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ANFIS control of a shunt active filter based with a five-level NPC inverter to improve power quality

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ABSTRACT

This paper addresses the problem of power quality, and the degradation of the current waveform in the distribution network which results directly from the proliferation of the nonlinear loads. We propose to use a five-level neutral point clamped (NPC) inverter topology for the implementation of the shunt active filter (SAPF). The aim of the SAPF is to inject harmonic currents in phase opposition at the connection point. The identification of harmonics is based on the pq method. A neuro-fuzzy controller based on ANFIS (adaptive neuro fuzzy inference system) is designed for the SAPF. The simulation study is carried out using MATLAB/Simulink and the results show a significant improvement in the quality of energy and a reduction in total harmonic distortion (THD) in accordance with IEC standard, IEEE-519, IEC 61000, EN 50160.

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1. INTRODUCTION

In recent years, power quality has become a great concern due to the widespread use of non-linear loads which has resulted in increased voltage distortion and current harmonics [1, 2]. Harmonics circulate into the impedances of electrical networks and impact the normal operation of certain electrical equipment. They lead to performance degradation, and can even damage the equipment in the long-term, because they affect the grid voltage waveform at the connection point, and they can also increase reactive power consumption. Several modern solutions have been proposed to reduce these harmonic disturbances, such as shunt active filters, series active filters, and the shunt-series active combination, which is better suited for industrial constraints than conventional passive filters [3, 4].

Multi-level inverters (MLI) have been extensively used in many recent applications because of their ability to handle high voltage capacity.However, increasing the complexity of the converter topology and the number of switching devices is a major disadvantage of multi-level converters [5, 6]. MLIs include a range of power semiconductors and capacitor voltage sources which can be combined to generate outputs voltages with stepped voltage waveforms. There are three different basic topologies of the multilevel converter, namely the neutral point clamped (NPC), the flying capacitors (FC) and the cascaded H-bridge (CHB) topologies [7]. Technically, the shunt active power filter (SAPF) is designed to produce a certain amount of current to be injected into the electrical network in order to drain out the harmonic components of the current or voltage signals. The amount of injected current is controlled based on the error between the reference and the measured current/voltage signals [8]. This error is then converted into pulse width modulation (PWM) signal to control the inverter. From the power electronics point of view, this process is quite similar with the voltage/current source inverter [9].

In this work, the SAPF based on a five-level NPC voltage inverter is controlled by ANFIS connected to a passive R-L series output filter and injects equal harmonic currents, but in phase opposition with that of the harmonics generated by the non-linear load in the network. A simulation study is presented to demonstrate the compensation performance of the SAPF and associated ANFIS control scheme under steady state operating conditions and the improvement in power quality [10].

2. MODELING AND CONTROL OF THE SAPF

2.1. Topologies of multilevel inverters

Multilevel converters seen as voltage synthesizers, in which the output voltage is synthesized from several discrete voltage levels [11, 12]. Figure 1 shows the different multilevel converter topologies.

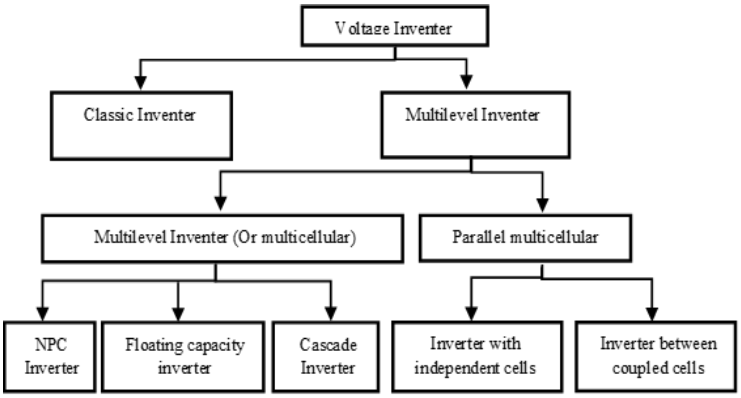

Figure 1. Different topologies of multi-level converters [13]

2.2. Structure of the five-level NPC inverter

The neutral-point-clamped (NPC) structure was proposed, by Nabae *et al.*, [14]. A three-phase five-level NPC inverter is composed of eight controlled switches, which are unidirectional in voltage, and bidirectional in current, and six sustaining diodes connected along the DC bus as shown in Figure 2.

