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EFFICIENT FUZZY LEFT SHIFT-SINUSOIDAL PULSE WIDTH MODULATION CONTROL SCHEME FOR SERIES ACTIVE POWER FILTER BASED ON SEVEN-LEVEL NEUTRAL POINT CLAMPED INVERTER TOPOLOGIES

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Keywords: Seven-level neutral point clamped inverter; Series active power filter; Power quality improvement; Fuzzy logic control; Left shift-sinusoidal pulse width modulation.

This paper presents the performance of a series active power filter (APF) based on a seven-level neutral point clamped (NPC) inverter using modified instantaneous reactive power control strategies. Today, multilevel inverters are being investigated and used in various industrial applications. Fuzzy control techniques are successfully employed in various applications; they represent a good alternative to classic control systems. To benefit from all these advantages, a novel control scheme for series APF based on a seven-level neutral point clamped (NPC) inverter using level-shifted multicarrier modulation and fuzzy control approach is proposed in this work. The simulation is carried out using MATLAB-Simulink and SimPowerSystem software. The results show the effectiveness and robustness of the proposed control scheme adopted for the series active power filter system in compensating harmonics and all voltage disturbances.

1. INTRODUCTION

In recent years, along with growing and developing power electronics, devices utilization in distribution systems, harmonics generation in an evitable effect. The effects of voltage harmonic distortions are voltage sag, swell, and fluctuation [1], mainly caused by the insertion of sudden loading at the point of common coupling of the system, large neutral currents due to unbalanced loading, improper grounding, *etc*. [2]. Passive filters can improve the performance of distribution systems, but problems like the possibility of occurring series or parallel resonance led researchers to active power filters.

Active power filters have been proposed as an interesting, high-performance solution to improve power quality [3]. These systems are frequently used to suppress power quality problems because they use the technology of power-electronic circuits incorporating power-switching devices and passive energy-storage elements with sophisticated control techniques [4]. A shunt active power filter is generally used to compensate for current harmonics. A series active power filter is one control device that feeds modern industry with a high-quality power supply [5]. It is inserted in series between the load and the ac power source voltage using a coupling transformer. It can significantly improve power quality and ensure a reliable voltage supply to the load by mitigating or eliminating issues such as voltage distortions, sags, swells, and unbalances [6].

Multilevel converters have shown some significant advantages over traditional two-level converters widely used in several industrial applications [7], especially for high-power and high-voltage applications. The multilevel inverters based on neutral point clamped (NPC) are the first multilevel topology widely used. Their main advantages are half of the dc-link voltage for voltages across the switches, the first group of voltage harmonics is centered on twice the switching frequency, and the output voltages have very low distortion with reduced stresses across the switches [8]. Most research has focused on converters with three to five voltage levels, although topologies with a very high number of voltage levels were also proposed [9]. In general, with the increase of the number of voltage levels, the quality of the output voltage increases, and the stress on the semiconductor devices is reduced [10]. The modulation techniques of multilevel inverters are used to obtain output voltage whose shape is close to the sine wave. Control techniques have been developed to reduce harmonic and minimize switching loss. These methods used in multilevel inverters can be classified according to switching frequency.

Various PWM strategies are available for multilevel converter applications [11]. Carrier-based pulse width modulation (CB-PWM) is generally classified into the phase disposition (PD), phase opposition disposition (POD), and alternate phase opposite disposition (APOD) categories [12]. Generally, in CB-PWM, (n-1) carrier signals are required, where n is the line-to-line number of levels [13]. The controller is the main part of any active power filter operation and has been the subject of much research in recent years [14,15]. To improve the performance of any active power filter system there's a great tendency to use fuzzy control techniques. Fuzzy logic control theory is a mathematical discipline based on vagueness and uncertainty [16]. The fuzzy control is nonlinear and adaptive, giving it robust performance under parameter variation and load disturbances [17].

The paper is structured as follows. The description of the series APF is presented in section 2. The seven-level (NPC) inverter is given in section 3. The control strategies method is addressed in section 4. The concept of switching pulse generation using a fuzzy logic controller and level-shifted multicarrier modulation is described in section 5. The simulation results and discussions are presented in section 6. Finally, a conclusion and a references list end the paper.

