OPTIMAL HARMONIC COMPENSATION IN THREE-PHASE POWER SYSTEM EMPLOYING VOLTAGE SOURCE INVERTER BASED ACTIVE POWER FILTER AND PARTICLE SWARM OPTIMIZATION

SUSHREE SANGITA PATNAIK[1], PROF. ANUP KUMAR PANDA[2]

Department of Electrical Engineering, National Institute of Technology, Rourkela 769008, INDIA

E-mail: [1]sspatnaik.ee@gmail.com, [2]akpanda.ee@gmail.com

Abstract: *Optimizing the performance of power system networks using conventional mathematical modeling based approaches is quite difficult because of the complex nature of systems that are highly nonlinear, non-stationary and involve a large number of inequality constraints. In this paper, Particle swarm optimization (PSO) is proposed to be implemented to enhance the harmonic compensation capability of conventional shunt active power filter (APF). An analysis of the APF performance is carried out under ideal, distorted and unbalanced supply voltage conditions. Extensive MATLAB simulations were carried out and results demonstrate that the APF with proposed implementation of PSO is very efficient in bringing down the Total harmonic distortion (THD) in source current to drastically small values so that IEEE–519 std. on harmonic levels is satisfied.*

Keywords: *Active power filter, Particle swarm optimization, Instantaneous active and reactive power (p-q) method, Total harmonic distortion.*

1. Introduction

Intensification of harmonic pollution in power system at an alarming rate has brought down the efficiency and power factor, with increase in the risk of electromagnetic interference with neighboring communication lines [1, 2]. This is principally due to the proliferation of typical nonlinear loads such as arc furnaces, fluorescent lights, power electronic converters, microprocessors, motor drives, electronic loads, saturated transformers, switching mode power supplies, various domestic appliances, etc. that draw significant amount of harmonic current from the utility. Moreover in three-phase networks, the harmonic currents with order in multiples of three (3^{rd}, 6^{th}, 9^{th}, etc.) add on to the neutral conductor being in-phase with each other. High neutral currents may result in overloaded power feeders, overloaded transformers, voltage distortion, and common mode noise [3].

Shunt APF emerged as a powerful solution to overcome the difficulties encountered in power system such as current harmonics, excessive neutral current and reactive power burden [4-7]. APF generates the required compensation filter current of same magnitude and opposite phase as that of the harmonics in load current. This is injected into power system at the point of common coupling (PCC) between the source and the load. Ultimately, sinusoidal, balanced and compensated current is drawn from the utility lowering down the THD in source current below 5% thereby satisfying the IEEE-519 standard recommendations. The APF comprising of Pulse-width modulation (PWM) based voltage source inverter (VSI) employing various control schemes has gained well-recognition [8, 9].

This paper evaluates the APF performance under both ideal and non-ideal supply voltage conditions. Distorted supply in power system may be categorized as DC off-set, harmonics, inter-harmonics, notching and noise; caused primarily due to static frequency converters, cycloconverters, arcing devices, switching power supplies and other power electronic devices. Unbalanced supply condition may result due to the generators in the system, presence of unequal single phase loads in a three-phase system, blown fuses in one of the phases of a three phase capacitor bank or single phasing conditions.

Control scheme for the APF makes use of a Proportional-Integral (PI) controller to overcome the inverter losses occurring inside APF itself. Proportional and integral gains of PI controller obtained by conventional approach may not give satisfactory result for a wide variety of operating conditions [10, 11]. In this paper, PSO algorithm is proposed to extract the optimized PI controller gains that can overcome the drawbacks in conventional methods.

Shunt APF configuration is briefly explained in Section 2. The DC-link voltage controller, APF reference compensation current generation scheme, PSO algorithm and simulation results are described in Sections 3, 4 and 5 respectively. Finally the conclusion is summarized in Section 6.

2. Shunt Active Power Filter

To implement an APF in three-phase four-wire systems, there are two possible configurations viz. three-leg VSI based APF and four-leg VSI based APF, which has been shown in Fig.1. In three-leg topology, the neutral wire is connected to mid-point of the split capacitor, whereas in four-leg topology, an extra leg is provided exclusively for neutral current compensation. Many researchers prefer the implementation of four-leg VSI based active filter topology over three-leg split capacitor topology [12, 13].

