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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.**

Вступ. *З моменту розробки першого фільтра активної потужності (ФАП) у 1976 р. багато зусиль було спрямовано на покращення характеристик управління ФАП, оскільки кількість різних нелінійних навантажень продовжувала зростати. Ці нелінійні навантаження призвели до генерації різних типів гармонік струму, що потребує більш досконалих засобів управління, у тому числі стійких, для отримання допустимого повного гармонічного спотворення (THD) в енергосистемі.* ***Мета***. *Метою даної статті є розробка надійного контуру фазового автопідстроювання частоти (ФАПЧ) на основі контролера відстеження еталонного сигналу оптимізації рою частинок (ВЕС ОРЧ) для трифазного трипровідного шунтуючого фільтра активної потужності.* ***Методологія***. *Розроблено надійну систему ФАПЧ на основі контролера ВЕС ОРЧ, вбудованого в непрямий d-q контроль шунтуючого фільтра активної потужності.* ***Результати***. *Результати моделювання, виконаного в середовищі MATLAB/SimPowerSystem, демонструють високу якість фільтрації та більшу надійність у порівнянні з класичним d-q керуванням.* ***Оригінальність***. *Звичайні ФАПЧ мають труднощі з визначенням фазового кута джерел напруги, коли напруга мережі спотворена. Неправильне визначення цього фазового кута призводить до порушення повного керування фільтрами активної потужності. Це означає погану компенсацію гармонік струму, створюваних нелінійними навантаженнями. Для вирішення цієї проблеми ми пропонуємо стійкий та простий ФАПЧ на основі контролера ВЕС ОРЧ для усунення впливу гармонік напруги.* ***Практична цінність***. *Запропоноване рішення може бути використане для поліпшення роботи шунтуючого фільтра активної потужності і зменшення обсягу потрібної пам'яті.* Бібл. 23, табл. 3, рис. 19.

Ключові слова: **фільтр активної потужності, надійний контур фазового автопідстроювання частоти, гармоніки, контролер відстеження еталонного сигналу оптимізації рою частинок.**

Introduction. In the last three decades a significant development and study of shunt active power filter (SAPF) control has been made. The main one is the direct control method based on instantaneous power introduced by Akagi [1]. Many other direct or indirect control strategies to achieve good filtering results for three-wire power systems have also been proposed [2-4]. Concerning the indirect control it has been developed by [5, 6]. Unlike the direct strategy, the alternating components of the instantaneous power will be removed to leave only the continuous component. This method allows compensating the current harmonics indirectly.

Since the appearance of SAPF many algorithms have been developed. Those algorithms can accomplish good performances (harmonics elimination) when the grid voltage is balanced and undistorted. Contrariwise, if the grid voltage is distributed, the performance of the SAPF will widely decrease [8]. To handle this issue some researchers propose the use of a self-tuning filter [8]. However, this method increases the number of filters and transformations. In this paper we propose to keep the basic indirect control without additional filters or transformations and the use of a new simple and robust phase-locked loop (PLL) to deal with the grid voltage perturbations.

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.

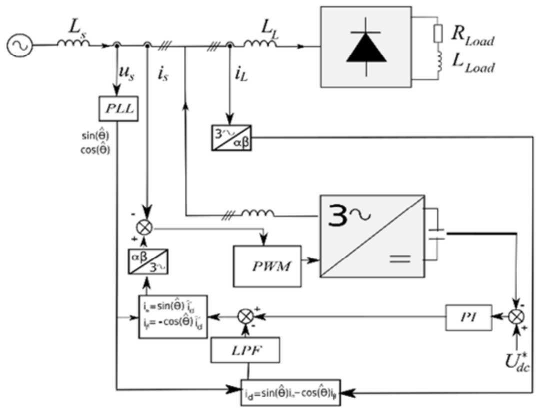

Fig. 1. Indirect control of SAPF system

Let be respectively the simple voltages and the line currents of a three-phase system without homopolar $v_{sa}(t)$, $v_{sb}(t)$, $v_{sc}(t)$ and $i_{La}(t)$, $i_{Lb}(t)$, $i_{Lc}(t)$.

