Impact of Converter Topology on the Shunt Active Power Filter Systems Efficiency

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Abstract: This paper presents the performance of shunt active power filters (Shunt APFs) which can compensate harmonic currents generated by no-linear load based on five and seven-level neural point clamped (NPC) inverters. Multilevel inverters are currently being investigated and used in several industrial applications. Their advantages include the capability to reduce the harmonic content and decrease the voltage or current ratings of the semiconductors. On the other side, fuzzy techniques are successfully employed in various industrial applications; they represent a good alternative to traditional control systems. To benefit of all these advantages an efficient control scheme for five and seven-level Shunt APF based on multi-carrier pulse width modulation (MC-PWM) and fuzzy control approaches are adopted in this work. The fuzzy controller is designed to improve compensation capability of shunt APF by adjusting the error using a fuzzy rule. The control strategy to identify the current reference uses synchronous detection method (SMD), this technique is easy to implement and achieves good performances. The numerical simulation results carried with MATLAB-Simulink and SimPowerSystems Toolbox show the effectiveness of the proposed systems and confirm the superiority of the seven-level shunt APF compared to five-level configuration 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 and series active power filters [2],[3] have proven as an important and flexible alternative to compensate most important voltage and current related power quality problems in the distribution system [4]. In this case, the Shunt APF should operate as a current source, and inject the compensation current into power system to cancel the harmonic current produced by the non-linear load [5]. The most power structures used in APF is the traditional two levels converters. The use of this topology is limited in low power applications, due to the power handling ability of semiconductors [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 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. 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 current detection method [12], [13] it is simple to implement and achieve a good 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 impact of inverter topology in the performance of Shunt APF based on five and seven-level (NPC) inverters using MC-PWM and Fuzzy control schemes for current harmonics compensation.

The performances of the proposed Shunt APF systems are evaluated using Matlab-Simulink software and SimPowerSystems Toolbox in transient and steady states. The obtained results confirm the accuracy of proposed models and illustrate the impact of level inverters in the reduction of the THD_i and harmonic currents mitigation.

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.

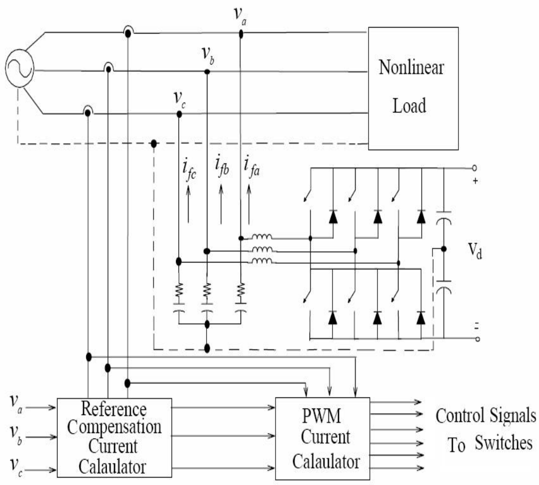


Fig. 1 Shunt APF configuration system

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. MULTI-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 $U_{dc}/(n-1)$.

Five-level(npc) inverter

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] corresponding to five switching states given by Table (1).

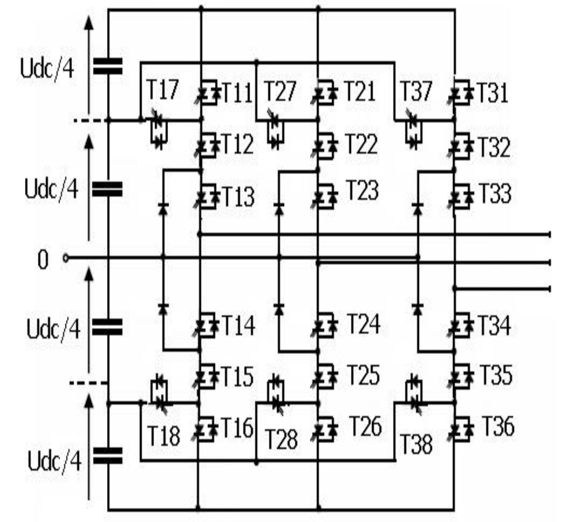


Fig. 2 Five-level (NPC) inverter

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

Seven-level(npc) inverter

The power circuit of the seven-level neutral point clamped inverter is given by Figure (2). The DC bus capacitor is split into six, providing a three neutral-point. Each arm of the inverter is made up of twelve bi-directional IGBTs (Insulated Gate Bipolar Transistor) devices [21]. These switches should not be simultaneously open or closed in order to prevent the short circuit of the DC source of the inverter input. Each switch consists of a transistor with a diode in anti-parallel and ten clamping diodes connected to the neutral-point; these clamping diodes are used to block the reverse voltage and used to create the connection with the point of reference to obtain midpoint voltages. Take note that the required numbers of clamping diodes are quite high and for higher number of voltage levels the (NPC) topology will be impractical due to this fact. 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 [22].

