An Improved SVPWM based Shunt Active Power Filter for Compensation of Power System Harmonics

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***Abstract*— Space vector pulse width modulation (SVPWM) has been extensively utilized in the three-phase voltage source inverters (VSI) for the benefit of fixed switching frequency, full utilization of DC bus voltage and superior control. In recent times, SVPWM technique was applied for active power filter (APF) control application, as the APF is nothing but of a current controlled VSI. The conventional SVPWM based APF has high computational burden due to complex trigonometric calculations and sector identification involved to generate the compensating signal, hence the response time for compensation is slow. In this paper, an improved SVPWM technique based shunt APF is presented based on the effective time concept. The effective time concept eliminates the trigonometric calculations and sector identification, thereby it reduces the computational effort. Simulation results demonstrate the efficacy of the APF with the improved SVPWM based control strategy. The response time for compensation is 0.02sec.**

***Index Terms*—SVPWM, shunt APF, VSI**

I. Introduction

The exponential growth in nonlinear loads has generated a prime concern in the power supply systems. Power electronics based applications draw non-sinusoidal currents, although the applied voltage being sinusoidal. Because of the non-ideal characteristics of voltage source, harmonic currents create voltage distortion. Various nonlinear loads such as arc furnaces, cycloconverters, rectifiers, variable speed drives and other asymmetrical loads can cause huge disturbances in the power supply system. In order to retain harmonic disturbances at reasonable levels, to comply with present standards, we can go through various solutions applicable to supply systems and to harmonics sources.

Conventional solutions like passive filters (PF) for mitigating the harmonic pollution are ineffective due to fixed compensation, large size, and resonance [1]. Furthermore, standard regulations and recommendations regarding the harmonics, such as IEEE 519-1992 and IEC 61000-3-2 [2]-[3], have become restricted and this has motivated the use of active power compensation. With the enormous growth of power electronics and applications, design and development of Active Power Filter (APF) to improve the power quality has been the focus of many papers presented in literature. In recent times, various publications have appeared on the harmonics, reactive power, load balancing, and neutral current compensation related with linear and nonlinear loads [4]-[16].

The development of control algorithm which influences the rating, the steady state and the dynamic performance constitutes the core part of the APF. Different control algorithms have been reported in the literature such as proportional integral (PI) control, dead-beat control, and hysteresis control [8]-[11]. Due to the restriction of the control bandwidth, the PI controller is not an appropriate solution for the APF applications as the current controller should deal with harmonic currents, which are high-frequency signals. In contrast, the dead-beat controller is capable of giving fast control response, but the control performance depends extensively on knowledge of the APF parameters. In spite of the simple and robust feature of the hysteresis control, this method also has an intrinsic drawback of switching frequency variation, which causes a difficulty in design of ripple filter for the APF and results in redundant resonance problems with the system. Additionally, in order to attain superior current control, the hysteresis band limit has to be set as small as possible. It results in a major increase of the switching frequency and as a result introduces huge switching loss on the APF. In order to overcome the deficiencies of the above mentioned control methods, various modern current control techniques have been developed [12]-[13].

Numerous applications of SVPWM control were reported earlier in VSI fed induction motor drives [18]-[21]. In recent times, the SVPWM technique is also gaining importance in APF control [14]-[17]. However, the computational burden involved due to complex trigonometric calculations and sector identification limits the application of SVPWM technique for APF application. An improved SVPWM technique with “effective time concept” has been developed to overcome the above drawback in induction motor drive applications [22]. This effective time concept in the improved SVPWM technique is able to overcome the disadvantages of complex trigonometric calculations and sector identification and it finds a useful application in APF control.

In this paper, an improved SVPWM based shunt APF topology is proposed. The harmonic currents are extracted by synchronous reference frame (SRF) theory and the switching instants for each inverter arm are computed directly using the effective time relocation algorithm. The DC bus voltage of

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the APF is stabilized with a traditional PI voltage feedback controller. Simulation results in MATLAB/Simulink environment demonstrate the improvement in the performance of the proposed SVPWM based shunt APF.

II. SHUNT APF TOPOLOGY

The core part of the shunt APF is shown in Figure 1. This topology consists of two-level VSI coupled with DC capacitor, which is connected in shunt to the nonlinear load at the Point of Common Coupling (PCC) through a ripple filter. Here, V_{sa}, V_{sb}, V_{sc} represent the source voltages. Load currents drawn by the nonlinear load are represented as i_{la}, i_{lb}, i_{lc}. Source currents and active filter currents are represented as i_{sa}, i_{sb}, i_{sc} and i_{fa}, i_{fb}, i_{fc} respectively. Capacitor C is the energy storage element on the dc side to maintain the dc bus voltage V_{dc} constant. The compensation signals are generated based on the improved SVPWM based controller.