2. SERIES ACTIVE POWER FILTER CONFIGURATION

The bloc scheme of the proposed series active power filter is shown in Fig. 1. The seven-level inverter can

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produce an output voltage that contains much less switching frequency ripple than the conventional voltage source inverter (VSI). The configuration is controlled to cancel voltage harmonics and all voltage disturbances. The series APF inject compensation voltage equal to the difference between voltage load and voltage source using three injection transformers.

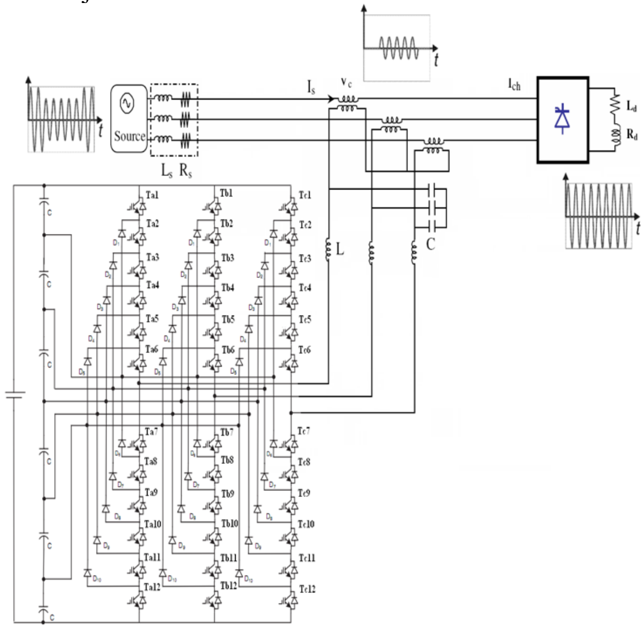


Fig. 1 – Series active power system based on a seven-level (NPC) inverter

3. SEVEN-LEVEL (NPC) INVERTER

In recent years, multilevel converters have shown some significant advantages over traditional two-level converters [18,19], especially for high-power and high-voltage applications. The 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 is achieved, which greatly alleviates electromagnetic interference problems due to high-frequency switching [20].

Over the past years, different research works have focused on multi-level voltage converters; the more voltage levels have the less harmonic and better power quality it provides. However, this improvement is accompanied by an increase in converter complexity. 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. The conventional three-phase (NPC) n-level inverter based on voltage-source will need several (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 $U_{dc}/(n-1)$ [21].

The power circuit of the seven-level neutral point clamped inverter is given in Fig. 2, and the direct current (dc) bus capacitor is split into six, providing a three neutral point. Each arm of the inverter comprises twelve bi-directional Insulated Gate Bipolar Transistor (IGBTs) devices. These switches should not be simultaneously open or closed 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 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 a higher number of voltage levels, the (NPC) topology will be impractical due to this fact [22]. This structure allows the switches to endure larger dc voltage input on the premise that the switches will not raise their level to withstand voltage.

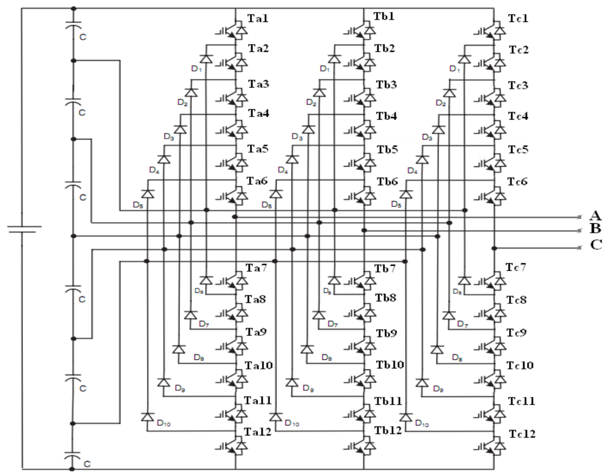


Fig. 2 – Seven-level (npc) inverter

For this structure, seven output voltage levels can be obtained, namely, $U_{dc}/2$, $U_{dc}/3$, $U_{dc}/6$, 0, $-U_{dc}/6$, $-U_{dc}/3$, and $-U_{dc}/2$ corresponding to seven switching states A, B, C, 0, D, E, and F:

