Co-Simulation of IBC Type PFC Converter with Fuzzy Logic Controller

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Abstract:** Many electronic power systems use bridge rectifiers, which are nonlinear, resulting in low power factor activity and high harmonic distortion due to the existence of nonlinear devices. To conform to harmonic standard requirements, longer device lifetime, and smooth operation of other devices in the system, power factor correction is required in these devices. The proposed system with an input power supply linked to a bridge rectifier which transforms ac to dc in this analysis, which is then linked to an Interleaved Boost Converter (IBC) with two parallel boost converters. The Interleaved Boost Converter uses Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) to work with the switches. The proportional controller gain has the effect of minimizing the time of increase and does not remove the error of steady-state. The result of removing the steady-state error is an integral control gain but deteriorate the transient response. The fuzzy controller takes inputs from the actual signals feedback values. Using the membership functions in the fuzzification method, the data provided to the fuzzy system is transformed into linguistic variables. To evaluate the performance, a series of rules that mimic the decision-making process of the human expert running the machine is then implemented using such inference mechanisms. Finally, a defuzzification block that transforms the output to a crisp value in such a manner that both structures are consistent. The proposed method is implemented using the software of MATLAB/Simulink and PSIM. The co-simulation result shows that the power factor achieved here is 0.9988, the Total Harmonic Distortion (THD) maintained is less than 5% and the average efficiency concluded here is 98% respectively. To verify the feasibility of the proposed scheme, a prototype model of a 5kW IBC type PFC converter is developed which is converting 230V AC input voltage to 400V DC output voltage, is implemented using a Microchip IC dsPIC33FJ16GS504. The experimental results are satisfactory, which uncover that a power factor is 0.9992 (close to unity), THD is 4.11; less than 5% and 98% overall efficiency at 100 kHz switching frequency, 230Vrms input voltage. With the higher performance, as a result, topology with high switching frequency makes a more compact, but costlier converter.

***Keywords:** Total Harmonic Distortion, Interleaved Boost Converter, Bridge Rectifier, PI Controller, Fuzzy Logic Controller, Co-Simulation, Power Factor Correction.*

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1. Introduction

While designing power supplies, power efficiency has become an important factor. As a consequence, the development of power supplies with strong power factor correction (PFC) and reduced input harmonics has gained further focus. For high dynamics systems and higher power, PFC regulators are usually mandatory for the use of maximum line power and the reduction of line current harmonics. In ac/dc power conversions, PFCs were mainly used to balance the higher dc-link voltage and regulate a near unity power factor (PF), thus the power supply's line input current to be aligned with the mainline voltage is created by the PFC converter [2-3], in-order-to conforms with harmonic requirements, longer device lifetime, and smooth operation of other devices in the system, power factor correction is required in these devices. Additional benefits of the PFC include improved branch capability of the electrical grid, decreased power losses in the delivery system, decrease in the voltage drop that doesn't allow motors and other inductive machinery to overheat and premature failure. As compared to conventional boost converter, the interleaved boost converter is used for power factor correction, the sharing of the load makes it sure that there is a reduction of inductor size [4].

The main purpose of the PFC is to shape the line current sinusoidal and in phase with line voltage, simultaneously maintain the DC output voltage constant. In this device, there is a control circuit that is used to calculate the input current and to equate it with the waveform of the input voltage and change the duty cycle of the boost converter to get the same shape of the input current waveform. The limitation of the boost converter is that it needs higher inductor volumes. It also has a drawback that at high power it is not recommended because the switch is subjected to higher levels of current. Interleaved boost converters are suggested to address the drawback of boost converters [5]. To control the output voltage and allow load sharing, they run under closed-loop feedback control.

Because of their simplicity (just one switch and a diode), voltage step-up function, reliability and output, Boost power factor pre-regulators are being commonly used. It is also important to associate converters in series or parallel as the power rating rises. It was partly due to the absence of a single unit that can tolerate high power applications' voltage and/or current stresses. Likewise, interleaved boost converters are preferable for high-stream applications since the currents by the switches are just a fraction of the input current [7-8]. Parallel converters with interleaving technology will, however, minimize the output capacitor ripple current and decrease the inductor size in these high-power applications. This is feasible with the interleaving inductor ripple current cancellation. Furthermore, as opposed to traditional parallel and exchanging methods, the interleaved boost will even lower the input current ripple for the same switching frequency. This converter is a fundamentally non-linear device. The well-established chopper converter control system still relies on average small-signal models that allow the implementation of linear controller theories, such as PI (proportional-integral) controller [9].

Many researchers have addressed this issue. The high-performance PI controller for manipulating cascaded boost power converters that simulate the process with a computer program. The result of the PI controller helps the circuit referred to be efficiently regulated [10]. The three-stage flying condenser boost converter based on an average-controller computer system is added to the control of the active condenser voltage balancing mechanism [11]. The appeal was made for the FPGA test board. The experiment results show that the reaction to a stable mode occurred rapidly and can hold the status properly. Application with the PI controller for DC-DC boost converters leveraging artificial intelligence. In current methods, the effects of the use of PI controllers with artificial intelligence search value will control the circuit satisfactorily [12]. A recent administrative rule based on a multi-phased interleaved DC-DC converter with differential flatness theory. In another system that has been developed, the control uses a PI controller for the closed-loop operation in the current loop for transmitting fuel cell energy [13].

To minimize total harmonic distortion, PI and fuzzy controllers are used. PI controller is based on a defined device mathematical model. However, there are cases of the limited success of this technique. The controller parameters based on linear methods include a linear, operating point-dependent approximation. Since the boost converter model is nonlinear, nonlinear control methods that compensate for the nonlinearity of the system can be employed explicitly without needing a linear approximation [14].

The above-mentioned controller is also not reliable under complex situations. Thus an intelligent control strategy is added, to address the drawback of a PI controller, a fuzzy logic controller is the best solution that gives smoother and faster control. To eliminate the errors, the Fuzzy system operates on the linguistic variables and chooses intelligently. It has superior functionality for reducing harmonics than the PI controller. The fuzzy system, therefore, provides increased efficiency to minimize total harmonic distortion (THD). This study, therefore, introduces controlling interleaved topology by using the PI controller and Fuzzy Logic controller for interleaved boost converter [15]. The rest of the paper is organized as follows, section 1 explains the introduction of the research, section 2 briefly explains the literature survey and proposed methods of this research, section 3 explains the simulation and experimental result of the proposed research method and the final section 4 detailed about the results and section 5 describes conclusion part of this research.

II. Proposed Research Methodology

This study is aimed at investigating the proposed ac to dc conversion system with improved power factor by the use of interleaved boost converter. The power factor is a helpful figure that shows how power taken from a source is effectively utilized. It ranges from zero to one. It is recommended to use an interleaved DC-DC boost converter with a non-isolated topology that is used for stepping up the voltage. It also converts unregulated DC voltage to higher magnitude regulated DC voltage. Therefore, the proposed topology has the benefit of increased stability, better transient response, lower switching stress, lower input current ripple, and considerably less electromagnetic emission than the traditional DC to DC boost converter.