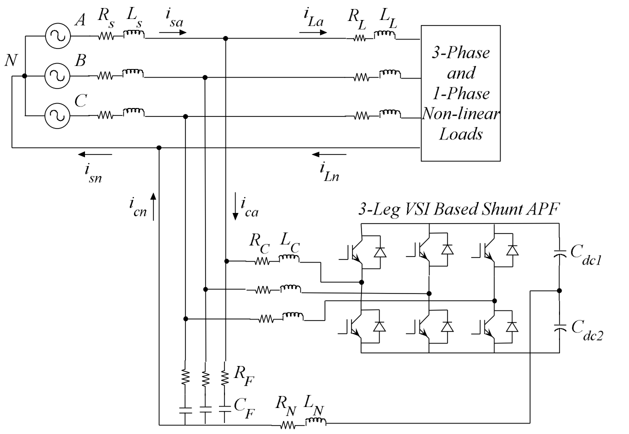

Fig.1(a). Three-leg VSI based APF configuration

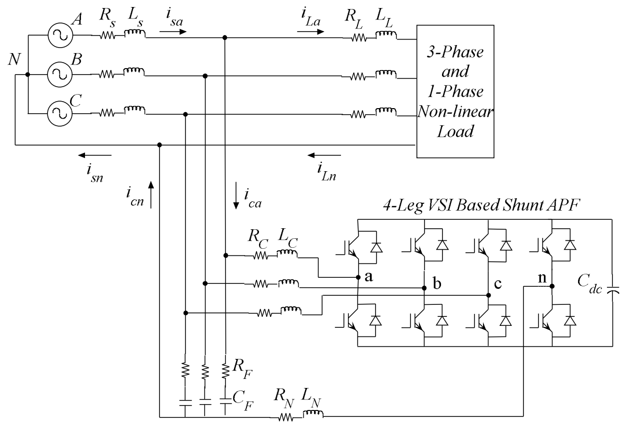

Fig.1(b). Four-leg VSI based APF configuration

This is because the three-leg VSI based APF topology suffers from following drawbacks.

(a) Requirement of large DC-link capacitors

(b) The DC-link capacitor voltages need to be properly balanced

(c) Control scheme is comparatively complex as it requires DC-link voltage balancing

3. DC-Link Voltage Control of VSI

Inherent switching actions carried out inside the inverter leads to high switching losses in three-phase four-leg inverters due to the presence of more number of switching devices. The DC-link capacitor voltage is utilized to overcome these losses. For quality performance of the APF, DC-link voltage (V_{dc}) needs to be maintained at a constant pre-specified reference value (V_{dc}*) by the utilization of a PI controller. The tuning of PI controller using conventional methodologies becomes complicated as the power system network presents itself as highly nonlinear and non-stationary. Moreover, the PI controller response may not be satisfactory at an operating point other than the point at which it is designed to operate. Thus, optimized values of proportional gain (K_p) and integral gain (K_i) can be obtained by the use of PSO which does not require any prior system information and is independent of the system dynamics. Performance criteria chosen in this paper is integral square error (ISE). Objective function to be optimized (J) is formulated using maximum overshoot (ΔV_{dcmax}), V_{dc} transient settling time (t_s) and steady-state error (E_{ss}) as the parameters which is shown in (1).

$$J = ISE = \int_0^t \left(\Delta V_{dc}\right)^2 dt$$
$$= \beta \cdot \Delta V_{dc\max} + (1-\beta)(t_s - t_0) + \alpha \cdot \left|E_{ss}\right| \qquad (1)$$

In the expression, t_0 indicates starting time of the transient V_{dc}; α and β are weighing factors. Factor α is used to overcome the steady-state error, β controls the overshoot and settling time.