- Voltage level $V_{an}=U_{dc}/2$; turn on all upper switches S_1, S_2, S_3, S_4, S_5 and S_6.
- Voltage level $V_{an}=U_{dc}/3$, turn on the switches S_2, S_3, S_4, S_5, S_6 and S_7.
- Voltage level $V_{an}=U_{dc}/6$, turn on the switches S_3, S_4, S_5, S_6, S_7 and S_8.
- Voltage level $V_{an}=0$, turn on the switches S4, S5, S6, S7, S8 and S9.
- Voltage level $V_{an}=-U_{dc}/6$ turn on the switches S_5, S_6, S_7, S_8, S_9 and S_{10}.
- Voltage level $V_{an}=-U_{dc}/3$ turn on the switches S_6, S_7, S_8, S_9, S_{10} and S_{11}.
- Voltage level $V_{an}=-U_{dc}/2$; turn on all lower switches S_7, S_8, S_9, S_{10}, S_{11} and S_{12}.

Table 1 shows the switching states of this inverter topology.

Table 1

Seven-level (NPC) inverter witching states

	Switch	A	B	C	0	D	E	F
Switching States	S_1	1	0	0	0	0	0	0
	S_2	1	1	0	0	0	0	0
	S_3	1	1	1	0	0	0	0
	S_4	1	1	1	1	0	0	0
	S_5	1	1	1	1	1	0	0
	S_6	1	1	1	1	1	1	0
	S_7	0	1	1	1	1	1	1
	S_8	0	0	1	1	1	1	1
	S_9	0	0	0	1	1	1	1
	S_{10}	0	0	0	0	1	1	1
	S_{11}	0	0	0	0	0	1	1
	S_{12}	0	0	0	0	0	0	1
Output voltages $E=U_{dc}$		E/2	E/3	E/6	0	-E/6	-E/3	-E/2

4. CONTROL STRATEGIES

When the three-phase load instantaneous voltages U_{Lu}, U_{Lv}, U_{LW} and currents i_{Lu}, i_{Lv}, i_{LW} are transformed into two-phase (α–β) coordinates. The two-phase voltages $\vec{u}_{\alpha}$, $\vec{u}_{\beta}$ and currents $\vec{i}_{\alpha}$, $\vec{i}_{\beta}$ are respectively given by [23]:

$$\begin{bmatrix} U_{s\alpha} \\ U_{s\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} U_{Lu} \\ U_{Lv} \\ U_{Lw} \end{bmatrix} = C_{32} \begin{bmatrix} U_{Lu} \\ U_{Lv} \\ U_{Lw} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{Lu} \\ i_{Lv} \\ i_{Lw} \end{bmatrix} = C_{32} \begin{bmatrix} i_{Lu} \\ i_{Lv} \\ i_{Lw} \end{bmatrix} \quad (02)$$

On the (α–β) plane, $\vec{u}$ can be considered to be composed of $\vec{u}_{\alpha}$ and $\vec{u}_{\beta}$, $\vec{i}$ of $\vec{i}_{\alpha}$ and $\vec{i}_{\beta}$:

$$\vec{u} = \vec{u}_{\alpha} + \vec{u}_{\beta}$$
$$\vec{i} = \vec{i}_{\alpha} + \vec{i}_{\beta} \quad (03)$$

