Comprehensive Comparison between Hybrid Fuzzy-PI and PSO-PI Controllers Based Active Power Filter for Compensation of Harmonics and Reactive Power under Different Load Conditions

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Abstract- **This paper presents the application of two different control methods of Hybrid Fuzzy-PI and PSO-PI controllers for the active power filter (APF) in order to compensate the harmonics and reactive power under different load conditions. Firstly, the particle swarm optimization (PSO) is used for determining the optimal values of (L-C) parameters for the active power filter and gains of PI controller (Kp,Ki). Secondly, the PI controller gains have been tuned using fuzzy logic controller to achieve the optimal performance of the DC-link voltage of APF. The control schemes have been tested with nonlinear loads under different conditions of operation. The performance of PSO-PI, fuzzy-PI is compared under different load conditions. The results show the effectiveness of proposed fuzzy-PI and PSO-PI controllers to optimize the energy storage of the DC capacitor and achieve a good performance under load change. Matlab/Simulink software package has been used to simulate and evaluate the overall system.**

Keywords—Active power filter; PI controller; particle swarm optimization (PSO); Fuzzy logic controller

I. INTRODUCTION

Recently the power quality (PQ) problems in power utility distribution systems and their effects have gained public awareness. Advances in semiconductor device technology have fuelled a revolution in power electronics over the past decade, and there are indications that this trend will continue. The rapid use of nonlinear load in electrical distribution as adjustable electric drives, electrolysis plants, uninterruptible power supplies, powerful arc furnaces, etc produces voltage and current waveforms distortions. Their work is accompanied by a violation of the quality power system, such as voltage fluctuation, harmonics, unbalanced voltage and voltage dips, which leads to overheating and damage to cables, motors, transformers, sensitive equipment and increasing losses[1-3].

With great interest active power filters are used for compensating harmonics and reactive power simultaneously. The APF based on voltage source inverter (VSI) is a device built on the elemental base of power electronics especially isolated gate bipolar transistors (IGBT) with a capacitor installed in the DC link. The capacitor serves to accumulate the energy necessary to compensate higher harmonics and reactive power. The principle of APF is based on the detection and estimation of the harmonic composition of the nonlinear load and injection and injection the equal value of the harmonic component of the load current at the point of common coupling (PCC) but opposite in phase [1-5]. As a result, the harmonic components of the load current are compensated and their propagation into the network is prevented, thereby maintaining source current purely sinusoidal.

Maintaining the constant voltage in DC - link of the VSI and improving the dynamic performance of the APF are considered an important research topic, where there is energy loss in the VSI associated with the controllable switches of the inverter, which lead to reduce in the value of voltage across the DC capacitor. This in turn adversely affects the overall dynamic performance of the APF. The conventional methods use PI controller to regulate the DC bus voltage of VSI. As known there are many methods for tuning PI controller: traditional method like Ziegler Nichols Method and modern control methods like artificial intelligence approaches. Artificial intelligence is one of the key areas to solve such system complexity and make control more robust for transient conditions [3-5].

In this paper, fuzzy logic control and PSO algorithm have been applied for optimal tuning of PI controller. Firstly, the particle swarm optimization (PSO) is used for determining the optimal values of (L-C) parameters for active power filter and gains of PI controller (K_p, K_i). Secondly, the PI controller gains have been tuned using fuzzy logic controller to achieve the optimal performance of the DC-link voltage of APF. The control schemes have been evaluated with nonlinear loads under different conditions of operation. The performance of the two control schemes based on fuzzy -PI and PSO-PI is compared under different load conditions.

II. TUNNING PI CONTROLLER

There is no doubt that, the PI controller is the most used controller in the industry process control, because of its relatively simple structure, which can be easily understood and implemented in practice [3-5]. Tuning PI controller i.e. determination the optimal value of gains (K_p, K_i) is an important task for researchers, where these parameters determine the performance of PI controller and in turn the overall controlled system[6,9-11].

A. Fuzzy –PI controller

The transfer function of PI controller is presented as [6]:

$$G_c(s) = K_p + \frac{K_i}{s} \tag{1}$$

Where K_p and K_i are the proportional and integral gains respectively.

The PI controllers are simple, but cannot always effective controller with changing parameters system. Control engineers have traditionally relied on mathematical models for their designs, but when the system is more complex, the less effective the mathematical model will be. Tuning PI controller based on the fuzzy logic controller has good benefits according to on line adapted controller gains. The rapid increase of application of knowledge-based systems in process control, especially in the field of fuzzy control has been noticed. In fuzzy control, linguistic descriptions of human expertise in controlling a process are represented as fuzzy rules [4-6, 9-11]. Fig.1 shows the block diagram of PI controller with fuzzy logic tuning.

