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Design of Controller for Active Power Factor Correction System Using Metaheuristic Optimization Algorithms

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ABSTRACT

There is an increase in using electronic power converters like rectifiers in industry nowadays. These converters reduce the supply power factor and introduce harmonics into the source. Hence, it is becoming more necessary to improve the source power factor and to reduce harmonics. Active power factor correction is used in this work. The boost converter is used as it is the most popular topology for active power factor correction. Advanced optimization techniques are used to design the controller for the boost converter. These techniques include the particle swarm and the ant lion optimization methods. In this paper, the design and simulation of a single phase rectifier supplying a DC motor is investigated with and without active power factor correction. The well-known software package MATLAB / SIMULINK is used for simulation. The source power factor with and without using active power factor correction are compared and hence the effect of using the active power factor correction is explored. It is found that the source power factor is greatly improved and the total harmonic distortion is greatly reduced. This is very important for improving the quality of the power supply.

1. Introduction

There are many appliances that use DC motors and require DC power supply. So to obtain this DC power, an interface must be installed between the AC line and the DC load. Generally, for low power applications, this conversion process is done by single phase diode rectifiers [1-2]. These converters rectify the input AC source voltage to obtain DC output voltage, but this DC voltage oscillates from zero to peak. For reducing the output voltage ripple a capacitor is used. The capacitor keeps the DC voltage at a constant value but the supply current will be non-sinusoidal. The capacitor draws the supply current only at the line voltage peaks. So the supply current becomes pulsating which results in poor power factor and high total harmonic distortion (THD).

PFC (power factor correction) is used as a positive method for improving the power quality [1]. Essentially PFC can eliminate the harmonic source of rectifier devices and hence get the current waveform as sine wave and in phase with voltage waveform.

1.1 Power factor correction techniques

There are two types of power factor correction techniques

1.1.1 Passive power factor correction methods

In these methods the harmonic current can be controlled by using an LC filter that passes the current only at line frequency (50 or 60 Hz). Harmonic currents are decreased and the nonlinear device looks like a linear load. Power factor can be improved by using inductors and capacitors. But the disadvantage of passive PFC is that it requires high current inductors which are expensive and bulky.

1.1.2 Active power factor correction methods.

Active power factor correction (APFC) is the most effective way to correct power factor of electronic supplies. A boost converter is placed between the bridge rectifier and the load. The converter tries to keep constant DC output voltage and keep the line current in phase with the line voltage and the same frequency [3]. The advantages of the boost APFC are active wave shaping of supply current, filtering of the high frequency switching, feedback sensing of the source current for waveform control and feedback control to regulate output voltage.

1.2 Boost converter

The principle of the boost converter is based on the inductor tendency to resist the current changes. When the inductor charges, it acts as a load and absorbs energy (like a resistor). When the inductor discharges, it acts as an energy source (like a battery). The output voltage produced during the discharge phase is related to the current change rate and not to the original charging voltage that allows the output voltage to be higher than the input voltage.
Fig. 1 shows the boost converter and the smoothing inductor.

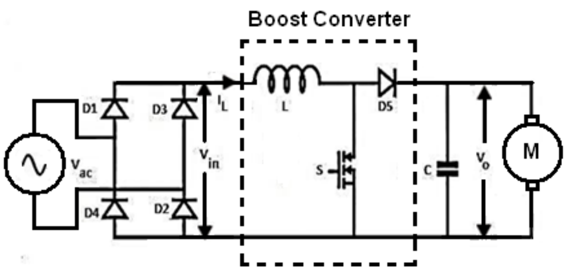

Fig. 1 Boost converter

When the boost converter operates in continuous current mode, the current through the inductor I_L never falls to zero. The output voltage can be obtained from Eq. (1), assume ideal converter case and operate in steady state condition [4-5].

$$V_o = \frac{V_{in}}{1-D} \quad (1)$$

When switch S is on:

$$\frac{dI_L}{dt} = \frac{V_{in}}{L} \quad (2)$$

When switch S is off:

$$\frac{dI_L}{dt} = \frac{V_{in} - V_o}{L} \quad (3)$$

Here D is the duty cycle, $\boldsymbol{V_{in}}$is the boost converter input voltage (the output voltage of the bridge rectifier) and $\boldsymbol{V_o}$ is the output voltage.

1.3 Active power factor correction circuit components

As shown in Fig. 2, the main circuit consists of single phase full wave bridge rectifier, boost converter and the load. The control circuit consists of error amplifier, the output of which is multiplied by the rectified voltage $\mathrm{V_{in}}$ and a factor to get $\mathrm{i_{ref}}$, $\mathrm{i_{ref}}$ is then compared with $\mathrm{I_L}$ and the result is fed to the drive circuit which gives pulses to the MOSFET switch to achieve unity power factor.
The fundamental APFC principle is that the rectifier voltage which is the input (AC) signal is converted into (DC) voltage using the bridge diode rectifier and it is changed into a current signal by the DC/DC converter using control methods [6]. So the current signal can auto track the voltage signal to be in phase.

