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A Practical Approach to Harmonic Compensation in Electrical Power Systems-Using Shunt Active Power Filter

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Abstract: The shunt active power filters are used in power systems for the compensation of harmonic currents generated for non linear loads. A reference current estimation method for control of SAPF using a digital filter based synchronous reference frame theory is presented. To extract the fundamental component of source current, the Synchronous Reference Frame (SRF) theory is suitable because of its easy mathematical calculation compared to the d-q Control algorithms. The compensation process is based on sensing line currents only which require sensing of harmonics or reactive power components of the load. Various simulation results are presented under steady-state conditions and the performance of PI controllers. Simulation results obtained with MATLAB and testing results on an experimental SAPF are presented to validate the proposed method. The synchronous reference frame based SAPF System to meet IEEE Standard 519 recommended harmonic standards for different rated nonlinear loads under balanced supply conditions.

Key words: Synchronous Reference Frame theory, phase locked loop, total harmonic distortion, hysteresis current controller

INTRODUCTION

The wide use of nonlinear loads, such as diode and thyristor rectifiers, consumer electronics, uninterruptible power supplies and adjustable speed drive results in the distorted current waveforms in the electrical distribution systems. These harmonic currents can cause voltage and current distortion throughout the system which can result in additional losses, measurement errors and malfunctions of protection devices (Othman *et al*., 2006). Traditionally, passive filters have been used to attenuate the harmonic distortion and compensate reactive power but passive filters are bulky, detuned with aging and can resonate with the supply impedance. As active power filters are powerful tools for the compensation not only of current harmonics produced by distorting loads but also of reactive power and unbalance of nonlinear and fluctuating loads (Baggini, 2008). In recent times shunt active power filters are developed for compensating the harmonics and reactive power simultaneously. The active power filter topology can be connected in series or shunt and combinations of both (unified power quality conditioners) and hybrid configurations (Akagi, 1996; Mattavelli, 2001). The shunt active filter is the most popular than the series active filter because most of the industrial applications require the current harmonic's compensation (Kale and Ozdemir, 2005; El-Habrouk *et al*., 2000) and the active filters are very small, more versatile, more selective and less prone to failure for component drift than its passive counterpart. They are studied widely and great developments have taken place in theory and application of Shunt Active Power Filters (SAPF) (Jain *et al*., 2004).

The shunt active power filter has two major parts, one is reference current extraction from the distorted line current and another is the PWM current controller to generate switching patterns for voltage source inverter. Various current control techniques are proposed for APF inner current control loop such as a triangular current controller, sinusoidal-PWM, periodical-sampling controller and hysteresis current controller (Hooshmand and Esfahani, 2011; Zhaoan *et al*., 1998). The Hysteresis Current Controller (HCC) Method attracts researchers' attention due to unconditional stability and simple implementation (Newman *et al*., 2002). In this study, hysteresis Current Controllers have been analyzed which generates the PWM pulses and gives to the active power filter. The performance of SAPF strictly depends upon the features of the Current Control algorithms and controllers. However, usually one control scheme is more appropriate to some situation but not to all situations. A Synchronous Reference Frame theory based current

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control scheme of SAPF for harmonic elimination, power factor correction and balancing of nonlinear loads is proposed in this study.

PRINCIPLE OF SHUNT COMPENSATION SYSTEM

The Shunt Active Power Filter (SAPF) is connected in the distribution grid at Point of Common Coupling (PCC) through filter inductance. The filter inductance suppresses the harmonics caused by the switching operation of the power inverter. The current harmonic compensation is achieved by injecting equal but opposite current harmonic components at PCC, there by canceling the original distortion and improving the power quality on the connected power distribution system (Cavallini and Montanari, 1994; Singh *et al.*, 1998). The instantaneous source current is represented as Fig. 1:

$$I_S(t) = I_L(t) - I_C(t) \quad (1)$$

The instantaneous source voltage is:

$$V_S(t) = V_m \text{Sin}\,\omega t \quad (2)$$

The load current contains the fundamental component and harmonic current components which is represented as (Akagi, 1996):

$$I_L(t) = \sum_{n=1}^{\infty} I_n \sin(n\omega t + \phi_n) = I_1 \sin(\omega t + \phi_1) + \left[\sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n)\right] \quad (3)$$

The instantaneous load power (P_L) can be computed from the source voltage and load current and the calculation is given as:

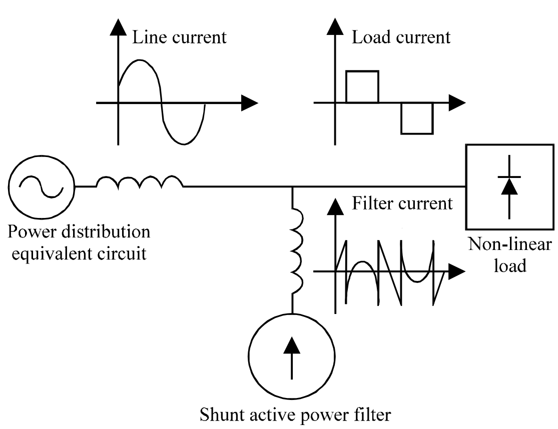

Fig. 1: Instantaneous source current

$$\begin{aligned} P_L(t) &= I_S(t) \times V_S(t) \\ &= V_m \text{Sin}^2\omega t \times \text{Cos}\phi_1 + V_m I_1 \text{Sin}\omega t \times \text{Cos}\omega t \times \\ &\quad \text{Sin}\phi_1 + V_m \text{Sin}\omega t \times \left(\sum_{n=2}^{\infty} I_n \text{Sin}\,(n\omega t + \phi_n)\right) \\ &= P_F(t) + P_R(t) + P_H(t) \end{aligned} \quad (4)$$

This load power contains fundamental active power, reactive power and harmonic power. From Eq. 4, it is found the real fundamental power drawn from the load is:

$$P_F(t) = V_m I_1 \text{Sin}^2\omega t \times \text{Cos}\phi_1 \quad (5)$$

If the active power filter provides the total reactive and harmonic power, the source current $I_s(t)$ will be in phase with the utility voltage and sinusoidal. The three phase source currents after compensation can be expressed as:

$$I_A^* = I_m \text{Sin}\,\omega t \quad (6)$$

$$I_B^* = I_m \text{Sin}\,(\omega t - 120^\circ) \quad (7)$$

$$I_C^* = I_m \text{Sin}(\omega t + 120^\circ) \quad (8)$$

This peak value of the reference current Iref is estimated by regulating the DC-bus capacitor voltage of the inverter.

SRF CONTROL ALGORITHM

The Synchronous Reference Frame theory is based on time domain reference signal estimation techniques. It performs the operation in steady state or transient state as well as for generic voltage and current waveforms. It allows controlling the active power filters in real time system. Another important characteristic of this theory is the simplicity of the calculations which involves only algebraic calculation (Marques *et al.*, 2007). The basic structure of SRF controller consists of direct (dq) and inverse $(dq)^{-1}$ park transformations as shown in Fig. 2.

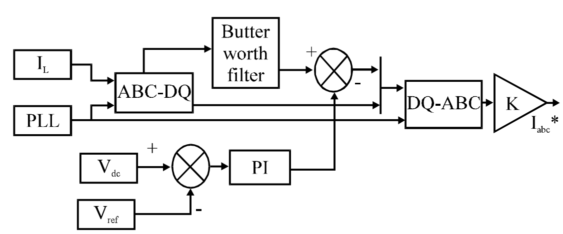

Fig. 2: Control algorithm for SAPF System

These can be useful in the evaluation of a specific harmonic component of the input signals. The reference frame transformation is formulated from a three phase a-c Stationary System to the direct axis (d) and quadratic axis (q) rotating coordinate system. In a-c, stationary axes are separated from each other by 1200 as shown in Fig. 3. The instantaneous space vectors, va and ia are set on the a axis, vb and ib are on the b axis, similarly vc and ic are on the c axis. These three-phase space vectors stationary coordinate are easily transformed into two axis d-q rotating reference frame transformation. This algorithm facilitates deriving id-iq (rotating current coordinate) from three-phase stationary coordinate load current Ila, iLb, iLc as shown in Eq. 9:

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos\left(\theta-\frac{2\pi}{3}\right) & \cos\left(\theta-\frac{4\pi}{3}\right) \\ \sin\theta & \sin\left(\theta-\frac{2\pi}{3}\right) & \sin\left(\theta-\frac{4\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} \quad (9)$$

The d-q transformation output signals depend on the load current (fundamental and harmonic components) and the performance of the Phase Locked Loop (PLL). The PLL circuit provides the rotation speed of the rotating reference frame where ωt is set as fundamental frequency component. The PLL circuit provides the vectorized 50 Hz frequency and 30° phase angle followed by sinθ and cosθ for synchronization. The second order butterworth filter whose cut off frequency is selected to be 50 Hz for eliminating the higher order harmonics. The PI controller is used to eliminate the steady state error of the DC component of the d axis reference signals. Furthermore, it maintains the capacitor voltage nearly constant.

