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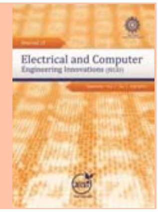

Mitigation of Switching Harmonics in Shunt Active Power Filter Based on Variable Structure Control Approach

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ABSTRACT

This paper presents a novel control approach used in shunt active power filter based on variable structure control combined with Random PWM technique (RVSC) that provides robust, fast, and more favorable performance for active power filter. This control strategy is compared with two other strategies to show the effectiveness of the introduced methods; pulse width modulated proportional-integral control (PIC), and Random Pulse Width Modulated proportional-integral control (RPIC). The simulation results with and without the shunt active power filter in the system are presented and analyzed. The simulation results show that the RVSC controller has a better performance than other control strategies, allowing compensation of reactive power, reducing high frequency harmonics thus overcoming the problem of electromagnetic interference (EMI), reducing dc current injection below the limit specified in IEEE-1547 standard, and also reducing the harmonic level below the limit specified in IEEE-519 standard.

1. Introduction

In recent years, the rapid development of power semiconductor technology and the extensive use of electronic equipments, industrial machines, and automation devices in industries, commerce and households have led to a significant increase in disturbances which affect power quality in transmission and distribution systems. Customers as well as power transmission and distribution companies are increasingly interested in energy efficiency and power quality problems. This interest is mainly due to the technical and economic losses produced by a poor power quality, which affect both supply side and demand side. Therefore, the need arose to develop and implement solutions to improve energy efficiency and provide an adequate power quality in the electrical power systems. Conventionally passive L-C Filters were employed to reduce harmonics and capacitors were used to improve the power factor of the loads. But passive filters have the demerits of fixed compensation, large size and resonance.

The increased severity of harmonic pollution in power distribution network has attracted the attention to develop dynamic and adjustable solutions to the power quality problems giving rise to active filter [1-3]. In recent years, three-phase shunt active power filters have appeared as an effective method to solve the problem of harmonics, unbalanced load currents together with reactive power compensation. Active power filters are connected to AC mains in order to eliminate voltage variations and harmonic components. Shunt active power filter eliminates the current harmonic components working as a source with only the harmonic components and power factor correction, so that only the fundamental component is supplied in the AC mains. In active power filters there are many control strategies which have been studied in order to obtain a good performance. Random Pulse Width Modulation (RPWM) technique has become a common method to distribute the noise spectrum over a wide range of the frequency domain thus reducing EMI problems [4, 5].

This paper presents a novel control approach based on variable structure control in order to improve the performance of active power filter under the modulation technique. This control strategy is compared with two other strategies to show the better performance of the introduced method: pulse width modulated proportional-integral control (PIC), and random pulse width modulated proportional-integral control (RPIC). Analysis and modeling of the active power filter are presented as well as simulation results which show high performance of the proposed control structure.

The active power filter topology used in the present work is shown in Figure 1.

2. ACTIVE POWER FILTER MODEL AND CONTROL STRUCTURES

A. *Reference Current Generation*

In this paper, reference current for shunt active power filter is obtained using instantaneous reactive power theory. The p-q theory formally known as the generalized theory of the instantaneous reactive power in three-phase circuit was first developed by H. Akagi in 1983 [6]. It is based on instantaneous values in three phase systems with or without neutral wire, and is valid for steady state or transitory operations, as well as for generic voltage and current wave forms. The instantaneous reactive power theory consists of an algebraic transformation known as a Clarke transformation of three phase input voltages and the load harmonic currents in the a−b−c coordinates to the α−β reference frame followed by the calculation of the real and reactive instantaneous power components. The transformation matrix associated is as follows:

$$\begin{bmatrix} v\alpha \\ v\beta \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} \end{bmatrix} \begin{bmatrix} va \\ vb \\ vc \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} \end{bmatrix} \begin{bmatrix} iLa \\ iLb \\ iLc \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v\alpha & v\beta \\ -v\beta & v\alpha \end{bmatrix} \begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} \quad (3)$$

