electrical devices, and the losses in distribution lines [2-5].

There are a few different kinds of filtering strategies that have been presented in the existing body of research to cut down on harmonics [6]. These include passive power filtering, active power filtering, and hybrid power filtering. The PPF approach provides a low-impedance channel to harmonics of varied frequencies by making use of tuned capacitors, reactors, and resistors. As a result, the effect that these harmonics have is diminished [7]. The PPF has a number of advantages, including its low cost, but one of the most significant disadvantages is the resonance it generates in the power system. In addition, the usage of APF should be considered in circumstances when there is a presence of voltage dips and spikes [8]. The primary limitations of using them include the high operating costs associated with them and the fact that they are unable to deal with low rating loads in industrial environments [9].

In the same vein, taking a voltage reading at the source is an absolutely necessary step in order to calculate the load's harmonic power consumption. The voltage that is derived from the source is necessary for correcting the reactive power and harmonics, both of which contribute to the control scheme's increased complexity [11]. A PI controller is utilized by a DC-link voltage regulator in order to maintain a consistent SAPF DC voltage. This allows the voltage to be kept at a constant level. In order to gather the requisite voltage-related information for this PI-controlled DC-link voltage regulator, voltage sensors are required. When there is a disruption in the voltage and current, the DC-linked capacitor and batteries are activated so that they can store the excess energy and supply the load with the necessary amount of power.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 11 Issue IX Sep 2023- Available at www.ijraset.com

Because of the restricted amount of energy that can be stored in these devices, the ability of the shunt APF to compensate is hindered [12–16]. Because errors in the evaluation of the reference source current signal must be avoided at all costs in order to prevent inaccurate compensation, the control approach that is used to estimate it is of the utmost importance to the ability of the APF to provide compensation [16–18]. Errors in the evaluation of the reference source current signal will result in inaccurate compensation. A number of scholars have already experimented with a variety of control schemes to get an approximation of the reference current signal produced by the shunt active filter [19]. testing and calculating (DTC) methods, recursive discrete Fourier transformation (RDFT), fast Fourier transformation technique (FFT), Pq0, notch filter, extrapolated integral, synchronous detection algorithm, sine wave multiplication, artificial neural network (ANN), and synchronous detection algorithm are some of the techniques that have been developed by various researchers in order to reduce the Total Harmonics Distortion (THD) .

A second order generalized integrator (SOGI) that is fed into an artificial neural network (ANN) is used in the system that is being proposed to generate the reference current signal for the shunt PF. When implementing the SOGI control algorithm inside of a SAPF that is coupled with a photovoltaic array and a storage battery. Current sensors are embedded within the circuit, and with their assistance, the currents flowing through the inverter can be detected. Because of this, we are able to make more accurate predictions regarding the overall amount of energy that is used by the loads in the distribution system, and it also removes the need for a PI regulator in the control algorithm for the shunt inverter. The gate signal for the three-phase voltage source inverter (VSI) switches that make up the core control circuitry is generated by a SOGI control algorithm trained on ANNs. In the distribution system that serves commercial and residential customers, current-based disturbance compensation is provided by a photovoltaic generation-based SAPF that makes use of an ANN-based SOGI control algorithm. The interconnected photovoltaic system that the SAPF has suggested can be found explained in Section 2. Discussion of the control plan for the SAPF was included in Section 3. The results of the simulation as well as the experimental validations are presented in the subsequent section, which is titled Section 4. At this point in the article, we have reached the culmination of the work that has been proposed.There are a lot of different control systems, such as selective harmonic elimination-based pulse width modulation (SHE-PWM), Various researchers have developed several methods to reduce Total Harmonic Distortion (THD), including Direct Testing and Calculating (DTC) methods, Recursive Discrete Fourier Transformation (RDFT), Fast Fourier Transformation technique (FFT), Pq0, Notch Filter, Extrapolated Integral, Synchronous Detection Algorithm, Sine Wave Multiplication, Artificial Neural Network (ANN), and Synchronous Detection Algorithm .