The DC-side capacitor voltage of PWM-voltage source inverter is sensed and compared with desired reference voltage for calculating the error voltage. This error voltage is passed through a PI controller whose propagation gain (K_P) and integral gain (K_I) is 0.1 and 1, respectively.

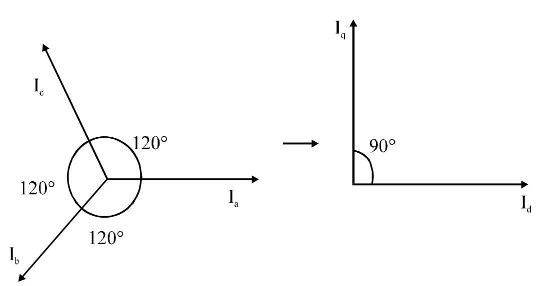

Fig. 3: Park transformation

TWO STAGE PWM CURRENT CONTROLLER

There are various current control methods proposed for active power filter configurations but in terms of fast current controllability, quick response current loop and inherent peak current limiting capability, unconditioned stability, very fast response and good accuracy and easy implementation Hysteresis Current Control Method has the highest rating among Current Control Methods. On the other hand, the basic hysteresis technique exhibits also several undesirable features; such as uneven switching frequency that causes acoustic noise and difficulty in designing input filters (Holtz, 1992; Nabae *et al*., 1986; Brod and Novotny, 1985). The conventional hysteresis band current control scheme used for the control of active power filter line current is shown in Fig. 4, composed of a hysteresis around the reference line current. The reference line current of the active power filter is referred to as I_c* and actual line current of the active power filter is referred to as I_c.

Conventional hysteresis current control operates the PWM voltage source inverter by comparing the current error E(t) against fixed hysteresis bands. This current error is difference between the desired current $I_{reference}$ (t) and the current being injected by the inverter I_{actual} (t) as shown in Fig. 4. If the error current exceeds the upper limit of the hysteresis band, the upper switch of the inverter arm is turned off and the lower switch is turned on. If the error current crosses the lower limit of the hysteresis band, the

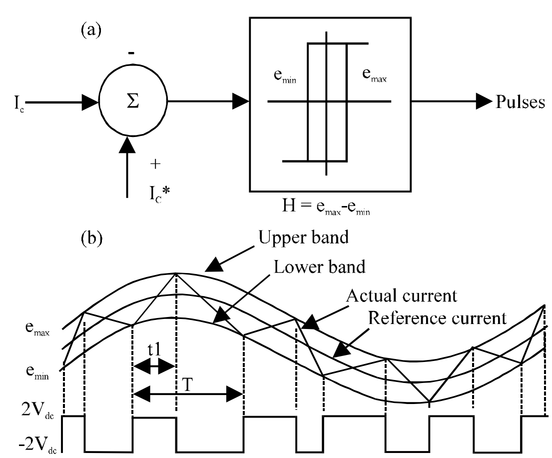

Fig. 4: Hysteresis current controller

lower switch of the inverter arm is turned off and the upper switch is turned on (Zeng *et al*., 2004). This control strategy of the switching frequency is determined as follows. The rate of change of phase current at any point of time is written as:

$$\frac{di}{dt} = \frac{\Delta i}{\Delta t} = \frac{\pm 2V_{dc}}{l} \tag{10}$$

$$\Delta t = \frac{\Delta il}{\pm 2V_{dc}} \tag{11}$$

Where:

$\pm 2V_{dc}$ = Depending on inverter switching state
Δi = Rate of change of inverter current
Δt = Rate of change of time period
l = The series inductance of the filter

A complete switching cycle goes from $0 \to t_1 \to T$ for the period $0 \to t_1$:

$$t_1 = \frac{+\Delta il}{2V_{dc}} \tag{12}$$

From the period $t_1 \to \frac{T}{2}$ substituting $T\text{-}t_1$ in Eq. 11, researchers get:

$$T\text{-}t_1 = \frac{-\Delta il}{-2V_{dc}} \tag{13}$$

The total switching time is obtained by combining these two equations and it give as:

$$f_s = \frac{1}{T} = \frac{V_{dc}^2}{\Delta il V_{dc}} \tag{14}$$

$$f_{maximum} = \frac{V_{dc}}{\Delta il} \tag{15}$$

$f_{maximum}$ is maximum switching frequency of the voltage source inverter. The variation in the switching frequency influences the performance of the current controller both in terms of harmonics and the maximum switching frequency.

