Harmonic Suppression Using On-Line Particle Swarm Optimization Based Three-Phase Shunt Active Power Filter

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Abstract:- The harmonics due to using of nonlinear industry loads based on power electronic elements have resulted in enormous economic loss. Therefore, the power utilities always need new technologies to deal with the harmonic problems. Active power filter (APF) has been considered as an attractive solution due to its effective performance for harmonic mitigation. The compensation currents injected by the APF are determined to eliminate harmonic currents of the nonlinear load and maintain the sinusoidal source currents. These compensation currents are not consistent, but they vary based on the output of the controller techniques. Traditionally, the classical PI controller is used for harmonic compensation with APF but the results of its use do not satisfy for the power suppliers and the power consumers. In this research, a new artificial intelligent technique called Particle Swarm Optimization (PSO) has been introduced to on-line tuning for the PI controller parameters. This self-adaptation makes robust PI controller scheme for facing the generated harmonics during the operation of the nonlinear system. The inverter used in this paper can be considered as a Shunt Active Power Filter (SAPF) in order to eliminate the nonlinear load current harmonics. The hysteresis nonlinear current control method is used in this approach to compare the extracting reference currents and the actual currents in order to generate the pulse gate required for the Active Power Filter. Results obtained by simulations with Matlab/Simulink show that the proposed approach is very flexible and effective for eliminating harmonic currents generated by the nonlinear load with the shunt APF based online PSO tuning.
1 Introduction

Using of nonlinear industry loads based on power electronic elements increases such as: industrial equipments, offices equipments, domestic devices and power inverters leads to high current harmonics and low power factor which lead to power quality problems. The harmonic currents spread into electric grid and interact adversely with a wide range of power system equipments, control systems, protection circuits, and other harmonic sensitive loads which leads to negative effect on them.

To overcome the harmonic problems, passive filters were used to eliminate the harmonics and improve the power factor. These passive filters have disadvantages such as: resonance, the large size, insufficient fitness for large bands of harmonic frequencies which implies using of many filters, fixed compensation (very low flexibility for load variations which implies new filter design for each load variation) [1]. During the last three decades, the concept of Active Power Filter (APF) has been introduced and many publications have represented in this subject [2-5]. To reduce the size of APF, several approaches such as, multistep inverters and hybrid filters are reported [6]. Also, Many control techniques such as instantaneous power theory [7], flux based controllers [8], and notch filters [9] have been introduced. Most of these control schemes are difficult to implement and require various transformations.

This research presents a new algorithm based on swarm intelligence called Particle Swarm Optimization (PSO). It is motivated by the observation of social interaction and animal behaviors such as fish schooling and bird flocking. PSO is originally introduced by Kennedy and Eberhart in 1995 [10], it is achieved good results for all kinds of complex optimization problems in nonlinear systems. The computation efficiency is the advantage of Particle Swarm Optimization over other techniques for tuning of the PI controller. Several publications used PSO technique which proved the strong effectiveness for improving and enhancing nonlinear systems quality [11-20]. The PI controller based PSO technique converges faster than the classical PI controller to reach the global minimum optimal solution.

The hysteresis current control method is used to generate the gate pulses required for the SAPF by comparing between the actual currents and the reference currents.

2 The model of the nonlinear system under study

Fig. 1 shows the system under study. It consists of three basic units which are three-phase supply voltages, active power filter and non-linear load. These units are analyzed separately and integrated to develop the complete model for simulation.
filter

Fig. 1 Block diagram of the system with shunt APF

2.1 Three-phase supply voltages

Under ideal conditions, the three-phase supply voltages are obtained by the following equations:

\[ V_{sa} = V_m \sin (\omega t) \]
\[ V_{sb} = V_m \sin (\omega t - 120) \]
\[ V_{sc} = V_m \sin (\omega t + 120) \]

Where, \( V_m \) is the peak value of the supply voltage and \( \omega \) is the frequency of the AC source in rad/sec.

