Performance improvement of shunt active power filter based on indirect control with a new robust phase-locked loop

Introduction. Since the development of the first active power filter (APF) in 1976, many efforts have been focused on improving the performances of the APF control as the number of different nonlinear loads has continued to increase. These nonlinear loads have led to the generation of different types of current harmonics, which requires more advanced controls, including robustness, to get an admissible total harmonic distortion (THD) in the power system. Purpose. The purpose of this paper is to develop a robust phase-locked loop (PLL) based on particle swarm optimization-reference signal tracking (PSO-RST) controller for a three phase three wires shunt active power filter control. Methodology. A robust PLL based on PSO-RST controller insert into the indirect d-q control of a shunt active power filter was developed. Results. Simulation results performed under the MATLAB/SimPowerSystem environment show a higher filtering quality and a better robustness compared to the classical d-q controls. Originality. Conventional PLLs have difficulty determining the phase angle of the utility voltage sources when grid voltage is distorted. If this phase angle is incorrectly determined, this leads to a malfunction of the complete control of the active power filters. This implies a bad compensation of the current harmonics generated by the nonlinear loads. To solve this problem we propose a robust and simple PLL based on PSO-RST controller to eliminate the influence of the voltage harmonics. Practical value. The proposed solution can be used to improve the functioning of the shunt active power filter and to reduce the amount of memory implementation. References 23, tables 3, figures 19.

Key words: active power filter, robust phase-locked loop, harmonics, particle swarm optimization-reference signal tracking controller.

Purpose. The purpose of this paper is to develop a robust phase-locked loop (PLL) based on particle swarm optimization-reference signal tracking controller. Mathematical models of the three phase three wires shunt active power filter (G-APF) are described in [7] and [8]. The G-APF is controlled by a classical d-q controller [7], what is a direct control method. The active power filter and its control are modeled in MATLAB/Simulink. They are conducted under the same conditions, with the same parameters for the system and the control in order to compare the results obtained between the classical and the proposed control. In the first part of this paper we will present the classical active power filter (APF) control which is; the d-q theory for indirect control. The harmonics and total harmonic distortion (THD) of the lines current are the quality criteria chosen all over the paper. Then, an improvement will be made for this control in order to minimize the influence of grid voltage harmonics by introducing a new robust PLL based on a particle swarm optimization-reference signal tracking (PSO-RST) controller, where unlike the PLL proposed in [7]; this new PLL is simple and his implementation doesn’t need a large amount of memory. This new approach is then applied to the control of a three-phase three-leg SAPF and its effectiveness is validated by simulations.

All the simulations are carried out with MATLAB/Simulink. They are conducted under the same conditions, with the same parameters for the system and the control in order to compare the results obtained between the classical and the proposed control. Basic indirect control theory for SAPF. The active power filter that we will be using in our study is a three-leg active power filter connected in parallel to a three-wire electrical network. The control strategy used for this SAPF is an indirect d-q control. The active power filter and its
control are shown in Fig. 1. The control strategy is based on the theory introduced in 1983 by Akagi et al [1] which uses the Concordia transform. It is stated as follows.

![Fig. 1. Indirect control of SAPF system](image)

Let be respectively the simple voltages and the line currents of a three-phase system without homopolar \(v_{a}(t), v_{b}(t), v_{c}(t)\) and \(i_{a}(t), i_{b}(t), i_{c}(t)\).

The Concordia transformation of the line current allows us to obtain:

\[
\begin{bmatrix}
i_{a} \\
i_{b}
\end{bmatrix} = \frac{2}{\sqrt{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\
0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix} \begin{bmatrix}
i_{La} \\
i_{Lb} \\
i_{Lc}
\end{bmatrix}.
\]  

(1)

A PLL is used to extract \(\hat{\theta}\) in order to generate two signals \(\sin(\hat{\theta})\) and \(\cos(\hat{\theta})\) which are in phase with the simple voltage of the electrical network. We then multiply these two signals by \(i_{a}\) and \(i_{b}\) to obtain only the current in the \(d\)-axis, as shown by the following expression:

\[
i_{d} = i_{a} \cdot \sin(\hat{\theta}) - i_{b} \cdot \cos(\hat{\theta}).
\]  

(2)

The resulting current can be expressed as the sum of a continuous component and an alternating component:

\[
i_{d} = \bar{i}_{d} + \tilde{i}_{d},
\]  

(3)

where \(\bar{i}_{d}\) is the continuous component of \(i_{d}\), \(\tilde{i}_{d}\) is the alternating component of \(i_{d}\).