Assume that u_p is the projection of $\vec{u}$ in the direction of $\vec{i}$ and u_q the projection of $\vec{u}$ in the vertical direction of $\vec{i}$; u_p and u_q can be represented by:

$$\begin{bmatrix} U_p \\ U_q \end{bmatrix} = \begin{bmatrix} \sin(\omega t) & -\cos(\omega t) \\ -\cos(\omega t) & -\sin(\omega t) \end{bmatrix} \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} U_{Lu} \\ U_{Lv} \\ U_{Lw} \end{bmatrix} \quad (04)$$

$$\begin{bmatrix} U_p \\ U_q \end{bmatrix} = C_{pq} C_{32} \begin{bmatrix} U_{Lu} \\ U_{Lv} \\ U_{Lw} \end{bmatrix}$$

where C_{pq} is the pq transformation matrix, which executes the calculation to convert the two-phase voltages $u_{s\alpha}$ and $u_{s\beta}$ into u_p and u_q. U_{Lu}, U_{LV}, U_{LW} are the three-phase voltage source, the respective components $\overline{u_p}$ and $\overline{u_q}$ in u_p and u_q correspond to the positive sequence fundamental active and reactive components in three-phase voltages.

The fundamental components U_{Luf}, U_{Lvf}, U_{Lwf} can be obtained by an inverse transformation:

$$\begin{bmatrix} U_{Luf} \\ U_{Lvf} \\ U_{Lwf} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \sin(\omega t) & -\cos(\omega t) \\ -\cos(\omega t) & -\sin(\omega t) \end{bmatrix} \begin{bmatrix} \overline{U_p} \\ \overline{U_q} \end{bmatrix} \quad (05)$$

$$\begin{bmatrix} U_{Luf} \\ U_{Lvf} \\ U_{Lwf} \end{bmatrix} = C_{23} C^{-1}{}_{pq} \begin{bmatrix} \overline{U_p} \\ \overline{U_q} \end{bmatrix}$$

where $C^{-1}{}_{pq}$ is the inverse matrix of C_{pq}, which executes the calculation to convert $\overline{u_p}$ and $\overline{u_q}$ back into (α–β) coordinates. Hence the voltage compensation is the difference between the load voltage and the reference voltage for the three phases u, v and w:

$$\begin{bmatrix} U_{Luc} \\ U_{Lvc} \\ U_{Lwc} \end{bmatrix} = \begin{bmatrix} U_{Lu} \\ U_{Lv} \\ U_{Lw} \end{bmatrix} - \begin{bmatrix} U_{Luf} \\ U_{Lvf} \\ U_{Lwf} \end{bmatrix} \quad (06)$$

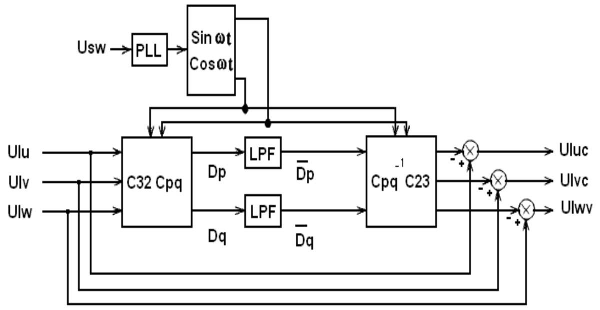


Fig. 3 – Modified p-q reference voltage identification.

4. FUZZY LOGIC CONTROL

Fuzzy logic controllers have gained interest from many researchers and engineers in more power electronics applications. Their advantages are robustness and simplicity of control. To benefit from these advantages, a novel control scheme based on fuzzy logic and DP-SPWM is proposed for a seven-level (NPC) inverter. There are four main parts to the fuzzy logic approach [24]. The first part is the 'fuzzification unit' to convert the input variable to the linguistic or fuzzy variable. The second part is the 'knowledge base' to keep the necessary data for setting the control method by the expert engineer. The 'decision-making logic' or the inference engine is the third part to imitates the human decision using rule bases and databases from the second part. The final part is the 'defuzzification unit' to convert the fuzzy variable to an easy-understanding variable [25].

The fuzzy controller proposed in this paper is designed to improve the compensation capability of series APF by adjusting the voltage error using fuzzy rules. This error voltage is injected into the logic control block to generate the switching pulses of the seven-level (NPC) inverter used as series APF. In this case, the fuzzy logic controller has two inputs, error e and change of error de, and one output, S [26]. To convert it into a 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). The fuzzy rules used are given in Table 2.