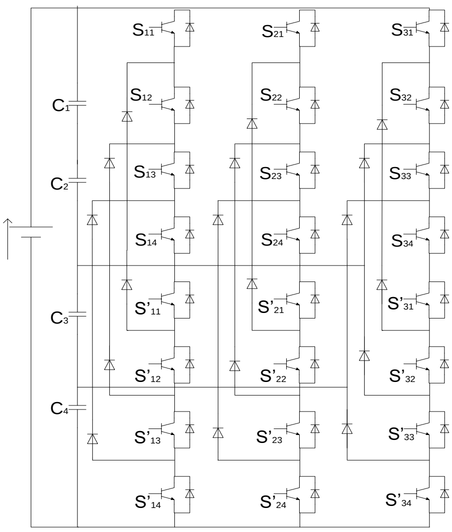

Figure 2. Circuit diagram of a three-phase NPC inverter with five levels [12]

The inverter is supplied from a DC source Vdc, consisting of four capacitors of equal values which generate four separate svoltage sources of Vdc/4 [6, 15]. The clamping diodes connected to the midpoints of the voltage sources protect the external switches against excessive voltages. In addition, the number of diodes increases with the number of levels [16].

2.3. Operation principle of a five-level inverter arm

Because of the symmetry of the three-phase, five-level NPC inverter structure, only one arm is modeled [17]. Its configuration is depicted in Figure 3. Table 1 shows the output voltage (Vao) and the states of the switches. State "1" represents the closed switch and state "0" represents the open switch.

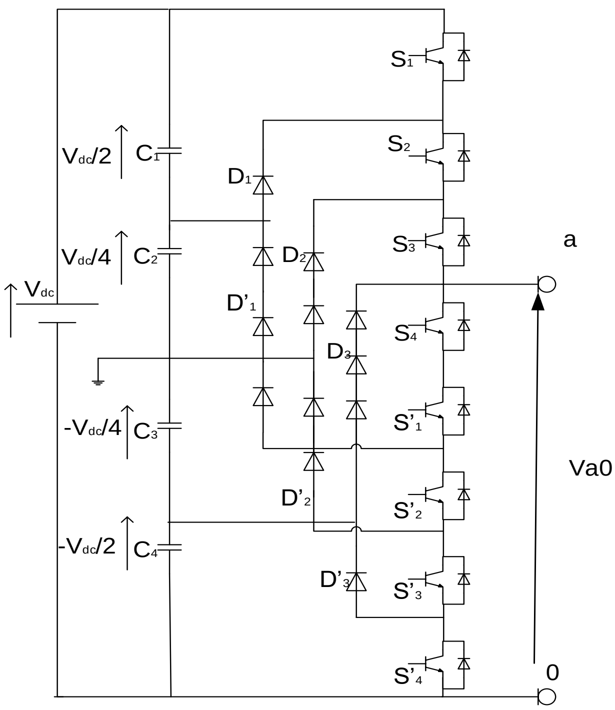

Figure 3. Structure of an NPC five-level inverter arm

Table 1. Output voltage and switch states of a five-level NPC inverter

switch states								Out V_{ao}
S_1	S_2	S_3	S_4	$S_{'1}$	$S_{'2}$	$S_{'3}$	$S_{'4}$	
1	1	1	1	0	0	0	0	$V_5 = V_{dc}$
0	1	1	1	1	0	0	0	$V_4 = V_{dc/4}$
0	0	1	1	1	1	0	0	$V_3 = V_{dc/2}$
0	0	0	1	1	1	1	0	$V_2 = V_{dc/4}$
0	0	0	0	1	1	1	1	$V_1 = 0$

2.4. Shunt active power filter based on a five-level NPC inverter topology

Active filters are used to reduce harmonics generated by non-linear industrial loads. Usually the control circuit of the filter detects the non-linear load harmonics and controls the active filter to inject the compensating harmonic with an opposite phase [4]. The expression of the load current is:

$$i_L(t) = i_\alpha(t) + i_\beta(t) + i_H(t) \quad (1)$$

where $i_\alpha(t)$ is in phase component and $i_\beta(t)$ is quadrature component of phase current at fundamental frequency. Except these, all the remaining in $i_H(t)$ [18].