In order to extract only the continuous component, which will be injected by the APF, the alternating component should be eliminated by a low pass filter (LPF). Thus, the currents in \(\alpha-\beta\) coordinates will become:

\[
\begin{align*}
i_{\alpha}^{ref} &= \sin(\hat{\theta}) \cdot i_{d}^\alpha; \\
i_{\beta}^{ref} &= -\cos(\hat{\theta}) \cdot i_{d}^\beta.
\end{align*}
\]  

(4)

The reference currents are given as before by the inverse Concordia transformation:

\[
\begin{bmatrix}
i_{\alpha}^{ref} \\
i_{\beta}^{ref}
\end{bmatrix} = \frac{2}{\sqrt{3}} \begin{bmatrix} 1 & 0 & \frac{1}{2} \\
-\frac{\sqrt{3}}{2} & 1 & \frac{\sqrt{3}}{2}
\end{bmatrix} \begin{bmatrix}
i_{d}^{ref} \\
i_{d}^{ref}
\end{bmatrix}.
\]  

(5)

**New robust PLL.** There are several types of PLL that have been developed to synchronize the signal outputs to the single-phase or to the three-phase fundamental voltage component. For the three-phase, for example, we find the following PLLs:

**Three-phase synchronous reference frame phase locked loop (SRF PLL) (dqPLL)** [9, 10, 12], where the instantaneous phase angle is determined by synchronizing when the PI controller sets the direct or quadrature axis reference voltage \(v_{d}\) or \(v_{q}\) to zero, resulting in the reference being latched to the phase angle of the utility’s voltage vector.

**Instantaneous power three-phase PLL (pPLL)** [11, 12]. Its structure is the same as that of the classical SRF-PLLS, but the theory behind this PLL is the use of the instantaneous power theory.

**Dual second-order generalized integrator based PLL (DSOGI-PLL)** [15, 16]. This PLL builds the orthogonal signals generator (OSG) using two first-order integrators based on a second-order integrator, which is easy to be implemented digitally, and the nonlinearity is lower than that of Park-PLL.

However, in single phase applications, we find the following PLLs:

**Single-phase enhanced PLL (EPLL)** [14] and single-phase adaptive linear combiner PLL (PLL-ALC) [13, 14]. This PLL method is designed on the basis of the adaptive filter theory by estimating its phase and frequency through the steepest descent algorithm.

Over time the PLLs have been improved to make them more robust against distortion and unbalance insensitivity. Among these PLLs we have the one proposed by [7] which add a multi-variable filter to eliminate the influence of voltages disturbance. This method has the disadvantage of making its implementation more complex due to the increase of a multivariate filter in the PLL.

The goal of this work is to develop a new robust and simple phase-locked loop to deal with the harmonic voltages, where the PI controller on the SRF-PLL is replaced by RST controller. This controller has a simple structure and good performances in large range of operating conditions. Moreover, we propose a new approach to adjust the RST parameters where unlike the conventional methods proposed in [17, 18], the parameters of the regulator are set by utilizing the particle swarm optimization (PSO) algorithm.

**RST controller.** The structure of the RST controller is based on the determination of a three polynomials \(R(p), S(p)\) and \(T(p)\) in order to obtain a good performances in term of reference tracking and disturbance rejection. It’s based on pole place ment theory by determining an arbitrary stability polynomial \(D(p)\) and computing \(S(p)\) and \(R(p)\) according to Bezout’s equation [19]

\[
D(p) = A(p)S(p) + B(p)R(p).
\]  

(6)

The design structure of a system with RST controller is represented in Fig. 2.

![Fig. 2. Block diagram of the RST controller](image)
The closed loop transfer function of the system is:

\[ Y = \frac{B(p)T(p)}{A(p)S(p) + B(p)R(p)} Y_{ref} + \frac{B(p)S(p)}{A(p)S(p) + B(p)R(p)} Y_\text{out} \quad (7) \]

The key to have good results depends on the choice of polynomials orders. A strictly proper regulator is chosen which means if \( \deg(A) = n \):

\[
\begin{align*}
\deg(D) &= 2n + 1 \\
\deg(S) &= \deg(A) + 1 \\
\deg(R) &= \deg(A)
\end{align*}
\] (8)

However, the polynomial forms are described as follows:

\[
\begin{align*}
A(p) &= a_1 + a_0 \\
B(p) &= b_0 \\
D(p) &= d_3 p^3 + d_2 p^2 + d_1 p + d_0 \\
R(p) &= \eta_1 p + \eta_0 \\
S(p) &= s_2 p^2 + s_1 p \\
F(p) &= \frac{1}{T_f}
\end{align*}
\] (9)

The transfer function of the PLL is [7] \( \sqrt{3} V_m \), which means that \( A(p) = p; B(p) = \sqrt{3} \), where \( V_m \) is the peak value of the source voltage.

