Control Scheme Influence on the Performance of Shunt Active Power Filter based on Five-level NPC Inverter in Steady and Transient Conditions

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Abstract: This paper presents an investigation on the performance of shunt active power filter (Shunt APF) systems based on five-level neural point clamped (NPC) inverter in steady and transient conditions adopting a fuzzy control scheme. The shunt APF is operated as a current source connected in parallel with the non-linear loads to inject compensates current harmonics into the AC source. The multi-level inverters have gained considerable interests in last year's. Five-level inverter is recommended in medium and high voltage applications; their advantages are low harmonic distortions, low switching losses, low electromagnetic interference, low voltage stress of power semiconductors and low acoustic noise. Secondly fuzzy logic has been widely used in various industrial applications. To benefit from these advantages a shunt active power filter based on five-level (NPC) inverter using fuzzy control scheme is presented in this work. To identify the reference currents, synchronous detection method (SMD) is adopted. Proportional integral voltage controller is used to maintain the dc voltage across capacitor constant and reduce inverter losses. The simulation is performed using MATLAB-Simulink software and SIMPOWERSYSTEM toolbox. The obtained results in steady and transient states illustrate the performances and the effectiveness of the proposed shunt APF system.

Keywords: Multi-level (NPC) inverter, Shunt active power filter, Power quality improvement; Fuzzy logic control, Harmonic current compensation, Total Harmonic Distortion (THD), IEE-519 standard norms

1. INTRODUCTION

The nonlinear electronic loads generate harmonic, reactive and negative sequence currents which lead to low power factor, low efficiency and harmful electromagnetic interference to the distribution systems [1]. To improve the power quality, some solutions have been proposed by several authors. Among them the shunt active power filters [2], [3] is considered an important and flexible solution to improve the power quality in the distribution system [4]. The Shunt APF operates as a current source, and injects the compensation current into power system to cancel the harmonic current produced by the non-linear load [5]. The conventional structure used is the voltage source inverter (VSI). But this topology is limited for low power applications [6]. Several multilevel inverter topologies are being used for shunt active filter applications, but some practical problems like power circuit packaging, switching circuit complexity and dynamic voltage stress have restricted the number of inverter levels to 3 or 5 [7]. Topologies with very high number of voltage levels were also proposed [8]. In general, the more voltage levels of converter can decrease the harmonic in the output. However, the increase in converter complexity and number of switching devices is a major disadvantage of multilevel converters. For these converters three pulse width modulation (PWM) strategies are available [9], [10]: Multi-Carrier PWM, Space Vector (SV) PWM and Selective Harmonic Elimination (SHE) PWM [11].

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. To generate the reference signals control, we chose the synchronous detection method (SDM) [12], [13] it is easy to implement and achieve an excellent performances.

To improve the control performances there's a great tendency to use intelligent control techniques. Fuzzy logic control theory is a mathematical discipline based on vagueness and uncertainty. The fuzzy control does not need an accurate mathematical model of a plant. It allows one to use non-precise or ill-defined concepts. Fuzzy logic control is also nonlinear and adaptive in nature that gives it robust performance under parameter variation and load disturbances. This control technique relies on the human capability to understand the system's behavior and is based on qualitative control rules. Thus, control design is simple since it is only based on if....then linguistic rules [14]. The investigation in this paper concentrates on the influence of the control scheme in the performance of Shunt APF based on five-level (NPC) inverter based on MC-PWM and Fuzzy control techniques for current harmonics compensation.

The performance of the proposed Shunt APF systems is evaluated using Matlab-Simulink software and SimPowerSystems Toolbox in transient and steady states. The obtained results confirm the validity and accuracy of model and illustrate the effectiveness of proposed shunt APF system.

2. SHUNT ACTIVE POWER FILTER

Figure (1) shows the Shunt APF principle scheme based on conventional voltage source inverter (VSI) with capacitive energy storage (C_{dc}) shared by all three phases [15]. The SAPF is connected to a three phase three wire electrical network in a point called the point of common coupling (PCC) on the loads side through a filter featured as L_f □□R_f. This is necessary for eliminating current ripples due to switching.