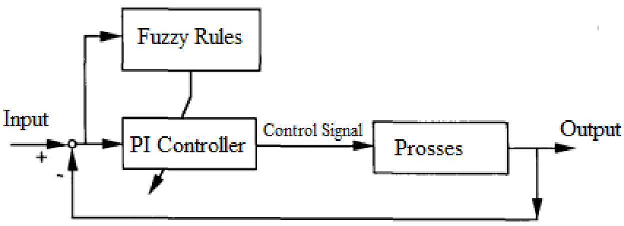


Fig.1. Block diagram of PI controller with FLC

The fuzzy control rules based on membership function (MF) defining or relate input variables to output variables. The determination of MFs depends on the designer's experience and knowledge. In our case the error and change in error are used as input signals for fuzzy logic controller, where as the output signals of fuzzy logic controller are (K_p', K_d', and α) [6,9-11].

K_p and K_d are normalized into the range between zero and one by the following linear transformation:

$$K_p' = (K_p - K_{p,min}) - (K_{p,max} - K_{p,min})$$
$$K_d = (K_d - K_{d,min}) - (K_{d,max} - K_{d,min}) \tag{2}$$

The integral time constant T_i is determined with reference to the derivative time constant T_d:

$$T_i = \alpha T_d \tag{3}$$

where α is a constant.

The integral gain of PI controller is obtained by:

$$K_i = \frac{K_p}{(\alpha T_d)} \tag{4}$$

The parameters K_p', K_d', and α are determined as outputs signals by a set of fuzzy rules. Fig.2 and Fig.3 show the membership function for input and output signals

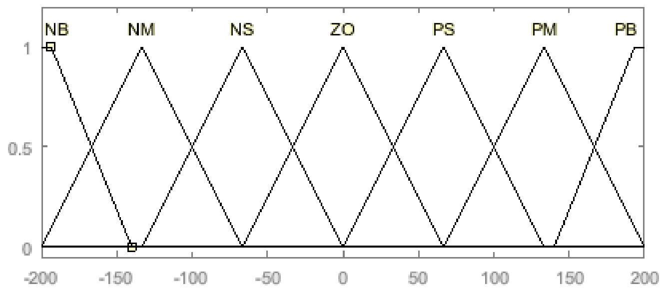
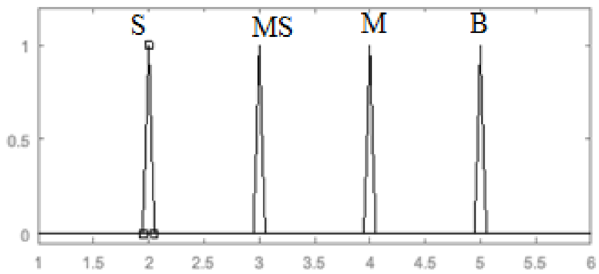
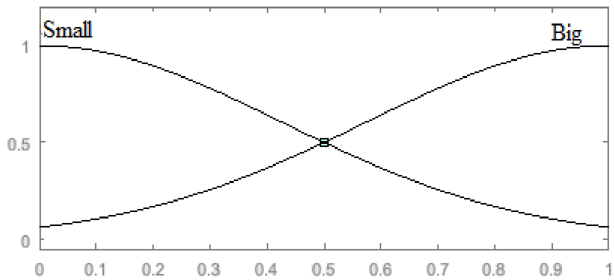


Fig.2. Membership functions terms for input signals $e(k)$,$\Delta e(k)$



(a)



(b)

Fig.3. Membership functions terms for output signals:a)for α, b) for K_p', K_d'

The fuzzy sets for input and output signals are characterized by the membership functions shown in Fig.2 and Fig.3, where in these figures, N represents negative, B represents big , S:small and M: medium, Thus NM represents negative-medium, PM positive medium , ZO approximately zero, PB positive big and so on.