The proposed method utilizes a second-order generalized integrator (SOGI) that is input into an Artificial Neural Network (ANN) to generate the reference current signal for the shunt power factor (PF). When implementing the SOGI control algorithm within a Static Synchronous Compensator (SAPF) system that is connected to a Photovoltaic (PV) system and a storage battery. The currents of the inverter are quantified through the utilization of current sensors that are strategically positioned throughout the circuit. This enables a more precise estimation of the aggregate energy consumption of the loads within the distribution system, hence obviating the need for a proportional-integral (PI) regulator in the control algorithm of the shunt inverter. The generation of the gate signal for the switches of the three-phase voltage source inverter (VSI) is facilitated by an artificial neural network (ANN) based second-order generalized integrator (SOGI) control method. The distribution system that caters to commercial and residential consumers utilizes an Artificial Neural Network (ANN) based Second-Order Generalized Integrator (SOGI) control algorithm in a Photovoltaic (PV) generation based Static Synchronous Compensator (STATCOM) to provide compensation for disturbances based on current.

The SAPF interconnected photovoltaic system is elucidated in Section 2. In the third section, the control plan for the SAPF was explored. The results of the simulation and experimental validations are presented in Section 4. The conclusion of the suggested study is provided in the concluding section.

II. SYSTEM DESCRIPTION

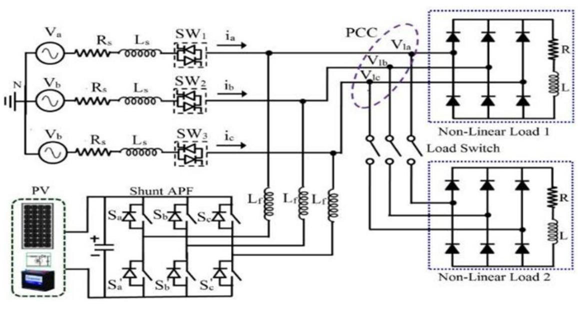


Figure .1 Schematic diagram of the proposed shunt active filter circuit.

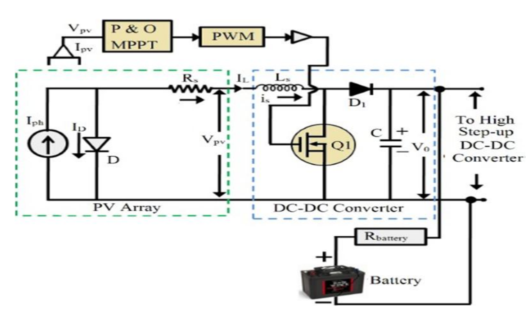


Figure 2: A schematic of a PV system with MPPT

Figure 1 illustrates the circuitry of a shunt Active Power Filter (APF) in conjunction with a Photovoltaic (PV) generating system. The grid-connected solar photovoltaic (SPV) power generating system incorporates shunt active power filtering (APF) to service both linear and nonlinear loads. The consumer load is electrically connected in a parallel configuration with the three-phase Voltage Source Inverter (VSI) by means of the interface inductor (Lf). The photovoltaic (PV) power generation system maintains the operation of the direct current (DC) link of the shunt active power filter (APF) in order to consistently provide compensation for variations in load current or disturbances in current. The photovoltaic (PV) array, in conjunction with the high and low DC-DC converters utilized for the battery bank, constitutes the photovoltaic power generation system. The utilization of a DC-DC step-up converter is implemented in order to maintain a consistent DC bus voltage for the shunt inverter.

In instances where the photovoltaic (PV) power generation system generates an excess of electricity beyond the immediate demand, the surplus can be directed towards a battery using the power conditioning circuitry. Consequently, during periods when the PV system fails to generate sufficient electricity, the stored energy in the battery can be utilized to meet the electricity requirements. Nonlinear loading is achieved through the utilization of an unregulated diode rectifier configuration, wherein a resistor and an inductor are interconnected at their point of common coupling (PCC). The utilization of a current transformer is employed for the purpose of quantifying the electrical current consumed by a nonlinear load.