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

$$\begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \cdot \begin{pmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{pmatrix}. \quad (1)$$

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_α and i_β to obtain only the current in the d-axis, as shown by the following expression:

$$i_d = i_\alpha \cdot \sin(\hat{\theta}) - i_\beta \cdot \cos(\hat{\theta}). \quad (2)$$

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

$$i_d = \bar{i}_d + \tilde{i}_d, \quad (3)$$

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 α–β coordinates will become:

$$\begin{cases} i_\alpha^{ref} = \sin(\hat{\theta}) \cdot i_d; \\ i_\beta^{ref} = -\cos(\hat{\theta}) \cdot i_d. \end{cases} \quad (4)$$

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

$$\begin{pmatrix} i_{La}^{ref} \\ i_{Lb}^{ref} \\ i_{Lc}^{ref} \end{pmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{pmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \cdot \begin{pmatrix} i_\alpha^{ref} \\ i_\beta^{ref} \end{pmatrix}. \quad (5)$$

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 structure 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 placement theory by determining an arbitrary stability polynomial $D(p)$ and computing $S(p)$ and $R(p)$ according to Bezout's equation [19]

$$D(p) = A(p) \cdot S(p) + B(p) \cdot R(p). \quad (6)$$

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

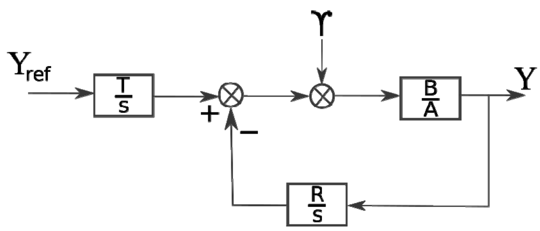

Fig. 2. Block diagram of the RST controller

The closed loop transfer function of the system is:

$$Y = \frac{B(p)T(p)}{A(p)S(p)+B(p)R(p)} Y_{ref} + \frac{B(p)S(p)}{A(p)S(p)+B(p)R(p)} \gamma \quad (7)$$

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

$$\begin{cases} \deg(D) = 2n+1 \\ \deg(S) = \deg(A)+1 \\ \deg(R) = \deg(A) \end{cases} \quad (8)$$

However, the polynomial forms are described as follows:

$$\begin{cases} A(p) = a_1 p + a_0 \\ B(p) = b_0 \\ D(p) = d_3 p^3 + d_2 p^2 + d_1 p + d_0 \\ R(p) = r_1 p + r_0 \\ S(p) = s_2 p^2 + s_1 p \end{cases} . \quad (9)$$

The transfer function of the PLL is [7] $\frac{\sqrt{3}\cdot V_m}{p}$, which mean 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:

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

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_A, where P_A 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:

$$\begin{cases} a_1 s_2 = 1 \\ a_1 s_1 + a_0 s_2 = \frac{2}{T_f} + \frac{1}{T_c} \\ a_0 s_1 + b_0 r_1 = \frac{1}{T_f^2} + \frac{2}{T_c T_f} \\ b_0 r = \frac{1}{T_c T_f^2} \end{cases} . \quad (11)$$

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

$$\lim_{p\to 0} \frac{B(p)T(p)}{A(p)S(p)+B(p)R(p)} = 1 . \quad (12)$$

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

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

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.