4. Reference Filter Current Extraction for APF

Initially proposed by Akagi [14, 15], the conventional instantaneous active and reactive power (p-q) theory has gained popularity worldwide as a powerful control scheme for active filters. However, it is not capable of yielding satisfactory solution when the mains voltages are not ideal; because while calculating the instantaneous active and reactive powers, the multiplication of distorted load current and distorted source voltage caused amplification of harmonic content. Hence this theory has been subjected to various improvements to enhance the compensation capabilities of active filter. This paper exploits the modified p-q method proposed by Kale and Ozdemir in the year 2005 [16] for generation of reference compensation filter current. Voltage harmonic filtering is done in this control scheme in order to make the source voltage balanced, sinusoidal. This entire method of reference current generation is illustrated in Fig.2, which can be realized as follows.

The source voltages (v_{sa}, v_{sb}, v_{sc}) are transformed into d-q coordinates using Park's transformation given by (2), where ω represents the rotational speed of synchronously rotating d-q axes.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin wt & \cos wt \\ -\cos wt & -\sin wt \end{bmatrix} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} \quad (2)$$

The voltages (v_d and v_q) are then subjected to harmonic filtering by use of 5th order low-pass filters with cut-off frequency of 50Hz. Since, the zero-sequence voltage component is filtered out; the zero-sequence power (p_0) is always zero.

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} \cos wt & \sin wt \\ -\sin wt & \cos wt \end{bmatrix} \begin{bmatrix} \overline{v_d} \\ \overline{v_q} \end{bmatrix} \qquad (3)$$

The voltages $\overline{v_d}$ and $\overline{v_q}$ are then transformed into α-β coordinates by using (3). Outputs of the voltage harmonic filtering block v_α and v_β are assumed ideal to be utilized for further calculations. The 3-phase load

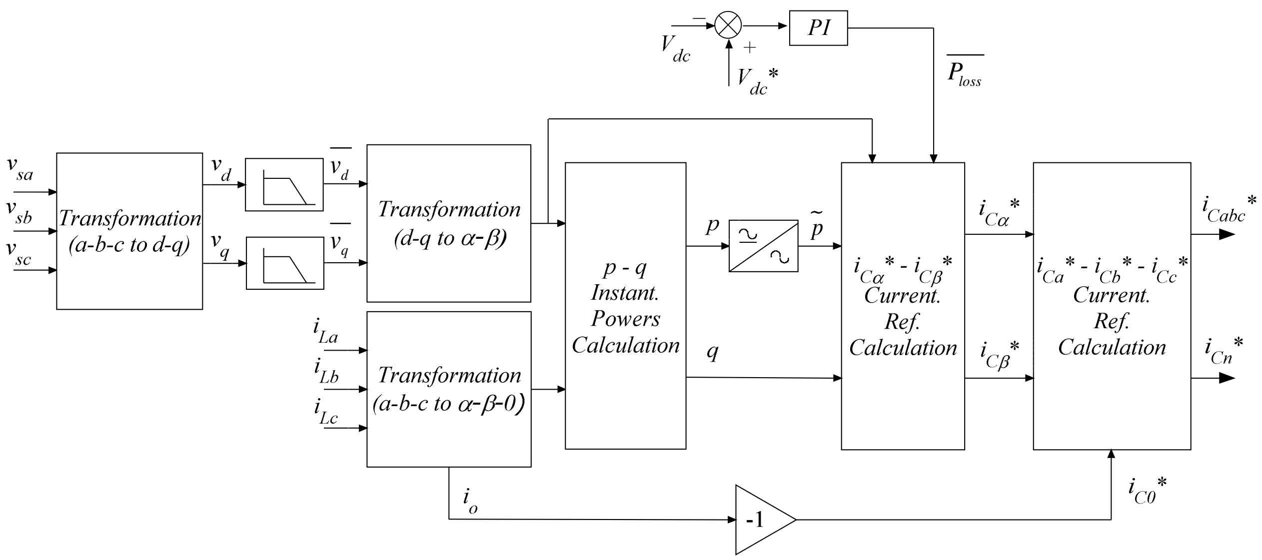

Fig.2. Reference compensation filter current extraction scheme for APF

currents (i_{La}, i_{Lb}, i_{Lc}) are tracked using current sensors and then transformed into α-β coordinates giving away the currents $i_{L\alpha}$ and $i_{L\beta}$, as given in (4).

$$\begin{bmatrix} i_0 \\ i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (4)$$

The currents $i_{L\alpha}$, $i_{L\beta}$ and voltages v_α, v_β are then used for the calculation of instantaneous active power (p) and reactive power (q) as per (5).