A. Photovoltaic Power Generation System

The solar power generation is facilitated by the PV system array, storage battery, and DC-DC boost converters. In order to optimize energy production in periods of reduced solar irradiation, the DC-DC converter is equipped with a maximum power point tracking (MPPT) function, which enhances its voltage capacity. Figure 2 illustrates the control circuitry for the maximum power point tracking (MPPT) of the solar photovoltaic (SPV) array and the DC-DC converter.

B. Photovoltaic System Operation Modes

The suggested photovoltaic system with battery interfaced shunt APF will operate in three unique modes. There are three distinct modes that are provided below:

1) Mode 1: Photovoltaic (PV) power Generation

The photovoltaic (PV) power generation mode is activated during daylight hours or when there is an adequate amount of solar irradiation to produce a satisfactory level of electricity. In this context, the photovoltaic system is integrated with a Static Active Power Filter (SAPF) to mitigate harmonic distortions and facilitate energy storage in a battery for subsequent utilization.

2) Mode 2: Battery Backup System

In instances where solar energy is not accessible, such as during periods of darkness or overcast weather conditions, the battery backup option is engaged. The battery-supported Static Synchronous Compensator (SAPF) is utilized to achieve balance in harmonics and reactive power. To ensure uninterrupted compensation, the battery backup mode employs a DC-DC boost converter.

3) Mode 3: The concept of uninterrupted supply.

The Photovoltaic-based SAPF system demonstrates consistent provision of power to critical/sensitive loads, even in the absence of voltage. In instances of this nature, the load power is supplied by the Battery based Photovoltaic (PV) generating system. The utility grid is disconnected by means of semiconductor switches.

III. MATHEMATICAL MODELLING FOR PROPOSED SHUNT ACTIVE FILTER

The non-sinusoidal currents is generated by nonlinear load, for the purpose of modelling, the phase ‘b’ is considered for deriving the equation as follows

$$i_{lb}(t) = \sum_{g=1}^{y} i_{Lb,g} \, \mathrm{Sin}(g\omega t + fg) \quad (1)$$

$$(t) = \sum_{g=1}^{\infty} {}_{Lb,1} \, Sin(\omega t + \phi_1) + \sum_{g=1}^{\infty} i_{Lb,g} \, Sin(g\omega t + \phi_g) \quad (2)$$

Where g is harmonic order, ϕg is harmonics phase angle and ω is angular frequency. The load current will often contain the fundamental and harmonic components.

$$i_{Lb} = i_{Lb,1} + \sum_{g=2}^{\infty} \sum i_{Lb,g} \quad (3)$$

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 11 Issue IX Sep 2023- Available at www.ijraset.com

The suggested Static Active Power Filter (SAPF) successfully mitigates the impact of harmonic currents. To ensure effective compensation, the control algorithm of the shunt Active Power Filter (APF) must ascertain the suitable reference currents. The compensating current denoted by the symbol 'b' is mathematically represented as

$$i_{cg} = \sum_{g=2}^{\infty} i_{c,g} = -(i_{cb,3} + i_{cb,5} + i_{cb,7} + i_{cb,9} + \ldots + i_{cb,n}) \quad (4)$$

The implementation of VSI's compensatory current injection leads to a reduction in current-based disturbances at the point of common coupling (PCC). Consequently, the current at the source will undergo sinusoidal evolution.

$$i_{sb} = i_{Lb,1} + \sum_{g=2}^{\infty} i_{Lb,g} - \sum_{g=2}^{\infty} i_{Cb,g} = i_{Lb,1} + i_{Lb,g} \quad (5)$$

The source current for the phase ‘b’ is expressed as

$$i_{sb} = i_1(\ + \phi_1) \quad (6)$$

As a result, we can compute the source reference compensation current as:

$$i^* = i_{sb} \sin(\omega t) \quad (7)$$

$$i_{ca} = \text{Reference source current } (i^* \ ) - \text{Load current}(i_{Lb}) \quad (8)$$

The utilization of a proportional-integral (PI) controller is frequently employed in the determination of the reference current in relation to the source. The acquisition of voltage-related data is crucial for the proper functioning of the PI regulator. Therefore, it is necessary to incorporate the voltage sensor into the power conditioning circuitry. The estimation of the reference current signal in the SOGI system is achieved by utilizing the load current and compensation current as feedback signals. The calculation of the source reference current to the shunt Active Power Filter (APF) is provided using the Second-Order Generalized Integrator (SOGI) algorithm, without taking into account the voltage sensor.