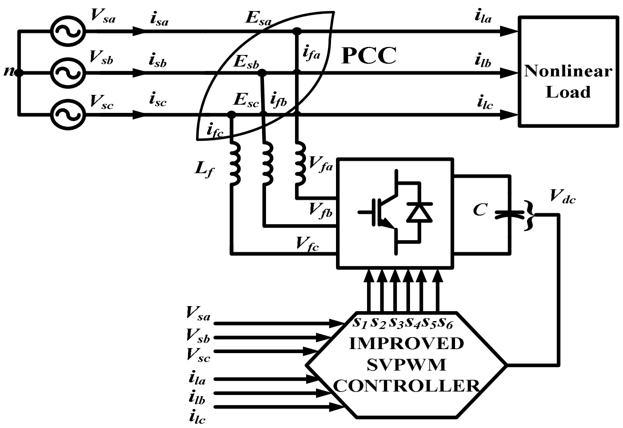

Figure 1. Configuration of Improved SVPWM based shunt APF

The compensation currents of the APF are given by

$$\begin{cases} i_{fa} = i_{la} - i_{sa} \\ i_{fb} = i_{lb} - i_{sb} \\ i_{fc} = i_{lc} - i_{sc} \end{cases} \tag{1}$$

The voltage-source PWM Inverter with a current controller should provide the ability of controlling the harmonic currents. The control circuit should extract the harmonic current from the nonlinear load, not only in steady states but also in transient states. As for three phase APFs, the instantaneous reactive power theory (IRPT) also called as p-q theory [1] or the synchronous reference frame (SRF) theory [6] are generally applied for estimation of the necessary compensation signals, and the PWM strategies for generation of gating signals. In the proposed shunt APF topology, SRF theory is used for harmonic current extraction and SVPWM technique is used to generate the switching signals. Furthermore, SVPWM does not require the triangle waveform generation circuit and is more suitable for realisation in digital control circuits.

Figure.2 shows the single phase (Phase-A) equivalent circuit of the APF system described in Figure 1.

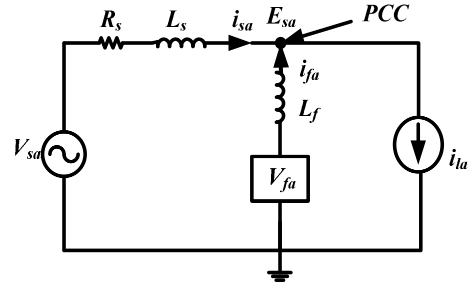

Figure 2. Single-phase equivalent circuit of APF topology

Here V_{sa} & i_{sa} are the phase-A source voltage and source current and R_s & L_s are the internal source resistance and inductance. E_{sa} is the instantaneous voltage of phase A at PCC. V_{fa}, i_{fa} & L_f are the phase A APF voltage, current and inductance, i_{la} is nonlinear load current. The above network can be described by the following equations in terms of APF voltage V_{fa} and current i_{fa}.

$$V_{fa} = L_f \frac{di_{fa}}{dt} + E_{sa} \tag{2}$$

Similarly

$$V_{fb} = L_f \frac{di_{fb}}{dt} + E_{sb} \tag{3}$$

$$V_{fc} = L_f \frac{di_{fc}}{dt} + E_{sc} \tag{4}$$

From the above equations the APF voltages in *a-b-c* frame can be written as

$$V_{f,abc} = L_f \frac{di_{f,abc}}{dt} + E_{s,abc} \tag{5}$$

The source current $i_{s,abc}$ is forced to be free of harmonics by suitable voltages from the APF, and the harmonic current emitted from the load is then automatically compensated. The proposed APF is connected into the network through the inductor L_f. The function of L_f is to attenuate the high frequency switching ripple generated by APF and to connect two AC voltage sources of the inverter and the supply system.