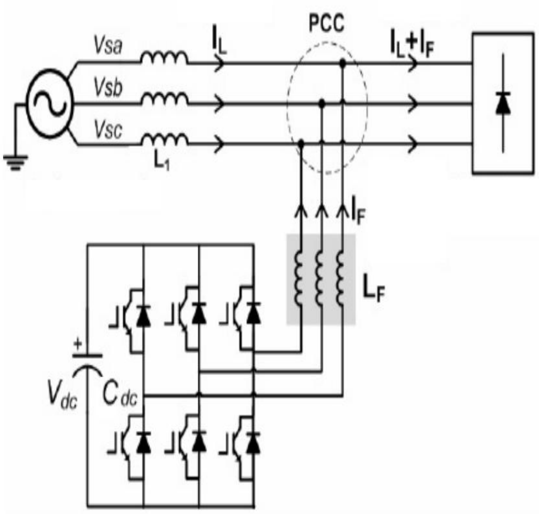

Fig. 1 Shunt APF configuration system

The configuration is controlled to cancel current harmonics on the AC side and make the source current in phase with the voltage source [16]. The source current, after compensation, becomes sinusoidal and in phase with the voltage source.

3. FIVE-LEVEL (NPC) INVERTERS

In recent years, multilevel converters have shown some significant advantages over traditional VSI converters [17] especially for high-power and high-voltage applications. Seven-level inverter is one of the most popular converters employed in high power applications. In addition to their superior output voltage quality, they can also reduce voltage stress across switching devices. Since the output voltages have multiple levels, lower *dv/dt* is achieved, which greatly alleviates electromagnetic interference problems due to high-frequency switching. Over the years, most research work has focused on converters with three to five voltage levels, although topologies with very high number of voltage levels were also proposed. In general, the more voltage levels a converter has the less harmonic and better power quality it provides. However, the increase in converter complexity and number of switching devices is a major concern for a multilevel converter. It has been shown that although more voltage levels generally mean lower total harmonic distortion (THD), the gain in THD is marginal for converters with more than seven levels [18]. The conventional three-phase (NPC) n-level inverter based on voltage-source will need a number of (n-1) dc-link capacitors, 2(3n-3) switches and (6n-12) diodes-clamped (despite anti-parallel diodes of inverter switches). In this inverter, the maximum voltage across each capacitor is equal to $U_{dc}/(n-1)$.

The five-level (NPC) inverter power circuit is given by Figure (2). In this structure the DC bus capacitor is split into four, providing a three neutral-point. Each arm of the inverter is made up of eight switches and six clamping diodes connected to the neutral-point. The diodes are used to create the connection with the point of reference to obtain midpoint voltages [19]. This structure allows the switches to endure larger dc voltage input on the premise that the switches will not raise the level of their withstand voltage. For this structure, five output voltage levels can be obtained, namely, $U_{dc}/2$, $U_{dc}/4$, 0, $-U_{dc}/4$ and $-U_{dc}/2$ [20], [21] corresponding to five switching states given by Table (1).

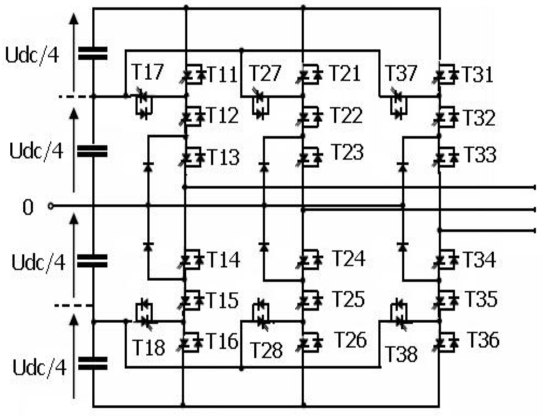

Fig. 2 Five-level (NPC) inverter

Table (1) shows the switching states of the five-level (NPC) inverter topology.

Table 1 5-level NPC inverter switching states

	Si	A	B	0	C	D
Switch States	S1	1	1	1	1	0
	S2	1	1	0	0	0
	S3	1	0	0	0	0
	S4	0	0	1	1	1
	S5	0	0	0	1	1
	S6	0	1	1	0	1
	S7	0	1	0	0	0
	S8	0	0	0	1	0
Output voltages E= Udc		Udc1+ Udc2	+ Udc1	0	- Udc3	-Udc3 -Udc4