Table 2

Fuzzy rules

e / de	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NM	NM	NS	NS	EZ
NM	NL	NM	NM	NS	NS	EZ	PS
NS	NM	NM	NS	NS	EZ	PS	PS
ZE	NM	NS	NS	EZ	PS	PS	PM
PS	NS	NS	EZ	PS	PS	PM	PM
PM	NS	EZ	PS	PS	PM	PM	PL
PL	EZ	PS	PS	PM	PM	PL	PL

Triangles or triangular membership functions (TMF) have been frequently used in several applications of FLC [27]. TMFs are preferred due to their simplicity, easy implementation, and symmetrical along the axis [28].

The fuzzy controller adopted is characterized by:

- seven fuzzy sets for each input, seven fuzzy sets for output;
- Triangular and trapezoidal membership function for the inputs and output;
- implication using the “min” operator;
- Mamdani fuzzy inference mechanism based on fuzzy implication;
- Defuzzification using the “centroid” method.

Figure (4) shows the membership functions used in fuzzification and defuzzification.

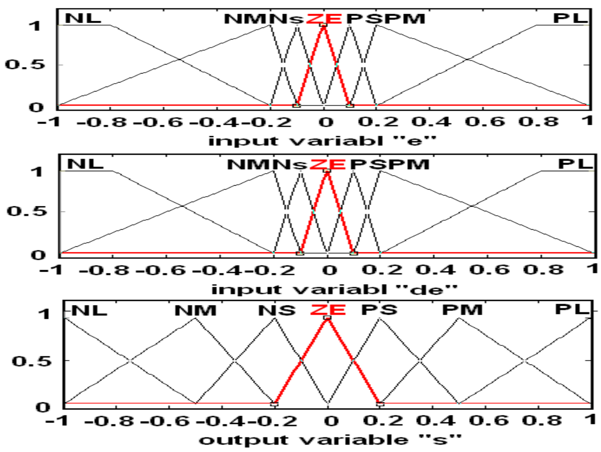


Fig. 4 – Membership function (inputs and output variables)

The zero-order hold blocks discretize errors for each phase. The error rate is derivative of the error, and it is obtained using a unit delay block [29]; when the input signal is within the range specified by the lower limit and upper limit parameters, the input signal passes through unchanged, and when the input signal is outside these bounds, he signals is clipped to the upper or lower bound [23]. The switching signals are generated using comparing six carrier signals with the output of the fuzzy logic controller. The series APF control scheme based on a seven-level (NPC) inverter using a fuzzy controller is given in Fig. 5.

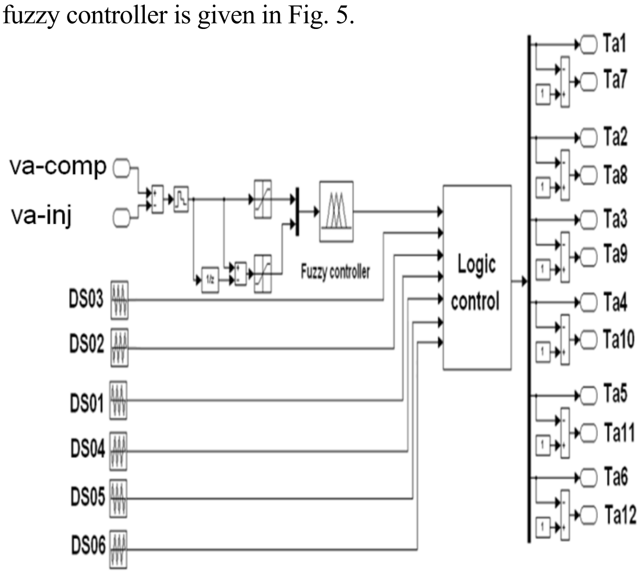


Fig. 5 – Seven-level (NPC) Series APF Fuzzy-PD-SPWM control scheme

Figures 6 and 7 show the Simulink logic control model designed for the seven-level (NPC) inverter.

