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Reduced Switch Multilevel Inverter Based Shunt Active Power Filter With ANN Controller for Power Quality Improvement

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***Abstract:* -** In order to improve power quality, this research investigates the use of SAPF with Seventeen Level Reduced Switch Multilevel Inverter. The electricity grid's stability is significantly influenced by various non-linear loads. To address this, SAPF is proposed and designed to monitor, manage the current movement between the power source and the load. The variance between the intended and real currents drawn from utility grid is assessed using p-q theory based hysteresis current controller. The calculated error current guides the controllers in forecasting the best-suited switching signals and modulation index for the seventeen level RSMLI-SAPF system. In this paper the traditional PI controller, Artificial Neural Network based controller are compared and the results are provided to validate the performance of SAPF. The proposed system is modelled and analysed using MATLAB/Simulink. The simulation results are provided for various modulation index using Hybrid Pulse Width Modulation in which Triangle saturated Phase disposition PWM using Unipolar Third harmonic injection as Reference is used and are subjected to non-linear loads.

Keywords: Shunt Active Power Filter (SAPF), Reduced switch Multilevel Inverter (RSMLI), Hysteresis band current controller (HBCC), Instantaneous Active and Reactive Power (IPQ) Theory, Pulse width Modulation (PWM) Techniques, and Total Harmonic Distortion (THD), Power Quality (PQ).

I. INTRODUCTION

In recent times, there's a growing concern about the quality of power supplied to various sectors like industries, businesses, and homes. This is driven by the rapid increase in the utilization of devices that generate harmonics due to their nonlinear nature. These devices include things like ASD, switched mode power supplies, Power converters, and arc furnaces. The concept of power quality refers to how clean and stable the voltage and current signals are. The deterioration of power quality happens primarily due to disturbances in the power lines. These disturbances manifest as issues like voltage sags, voltage swells, voltage notches, voltage imbalances, and harmonics. Among these, harmonics are a significant problem, particularly in the distribution side of the power grid. Harmonics refer to the distortion present in voltage and current waveforms.

Harmonics are introduced into the electrical circuit mainly because of the prevalent use of nonlinear devices. These devices draw abrupt, short bursts of power from the supply source, and when combined with the source's inherent impedance, they lead to distortions in voltage and current patterns. This distortion can result in problems like overheating, component failures, and even interference with communication lines. Various techniques can be employed to mitigate harmonics in an electric power distribution network. These approaches encompass the utilization of components such as line reactors, phase shifting transformers, active & Passive power filters. One effective and commonly adopted strategy involves the deployment of harmonics filters, which work by eliminating undesired frequency components.

However, the application of passive filters is constrained by issues like their bulky size and the potential for resonance problems. Moreover, passive filters can only address specific amounts of reactive power and aren't adaptable to varying conditions. To overcome these limitations, active power filters emerge as a solution. These filters come in two main types: series and shunt active power filters.

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This paper carries out a detailed study in the field of reduced switch MLI topologies and challenges in various control techniques and implementation that are adopted for shunt Active filters.

A literature review is carried out on RSMLI topologies and SAPF Control techniques and are presented in this section. Five level MLI topology is proposed and various modulation techniques are suggested for reducing the harmonics [1]. The effectiveness of the inverter is evaluated of THD by altering the Modulation Index(MI). Phase shift PWM has been examined for use with a five level inverter to lessen the harmonic effect [2]. In [3], a four-wire MLISAF is suggested for controlling reactive or harmonic power. A "K" type structure with two capacitors and two DC sources has been designed in [4]. Low boosting ability results from the problematic voltage balancing of the capacitors in this architecture. ‘’Harmonic Mitigation by Passive Harmonic Filters: Case Study in a Steel Mill Power System’’ was proposed in [5]. In [6] a seven level inverter topology was proposed to reduce harmonics. An envelope type asymmetrical mli level inverter is proposed with reduced number of components in [7]. Various control techniques and its integration to PV system were discussed in [8]. A hybrid symmetrical MLI topology with reduced switch count were reported in [9] & [10]. A hybrid modulation technique was proposed in [11] for the inverter used in SAF. Comparative analysis of PI and ANN based shunt active hybrid filter were given in [12]. A survey on various control strategies were given in [13] & [14]. A parabolic PWM currentcontrol is stated in [15]. Various grid connected converters under various fault conditions were discussed in [16]. For a grid-connected solar system, a proportional resonant controller with resonant harmonic compensator and fault ride through techniques was discussed in [17]. Different topologies of SAF connected to four wire system is discussed in [18]. In [19] and [20], it was described how to reduce harmonics using a single phase SAF based on instantaneous pq theory for cascaded multilevel inverters. Adaptive fuzzy global sliding mode control and model predictive current control techniques for shunt active filters is discussed in [21] & [22].

The contributions of the paper are stated below:

1. A Seventeen level reduced switch multilevel inverter is proposed with lower harmonic distortion and reduced switch count when compared to conventional Multilevel Inverters.

2. In order to control the RSMLI various carrier based hybrid modulation Techniques are compared and proposed a triangular saturated carrier waves and unipolar third harmonic injected wave as reference which yields better output.

3. The performance is carried out with different Modulation indices (MI).

The proposed RSMLI is applied to shunt active filter application with different nonlinear load conditions with PI and ANN Controllers.