The derivation of the second order generalized integrator is performed to estimate the compensation current using the specified function.

$$F_1(S) = \frac{i_{Lb\alpha(s)}}{i_{(s)}} = \frac{k_{\omega s}}{s^2 + k_{\omega s} + \omega^2} \quad (9)$$

$$F_2(S) = \frac{i_{Lb\beta(s)}}{i_{(s)}} = \frac{k\omega^2}{s^2 + k_{\omega} + \omega^2} \quad (10)$$

In this particular scenario, the angular frequency is assigned a fixed value of 304 rad/s. In practical applications, the transfer function provided in equations (9) and (10) is utilized for the implementation of a band pass filter using function F1, while function F2 is employed as a low pass filter within the context of Second Order Generalized Integrator (SOGI). The transfer function exhibits a precise alignment of phase and amplitude between the input and receiving signals at the fundamental harmonic.

Hence, the obtained signal is regarded as the reference value of the source current.

$$i_{Lb\alpha} = i^* = I_{sa} \sin(\omega t) \quad (11)$$

Currently, the phase difference between the received signal from the transfer function F2(s) and the signal created by the transfer function F2(s) is 900. Once the calculation of the required current from the reference source is completed, the exact attainment of the reference current for compensation becomes possible. Once the data on the reference and measured compensation current has been collected, it is possible to calculate the error in the compensation current.

$$\Delta i_{cb} = i^* - i_{cb} \quad (12)$$

At the point of common coupling, the compensation current is injected utilizing the Artificial Neural Network (ANN)-based Second-Order Generalized Integrator (SOGI) technique. The artificial neural network (ANN) obtains its input signal from the inaccuracy in compensatory current. The hysteresis band comparator is responsible for receiving the signal from the artificial neural network (ANN) and utilizing it to generate the gate pulses required for the voltage source inverter (VSI). The compensation current of the active filter is regulated through the utilization of an Artificial Neural Network (ANN) based Second-Order Generalized Integrator (SOGI) method. The effectiveness of an artificial neural network controller is unparalleled when it comes to rapidly recognizing corrupted signals. When parametric variation is present, the typical controller is unable to operate effectively. The system under consideration is a complex network comprised of intelligent neurons that possess the capability to acquire novel knowledge and adjust their behavior in response to their environment. By adjusting the weight value, it is possible to program neurons in order to do a designated task. The training process entails the reduction of mean squared error (MSE) by the utilization of the Levenberg-Marquardt Back Propagation (LMBP) algorithm.

The neural network architecture comprises a solitary neuron in the input layer, twenty neurons in the hidden layer, and an additional solitary neuron in the output layer. The neural network is composed of two input nodes, twenty layers of hidden neurons, and a single output layer. The compensation current error, e(n), and the rate of change of the error over time, de(n), are represented by i*cabc and icabc, respectively. The former signifies the current reference value employed in compensation, while the latter denotes the measured actual compensation current. In order to get improved compensation outcomes, it is necessary to alter the weights of the Artificial Neural Network (ANN) in order to minimize the distortion depending on current. Table 1 presents the dataset pertaining to the proposed artificial neural network (ANN) controller. The generation of switching pulses was facilitated by the utilization of a hysteresis comparator, which performed a comparison between the reference current and the measured current.

Table 1: ANN Parameters

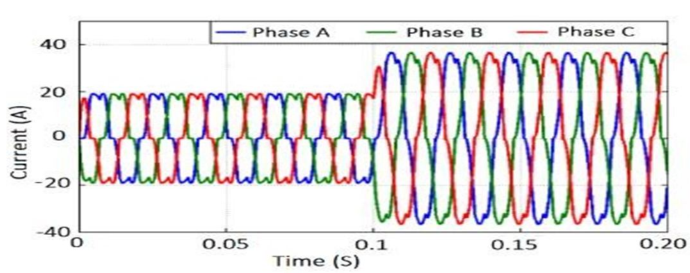
Parameters	Values
Maximum epochs	600
No of neurons in hidden layer	20
Performance goal	0.001
Learning rate	0.04
Activation function	5tansig/purelin

