

Power quality enhancement using optimal shunt active power filter based Meta heuristic method

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Abstract—This paper deals with optimal active power filter based Meta heuristic method. It shows immense promise in reducing harmonics problem created by nonlinear loads, such as rectifier equipment used in telecommunication system, power suppliers, domestic appliances, ect, and improving power factor. This work is performed to illustrate performance of optimized PI controller parameters of DC link voltage to a shunt active power filter using search harmony method. The control method is generally useful and applicable to any other active filters. Compared to the classical PI controller, the optimized PI controller shows the advantages of shorter response time and better control performance. The simulation results show that the Search harmony approach for finding the optimal controller parameters is not easy to be implemented, but very effective in reducing harmonic and power factor enhancement.

Keywords— Shunt active power filter, Total harmonic distortion THD, PI controller, Meta-heuristics, Harmony Search algorithm, power quality

I. INTRODUCTION

The recent progress of the power electronic devices and its use technology in the industry has caused an unfortunate result. These electronic equipments Such as converters, home applications as TVs, electromagnetic cookers and fluorescent lights is considered as a non-linear load which inject harmonic in line distribution [1]. The troubles associated to the harmonic components in the power electric system forced the researches to study and propose new technique to eliminate these harmonics. One of the theories is the instantaneous power theory (p-q theory). This theory was introduced by Akagi, Kanazawa and Nabae in 1983 [2] in Japanese.

By tradition, passives filters have been used to eliminate the current harmonic distortion and compensate the reactive power, but can resonate with supply impedance. The proposed optimized shunt active power filter system is a great tool for the compensation not only of current harmonics produced by distorting loads, but also of reactive power of non-linear loads [3].

As the important link influence steady and dynamic index, the optimization of PI regulator's parameters is crucial [4]. In this paper, we formulate the problem of design DC link voltage PI controller as an optimization problem. The

problem formulation adopts three performances indexes, the maximum overshoot, the rise time and the integral absolute error of step response as the objective function to determine the PI control parameters for getting a well performance under a given system, the primary design goal is to obtain good load disturbance response by minimizing the integral absolute control error. At the same time, the transient response is assured by minimizing the others three performance indexes. Furthermore, we provide work for solution algorithm based On harmony search optimization (HSO) technique that has been very successful in a wide variety of optimization problems [8], HSO is best tuning method for designing the PI controller, through this approach it has improved the trail system of HSO applied to PI of shunt active power filter. The remainder of this paper is organized in six major sections. The description of harmony search algorithm, establishment of fitness function in section 3 and (HSO) application in section 6 for DC link voltage. Results are given and discussed in Section 8 and conclusions are presented in Section 9.

II. HARMONY SEARCH ALGORITHM

Having recently given rise to a new meta heuristic method, a new algorithm can be conceptualized from a music performance process (say, a jazz improvisation) involving searching for a better harmony. Just like music improvisation seeks a best state (fantastic harmony) determined by aesthetic estimation, optimization process seeks a best state (global optimum) determined by objective function evaluation; Just like aesthetic estimation is determined by the set of the pitches played by ensemble instruments, function evaluation is determined by the set of the values assigned for decision variables; Just like aesthetic sound quality can be improved practice after practice, objective function value can be improved iteration by iteration [5]. The analogy between improvisation and optimization is shown in Fig. 1. Each music player (saxophonist, double bassist, and guitarist) can correspond to each decision variable (x_1 , x_2 , and x_3), and the range of each music instrument (saxophone = {Do, Re, Mi}); double bass = {Mi, Fa, Sol}; and guitar = {Sol, La, Si}) corresponds to the range of each variable

value ($x_1 = \{100, 200, 300\}$; $x_2 = \{300, 400, 500\}$; and $x_3 = \{500, 600, 700\}$). If the saxophonist toots the note Do, the double bassist plucks Mi, and the guitarist plucks Sol, their notes together make a new harmony (Do, Mi, Sol). If this new harmony is better than existing harmony, the new harmony is kept. Likewise, the new solution vector (100mm, 300mm, 500mm) generated in optimization process is kept if it is better than existing harmony in terms of objective function value. Just as the harmony quality is enhanced practice after practice, the solution quality is enhanced iteration by iteration.