B. Particle Swarm Optimization (PSO)

The PSO algorithm is used for determining the optimal values of (L-C) parameters for an active filter. Moreover, the adaptive gains of PI controller (DC-link voltage) (K_p, K_i) have been tuned using PSO to achieve the optimal performance of the DC-link voltage of APF under variable and nonlinear load. For determining the optimal value of capacitor, the objective function which leads to the minimum time multiply squared error of THD, ITSE can be calculated as follow:

$$ITSE = \int_0^{\infty} t.THD^2 dt \tag{5}$$

The objective function to minimize ITSE can be determined as follows [7-8]:

$$Minimize\{ITSE(C)\} \quad (6)$$

Now for tuning PI controller, the objective function to achieve the optimal values of K_p and K_i of the PI controller which lead to the minimum time multiply squared error, ITSE can be calculated as follow:

$$ITSE = \int_0^{\infty} t.e^2 dt \quad (7)$$

The objective function to minimize ITSE can be determined as follows:

$$\text{Minimize}\{\text{ITSE}(K_p, K_i)\} \quad (8)$$

The mechanism of the algorithm can be described as follows [7-8]:

- Creating the initial particles for objective function and assigning them initial velocities.
- Determine the personal best position *P*best and global best position *g*best for each particle of populations.
- Evaluate the first objective function for each particle of population.
- Determine the new position for each particle of population.
- Test the stop condition
- Update the particle position
- Re-evaluate the first objective function for each particle's new position if stop condition has not been achieved.
- Maximum iterations
- Stop

III. SIMULATION RESULTS

The distribution system under study (66/20/0.4) kV with industrial load (nonlinear and variable load) is modeled in Matlab/Simulink. Distribution system with active power filter has been shown in Fig.4.

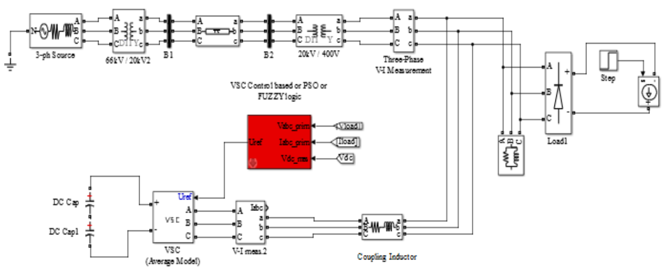


Fig.4. Distribution system under study with APF

The proposed controller for APF consists of an inner current regulation loop. This loop consists of two PI controllers that control the d-axis and q-axis currents. Where I_q reference is obtained from AC voltage regulator, I_d reference component is obtained from DC voltage regulator. The proposed PSO or Fuzzy controller has been used for DC voltage regulator i.e. for I_d reference component.

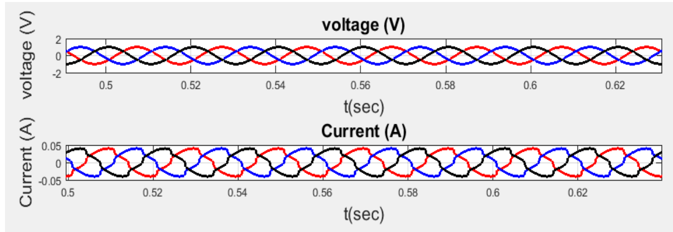
Simulation results include the current and voltage of nonlinear load c APF and without it, THD value, DC -link actual voltage. (V_{DC} reference=550 V).

A. *Distribution system without APF with non linear load*

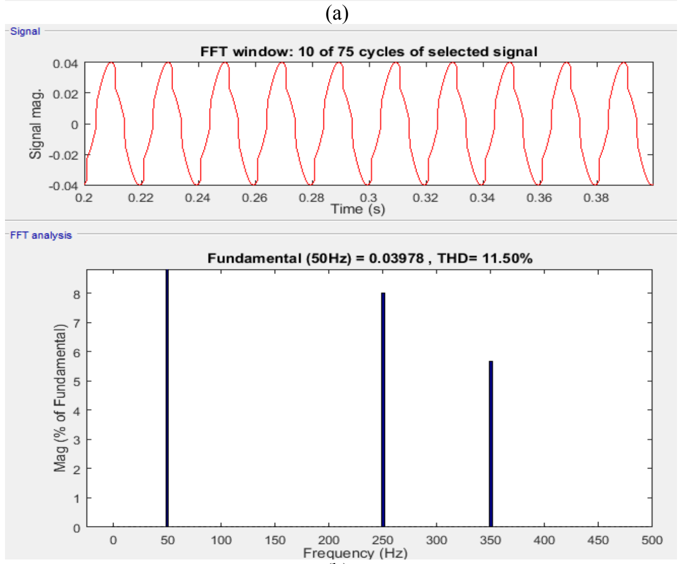
The system parameters selected for simulation studies are given in Table I, the current and voltage power supply (a) and their total harmonic distortion (b, c) are represented in Fig.5.