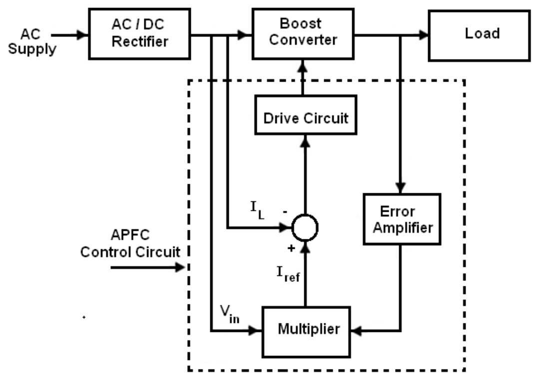

Fig. 2 The fundamental principle frame of APFC

In Fig. 2 the reference current $\mathrm{i_{ref}}$ is compared with the inductor current $\mathrm{I_L}$ and the result is fed to the drive circuit that gives the signal to the boost converter switch [7].

1.4 Control principle

This converter provides a regulated DC output voltage under variable load and input voltage conditions. The converter component values are also changing with time, pressure and temperature. Hence, the control of the output voltage should be performed in a closed loop manner using the principle of negative feedback. The most common closed loop control method for PWM DC-DC converters is the current control method.

1.5 Average current control method

There are different techniques for current control mode to get continuous input current obtained from the boost converter. The average current control mode provides good results. In this control mode the switching frequency is constant and it allows a good input current waveform [8-9]. In this control mode, both voltage control loop and current control loop are used.

The current reference i_{ref} is obtained by scaling down the line voltage by a resistive divider with scaling factor K and multiplied with the actuating signal obtained at the output of voltage PI controller. This actuating signal is obtained by comparing the output voltage with reference voltage and passing the voltage error v_{error} through the voltage PIcontroller. The comparison of i_L and i_{ref} gives i_{error} (error current) which has been amplified by another PI controller, and compared with the saw tooth wave (carrier) [10], and provides the PWM drive signal for the switch S. Fig. 3 shows the outline diagram of the average current control mode using PI controller.

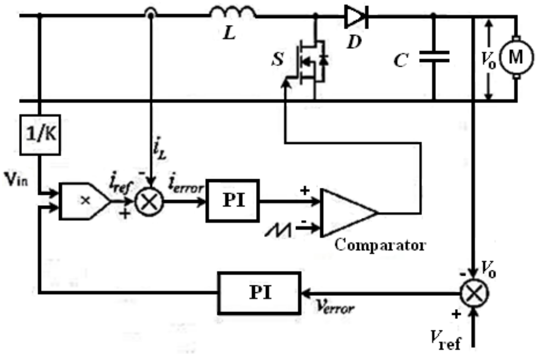

Fig. 3 Average current control mode using PI controller

1.6 Hysteresis band current control method

Fig. 4 shows this type of control in which two sinusoidal current references I_{Pref} and I_{Vref} are generated according to this control technique.The switch is turned on when the inductor current goes below the lower reference I_{Vref} and is turned off when the inductor current goes above the upper reference I_{Pref}, giving rise to a variable frequency control [11]. The advantages are no need for compensation ramp and low distorted input current wave forms. The disadvantages are variable switching frequency and the inductor current must be sensed.

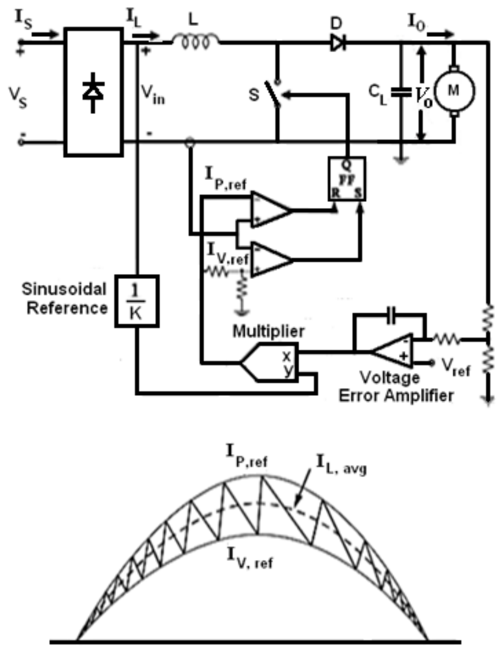

Fig. 4 Hysteresis band current control scheme

The system has the following specifications: L= 8 mH, C= 9 mF, DC motor voltage = 240 V_{dc}, field voltage = 300 V_{dc}, output power = 5 hp and source peak voltage = 220 V_{ac} .

The voltage loop controller parameters values K_p and K_i are designed to maintain constant output voltage irrespective of disturbance due to change in load or input voltage.While the current loop controller values for K_p and K_i are designed to optimize PWM pulses such that the converter operation maintains input current near sinusoidal with limited distortion and source power factor near unity [12].

2. The boost converter controller design

The boost converter controller is designed using the particle swarm optimization (PSO) and the ant lion optimization (ALO) algorithms.

2.1 The particle swarm algorithm

The particle swarm optimization is a computational method that optimizes a problem by using iterations and tries to enhance a candidate solution according to a given measure of quality. It solves a problem by having a population of candidate solutions, here called particles, these particles move around in the search space according to simple mathematical formula over the position and velocity of the particles. Each movement of the particle is influenced by its local best known position, but it is also guided toward the best known positions in the search space which are updated as better positions that are found by other particles. So the swarm moves towards the best position [12-13].