4. CONTROL STRATEGIES

The quality of the compensation of current harmonics strongly depends on the performance of the chosen identification method [22]; even a very effective control system cannot achieve satisfactory filtering if the harmonic currents are poorly identified. To generate the reference signals used for the control of the Shunt APF, we chose the method of synchronous detection method [23]. The compensating currents of active filter are calculated by sensing the load currents, the current delivered by DC voltage regulator I^*_{smd}, peak voltage of AC source (V_{sm}) and zero crossing point of source voltage. The last two parameters are used for calculation of instantaneous voltages of AC source as below:

$$U_{sa} = V_{sm}.\sin(\omega t)$$
$$U_{sb} = V_{sm}.\sin(\omega t + \frac{2\pi}{3}) \quad (1)$$
$$U_{sc} = V_{sm}.\sin(\omega t + \frac{4\pi}{3})$$

In order to compensating the current harmonics, the average active power of alternative current source must be equal with P_{Lav}, considering the unity power factor of AC source side currents the average active power can be calculated as bellow [24]:

$$P_s = \frac{3}{2} V_{sm}.I^*_{smp} = P_{Lav} \quad (2)$$

From this equation, the first component of AC side current can be calculated as bellow:

$$I^*_{smp} = \frac{2}{3} P_{Lav} / V_{sm} \quad (3)$$

The second component of AC source current I^*_{smd} is obtained from DC capacitor voltage regulator. The desired peak current of AC source can be calculated as bellow:

$$I^*_{sm} = I^*_{smp} + I^*_{smd} \quad (4)$$

The AC source currents must be sinusoidal and in phase with source voltages, theses currents can be calculated with multiplying peak source current to a unity sinusoidal signal, that these unity signals can be obtained from equation (5):

$$i_{ua}(t) = v_{sa} / V_{sm}$$
$$i_{ub}(t) = v_{sb} / V_{sm} \quad (5)$$
$$i_{uc}(t) = v_{sc} / V_{sm}$$

The desired source side currents can be obtained from equation (6):

$$i^*_{sa}(t) = I^*_{sm}.i_{ua}(t)$$
$$i^*_{sb}(t) = I^*_{sm}.i_{ub}(t) \quad (6)$$
$$i^*_{sc}(t) = I^*_{sm}.i_{uc}(t)$$

Finally, the reference currents of shunt APF can be obtained from (7):

$$i^*_{ca}(t) = i^*_{sa}(t) - i^*_{La}(t)$$
$$i^*_{cb}(t) = i^*_{sb}(t) - i^*_{Lb}(t) \quad (7)$$
$$i^*_{cc}(t) = i^*_{sc}(t) - i^*_{Lc}(t)$$

To compensate the inverter losses and regulate the DC link voltage U_{dc}, a proportional integral voltage controller is used. The control loop consists of the comparison of the measured voltage (U_{dc1} + U_{dc2}) with the reference voltage Udc-ref. The loop generates corresponding current $I_{c,los}$ is given by:

$$I_{c,los} = K_p \Delta U_{dc} + K_i \int \Delta U_{dc} dt \quad (8)$$

The principle of synchronous detection method in case of 5-level (NPC) inverter is shown in Figure (3).

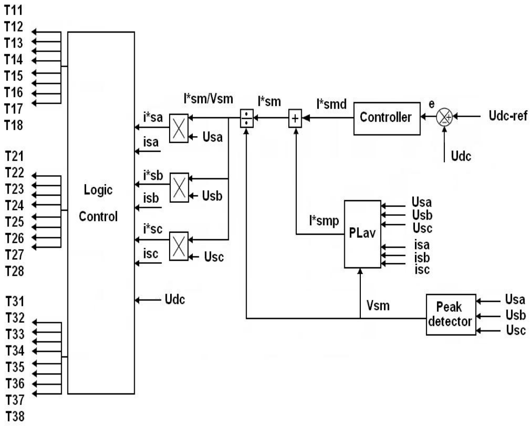

Fig. 3 Principle of the synchronous detection method in case of 5-level shunt APF system

5. SHUNT APF LOGIC CONTROL

Fuzzy logic controllers (FLCs) have been an interesting and good alternative in more power electronics application. Their advantages are robustness, non-requirement of a mathematical model, and acceptance of non-linearity. To benefit from these advantages, a fuzzy logic controller is adopted for proposed Shunt APF systems. The controller is designed to improve the compensation capability of APF by adjusting the error using fuzzy rules. Fuzzy logic control is the evaluation of a set of simple linguistic rules to determine the control action. The desired inverter switching signals of the five-level Shunt APF are determined according to the error between the compensation currents and reference currents. In this case, the fuzzy logic controller has two inputs, error "e" and change of error "de", and one output "s" [25]. To convert it into linguistic variable, we use seven fuzzy sets: NL (Negative Large), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium) and PL (Positive Large) [26]. Triangles or triangular membership function (TMF) have been frequently used in several applications of FLC. TMF are preferred due to simplicity, easy implementation, symmetrical along the axis [27].