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \quad (5)$$

Both the instantaneous powers p and q include an average component $(\bar{p}, \bar{q})$ and an oscillating component $(\tilde{p}, \tilde{q})$, which can be described as (6).

$$p = \bar{p} + \tilde{p}$$
$$q = \bar{q} + \tilde{q} \quad (6)$$

For absolute compensation of harmonics, unbalance and neutral current, the whole of reactive power (q), oscillating component of active power ($\tilde{p}$) and average power loss occurring inside inverter ($\overline{P_{loss}}$) are taken into account for extraction of reference filter currents in α-β coordinates ($i_{c\alpha}*$, $i_{c\beta}*$).

$$\begin{bmatrix} i_{c\alpha}* \\ i_{c\beta}* \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} + \overline{P_{loss}} \\ -q \end{bmatrix} \quad (7)$$

The zero-sequence reference compensation current ($i_{c0}*$) should be same as that detected in the load current (i_0), but in opposite sign; so that it can provide the required zero-sequence current compensation.

$$i_{c0}* = -i_0 \quad (8)$$

$$\begin{bmatrix} i_{ca}* \\ i_{cb}* \\ i_{cc}* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{c0}* \\ i_{c\alpha}* \\ i_{c\beta}* \end{bmatrix} \quad (9)$$

$$i_{cn}* = i_{ca}* + i_{cb}* + i_{cc}* \quad (10)$$

The reference filter currents in a-b-c coordinates ($i_{ca}*$, $i_{cb}*$, $i_{cc}*$) and for the neutral conductor ($i_{cn}*$) can be calculated by (9) and (10). The actual filter currents are then forced to follow the reference current in a hysteresis current controller which in turn generates the switching signals for the VSI. Ultimately, the generated filter current provides the necessary compensation for current harmonics present in the source current.

5. Particle Swarm Optimization

The particle swarm optimization is a nature inspired stochastic optimization tool which mimics the swarming behavior exhibited by a bird flock or fish school. Proposed by Eberhart and Kennedy in the year 1995 [17, 18], PSO has been employed in various fields of research and applications and is successful in yielding optimized solution [19, 20].

For initialization, a group of randomly dispersed particles are assigned with some arbitrary velocities. The particles fly through the problem space in search of global optimum position by updating their positions and velocities at every iteration as per (11) and (12).

$$v_{k+1}^i = w \cdot v_k^i + c_1 \cdot r_1 \cdot [P_{Lbest}^i - x_k^i] + c_2 \cdot r_2 \cdot [P_{Gbest}^i - x_k^i] \quad (11)$$

$$x_{k+1}^i = x_k^i + v_{k+1}^i \quad (12)$$

While flying each particle keeps track of its coordinates in the search space corresponding to the best fitness value attained by that particle as yet in P_{Lbest}^i. Along with this, the particle swarm optimizer keeps track of