Figure 4 represents the configuration of the power circuit of the system contains SAPF based on an inverter with five levels NPC, to compensate for the harmonics of currents generated by a non-linear load.

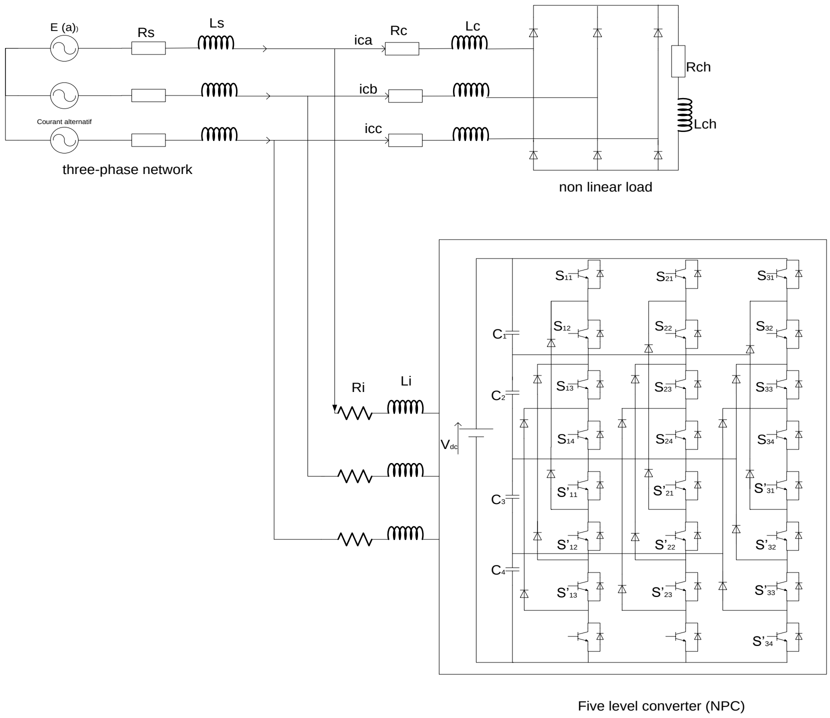

Figure 4. Synoptic diagram of application of the shunt active power filter (SAPF) [19]

2.5. Control algorithm

The quality of the compensation of current harmonics strongly depends on the performance of the chosen identification method; even a very effective control system cannot achieve satisfactory filtering if the harmonic currents are poorly identified [20]. To generate the reference signals used for the control of the SAPF, we chose the method of instantaneous active and reactive powers p-q [21, 22]. This method requires the measurement of instantaneous three-phase quantities of the electric network. The voltages at the connection points and the currents absorbed by the non-linear polluting load can represented by the components of Concordia.

$$\begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{s1} \\ V_{s2} \\ V_{s3} \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} I_{c\alpha} \\ I_{c\beta} \end{bmatrix} \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{c1} \\ I_{c2} \\ I_{c3} \end{bmatrix} \quad (3)$$

The active instantaneous real power p, and the reactive power q, can be expressed by a two-phase system:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_{s\alpha} & V_{s\beta} \\ -V_{s\beta} & V_{s\alpha} \end{bmatrix} \begin{bmatrix} I_{c\alpha} \\ I_{c\beta} \end{bmatrix} \quad (4)$$

The instantaneous power can be expressed as (5).

$$p = p_c + p_h \quad , \quad q = q_c + q_h \quad (5)$$

To eliminate the continuous components, two low-pass filters of order 2 are used. The reference currents are calculated as (6) and (7).

$$\begin{bmatrix} \mathrm{I_{ref\alpha}} \\ \mathrm{I_{ref\beta}} \end{bmatrix} = \frac{1}{\mathrm{V_{s\alpha}^2 + \; V_{s\beta}^2}} \begin{bmatrix} \mathrm{V_{s\alpha}} & -\mathrm{V_{s\beta}} \\ \mathrm{V_{s\beta}} & \mathrm{V_{s\alpha}} \end{bmatrix} \begin{bmatrix} \mathrm{p_h} \\ \mathrm{q_h} \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} I_{ref1} \\ I_{ref2} \\ I_{ref3} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} Iref_{\alpha} \\ Iref_{\beta} \end{bmatrix} \quad (7)$$

