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RESEARCH ARTICLE

Fractional fuzzy PI controller using particle swarm optimization to improve power factor by boost converter

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ABSTRACT

The power circuit of AC voltage controller capable of operating at a leading, lagging, and unity power factor is studied by a lot of researchers in the literature. Circuits working with high switching frequency are known as power factor correctors (PFCs). The single-phase boost converter has become the most popular topology for power factor correction (PFC) in general purpose power supplies. Power factor correction circuit provides conventional benefits to electric power systems. The benefits are the reduction of power factor penalty and utility bill and power loss. Therefore, a boost converter power factor correction scheme is presented in this paper. A PI, fuzzy logic PI and fractional order PI (FOPI) controllers are used to fix an active shaping of input current of the circuit and to improve the power factor. The controller parameters (coefficients) are optimized using the Particle Swarm Optimization (PSO) algorithm. Average current mode control (ACMC) method is used in the circuit. The converter circuit consists of a single-phase bridge rectifier, boost converter, transformer and load. A mathematical model of the plant is required to design the PI controller. A model for power factor correction circuit is formed in MATLAB/Simulink toolbox and a filter is designed to reduce THD value. The proposed model is simulated using a combination of PI, fuzzy logic and FOPI controllers. The control scheme is applied to 600 Watt PFC boost converter to get 400 Volt DC output voltage and 0.99 power factor. The input voltage is 230 V_{RMS} with 50 Hz. The combination of FOPI and PI controller has the best solution to control the power factor according to PI and fuzzy controllers.

1. Introduction

With the recent advancement in industrial equipments, power electronic components have gained popularity due to energy crises in the world and power converters for renewable energy (solar, wind) have become more important. AC-DC converters are played a vital role in power supplies such as different level power charging, mobile charging and battery charging unit.

The advantage of semiconductor switches has dramatically increased the DC-DC boost converter [1]. One of the major applications is power factor correction. Using of switched mode power supply (SMPS) has increased in some industrial applications such as robotics, air/space craft, see vehicles etc. [2].

If a non-linear load is connected to grid, there will be a voltage distortion in side of the grid. Power factor correction (PFC) is required to eliminate the distortions. Generally, a high power factor is required in power systems connected to grid to reduce the harmonics occurring by high switching frequency. If a nonlinear load such as rectifier or converter is tied to grid, the harmonics with different frequency happen in the current waveform. They are multiples of the input frequency. Therefore, the less average power is transferred to load. Limits of power factor and input current harmonics are determined according to international standard IEC 61003-2 and IEE/ANSI519, respectively [3].

PFC correction circuits are widely used in the input part of electronic circuits to decrease the rective power drawn from the grid [4]. The aim of this study is to reduce reactive power consumption and obtain better performance in the circuit by improvement of power factor. When line current with high power factor is

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drawn by SMPS, total harmonic distortion (THD) decreases in side of grid and a filter is designed to reduce the THD value on grid side. The performance of power factor correction is depended on the current and voltage controllers. There are different control modes such as average current mode control (ACMC), peak current mode control and inductor hysteric control. Various small signal modelling analysis and pulse width modulation (PWM) control techniques has been proposed in early 1970's. The most common method is the average technique [5]. The distinctive feature of ACMC is a good tracking of average current [2].

Many researchers have been directed to apply nonlinear circuit techniques to dynamic control of circuit. The average current mode control method is used to sense and control the peak voltage across inductor in power supplies. This method eliminates the noise, immunity, slope compensation and peak to average current errors [6]. Cascade control structure is presented for the converter with PSO-based FOPI controller as inner current and outer voltage controllers for PFC and load voltage regulation. The main contribution of this paper is to correct the PFC and output voltage using Fuzzy+FOPI controllers with together. The paper is concerted in the following manner: Section 1 describes the introduction, section 2 illustrates the average current control method, section 3 illustrates the boost converter model, fuzzy logic controller, classic PI controller, FOPI controller, selection of voltage controller, selection of current controller, measuring of power factor and THD values, section 4 describes the results and discussions, and section 5 prescribes the conclusion.