2.2 The ant lion algorithm

Antlions belong to a group of insects. The ant lion algorithm (ALO) mimics the hunting mechanism of antlions in nature. The two main phases of the antlions life cycle are larval stage and adult stage. The ant lion larva is often called "doodlebug" due to the trails which it leaves in the sand while searching for a good location to build its trap. During the process of hunting, ant lion makes funnel pits in soft sand and then waits patiently at the bottom of the pits. Slipping to the bottom, the prey is immediately seized by the ant lion. Or, if prey attempts to escape from the trap, ant lion throw sands towards the edge of the pit to slide the prey into the bottom of the pit. By throwing up loose sand from the bottom of the pit, the larva also undermines the sides of the pit, causing them to collapse and bring the prey with them [14].

2.3 Results

2.3.1 Voltage control loop

The objective function is the integration of the error squared of voltage control loop according to limit for output voltage overshoot.

The objective function $=\int_0^t e^2.dt$, where e (error) is the difference between output voltage and reference voltage.

2.3.1.1 Hysteresis band current control method

2.3.1.1.1 Particle swarm optimization algorithm

The optimum values for the PI gains of voltage control loop for hysteresis band current control method using (PSO) are found as K_p = 0.0488, and K_i = 0.1.

The number of iterations is 10 iterations with 10 particles. The iterations number and the objective function are shown in Fig. 5.

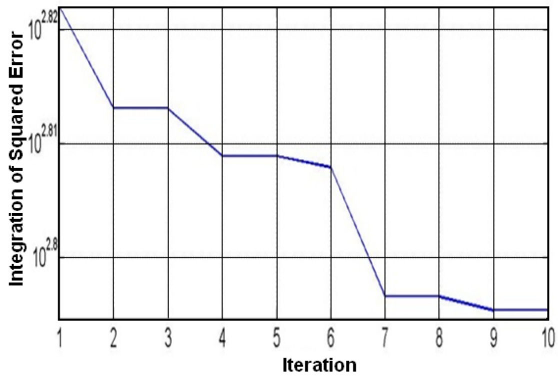

Fig. 5 The objective function versus the number of iterations when using (PSO) for hysteresis current control method

2.3.1.1.2 The ant lion algorithm

The optimum values for the PI gains of voltage control loop for hysteresis band current control method using (ALO) are found to be K_p = 0.0505, and K_i = 0.0959. The number of iteration is 10 iterations. The iterations number and objective function are shown in Fig. 6.

Fig. 6 The objective function versus the number of iterations when using (ALO) for hysteresis current control method

2.3.1.2 Average current control method

2.3.1.2.1 Particle swarm optimization algorithm

The optimum values for the PI gains of voltage control loop using average current control method using (PSO) are found to be $\boldsymbol{K_P}$= 0.0506, and $\mathbf{K_i}$ = 0.1. The number of iterations is 10 iterations with 10 particles.

The iterations number and the objective function are shown in Fig. 7.

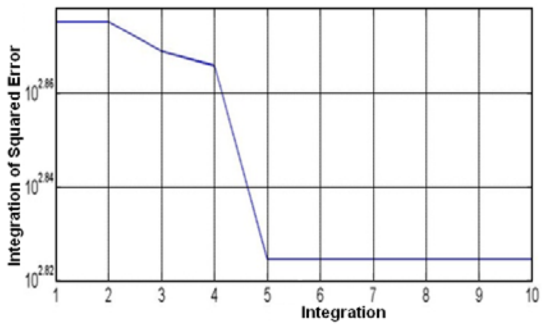

Fig. 7 The objective function versus the number of iterations when using (PSO) for average current control method

2.3.1.2.2 The ant lion algorithm

The optimum values for the PI gains of voltage control loop using average current control method using (ALO) are found as K_P= 0.0633, and K_i= 0.0933. The umber of iteration is 10 iterations. The iterations number and objective function are shown in Fig. 8.

Fig. 8 The objective function versus the number of iterations when using (ALO) for average current control method

2.3.2 Current control loop

The objective function is the integration of the error squared of current control loop. The objective function $=\int_0^t e^2 \, . dt$, where e (error) is the difference between the reference current and the inductor current.

2.3.2.1 Average current control method

2.3.2.1.1 Particle swarm optimization

The optimum values for the PI gains of current control loop using average current control method are $\boldsymbol{K_P}$= 0.2824, and $\mathbf{K_i}$ = 0.1140**.** The number of iterations is 10 iterations with 10 particles. The iterations number and the objective function are shown in Fig. 9.

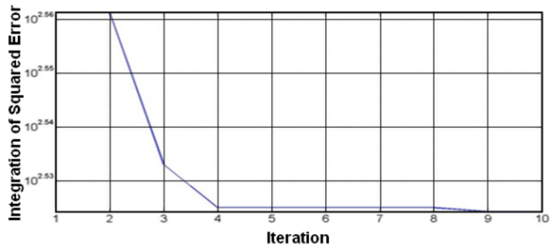

Fig. 9 The objective function versus the number of iterations using the (PSO) for average current control method

2.3.2.1.2 The ant lion optimization algorithm

The optimum values for the PI gains of current control loop using the average current control method are K_p= 0.0517, and K_i= 0.1949. The number of iteration is 10 iterations. The iterations number and objective function are shown in Fig. 10.