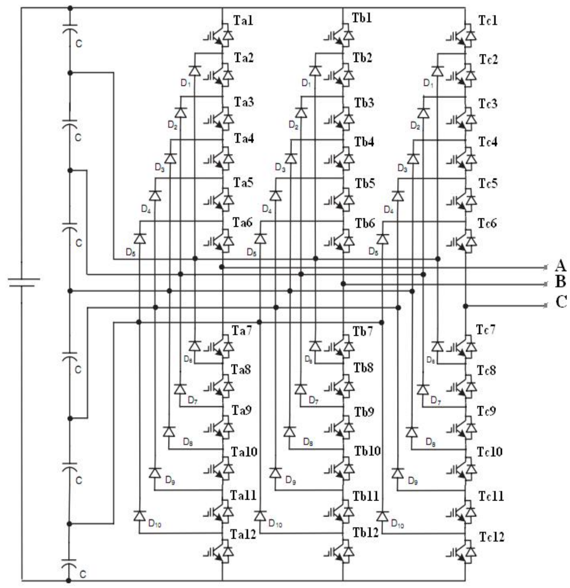


Fig. 3 Seven-level (NPC) inverter

Table (2) shows the switching states of the seven-level (NPC) inverter topology.

Table 2 7-level NPC inverter witching states

	Si	A	B	C	0	D	E	F
Switch States	S1	1	0	0	0	0	0	0
	S2	1	1	0	0	0	0	0
	S3	1	1	1	0	0	0	0
	S4	1	1	1	1	0	0	0
	S5	1	1	1	1	1	0	0
	S6	1	1	1	1	1	1	0
	S7	0	1	1	1	1	1	1
	S8	0	0	1	1	1	1	1
	S9	0	0	0	1	1	1	1
	S10	0	0	0	0	1	1	1
	S11	0	0	0	0	0	1	1
	S12	0	0	0	0	0	0	1
Output voltages E= Udc		+ E/2	+ E/3	+ E/6	0	- E/6	- E/3	- E/2

4. CONTROL STRATEGIES

The quality of the compensation of current harmonics strongly depends on the performance of the chosen identification method [23]; 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 [21], [24]. 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 [25]:

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

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 7-level (NPC) inverter is shown in Figure (4).

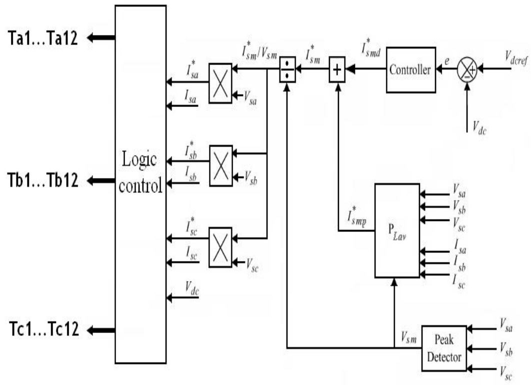


Fig. 4 Principle of the synchronous detection method in case of 7-level shunt APF system

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 and seven-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”. 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].

Five-level (NPC) inverter

The logic control in case of five-level (NPC) inverter is shown in Figure (5). 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.