2. Average current control method

In DC-DC Converters, average current control method is very popular due to simplicity of implimentation and good performance. In this method, the value of current is sensed by a shunt resistor R_s [7]. The output voltage are subratracted from the reference voltages to gain the output voltage and this signal is used for the multiplication block. The inverse of square input value of voltage is taken and multiply by the with the input voltage to gain the reference curent. Afterwards, the current flowing from the inductor is measured using the R_s and it is subtrachted from the reference current. This signal is used to control the MOSFET to get the output voltage as well as to for the PFC [3].

3. Boost converter model

Boost converters are step-up converters. It is one of the simplest type of switch-mode converter. Its duty is to increase the voltage at the input of circuit at the output of circuit. An ideal circuit of boost converter is shown in Figure 1. It is utilized in regulation of DC power supplies and bidirectional DC power supplies. When the switch Q is on state (close), the diode is reverse biased. The output resistance is isolated from source and the energy is transferred from the source to the inductor L. In the steady-state analysis, the capacitor C is supposed too large to maintain a constant output voltage $v_o(t) \cong v_o$.

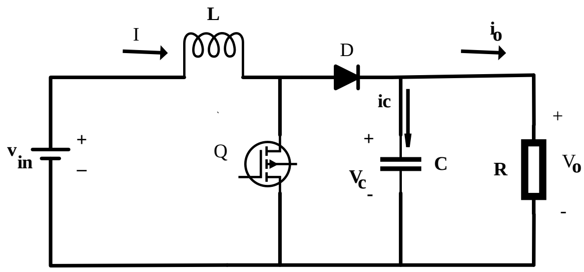


Figure 1. Ideal DC-DC boost converter circuit topology

There are two different operation modes of the circuit depending on the switch position u. When Kirchhoff's Law is applied to the circuit with switch off (u=0) and the derived equations for voltage and current are written as below.

$$L\frac{di_L}{dt} = v_{in} - v_o \tag{1}$$

$$i_C = C\frac{dv_o}{dt} = i_L - \frac{v_o}{R} \tag{2}$$

When the switch position is on (u=1), Eq. (3) and Eq. (4) for the circuit can be written as below

$$L\frac{di_L}{dt} = v_{in} \tag{3}$$

$$C\frac{dv_o}{dt} = -\frac{v_o}{RC} \tag{4}$$

Where V_{in} , I_L and V_o are the input voltage, inductor current and output voltage, respectively. The output voltage is equal to the capacitor voltage because the capacitor is connected parallel with load and are selected as state variables depending on *u* for a period, the state space equations for boost converter by combining the above equations are written as shown in Eq. (5) and Eq. (6).

$$\frac{di_L}{dt} = \frac{v_{in}}{L} - \frac{v_o}{L} + \frac{v_o}{L}u \tag{5}$$

$$\frac{dv_o}{dt} = \frac{i_L}{C} - \frac{i_L}{C}u - \frac{v_o}{RC} \tag{6}$$

3.1 Fuzzy logic controller

Fuzzy Logic Controller (FLC) has been used in many industrial applications such as AC and DC drives, PWM inverter and DC-DC converters in past years. Many research articles has been written by using FLC but they did not defined any exact model for converters [4,5]. FLC is an application of fuzzy set theory [8]. This theory is about uncertainty. It enables one to use non precise, ill-defined concepts [9]. FLC has an advanced level of efficiency for nonlinear converters [10]. Many researchers approved FLC to become one of intelligent controller for their appliances and successfully implemented their tactics [11-14]. FLC does not require an accurate mathematical model of a circuit. Therefore, it is valid to a process where the circuit model is unknown or ill-defined. Fuzzy control is adaptive in nature and nonlinear. It gives smooth performance under variations of parameters and load disturbances [9]. FLC is completely based on linguistic control variables. FLC is like human thinking, so it lowers the gap between mathematical calculation of plant and human certainty. FLC algorithm consists of three steps. The first step is fuzzification, second step is inference and third is defuzzification [15]. The schematic diagram of FLC is shown in Figure 2. Fuzzy controller has two inputs. Comparing the reference value with output value at each interval, error (v) and change in error (Δv) are calculated. Here the reference voltage is r(k) and output voltage is y(K). Error voltage e (k) is calculated as shown in Eq. (8).