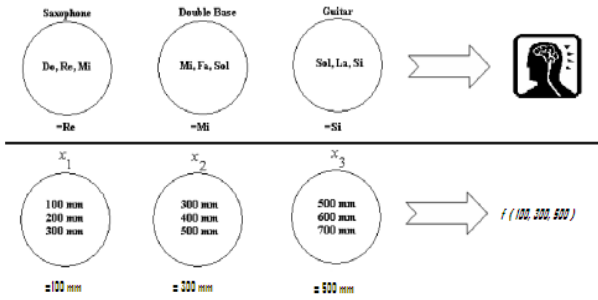


Fig 1. Analogy between music improvisation and optimization

According to the above concept, the HS meta-heuristic algorithm consists of the following five steps [9]:

- Step 1: Initialization of the optimization problem and algorithm parameters.
- Step 2: Harmony memory initialization.
- Step 3: New Harmony improvisation.
- Step 4: Harmony memory update.
- Step 5: Repetition of Steps 3 and 4 until the termination criterion is satisfied.

Step 1. Initialization of the optimization problem and algorithm parameters:

In the first step, the optimization problem is specified as follows: Minimize (or Maximize) $f(x)$ (1)
Subject to $x_i \in X_i, i = 1, 2, \dots, N$.

Where $f(x)$ is an objective function; x is a solution vector composed of each decision variable x_i ; X_i is the set of possible range of values for each decision variable, that is, $X_i = \{x_i(1), x_i(2), \dots, x_i(k)\}$ for discrete decision variables. However, there is no sorting required in this vehicle routing problem because each variable value represents just node number rather than physical amount such as node demand; N is the number of decision variables (= number of music instruments); and K is the number of candidate values for the discrete decision variables (= number of pitches for each instrument).

The HS algorithm parameters are also specified in this step: HMS (harmony memory size; = number of simultaneous solution vectors in harmony memory), HMS (harmony memory considering rate), PAR (pitch adjusting rate), and number of improvisations (= number of objective function evaluations). These algorithm parameters are explained in the following steps.

Step 2. Harmony memory initialization:

In the 2nd step each component of each vector in the parental population (Harmony Memory), which is of size HMS, is initialized with a uniformly distributed random number between the upper and lower bounds $[L^{xi}, U^{xi}]$, where $1 \leq i \leq N$. This is done for the i -th component of the j -th solution vector using the following equation:

$$x_i^j = L^{xi} + rand(0,1) \cdot (U^{xi} - L^{xi}) \quad (2)$$

Where $j = 1; 2; 3; \dots; HMS$ and $rand(0; 1)$ is a uniformly distributed random number between 0 and 1 and it is instantiated a new for each component of each vector.

Step 3. New Harmony improvisation:

In this step, a New Harmony vector: $\vec{x}' = (x'_1, x'_2, x'_3, x'_4, \dots, x'_N)$

The vector is generated based on three rules: (1) memory consideration, (2) pitch adjustment, and (3) random selection. Generating a new harmony is called 'improvisation'. In the memory consideration, the value of the first decision variable x'_1 for the new vector is chosen from any of the values already existing in the current HM i.e. from the set $x_1^1, \dots, x_1^N, x_1^{HMS}$ with a probability HMCR. Values of the other decision variables $x'_2, x'_3, x'_4, \dots, x'_N$ are also chosen in the same manner. The HMCR, which varies between 0 and 1, is the rate of choosing one value from the previous values stored in the HM, while $(1 - HMCR)$ is the rate of randomly selecting a fresh value from the possible range of values [12].

$$x'_i \leftarrow \begin{cases} x_i \in \{x_1^1, x_1^2, x_1^3, \dots, x_1^{HMS}\} & \text{with probability HMCR} \\ x_i \in X_i & \text{with probability } (1 - HMCR) \end{cases} \quad (3)$$