III. SYNCHRONOUS REFERENCE FRAME THEORY FOR HARMONIC EXTRACTION

In this work SRF is used for harmonic current extraction [6], [23]-[25]. The block diagram of proposed shunt APF control scheme shown in Figure 3. In order to maintain sinusoidal source currents with unity power factor at PCC, the source has to supply only the fundamental real component of load current. Hence, the harmonics, reactive component of load current should be supplied from APF. Therefore, the load currents are sensed and transformed to *dq0* reference frame as follows

$$\begin{pmatrix} i_{lq} \\ i_{ld} \\ i_{l0} \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ \sin\theta & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{pmatrix} \tag{6}$$

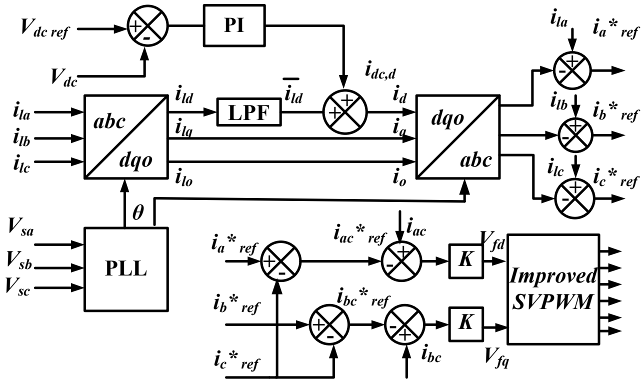

Figure 3. Proposed SVPWM control for APF topology

The harmonic currents for each of the three phases are derived by removing the fundamental frequency component from load currents. Thus, the reference currents normally consist of harmonic components drawn by the load. A low pass filter (LPF), with cut off frequency of 50Hz is used to extract i_{ld}. Here, i_{ld} corresponds to harmonic load currents in *a-b-c* frame. The loss component of VSI is $i_{dc,d}$ must be added to $\overline{i_{ld}}$ in order to acquire complete d-axis reference filter current. As i_{lq}, i_{l0} currents must be supplied directly, LPFs are not required in *q-axis* and *0-axis* controller as shown in Figure.3. Therefore, the *dq0* reference harmonic currents are given by

$$\begin{cases} i_d = \overline{i_{ld}} + i_{dc,d} \\ i_q = i_{lq} \\ i_0 = i_{l0} \end{cases} \tag{7}$$

The *dq0* transformation of (5) generates the following set of equations [26].

$$\begin{aligned} V_{fd} &= L_f \frac{di_{fd}}{dt} - \omega L_f i_{fq} + E_{sd} \\ V_{fq} &= L_f \frac{di_{fq}}{dt} + \omega L_f i_{fd} + E_{sq} \\ V_{f0} &= L_f \frac{di_{f0}}{dt} + E_{s0} \end{aligned} \tag{8}$$

Where, V_{fd}, V_{fq}, V_{f0} are the variables to be controlled, in order to achieve the desired filter currents at PCC in *dq0* frame, ω is the system frequency and i_{fd}, i_{fq} and i_{f0} are the stationary frame reference currents. E_{sd}, E_{sq} and E_{s0} are the stationary frame reference voltages. Neglecting the zero sequence terms, the dynamics of the APF ac side variables in an SRF (*dq* frame) is derived. Since the *d* and *q* components are orthogonal. Hence V_{fd} and V_{fq} from Equation (8) are considered for SVPWM switching signals generation.

IV. IMPROVED SVPWM ALGORITHM FOR APF

The voltage space vector synthesisation is critical in the conventional SVPWM method. As it uses Clarke transformation to transform the reference voltages to *d-q* coordinates in order to generate reference vectors. Subsequently, the reference vectors are synthesised by some optimally selected basic vectors with specific time duration. In that method, the sectors of reference vectors are determined by their phase angles, and the time duration of basic vectors are calculated through the computation of phase angles and reference vectors. As these computations involve huge quantities of irrational numbers and trigonometric functions, the computation burden would be enormous. These operations may bring about major calculation errors which would corrupt the performance of shunt APF.

To solve this problem, an effective time concept based SVPWM is used to generate the switching signals. It is possible to reconstruct the actual gating time without separation and recombination effort. The switching state diagram of the VSI is shown in Figure 4. The six non-null states are represented by space vectors mathematically represented as follows

$$\vec{V}_g = \frac{2}{3} V_{dc} e^{j(g-1)\frac{\pi}{3}} (g = 1......6) \tag{9}$$

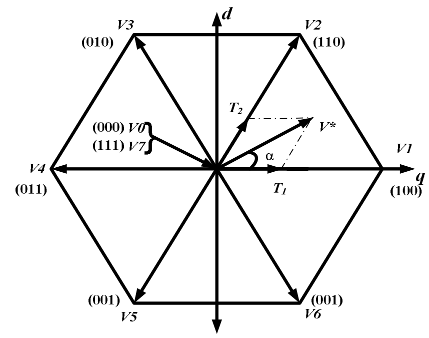

Figure 4. VSI switching states vectors

The APF reference voltages $V_{sa}*$, $V_{sb}*$ *and* $V_{sc}*$ for each phase are found from the stationary reference voltages.