II. PROPOSED SEVENTEEN LEVEL RSMLI TOPOLOGY

The block diagram of proposed 17 level RSMLI is shown in fig.1. and reduced switch MLI based Shunt active filter is shown in Fig.1 below. This consists of a H-bridge configuration which acts as a polarity changing unit which produces positive and negative voltages along with zero voltage. The proposed topology is symmetric in nature which means all the voltage source carry same voltage which is +Vdc. The switching states are provided in the Table 1. The hybrid pulse width modulation technique in which triangle saturated carrier wave is used and third harmonic injection is used as reference which is shown in fig.2.

An uncomplicated technique for generating reference currents involves the time domain-based p-q method. In this approach, the three-phase load current, observed in the a-b-c stationary frame, is transformed into its direct and quadrature axis components. This process facilitates the straightforward mitigation of harmonic components within the load current using a low-pass filter (LPF) [9] – [12]. The block diagram of SAPF with p-q theory is shown in fig.3.

III. CONTROL SCHEMES FOR RSMLI-SAPF

PI Control Design:

The PI controller transfer function is given by Eq.1

$$H_{PI}(s) = Kp + \frac{Ki}{s} \text{--------} \quad (1)$$

The proportional gain (KP) is determined through the equation KP = 2ξωnC, which defines the dynamic response of voltage control on the DC side. The integralgain (KI), which affects the control system's settling time, is also determined using the formula KI = Cωn^2. while controlling the DC-link voltage using a PI controller, inverter losses are taken into account while adjusting the amplitude of active current from the APF inverter to keep the DC link voltage at the appropriate reference level. The reference value for the APF current is produced by deducting the measured load current.