IV. SIMULATION RESULTS AND DISCUSSION

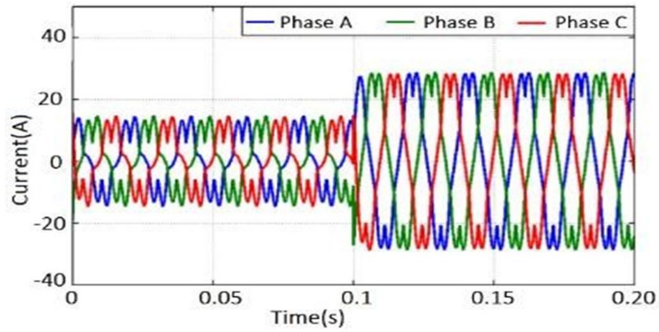
The evaluation of the SOGI-based artificial neural network (ANN) controller applied to a Photovoltaic integrated shunt Active Power Filter (APF) is conducted using MATLAB/Simulink. This evaluation is performed under various load current conditions. The simulation results are shown for both scenarios: one with a photovoltaic (PV) coupled to active power filter (APF), and the other without. The configurations of the Photovoltaic interfaced SAPF system are provided in Table 2. The proposed control strategy is evaluated by conducting two tests: Case 1, where the load current is increased, and Case 2, where the load current is decreased.

Table 2: Simulation System Parameters

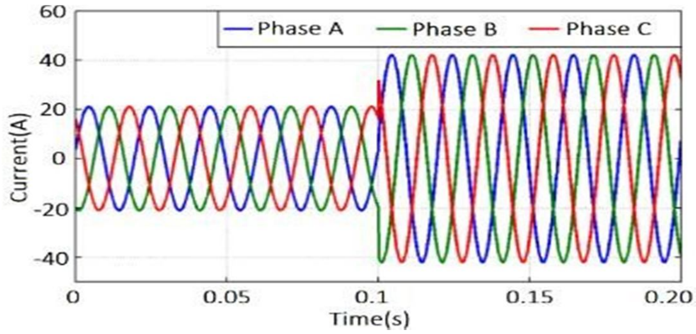
Parameters	Value
Input voltage (source)	220 V
Frequency	50 Hz
SAPF Filter (L, C)	22mH,1.2Ω
DC link capacitor and voltage	200µF and 600V
Feeder Impedance	1+j2.325 Ω
Nonlinear Load Diode rectifier with RL load	25Ω, 15mH
Battery bank rating	12V, 450Ah
PV Array rating	12V, Max Power- 210W (36.6 V x 5.75 A)



(a)Load current before installation of SAPF

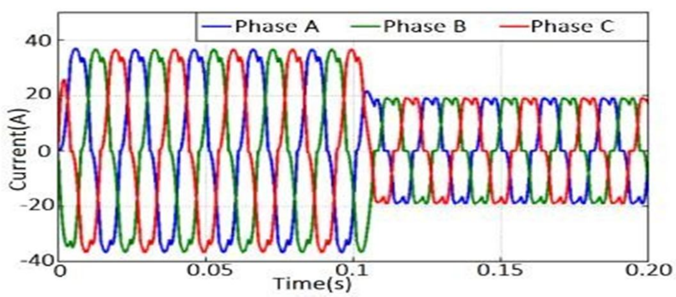


(b) Injected Current

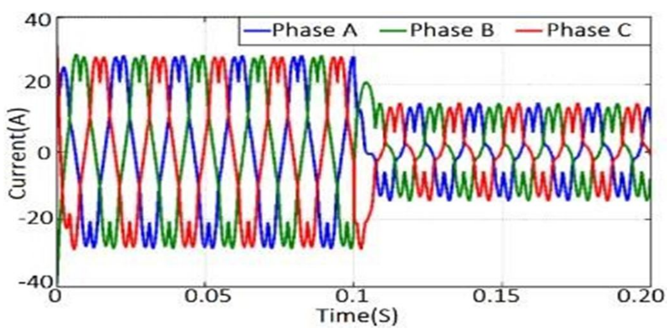


(c) Waveforms of Source current after installing SAPF

Figure 3: Increasing of load current (Case 1)

