

# Series Active Power Filter based on Seven-level Neutral Point Clamped Inverter with Fuzzy Control Technique

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**Abstract** - Improving the power quality in modern electrical distribution is a problem for industrialists and is currently the subject of many researchers around the world working in the field of active filtering systems. The series active power filter (Series APF) is a very interesting solution to compensate voltage sag/swell, harmonics and all other voltage disturbances. In this paper, advanced Series APF configuration based on seven-level neutral point clamped (NPC) inverter is presented. The control strategies adopted to estimate the reference voltages is the modified instantaneous power theory. The control scheme combine fuzzy logic and sinusoidal pulse width modulation to generate the switching pulses for seven-level (NPC) inverter. The simulation is carried using MATLAB-Simulink and SimPowerSystem Toolbox. The obtained results show the effectiveness of proposed Series APF system in harmonics voltage compensation and power quality improvement.

**Keywords** – Seven-level (npc) inverter, Fuzzy logic, Voltage disturbances, Power quality improvement, Total Harmonic Distortion (THD).

## I. 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], [2].

To improve the power quality, some solutions have been proposed by several researchers. Among them the shunt and series active power filters [3] have proven as an important and flexible alternative to compensate most important voltage and current related power quality problems in the distribution system [3], [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]. On the other side, the series active power filters have been proposed as an interesting and high performance solution to compensate most important voltage disturbances. The series active power filter (Series APF) is especially used to compensate unbalances, sags, swells and harmonics [6], [7]. It is inserted in series between the load and the source voltage and injects a

compensating voltage. To perform the series connection, three single phase transformers are used to inject the compensating voltage to the line. Several multilevel inverter topologies are being used for shunt or series 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 [8]. The controller is the main part of any active power filter and has been a subject of many researches in recent years [9], [10]; to improve the Series APF performances there's a great tendency to use intelligent control techniques [11], [12].

Fuzzy Logic Control (FLC) is one of the significant tools in control design originated by Zadh. The advantages of FLC over conventional controllers are high robustness, insensitivity to parameters variations, handling of non-linearity and independent on mathematical models.

The investigation in this paper concentrates on series APF based on seven-level Neutral Point Clamped (NPC) inverter using modified instantaneous reactive power theory [13] with efficient control scheme using fuzzy and SPWM

techniques. The performances of proposed series APF system is evaluated using Matlab-Simulink and SimPowerSystem Toolbox under harmonic voltage disturbances compensation.

**II. SERIES ACTIVE POWER FILTER**

Fig. 1 shows the principle blok diagram of series APF. It is inserted between the disturbance voltage source and a sensitive load.  $L_f$  and  $C_f$  are inductance and capacitance of passive filter used to suppress switching ripples and the three transformers to inject the compensating voltage.

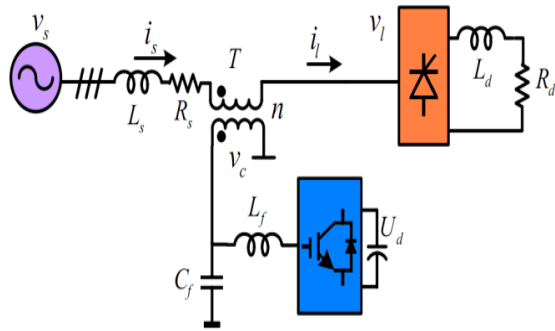


Fig. 1. Series active power filter principle.

**III. MULTI-LEVEL INVERTERS**

Multilevel inverters are currently being investigated and used in various industrial applications. Seven-level inverter is one of different converters employed in medium power applications [14]. Their advantages include the capability to reduce the harmonic content and decrease the voltage or current ratings of the semiconductors. The disadvantage of this topology is that more devices are needed and the control algorithm gets more complicated with the increasing of levels [15].

The circuit of seven-level NPC inverter [16] is given by Fig. 2. Each arm of the inverter is made up of twelve bi-directional IGBTs (Insulated Gate Bipolar Transistor) devices. 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.

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. The reason for the inverter to have clamping diodes connected in series is that all diodes can be of the same voltage rating and be able to block the right number of voltage levels [17]. 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, listed in (Table 1).