PI CONTROL SCHEME

Figure 5 shows the PI control scheme and also it consists of the proportional and integral term. PI controller mainly focuses upon the difference (error) between the process variable and the set point; the difference between harmonic's current reference signals

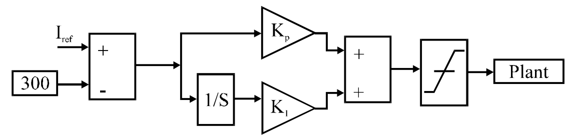

Fig. 5: PI control scheme

Ih and the filter current If. PI Controller algorithm involves two separate parameters; the proportional and the integral. The value of proportional controller which determines the reaction to the current error; the integral controller is to determine the reaction based upon the sum of recent errors. The weighted sum of these two actions is used to adjust the process at the plant. By tuning the two constants in the PI Controller algorithm, the PI controller can provide control action designed for specific process requirements. The control equation for the proportional Plus Integral (PI) is asgiven in Eq. 10 and 11:

$$U(t) = K_P e + K_i \int_{\tau}^{T} e(\tau)d\tau \tag{16}$$

$$D(s) = K_P + \frac{K_i}{S} \tag{17}$$

The proportional gain is derived using $K_P = 2\zeta\omega_{nv}C$, the damping factor $\zeta = \sqrt{2}/2$ and natural frequency on ω_{nv} should be chosen as the fundamental frequency. Similarly, the integral gain is derived using $K_i = 2\omega_{nv}^2$ this controller estimates the magnitude of peak reference current I_{max} and controls the dc-side voltage (Shu *et al*., 2008; Grino *et al*., 2007). The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the set-point and the degree of system oscillation.

SIMULATION CONDITIONS

Simulations based on MATLAB/SIMULINK were implemented to verify the proposed shunt active power filter with PI scheme. The circuit parameters of the equivalent power system based on Fig. 1 are as follows: V_{rms} = 90 V, V_{dc} = 300 V, L_s = 1.0 mH, L_f = 0.3 mH. The power converter is switched at a frequency of 10 kHz. Load current and source current were analyzed to obtain the total harmonic distortion. Figure 4 shows waveforms of the supply current after compensation and the corresponding harmonic spectra. The THD after compensation is 2.72% (Fig. 6-11).