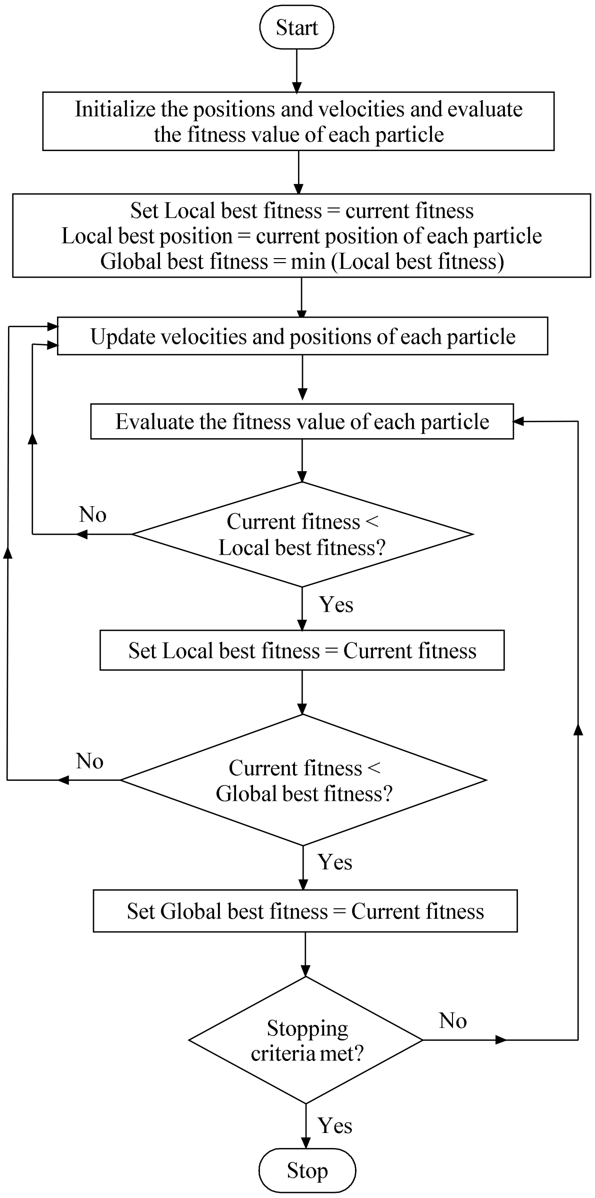

Fig.3. Flowchart of PSO

the location of the best solution achieved thus far by any particle in the swarm in P_{Gbest}^{i}. In the above expression, k and i indicate the pointers for number of iteration and particle number; x_k^i and v_k^i are the current position and velocity of ith particle at kth iteration; x_{k+1}^i and v_{k+1}^i the position and velocity of ith particle at (k+1)th iteration; w, c_1 and c_2 are inertia, cognitive and social constants respectively; r_1 and r_2 are random numbers in the interval [-1, 1]. Acceleration of the particles is decided by the values of constants c_1 and c_2, whereas w provides a sense of balance between local and global search. The search process comes to an end when the number of iterations executed becomes equal to the predefined maximum number of iterations or when a further better global optimum solution is not available. A flowchart showing the entire process of PSO has been illustrated in Fig.3.

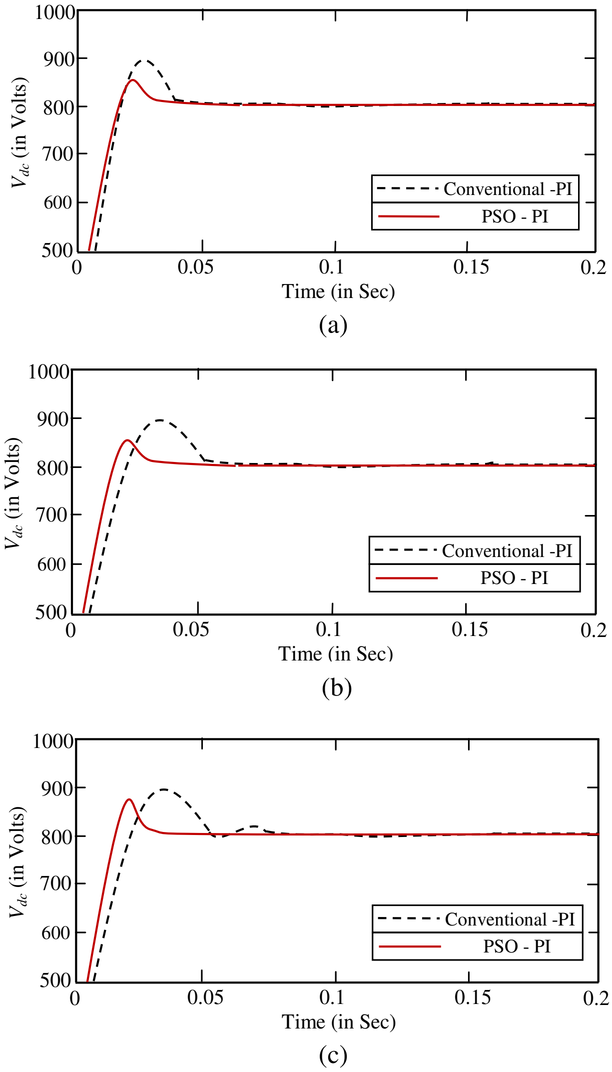

Fig.4. Convergence of V_{dc} with conventional PI controller and PSO based PI controller under (a) Ideal supply, (b) Distorted supply and (c) Unbalanced supply