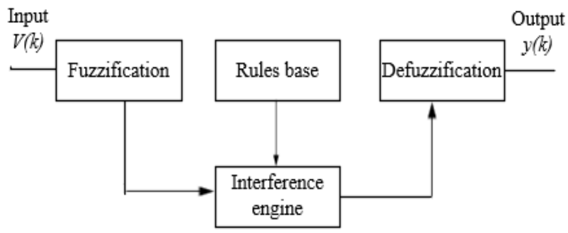
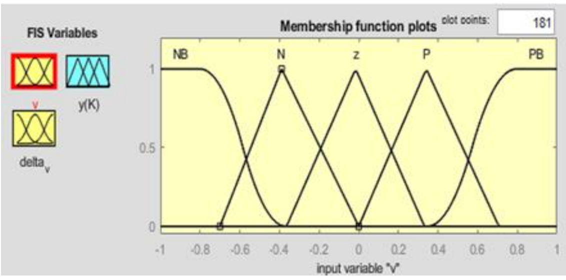
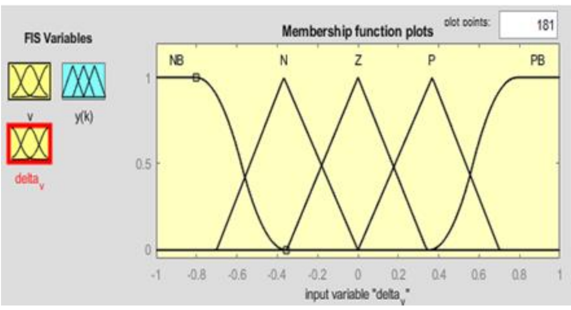


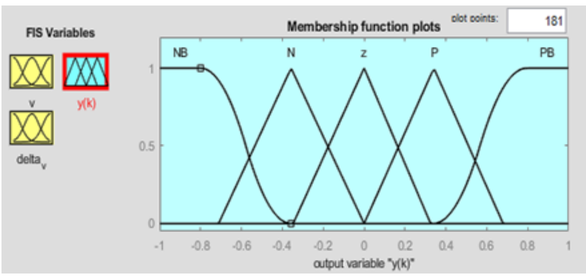
Figure 2. Block diagram of Fuzzy Logic Controller



(a)



(b)



(c)

Figure 3. Designed membership functions (a) error MFs (b) change in error MFs (c) Defuzzification MFs

$$v(k) = r(k) - y(k) \tag{7}$$

$$\Delta v(k) = e(k) - e(k-1) \tag{8}$$

These are extended at the input of the controller for fuzzification. Fuzzy sets utilize linguistic terms and membership functions (MF's). The selected memberships are presented in Figure 3. MF's depend upon the impact of the linguist term regarding the output value.

The fuzzy rule editor is shown in Figure 4, in which rules are selected according to user visualizing. The membership functions are selected by taking account the system limits. The overall fuzzy logic designer representation is shown in Figure 5. Fuzzy rules contain 5 error voltage as well as change in error of voltage. The selected fuzzy rules are given in Table 1.