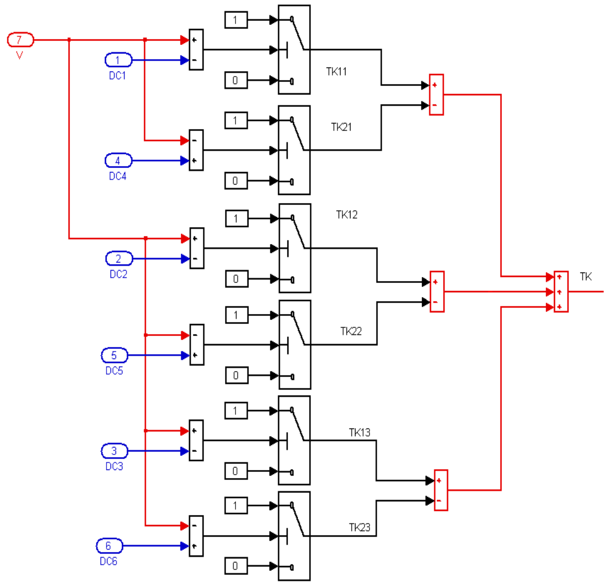


Fig. 6 – Tk evaluation for seven-level (NPC) inverter

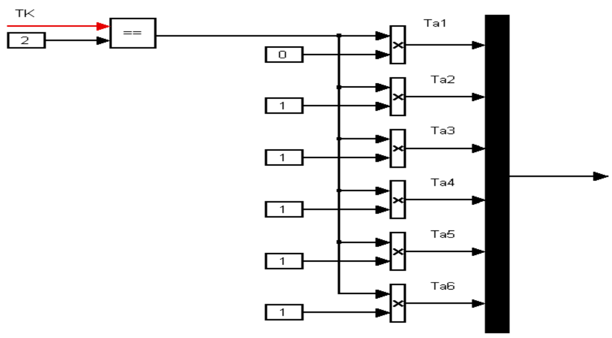


Fig. 7 – Pulses generation for the upper leg in case of Tk = 2 (Tk: -3, -2, -1, 0, 1, 2, 3) for seven-level (npc) inverter

The algorithm to generate switching pulses based on the output voltage while respecting the midpoint M of an arm k is given by:

if $V_{ref1} >= V_{p1j}$ then $T_{k1j} = 1$

if $V_{ref1} < V_{p1j}$ then $T_{k1j} = 0$

if $V_{ref1} <= V_{p1j}$ then $T_{k2j} = 1$

if $V_{ref1} > V_{p1j}$ then $T_{k2j} = 0$

K= 1, 2, 3 and j= 1, 2, 3

$T_K = (T_{k11}-T_{k21}) + (T_{k12}-T_{k22}) + (T_{k13}-T_{k23})$

If $T_K = 3$ Then $V_K = +U_{dc}/2$

If $T_K = 2$ Then $V_K = +U_{dc}/3$

If $T_K = 1$ Then $V_K = +U_{dc}/6$

If $T_K = 0$ Then $V_K = 0$

If $T_K = -3$ Then $V_K = -U_{dc}/2$

If $T_K = -2$ Then $V_K = -U_{dc}/3$

If $T_K = -1$ Then $V_K = -U_{dc}/6$

5. SIMULATION RESULTS AND DISCUSSION

The simulation results are provided to verify the performance and effectiveness of the series active power filter based on the seven-level (NPC) inverter using the proposed control scheme. To simulate the proposed series active power filter, a model is developed using MATLAB/Simulink and SimPowerSystem Toolbox; it is shown in Fig. 8. The active filter is composed mainly of the three-phase source, seven-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.