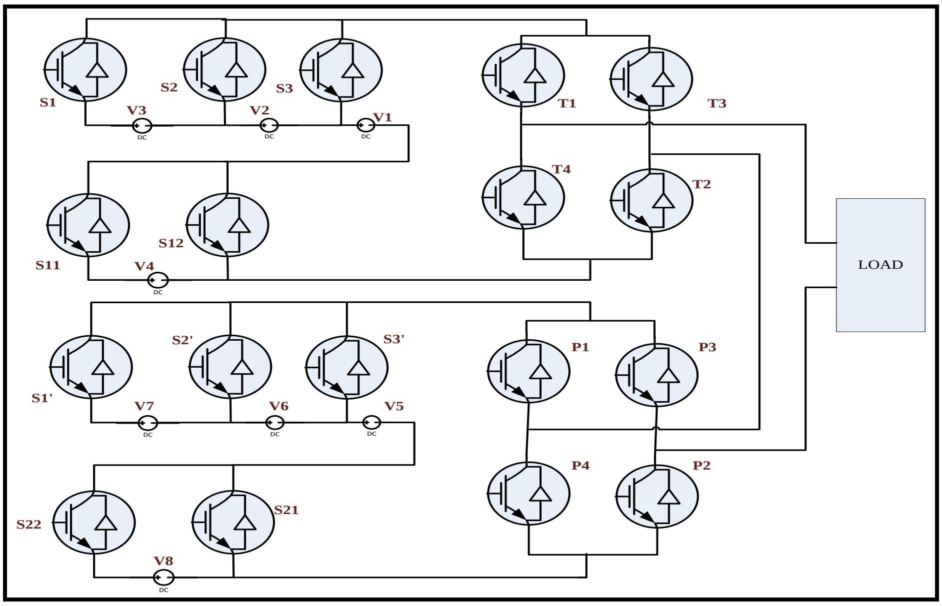

Fig.1. Proposed Seventeen level RSMLI Topology

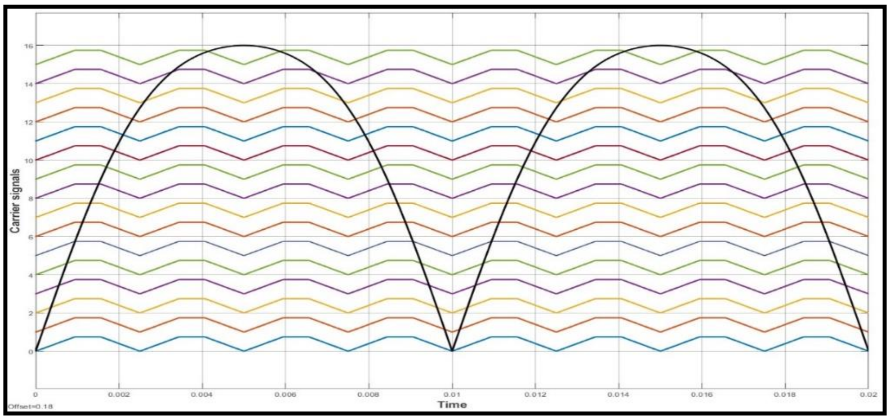

Fig.2. Hybrid Pulse Width Modulation

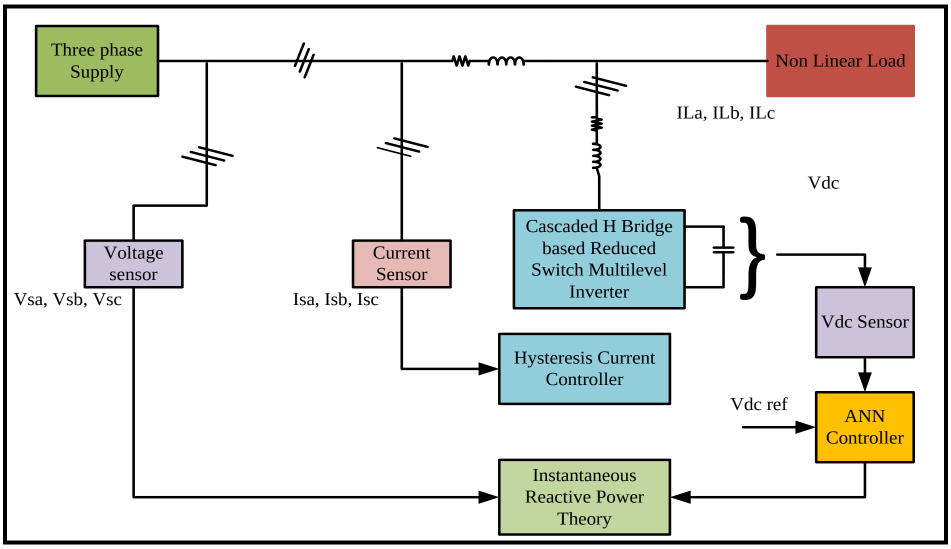

Fig.3. Block Diagram of RSMLI-SAF based p-q Theory

Table 1: Switching Pattern of Seventeen level RSMLI

S1	S2	S3	S1’	S2’	S3’	S11	S12	S22	S21	P1	P2	P3	P4	T1	T2	T3	T4	V0
0	0	1	0	0	0	0	1	0	0	1	0	1	0	1	1	0	0	+ V dc
0	1	0	0	0	0	0	1	0	0	1	0	1	0	1	1	0	0	+ 2 Vdc
1	0	0	0	0	0	0	1	0	0	1	0	1	0	1	1	0	0	+ 3 Vdc
1	0	0	0	0	0	1	0	0	0	1	0	1	0	1	1	0	0	+ 4 Vdc
1	0	0	0	0	1	1	0	0	1	1	1	0	0	1	1	0	0	+ 5
1	0	0	0	1	0	1	0	0	1	1	1	0	0	1	1	0	0	+ 6
1	0	0	1	0	0	1	0	0	1	1	1	0	0	1	1	0	0	+ 7
1	0	0	1	0	0	1	0	1	0	1	1	0	0	1	1	0	0	+ 8
0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	1	0	0
0	0	1	0	0	0	0	1	0	0	1	0	1	0	0	0	1	1	- Vdc
0	1	0	0	0	0	0	1	0	0	1	0	1	0	0	0	1	1	- 2 Vdc
1	0	0	0	0	0	0	1	0	0	1	0	1	0	0	0	1	1	-3 Vdc
1	0	0	0	0	0	1	0	0	0	1	0	1	0	0	0	1	1	-4 Vdc
1	0	0	0	0	1	1	0	0	1	0	0	1	1	0	0	1	1	-5
1	0	0	0	1	0	1	0	0	1	0	0	1	1	0	0	1	1	-6
1	0	0	1	0	0	1	0	0	1	0	0	1	1	0	0	1	1	-7
1	0	0	1	0	0	1	0	1	0	0	0	1	1	0	0	1	1	-8

ANN Based Control for reference current generation:

This study employs the p-q theory's representation, illustrated in Fig.4, utilizing ANN controllers. The ANN comprises two hidden layers, each containing 12neurons, and an outputlayer with 3 neurons. The activation function is utilized for the hidden layers' neurons, while the output layer neurons utilize a linear activation function.

As depicted in Figure 5, the ANN is designed with seven inputs (Vsa, Vsb, Vsc, Vdc; isa, isb, isc) and three outputs (i*ca, i*cb,i*cc), aligning with the principles of the p-q theory. The neuron configuration for the hidden layers is shown in Figure 5, where each neuron receives a variable number of inputs. This number, denoted as 'n,' varies based on the specific hidden layer; n is 7 for neurons in hidden layer 1 and 12 for neurons in hidden layer 2. For neurons in the output layer, n is set to 12.

Within the ANN, weights (W) and biases (b) are adjusted in two steps. By comparing the results of the p-q approach with those produced by the ANN, it is possible to determine the mean square error (MSE) in the beginning. In order to improve these weights and biases, the 'Levenberg-Marquardt backpropagation' algorithm is then used.