To find the coefficients of each polynomial a robust pole placement strategy is used [20]. By assuming that \( C(p) \) is the control pole and \( F(p) \) is the filter pole, we obtain the following expression:

\[
D(p) = C(p) \cdot F(p) = \left( p + \frac{1}{T_c} \right) \left( p + \frac{1}{T_f} \right)^2, \quad (10)
\]

where \( P_c = -1/T_c \) is the pole of \( C(p) \); \( P_f = -1/T_f \) is the double pole of \( F(p) \).

Usually \( P_c \) is chosen 2-5 times greater than \( P_d \), where \( P_d \) is the pole of \( A \); and \( P_f \) is chosen 3-5 times greater than \( P_c \). The identification between Bezout equation and equation (9) gives a system of four equations with four unknown terms, as is shown in the following equation:

\[
\begin{align*}
\alpha_1 \beta_1 &= 1 \\
\alpha_1 \beta_2 + \alpha_2 \beta_1 &= \frac{2}{T_f} + \frac{1}{T_c} \\
\alpha_1 \beta_3 + \beta_0 \beta_1 &= \frac{1}{T_f} + \frac{2}{T_c} \\
\beta_0 \beta_2 &= \frac{1}{T_f T_c}.
\end{align*}
\] (11)

For the determination of polynomial \( T \) we consider \( S(0) = 0 \) and in the steady state \( Y_{\text{ref}} = Y \). Then we get the following equation:

\[
\text{Lim}_{p \to 0} \frac{B(p)T(p)}{A(p)S(p) + B(p)R(p)} = 1 \quad (12)
\]

After finding the coefficients of the filter pole \( F(p) \) with the pole placement, we obtain the following equation:

\[ T(p) = h \cdot F(p) = h \left( p + \frac{1}{T_f} \right)^2, \quad (13) \]

where \( h = R(0)/F(0) \).

**PSO algorithm.** The PSO algorithm is an evolutionary technique which uses a population of candidate solutions to find an optimal solution to a problem. The degree of optimality is evaluated by an objective function. The algorithm used in this work is inspired by the collective comportment and the synchronous formation flight of birds. This technique is considered as a progressive algorithm with a populace of agents called particles «i» which are dispersed in the problem space [21].

In the beginning swarms are randomly allocated in the search space, each particle also having a random speed as shown in Fig. 3.

\[
\text{Fig. 3. A particle movement}
\]

A particle is capable to evaluate her position quality and remember her best performance. By asking her congener she can also obtain their best performances. According to this information, each particle changes its speed and moves. A particle «i» of the swarm is represented in the \( D \)-dimensional search space by its position vector \( (X) \) and by its speed vector \( (\dot{V}) \) formulated as follows:

\[
X_i = (x_{i_1}, x_{i_2}, ..., x_{i_n}); \quad (14)
\]

\[
V_i = (v_{i_1}, v_{i_2}, ..., v_{i_n}); \quad (15)
\]

The evaluation of his position quality is stopped by the objective function at this point. It is important that this particle can memorize the best position through which it has already passed, formulated as follows:

\[
P_{i_b} = (p_{i_1}, p_{i_2}, ..., p_{i_n}). \quad (16)
\]

The equation of a particle movement for each iteration \((i)\) is:

\[
X_i^{(i+1)} = X_i^{(i)} + c_1 \cdot r_1 \cdot (P_{i_b} - X_i^{(i)}) + c_2 \cdot r_2 \cdot (P_{i_g} - X_i^{(i)}). \quad (17)
\]

where \( \omega \) is the coefficient of inertia; \( c_1, c_2 \) are the acceleration coefficients which control respectively the attraction at its best and the attraction at the best overall; \( r_1, r_2 \in [0,1] \) are the uniform random variables.

The update of the position of the particle is done through the following equation:

\[
X_i^{(i+1)} = X_i^{(i)} + V_i^{(i+1)} \quad (18)
\]

**RST controller parameters optimization with PSO algorithm.** We will now integrate the PSO described in the previous paragraph in order to optimize the RST parameters in such a way to have a better rejection of the perturbations and a better tracking of the reference. In other words \( s_1, s_2, r_1, r_2 \) and \( t \) in (11) and (13) are optimized so that the error is minimized.