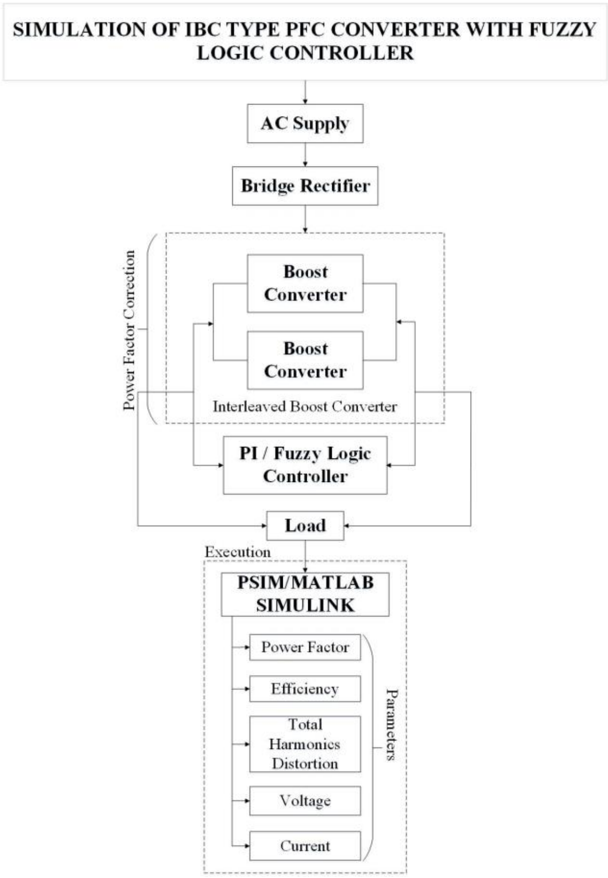


Fig. 1. Architecture of the Proposed Method

The main advantage of the interleaved boost converter is its much higher efficiency. Hence, for the power factor correction, the interleaved boost converter is used. It is fed with the PI controllers and Fuzzy logic controller to overcome the problem of Total Harmonic Distortion (THD). The PI controller is used to reduce rise time and helps to eliminate the steady-state error. In addition, the closed-loop fuzzy control provides smoother and faster control. Fuzzy is a method that is based on the rules. The process of fuzzy has two input variables, the error voltage obtained by comparing the reference voltage and output voltage and error shift. It helps to reduce the Total Harmonic Distortion (THD). In the proposed method of interleaved boost converter, the PI controller, and the fuzzy logic controller are employed and are briefly explained in the following sections.

A. Interleaved Boost Converter

Figure (2(a) and 2(b)) displays the planned power supply system connected to a bridge rectifier converting ac to dc and connected with two parallel boost systems to the interleaved boost converter. The inductor L_1, with a diode D_1, switching (MOSFET) S_1, forms a parallel boost circuit with an inductor L_2, a diode D_2 and, a switching (MOSFET) S_2 forms another boost converter. The capacitor C is used to keep the output voltage ripple in the limit, and RL is the system-connected load resistor. Interleaved Boost converters can be obtained easily by running two 180° out of phase boost converters.

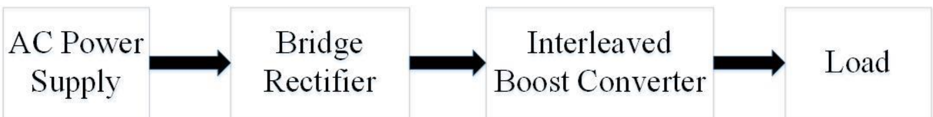


Fig. 2(a). Block Diagram of Interleaved Boost Converter

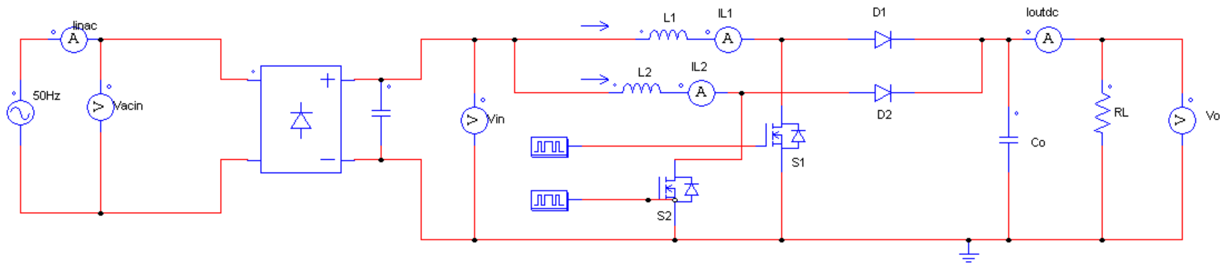


Fig. 2(b). Circuit Diagram of Interleaved Boost Converter

The DC-DC boost conversion mechanism is operated within the interleaved boost converter, defined by equations (1) and (2); the converter operation can be written; for the ON and OFF switching conditions. When the switch S_1 is on, the inductor L_1 goes up with the current I_L rises. The current I_L declines and flows through the inductor L_1, diode D_1, C and R while the switches were turned off.

When switch is ON

$$\frac{di_L}{dt} = \frac{1}{L_1}(V_{in}) \tag{1}$$

And when switch is OFF

$$\frac{di_L}{dt} = \frac{1}{L_1}(V_o - V_{in}) \tag{2}$$

Therefore, the boost converter draws a continuous input current and guarantees a continuous conduction mode of operation.

The following assumptions are made for simplifying circuit analysis: Input voltage is pure sinusoidal, ideal lossless components, switching frequency (f_S) is considerably greater than the frequency of the ac line (f_L), with output capacitor C sufficiently high to allow for a reliable voltage output over the entire line cycle.

1. Circuit Operation of Interleaved Boost Converter

The modes of operation of the proposed interleaved boost converter system are as follows. The switches are run at a duty cycle of 50%. On this system, there are two operating modes. These two operating modes are the same. Service of the interleaved boost converter at a duty cycle of 50% enables a continuous flow of current via the output capacitor C, minimizing the ripple voltage output, also reduces the input ripple currents thus reducing the inductor size with current sharing action.

Case (i) - ($t_0 < t < t_1$)

This stage begins when the switch S_1 is switched on and S_2 is switched off. The input current is flowing through the inductor L_1. A diode D_1 is reverse biased by the voltage across C_0, while D_2 is forward biased providing a parallel conducting path through inductor L_2 -(C // R). During this step, the current through L_1 is linearly increased with the input voltage, while the L_2 is discharged and the C_0 capacitor is charged in the process if any discharge over the resistor has been achieved earlier. The output voltage V_o stays stable through the capacitor.

Case (ii) - ($t_1 < t < t_2$)

This is initiated by turning the S_1 switch off and turning the S_2 switch on. A diode D_1 has a forward bias and the inductor L_1 discharges the inductor current i_{L1} by parallel direction (C//R) during this time. In this interval, Diode D_2 remains to be reverse biased. During this time, the L_2 inductor will be charged linearly and C_0 will be charged, likewise, the output voltage V_o maintained stable.

2. Design of Interleaved Boost Converter

The Interleaved Boost Converter is designed based on the following parameters switching frequency (f_s), output power (P_{out}), input voltage (V_{in}), output voltage (V_o), and the duty ratio (D). The duty ratio D is given by equation (3) as,

$$D = \frac{V_o - V_{in}}{V_o} \tag{3}$$

Load resistance is given by equation (4) as,

$$R = \frac{V_o^{\,2}}{P_o} \tag{4}$$

$$P_{in} = P_o \quad \text{, when PF is 1} \tag{5}$$

Inductor value is given by equation (6) as,

$$L = \frac{R \times D \times (1 - D^2)}{2F} \tag{6}$$

Where R = load resistance.