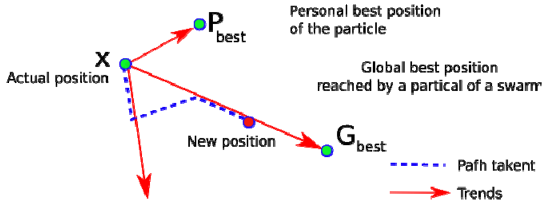

Fig. 3. A particle movement

A particle is capable to evaluate her position quality and remember her best performance. By asking her congeners 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 (V) formulated as follows:

$$X_i = (x_{i1}, x_{i2}, \ldots, x_{in}) ; \quad (14)$$

$$V_i = (v_{i1}, v_{i2}, \ldots, v_{in}) . \quad (15)$$

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:

$$P_i = (p_{i1}, p_{i2}, \ldots, p_{in}) . \quad (16)$$

The equation of a particle movement for each iteration (i_{ter}) is:

$$V_i^{iter+1} = X(w.v_i^{iter} + c_1.r_1^{iter}(p_i^{iter} - X_i^{iter}) + c_2.r_2^{iter}(p_g^{iter} - X_i^{iter})) , \quad (17)$$

where ω 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:

$$X_i^{iter+1} = X_i^{iter} + V_i^{iter+1} . \quad (18)$$

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_0 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:

$$f_{\min} = \int_0^{\infty} (U_{ref} - U_{mes})^2 (t) dt = \int_0^{\infty} (e)^2 (t) dt . \qquad (19)$$

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.

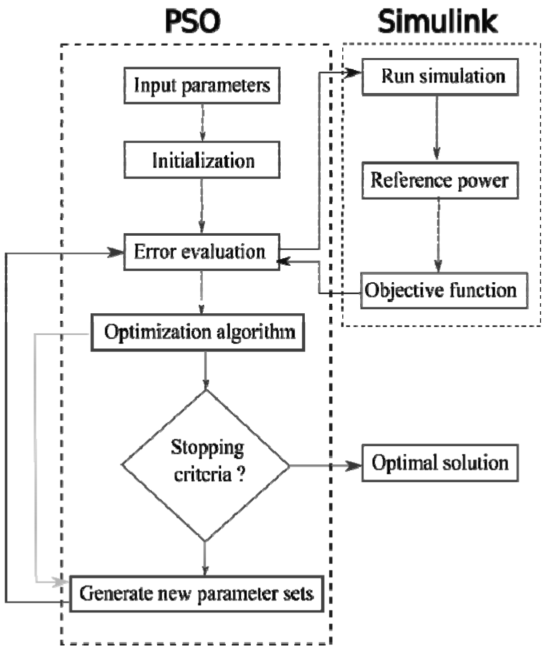

Fig. 4 .Schematic steps of proposed RST controllers with PSO algorithm

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.

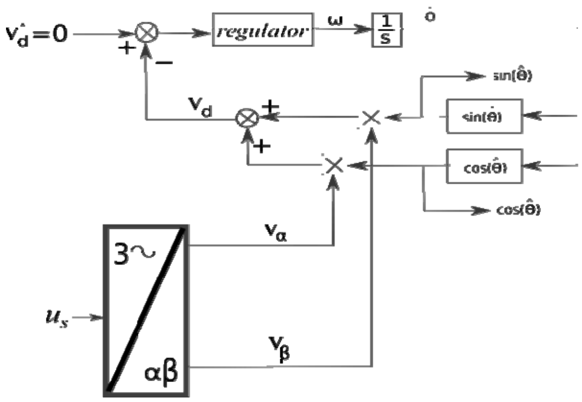

Fig. 5. Block diagram of PLL

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.