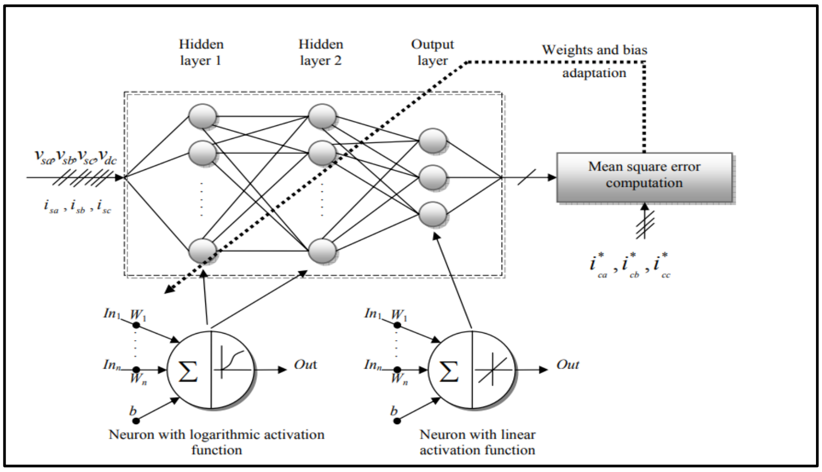

Fig.4.Neural Network for p-q theory

IV. SIMULATION RESULTS AND DISCUSSION

The implementation of the 17 level Reduced Switch Multilevel Inverter (RSMLI) is utilized for the purpose of applying SAF to the voltage source inverter (VSI) segment. A non-linear load, consisting of the rectifier unit with RL load, is interlinked with a three-phase source system that has a voltage of 415 V and operates at a frequency of 50 Hz. The current drawn from the system by the non-linear load produces distortion in the current waveforms, thereby affecting the harmonic level, as demonstrated in Fig 5 & 6. Consequently, SAPF is connected to the system at PCC location through a coupling transformer to minimize the harmonic level. Fig.7 shows the voltage states and voltage magnitude of the 17 level RSMLI. By altering the MI the resulting output can be modified. If source voltage magnitude (V_{dc}) remains constant, increasing the MI can lead to a higher voltage magnitude. The inverter's output voltage level is influenced by the MI, and various MIs like 0.7, 0.8, 0.9, and 1 are tested. The outcomes demonstrate that the suggested RSMLI has the ability to amplify or attenuate the output voltage, which is contingent on the Modulation Index shown in fig.7.