$$P = \tilde{P} + \overline{P} \quad (4)$$

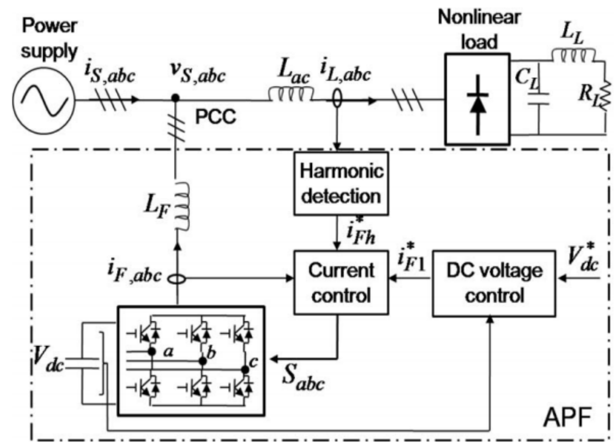


Figure 1: Typical control scheme of a shunt APF

$\tilde{P}$ represent oscillatory part and $\overline{P}$ represent average part of instantaneous real power which is obtained with a low pass filter in αβ system. compensation currents are calculated as follows:

$$\begin{bmatrix} ic_\alpha \\ ic_\beta \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix}^{-1} \begin{bmatrix} -\tilde{P} + \overline{P}_{loss} \\ -q \end{bmatrix} \quad (5)$$

$\overline{P}_{loss}$ is the amount of average active power that should be absorbed from power system to compensate switching and ohmic losses of PWM converter which is obtained from capacitor dc voltage regulator. Finally, reference currents can be obtained with the following equation*:*

$$\begin{bmatrix} i_{ref1} \\ i_{ref2} \\ i_{ref3} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \sqrt{\frac{1}{2}} \\ -\frac{1}{2} & -\sqrt{\frac{1}{2}} \end{bmatrix} \begin{bmatrix} ic_\alpha \\ ic_\beta \end{bmatrix} \quad (6)$$

B. *Random PWM modulation technique*

Random PWM techniques have been introduced to reduce EMI, and the annoying tonal sound given out by inverter-fed systems. The most popular approach consist in Randomization of the switching frequency. In this method, the triangular carrier signal, with which the reference current signal is compared, is generated with a randomly varying slope. This random switching frequency is often generated from uniform distribution in the range [0,1]. Figure 2 shows a triangular carrier signal uses this method of randomization [7-10].

Figure 2. A randomized triangular carier signal in RPWM modulator

C. proposed variable structure control

Due to the non linear nature of the active power filter and load, if the reference current is controlled by non linear controllers, more favorable performance of the active filter is obtained. Since, the sliding mode controller is robust to changes and uncertainties in the parameters of the control system, fast dynamic response and ability to compensate the effects of disturbances and uncertainties is taken into consideration.

However the robustness of this controller is only related to the sliding phase but reaching phase is designed to reach state trajectories of mechanical system to sliding phase as soon as possible. In other words, the system dynamic entirely is not robust for all times. Thus, the conventional sliding mode controller has a fundamental weakness that maybe it can't maintain its stability in reaching phase in the face of uncertainties and perturbations. The other disadvantage of sliding mode control is chattering effect.

In this paper a novel control approach that combines the linear PI controller and sliding mode controller is presented. In addition to simplicity of the implementation, it provides the best features of linear control (such as smooth performance without chattering) and sliding mode control (such as robustness to uncertainties). Block diagram of variable structure current controller is shown in Figure 3 .The main task of a variable structure controller shown in Figure 3, is fast and reliable access to current control. A unit of RPWM is responsible for generation of switching signals. The sliding surface is defined as below:

$$S_i = e_i + C_i \cdot \frac{de_i}{dt} \tag{7}$$

which $e_i = iref_i - iF_i$ is the error between inverter's output current and reference current. iF_i indicates the measured inverter's output current. Design constant, C_i is selected to achieve the desired sliding dynamic. The control law that produces the reference value of current in this method can be stated as:

$$\overset{*}{I} = (Kp + \frac{K_I}{s}).(e_i + Kvsc_i.Sgn(s_i)) \tag{8}$$

which S is Laplace operator, Kp and KI are the PI controller gains and Kvsc is the sliding mode control gain. With proper selection of gains for the linear PI controller and sliding mode controller, best response without occurrence of chattering effect can be