The three-phase supply currents can be expressed by:

\[ i_{sa} = i_{fa} + i_{La} \]  \hspace{1cm} (4)
\[ i_{sb} = i_{fb} + i_{Lb} \]  \hspace{1cm} (5)
\[ i_{sc} = i_{fc} + i_{Lc} \]  \hspace{1cm} (6)

Where \((i_{sa}, i_{sb}, i_{sc})\) are the three-phase supply currents, \((i_{fa}, i_{fb}, i_{fc})\) are the three-phase APF currents and \((i_{La}, i_{Lb}, i_{Lc})\) are the three-phase load currents.

2.2 Active power filter

The APF is composed of a standard three-phase supply inverter bridge with a dc bus capacitor to provide an effective current control. The controlled currents of the APF is given by differential equations as follow:

\[ p_{i_{fa}} = -(R_f/L_f)i_{fa} + (V_{sa} - V_{fa})/L_f \]  \hspace{1cm} (7)
\[ p_{i_{fc}} = -(R_f/L_f)i_{fc} + (V_{sc} - V_{fc})/L_f \]  \hspace{1cm} (8)

Where, \( R_c \) and \( L_c \) are the resistance and the inductance of the APF. \( V_{sa}, V_{sb}, \) and \( V_{sc} \) are the three-phase supply voltages and \( i_{fa}, i_{fb}, \) and \( i_{fc} \) are the three-phase APF currents. \( V_{fa}, V_{fb} \) and \( V_{fc} \) are three-phase APF voltages.

The DC capacitor current can be obtained in terms of phase currents \((i_{fa}, i_{fb}, \) and \( i_{fc})\) and the switching status of devices \((S_a, S_b, S_c)\).

\[ i_{dc} = i_{fa}S_a + i_{fb}S_b + i_{fc}S_c \]  \hspace{1cm} (10)

The dc side capacitor voltage can be given by:

\[ pV_{dc} = (i_{fa}S_a + i_{fb}S_b + i_{fc}S_c)/C_{dc} \]  \hspace{1cm} (11)

Where, \( S_a, S_b, \) and \( S_c \) are the switching functions determined by state of the APF devices.

The three-phase active power filter voltages can be determined by the following equations:

\[ V_{fa} = (V_{dc}/3) (2S_a - S_b - S_c) \]  \hspace{1cm} (12)
\[ V_{fb} = (V_{dc}/3) (-S_a + 2S_b - S_c) \]  \hspace{1cm} (13)
\[ V_{fc} = (V_{dc}/3) (-S_a - S_b + 2S_c) \]  \hspace{1cm} (14)

The shunt active power filter (SAPF) is mainly connected with the power grids to eliminate harmonics which are generated during the operation of them. The principle of SAPF is to generate harmonic currents equal in magnitude and opposite in phase to those harmonics. This can keep the grid current in sinusoidal form and the source does not process harmonics which can enhance the system efficiency and the overall system performance.

2.3 The nonlinear load

The nonlinear load comprises of three-phase uncontrolled diode bridge rectifier with inductive –resistive load. When the diodes are
conducting, the AC source is connected to the load and the basic equation are:

\[ 2R_s i_d + 2L_s \pi i_d + V_L = V_S \]  

(15)

Where, \( R_s \) and \( L_s \) are the resistance and the inductance of the AC source. \( V_L \) is the instantaneous voltage across the dc side and \( V_S \) is the source line voltage. \( \pi \) is the differential operator \((d/dt)\) and \( i_d \) is the current flowing from the AC source through the diodes.

So,

\[ p i_d = \frac{(V_S - V_L - 2R_s i_d)}{2L_s} \]  

(16)

The load currents in the three-phase \( (i_{La}, i_{Lb} \) and \( i_{Lc} \) ) are obtained using the magnitude of \( i_d \) and the sign according to the conducting diodes. When the diodes are not conducting the current \( i_d \) and its derivative will be zero.

3 The nonlinear system with the control scheme

Fig. 2 shows the proposed control scheme of the shunt APF. The components of this control are explained as follow:

![Concept of modification of a searching point](image)

**Fig. 3 Concept of modification of a searching point**

Where, \( s^k \) : current searching point.