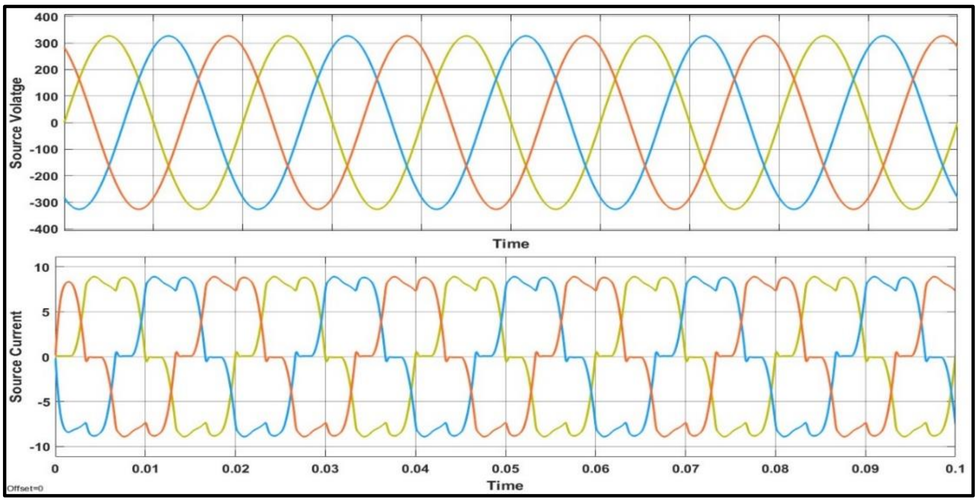

Fig.5. Source current and Voltage Waveforms Without SAPF

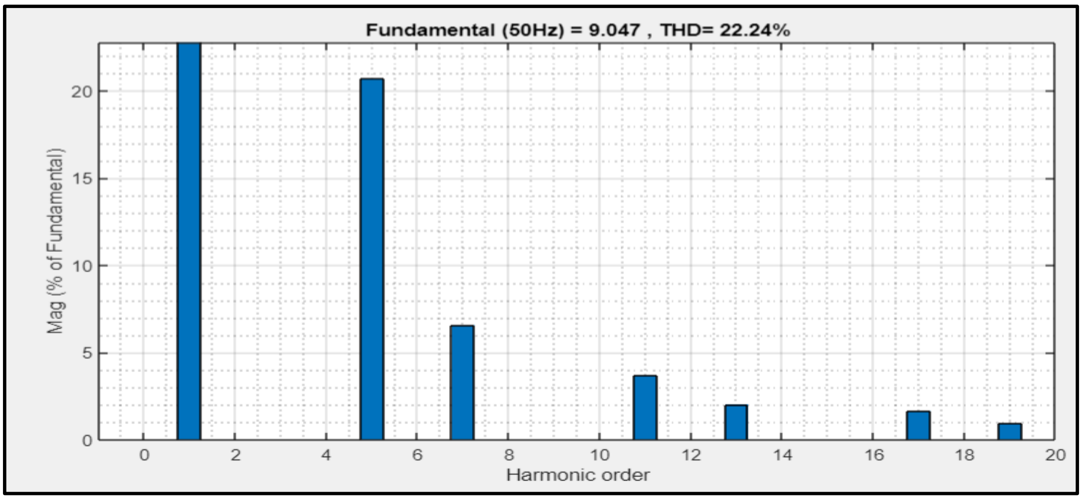

Fig.6. THD Without SAPF

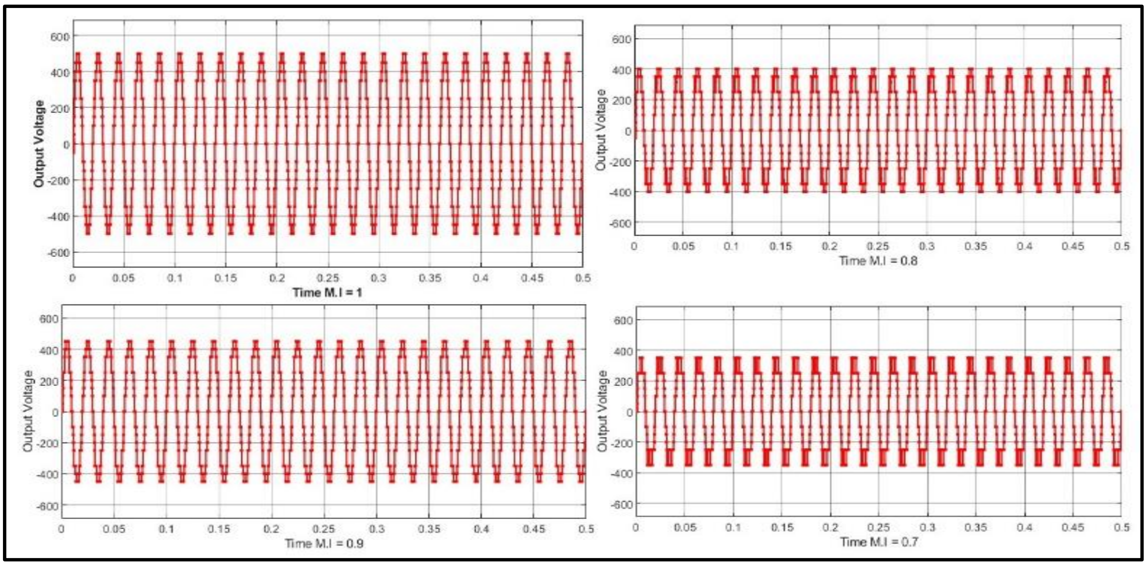

Fig.7. Output Voltage Waveforms for Various MI’s

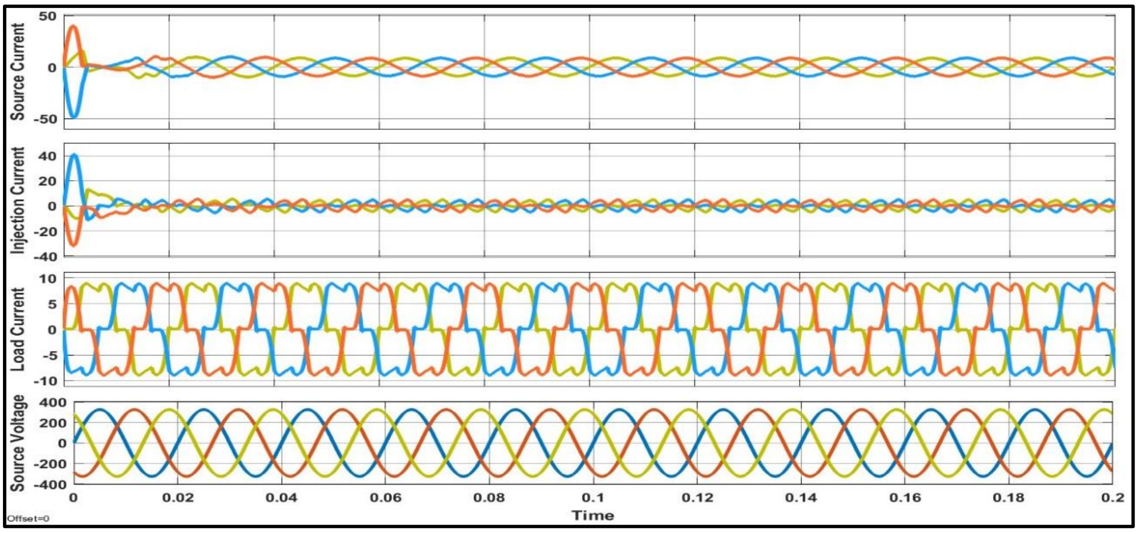

Fig.8. Source current Waveform with PI Controller

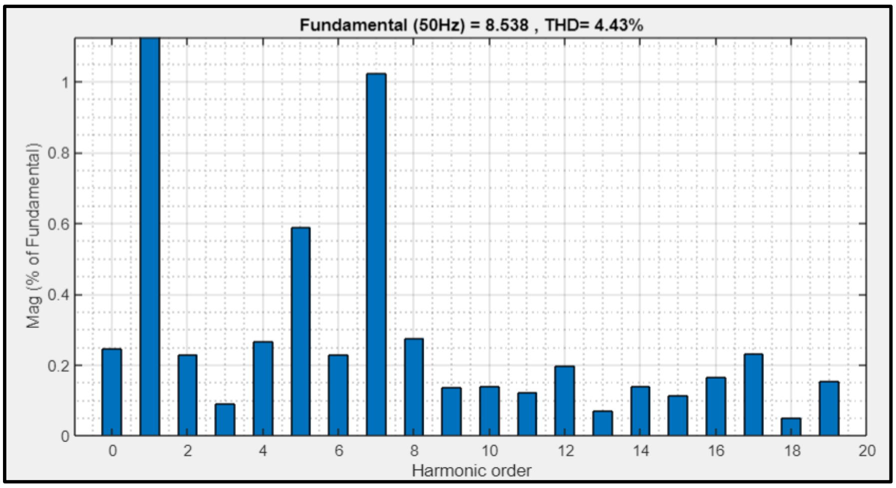

Fig.9.THD with PI Controller

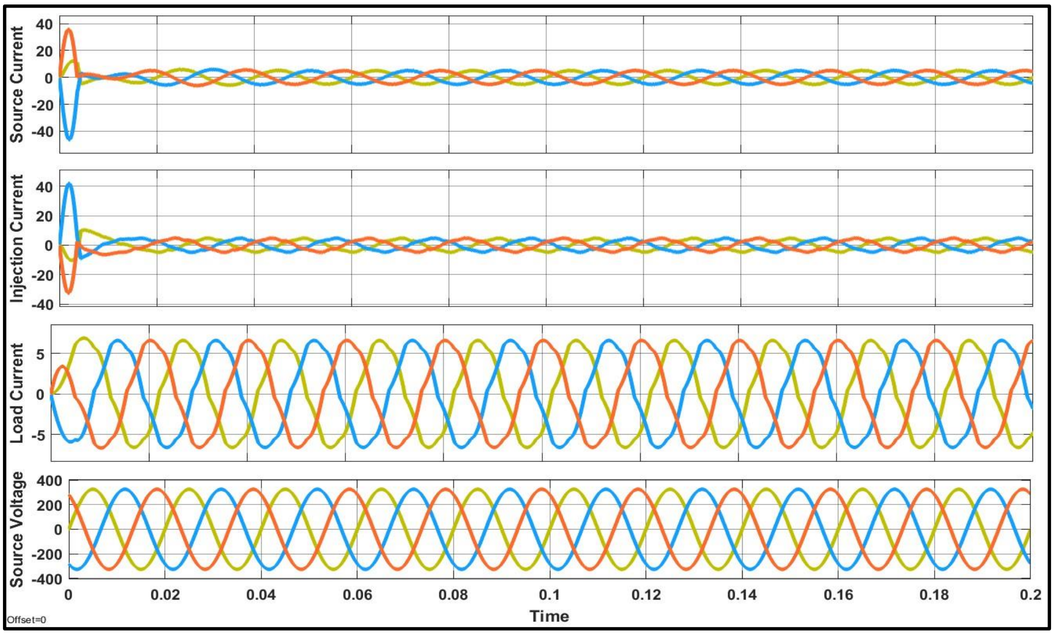

Fig.10. Source current Waveform with ANN Controller