For example, an $HMCR = 0.80$ indicate that the HS algorithm will choose the decision variable value from historically stored values in the HM with an 80% probability or from the entire possible range with a 20% probability [14]. Every component obtained by the memory consideration is further examined to determine whether it should be pitch-adjusted. This operation uses the parameter PAR (which is the rate of pitch adjustment) as follows:

Pitch Adjusting Decision for

$$x'_i \leftarrow \begin{cases} x'_i \pm rand(0,1) \cdot bw & \text{with probability PAR} \\ x'_i & \text{with probability } (1 - PAR) \end{cases} \quad (4)$$

Where bw is an arbitrary distance bandwidth (a scalar number) and $rand()$ is a uniformly distributed random number between 0 and 1. Evidently step 3 is responsible for generating new potential variation in the algorithm and is comparable to mutation in standard EAs. Thus either the decision variable is perturbed with a random number between 0 and bw or otherwise it is left unaltered with a probability PAR or else it is left unchanged with probability $(1 - PAR)$.

Step 4. Harmony memory update:

If the New Harmony vector : $\vec{x}' = (x'_1, x'_2, x'_3, x'_4, \dots, x'_N)$ is better than the worst harmony in the HM, judged in terms of the objective function value, the new harmony is included in the HM and the existing worst harmony is excluded from the HM. This is actually the selection step of the algorithm where the objective function value is evaluated to determine if the new variation should be included in the population (Harmony Memory).

Step 5. Check stopping criterion:

If the stopping criterion (maximum number of improvisations) is satisfied, computation is terminated. Otherwise, steps 3 and 4 are repeated.

III. ORGANIZATION OF OBJECTIVE FUNCTION

In this work, the optimized parameters objects are proportional gain K_p and integral gain K_i , the transfer function of PI controller is defined by:

$$G_c(s) = K_p + \frac{K_i}{s} \quad (5)$$

The gains K_p and K_i of PI controller are generated by the HSO algorithm for a given plant. As shown in fig.2. The output $u(t)$ of PI controller is (equation 6):

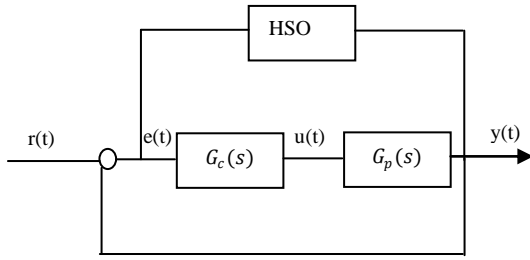


Fig.2 PI control system

$$U(t) = K_p e(t) + K_i \int_0^t e(t) dt \quad (6)$$

For a given plant, the problem of designing a PI controller is to adjust the parameters K_p and K_i for getting a desired performance of the considered system. Both the amplitude and time duration of the transient response must be kept within tolerable or prescribed limits, for this condition, three key indexes performance of the transient response are utilized to characterize the performance of PI control system [13]. These key indexes maximum overshoot, rise time and integral absolute control error are adopted to create objective function which is defined as:

$$F = f_{os} + f_{rt} + f_{iae} \quad (7)$$

The maximum overshoot is defined as:

$$f_{os} = y_{max} - y_{ss} \quad (8)$$

y_{max} characterize the maximum value of y and y_{ss} denote the steady-state value of y . For f_{rt} represent the function

of the rise time is defined as the time required for the step response. In the other hand, the integral of the absolute magnitude of control error is written as:

$$f_{iae} = \int_0^{\infty} |e(t)| dt \quad (9)$$

IV. CONFIGURATION OF SHUNT ACTIVE POWER FILTER

The most important objective of the APF is to compensate the harmonic currents due to the non linear load. Exactly to sense the load currents and extracts the harmonic component of the load current to produce a reference current I_r as shown in fig.3, The reference current consists of the harmonic components of the load current which the active filter must supply [10].