3. ADAPTIVE NEURO FUZZY INFERENCE SYSTEM (ANFIS) SYNTHESIS

ANFIS incorporates the concepts of fuzzy logic into neural networks. This neuro-fuzzy model maps the relationship between input and output of a process. It based on fuzzy rules. "If ... then" by Takagi and Sugéno [20]. ANFIS optimizes the membership functions of the fuzzy model [23]. For simplicity, we suppose that the fuzzy Inference system considered has two inputs (x y) and an output f (x y) Figure 5. The basis of the rules is of the form:

If x is $A1$ and y is $B1$ then $f1 = p1x + q1y + r1$
If x is $A2$ and y is $B2$ then $f2 = p2x + q2y + r2$

where (x y) are the inputs, A1, A2, B1, and B2: are fuzzy sets, f1, f2: are the outputs of the fuzzy system, p1, p2, q1, q2, r1, r2: are design parameters, which are determined during the training process. The final output is the weighted average of the output of each rule.

3.1. Structure of ANFIS

Figure 5 shows the structure of ANFIS or in which a circle indicates a fixed node while a square indicates an adaptive node. The fuzzy logic controller has two inputs, the error and rate of change of the error, and one output named actuating (actuation). The error is the difference between the current data of the voltage source inverter and the reference current data for each phase.

$$E_{error} = I_{inj} + I_{ref} \quad (8)$$

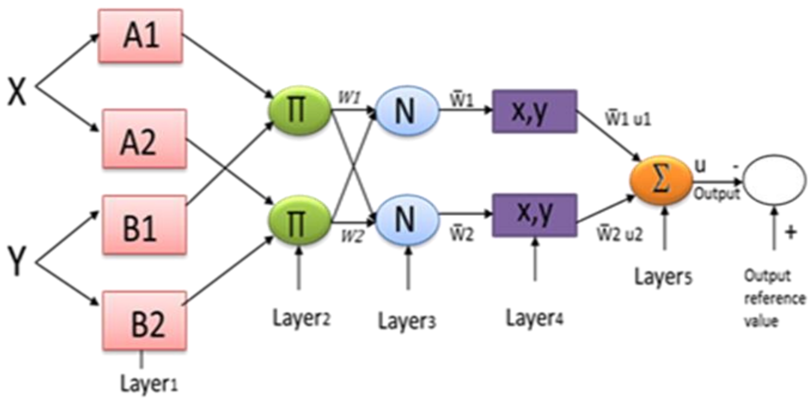

Figure 5. Structure of ANFIS [20, 24]

3.2. Description of the proposed system

The five-level NPC SAPF controlled by ANFIS is designed to attenuate the current harmonics, and compensate for reactive power [25]. The basic equations for the SAPF and the system can given as (9-11).

$$V_{sa} = v_a + R_f I_{fa} + L_f \frac{d}{dt} I_{fa} \quad (9)$$

$$V_{sb} = v_b + R_f I_{fb} + L_f \frac{d}{dt} I_{fb} \quad (10)$$

$$V_{sc} = v_c + R_f I_{fc} + L_f \frac{d}{dt} I_{fc} \quad (11)$$

The block diagram of the proposed overall system divided into six sections as shown in Figure 6.

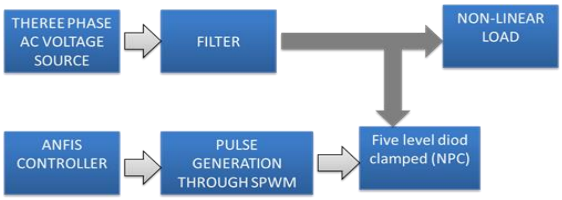

Figure 6. Functional diagram of the SAPF based on the ANFIS controller [23]

4. SIMULATION RESULTS

The model of the SAPF and its control scheme are implemented in MATLAB. The proposed ANFIS-based controller is compared with a conventional PI controller with respect to the THD level and the results are presented below.

4.1. Simulation parameters

The Table 2 represents the necessary data of the parts of the system for the simulation by Matlab/Simulink such as -the source, -the nonlinear load, -the load of the rectifier, -SAPF and the data Ki and Kp of the PI controller.