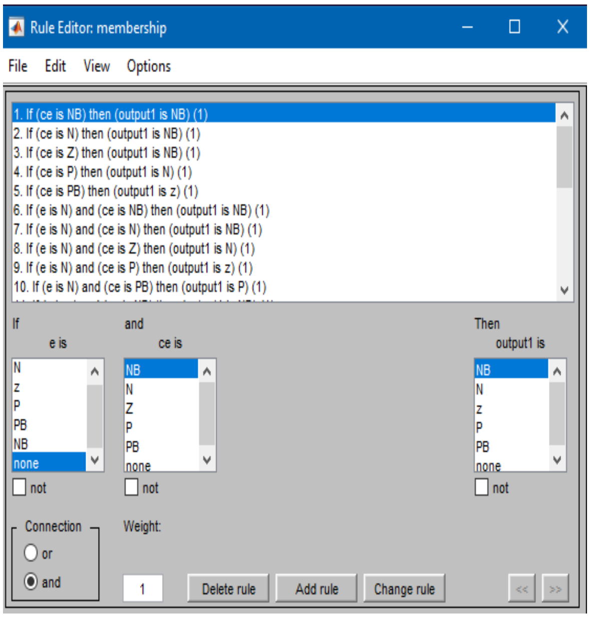


Figure 4. Fuzzy rules editor

Table 1. Fuzzy rules

v /*Δv*	NB	N	Z	P	PB
NB	NB	NB	NB	N	Z
N	NB	NB	N	Z	P
Z	NB	N	Z	P	PB
P	Z	Z	P	PB	PB
PB	N	P	PB	PB	PB

3.2 Classical PI controller

Classical PI controller is the simplest controller [16] which is frequently used in most of the circuits to control the output voltage and to meet the user's demand. These types of controllers are used mostly in situations where there are no load changes. The accuracy of classical PI controller can be disturbed when the load is varied frequently. Performance of classical PI controllers used in the inner loop and outer loop is also discussed in this section. The transfer function of classical PI controller is written as below.

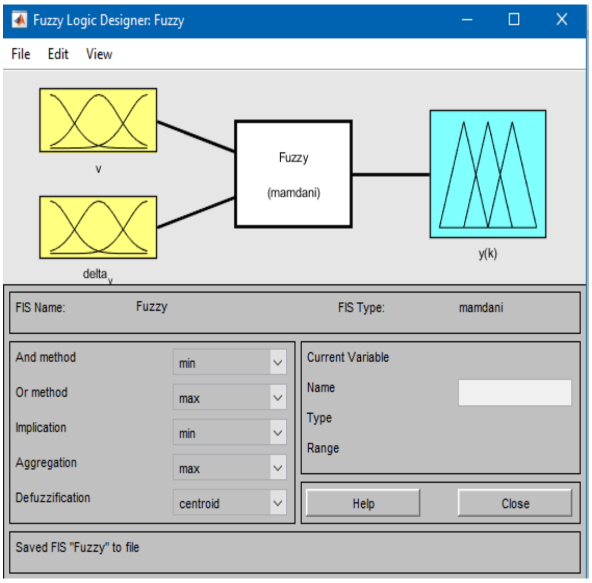


Figure 5. Overall fuzzy logic designer representation

$$G(s) = k_p + \frac{k_I}{s} \tag{9}$$

Where K_P and K_I are gain coefficients of proportional and integral controller [17].

3.3 Fractional order PI$^{\lambda}$ controller

A generalization form of fractional calculus is classical integer order calculus, which consists of integral differential operators of fractional orders. Different approaches are executed to find optimum values of the three parameters of FOPD controller. One of the tuning rules of FOPID controller is Ziegler–Nichols method [18]. The mathematical expression of fractional derivatives defined by Grünwald-Letnikov is [19,20]:

$${}_cD_t^{\alpha} f(t) = \lim_{h\to 0} \frac{\sum_{k=1}^{\left[\frac{t-c}{h}\right]} (-1)^k \binom{\alpha}{k} f(t-kh)}{h^{\alpha}} \tag{10}$$

This technique is used to calculate the transfer function of FOPI. It is described as below [21-26]:

$$G_c(S) = k_p + k_I s^{-\lambda} \tag{11}$$

Here K_p is representing the proportional constant, K_I is representing the integral constant and λ is representing fractional integral constant.

3.4 Selection of voltage controller

The simulation of FLC circuit diagram on boost PFC using the average current control method is presented in Figure 6. In this paper, FLC is based on Mamdani fuzzy system which contains two inputs and one output. The circuit includes inner loop controller and outer loop controller. Inner controller is also known as current controller which controls the input current. Outer loop controller also called voltage controller controls the output voltage. Output voltage is compared with reference voltage. Here error (e) and change in error (Δe) are calculated at every interval, after it takes the derivative of change in error value. The voltage controller generates a signal which is transferred to the multiplier block. It multiplies the rectified voltage of circuit with the square of peak voltage of source v_{in}^2 [3]. Then signal goes towards the current controller after subtracting from reference current. After that PWM generator block leads this signal to the gate of switch IGBT or MOSFET. A shunt resistance (Rs) is used in simulations to sense the inductor current in the circuit.

In this paper, different controllers are used to determine the best performance of the circuit. Classical PI, Fuzzy and FOPI controllers are utilised to control the voltage and current in this study. To find the best controller for outer loop, different controllers are used at the outer loop while PI controller is only used in the inner loop.