An algorithm was developed for which the «min-max» function is adopted to perform the preprocessing data. The population size was set at 200 particles. This parameter has an influence on the behavior of the algorithm (a small population does not create enough interactions to guarantee the proper functioning of the algorithm). If the acceleration coefficient is too small, the algorithm will explore very slowly, which degrades its performance. Experience has shown that with a value
of 2.05 often achieves the best results [22]. According to [23] the coefficient of inertia is chosen between 0.5 and 1. In our study we have chosen a value of 0.5 that we consider suitable.

The PSO begins to search for a solution in a research space. These values are then injected into Simulink (Fig. 4). The difference between the measure and the reference is evaluated by the objective function. The values of $s_1$, $s_2$, $r_1$, $r_0$ and $t$ are then modified until the objective function (19) is minimized, as shown in the following equation:

$$f_{\text{min}} = \int_0^\infty (U_{\text{ref}} - U_{\text{mes}})^2(t)dt = \int_0^\infty (e)^2(t)dt.$$

(19)

The process is repeated until the difference between the measured values and the reference values is minimal or a maximum number of iterations are achieved.

Simulation and results. The performances of the proposed system (Fig. 5) are evaluated and simulated in MATLAB/Simulink environment where the robustness of the PLL is tested under distorted voltage source.

Figures 6-14 give respectively the simulation results of the proposed controller (RST-PSO) that are compared to classical PLL with PI controller and the PLL with conventional RST controller.
We notice from these simulations that the PLL using the PSO-RST gives very good results compared to the use of the classical PLL which uses a PI regulator or the conventional RST when the source voltage contains harmonics. Where from Fig. 7, 8 we can see that the classical PLL doesn’t reject the harmonics; Fig. 9, 10, 12, 13 show that the PLL based on the RST controller and the PSO-RST controller respectively can reject the harmonics with faster response for the PSO-RST (0.1 s). From Fig. 11, 14 it can be seen that the proposed PLL has better rejection for the harmonics where the THD obtained in the steady state is 0.53 %.

To show the efficiency of our PLL using a PSO-RST controller we will show in addition the results of simulations of the APF. Thus the Fig. 15-19 show the utility voltage source under harmonics, the current load before filtering, the current injected by the APF, the current source after filtering and the DC voltage. We notice from these simulations that the APF correctly compensates the current harmonics despite a voltage source containing harmonics and the step change in load current at 0.5 s (Table 1).

The controller’s parameters and studied system parameters are represented in Table 2, 3 respectively.

<table>
<thead>
<tr>
<th>Source current THD’s</th>
<th>Before filtering</th>
<th>After filtering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before 0.5 s</td>
<td>24.3 %</td>
<td>1.92 %</td>
</tr>
<tr>
<td>After 0.5 s</td>
<td>28.51 %</td>
<td>3.66 %</td>
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</table>

<table>
<thead>
<tr>
<th>Controller’s parameters</th>
<th>RST</th>
<th>PSO-RST</th>
</tr>
</thead>
<tbody>
<tr>
<td>( s_2 )</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>( s_1 )</td>
<td>439</td>
<td>1452.048</td>
</tr>
<tr>
<td>( r_1 )</td>
<td>316.557</td>
<td>603</td>
</tr>
<tr>
<td>( r_0 )</td>
<td>900</td>
<td>71348.6</td>
</tr>
<tr>
<td>( t )</td>
<td>900</td>
<td>71348.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Studied system parameters</th>
<th>( V ), V</th>
<th>240</th>
<th>( L_{\text{load}} ), mH</th>
<th>2.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_s ), m\Omega</td>
<td>1.59</td>
<td></td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>( L_{\text{out}} ), \mu H</td>
<td>45.56</td>
<td></td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>( R_{\text{load}} ), \Omega</td>
<td>0.788</td>
<td></td>
<td>( V_{dc} ), V</td>
<td>700</td>
</tr>
</tbody>
</table>
Conclusions. In this paper, a new robust phase-locked loop based on PSO-RST controller is proposed and applied to an indirect control of a shunt active power filter. The performances of the proposed phase-locked loop has been evaluated and compared to the classical phase-locked loop based on PI and conventional RST controller. The obtained results show that the proposed phase-locked loop reject disturbances in the utility voltage source with fast response which allow having good performances in the control of SAPF even if the source grid is distorted.

Conflict of Interest. The authors declare that they have no conflicts of interest.

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