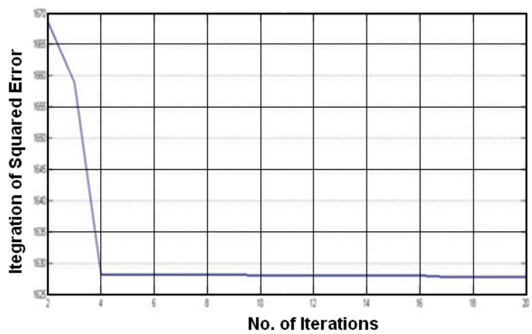

Fig. 10 The objective function versus the number of iterations using the (ALO) for average current control method

2.4 Comparison

In this section a comparison is made between different methods used to obtain the parameters of the controller. These methods are the try and error method, the particle swarm optimization method and the ant lion method. The comparison which is done here is based on the value of the objective function (the integration of the error squared) calculated in each method of optimization.

2.4.1 Hysteresis band current control method

The results obtained based on the hysteresis current control method are given in Table 1.

Table 1 the controller parameters

Method	K_p	K_i	*Objective function*	*Power factor*
ALO	0.0505	0.0959	626.19	0.9955
PSO	0.0488	0.1	624.17	0.9957
Try and Error	0.01	0.03	2200	0.9889

2.4.2 Average current control method

The results obtained based on the average current control method are given in Table 2.

Table 2 the controller parameters

Method	K_p	K_i	*Objective function*	*Power factor*
ALO	0.0633	0.0933	739.87	0.9924
PSO	0.0506	0.1	624.17	0.9947
Try and error	0.01	0.03	2600	0.9887

3. Simulation study

In order to explore the effectiveness of the controller obtained in the above section, a simulation study for a single-phase rectifier circuit supplying a DC motor is carried out. First, the system is simulated without the APFC circuit. Then, it is simulated using the APFC circuit. In each case, the power factor, the current and the voltage waveforms are obtained using the two current control methods explained above. The well-known simulation package, MATLAB/SIMULINK is used in this simulation work. Fig. A1 (appendix A) shows the MATLAB block diagram of the simulated system.

3.1. *Simulation results for single phase rectifier supplying DC motor without APFC*

Figs 11-15 display the results obtained by simulation for the system without using APFC. Fig. 11 shows that the input current wave form is pulsating in nature which means that it contains many harmonics. The THD is very high as shown in Fig. 12. The supply power factor is less than 0.4 as shown in Fig. 13. In the motor side, the steady state voltage, current, and speed are reached quickly as indicated by Figs 14 and 15.

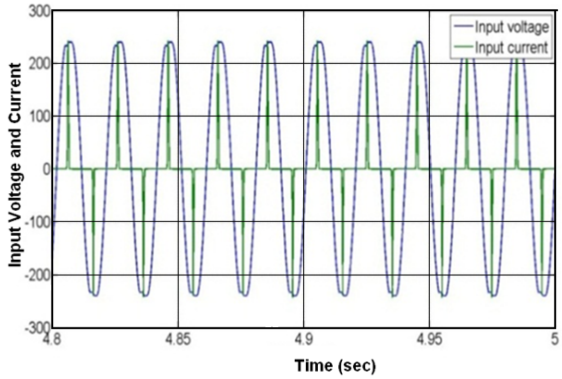

Fig. 11 Source current and voltage waveforms without APFC

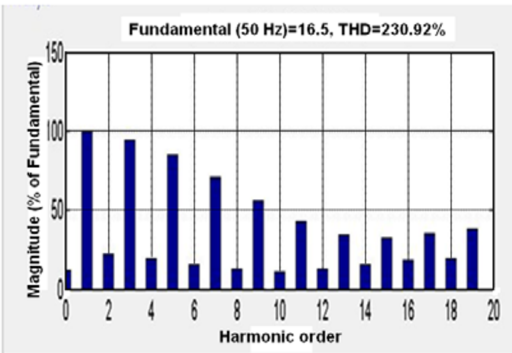

Fig.12 FFT analysis for source current wave form without APFC

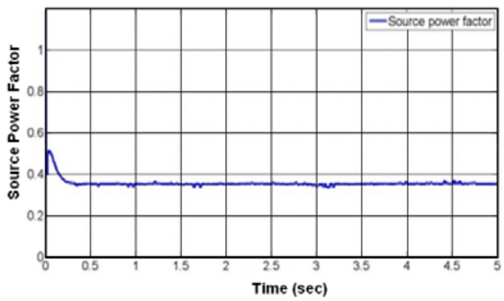

Fig. 13 Source power factor without using APFC

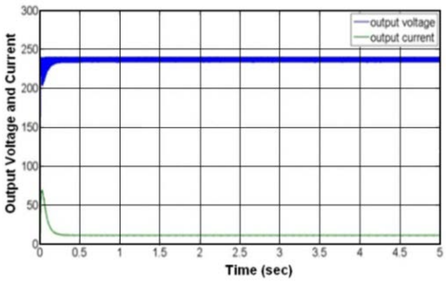

Fig.14. Motor current and voltage without using APFC

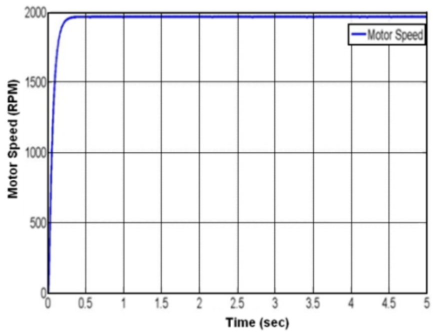

Fig.15.Motor speed without using APFC

3.2 Simulation results for the system using APFC with average current control method

Fig A2 shows the MATLAB block diagram of the simulated system and Fig. A3 shows the controller in this case. Figs 16-20 display the results obtained by simulation for the system using APFC. Fig. 16 shows that the input current wave form is almost sine wave which means that it has less harmonic content. The THD is very low as shown in Fig. 17. The supply power factor is almost unity as shown in Fig. 18. In the motor side, the steady state voltage, current, and speed are reached quickly as indicated by Figs 19 and 20. Thus the supply characteristics are much improved due to the using of APFC.