3.5 Selection of current controller

The selection of inner loop controller is done by taking account the best performance of outer loop. It is performed by keeping the FOPI as the outer loop controller while the inner loop controller is changed. The boost converter PFC circuit diagram is shown in Figure 7. In this paper, FOPI controller is found as the best controller for the inner loop.

3.6 Measuring of power factor and THD values

Power factor is measured at the input side of circuit. To perform the Fourier analysis, Fourier block is used in the designed circuits with the help of MATLAB-Simulink, as shown in Figure 6 and Figure 7. Voltage distortion occurs when the current drawn by the load does not do remain sinusoidal form. Harmonics play a critical role for life of electrical and electronics systems. THD is the most common measured parameters of voltage and current of grid. THD is described as the root mean square (RMS) value of harmonics divided by the RMS value of fundamental and multiply by 100.

$$THD_I\,\% = \frac{\sqrt{I_{rms(2)} + \cdots + I_{rms(n)}}}{I_{rms(1)}} \times 100 \tag{12}$$

Where $I_{rms(n)}$ is the RMS value of the nth harmonic current and $I_{rms(1)}$ is the RMS value of the fundamental component. If the THD value of current is below 5%, it is considered within acceptable limits according to international standards. If it is more than 10%, it causes problem for the equipment's and loads [27]. According to standards, the power factor should be between 0.90-0.99 or near to unity. So, both designed controllers show that the power factor is almost near to unity as shown in Figure 8. The designed filter capacitance value is 31.8 mF and resistance value is 1.5 Ω. The THD value of circuit is decreased to 4.72% as shown in Figure 10 when passive filter is used in the input side of rectifier.

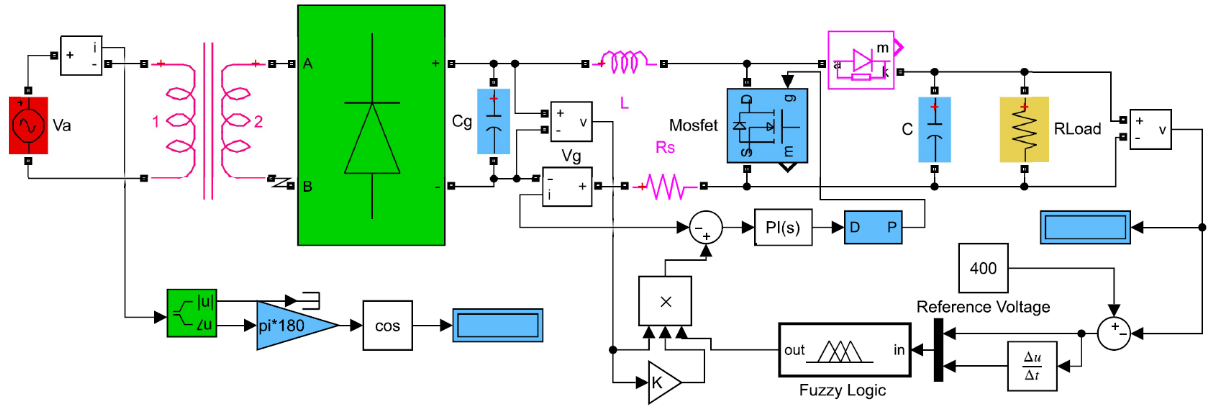


Figure 6. Simulation diagram for the selection of outer loop controller using FLC