6. SWITCHING PULSES GENERATION

The logic control in case of five-level (NPC) inverter is shown in Figure (4). The outputs of fuzzy logic controllers are used in generation of pulses switching signals [28]. The switching signals are generated by means of comparing a four carrier signals with the output of the fuzzy logic controllers.

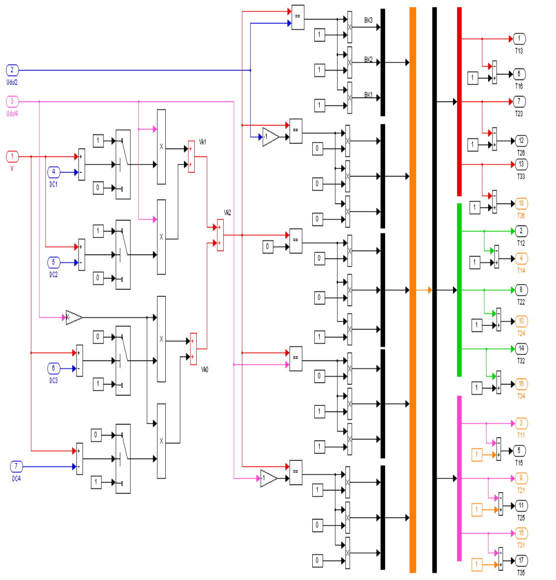

Fig. 4 Five-level (NPC) inverter switching pulse generation

7. SIMULATION RESULTS AND DISSCUSSION

The simulation results are provided to verify the performance and effectiveness of the proposed shunt active power filter based on 5 -level (NPC) inverters. To simulate the shunt active power filters, a model is developed using MATLAB/Simulink and SimPowerSystem Toolbox shown in Figure (5). The active filter is composed mainly of the three-phase source, multi-level (NPC) inverter, a nonlinear load (Rectifier & R, L or R, C) and Fuzzy Logic Controller. The parameters of the simulation are: L_f =3 mH, C_1=C_2= C_3= C_4= 3000 μF, V_s=220 V/50 Hz, and $U_{dc\text{-}ref}$ =800 V.

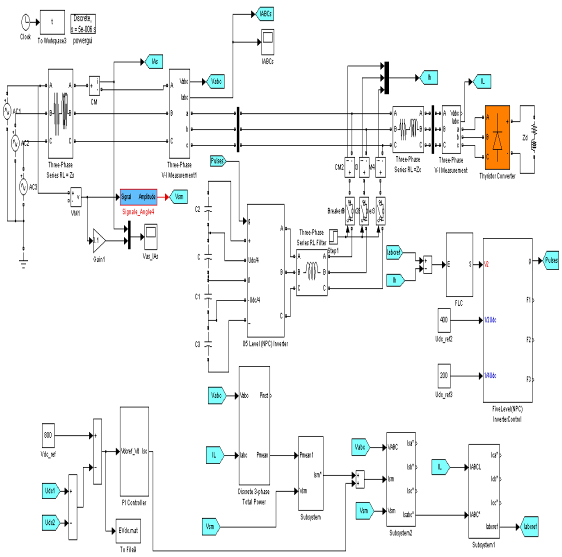

Fig. 5 Shunt APF SimPowerSystem model based on 5-level (NPC) inverter

Current harmonics compensation

Figure (6) shows the simulated waveforms of the source current and corresponding source voltage before compensation (1/10 of vsa (t)). The corresponding harmonic spectrum is shown in Figure (7). The harmonic spectrum of the source current after compensation using shunt APF based on five-level (NPC) inverters is shown in Figures (8).