This reference current is fed through a controller and then the switching signal is generated to switch the power switching devices of the active filter such that the active filter will indeed produce the harmonics required by the load. Finally, the AC supply will only need to provide the fundamental component for the load, resulting in a low harmonic sinusoidal supply.

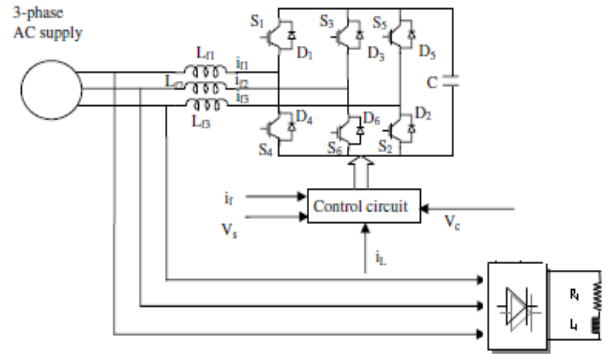


Fig.3 Equivalent schematic of shunt APF

V. INSTANTANEOUS ACTIVE AND REACTIVE P-Q POWER THEORY

The identification theory that we have used on shunt APF is known as instantaneous power theory, or PQ theory.

It is based on instantaneous values in three-phase power systems with or without neutral wire, and is valid for steady-state or transitory operations, as well as for generic voltage and current waveforms.

Inputs:

Vector of tension: $v_a(t)$, $v_b(t)$ and $v_c(t)$

Vector of current: $i_a(t)$, $i_b(t)$ and $i_c(t)$

The PQ theory consists of an algebraic transformation (Clarke transformation) of the three phase voltages and current in the abc coordinates to the $\alpha\beta$ coordinates [11].

$$\begin{bmatrix} v_{\alpha} \\ v_{\beta} \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (10)$$

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (11)$$

The instantaneous power is calculated as:

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (12)$$

The harmonic component of the total power can be extracted as:

$$p_L = \bar{p}_L + \tilde{p}_L \quad (13)$$

Where,

\bar{p}_L : The DC component \tilde{p}_L : Harmonic component

Similarly,

$$q_L = \bar{q}_L + \tilde{q}_L \quad (14)$$

Finally, we can calculate reference current as:

$$\begin{bmatrix} i_{fa}^* \\ i_{fb}^* \\ i_{fc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (15)$$

Where,

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} \quad (16)$$

VI. HSO APPLIED TO OPTIMIZE PI PARAMETERS OF DC-LINK CAPACITOR

In this paper, we present the SAPF as controlled plant, the SAPF diagram is shown in Fig.4.

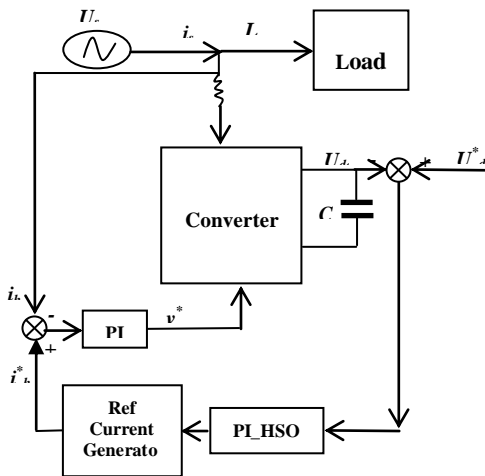


Fig.4 Optimal control diagram of APF system

The estimation of the reference currents from the measured DC bus voltage is the basic idea behind the PI controller based operation of the SAF. The capacitor voltage is compared with its reference value v_{dc}^* in order to

maintain the energy stored in the capacitor constant. The DC link voltage discretely at the positive zero-crossing point of respective phase source voltage, computes the variation of power according to difference of DC link voltage between two sampling points.