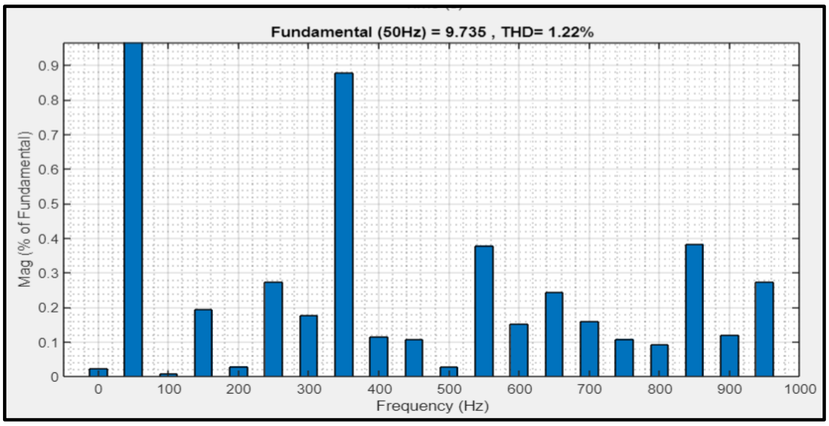

Fig.11. Source current Waveform with ANN Controller

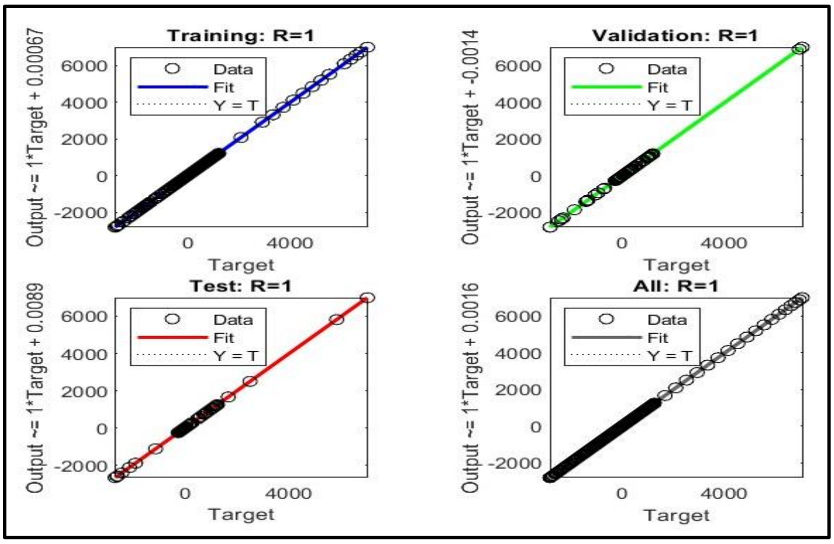

Fig.12. Mean Error

Table 2: THD Analysis of SAF

References	Controllers	%THD	
		Before Compensation	**After Compensation**
Proposed Controllers	PWM	22.24%	7.37%
	PI-PWM	22.24%	4.43%
	ANN-PWM	22.24%	1.22%
[18]	PI-PWM	33.0%	3.5%
[19]	Model Predictive Controller	40.19%	2.94%
	Predictive PWM Controller	40.19%	4.79%
	Hysteresis Controller	40.19%	3.67%