$$\begin{pmatrix} V_{sa}^* \\ V_{sb}^* \\ V_{sc}^* \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} V_{fq} \\ V_{fd} \end{pmatrix} \tag{10}$$

In order to obtain the actual switching time directly from the APF phase voltages, the stationary reference frame voltages are utilized and effective times are transformed to the phase voltages using equation (11).

$$\begin{aligned} T_1 &= \frac{\sqrt{3}.T_s}{V_{dc}} \left[\frac{\sqrt{3}}{2}.V_{fq} + \frac{1}{2}.V_{fd} \right] \\ &= \frac{T_s}{V_{dc}} \left[V_{fq} + \frac{1}{2}.V_{fq} + \frac{\sqrt{3}}{2}.V_{fd} \right] \\ &= \frac{T_s}{V_{dc}} V_{sa}^* - \frac{T_s}{V_{dc}} V_{sb}^* = T_{sa} - T_{sb} \end{aligned} \tag{11}$$

$$T_2 = \frac{\sqrt{3}.T_s}{V_{dc}}\left[0.V_{fq} + 1.V_{fd}\right]$$
$$= \frac{T_s}{V_{dc}}\left[\left(-\frac{1}{2}.V_{fq} - \frac{\sqrt{3}}{2}.V_{fd}\right) - \left(-\frac{1}{2}.V_{fq} + \frac{\sqrt{3}}{2}.V_{fd}\right)\right] \quad (12)$$
$$= \frac{T_s}{V_{dc}}V_{sb}^* - \frac{T_s}{V_{dc}}V_{sc}^* = T_{sb} - T_{sc}$$

From the equations (11) and (12), the effective times T_1, T_2 can be calculated by the time difference between the times T_{sa}, T_{sb} and T_{sc} matching to the phase voltages. Furthermore, in the remaining sectors case, the effective times can be substituted with the phase voltage times in the same method described above. This result, demonstrates that the effective time calculated in the conventional SVPWM is the difference between two applied times resultant to the phase voltage. Hence, despite of the sector location of the reference vector, the resultant times for each phase voltages are defined as following.

$$T_{sa} = \frac{T_s}{V_{dc}}.V_{sa}^*$$
$$T_{sb} = \frac{T_s}{V_{dc}}.V_{sb}^* \quad (13)$$
$$T_{sc} = \frac{T_s}{V_{dc}}.V_{sc}^*$$

The effective time T_{eff} will be defined as the time duration between T_{max} and T_{min}, and the effective voltage is supplied to the VSI during this time interval. Therefore, the actual switching times for each VSI arm can be obtained as follows.

$$T_{ga} = T_{sa} + T_{offset}$$
$$T_{gb} = T_{sb} + T_{offset} \quad (14)$$
$$T_{gc} = T_{sc} + T_{offset}$$

To allocate the zero voltage symmetrically during one sampling period, the offset time T_{offset} is calculated as follows. The switching pulse pattern is shown in Figure.5.

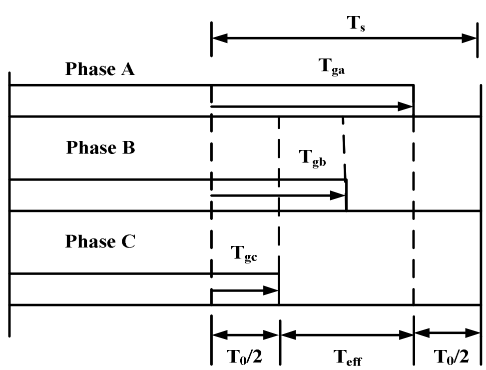

Figure 5. Proposed shunt APF switching pattern

$$\begin{cases} T_{eff} = T_{\max} - T_{\min} \\ T_0 = T_s - T_{eff} \end{cases} \quad (15)$$

and, $T_{min}+T_{offset}=T_0/2$ Therefore $T_{offset} = T_0/2-T_{min}$

Thus, the actual switching times can be obtained from (13), (14) and (15).By using the effective time concept, the actual switching times can be directly computed from the stationary reference frame voltages. Therefore, the computation effort of the proposed PWM method is greatly reduced. With this PWM method the Harmonic compensation signals are generated at PCC using VSI.

V. Simulation Results

The proposed shunt APF topology presented in this paper is simulated with MATLAB/Simulink sim power system toolbox. The system parameters used for the simulation are given in Table.I.