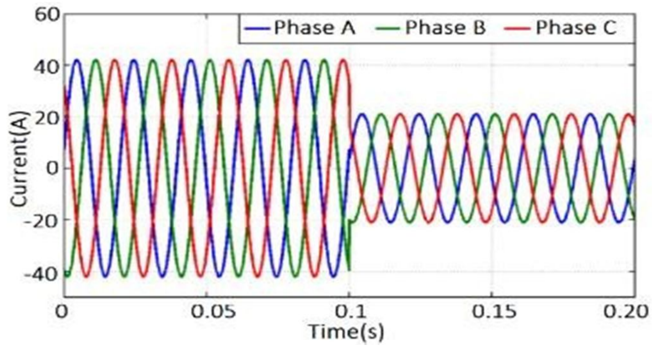


(a) Load current before installation of SAPF



(b) Injected Current

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 11 Issue IX Sep 2023- Available at www.ijraset.com



(c) Waveforms of Source voltage after installing SAPF
Figure 4: Decreasing of load current (Case 2)

The results of a simulation run investigating the impact of an increasing load current on several electrical parameters, including the load current, injected current, three-phase source voltage, and current, are depicted in Figure 3. The data presented in the figure represents the conditions both before and after the installation of a SAPF. The load switch is utilized to activate a nonlinear load in order to verify the accuracy of the current compensation obtained by the Photovoltaic cell-based shunt Active Power Filter (APF) using the Artificial Neural Network (ANN) - Second Order Generalized Integrator (SOGI) algorithm. If the load switch is closed, it results in an increased load current.Figure 4 illustrates the three-phase source currents and voltages, load currents, and compensation currents both before and after the implementation of a Shunt Active Power Filter (APF) based on Photovoltaic (PV) cells. The purpose of this APF is to reduce the load current. Upon the opening of the load switch, there is a reduction in the current flowing through the load.

Prior to the installation of the PV-shunt Active Power Filter (APF), the source currents exhibited harmonic distortion values of 25.63%, 24.55%, and 26.21% individually. However, subsequent to the installation of the APF, these distortion levels significantly reduced to 1.87%, 1.81%, and 1.87% separately. The results of the simulation confirmed the ability of the artificial neural network (ANN) - second-order generalized integrator (SOGI) control algorithm to reduce the overall level of harmonic distortion, as indicated in Table 3.

Table 3: Comparison of THD

	Phase	Before installation of PV-SAPF	After SOGI installed for PV-SAPF	After SOGI with ANN installed for PV-SAPF
Case 1THD %	A	26.68%	2.72%	2.18%
	B	26.63%	2.79%	2.21%
	C	26.43%	2.74%	2.19%
Case 2THD %	A	25.63%	2.45%	1.87%
	B	24.55%	2.47%	1.81%
	C	26.21%	2.48%	1.87%

V. CONCLUSION

In order to mitigate the existing harmonic distortions and address the reactive power, a shunt active power filter (APF) is employed, which incorporates a Second-Order Generalized Integrator-Artificial Neural Network (SOGI-ANN) control algorithm. The Artificial Neural Network (ANN) is utilized in the estimation of the reference signal, known as the Second-Order Generalized Integrator (SOGI), without the dependence on voltage-related information. Consequently, the inclusion of the voltage sensor and PI regulator can be deemed unnecessary, as the system has the capability to operate effectively in their absence. The utilization of a solar system integrated with a Static Active Power Filter (SAPF) actively mitigates current harmonics within the distribution system, thereby guaranteeing a consistent and clean power supply.

In order to maintain a consistent supply of energy to end-users, photovoltaic systems can be configured in several operational modes through the implementation of a simple coordination logic control mechanism. The employed control technique facilitated the effective mitigation of current harmonics, reactive power, and voltage interruption throughout a diverse spectrum of load and voltage conditions. In the presence of fluctuating current conditions, a nonlinear load exhibits a source current with a Total Harmonic Distortion (THD) of around 1.81%. This value is under the acceptable threshold of 5% as stipulated by the IEEE Std.519-1992.