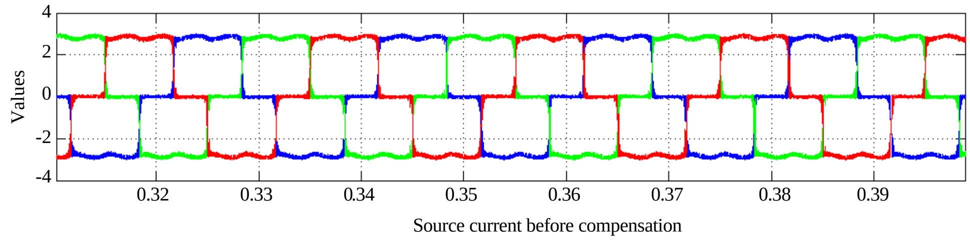

Fig. 6: Before compensation

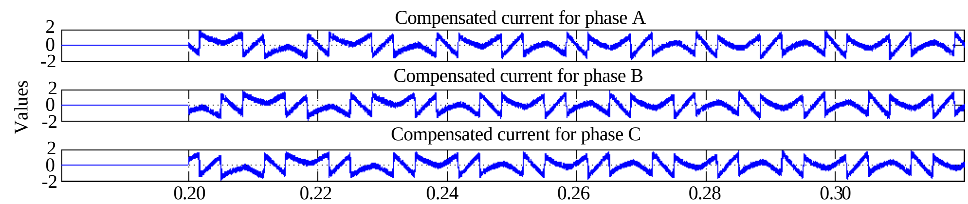

Fig. 7: Compensation current

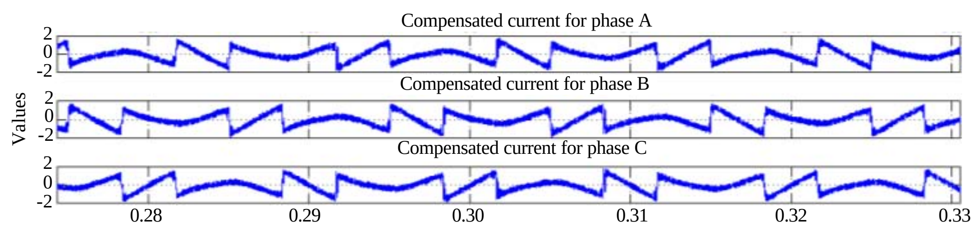

Fig. 8: Compensation current with different time interval

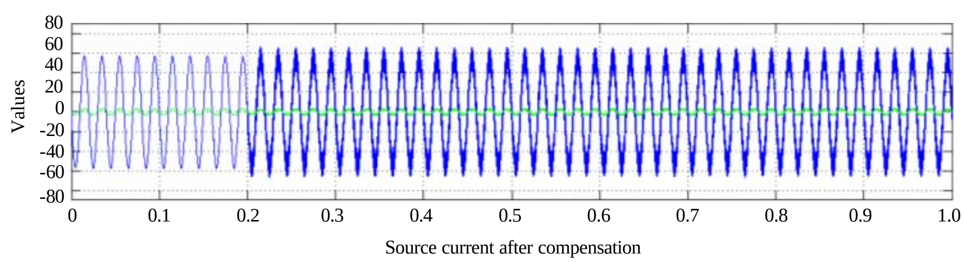

Fig. 9: Source current after compensation

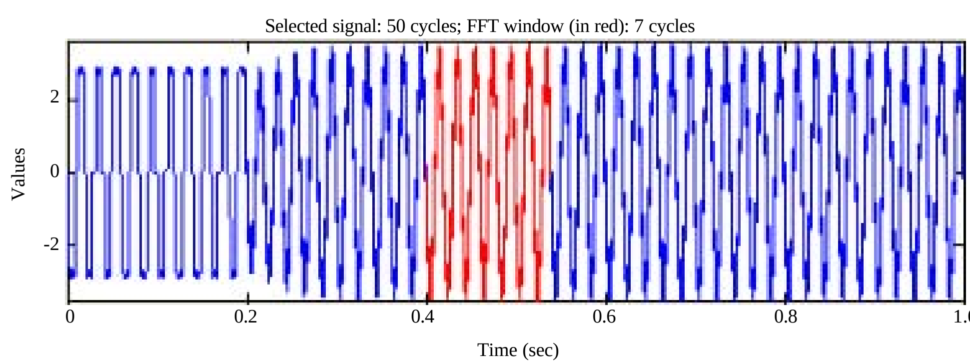

Fig. 10: THD for 7 cycles

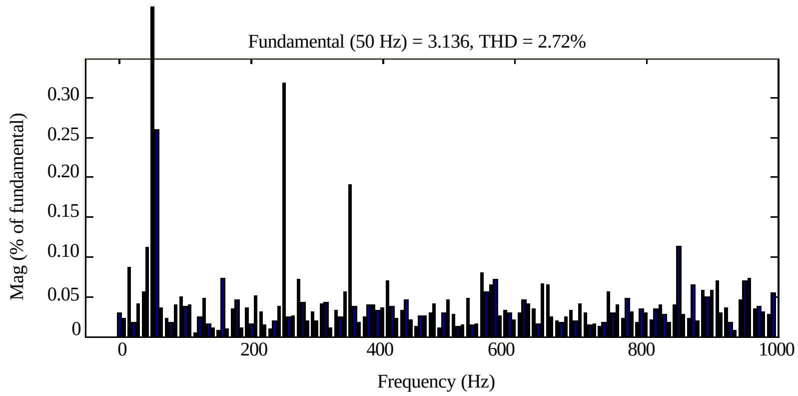

Fig. 11: THD plot

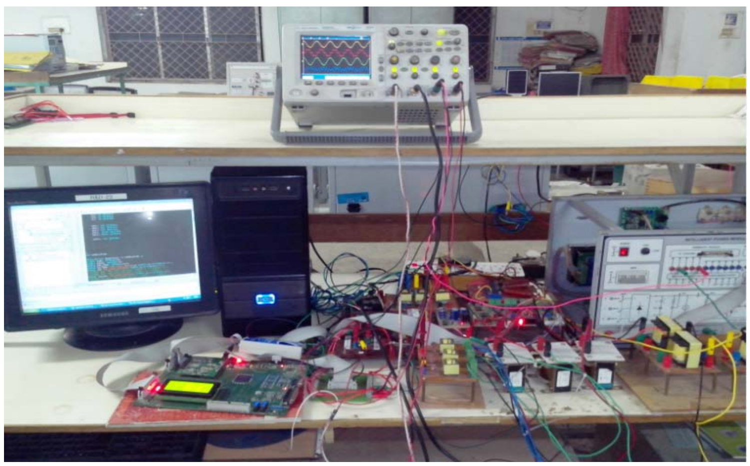

Fig. 12: Hardware setup

CONFIGURATION OF SAPF

A SAPF is developed which is multiplex and composed of two models. The current control algorithm proposed in this study is adopted in the APF System and complemented by a 32-bit floating point FPGA-SPARTAN 3A QFP by which the precision of calculation can be ensured. The IGBT module which has PM 25 RSB 120 is used and also necessary protection (over voltage and over current protection) maintained. Here, nine current sensors (Hall effect LPS 25 MP) and three voltage sensors (LV 25-NP). The current control is implemented by analog circuit instead of digital circuit to avoid using too many A/D converters. In the presented control system, the number of D/A converters is always three, no matter how many models exist in the APF System because