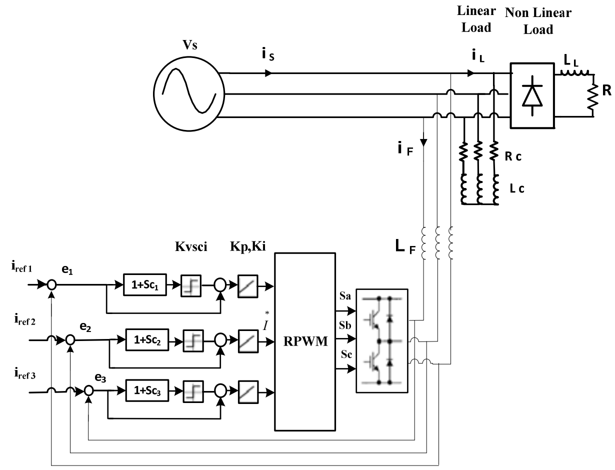


Figure 3.proposed variable structure controller

achieved. For transient responses, the linear controller is dominant, and the PI gains are selected so as to achieve the desired dynamic response. However in the steady state operation, the sliding mode component is dominant and the ripple magnitude depends on the *Kvsc*.

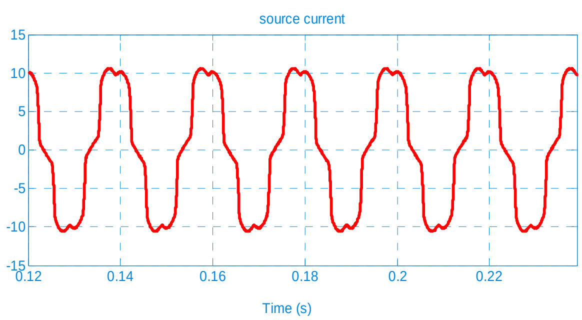
3. SIMULATION RESULTS

In this section, the active power filter system control strategies are implemented on realistic models by using the SimPower Systems blockset of MATLAB. The non-linear load consists of three-phase Universal Bridge and Series RL branch. The components and parameters are listed in Table1.

TABLE 1: MAIN PARAMETERS OF THE SIMULATED CIRCUIT

Parameter	Value	Description
Vs (v)	220	Phase to neutral voltage source
f (Hz)	50	Grid Frequency
R_L(Ω)	50	Resistance in non-linear load
Rc(Ω)	70	Resistance in linear load
L_L(mH)	20	Inductance in non-linear load
Lc(mH)	7	Inductance in linear load
L_F(mH)	0.1	Inductance in compensator
C(F)	2e-3	DC-link capacitor
V_{dc} (V)	700	set Value of capacitor voltage
f_{sw}(kHz)	10	Switching frequency in PIC method
f_{sw}(kHz)	$7<f_{sw}<10$	Switching frequency in RPIC,RVSC methods

Generally diode rectifiers are used to feed loads with large inductance such as DC motors. Therefore simulation is performed using diode rectifiers with RL element on its DC side as nonlinear load. Figure 4 shows waveform for source current and its spectrum without APF. As a three phase balanced load is considered, only phase 'A' waveforms are shown here. Figure 5 shows reference current obtained by applying p-q theory that should be injected to line current for compensation. Figure 6 illustrates the line current and its frequency spectrum applying PI controller. Before active power filter compensation, the THD of supply current was 18.85%. The THD of supply current is reduced to 3.87% by applying PI controller in active power filter. It shows the THD of the compensated current reduces well below 5% recommended limit by IEEE-519 standard. Applying RPIC method in Figure 7 reduces THD to 3.56%, also it reduces high frequency harmonics in switching frequency and its multiples. Finally RVSC technique performance shown in Figure 8 can reduce THD to 3.3%, meanwhile, reducing high frequency harmonics. Analysis of low frequency harmonics in PIC, RPIC and RVSC methods has been shown in Figure 9 . according to IEEE-1547 standard, injection of DC component for grid connected converters should be lesser than 1% of rated current, so active power filter controlled by RVSC technique, can reduce DC component injection of APF to standard level. Simulation results shows that RVSC method applied in APF offers better performance than other two methods.