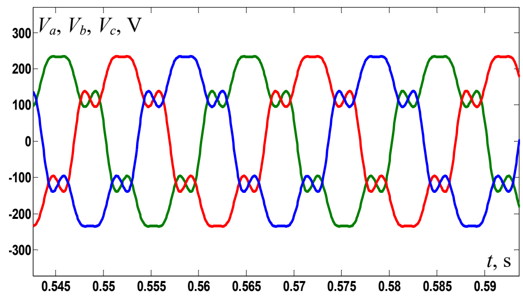

Fig. 6. Utility voltages source under harmonics

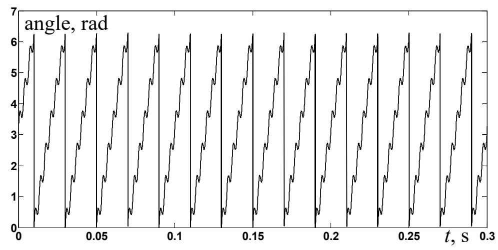

Fig. 7. Angular position estimated by the PLL based on PI controller

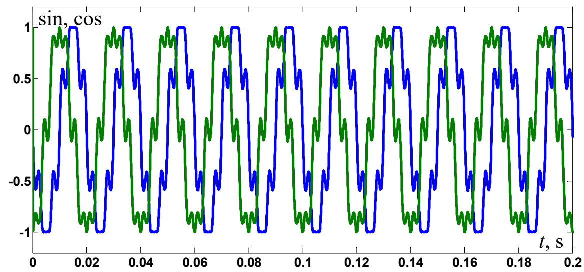

Fig. 8. Sin and cos generated by the PLL based on PI controller

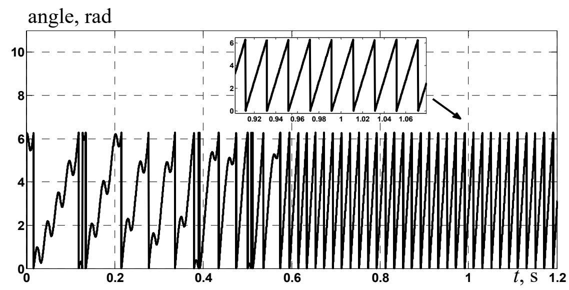

Fig. 9. Angular position estimated by the PLL based on RST controller

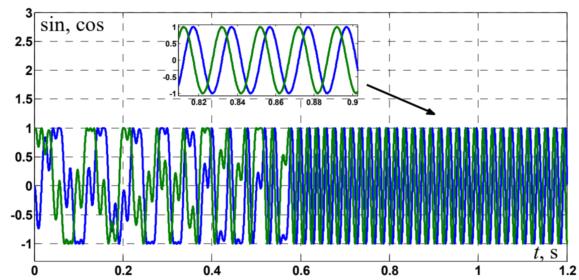

Fig. 10. Sine and cosine generated by the PLL based on RST controller

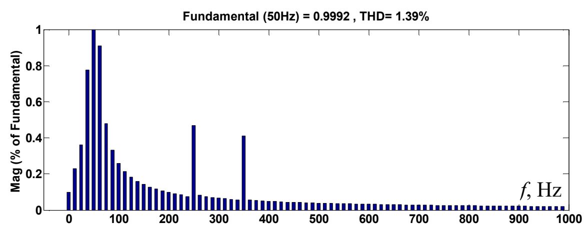

Fig. 11. Spectrum of the cosine generated by the PLL based on RST controller

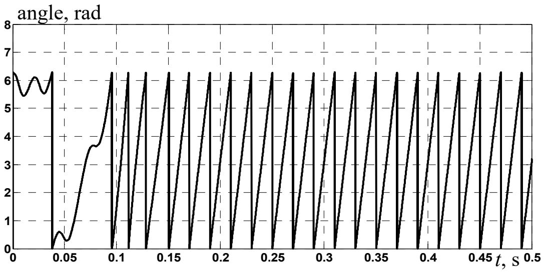

Fig. 12. Angular position estimated by the PLL based on PSO-RST

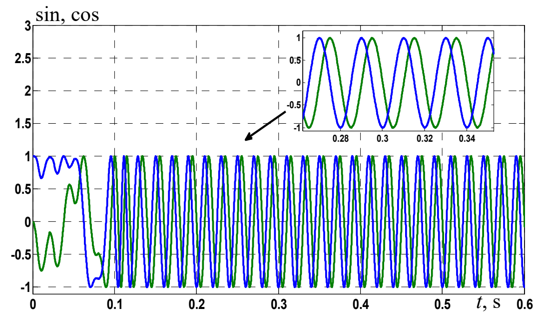

Fig. 13. Sin and cos generated by the PLL based on PSO-RST controller

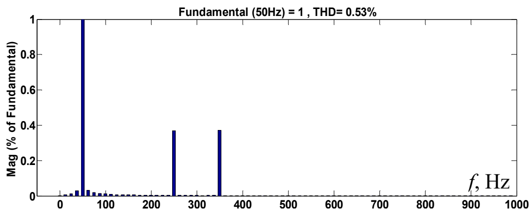

Fig. 14. Spectrum of the cosine generated by the PLL based on PSO-RST controller