TABLE I. PARAMETERES DISTRIBUTION SYSTEM

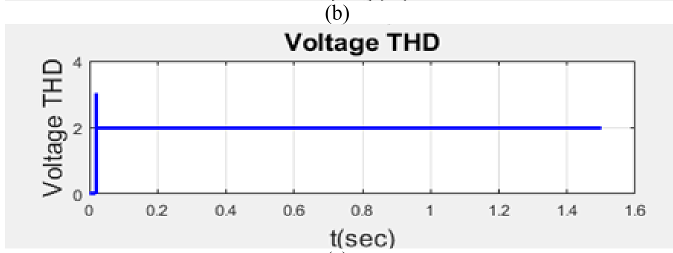
	Distribution system parameters	Value
1	Three phase source voltage	66 kV
2	Transformers (T_1&T_2)	66/20 kV & 20/0.4 kV
3	S (T_1&T_2)	1 MVA & 800 KVA
4	Transmission line	5 Km
5	Load & Heavily load	600 KVA &800 KVA
7	DC Reference Voltage, V_{dc}	550 V
8	S base	5000 KVA



(a)



(b)



(c)

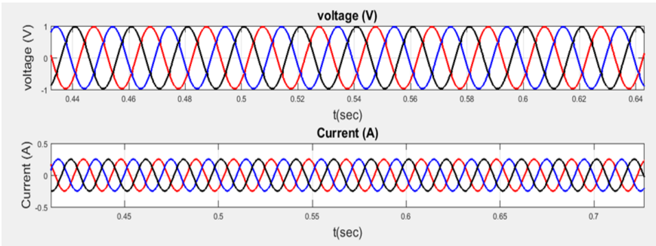
Fig.5. Simulation results:a) The current, voltage supply ,b,c) their THD without APF

The results of simulation for the distribution system under study showed that the system sufferers from harmonics current, where the THD of the current supply has unacceptance value (11.5%) (Fig.6,b) according to IEEE-519 standard recommendations on harmonic levels.

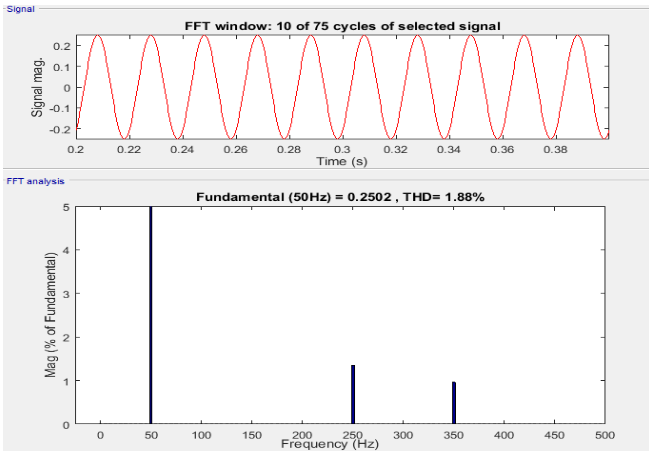
B. *APF with fuzzy logic controller and PSO*

B.1. Nonlinear Load

In this case of study, the PSO algorithm has been used to determine the optimum value of APF capacitor in order to minimize the THD value. Moreover, the fuzzy logic controller has been used for DC voltage regulation i.e. for I_d reference component. Fig. 6 shows the simulation results of this case of study. The results of fuzzy logic controller show a high efficiency and robustness especially in the transient period. In addition, the voltage across the capacitor (VSI) reached to the reference value of 550 volts. Figure 6 shows the current and voltage of the power supply (a) and its THD (b,c) and DC-link voltage with APF and fuzzy logic controller.



(a)



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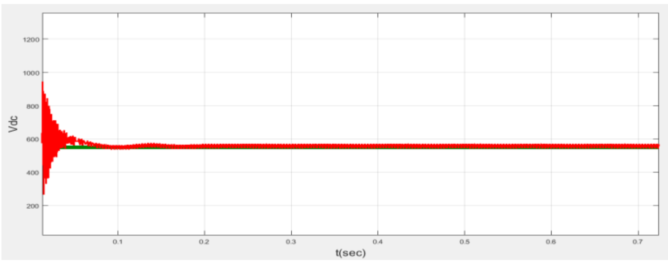


(c)

Fig.6. Simulation results: a) The current, voltage supply ,b) their THD with APF (Fuzzy-PI) controller ,c) DC-link voltage

B.2. Variable Load

Another case of study is simulated. In this case, it is assumed that a variable load is connecting at time T= 0.5 sec. the results of this case of study, has been shown in figure 7.The results shows, that the proposed controller has the ability to track the changes in the system parameters and maintain the voltage load at a value of 1pu.