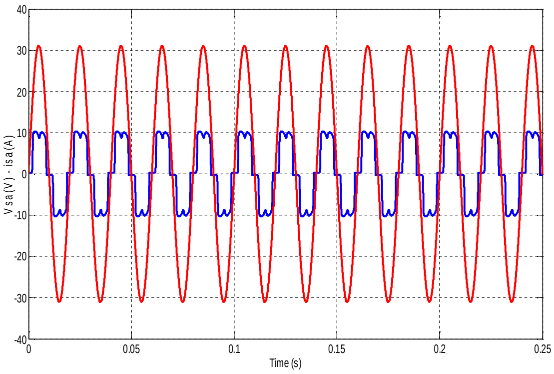

Fig. 6 Source voltage and corresponding source current without APF

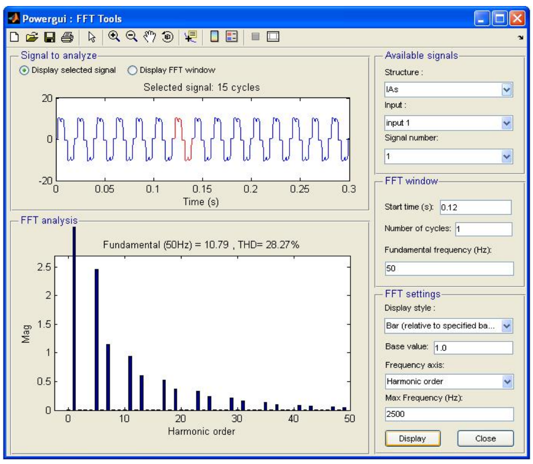

Fig. 7 Source current spectrum without APF (THDi= 28.27%)

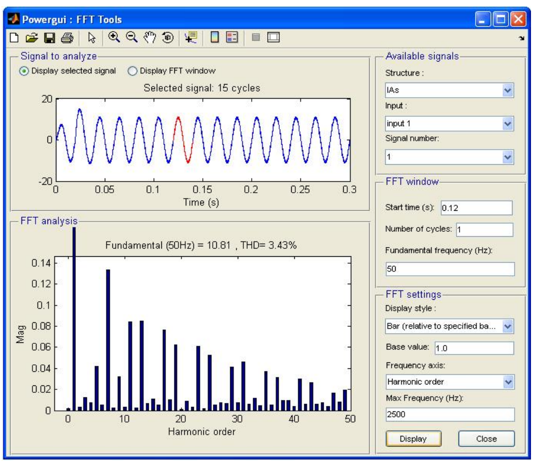

Fig. 8 Source current spectrum with shunt APF based on 5-level (NPC) inverter (THDi= 3.43%)

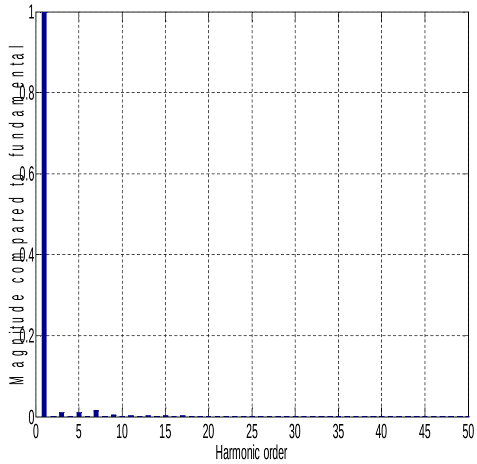

Fig. 9 Source current spectrum with shunt APF based on 5-level (NPC) inverter using fuzzy controller (THDi= 2.80%)

Before compensation, the source current is much distorted with high Total Harmonic Distortion (THDi) value equal to 28.27%, after compensation the THDi is decreased to 3.43% using conventional SPWM controller and to 2.80% using fuzzy control scheme.

Steady state performances

The output DC capacitor voltage is presented in Fig (10). The waveforms of source voltage with source current after compensation are simultaneously shown in Fig (11).