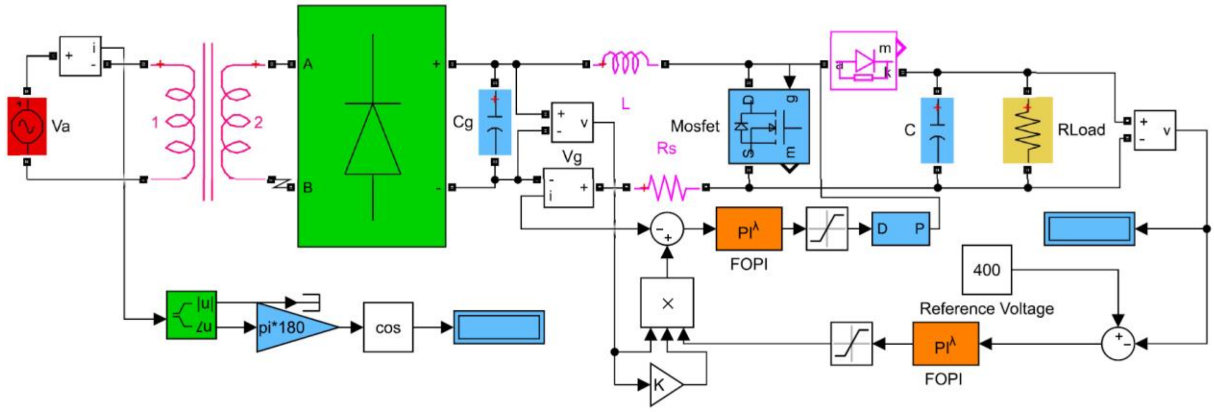


Figure 7. Simulation diagram for selection of inner loop controller

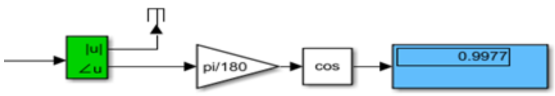


Figure 8. Power factor measuring

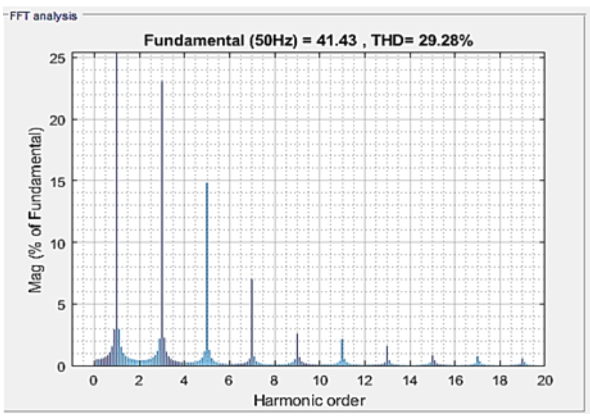


Figure 9. THD value of designed controller without filter

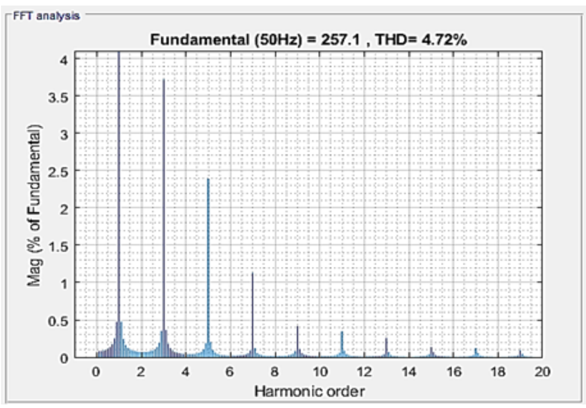


Figure 10. THD value of designed controller with filter

When the passive filter is not utilized in the input side of circuit, THD value is 29.28%. The current contains harmonics, and its waveform is distorted as shown in Figure 11.

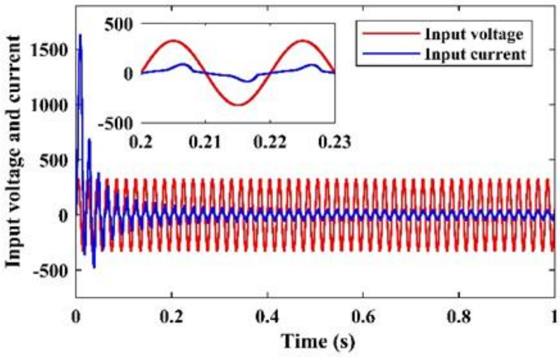


Figure 11. Input voltage and current without filter

As shown in Figure 10, THD value decreases from 29.28% to 4.72% when the passive filter is used in the output side of grid. The current drawn by the load contains lower harmonics and its waveform is closer to the sinusoidal waveform with distortion as given in Figure 10 when the passive filter is settled in the input side of circuit.