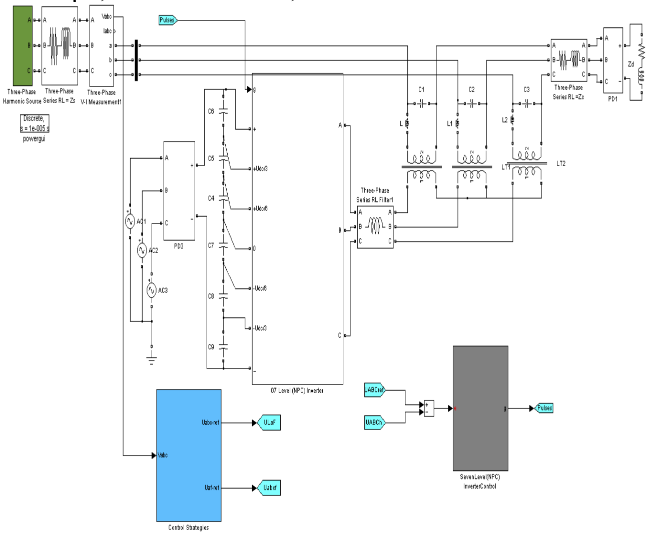
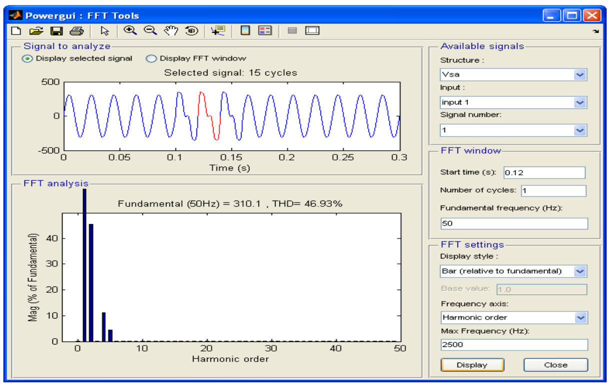


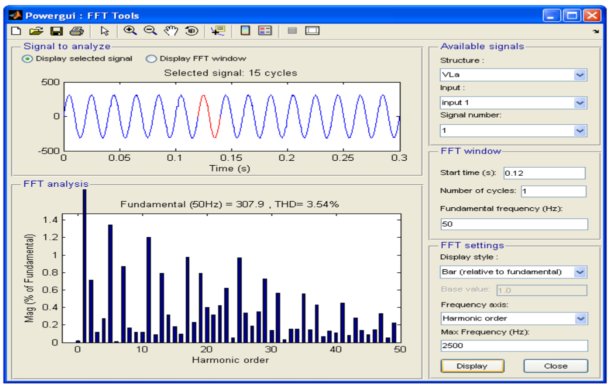
Fig. 8 – Series APF simulation model based on a seven-level (NPC) inverter

The performance of the proposed Series AF system based on modified p-q control strategies is tested under a distorted voltage supply. The harmonic voltage disturbances are introduced voluntarily at t_1=0.1s to t_2=0.16s. Between t_2=0.16 s and t_3=0.2s, the system is again at normal working condition. The series APF starts compensating voltage harmonics instantly. Figure 9 shows the harmonic spectrum of the load voltage before compensation, and the corresponding harmonic spectrum after compensation is shown in Fig. 10.



THDv (%) = 46.93%

Fig. 9 – Load voltage VL-abc(V) spectrum without Series AF

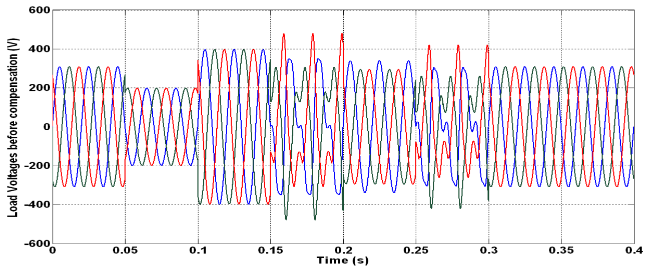


Fundamental (50Hz) = 307.9, THDv (%) = 3.54 %

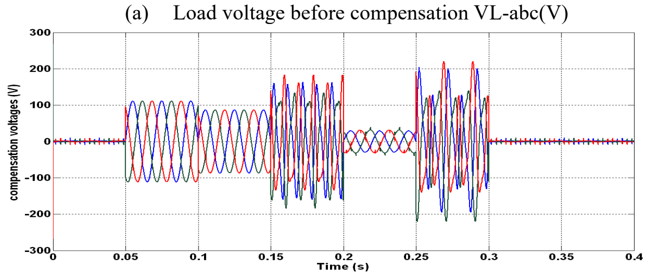
Fig. 10 – Load voltage VL-abc(V) spectrum after compensation

Figures 9 and 10 show the harmonic spectrum of the voltage delivered to the loads before and after the application of the proposed APF. It is observed that the load voltage harmonics are widely reduced in conformity with IEEE standard norms from 46.93 % to 3.54 %.