It is evident from the Table 2 and simulation results obtained that source current THD is lowered down to below 5% using PI control and neural network control. It is seen that the THD is 28% with uncompensated system. All the control schemes are successful in lowering THD in source current below 5% shown in Fig. 8 & 9. It is also observed that from period 0 to 0.022 sec there are distortions in the source current waveform and from 0.02 sec the source current is transformed into pure sinusoidal waveform. However neural network control is found to be proficient and provides THD less than 3% also the settling time of source current harmonics is 0.012 sec proves better settling time than PI controller which is shown in Fig.10 & 11. By using Levenberg-Marquardt Back Propagation ANN Algorithm method, Fig. 12 depicts the mean error (ME) graph in off-retraining. There have been three data segments: 70 percent of the total for instruction, 15 percent respectively for confirmation, plus 15 percent of the total number for assessment. The performance will improve with decreasing ME. The reduced switch MLI based SAF provides improved THD when compared to the previous findings cited in [21] conventional PI controller is used and THD after compensation was found to be 3.5% and reference cited in [22] uses Model Predictive controllers and Hysteresis Controllers and THD is found to be more than the proposed topology.

V. CONCLUSION & FUTURE WORK

This paper is presented for Seventeen level reduced switch MLI based SAF for compensation of source current harmonics. A reference current is generated using synchronous reference frame theory. Triangle saturated multi carrier based phase disposition PWM using unipolar Third Harmonic Injection as reference is used. The proposed

RSMLI-SAPF uses PI and ANN controllers and THD's are compared. The comparison proves the ability of ANN controller for the proposed RSMLI-SAF application.

The following observations, which can be summed up as follows, have been made as a result of the research findings:

1) A three phase seventeen level inverter with fewer switches is presented, and simulation is performed to assess system performance in terms of THD.
2) PI and Neural Networks controllers were used to carry out stability analysis.
3) Various ranges of Modulation index are used to test the suitability of the proposed inverter.
4) Table 2 shows THD response for the PI controller and the neural network controller is 4.59% and 1.67%, respectively, after compensation, demonstrating that the suggested SAF can reduce the current harmonics to below 5% in accordance with IEEE-519 standards.

The proposed study can be carried out experimentally in the future, and the following results can be confirmed. Further various nonlinear control techniques can be explored and implemented to further improve the power quality and robustness of the filter.

REFERENCES

[1] Venkatesan, M., B. Adhavan, K. Suresh, K. Balachander, and M. Lordwin Cencil Prabakar. "Research on FPGA Controlled Three Phase PV Inverter Using Multi Carrier PWM Control Schemes." *Microprocessors and Microsystems* 76 (July 2020): 103089. https://doi.org/10.1016/j.micpro.2020.103089.

[2] De Almeida Carlos, Gregory Arthur, Cursino Brandao Jacobina, Joao Paulo Ramos Agra Mello, and Euzeli Cipriano Dos Santos. "Shunt Active Power Filter Based on Cascaded Transformers Coupled With Three-Phase Bridge Converters." *IEEE Transactions on Idustry Applications* 53, no. 5 (September 2017): 4673–81. https://doi.org/10.1109/TIA.2017.2702666.

[3] De Almeida Carlos, Gregory A., Cursino B. Jacobina, and Euzeli C. Dos Santos. "Alternative Breed of Three-Phase Four-Wire Shunt Compensators Based on Cascaded Transformer with Single Dc-Link." In *2017 IEEE Applied Power Electronics Conference and Exposition (APEC)*, 3321–28. Tampa, FL, USA: IEEE, 2017. https://doi.org/10.1109/APEC.2017.7931173.

[4] Samadaei, Emad, Mohammad Kaviani, and Kent Bertilsson. "A 13-Levels Module (K-Type) With Two DC Sources for Multilevel Inverters." *IEEE Transactions on Industrial Electronics* 66, no. 7 (July 2019): 5186–96. https://doi.org/10.1109/TIE.2018.2868325.

[5] Park, Byungju, Jaehyeong Lee, Hangkyu Yoo, and Gilsoo Jang. "Harmonic Mitigation Using Passive Harmonic Filters: Case Study in a Steel Mill Power System." *Energies* 14, no. 8 (April 18, 2021): 2278. https://doi.org/10.3390/en14082278.

[6] Rajagopal, Ragam, K. Palanisamy, and S. Paramasivam. "Shunt Active Filter Based on 7-Level Cascaded Multilevel Inverter for Harmonic and Reactive Power Compensation." *Journal of Electrical Engineering & Technology* 14, no. 4 (July 2019): 1543–51. https://doi.org/10.1007/s42835-019-00201-1.