Table 2. Simulation parameters

Source side	Vs=220 V between phase; f=50 Hz; Rs=0 Ω; Ls=1.5 mH
Dimensioned nonlinear load	R_C=4 Ω; L_C=70 mH
Rectifier side	Rch=100 Ω; Lch=0.1 µF
Shunt active filter side	$V_{dc\text{-}ref}$ =900 V; C_{dc}=2200 µF; R_i=1 Ω; L_i=1 mH
Proportional integral regulator (PI)	Ki=37; Kp=300

4.2. Description of the simulation results

Figure 7 indicates the source current wave and the corresponding harmonic spectra before filter operation (SAPF), before filtering. Figure 8 represents the source current simulation results for phase (A) during the SAPF control by PI, after filtering. Simulation results of the source current of phase (A) when the SAPF is controlled by an ANFIS controller represent in Figure 9. The shape of the current injected by the SAPF controller by ANFIS shown in Figure 10 and the shape of the DC bus voltage (DC-Link) during the control by ANFIS of the filter shown in Figure 11.

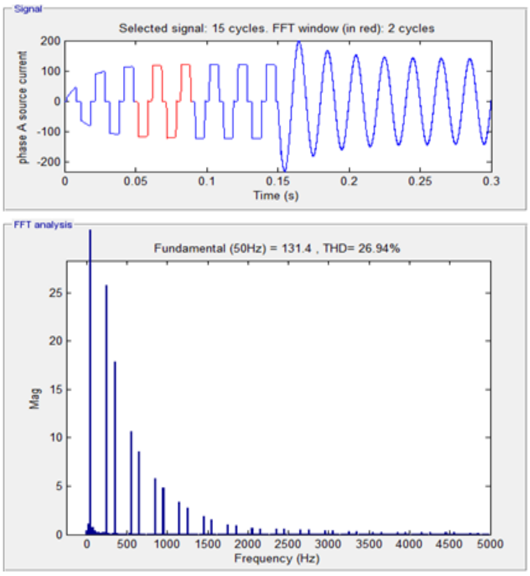

Figure 7. Source current (Phase A) without SAPF and the harmonic spectrum of the source current

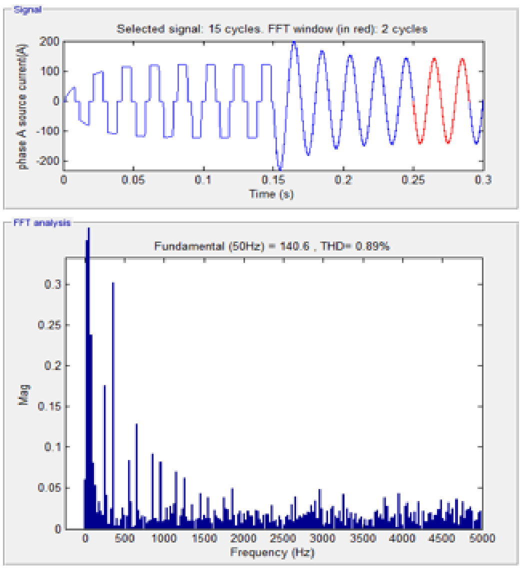

Figure 8. Source current (phase A) with SAPF and the harmonic spectrum of the source current using PI controler

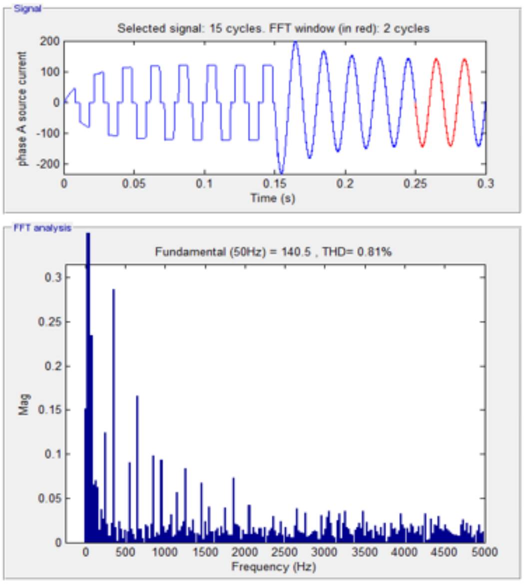

Figure 9. Source current (phase A) with SAPF and the harmonic spectrum of the source current using ANFIS-based controller