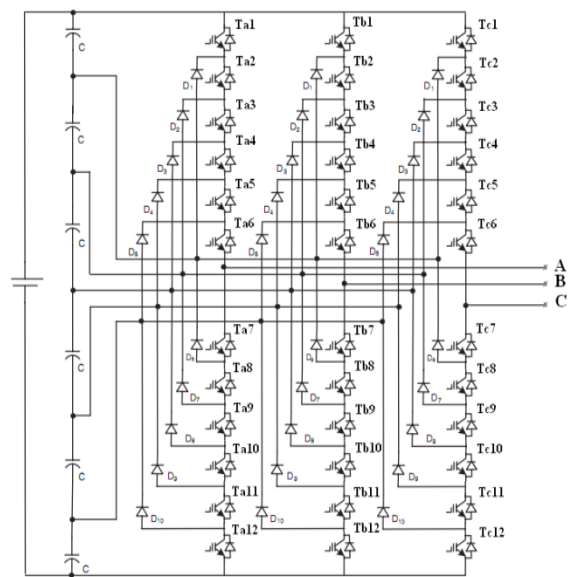


Fig. 2. Seven-level NPC inverter.

Table 1. Seven-level (npc) inverter states.

	Si	A	B	C	0	D	E	F
Switching States	T1	1	0	0	0	0	0	0
	T2	1	1	0	0	0	0	0
	T3	1	1	1	0	0	0	0
	T4	1	1	1	1	0	0	0
	T5	1	1	1	1	1	0	0
	T6	1	1	1	1	1	1	0
	T7	0	1	1	1	1	1	1
	T8	0	0	1	1	1	1	1
	T9	0	0	0	1	1	1	1
	T10	0	0	0	0	1	1	1
	T11	0	0	0	0	0	1	1
	T12	0	0	0	0	0	0	1

#### IV. CONTROL STRATEGIES

The control strategy used for extracting the series APF reference voltages is based on the modified instantaneous reactive power theory described in [18].

$U_{Lu}, U_{Lv}, U_{Lw}$  and currents  $i_{Lu}, i_{Lv}, i_{Lw}$  are respectively the three-phase load voltages and currents. Using  $(\alpha-\beta)$  coordinates, we can transform these voltages and currents from three to two-phase coordinates. After transformation  $\vec{u}_{\alpha}, \vec{u}_{\beta}$  and currents  $\vec{i}_{\alpha}, \vec{i}_{\beta}$  are given by :

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

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

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

$$\begin{aligned} \vec{u} &= \vec{u}_{\alpha} + \vec{u}_{\beta} \\ \vec{i} &= \vec{i}_{\alpha} + \vec{i}_{\beta} \end{aligned} \quad (3)$$

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:

$$\begin{bmatrix} U_p \\ U_q \end{bmatrix} = \begin{bmatrix} \sin(\omega t) & -\cos(\omega t) \\ -\cos(\omega t) & -\sin(\omega t) \end{bmatrix} \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} U_{Lu} \\ U_{Lv} \\ U_{Lw} \end{bmatrix} \quad (4)$$

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

$C_{pq}$  is the p-q 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  $\vec{u}_p$  and  $\vec{u}_q$  in  $u_p$  and  $u_q$  are corresponding 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:

$$\begin{bmatrix} U_{Luf} \\ U_{Lvf} \\ U_{Lwf} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \sin(\omega t) & -\cos(\omega t) \\ -\cos(\omega t) & -\sin(\omega t) \end{bmatrix} \begin{bmatrix} U_p \\ U_q \end{bmatrix} \quad (5)$$

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

$C_{pq}^{-1}$  is the inverse matrix of  $C_{pq}$ , which executes the calculation to convert up and uq back into  $(\alpha-\beta)$  coordinates.

#### V. FUZZY LOGIC CONTROL

Fuzzy logic serves to represent uncertain and imprecise knowledge of the system, whereas fuzzy control allows taking a decision even if we can't estimate inputs/outputs only from uncertain predicates [19]. Their advantages are robustness, not need a mathematical model and accepting non-linearity. To benefit of these advantages a new control scheme based on fuzzy logic and LS-PWM controller for seven-level (npc) inverter is designed. The structure of the FLC is shown in Fig. 3.

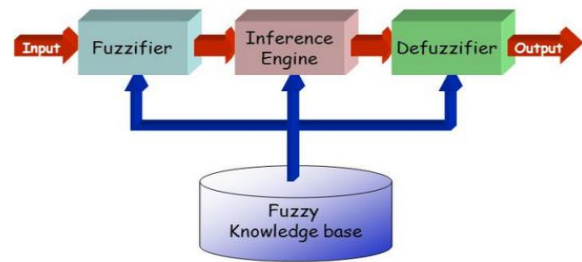


Fig. 3. Fuzzy logic controller.