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 containing 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 1

Source current THD's

	Before filtering	After filtering
Before 0.5 s	24.3 %	1.92 %
After 0.5 s	28.51 %	3.66 %

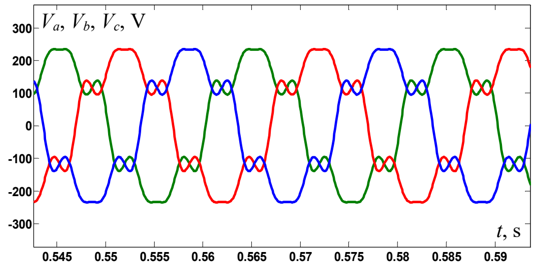

Fig. 15. Utility voltages source under harmonics for SAPF system

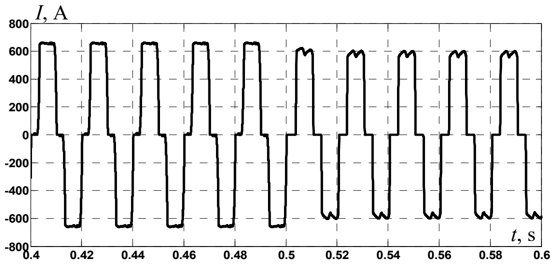

Fig. 16. Current before filtering

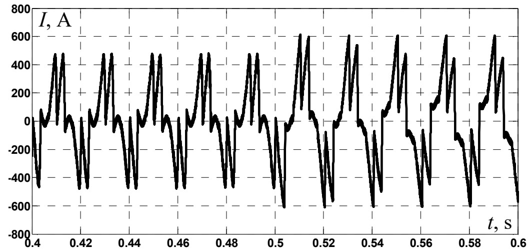

Fig. 17. Current injected by the active power filter

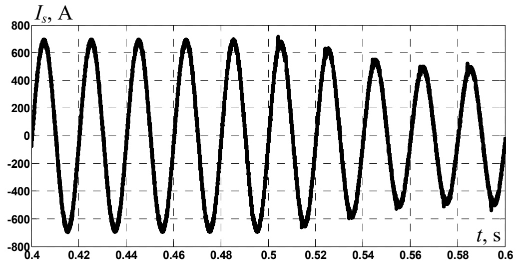

Fig. 18. Current source after filtering

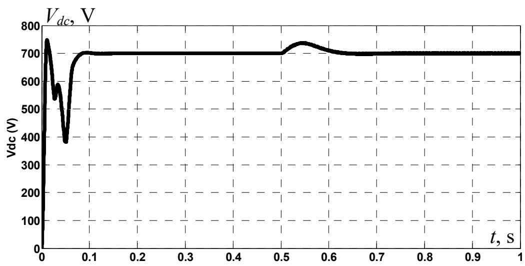

Fig. 19. DC voltage

Table 2

Controller's parameters

	RST	PSO-RST
s_2	1	2
s_1	439	1452.048
r_1	316.557	603
r_0	900	71348.6
t	900	71348.6

Table 3

Studied system parameters

V, V	240	L_{Load}, mH	2.6
R_s, mΩ	1.59	R_f, mΩ	5
L_s, μH	45.56	L_f, μH	100
R_{Load}, Ω	0.788	V_{dc}, V	700

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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