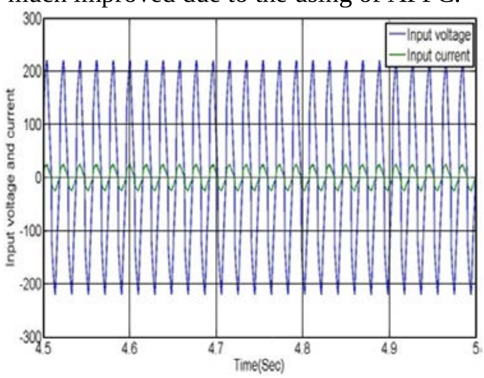

Fig. 16 Source current and voltage wave forms using APFC with average current control method

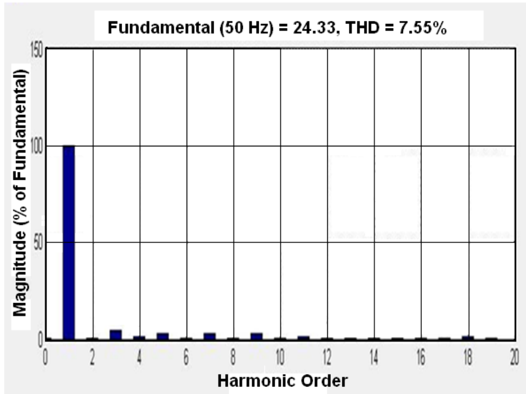

Fig. 17 FFT analysis for source current Wave form with APFC using average current control method

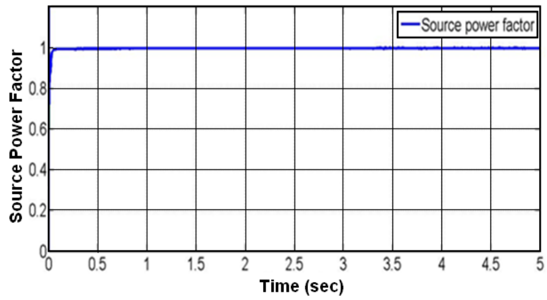

Fig. 18 Source power factor with APFC using average current control method

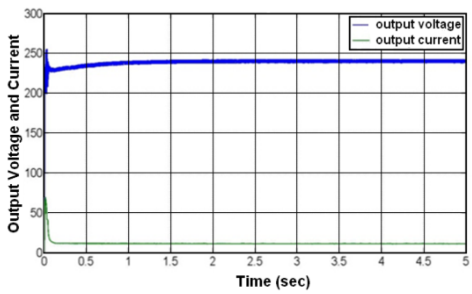

Fig. 19 Motor voltage and current with APFC using average current control method

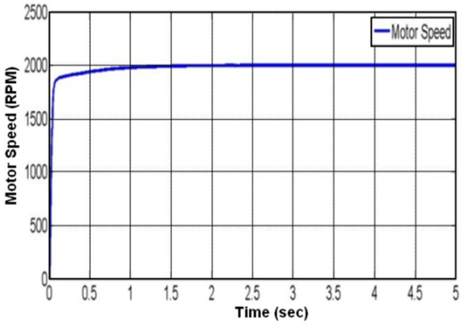

Fig. 20 Motor speed with APFC using average current control method

3.3 Simulation results for the system with APFC using hysteresis band current control method

The APFC controller in this case is shown in Fig. A4. Figs 21-25 display the results obtained by simulation for the system using APFC. Fig. 21 shows that the input current wave form is almost sine wave which means that it has less harmonic content. The THD is very low as shown in Fig. 24. The supply power factor is almost unity as shown in Fig. 25. In the motor side, the steady state voltage, current, and speed are reached quickly as indicated by Figs 22 and 23. Thus the supply characteristics are much improved due to the using of APFC.

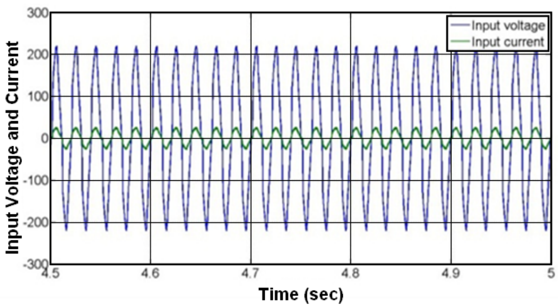

Fig. 21 Source current and voltage wave forms using APFC with hysteresis band current control method

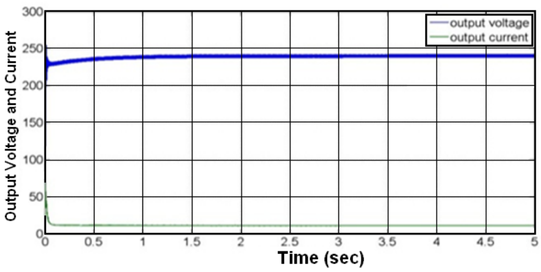

Fig. 22 Motor voltage and current with APFC using hysteresis band current control method