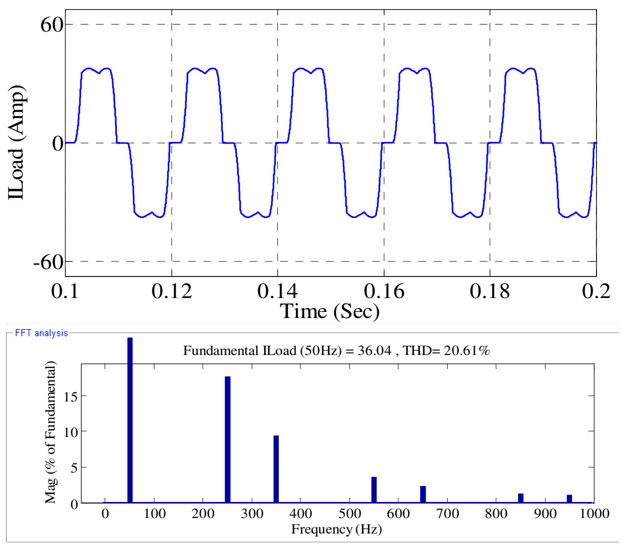

Fig.5. Load current and FFT analysis indicating its THD

6. Simulation Results

Extensive MATLAB simulation was carried out for three different supply conditions. A comparative evaluation of the V_{dc} convergence characteristics reveals that PSO converges to the desired solution at a faster rate compared to the conventionally tuned PI controller. Hence PSO is more efficient method as it provides quick prevail over the current harmonics i.e. within 1.5 cycles (0.03 s). Moreover, the overshoot in PSO based PI controller is much less compared to that

Table 1
Comparison of V_{dc} transient response with conventional and PSO based PI controllers

Supply voltage condition	*ΔV_{dcmax} in Volts for conventional-PI*	*ΔV_{dcmax} in Volts for PSO-PI*	*Settling time (t_s) in Sec for conventional-PI*	*Settling time (t_s) in Sec for PSO-PI*
Ideal supply	893.2	847.6	0.056	0.037
Distorted supply	898.7	852.2	0.074	0.039
Unbalanced supply	902.6	879.5	0.081	0.039