the current instructions of the models are the same. So, it is easier to expand the power rating of APF through the digital-analog hybrid control method. The load current is sampled 500 times in a fundamental cycle by three rapid 12 bit parallel A/D converters (AD7892). The current references calculated by FPGA-SPARTAN 3A QFP are given to the analog tracking circuit via a rapid parallel DAC-MAX547 which is 13 bits and has eight channels (Fig. 12).

Steady-state conditions experiments: The test system for steady-state experiments consisted of a three phase diode bridge rectifier with a RL Load (20Ω, 30 mH). Figure 13 and 14 show the phase voltage and the line current before compensation which is non sinusoidal and unbalanced and has a reactive power component. The results according to different compensation purposes where V is phase voltage and I_l is line current. In Fig. 14, these waveforms, the steady state performance of APF adopting the proposed method is working properly.

Dynamic response experiments: In Fig. 15, the dynamic response of the APF adopting. The SRF Based algorithm are shown, respectively where I_S is the line current after

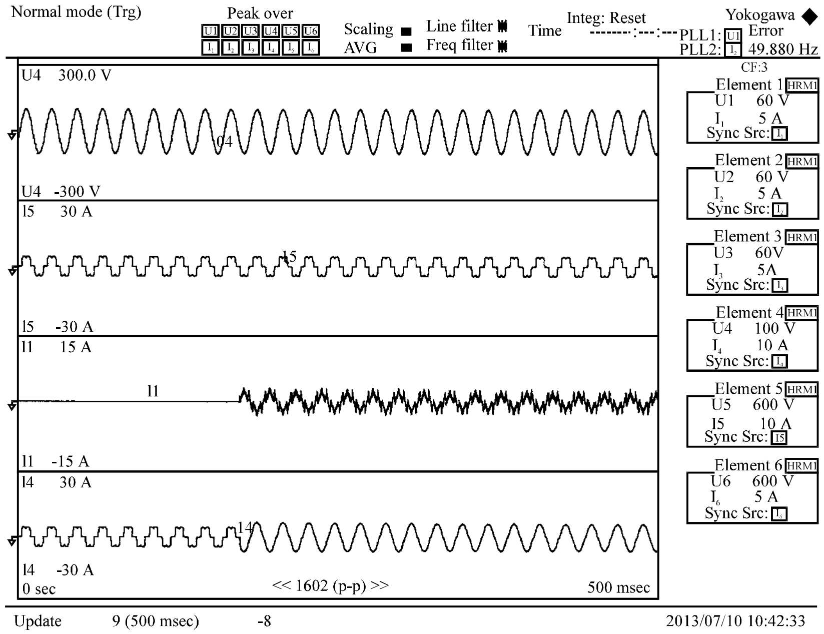

Fig. 13: Phase voltage and line current before and after compensation and filter current