There are four main parts for fuzzy logic approach. The first part is 'fuzzification unit' to convert the input variable to the linguistic variable or fuzzy variable. The second part is '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 imitate the human decision using rule bases and data bases from the second part. The final part is ‘defuzzification unit’ to convert the fuzzy variable to easy understanding variable [20].

The fuzzy voltage controller proposed in this paper is designed to improve compensation capability of series APF by adjusting the voltage error using fuzzy rules. The desired inverter switching signals are determined according the error between the injected voltage and reference voltage. In this case, the fuzzy logic voltage controller has two inputs, error  $e$  and change of error  $de$  and one output  $S$  [21], [22]. 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). The shape decision of MFs affects how well a fuzzy system rules approximate a function. 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 [23], [24]. The fuzzy controller for every phase is characterized for the following:

- 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.

The switching pulses of the seven-level inverter are generated by means of comparing a six carrier signals with the output of the fuzzy logic controller. The series APF control scheme based on seven-level (NPC) inverter using fuzzy control technique is given by Fig. 4.

The difference between the injected and compensate voltages determines the reference signal control. These signals are compared with six triangular-carrying identical waves shifted from one to the other by a  $(+3U_{pm}, +2U_{pm}, +U_{pm}, -U_{pm}, -2U_{pm}$  and  $-3U_{pm},)$  for the

switching pulses generation. Fig. 5 shows the intermediary signals  $TKJ$ .

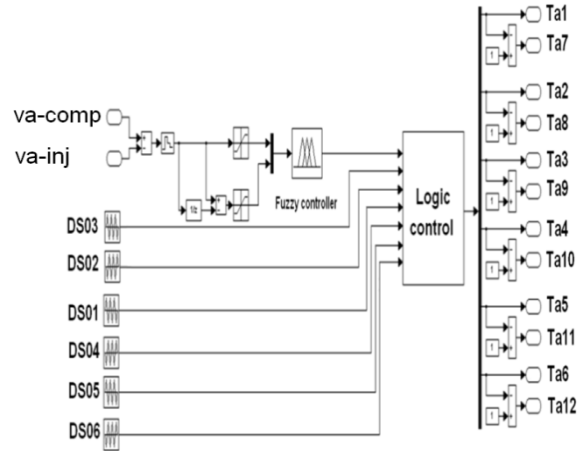


Fig. 4. Series APF control scheme .

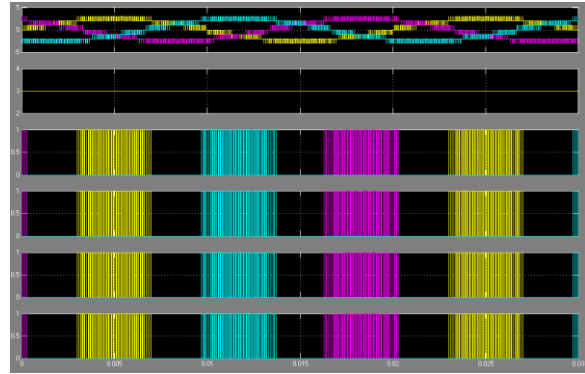


Fig. 5. Intermediary signals  $TKJ$  in case of seven-level (npc) inverter for switching pulses generation.

## VI. SIMULATION RESULTS AND DISCUSSION

To simulate the proposed series active power filters a model is developed using MATLAB/Simulink and SimPowerSystem Toolbox shown in Fig. 6. 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,  $C_1 = C_2 = C_3 = C_4 = C_5 = C_6 = 3000$   $\mu$ F,  $V_s = 220$  V/50 Hz, and  $U_{dc-ref} = 800$  V.

The performance of the proposed Series AF system using modified p-q control strategies is tested under distorted voltage supply. The harmonic voltage disturbances is introduced voluntarily at  $t_1 = 0.1$  sec to  $t_2 = 0.16$  sec. The series APF starts compensating voltage

harmonics instantly. Fig. 7 shows the harmonic spectrum of the load voltage before compensation and Fig. 8, the corresponding harmonic spectrum after compensation.