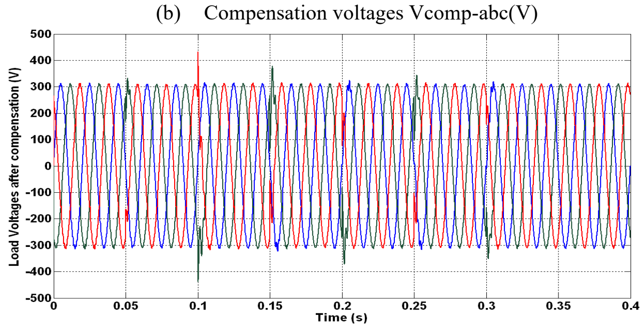
The performance of the proposed Series APF system is also tested under all voltage disturbances introduced simultaneously: harmonics, swells, sags, and unbalances. At the start, we suppose that the three-phase voltages are balanced and non-distorted. A sag voltage disturbance is introduced voluntarily at t_1 = 0.05 s to t_2 = 0.1 s. After sags, a swell voltage is introduced between t_2 = 0.1 s and t_3 = 0.15 s. Harmonics voltage disturbances are introduced between t_4 = 0.15 s and t_5 = 0.2 s. Unbalance voltages is introduced at t_6 = 0.2 s and t_7 = 0.25 s flowed by harmonics voltage disturbances between t_8 = 0.25 s and t_9 = 0.3 s. After t_9 = 0.3 s the system is again at normal working condition. The simulation results are shown in Fig. 11.



(a) Load voltage before compensation VL-abc(V)



(b) Compensation voltages Vcomp-abc(V)



Load voltage after compensation VL-abc(V)

Fig. 11– All voltage disturbances compensation

It is shown in Fig. 11 that after introducing voluntarily the voltage swell (35 %), voltage sag (30 %), or unbalances in the supply voltage, the load voltage is instantly compensated. The effectiveness of the proposed series active filter has been demonstrated in maintaining the three-phase load voltages balanced and sinusoidal; moreover, the proposed system does not show any disturbance significant effect present in the utility voltages on its compensation capability.

Figure 12 shows that the load voltage U_{la} (V) after compensation follows its reference U_{fa} (V) perfectly; it is practically almost sinusoidal.

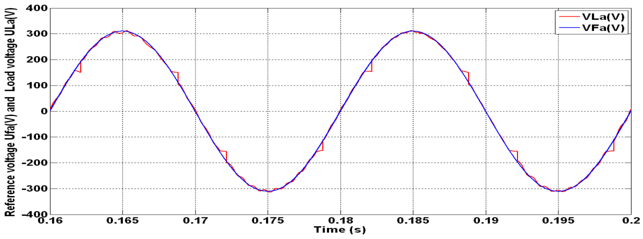


Fig. 12 – Reference voltage Ufa (V) and load voltage Ula (V) after compensation.

6. CONCLUSIONS

This paper proposes a novel series APF based on a seven-level (NPC) inverter using combined level-shifted multicarrier modulation and fuzzy control techniques to enhance the power quality. Most voltage disturbances studied concern voltage harmonics, sags, swells, and unbalances. All these disturbances are successfully compensated using the proposed system. The load voltage harmonic levels are maintained below IEEE-519 standard Norms when the THDv (%) is significantly reduced from 46.93 % to 3.54 % using the proposed system. The simulation results obtained using MATLAB-Simulink and SimPowerSystem show that the proposed series APF is efficient and instantly compensates for all voltage disturbances. From this study, it was proven that the use of multi-level inverters permits to reduce considerably the THDv. Future work will be focused on the nine-level (NPC) inverter with neuro-fuzzy control approaches.

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