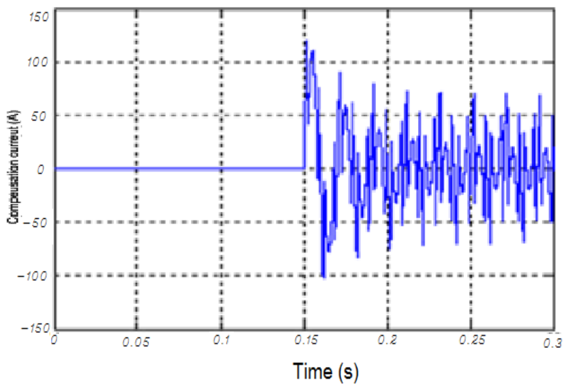

Figure 10. Compensation of the current using ANFIS controller

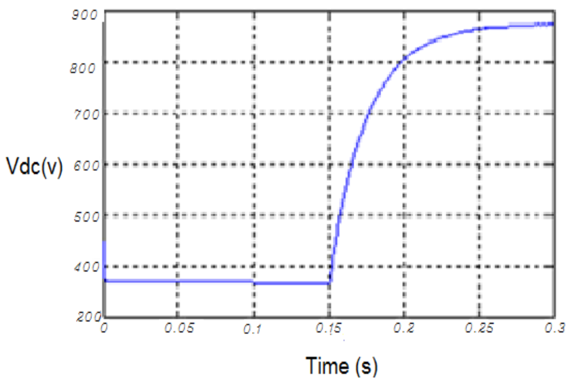

Figure 11. DC voltage using ANFIS controller

5. CONCLUSION

The shunt active power filter based in five-level inverter (NPC) is designed for the suppression of harmonics. The proposed control scheme consists of two-control loops. One control-loop regulates the DC link voltage and the other loop controls the AC voltage. A THD level of 0.89% is achieved with PI controller and in the case of ANFIS-based control of the SAPF the THD is 0.81%. Hence it can be concluded that the proposed ANFIS-based controller of SAPF with five-level converter leads to a substantial improvement of the THD. In addition, the instantaneous power method has good performance in detecting reference harmonic currents and adapts well to the variations of the non-linear load. Combining this p-q control strategy with ANFIS based on the five-level inverter further improves dynamic behavior as well as power quality in the distribution network.

REFERENCES

[1] M. O. Mahmoud, W. Mamdouh, H. Khalil, "Source current harmonic mitigation of distorted voltage source by using shunt active power filter," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, no. 4, pp. 3967-3977, 2020.
[2] T. Toumi, et al., "Robust control of series active power filters for power quality enhancement in distribution grids: Simulation and experimental validation," *ISA Transactions*, 2020.