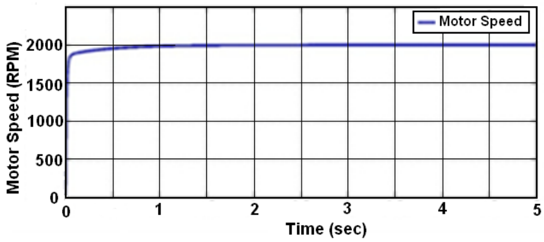

Fig. 23 Motor speed with APFC using hysteresis band current control method

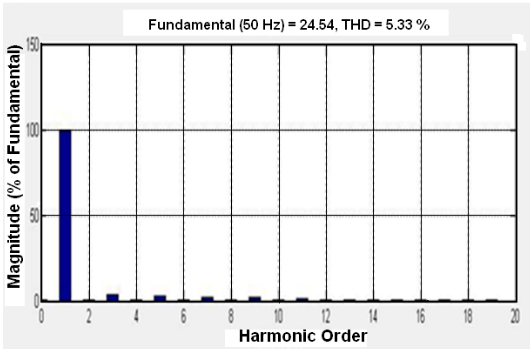

Fig. 24 FFT Analysis for source current Wave form using APFC with hysteresis band current control method

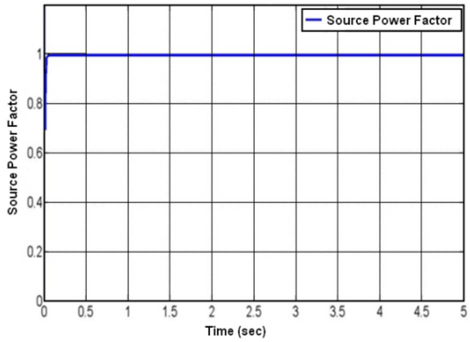

Fig. 25 Source power factor using APFC with hysteresis band current control method

4. Conclusion

In this paper, the boost converter is used for active power factor correction because it is the most used topology. Advanced optimization techniques are used to design the controller for the boost converter. These techniques include the particle swarm and the ant lion optimization methods. The designed controller is then used to study a system consists of source supplying single phase rectifier with DC motor as load. The system is studied and simulated using MATLAB/SIMULINK. The power factor of the source and total harmonic distortion (THD) for source current wave form for this circuit is studied without using APFC and using APFC with the two proper control methods. The power factor for the source without APFC is 0.3857, THD = 230 % and the power factor for the source using hysteresis band current control APFC method is 0.9957 with (PSO) and equals 0.9955 with (ALO) also THD equals 5.33%. The power factor for the source using average current control method APFC is 0.9947 with (PSO) and equals 0.9924 with (ALO) also THD equal 7.55 %, the motor operation is very normal with the two control methods for APFC also the wave form of the source current in hysteresis band method has less harmonic content than the wave form in average current control method.

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Appendix A: Matlab block diagrams