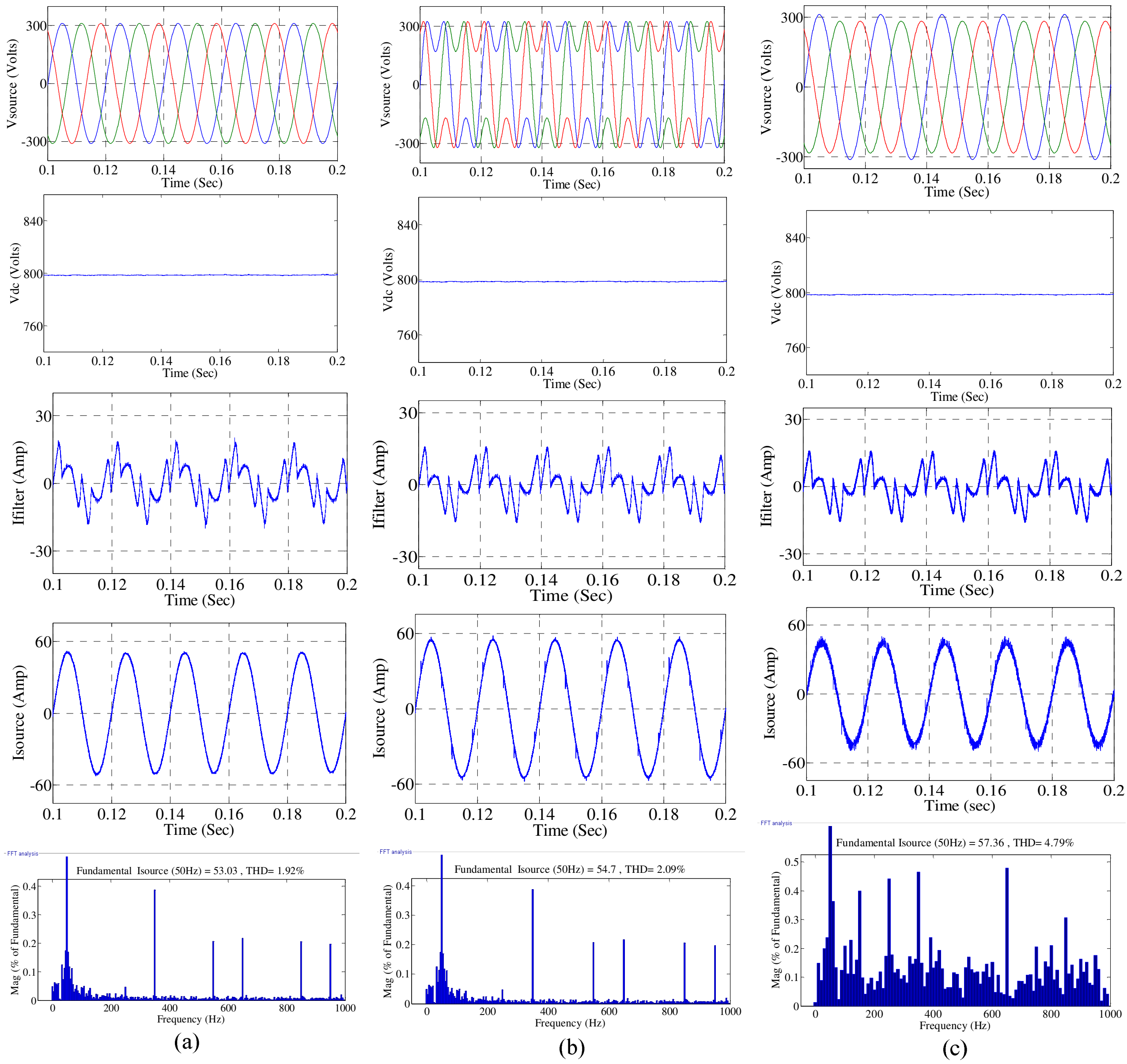

Fig.6. Simulation waveforms for source voltage, DC-link voltage, Compensation filter current, Source current after compensation and THD in source current after compensation under (a) Ideal supply voltage, (b) Distorted supply voltage and (c) Unbalanced supply voltage

in conventional PI controller. A comparison of the V_{dc} transient response is given in Fig. 4 and the maximum overshoot and settling times of the two controllers have been compared in Table 1. When the APF is not being operated, the source current is exactly same as the load current as shown in Fig.5. The THD in the source current before compensation is 20.61%.

The various simulation waveforms obtained with PSO-PI controller based APF have been presented in Fig.6. The THD in source current after compensation is reduced to 1.92%, 2.09% and 4.79% under ideal, distorted and unbalanced supply conditions respectively from its value of 20.61% before compensation. Hence the ultimate objective of lowering down the THD below 5% is fulfilled.

7. Conclusion

To verify the robustness of APF, evaluation was carried out taking huge distortion and unbalance in supply voltage and it is revealed that the proposed implementation of PSO algorithm to APF offers faster convergence to reach the global optima, resulting in quick prevail over the APF losses, thereby fulfilling the ultimate objective of lowering down the value of THD in source current. Since it is not empirical in nature, it does not require extensive experimentation. Furthermore, the proposed implementation of PSO makes it computationally less expensive, independent of the objective function gradient.