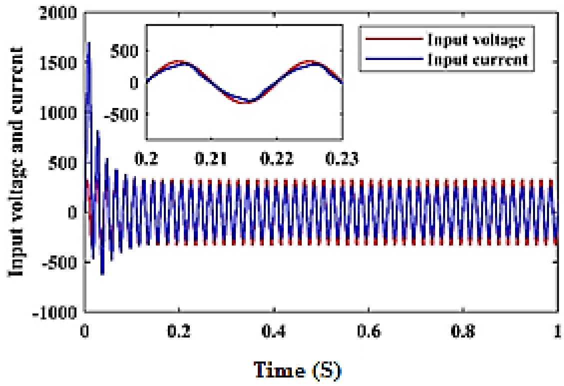


Figure 12. Input voltage and current with filter

4. Results and discussions

In this paper, the power factor correction is performed using the boost converter. The power factor is measured for each step by selecting the inner loop and outer loop controller. The simulations are done by using the DELL core I3 laptop. Nominal load is used as 266 Ω and a disturbance load is added to the circuit as 100 Ω. It can be seen in Figure 10 that the input current is not sinusoidal and have a THD like 29.28%. When the passive filter R-C is added to the circuit, the current waveform came into sinusoidal waveform and THD value becomes 4.72%. When the passive filter is added into a circuit, the harmonics come in a range of intentional standards. The output voltages for the selection of outer loop and inner loop controllers are shown in Figure 13 and Figure 14, respectively. It is seen from Figure 13, when FOPI controller is utilized in the outer loop while keeping PI controller in the inner loop, the system has a good response compared to reference voltage. When disturbance or variable load is added to the circuit for an interval of time, it does not maintain its accuracy and performance. As shown in Figure 13, FOPI controller is faster response than the other controllers. It also maintains its accuracy and performance according to the others.

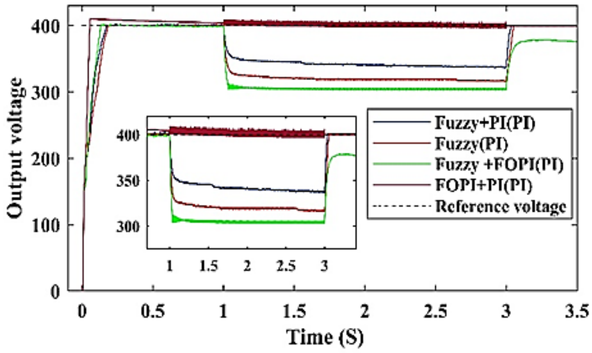


Figure 13. Output voltage for the selection of voltage controller

To select the inner loop controller (current controller), the best performance of voltage controller is obtained by FOPI controller. Therefore, FOPI controller for the outer loop is not changed when different controllers such as Fuzzy, PI, Fuzzy+PI structure are used in the inner loop to determine the best controller for the system. The output results of these controllers are shown in Figure 14. It can be seen that Fuzzy, PI and Fuzzy+PI achieve a good response at settling time. When the variable load is added into the system, FOPI controller is faster than the others in view of performance of current controller. The performance of current controllers is almost same when load change occurs in the system.

In the circuit, power factor correction and output voltage control are implemented at the same time. THD value is very high according to the international standard as the power factor value approaches to unity. To decrease THD value, passive filter R-C is used in the input side of circuit. Thus, unity power factor is adjusted 0,99 and THD value has been brought to international standard.

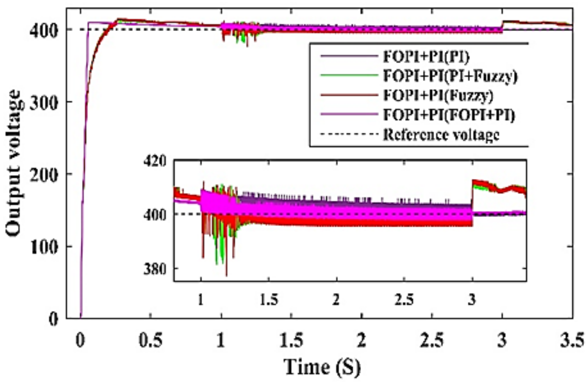


Figure 14. Output voltage for the selection of current controller

The selected parameters of designed circuit are shown in Table 2 and the optimized parameter using the PSO are shown in Table 3. For the optimization Integral Time Absolute Error (ITAE) function is used for optimization of controller parameters [21].