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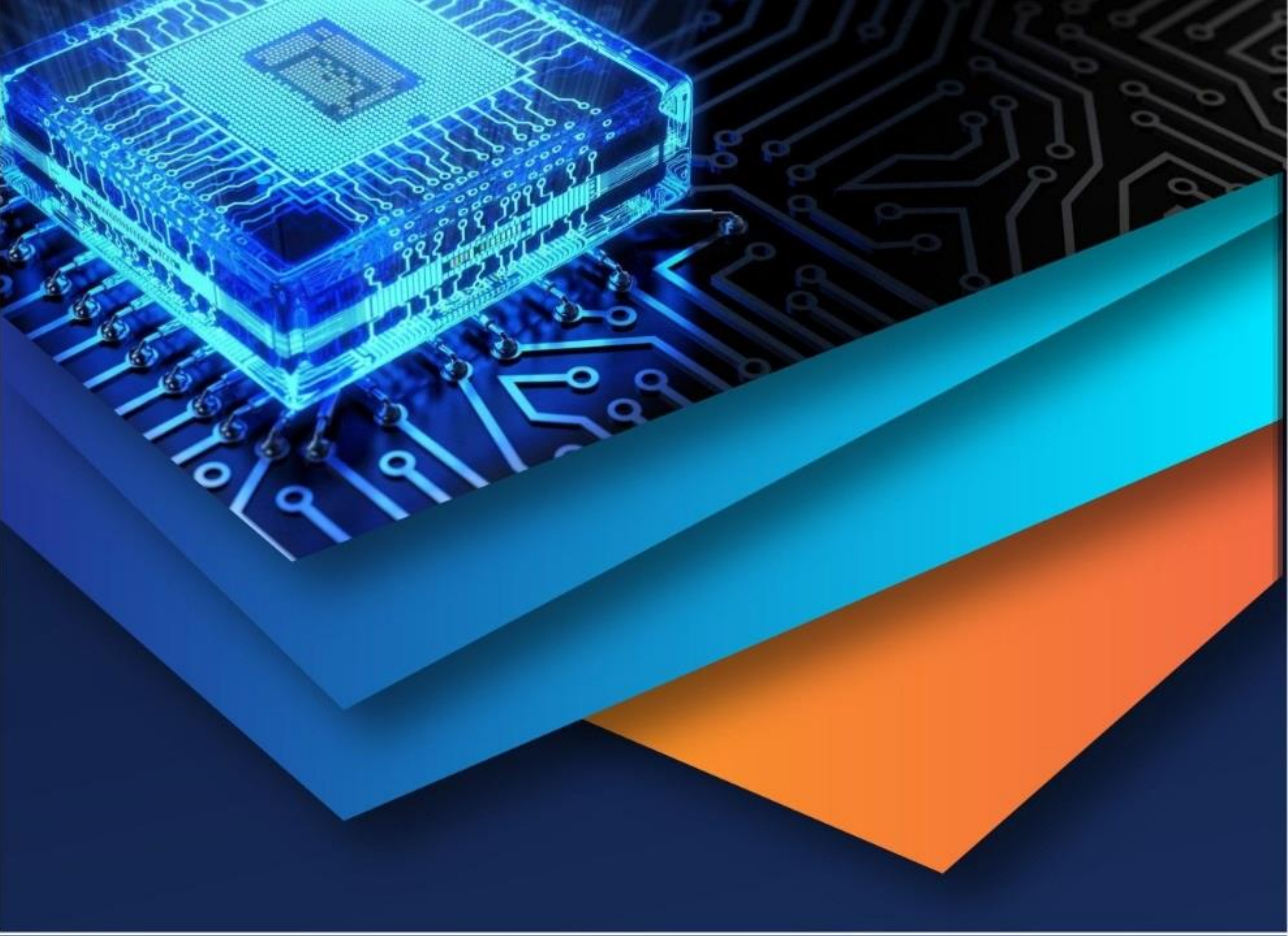

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TOGETHER WE REACH THE GOAL
IMPACT FACTOR:
7.429

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