The value of the capacitor is given by,

$$C = \frac{V_o \times D}{F \times \Delta V \times R} \quad (7)$$

Where ΔV is ripple content in the output voltage?

This research elaborates interleaved boost converter fed power factor correction system controlled by PI and Fuzzy Logic Controller.

B. PI Controller

In industrial control systems, the PI controller is the most commonly used controller for reducing steady-state errors in the output. The value for error between a calculating process parameter and the target fixed point is determined in a PI control. To generate a control signal sufficient to minimize the error signal to about zero, the PI controller takes into account the desired output of the converter. A proportional control gains (K_p) reduces rise time and but does not eradicate the steady-state errors. An integral control gains (K_i) eliminates the steady status error but aggravates the transient response. To reach the maximum of output values, the error voltage calculated from the relation of the reference output voltage with that of real output is fed into the PI voltage controller. However, it harms the transient response and the system's overall stability. This controller is used where the system's speed is not a concern. Although the PI controller cannot anticipate possible device failures, the increased time cannot be minimized and oscillations can be removed. The transfer function of the boost converter by MATLAB auto-tuning obtains relative proportional gain and integral gain values.

$$V_o = K_p \cdot e + K_i \int e \cdot dt \quad (8)$$

Whereas, K_i = integral constant, K_p = proportional constant, V_o = controller output signal, e = error or deviation of actual output voltage AV from the desired reference voltage RV value.

$$e = RV - AV \quad (9)$$

C. Fuzzy Logic Controller

This system uses closed-loop control with fuzzy logic to provide smoother and faster control. Fuzzy logic is a method for the manipulation of unreliable results, which is much easier than the other methods of control such as linear algebraic equations, etc. Fuzzy is a method that is based on the rules. The process of fuzzy is to add, two inputs to the fuzzy logic controller; the error voltage obtained by comparing the reference voltage and output voltage and error shift. Input values of the actual signals are obtained by the fuzzy controller. Via the membership functions of the fuzzification procedure, the data provided to the fuzzy scheme is translated into linguistic variables. A collection of rules emulating the system's human-management specialist decision-making method is then used to evaluate performance using certain inference mechanisms. A knowledge base with required descriptions of all language variables and the control rule set is available. Input is generated by the fuzzification block by the fuzzy inference method and provides a weighted rendering according to the control rules, i.e. if-then statements given by the knowledge base. The set of rules is called the basis of rules, and if-then are the rules in the familiar style, and the if-side is formally called the state, then the consequence is the one. The result is now given to a defuzzification block that transforms output words to a crisp value such that both structures are consistent.

Fuzzy inference is the method using fuzzy logic of formulating maps from a certain input into the result. The mapping then offers a space for decision-making. The fuzzy inference method contains membership elements, fuzzy logic operators and rules if so. Fuzzification which transforms controller inputs into data easily used to enable and apply the rules by the inference mechanism. The mechanism for the inference of experienced decision-makers in terms of the understanding and the application of experience about how to better track the system (what is often called "inferior engine" or "fuzzy inference" module. The defuzzification transforms the results of the process into a real crispy outcome. Figure (3) shows the general structure of a PFC converter system regulated by a fuzzy logic controller.

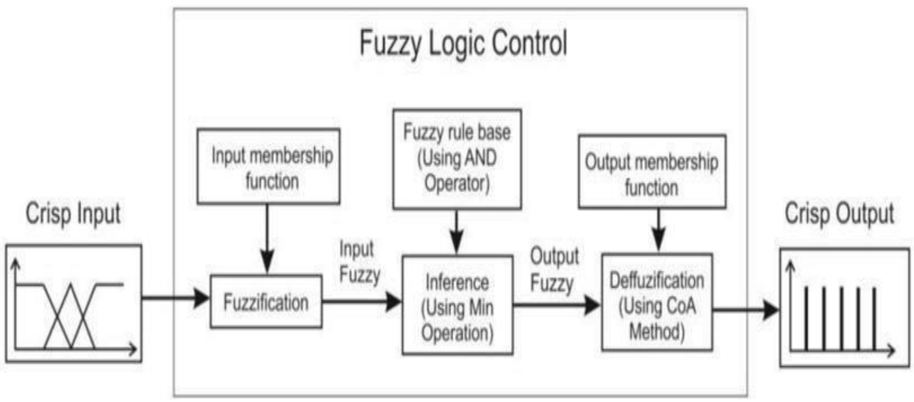


Fig. 3. General Structure of a Fuzzy Logic Controller

The error signals are produced when the actual voltage sensed by the potential divider and the reference voltage of the converter varies, the fuzzy rules are formed which result in PWM signals for the switching of MOSFETs, and the wide-range output voltage of the Fuzzy controller can be controlled by this Fuzzy logic controlled device with adaptability.

For the assessment of the PFC converter system's control competence, fuzzy sets and rules are used. Instead of number variables, fuzzy logic uses linguistic variables. The mechanism by which a numerical variable is transformed into a linguistic variable is called fuzzification. The fuzzifier includes two parts, membership function and scaling factor selection. Using the vocabulary words NB, NM, NS, ZE, PS, PM, and PB the fuzzy variables; change in error, error, and change of duty cycles are mentioned (negative small, negative big, negative medium, zero, positive small, positive big and positive medium respectively).

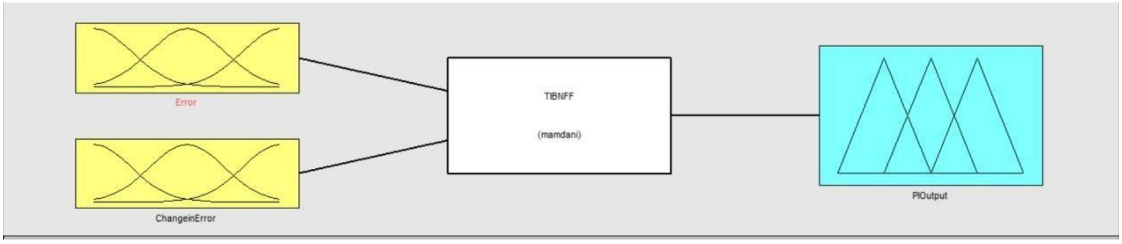


Fig. 4. Membership Functions of Fuzzy Logic Controller

Figure (4) represents the membership functions of the fuzzy logic controller that used the fuzzification" of two input values and the "defuzzification" output of the controller.

1. Rule Base for Fuzzy Logic Controller

A rule base (a set of If-Then rules), which contains a fuzzy logic quantification of the experts' linguistic description of how to accomplish control activity. Once the rules have been established, a fuzzy logic system can be viewed as a mapping from inputs to outputs. Rules may be provided by experts or can be extracted from numerical data. The performance of the controller can be improved by adjusting the membership function and rules. Different types of inferential procedures are there to help us understand things or to make decisions, there are many different fuzzy logic inferential procedures.

Fuzzy logic uses linguistic variables instead of numerical variables. In a control system, the error between the reference signal and output signal can be assigned as Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive small (PS), Positive Medium (PM), Positive Big (PB). To convert numerical inputs to linguistic variables fuzzy system uses above mentioned fuzzy levels. The fuzzy inference operation is executed by using the 49 rules. Some of these rules are:

- ❖ If error voltage (E) is NB and the change in error voltage (CE) is NB, then output is NB.
- ❖ If error voltage(E) is NB and the change in error voltage (CE) is NM, then output is NB.
- ❖ If error voltage(E) is NB and change in error (CE) is NS, then output is NB.
- ❖ If error voltage (E) is NB and the change in error voltage (CE) is NS, then output is NB.