3.1 PI controller

The DC side capacitor voltage is sensed and compared with a reference voltage. This error \( e = V_{dcref} - V_{dc} \) is used as an input for PI Controller and the output is the peak value of source current \( (i_{sp}) \). After \( i_{sp} \) is obtained, it is multiplied by the unit sine vectors in phase with the respective source voltages \((u_{sa}, u_{sb} \) and \( u_{sc} \)) to obtain the reference source currents \((i_{sa}^*, i_{sb}^* \) and \( i_{sc}^* \)). The transfer function of the PI Controller is:

\[ H(s) = K_p + \frac{K_i}{s} \]  

(17)

where, \( K_p \) is the proportional constant and \( K_i \) is the integral constant. These parameters are traditionally tuned by classical methods such as “Ziegler-Nichols” method which is called classical PI controller. This paper presents an artificial intelligent technique for on-line PI controller tuning. This technique is Particle Swarm Optimization (PSO).

3.1.1 Particle swarm optimization

PSO is one of the most powerful methods for solving the nonlinear optimization problems. It is basically developed through the simulation of bird flocking in two-dimensional space [21]. Bird flocking optimizes a certain objective function. Each agent knows its best value so far (pbest) and its XY position. Moreover, each agent knows the best value so far in the group (gbest) among pbests. Each agent tries to modify its position using the following information:

1. the current position \((x, y)\),
2. the current velocities \((v_x, v_y)\),
3. the distance between the current position, and pbest and gbest.

The conception of modification of a searching point in Particle Swarm Optimization can be represented in Fig. 3.
Step. 1 Initialize an array of particles with random positions and their associated velocities to satisfy the inequality constraints.

Step. 2 Check for the satisfaction of the quality constraints and modify the solution if required.

Step. 3 Evaluate the fitness function of each particle.

Step. 4 Compare the current value of the fitness function with the particles previous best value (pbest). If the current fitness value is less, then assign the current coordinates (positions) to pbestx.

Step. 5 Determine the current global minimum fitness value among the current positions.

Step. 6 Compare the current global minimum with the previous global minimum (gbest). If the current global minimum is better than gbest, than assign the current global minimum to gbest and assign the current coordinates (positions) to gbestx.

Step. 7 Change the velocities according to Eq. 18.

\[ v_i^{k+1} = W v_i^k + c_1 \text{rand}_1 (pbest_i - s_i^k) + c_2 \text{rand}_2 (gbest - s_i^k) \]

(18)

Where, \(c_1, c_2\) : acceleration factors.
\(gbest\) : gbest of the group.
\(pbest_i\) : pbest of agent i.
\(\text{rand}\) : random number between 0 and 1.
\(s_i^k\) : current position of agent i at iteration k.
\(v_i^k\) : velocity of agent i at iteration k.
\(W\) : weighting function.

Step. 8 Move each particle to the new position according to Eq. 19 and return to step (2).

\[ s_i^{k+1} = s_i^k + v_i^{k+1} \]

(19)

Where, \(s_i^{k+1}\) : new current position of agent i at iteration k+1.
\(v_i^{k+1}\) : new velocity of agent i at iteration k+1.

Step. 9 Repeat Steps 2-8 until a stopping criterion is satisfied or the maximum number of iterations is reached.

The advantages of the PSO algorithm are:

1. It is easy to implement.
2. It has a limited number of parameters and the impact of parameters to the solution is small compared to other optimization techniques.
3. The calculation in PSO algorithm is very simple.
4. It is less dependent of a set of initial points than other optimization methods.

Flowchart of Particle Swarm Optimization

The steps of the Particle Swarm Algorithm can be represented in flowchart as shown in Fig. 4.
The rms source voltage amplitude ($V_{sm}$) is calculated from the three-phase source voltages ($V_{sa}$, $V_{sb}$ and $V_{sc}$) by

$$V_{sm} = \frac{1}{\sqrt{3}} (V_{sa}^2 + V_{sb}^2 + V_{sc}^2)^{\frac{1}{2}}$$

(20)

The direct (or in-phase) unit current vectors are given from the three-phase source voltages ($V_{sa}$, $V_{sb}$ and $V_{sc}$) and the rms source voltage amplitude ($V_{sm}$) as expressed in the following equations.