[3] B. Singh and V. Verma, "An improved hybrid filter for compensation of current and voltage harmonics for varying rectifier loads," *International Journal of Electrical Power and Energy Systems*, vol. 29, no. 4, pp. 312-321, 2007.
[4] M. Hacil, L. Zarour, L. Louze, A. L. Nemmour, "Developing a grid-connected DFIG strategy for the integration of wind power with harmonic current mitigation," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 9, no. 5, pp. 3905-3915, 2019
[5] K. Dhineshkumar, C. Subramani, A. Geetha, C. Vimala, "Performance analysis of PV powered multilevel inverter," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 9, no. 2, pp. 753-760, 2019.
[6] M. Jamma, M. Akherraz, M. Barar, "ANFIS Based DC-Link Voltage Control of PWM Rectifier-Inverter System with Enhanced Dynamic Performance," *IECON 2018-44th Annual Conference of the IEEE Industrial Electronics Society*, Washington, DC, 2018, pp. 2219-2224.
[7] K. Vasantha Sena, "Power Quality Improvement using Five Level Active Power Filter with SRF Control Technique," *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering (IJAREEIE)*, vol. 3, no. 7, pp. 10468-10476, 2014
[8] S. Khalid, and S. Kumar, "ANFIS-SCC Control of Shunt Active Power Filter for Minimization of Harmonic for More Electric Aircraft System," *IGI Global*, pp. 1-22, 2020.
[9] N. S. Hasan, N. Rosmin, S. Abd Khalid, et al., "Harmonic Suppression of Shunt Hybrid Filter using LQR-PSO based," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 7, no. 2, pp. 869-876, 2017.
[10] M. S. Kamel, and C. H. Ravi Kumar, "An ANFIS Based Control Strategy to Improve Performance of Shunt Active Power Filter for Renewable Power Generation Systems," *International Journal of Scientific Engineering and Technology Research (IJSETS)*, vol. 4, no. 26, pp. 4994-5002, 2015.
[11] S. Chennai, "Efficient Control Schema for Five-Level (NPC) Shunt Active Filters Based on Fuzzy Control Approaches," *Periodica Polytechnica Electrical Engineering and Computer Science*, vol. 60, no. 2, pp. 135-142, 2016.
[12] T. S. Kumar, and J. Shanmugam, "Application of ANFIS Controller to 3-Level NPC Based APF to Improve Power Quality," *Journal of Critical Reviews (JCR*), vol. 7, no. 14, pp. 318-321, 2020.
[13] M. Chabakata, "Analysis and control of multi-level converter for a photovoltaic generator connected to the electrical network," Doctoral Thesis, Paris-Saclay University, France, 2018.
[14] A. Nabae, I. Takahashi and H. Akagi, "A New Neutral-Point-Clamped PWM Inverter," *IEEE Transaction on Industry Application*, vol. IA-17, no. 5, pp. 518-523, 1981.
[15] M. Nadhir, "Contribution to the study of the Performance of Multilevel Inverters on Distribution Networks," Doctoral Thesis in Sciences, Badji Mokhtar University, Annaba, 2014
[16] K. Guepratte, "Three-phase inverter with innovative structure for aeronautical application," Doctoral dissertation, University of Grenoble, Thesis, Grenoble, 2011
[17] P. Aparna, B. Sanjay, "A Comparative analysis of classical three phase multilvel (five level) inverter topologies," *2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, Delhi, 2016, pp. 1-5.
[18] J. Choudhary, D. K. Singh, S. N. Verma, K. Ahmed, "Artificial Intelligence Based Control of a Shunt Active Power Filter," *Procedia Computer Science*, vol. 92, pp. 273-281, 2016.
[19] K. Benamrane, T. Abdelkrim, A. Benkhelifa, B. Bezza, "Modeling and Control of Three-Phase Multilevel Shunt Active Power Filter for Medium Voltage Applications," *African Review of Science, Technology and Development*, vol. 1, no. 1, 2016
[20] M. Radek, J. Manas, J. Zidek and P. Bilik, "Power Quality Improvement by Shunt Active Performance Filters Emulated by Artificial Intelligence Techniques," *Proceedings of the 2nd International Conference on Advances in Computer Science and Engineering (CSE 2013)*, 2013.
[21] M. A. Alali, "Contribution to the study of active compensators for low-voltage electrical networks," Doctoral thesis, doctoral school of engineering sciences, Louis Pasteur University, Strasbourg, France, 2002.
[22] H. Akagi, Y. Kanazawa, and A. Nabae, "Instantaneous reactive power compensators comprising switching devices without energy Storage components," *IEEE Transactions on Industry Applications*, vol. IA-20, no. 3, pp. 625-630, 1984.
[23] M. Sahu, and H. S. Thakur, "Design of anfis controller based shunt active filter for mitigation of harmonics in a three phase transmission line," *international journal of engineering sciences & research technology (IJESRT)*, vol. 7, no. 6, pp. 573-581, 2018.
[24] R. P. Maharuda, M. S. Nagaraj, P. S. Venkataramu, "Novel Design of a Neuro-Fuzzy (ANFIS) Controller to Improve the Power Dynamics for Minimization of Harmonics Using a Hybrid Scheme," *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, vol. 5, no. 9, pp 7456-7468, 2016.
[25] H. Benbouhenni, "Utilization of an ANFIS-STSM Algorithm to Minimize Total Harmonic Distorsion," *International Journal of Smart Grid*, vol. 4, no. 2, pp. 56-67, 2020.