TABLE I. CONTROL RULE BASE OF FUZZY LOGIC

		Error (E)						
		NB	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
Change in Error (CE)	**PB**	ZE	PS	PM	PB	PB	PB	PB
	PM	NS	ZE	PS	PM	PB	PB	PB
	PS	NM	NS	ZE	PS	PM	PB	PB
	ZE	NB	NM	NS	ZE	PS	PM	PB
	NS	NB	NB	NM	NS	ZE	PS	PM
	NM	NB	NB	NB	NM	NS	ZE	PS
	NB	NB	NB	NB	NB	NM	NS	ZE

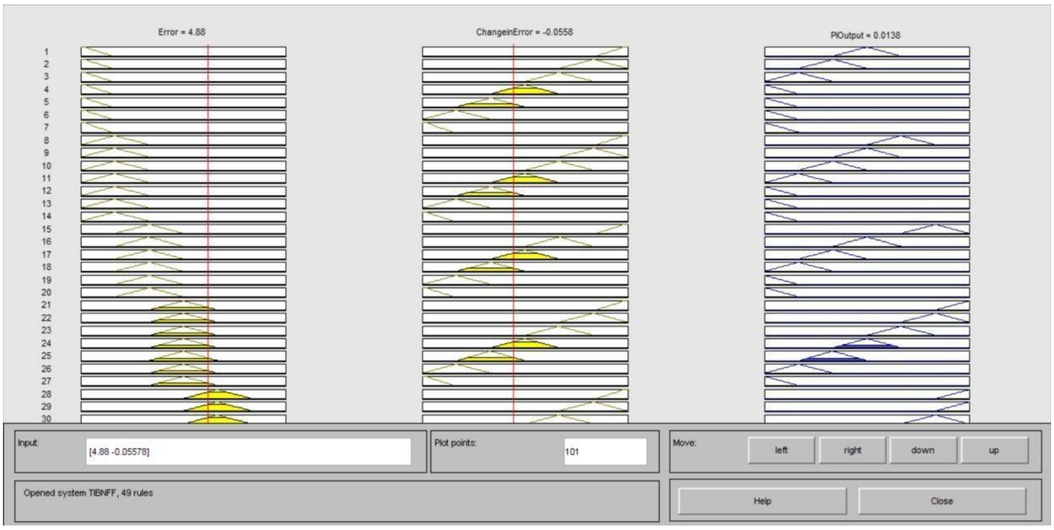


Fig. 5. Screenshot of Rule-Based Fuzzy Operation

Similarly, 49 rules are defined. A more compact representation of fuzzy rules is given in Table (1). Rule base Screenshot is appeared in Figure (5). The triangular membership function is chosen.

Finally, the fuzzy output is converted into real value output by the process called defuzzification. The centroid method of defuzzification is used because it tends to be effectively executed and requires less calculation time.

III. Software Simulation And Experimentation

The process of power factor correction using interleaved boost converter with the PI controller and Fuzzy Logic Controller is designed and executed using PSIM and MATLAB/Simulink. The system configuration for the simulation of this research is mentioned in the following Table (2). The proposed method of this research work was done using MATLAB/Simulink of version R2018a and PSIM of version 11 with the processor of core i3@ 3.5GHz and the RAM of DDR3 – 6GB. There is a time limit to get the output of the proposed method that is simulation time. The simulation time is taken in this research work in MATLAB Simulink and PSIM was 0.9 seconds as mentioned in Table (2).

TABLE II. TABLE OF SYSTEM CONFIGURATION FOR SIMULATION

Simulation System Configuration	
MATLAB	Version R2018a
PSIM	Version 9
Operating System	Windows 10 Home
Memory Capacity	8GB DDR3
Processor	Intel Core i5 @ 3.5GHz
Simulation Time	0.9 Seconds

Thereby, using the above configuration of PSIM software, the interleaved boost converter was designed with the bridge rectifier and two parallel boost converters connected to the load. The structure of the PFC Converter system as shown in Figure (5) has an AC source, where the

AC supply is fed to the rectifier circuit which converts AC voltage into DC voltage, through the power factor correction block where it has *L* and *C* elements used for Power factor correction. Where the PI controller has been introduced to regulate the output voltage, whatever may be the load condition, an output voltage is maintained constant.

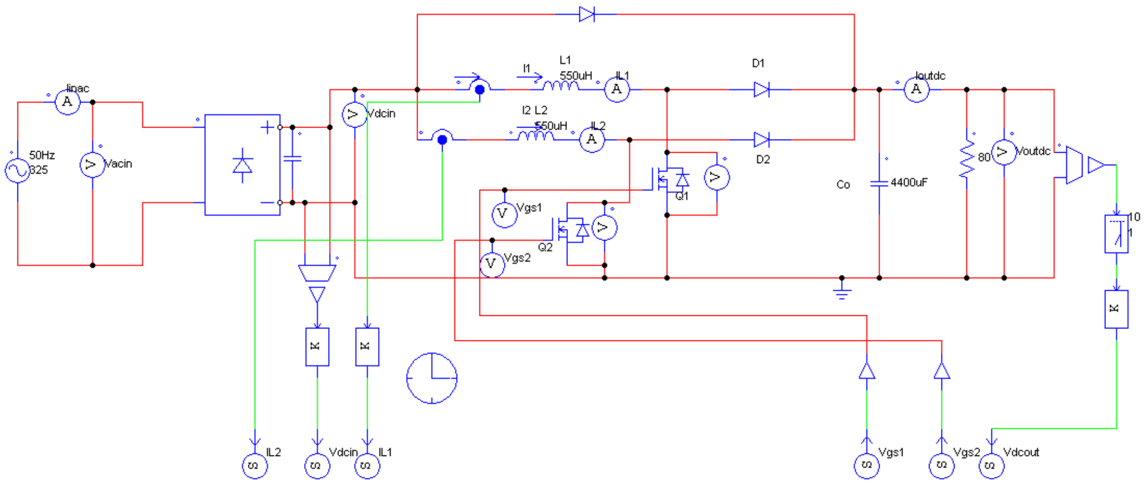


Fig. 6. Power circuit for Co-simulation of Interleaved Boost Converter with PSIM

Figure (6) represents the power circuit for co-simulation of interleaved boost converter using PSIM. The simulation for the interleaved boost converter is done off-the-line font-end with the bridge rectifier without any step-down transformer.

TABLE III. SIMULATION PARAMETERS

Components	Values
Output Power	5000 W
Inductance (L1, L2)	520 μH
Output Capacitance (Co)	4400 μF
Switching Frequency	100 KHz

Table (3) represents the values of the parameters of the simulation. The output power of the converter is 5000W, the inductance used in the converter of L1, L2 gets the value of 520 μH , the output capacitance (Co) of the converter is noted as 4400 μF and the switching frequency in the converter is examined as 100 KHz .