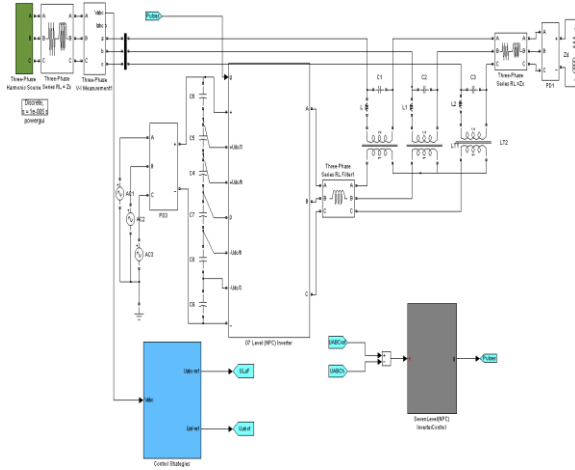
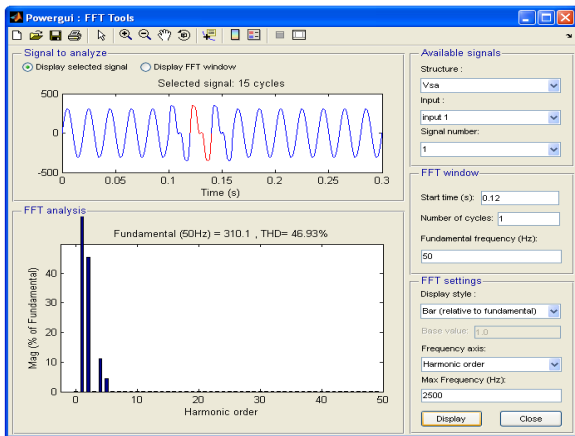
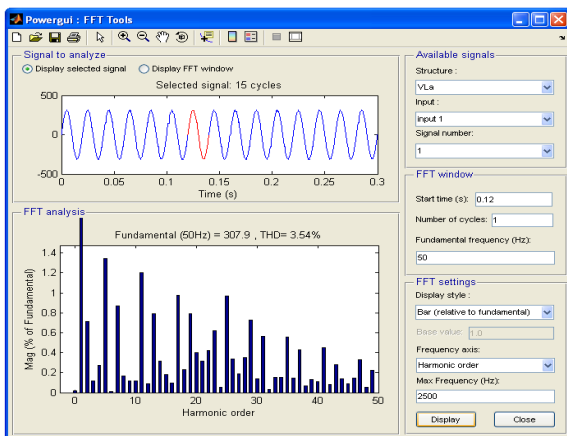


Fig. 6. Series APF SimPowerSystems model.



THDv (%) = 46.93%

Fig. 7. Load voltage harmonics without Series APF.



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

Fig. 8. Load voltage harmonics with series APF.

Fig. 9 shows that the load voltage  $U_{La}(V)$  after compensation track well its reference signals  $U_{fa}(V)$  perfectly using proposed series APF, it is practically almost sinusoidal.

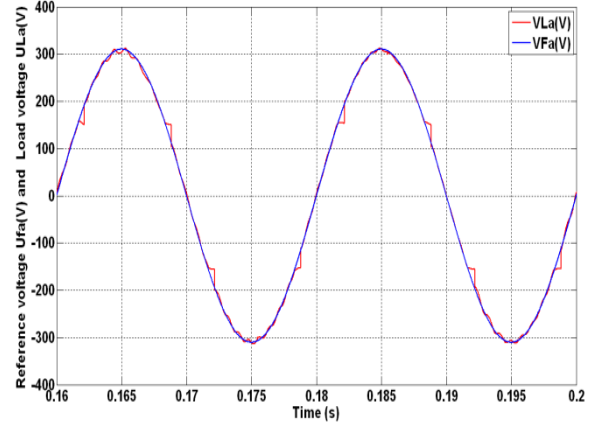


Fig. 9. Reference voltage  $U_{fa}(V)$  and load voltage  $U_{La}(V)$  after compensation.

The performance of the proposed series APF system is tested under harmonic voltage disturbances compensation. Figures 13 and 14 show respectively the harmonic spectrum of the voltage delivered to sensitive loads before and after application of the proposed series APF based on seven level (NPC) inverter. It is observed that the load voltage harmonics are widely reduced in conformity with IEEE standard norms from 46.93% to 3.54% using modified instantaneous reactive power theory. This method is easy to implement, efficient and necessities less calculation compared to conventional p-q method. 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 and the load voltage is maintained constant and sinusoidal.

## VII. CONCLUSION

In this paper, a series APF based on seven-level (NPC) inverter topologies has been proposed, which can assure the function of harmonic suppression and dynamic voltage compensation at the same time. The main voltage

disturbances studied concern voltage harmonics, this voltage disturbances is successfully compensated using the proposed system. The load voltage harmonic levels are maintained below IEEE-519 standard Norms when the source voltage is distorted, the THDv (%) is significantly reduced from 46.93% to 3.54%. The Series APF acts immediately and compensates the harmonic voltage disturbances instantly. The simulation results obtained using MATLAB-Simulink and SimPowerSystem prove that the proposed series APF is efficient and can improve the power quality.

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