The regulation of the error between the capacitor voltage and its reference is assured by The PI controller which its output is multiplied by the mains voltage waveform V_{s1} , V_{s2} , V_{s3} in order to obtain the supply reference currents. The equivalent schematic diagram of system which is used to maintain the DC link voltage constantly is shown in Fig.5

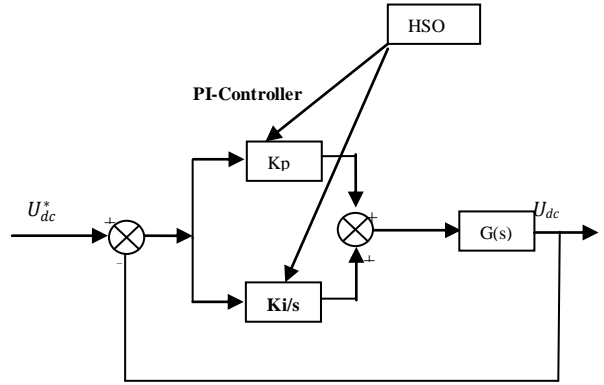


Fig.5 Equivalent schematic diagram system

In this work, the objective of an optimal design of PI controller DC-Link for given plant is to find a best parameters K_p and K_i of PI control system such that the performance indexes on the transient response is minimum.

The following solution algorithm applied for designing PI controller is presented as:

- Initialization.
Specify of each decision variable, a possible value range in each decision variable, harmony memory size HMS, harmony memory consideration rate HMCR, pitch adjusting rate PAR, maximum iteration
- Harmony memory initialization.
Harmony memory matrix is filled by many numbers of randomly generated value of objective function F, HMS is stored by the values of objective function.
- Improvisation of New Harmony.
Based on three rules, memory considering, pitch adjusting and random choosing.
- Updating of harmony memory
If the New Harmony vector is better than old harmony for finding optimal objective function, the New Harmony is included in HM and the oldest is rejected.
- Termination criterion satisfied
If the termination criterion (number of improvisations) is reached, computation is stopped. Otherwise, Steps 3 and 4 are repeated Stop.

VII. DESIGN OF OPTIMIZING ALGORITHM

In this work, we have used the following parameters values for the ant colony optimization which is step in the table.1.

TABLE.1
INITIAL VALUES PARAMETERS OF HSO

Number of musical instruments	10
Harmony memory size HMS	5 - 95
Harmony memory considering rate HMCR	0.2 - 0.8
Pitch adjusting rate PAR	0.01 - 0.004
Stopping criterion	50

VIII. SIMULATION RESULT

The proposed PI controller of DC link capacitor designed by HSO on filtering system that was set in Matlab / Simulink environment to predict performance of the proposed method. The SAPF model parameters are shown in the following Table 2.

TABLE.2
SAPF PARAMETERS

Supply phase voltage U	220 V
Supply frequency fs	50 HZ
Filter inductor Lf	1mH
Dc link capacitor Cf	4.4 mF
Smoothing inductor	0.1 mH
Sample time Ts	4 μs

A number of simulation results were developed with different cases. The SAPF is connected in parallel with nonlinear load, the first case is the PI-classical using on the system to allow us to see the regulation of DC link voltage and its effect for damping harmonic current and reducing total harmonic distortion (THD). For the second case the proposed optimized PI-controller has been introduced in order to improve a SAPF performance and meet the requirements of harmonic elimination and reactive compensation.

VIII.A) Case of classical PI-controller

In the conventional PI controller the parameters K_p and K_i has been determined by classical method, The PI control scheme involves regulation of the dc link voltage to set the amplitude of reference current for harmonic and reactive power compensation [4], [6]. In this study, we have simulated only the network supply connected on the nonlinear load, the total harmonic distortion found is 20.90 % which indicate the harmonic presence in the current source caused by nonlinear load. In the first case, the SAPF has been introduced in order to compensate these harmonics and has reduced the THD from 20.90% to 1.45 %. The results founded are shown in the following figures.