TABLE IV. CO-SIMULATION RESULTS OF INTERLEAVED BOOST CONVERTER WITH PI CONTROLLER

V_{in} AC (V_{rms})	I_{in} AC (A)	P_{in} (W)	R_L (Ω)	V_{out} DC (V)	I_{out} DC (A)	P_{out} (W)	P.F.	THD%	Effi.%
230	31.21	5048	32	396.68	12.4	4985	0.9943	3.67	99.76
230	25.14	4031	40	398.32	9.97	4008	0.9968	4	99.43
230	20.2	3238	50	400.6	8.02	3222	0.9982	4.25	99.52
230	16.82	2694	60	400.69	6.67	2681	0.9987	4.4	99.52
230	12.61	2030	80	400.83	5.02	2020	0.9988	4.76	99.46
230	10.03	1616	100	400.36	4	1602	0.9982	5.05	99.09
230	7.55	1218	133	400.22	3	1203	0.9968	6.17	98.71
230	5.49	852	200	399.98	1.99	799	0.9952	8.38	97.69
230	3.97	586	300	398.33	1.33	528	0.9911	12.1	95.07
230	2.96	447	400	399.9	0.999	403	0.9867	19.9	93.58

Table (4) represents the input and output values of the interleaved boost converter with the PI controller. The input voltage of AC is considered as $230V_{rms}$, the input frequency is 50 Hz. The technical specifications of the IBC converter are as follows, that is, the input voltage to the converter is around 207V, with the use of an IBC converter, the output voltage is maintained at 400V with $\pm 5\%$, the output current is in the range of 1A to 12.5A. The interleaved boost PFC converter is based on MOSFETs, so the pulse width to boost MOSFET is 0.5 duty cycle (50%), the switches are performed/operated with T_{on} the condition of 50% and T_{off} condition of 50%.

A. Simulation of PI Controller

The PI controller is implemented to minimize output voltage ripples. The error signal is obtained by determining the difference between the reference voltage signal and the actual output voltage for the PI controller input. Then modulation index value is acquired and is multiplied with the reference sinusoidal wave. Figure (6) shows the interleaved boost converter fed with the PI controller. The switching pulse is generated by comparing triangular waves and multiplied reference sinusoidal waves.

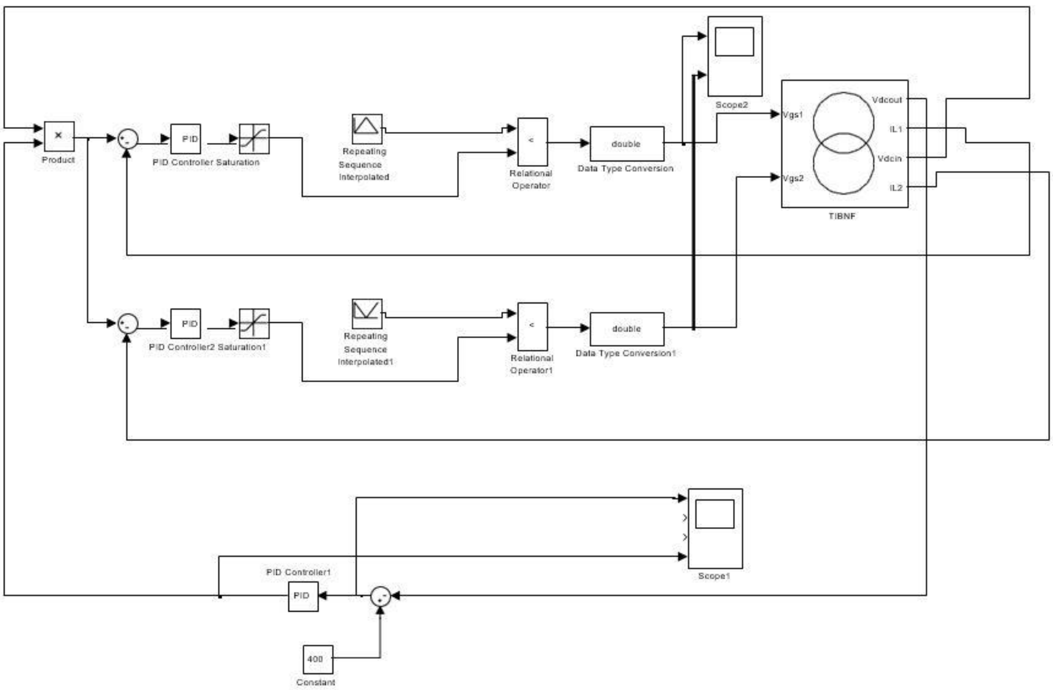


Fig. 7. Structure of a PI Controller for Co-simulation of IBC with PSIM and MATLAB/Simulink

Figure (7) represents the structure of a PI controller for co-simulation of IBC with PSIM and implemented in MATLAB/Simulink software. The structure shows that the PI controller implemented in the MATLAB environment is coupled to a power circuit in the PSIM environment by using the Sim-coupler block.

TABLE V. CONSTANT VALUES OF PI CONTROLLER.

Controller	K_p	K_i
PI	5e-4	1e-2

Table (5) represents the constant values of the PI controller. In this study, parameters of the PI controller are defined, where K_p the value is adjusted to 5e-4 and K_i is adjusted to 1e-2.

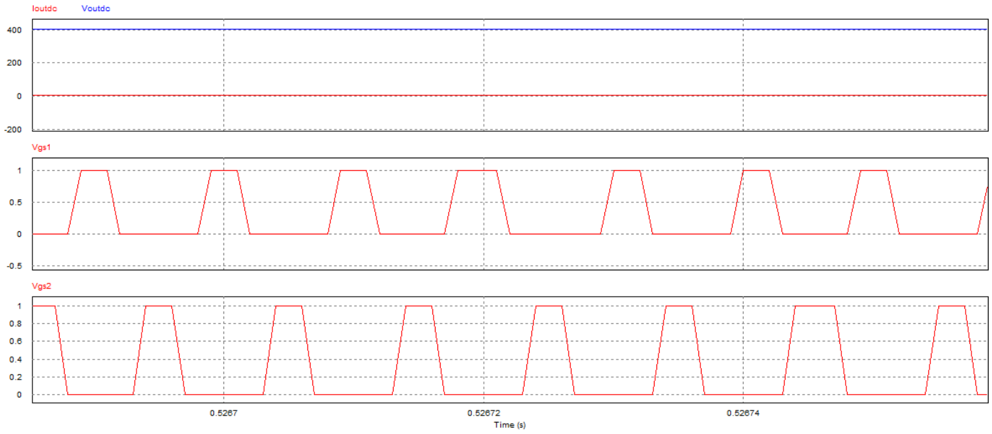


Fig. 8. Switching Pulses for MOSFET's 1, and 2 and the Output Voltage of Interleaved Boost Converter with PI Using PSIM Software.

Figure (8) represents the switching pulses for MOSFET's 1 and 2 and the output voltage of Interleaved Boost Converter with PI using PSIM software. The output voltage remains constant from the interleaved boost converter with the PI controller.