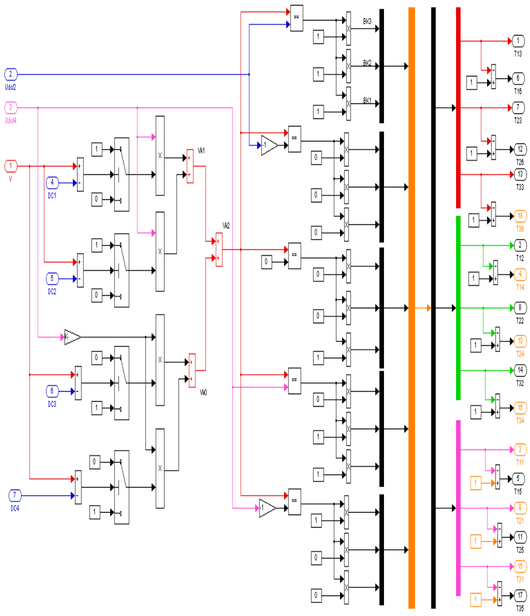
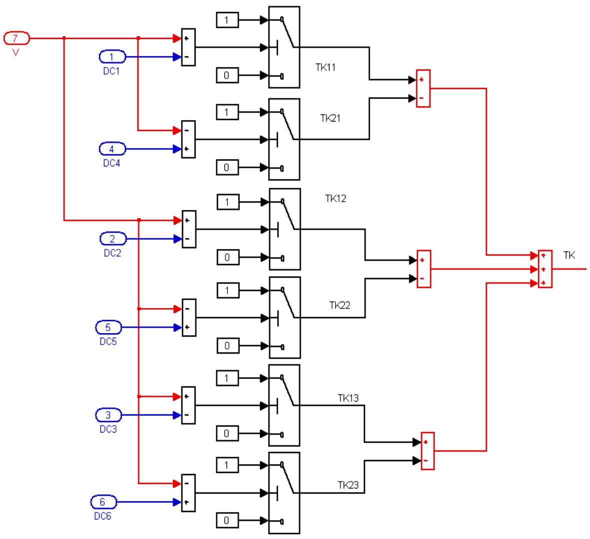


Fig. 5 Five-level (NPC) inverter switching pulse generation

Seven-level(NPC) inverter

The switching signals are generated by means of comparing a six carrier signals with the output of the fuzzy logic controller [19], [29]. The Simulink model of the logic control designed for the seven-level (NPC) inverter is shown in Figure (6).



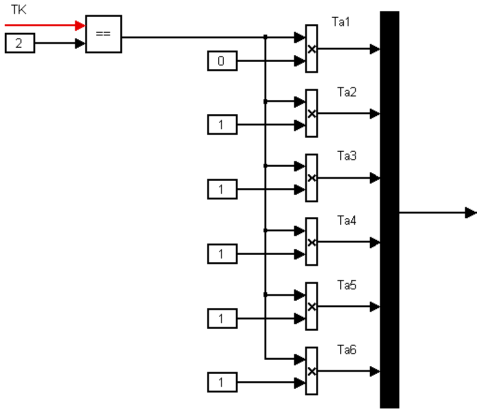


Fig. 6 Pulses generation for upper leg in case of Tk=2 (Tk:-3,-2,-1,0,1,2,3) for seven-level (NPC) inverter

6. 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 and 7-level (NPC) inverters. To simulate the shunt active power filters, two models are developed using MATLAB/Simulink and SimPowerSystem Toolbox shown in Figures (7) and (8). 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= C_5= C_6=3000 μF, V_s=220 V/50 Hz, and $U_{dc\text{-}ref}$ =800 V.