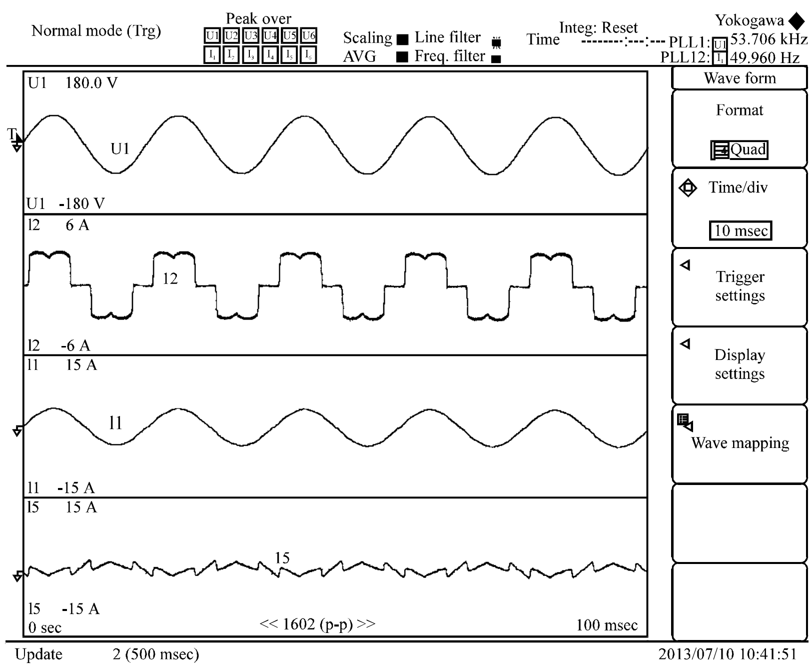

Fig. 14: Phase voltage and line current before and after compensation and filter current with different time intervals

compensation, I_L is the load current and $I_{Reference}$ is the reference for compensation purpose. The THD of the line current after compensation is higher than 8% in the transient period. However, the APF adopting the SRF algorithm has good dynamic response and the THD of the line current after compensation is lower than 3% in the transient period. Table 1 shows real, reactive and apparent has calculated and Table 2 shows harmonic order.

Figure 16 shows the results of the simulation indicate that this algorithm can active control the harmonics and

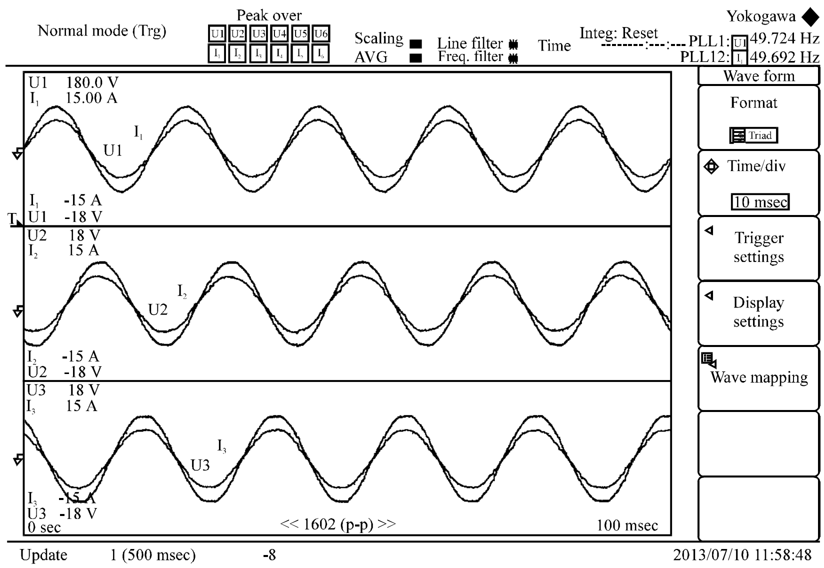

Fig. 15: Phase voltage and line current after compensation

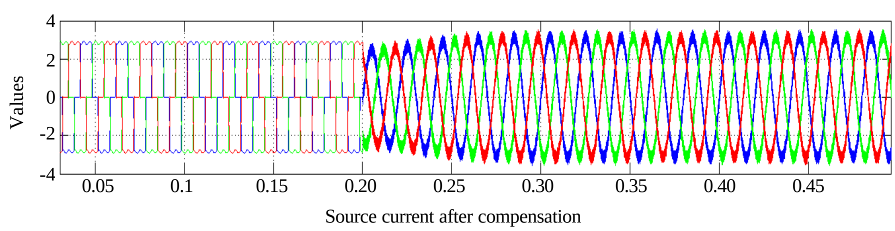

Fig. 16: Source current compensation

Table 1: After compensation real, reactive and apparent powers

Data	Phase R	Phase Y	Phase B
V_{rms}	70.69	69.32	71.92
I_{rms}	3.86	3.80	3.98
Power	272.47	262.32	285.85
Apparent power	273.29	263.51	286.78
Reactive power	21.21	-25.04	-25.52
Power factor	0.99	0.99	0.99

Table 2: Harmonic profile for experimental test

Order	H	In (%)
1	70.79	99.975
3	0.85	1.199
5	0.84	1.191
7	0.12	0.170
9	0.55	0.773
11	0.49	0.700
13	0.26	0.364
15	0.09	0.133
17	0.08	0.109
19	0.18	0.250
21	0.10	0.135
23	0.14	0.199
25	0.16	0.230
27	0.09	0.129
29	0.20	0.286
31	0.14	0.197
33	0.03	0.045
35	0.14	0.198
37	0.10	0.145
39	0.01	0.021

achieving good power quality, reactive power compensation. The experimental results indicate that the APF adopting the new algorithm performs well and can be used in practice. The results show that an digital filter based algorithm the THD meets the recommended harmonic standards such as IEEE 519 where the one with the PI scheme achieved the best performance in terms of active filtering. The results yield good agreement with the expected APF goals.