References

1. Subjak J.S., Mcquilkin J.S.: *Harmonics – Causes, Effects, Measurements, and Analysis: An Update*. In: IEEE Transactions on Industry Applications, 26 (1990), No. 6, November/December 1990, p. 1034–1042.
2. Arrillaga J., Watson N.R.: *Power system harmonics*. 2nd ed., John Wiley and Sons Ltd., Chichester, West Sussex, England, 2003.
3. Gruzs T.M.: *A Survey of Neutral Currents in Three-Phase Computer Power Systems*. In: IEEE Transactions on Industry Applications, 26 (1990), No.4, July/August 1990, p. 719–725.
4. Akagi H.: *Active Harmonic Filters*. In: Proceedings of the IEEE, 93 (2005), No. 12, December 2005, p. 2128–2141.
5. Singh B., Al-Haddad K., Chandra A.: *A New Control Approach to Three-phase Active Filter for Harmonics and Reactive Power Compensation*. In: IEEE Transactions on Power Systems, 13 (1998), No. 1, February 1998, p. 133–138.
6. Asiminoaei L. et al: *Adaptive Compensation of Reactive Power with Shunt Active Power Filters*. In: IEEE Transactions on Industry Applications, 44 (2008), No. 3, May/June 2008, p. 867–877.
7. Moran L.A., Dixon J.W., Wallace R.R.: *A Three-Phase Active Power Filter Operating with Fixed Switching Frequency for Reactive Power and Current Harmonic Compensation*. In: IEEE Transactions on Industrial Electronics, 42 (1995), No. 4, August 1995, p. 402–408.
8. Singh B., Al-Haddad K., Chandra A.: *A Review of Active Filters for Power Quality Improvement*. In: IEEE Transactions on Industrial Electronics, 46 (1999), No.5, October 1999, p. 960–971.
9. Aredes M., Hafner J., Heumann K.: *Three-Phase Four-Wire Shunt Active Filter Control Strategies*. In: IEEE Transactions on Power Electronics, 12 (1997), No. 2, March 1997, p. 311–318.
10. Zak S.H.: *Systems and Control*. Oxford University Press, New York, p. xv–574, 2003.
11. Smith C.A., Corripio A.B.: *Automatic Process Control*. México D.F., México, p. 212–296, 1991.
12. Quinn C.A., Mohan N.: *Active Filtering of Harmonic Currents in Three-Phase Four-Wire Systems with Three-Phase and Single-Phase Nonlinear loads*. In: Applied Power Electronics Conference, 1992, p. 829–836.
13. Quinn C.A., Mohan N., Mehta H.: *A Four-Wire Current Controlled Converter Provides Harmonic Neutralization in Three-Phase Four-Wire Systems*. In: Applied Power Electronics Conference, 1993, p. 841–846.
14. Akagi H., Watanabe E.H., Aredes M.: *Instantaneous Power Theory and Applications to Power Conditioning*. IEEE Press, New Jersey, 2007.
15. Akagi H., Kanazawa Y., Nabae A.: *Instantaneous Reactive Power Compensators Comprising Switching Devices without Energy Storage Components*. In: IEEE Transactions on Industry Applications, IA–20 (1984), No.3, May/June 1984, p. 625–630.
16. Kale M., Ozdemir E.: *Harmonic and Reactive Power Compensation with Shunt Active Power Filter under Non-ideal Mains Voltage*. In: Electric Power System Research, 77 (2005), No.3, May/June 1984, p. 363-370.
17. Kennedy J., Eberhart R.: *Particle Swarm Optimization*. In: Proceedings of IEEE International Conference on Neural Networks, 1995, Perth, Australia, Vol. IV, p.1942–1948.
18. Eberhart R., Kennedy J.: *A New Optimizer using Particle Swarm Theory*. In: Proceedings of International Symposium on Micro Machine and Human Science, October 1995, p. 39–43.
19. Chen M.-R. et al.: *A Novel Particle Swarm Optimizer Hybridized with Extremal Optimization*. In: Applied Soft Computing, 2010, p. 367–373.
20. Monson C.K., Seppi K.D.: *Adaptive Diversity in PSO*. In: Proceedings of 8th Annual Conference on Genetic and evolutionary Computation, ACM Press, New York, 2006, p. 59–66.