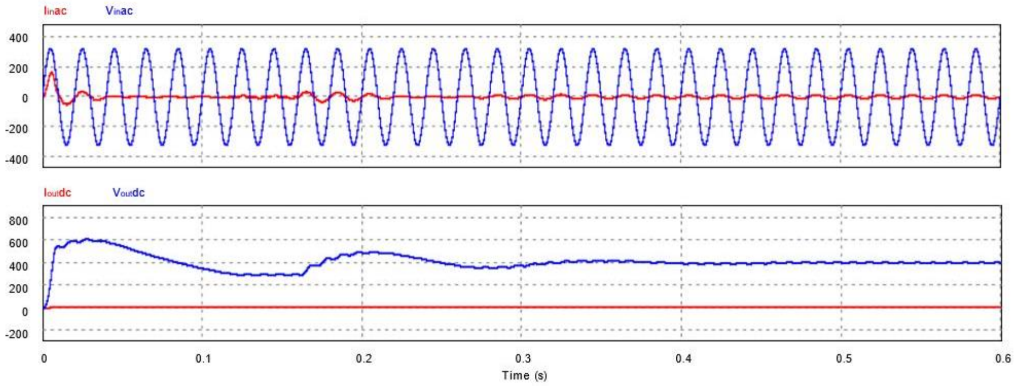


Fig. 9. Input-Output Waveform with PI Controller

Figure (9) represents the input-output waveform with the PI controller. The input ac voltage applied to the converter is a single-phase 230Vrms 50Hz sine waveform. Where the interleaved boost converter fed with PI controller gets the enhanced output dc voltage of 400V and the output DC is in the range of 1A to 12.5A.

The output voltage of the PFC converter initially swings between 600volts to 250volts and finally settles at 400volts.

B. Simulation of Fuzzy Logic Controller

The structure of the closed-loop IBC type PFC controller system with a fuzzy logic controller is shown in Figure (10), where the fuzzy logic controller has been introduced to feed the converter with a constant output voltage, whatever may be the load condition. By using the fuzzy controller, the output voltage is controlled.

The output response is shown in Figure (12). Here cascade controller is used for power factor correction. In cascade controller inner loop is implemented using the PI controller which takes care of input current shaping and for the outer loop only a fuzzy logic controller is used which regulates the output voltage. It can be seen that the output voltage is maintained constant after 0.5 secs by the fuzzy controller. The developed output voltage increases and settles in 0.5 secs.

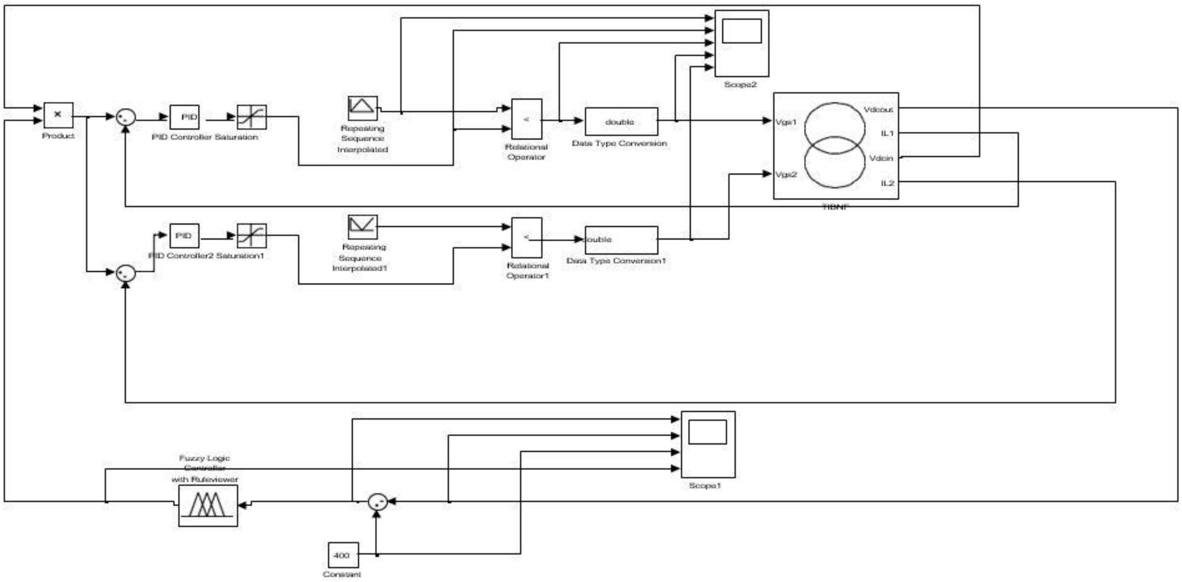


Fig. 10. Simulink Diagram of the Fuzzy Controller fed closed-loop PFC Converter system

In this system, seven membership functions NB, NM, NS, ZE, PS, PM, PB, are used in input variables as shown in Figure (11a, 11b). So a total of forty-nine rules can be created relating this to the membership function of the output variable. The membership functions of the output variable are NB, NM, NS, ZE, PS, PM, PB, as shown in Figure (11c). Fuzzy Logic Controller is designed to control the output of interleaved boost converter using Mamdani style fuzzy inference system. The Converter output voltage is 400V DC. The possible range of error is –20 to + 20 volts. The universe of discourse for error is - 20 volts to +20 volts and for the change in duty cycle, defined as 10 % to 90%.

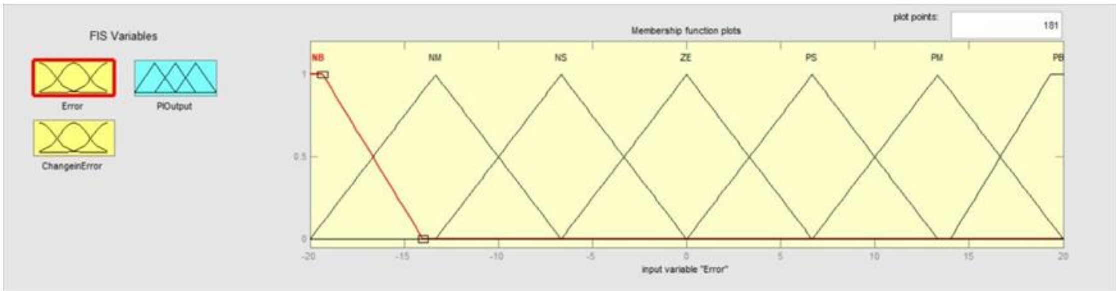


Fig. 11(a). Fuzzy Variable Error and its Triangular Membership Functions

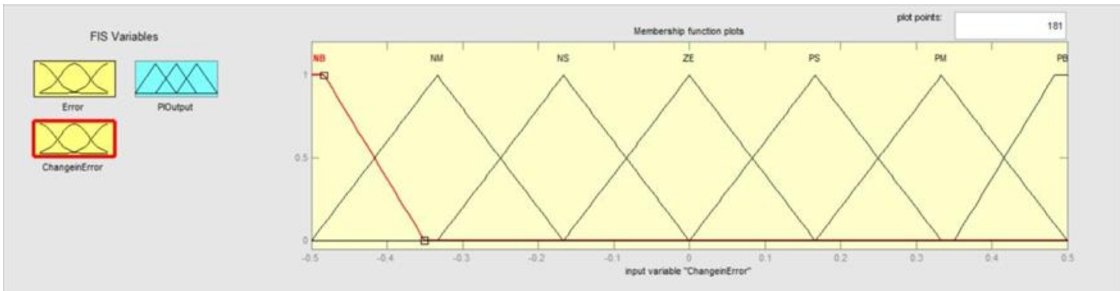


Fig. 11(b). Fuzzy Variable Change-in-Error and its Triangular Membership Functions