$$u_{sa} = \frac{V_{sa}}{V_{sm}}$$

(21)

$$u_{sb} = \frac{V_{sb}}{V_{sm}}$$

(22)

$$u_{sc} = \frac{V_{sc}}{V_{sm}}$$

(23)

The reference three-phase source currents ($i_{sa}^*, i_{sb}^*$ and $i_{sc}^*$) are estimated as:

$$i_{sa}^* = I_{sp}^* u_{sa}$$

(24)

$$i_{sb}^* = I_{sp}^* u_{sb}$$

(25)

$$i_{sc}^* = I_{sp}^* u_{sc}$$

(26)

Where, $I_{sp}^*$ is the peak value of the source current which is the output of the PI controller.

### 3.3 Hysteresis nonlinear current control

The hysteresis nonlinear current control is the most commonly proposed control method in time domain. This method provides instantaneous current corrective response, good accuracy and unconditioned stability to the system. Also, it aims to keep the controlled current inside a defined rejoin around the desired reference current [9]. In this method, the reference three-phase source currents ($i_{sa}^*, i_{sb}^*$ and $i_{sc}^*$) are compared with the three-phase source currents ($i_{sa}, i_{sb}$ and $i_{sc}$) to obtain the gating pulses to the devices of APF. The current controller decides the switching pattern of the APF devices. The switching logic is determined as follows:

- If $i_{sa} < (i_{sa}^* - HB)$ for leg "a" ($S_a=1$), the upper switch is OFF and the lower switch is ON.
- If $i_{sa} > (i_{sa}^* + HB)$ for leg "a" ($S_a=0$), the upper switch is ON and the lower switch is OFF.

The switching functions $S_b$ and $S_c$ which are phases leg "b" and leg "c" respectively are formulated similarly by the measured currents ($i_{sb}$ and $i_{sc}$), the corresponding reference currents ($i_{sb}^*$ and $i_{sc}^*$) and the hysteresis bandwidth (HB). The switching logic and the generated gate pulse which required for the Active Power Filter can be represented as shown in Fig. 5.
Fig. 5. Hysteresis Control Principle.

4 Objective function

In this research, the bacterial foraging optimization is used for obtaining the coefficients of PI controller $K_P$ and $K_i$. The objective in the optimal PI controller design is to eliminate the harmonic currents generated by the nonlinear load in the electric grid. The integral of squared error (ISE) is considered as the cost function to be minimized. The objective function is given by Eq. 27.

$$J = \int_0^\infty (e^2) \, dt$$  
(27)

Where (J) is the cost function and (e) is the error which evaluated from the following Equation.

$$e = V_{\text{dc ref}} - V_{\text{dc}}$$  
(28)

Therefore, the design problem can be formulated as the following optimization problem.

Minimize $J$  
Subject to $Z_{\text{min}} \leq Z \leq Z_{\text{max}}$  
(29)

Where $Z$ is a vector, which consists of the parameters of the PI controller. The proposed approach employs PSO to search for the optimal set of PI controller coefficients which leads to minimizing the total harmonic distortion.

5 Simulation results and discussions

5.1 The nonlinear system without the SAPF

The nonlinear system components values (source and nonlinear load) are obtained in Appendix. Fig. 6 shows the three phase source voltages as presented in Equations (1:3). The supply current ($i_{sa}$) and its harmonic distortion are shown in Fig. 7. Also, the load current ($i_{la}$) and its harmonic distortion are shown in Fig. 8. The Total Harmonic Distortion response (THD) of the supply current ($i_{sa}$) before connecting the Active Power Filter is represented in Fig. 9.
The Total Harmonic Distortion (THD) of the supply current ($i_{sa}$) and the load current ($i_{la}$) are 27.47%. This increasing in the harmonics has negative effect on the grid. To eliminate this Harmonics, the Shunt Active Power Filter (SAPF) is used. This filter is controlled by the classical PI controller.