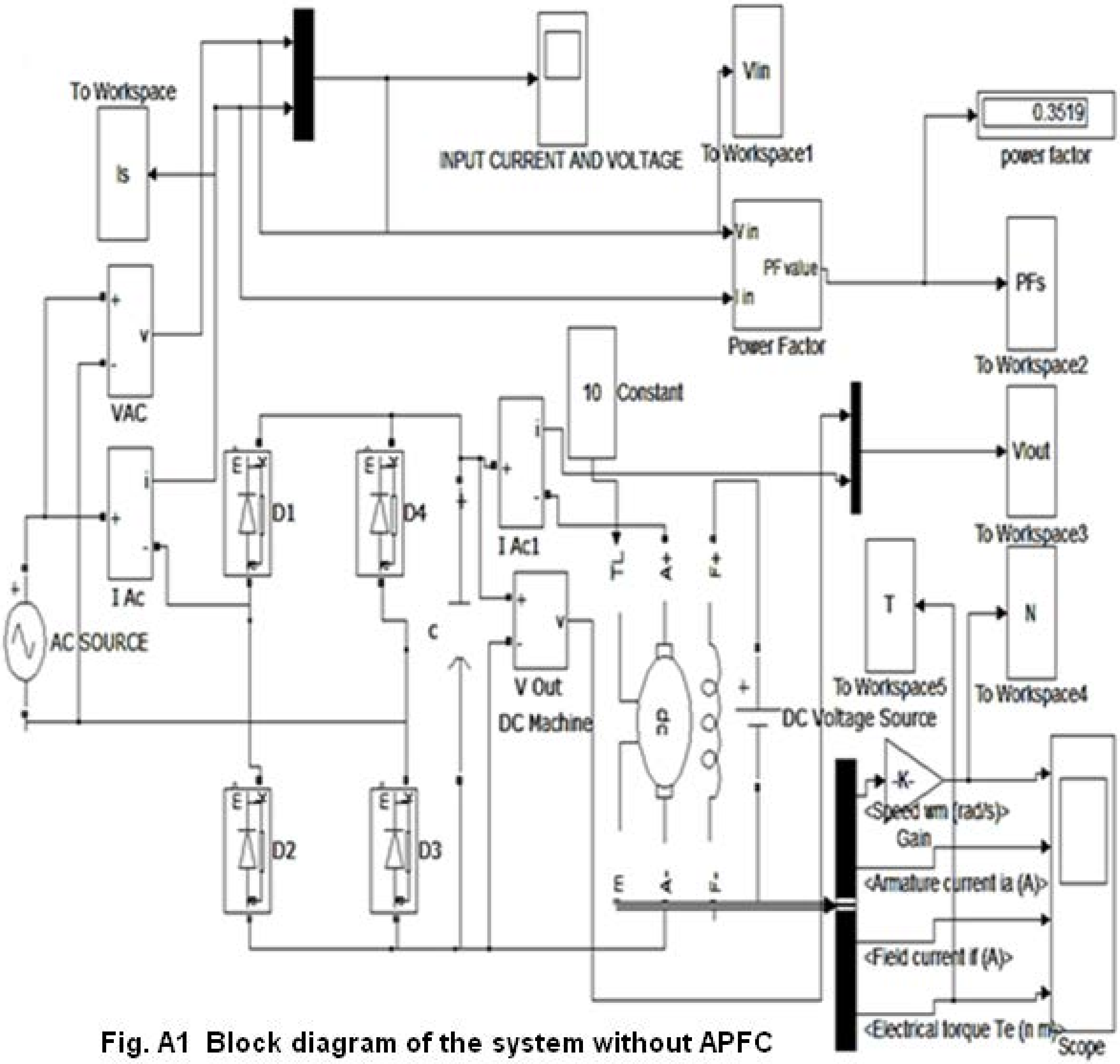

Fig. A1 Block diagram of the system without APFC

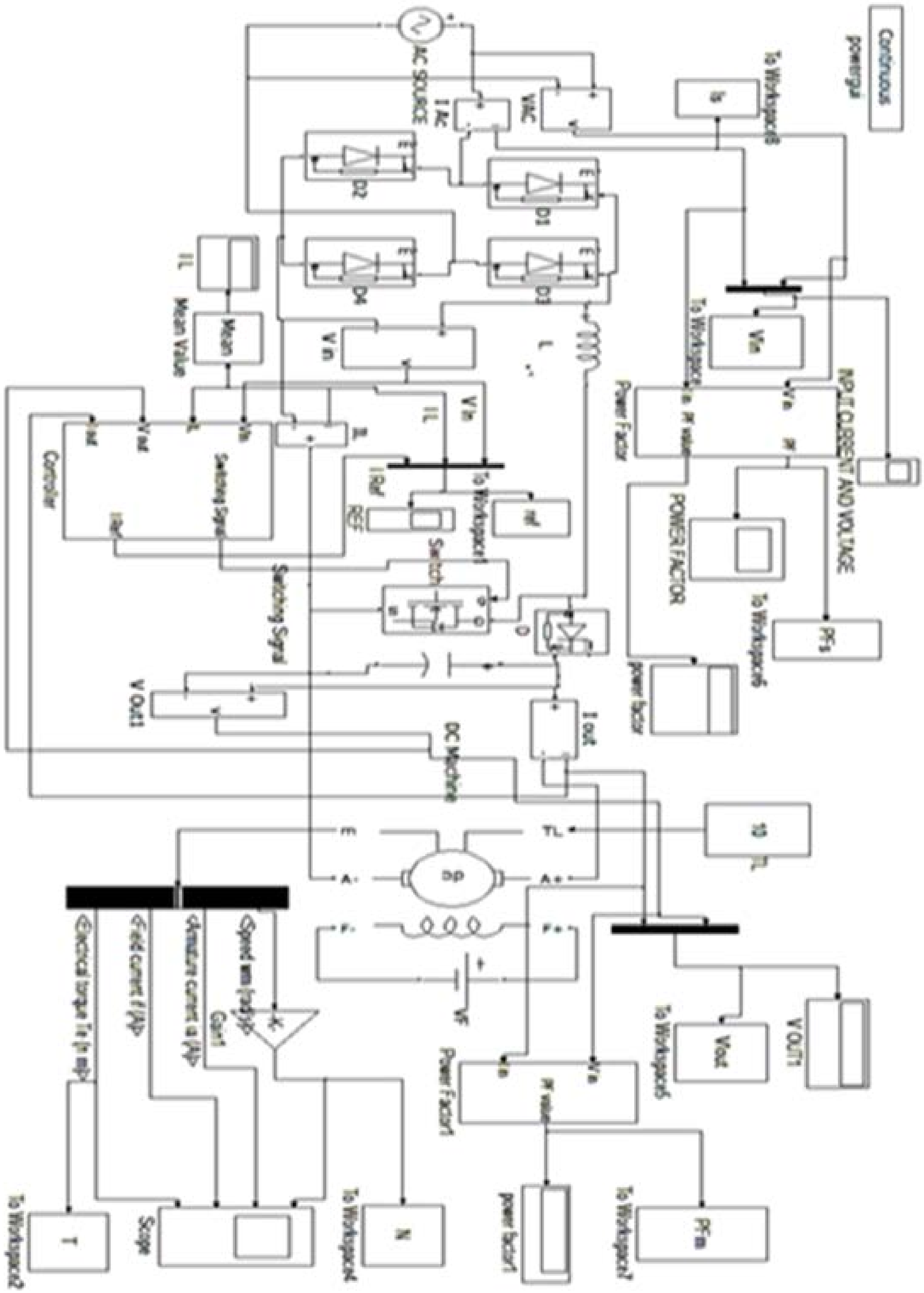

Fig. A2 Block diagram of the system with APFC

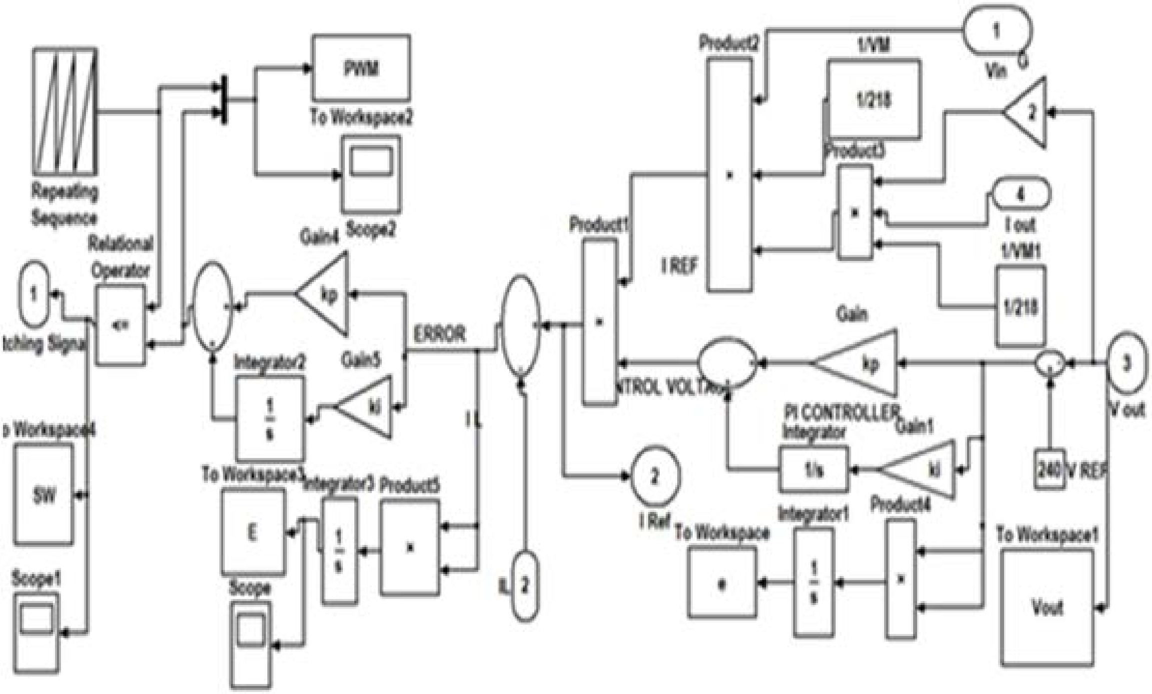