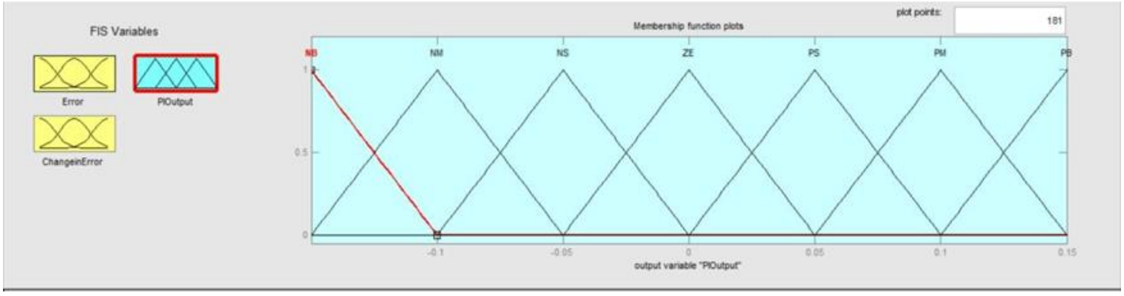


Fig. 11(c). Fuzzy Variable Output and its Triangular Membership Functions

The error signal is produced by subtracting the voltage output value of the converter with a reference value of output voltage. When this error is provided to the unit delay block a change in the error signal occurs. Both these signals are given as input to the mux block and the output of the mux block is provided as input to the Fuzzy block. The output of the Fuzzy block will be the duty ratio. The output of the fuzzy logic controller is provided as input to the PWM generating block to produce PWM signals with 180° a phase difference. These triggering pulses are provided to the switches S1 and S2.

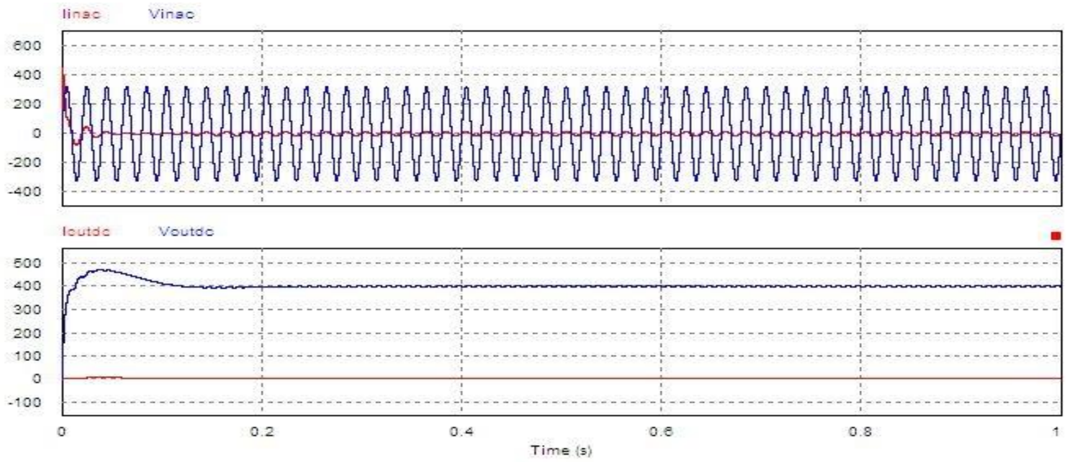


Fig. 12. Input-Output Waveform with Fuzzy Logic Controller

Figure (12) represents the input-output waveform of the fuzzy logic controlled interleaved boost converter. The input ac voltage applied to the converter is a single-phase 230Vrms 50Hz sine waveform. Where the interleaved boost converter fed with fuzzy logic controller gets the enhanced output dc voltage of 400V and the output DC in between 1A to 12.5A, it gets the better result with the proposed controller.

TABLE VI. COMPARISON OF RESPONSES OF PI AND FLC BASED SYSTEMS

Sr. No	Type of Controller	Rise Time (Sec)	Peak Time (Sec)	Settling Time (Sec)	Steady State Error (ess) (Volts)
1	PI	0.02	0.019	0.42	±8
2	Fuzzy	0.04	0.026	0.22	±4

Comparison of responses of PI and FLC based systems are given in Table 6. The table shows the settling time is reduced from 0.42 to 0.22 Seconds and the steady-state error in the output voltage is reduced from ±8 to ±4 volts.

C. Development of Prototype Model and Experimentation

An experimental prototype of a high-power rectifier based on average current control with IBC topology, which is controlled by dsPIC33fj16gs504, is developed to confirm the operational working of the proposed converter. Fig.13 shows the test model for the proposed 5KW Interleaved Boost PFC converter. The components and devices used are recorded in Table 7.

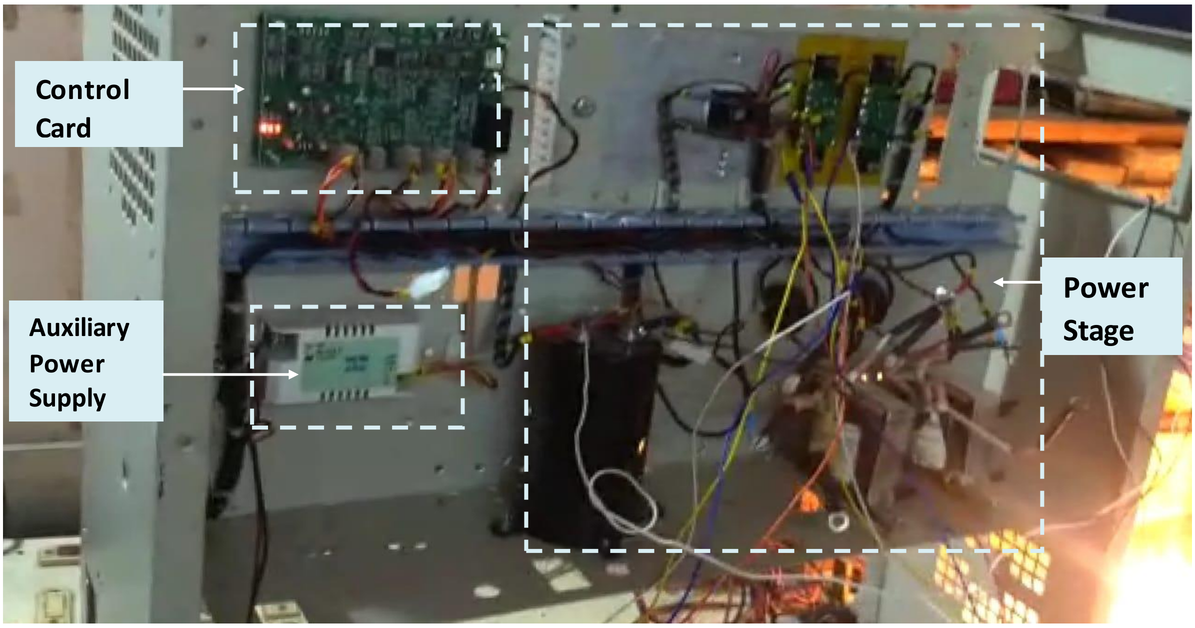


Fig. 13. Screenshot of Hardware Model of IBC Type High Power Converter

Figure 13 exhibits the image of the hardware model: the power circuit, control card and auxiliary power supply. The power circuit contains the high power converter and the regulated auxiliary power supplies for the control circuit. The control PCB contains the signal conditioning circuits and the micro-controller. The power stage is a well-known circuit and; hence, we mention only the characteristics of the control circuit.