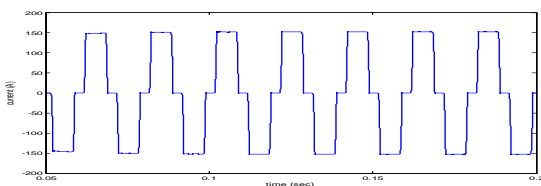


Fig.6 Load current waveform

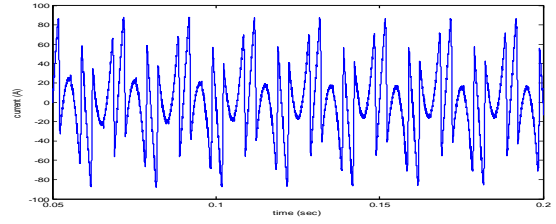


Fig.7 Injected current waveform

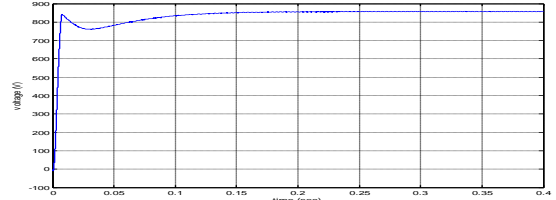


Fig.8 DC link voltage waveform

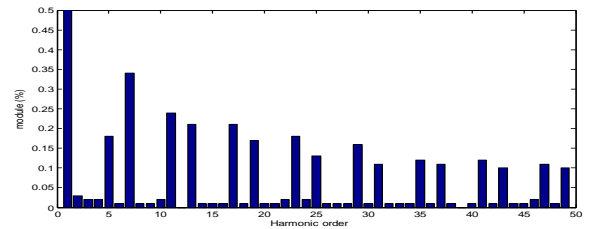


Fig.9 Harmonic spectrum of supply current

TABLE.3
THD AND PF RESULTS

	Without filtering	SAPF filtering with classical PI DC link voltage	Robustness
THD _i (%)	20.90	1.45	4.15
Power factor		0.86	

VIII.B) Case of optimized PI-controller

In the second case, the shunt active power filter was examined using optimized PI –controller DC link voltage, the optimal parameters has been determined by harmony search optimization (HSO). The main objective is to minimize the fitness function that is defined by the equation (7). In this work, we have based on the minimizing integral absolute error, so it has been multiplied by coefficient α . The objective function is returned by the following equation:

$$F = f_{os} + f_{rt} + \alpha * f_{iae} \quad (17)$$

In this case, we have fixed α value: $\alpha = 2.2$ and that to give an importance for the integral error in formulation function. Simulation studies are carried out to predict performance of the proposed method. The Fig. 10 shows the DC link voltage response curves of system used primal PI parameters and optimized PI parameters, and the value of system indexes are compared in Tab.4. The source voltage, current, load current, harmonic order and Dc link voltage waveforms are shown in the following figures after adopted the optimized system.

TABLE 4
COMPARISONS OF SAPF INDEXES BETWEEN USED AND UNUSED HARMONY SEARCH ALGORITHM

Parameter and indexes	Classical controller	Optimized controller
Proportional gain	145	190
Integral gain	1.002	0.0004
Overshoot (%)	85.42	88.25
Rise time (sec)	0.0009	0.00088
Integral absolute error	$1.0157e^{+001}$	$6.7583e^{+000}$