The simulation result which illustrated in Fig.7, shows the impact of APF with fuzzy logic controller which used for compensation reactive power at the moment of connecting variable load (600 KVA) at T= 0.5 sec, where the load voltage had a closed value to 1pu.

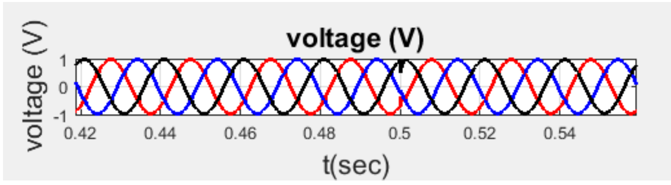


Fig.7. The voltage load under variable load condition using (Fuzzy-PI) controller

C. APF with particle swarm optimization

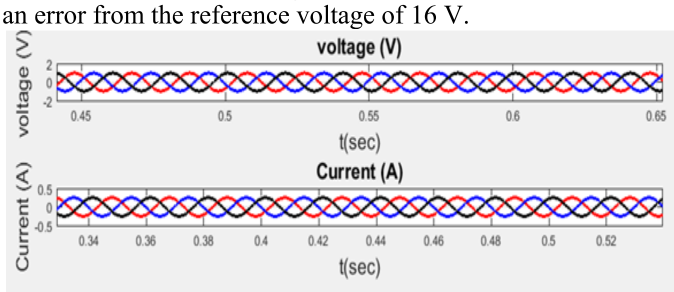
C.1. Nonlinear Load

Particle swarm optimization has been used for finding the optimal value of capacitor of the VSI. Moreover, the PSO is applied for optimal tunning of the gains of the PI controller in the DC voltage regulator loop. The application of the PSO results a precise adjustment of the PI gains, gives a significant effect and improvements in APF performance. In order to save the implementation and processing time, the gains of the PI controller have been tuned off-line. So, the application of the PSO-PI controller is tuned for a fixed point of operation.

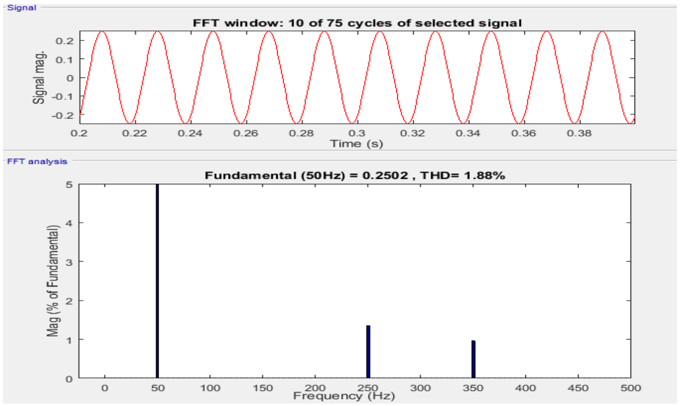
The result of the optimal value of capacitor which is obtained from the PSO algorithm is (352.94 µF) after 5 of iterations. Moreover, the optimal values of the gains of the PI controller are (0.1) for K_p and (844.42) for K_i.

The simulation results of this case with PSO-PI controller have been shown in Fig.8. The results show the current and voltage of the supply power (a) and its THD (b,c) and DC-link voltage with APF with the (PI-PSO) controller.

From Fig.8 can be noticed, that the total harmonics distortion for supply current has decreased from 11.5% to 1.88% with APF and voltage DC-link stabilized at 534 V with an error from the reference voltage of 16 V.