A 16-bit micro-controller dsPIC33FJ16GS504 from Microchip technologies is utilized for controlling the converter. The micro-controller operates with a clock frequency of 40 MHz. We have utilized five ADCs simultaneously operating at the same sampling rate. The input current sensed by Shunt resistance is amplified by the differential amplifier and fed to the analogue channel of the ADC (0 - 3.3v). The detected output voltage is conditioned by a potential divider and to limit the ripple current in the output it is filtered by a low-pass filter with a cut off frequency of 88Hz. A +12V auxiliary power supply is essential to feed the gate drive circuit. To feed the micro-controller an auxiliary source of 5V has been utilized. The gating signals for MOSFETs are produced with a driver circuit IC MCP1403 of Microchip Technologies.

TABLE VII. COMPONENTS USED FOR HARDWARE MODEL

Parameter	Value
Bridge Rectifier	GBPC5012A (Won-Top Electronics)
MOSFETs	SPI20N60C3 To-220 (Cool-MOS power MOSFETs Infineon Technologies)
Fast-recovery Diodes	DSEI60-12A To-247AD (IXYS Semiconductors)
Boost Inductor	150-750 µH, (Neha Tech Services)
Output Capacitor	2200µF,450V (ALCON Aluminium Electrolytic Capacitors)
Current Transformer	1:125, 25A (Neha Tech Services)
Controller IC	Microchip Technology dspic33fj16gs504

TABLE 8: RESULTS OF HARDWARE MODEL OF THE CONVERTER, PO = 5000WATTS, L1 =L2= 520µH, CO = 2200µF

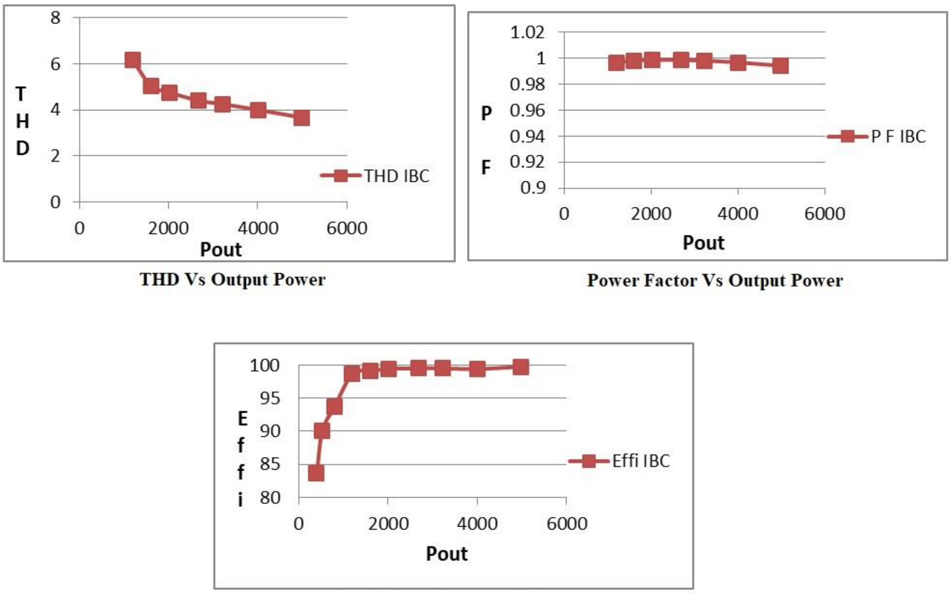
Vin AC Vrms	I_{in} AC (A)	P_{in} (W)	RL (Ω)	V_{out} DC (V)	I_{out} DC (A)	P_{out} (W)	P.F.	THD %	Effi %
230	31.21	5048	32	396.68	12.4	4955	0.9930	4.04	98.15
230	25.14	4031	40	398.32	9.97	3952	0.9918	4.11	98.02
230	20.2	3288	50	400.6	8.02	3222	0.9900	4.55	98.00
230	16.82	2694	60	400.69	6.67	2627	0.9887	4.44	97.52
230	12.61	2073	80	400.83	5.02	2020	0.9838	4.96	97.46
230	10.03	1667	100	400.36	4	1602	0.9782	5.25	96.09
230	7.55	1256	133	400.22	3	1203	0.9768	6.71	95.71
230	5.19	845	200	401.25	2	803	0.9648	18.40	94.98
230	3.33	592	300	406.4	1.35	551	0.9552	28.75	92.93
230	1.84	454	400	410.1	1.02	411	0.9332	36.44	90.37

Table 8 shows the results of the hardware model developed. With the AC input voltage constant at 230 Vrms, at different load conditions, the converter is tested and results are recorded. The plots of THD, PF and efficiency with the results obtained from the hardware model are presented in Fig.14 respectively.

IV. RESULTS AND DISCUSSION

TABLE IX. COMPARATIVE RESULT ANALYSIS OF THE PROPOSED CONVERTER FOR 5000 W OUTPUT POWER

Topology	P.F.	T.H.D. %	Efficiency %
IBC Co-Simulation with PI Controller	0.9943	3.67	98.86
IBC Hardware Model with PI Controller	0.9930	4.04	98.15



THD Vs Output Power

Power Factor Vs Output Power

Efficiency Vs Output Power

Fig. 14. Performance Measures of IBC Hardware Model

The comparative result analysis is shown in Table 9 respectively. The proposed 5KW IBCPFC Converter which is having two-stage interleaved support PFC have the resulting highlights: As in IBC two boost topologies are exchanging at 180 degrees, i. e. out of phase, their inductor current flows are additionally stunned and drop with one another; so viable wave in input current is decreased. So

THD is diminished. As switches are worked at high frequency and ripple current is twice for each stage, which lessens the required size of the EMI filter. As the high-recurrence ripple current in the yield capacitor is diminished, so required worth of yield capacitor decays. At last, the input line current wave tracks better the inline voltage wave, so the power factor is exceptionally high.

V. CONCLUSION

The power converters with small power factors have many drawbacks; such as heavy copper loads, poor voltage controls, higher kVA rating, etc. Because of these results, the power factor must be increased. In this analysis, a proposed input power supply system is connected to a bridge rectifier converting ac to dc and connected to an interleaved boost converter for power factor correction with the controllers, two parallel boost circuits. A proportional controller gains (K_p) in the PI controller decreases the rise time and but does not eradicate a steady-state error. An integral control gains (K_i) eliminate the steady-state error but aggravates the transient response. The fuzzy logic controller is used to avoid these limitations of conventional PI controllers. The fuzzy logic controller provides a smoother and faster output response. The simulation result shows that the power factor achieved here is 0.9988, the total harmonic distortion (THD) maintained was less than 5% at full load and the average efficiency concluded here was 98%. The output power, inductance, and capacitance in the converter were 5000W, 520µH, and 4400µF. The PI controller parameters used were proportional controller (K_p) to be 5e-4 and the integral controller (K_i) was 1e-2. Finally, the output voltage enhanced in the fuzzy logic controller is 400V and with the load current of 1 to 12.5A. The settling time is reduced by 52% and steady-state error is reduced by 50% using FLC. The co-simulation process using the interleaved boost converter fed with the PI controller and Fuzzy Logic controller was done by PSIM and MATLAB/Simulink software. The computer simulation shows reduced THD and input power factor is close to unity; with less harmonic distortion in FLC compared to PI. Hence Fuzzy logic controllers can provide improved power quality compared to other controllers. The results of the simulation are deep-rooted by the hardware MODEL of the converter for 5kWatt output power. Results of the prototype model found that the total harmonic distortion THD is 4.04% which is as per IEC 61000-3-2 standard, the power factor PF is 0.9930 with an efficiency of 98.15%.

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