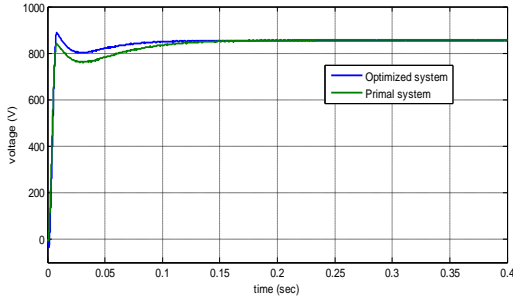


Fig.10 DC link voltage response curve of SAPF used ant colony optimization

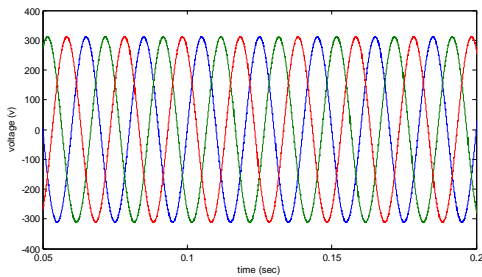


Fig.11. Source voltage waveform

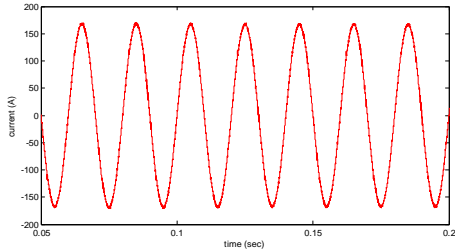


Fig.12 Supply current waveform of single phase

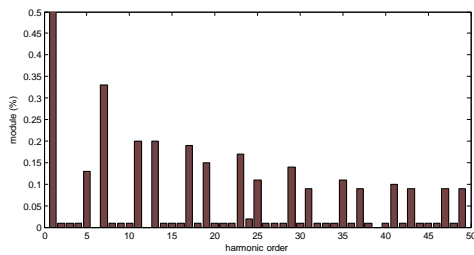


Fig.13 Harmonic spectrum of supply current

The results we obtained demonstrate that a low THD value can be reached by using the optimized system studied in this paper. The current source represented by figure 12 takes the sinusoidal form, as well as the spectral analysis (figure 13) shows the absence of the more share of the harmonics rows which implies the good performances of the optimized PI-controller compared with classical PI.

TABLE 5
HARMONIC SUPPLY CURRENT PHASE –A COMPONENT

HARMONIC SUPPLY CURRENT COMPONENTS		
$I_{sa(n)}/I_{sa(1)} [\%]$		
N	Without optimization	With optimization
5	0.18	0.13
7	0.37	0.33
11	0.26	0.20
13	0.21	0.20
17	0.21	0.19
19	0.19	0.15
23	0.18	0.17
25	0.13	0.11
29	0.16	0.14
31	0.11	0.09
35	0.14	0.11
37	0.11	0.09
41	0.14	0.10
43	0.12	0.09
47	0.13	0.09
49	0.12	0.09
THD	1.45	0.92

TABLE 6
THD AND PF RESULTS

	Without filtering	SAPF using optimized PI DC link voltage	Robustness
THD_i (%)	20.90	0.92	5.25
Power factor		0.90	

VIII.C) Comparative Study

In this paper we have presented a comparative between traditional PI controller using and optimized PI. An optimization approach (HSO) has been used to define the optimal parameters of PI controller. The PI-HSO control method has improved the active power filter performance, and it can be seen in the Supply current filtering result Fig.12. The deformations have been clearly reduced and also the harmonic distortion has been decreased compared with the SAPF filtering using traditional PI controller method, so this comparison can be shown in the following figure.

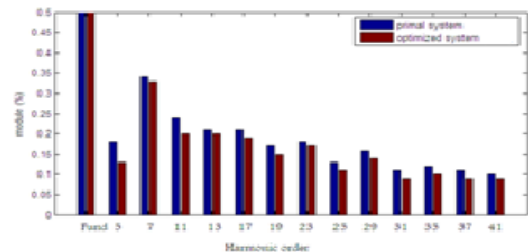


Fig.14 Comparative harmonic spectrum of supply current for both with classical PI and optimized PI controller

IX. CONCLUSION

In this paper, a new ant colony optimized DC-link voltage control has been examined for shunt power active filter. For this purpose, to obtain further adaptive tuning mechanism for the PI controller parameters and sympathy of the system is increased. The simulation results have demonstrated that the control strategy with HSO for DC link voltage is efficient for compensating the current harmonics and power factor improvement. The proposed system has reduced the THD with 4.8 % less than primal system (SAPF without HSO) as shown in Fig.14.

According to these results, the PI controller with HSO algorithm is better than the traditional PI without HSO algorithm, and then we can say that the PI-HSO is the best controller which presented satisfactory performance and good robustness.

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