Fig. A3 APFC controller in case of average current control method

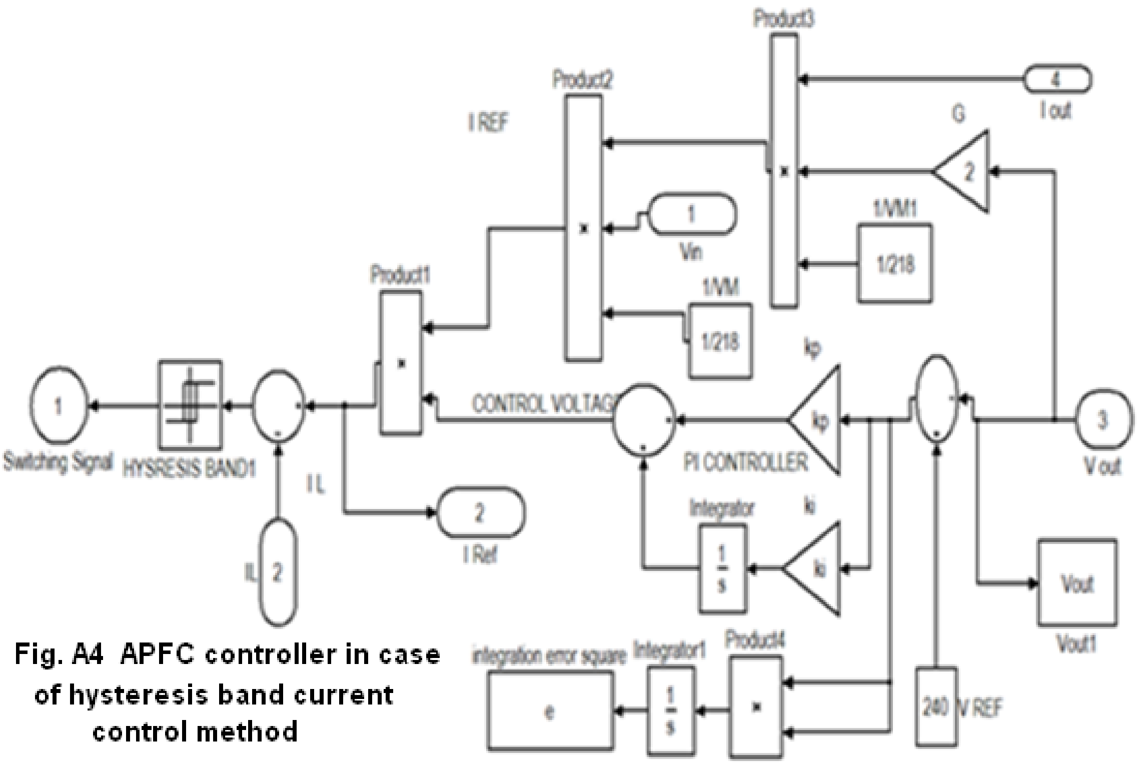

Fig. A4 APFC controller in case of hysteresis band current control method