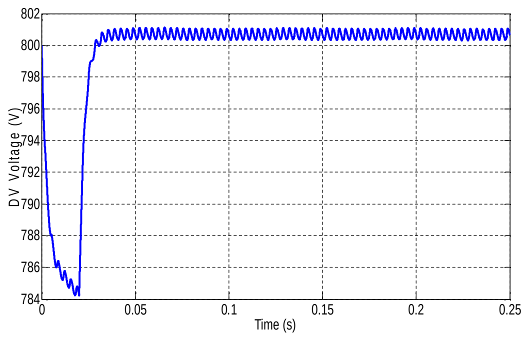

Fig. 10 Capacitor voltage Udc(V)

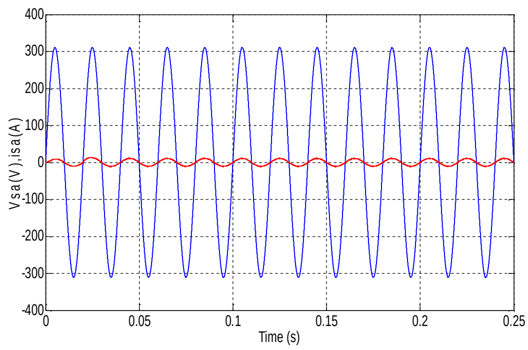

Fig. 11 Current and voltage source after compensation (Vsa = 0.1 vsa)

Transient state performances

To evaluate dynamic responses and test robustness of the proposed shunt active filter based on five-level (NP) inverter, a step change in load is introduced between $t_1 = 0.2$ sec and $t_2 = 0.4$ sec. Figure (12) shows the source current waveforms after compensation and Figure (13) shows the dc side capacitor voltage.

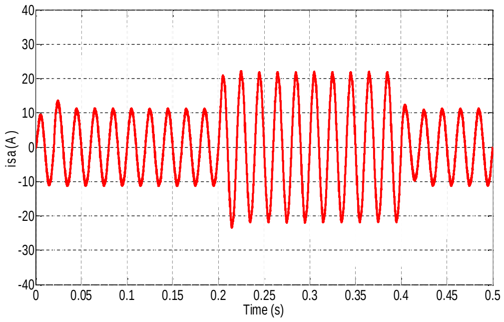

Fig. 12 Load current with step change in load (between t1=0.2 sec and t2=0.4 sec)

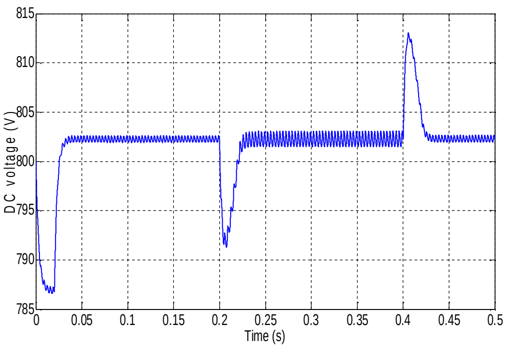

Fig. 13 DC voltage with step change in load (between t1=0.2 sec and t2=0.4 sec)

Through visualization Figures (8) , (11) and (12), we are able to conclude that the operation of the proposed shunt active based on five-level (NPC) inverter is successful. Before the application of shunt active power filter, the source current is equal to non-linear load current; highly distorted and rich in harmonic. After compensation, the THD_i is considerably reduced from 28.16% to 3.43% using proposed shunt APF system with SPWM controller and to 2.80% using fuzzy control scheme. The dc voltage is maintained at a constant value which is equal to the reference value $U_{dc\text{-}ref}$=800 V by using PI voltage controller. Figures (11) and (12) illustrate the dynamic response of the proposed Shut APF. It is observed that the dc voltage pass through a transitional period of 0.06 sec before stabilization and reaches its reference $U_{dc\text{-}ref}$=800 V with moderate peak voltage approximately equal to 10 V when a step change in load current is introduced between t_1=0.2 sec and t_2=0.4sec.

The performances of the proposed shunt active filter based on five-level (NPC), in terms of harmonics elimination and reactive power compensation is very satisfactory. The THD_i values obtained respect the 519 IEEE standard Norms (THDi≤5%) [29], [30].

8. CONCLUSION

To cancel harmonic currents delivered by non-linear loads a shunt APF system based on five-level (NPC) inverter topologies with combined SPWM and fuzzy control scheme has been proposed in this paper. The control strategy based on synchronous detection method permits a good extraction of reference currents compensation. The current harmonics levels are maintained below IEEE-519 standard. The THDi (%) is significantly reduced from 28.27% to 3.43% using five-level (NPC) inverter topologies with conventional controller and to 2.80% using fuzzy control scheme.

Through this study, we can conclude that the proposed shunt APF system based on five-level (NPC) inverter using fuzzy control scheme offers better THD_i in current and conversion efficiency than the same system with conventional controller and permit to obtain sinusoidal current source in phase with correspondent voltage after compensation.

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