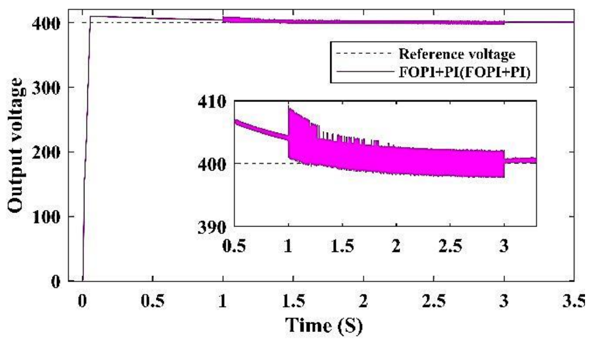


Figure 15. Output voltage for the FOPI+PI controller

The THD value of the designed circuit with filter is shown in Figure 16. It is clearly shown in the Figure 9 that without the filter, THD value was 29.28% while using the filter THD value is decreased to 4.27% as shown in Figure 16. This is acceptable according to IEE/ANSI519.

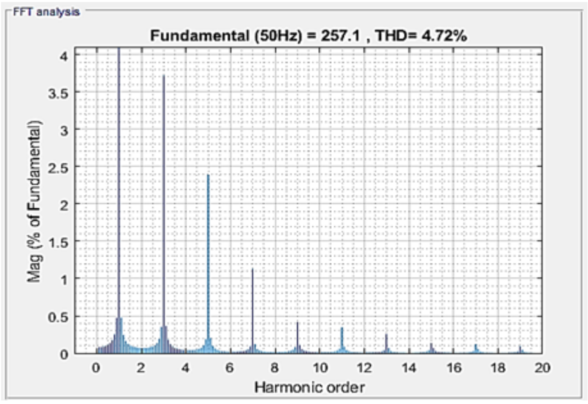


Figure 16. THD value of designed controller with filter

The designed parameters of discussed boost converter are calculated according to using Eqs. (13)-(16).
The value of the inductor is calculated using the Eq. (13).

$$L = \frac{D(1-D)^2 \times R}{2 \times f} \tag{13}$$

In practical application, the inductor value is selected 25% greater than this calculated for better performance. Here the R is the resistance/output load, f is the switching frequency, L is the inductor value calculated by Eq.(13) and the D is the duty cycle. The D is calculated according to Eq.(14)

$$D = 1 - \frac{v_{in}}{v_o} \tag{14}$$

Here the v_{in} is the input voltage and v_o is representing the output voltage. The value of output capacitor is calculated using the Eq.(15).

$$C_{out} \geq \frac{D}{R\left(\frac{\Delta v_o}{v_o}\right) \times f} \tag{15}$$

Here D is the duty cycle, f is the frequency and $\left(\frac{\Delta v_o}{v_o}\right)$ is representing the ripple factor of the output voltage which is taking 1% of the output voltage. The capacitor C_g value is selected maximum to remove the ripple of the input voltage.

$$C_g = \frac{I_{rms} \times I_{ripple}}{v_{rms} \times v_{ripple} \times 2\pi f} \tag{16}$$

Here the I_{rms}, V_{rms} is the RMS value of current and voltage representing respectively. I_{ripple} and V_{ripple} representing the ripple current and ripple voltage and their values are taken 5% and 1% respectively [17].

Table 2. The parameter values of designed circuit

Parameters	values
L	4.34 mH
C_{out}	600 µF
R_{Load}	266 Ω
V_{in}	230 V_{RMS}
Supply frequency	50 Hz
R_s	0.02 Ω
Cg	100 mF
V_{ref}	400 V
Switching frequency	1000 HZ

Table 3. Optimized parameter values of the designed controllers

Parameters	Values
FOPI	K_P=1.5981 K_I=1.5981 λ=1
Classic PI controller	K_P=4.1437 K_I=0.1

5. Conclusions

In this paper, fuzzy, PI and FOPI controllers and different variations of these controllers are applied to in the inner and outer loops to increase the power factor value and regulate the output voltage. The best performance of voltage and current controllers are assessed for the PFC using boost converter. When the FOPI contoller in the inner loop and PI controller in outer loop are used, the obtained results have faster and more smoothly responses. The results are compared with PI and fuzzy PI (FPI) controller. They show the FOFPI has less fluctuations, overshoot and settling time compared to FPI. The presented system can be used to provide electrical power to electronic devices in critical applications such as military, space craft, and sea vehicles.

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