TABLE I. System Parameters

Elements	Values
System voltage	400V RMS , 50 Hz
Nonlinear load	Three phase diode bridge rectifier with R-load of 10 Ω
VSI parameters	C_{dc}=1500 µF,V_{dc} = 950 V
Ripple filter	L_f = 1.2 mH
Switching frequency	10 kHz
PI voltage controller gains	K_p=4, K_i=1

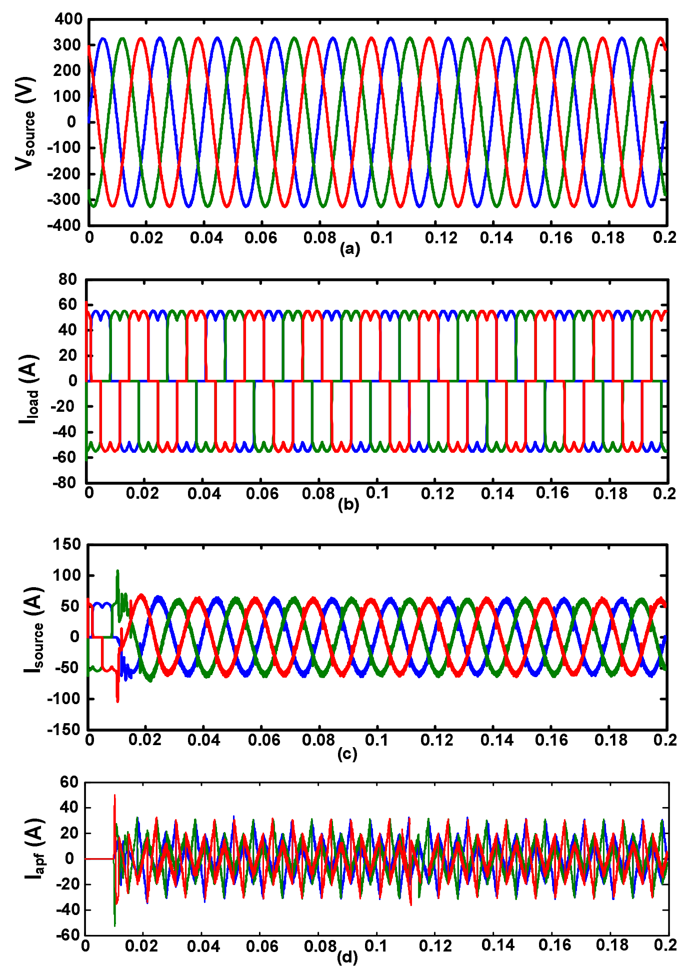

Figure 6. Simulation results (a) Source voltages, (b) Load currents, (c) Compensated source currents, and (d) Filter currents (APF).

The performance of the proposed SVPWM based shunt APF under the application of non-linear loads is shown in Figure 6(a), (b), (c), and (d). It shows the source voltages at PCC, load currents, compensated source currents and injected filter currents respectively. The load currents and the source currents are same before compensation. After employing the shunt APF the simulation results shows that the source currents are sinusoidal at PCC. It can be seen that the response time for compensation is 0.02sec, thus the proposed shunt APF provides the compensation with less computation effort.

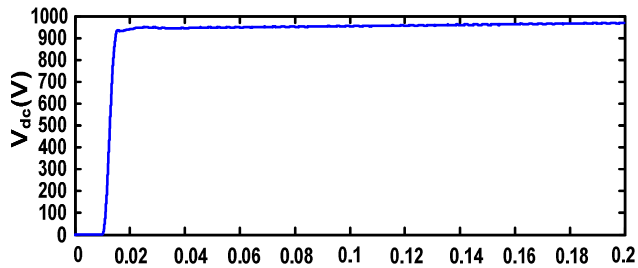

Figure 7.DC Bus voltage of the proposed shunt APF

The DC Bus voltage across the capacitor is 950V.Table II shows the percentage THD comparisons of source currents without and with APF cases. The THD percentage of with APF case is within the limits of IEEE 519 standards.

TABLE II. THD COMPARISION

Without shunt APF (%THD)	With shunt APF (%THD)
24.38%	4.47%

VI. CONCLUSION

In this paper, an improved SVPWM based shunt APF is proposed, which is suitable for digital control realization. This method requires less computation when compared to the conventional SVPWM technique as it eliminates the complex trigonometric calculation and sector identification, The performance of shunt APF with this proposed SVPWM method for harmonic compensation is examined and proved to be worthy where the THD of the source currents was reduced from 24.38% to 4.47% and the response time for harmonic compensation is 0.02 sec.

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