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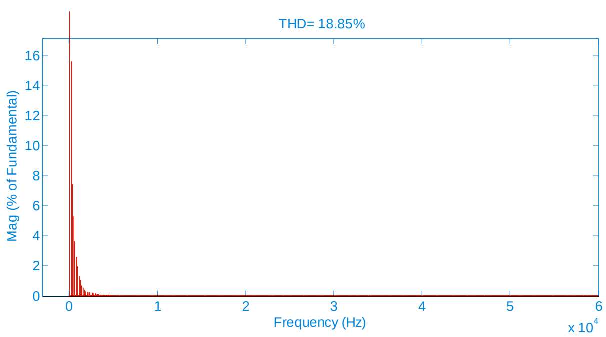


(b)

Figure 4: System performance before compensation a) source current b) its frequency spectrum

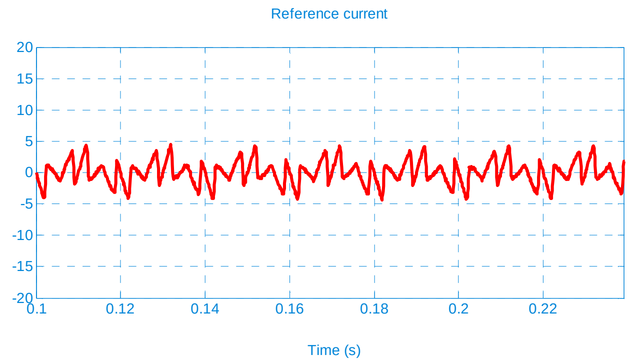
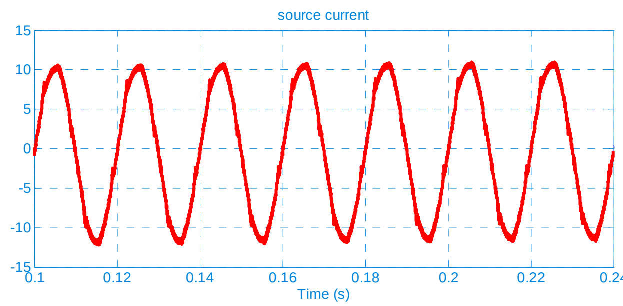


Figure 5: Reference current obtained by applying p-q theory



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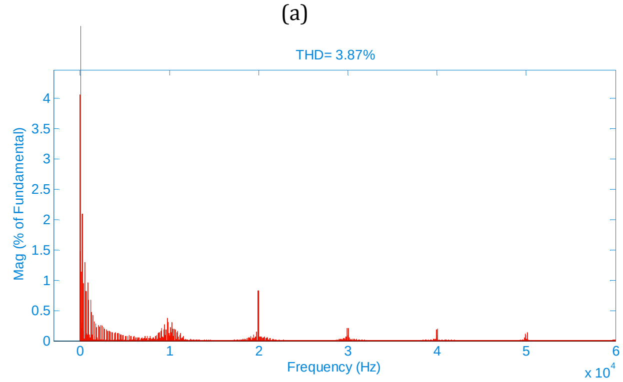


(b)

Figure 6: system performance after compensation by PIC method a) Source current b) its frequency spectrum