[7] Samadaei, Emad, Sayyed Asghar Gholamian, Abdolreza Sheikholeslami, and Jafar Adabi. "An Envelope Type (E-Type) Module: Asymmetric Multilevel Inverters With Reduced Components." *IEEE Transactions on Industrial Electronics* 63, no. 11 (November 2016): 7148–56. https://doi.org/10.1109/TIE.2016.2520913.

[8] Kumar, Ravinder, and Hari Om Bansal. "Shunt Active Power Filter: Current Status of Control Techniques and Its Integration to Renewable Energy Sources." *Sustainable Cities and Society* 42 (October 2018): 574–92. https://doi.org/10.1016/j.scs.2018.07.002.

[9] Gautam, Shivam Prakash, Lalit Kumar, and Shubhrata Gupta. "Hybrid Topology of Symmetrical Multilevel Inverter Using Less Number of Devices." *IET Power Electronics* 8, no. 11 (November 2015): 2125–35. https://doi.org/10.1049/iet-pel.2015.0037.

[10] Gautam, Shivam Prakash, Lalit Kumar Sahu, and Shubhrata Gupta. "Reduction in Number of Devices for Symmetrical and Asymmetrical Multilevel Inverters." *IET Power Electronics* 9, no. 4 (March 2016): 698–709. https://doi.org/10.1049/iet-pel.2015.0176.

[11] Son, Gibong, Hye-Jin Kim, and Bo-Hyung Cho. "Improved Modulated Carrier Control With On-Time Doubler for a Single-Phase Shunt Active Power Filter." *IEEE Transactions on Power Electronics* 33, no. 2 (February 2018): 1715–23. https://doi.org/10.1109/TPEL.2017.2682794.

[12] Omran, Mohamed Asghaiyer, Izzeldin. I. Ibrahim, Abu Zaharin Ahmad, Mohamed Salem, Mohamad Milood Almelian, Awang Jusoh, and Tole Sutikno. "Comparisons of PI and ANN Controllers for Shunt HPF Based on STF-PQ Algorithm under Distorted Grid Voltage." *International Journal of Power Electronics and Drive Systems (IJPEDS)* 10, no. 3 (September 1, 2019): 1339. https://doi.org/10.11591/ijpeds.v10.i3.pp1339-1346.

[13] Talebkhah, Amin, Milad Samady Shadlu, and Seyyed Majid Fatemi. "Control Strategy of a Single Phase Active Power Filter with Adjustable DC Link Capacitor Voltage for THD Reduction in Non-Linear Loads." In *2019 10th International Power Electronics, Drive Systems and Technologies Conference (PEDSTC)*, 606–11. Shiraz, Iran: IEEE, 2019. https://doi.org/10.1109/PEDSTC.2019.8697234.

[14] Hoon, Yap, Mohd Amran Mohd Radzi, Muhammad Ammirrul Atiqi Mohd Zainuri, and Mohamad Adzhar Md Zawawi. "Shunt Active Power Filter: A Review on Phase Synchronization Control Techniques." *Electronics* 8, no. 7 (July 15, 2019): 791. https://doi.org/10.3390/electronics8070791.

[15] Islam, Saif, Kamran Zeb, Waqar Din, Imran Khan, Muhammad Ishfaq, Tiago Busarello, and Hee Kim. "Design of a Proportional Resonant Controller with Resonant Harmonic Compensator and Fault Ride Trough Strategies for a Grid-Connected Photovoltaic System." *Electronics* 7, no. 12 (December 19, 2018): 451. https://doi.org/10.3390/electronics7120451.

[16] Fabricio, Edgard Luiz Lopes, Samuel Carvalho Silva Junior, Cursino Brandao Jacobina, and Mauricio Beltrao De Rossiter Correa. "Analysis of Main Topologies of Shunt Active Power Filters Applied to Four-Wire Systems." *IEEE Transactions on Power Electronics* 33, no. 3 (March 2018): 2100–2112. https://doi.org/10.1109/TPEL.2017.2698439.

[17] Lada, Musa Yusup, Sabiq Safiuddin Mohamad, Johar Akbar Mohamat Gani, Mohamad Riduwan Md Nawawi, and Gan Chin Kim. "Reduction of Harmonic Using Single Phase Shunt Active Power Filter Based on Instantaneous Power Theory for Cascaded Multilevel Inverter." In *2016 IEEE International Conference on Power and Energy (PECon)*, 702–6. Melaka, Malaysia: IEEE, 2016. https://doi.org/10.1109/PECON.2016.7951650.

[18] Hou, Shixi, Juntao Fei, Yundi Chu, and Chen Chen. "Experimental Investigation of Adaptive Fuzzy Global Sliding Mode Control of Single-Phase Shunt Active Power Filters." *IEEE Access* 7 (2019): 64442–49. https://doi.org/10.1109/ACCESS.2019.2917020.

[19] Kanagavel, Rameshkumar, Indragandhi Vairavasundaram, and Sanjeevikumar Padmanaban. "Design and Prototyping of Single-phase Shunt Active Power Filter for Harmonics Elimination Using Model Predictive Current Control." *International Transactions on Electrical Energy Systems* 30, no. 2 (February 2020). https://doi.org/10.1002/2050-7038.12231.