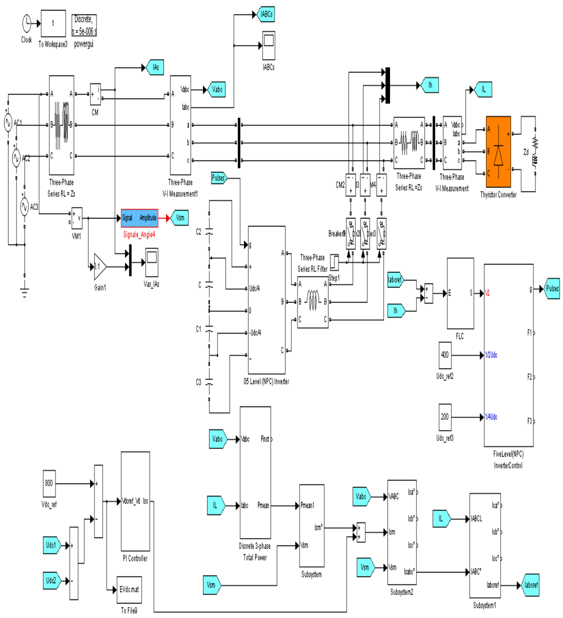


Fig. 7 Shunt APF SimPowerSystem model based on 5-level (NPC) inverter

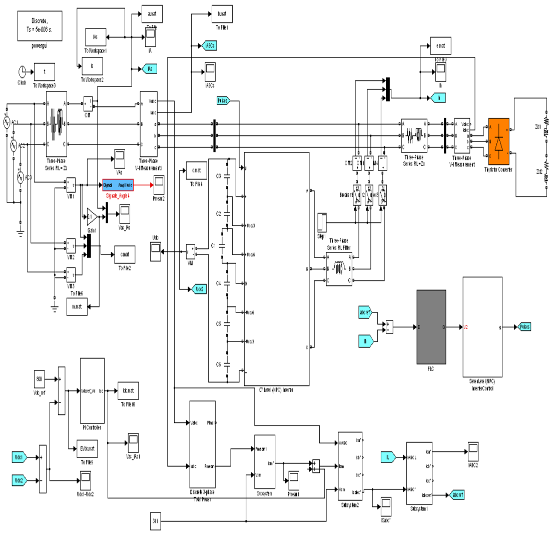


Fig. 8 Shunt APF SimPowerSystem model based on 7-level (NPC) inverter

Figure (9) 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 (10). The harmonic spectrum of the source current after compensation using respectively five and seven-level (NPC) inverters are shown in Figures (11) and (12).

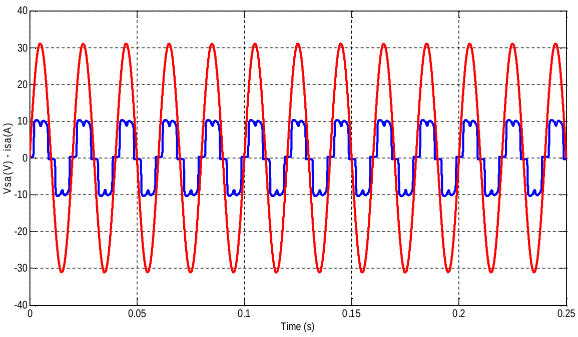


Fig. 9 Source voltage and corresponding source current without APF

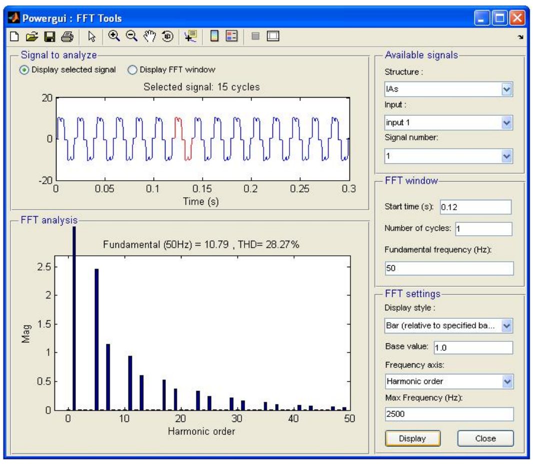


Fig. 10 Source current spectrum without APF (THDi= 28.27%)

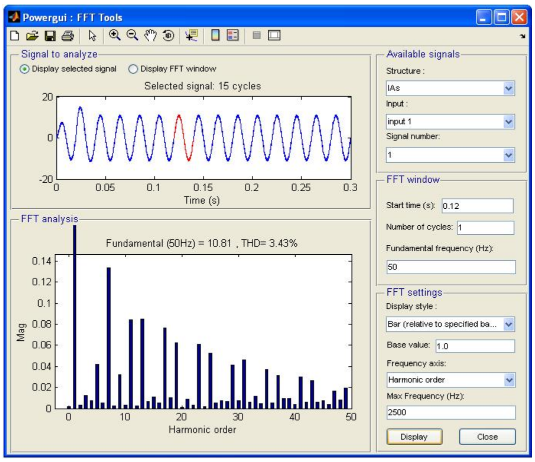


Fig. 11 Source current spectrum with shunt APF based on 5-level (NPC) inverter (THDi= 3.43%)

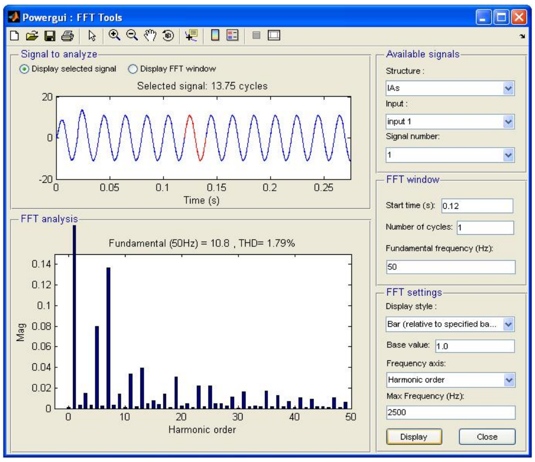


Fig. 12 Source current spectrum with shunt APF based on 7-level (NPC) inverter (THDi= 1.79%)

The performances of Shunt APF based on 5 and 7 level (NPC) inverters in term of harmonic currents compensation are presented in Table 3.