CONCLUSION

As described in the study, a well designed shunt active power filter should be able to effectively compensate reactive power and suppress harmonic distorted loads. The shunt active power filter with digital filter based SRF algorithm was examined in this study. From the analysis, simulation and experiment, researchers can see that the algorithm presented in this study has some advantages: clear physical meaning, flexible operation, rapid, accurate and easy to implement. The research of simulation and experiment is also done.

REFERENCES

Akagi, H., 1996. New trends in active filters for power conditioning. IEEE Trans. Ind. Appl., 32: 1312-1322.

Baggini, A., 2008. Hand Book of Power Quality. John Wiley and Sons, Ltd., USA., ISBN: 9780470754238, Pages: 642.

Brod, D.M. and D.W. Novotny, 1985. Current control of VSI-PWM inverters. IEEE Trans. Ind. Appl., 21: 562-570.

Cavallini A. and G.C. Montanari, 1994. Compensation strategies for shunt active-filter control. IEEE Trans. Power Electron., 9: 587-593.

El-Habrouk, M., M.K. Darwish and P. Mehta, 2000. Active power filters: A review. IEE Proc. Elect. Power Appl., 147: 403-413.

Grino, R., R. Cardoner, R. Costa-Castello and E. Fossas, 2007. Digital repetitive control of a three-phase four-wire shunt active filter. IEEE Trans. Ind. Electron., 54: 1495-1503.

Holtz, J., 1992. Pulsewidth modulation: A survey. IEEE Trans. Ind. Electron., 39: 410-420.

Hooshmand, R.A. and M.T. Esfahani, 2011. A new combined method in active filter design for power quality improvement in power systems. ISA Trans., 50: 150-158.

Jain, S.K., P. Agarwal and H.O. Gupta, 2004. A control algorithm for compensation of customer-generated harmonics and reactive power. IEEE Trans. Power Delivery, 19: 357-366.

Kale, M. and E. Ozdemir, 2005. Harmonic and reactive power compensation with shunt active power filter under non-ideal mains voltage. Electr. Power Syst. Res., 74: 363-370.

Marques, G.D., V.F. Pires, M. Mlinowski and M. Kazmierkowski, 2007. An improved synchronous reference frame method for active filters. Proceedings of the International Conference on Computer as a Tool, September 9-12, 2007, Warsaw, Poland, pp: 2564-2569.

Mattavelli, P., 2001. A closed-loop selective harmonic compensation for active filters. IEEE Trans. Ind. Appl., 37: 81-89.

Nabae, A., S. Ogasawara and H. Akagi, 1986. A novel control scheme for current-controlled PWM inverters. IEEE Trans. Ind. Appl., 22: 697-701.

Newman, M.J., D.N. Zmood and D.G. Holmes, 2002. Stationary frame harmonic reference generation for active filter systems. IEEE Trans. Ind. Applied, 38: 1591-1599.

Othman, S.B., A. Braha and S.B. Saoud, 2006. Hardware design and implementation of digital controller for parallel active filters. Proceedings of the International Conference on Design and Test of Integrated Systems in Nanoscale Technology, September 5-7, 2006, Tunis, Tunisia, pp: 331-334.

Shu, Z., Y. Guo and J. Lian, 2008. Steady-state and dynamic study of active power filter with efficient FPGA-based control algorithm. IEEE Trans. Ind. Electron., 55: 1527-1536.

Singh, B., K. Al-Haddad and A. Chandra, 1998. Harmonic elimination, reactive power compensation and load balancing in three-phase, four-wire electric distribution systems supplying non-linear loads. Electr. Power Syst. Res., 44: 93-100.

Zeng, J., C. Yu, Q. Qi, Z. Yan and Y. Ni *et al*., 2004. A novel hysteresis current control for active power filter with constant frequency. Electr. Power Syst. Res., 68: 75-82.

Zhaoan, W., Y. Jun and L. Jinjun, 1998. Harmonics Elimination and Reactive Power Compensation. China Machine Press, Beijing, China.