(a)



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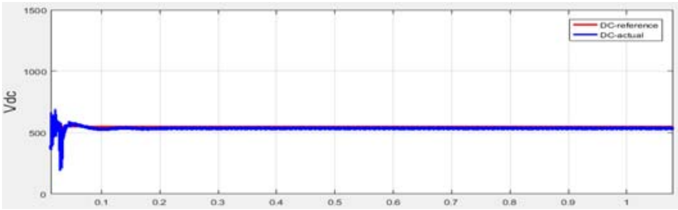

(c)

Fig.8. Simulation results: a) The current, voltage supply ,b) their THD with APF (PSO-PI) controller ,c) DC-link voltage

C.2. Variable Load

This case of study is to evaluate the performance of the PSO-PI controller against load variation. Fig. 9 shows the performance of the control scheme (the load voltage) when a variable load is connected to the system at T= 0.5 sec. As shown from the figure, APF with the PSO-PI controller can maintain the voltage load at 1pu with the compensation of reactive power at the moment of connecting variable load (800 KVA),it's mean that PI-PSO controller has a satisfactory performance with nonlinear and variable load.

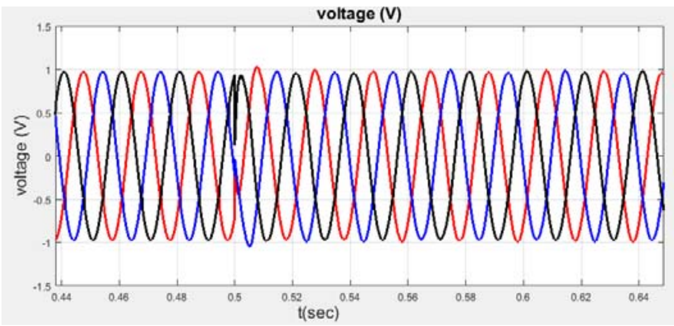

Fig.9. The voltage load under variable load condition using PSO-PI controller

D. (Fuzzy-PSO) PI controller

It can be noticed, From B.1 and C.1, that the fuzzy-PI controller has the ability to regulate the DC-link voltage more than the PSO-PI controller. In the other hand, the PSO-PI controller is more robust against the load variation, and its performance in this case of study is better than the performance of the Fuzzy-PI controller as shown from B.2 and C.2.

In order to improve the performance of overall control algorithm, a hybrid parallel controller with a combination of PSO-PI and fuzzy-PI controller is suggested in this paper to take the advantages of each method.

A comparison between the three controllers (fuzzy-PI), (PSO-PI) and (PSO-Fuzzy PI) is described in Table II. Furthermore, Table II shows that the application of the hybrid PSO-Fuzzy PI controller has been able to combine the merits of the two controllers of PSO-PI and Fuzzy-PI. With the application of the proposed hybrid controller, the voltage of DC-link reaches to its reference of 550 V without error. Moreover, the ability of control system to compensate reactive power has been increased, where the load voltage has a closed value to 1pu when the variable load is connected (800 KVA) to the system.

Table II also shows the THD with APF is reduced to 1.88 with any of the three controllers, while the initial THD of the system without APF is 11.50%.

TABLE II. COMPARISON BETWEEN THREE CONTROLLERS

Type controller	**Fuzzy-PI**	**PSO-PI**	**PSO-Fuzzy PI**
THD %	1.88	1.88	1.88
Maximum variable load (KVA)	to 600	to 800	to 800
Load voltage (pu)	1	1	1
Voltage (DC-link) V	550	534	550

IV. CONCLUSION

The application of two different control methods of hybrid Fuzzy-PI and PSO-PI controllers for the active power filter (APF) in order to compensate the harmonics and reactive power under different load conditions has been presented in this paper. The control schemes have been evaluated through simulation using Matlab/Simulink. Based on the simulation results, a comparison between the control schemes has been done. Form the results of the comparison, the error between the DC-link voltage of the VSI and its reference value is relatively small using PSO-PI controller and equal to 16 V but the error is disappeared with Fuzzy-PI controller. However, the overall system performance with nonlinear load and variable load is satisfactory, where the total harmonics distortion for supply current has decreased from 11.5% to 1.88%, with using the fuzzy-PI or PSO-PI controller. In addition, the possibility of overloading with the PSO-PI controller was greater than the with the fuzzy-PI controller. In this case study, the variable load can be increased to (800 KVA) using PSO-PI whereas using fuzzy-PI the variable load had increased to (600 KVA).

The advantages of the two controllers have been combined in the proposed hybrid parallel fuzzy-PI with PSO-PI controllers, which is called fuzzy-PSO PI controller. The performance of this control system ensures that's no deviation voltage in the DC-link voltage. Also the THD is reduced to 1.88%. Moreover, the ability to track the load change has been increased using PSO-Fuzzy PI. The results confirm the good filtering quality of harmonic currents and a perfect compensation of reactive power using the active power filter with the hybrid Fuzzy-PSO-PI controller.

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