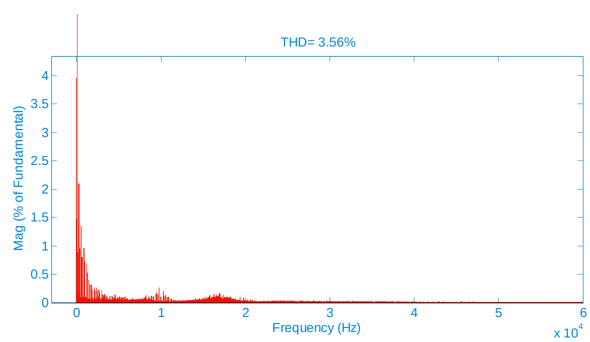


Figure 7: frequency spectrum of source current using RPIC method

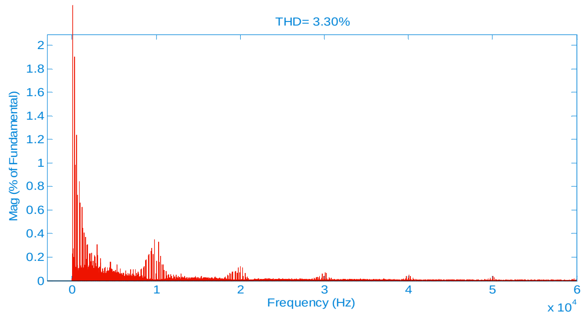
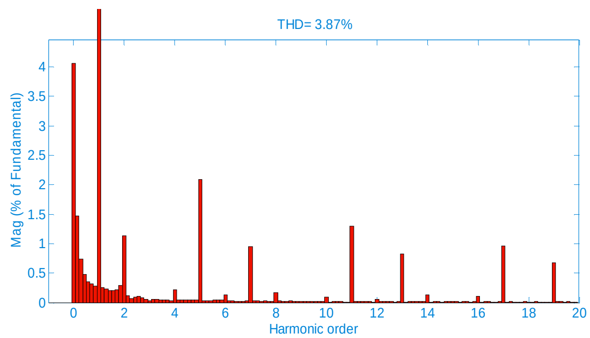


Figure 8: frequency spectrum of source current using RVSC method



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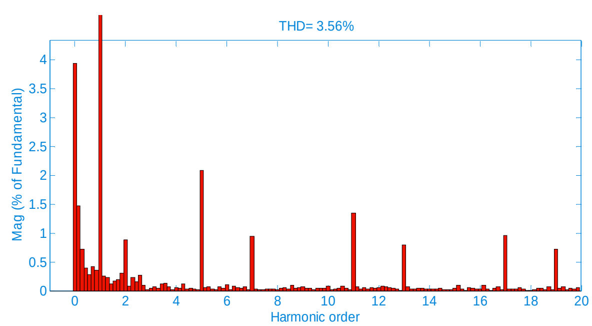

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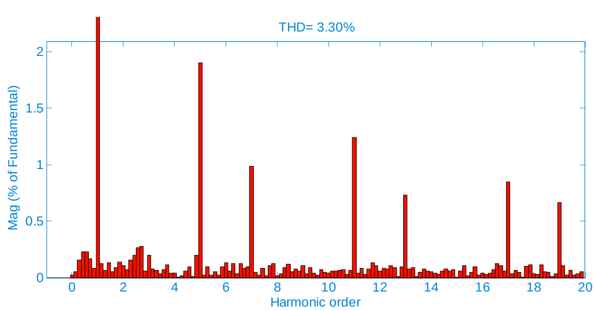

(c)

Figure 9: low frequency spectrum of source current: a) PIC method b) RPIC method c) RVSC method

4. CONCLUSION

Active power filter using PWM modulation technique generates harmonics at switching frequency and its multiples. This concentrated power spectrum may produce Electromagnetic Interference (EMI) problems. Also, active power filter injects unacceptable amount of dc current into the grid that it might cause the saturation of the distribution transformers along the grid. Variable switching frequency applied with RPWM technique is a common method to distribute the noise spectrum over a wide range of the frequency domain and reduces high frequency harmonics. simulation results show that RPWM method offers a better performance by using random variable structure control (RVSC technique) allowing the reduction of high frequency harmonics THD and dc current injection into the grid, compatible with IEEE 1547 and IEEE 519 standards.

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BIOGRAPHIES

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