Table 3 Performance of Shunt APF based on 5 and 7 Level (npc) inverters in term of harmonic current compensation

Parameters	**Five-level (NPC) inverter**	**Seven-level (NPC) inverter**
No. of sources	1	1
No. of switches	8	12
No. of power diodes	8	10
No. of capacitors	4	6
PWM technique	MC-PD (LS-SPWM)	MC-PD (LS-SPWM)
THDi (%)	3.43%	1.79%

Figure (13) and Figure (14) shows the source current and injected current after Shunt APF application in case of seven-level (NPC) inverter. The output DC capacitor voltage is presented in Figure (15). Lastly, the waveforms of source voltage with source current after compensation are simultaneously shown in Figure (16).

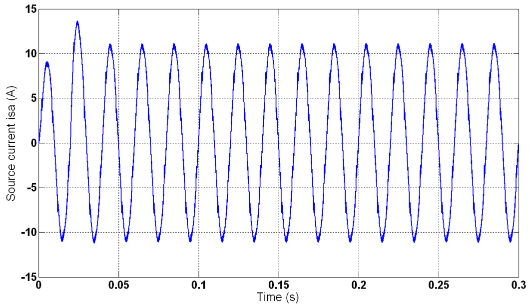


Fig. 13 Source current after compensation is-a(A) based on 7L (NPC) inverter

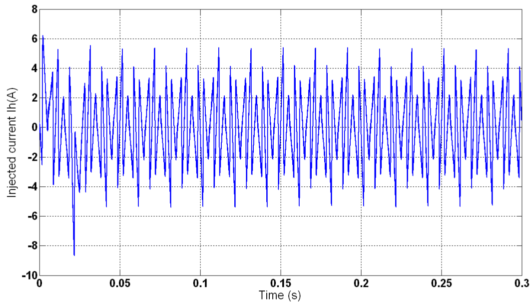


Fig. 14 Injected current ih-a(A) based on 7L (NPC) inverter

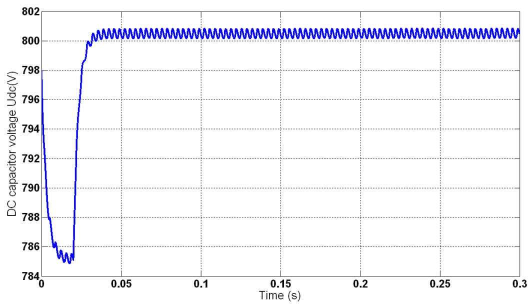


Fig. 15 DC capacitor voltages Udc(V) based on 7L (NPC) inverter

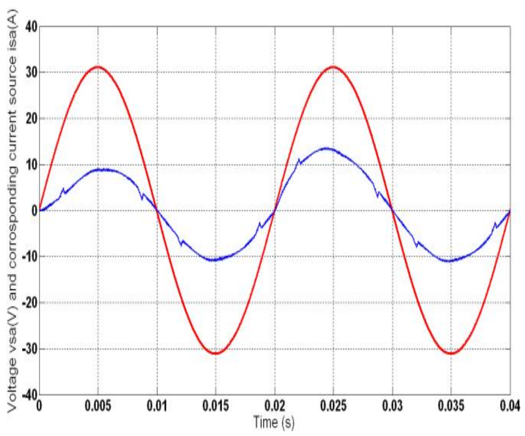


Fig. 16 Source voltage vs-a(V) and corresponding current is-a(A) after compensation based on 7L (NPC) inverter

7. CONCLUSION

To cancel harmonic currents delivered by non-linear loads a shunt APF system based on five and seven-level (NPC) inverter topologies with combined CB-PWM and fuzzy control schemes 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 [30], the THDi (%) is significantly reduced from 28.27% to 3.43% using five-level (NPC) inverter and to 1.79% using seven-level (NPC) inverter topologies. According to the obtained results, the seven level inverters have less THDi level of the supply currents as compared to the five-level in active power filter applications. While the performances in transient and in steady state do not show a significant difference.

Through this study, we can conclude that the proposed shunt APF system based on seven-level (NPC) inverter offers better THD in current and conversion efficiency than the less-level existing topologies and permit to obtain sinusoidal current source in phase with correspondent voltage after compensation.

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