5.2 The system under SAPF controlled by classical PI controller

The classical PI controller is used to control in the Shunt Active Filter (SAPF) for harmonic compensation. Fig. 10 shows the response of the source current ($i_{sa}$) and its harmonic distortion after using the controlled filter. Also, the Total Harmonic Distortion response (THD) of the supply current ($i_{sa}$) is represented in Fig. 11.

The results obtained in Fig. 10 and Fig. 11 show that the system behavior is improved when the SAPF based classical PI controller is connected and the THD is reduced from 27.47% to 7.37% where the parameters of the PI controller are $K_p = 0.1$ and $K_i = 0.2$. These results are not satisfied. So, we need to enhance the system performance for suppressing the generated harmonics during the system operation with the nonlinear loads. To achieve that, the on-line Particle Swarm Optimization technique is used to tune the PI controller.

5.3 The system under SAPF controlled by PI controller based PSO

To obtain more enhancement in the performance of the system for facing the generated harmonics due to the connection of the nonlinear load, the on-line PSO is used. This artificial intelligent technique is used for on-line PI controller tuning. This on-line tuning makes the PI controller to be robust controller to eliminate the harmonics generated during the operation of the nonlinear system. The on-line parameters of the PI controller ($K_p, K_i$) are tuned by the Particle Swarm Optimization (PSO) technique and represented in Fig. 12 and Fig. 13 respectively. Fig. 14 shows the Total Harmonic Distortion (THD) of the supply current ($i_{sa}$) before connecting the SAPF.
current ($i_{sa}$) after the artificial intelligent technique is used to tune the PI controller. The supply voltage ($V_{sa}$) and the supply current ($i_{sa}$) and its harmonic distortion after using the Shunt Active Power Filter (SAPF) are shown in Fig. 15. Fig.16 represents the supply current ($i_{sa}$) after using the Shunt Active Power Filter (SAPF) controlled by the PI controller based PSO.

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**Fig. 12** On-line tuning of $K_p$ of PI-controller

**Fig. 13** On-line tuning of $K_i$ of PI-controller

**Fig. 14** THD for on-line PSO tuning

**Fig. 15** The supply voltage ($V_{sa}$) and current ($i_{sa}$) with APF Based on-line PI-PSO
Fig. 16 The supply current ($i_n$)

The system behavior is improved and its performance is enhanced when it is connected to the Shunt APF controlled by PI controller based on-line PSO tuning. This on-line tuning makes better performance for the system in facing the generated harmonics during the operation. The self-adaptation of the controller parameters ($K_p$, $K_i$) shown in Fig. 12 and Fig. 13 respectively makes the system to be more sensitive for the generated harmonics due to the connection of the nonlinear loads with the grid. Fig. 14 shows that THD was reduced to minimum values (1.29%) which indicates the marked improvement in the system behavior for harmonic mitigation. The power factor approximately reached unity as shown in Fig. 15. Fig. 16 shows that the response of the supply current ($i_n$) is enhanced and seemed as sine wave after using SAPF controlled by PI controller based PSO. This proves that the shunt active filter based on-line Particle Swarm Optimization has strong effectiveness for harmonics elimination and improvement of the overall power system performance.

6 Conclusions

In this paper, shunt active power filter is used for harmonics elimination. It is controlled by the PI controller which is tuned by the traditional technique (classical PI controller) and on-line Particle Swarm Optimization. The system without the controller is affected by the nonlinear load and failed for facing the generating harmonics during the operation where THD=27.47%. In case of the classical PI controller, the system performance is improved but this improvement isn't satisfactory for harmonics elimination where THD=7.37%. On the other hand, when the on-line particle swarm optimization is used, marked improvement occurs in the system behavior and its performance is enhanced where THD=1.29%. The system with on-line tuning overcome the generated harmonics during the system operation where the PI controller parameters ($K_p$, $K_i$) are not constant. These changes of the parameters make robust PI controller for the nonlinear system to eliminate the generated harmonics during the operation. So, it is clearly understood that using the shunt active power filter under the PI controller tuned by on-line PSO gives good promotion for its use in the harmonics elimination of the nonlinear electric grids.

References:


Appendix

- The Particle Swarm Optimization parameters:

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• The system parameters:

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<th>Nonlinear system parameters</th>
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