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Comparative Analysis of PI, SMC and Fuzzy Logic Control Technique for Power Factor Correction of a single phase AC to DC Interleaved Boost Converter

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***Abstract-* In this paper, the different controller like PI, Fuzzy Logic Controller and Slide Mode Control are compared for the power factor correction (PFC) single phase AC to DC interleaved Boost topologies for a high density and efficient. Based on this, an optimal topology is selected for which an additional comparative analysis involving input line measure improvement control is conducted. The results of these experiments can be adapted for use in the circuit selection of high performance converters with power factor improvement circuits. .An outer loop regulates the output voltage by means of a proportional–integral (PI) compensator directly obtained from a small-signal model of the ideal sliding mode control dynamics. The control law proposed has been validated using numerical simulations and experimental results in a 0.5-kW prototype. Based on this, an optimal topology is selected for which an additional comparative analysis involving input line measure improvement control is conducted by using PI controller, Fuzzzy logic control and Sliding Mode Control.**

***Index Terms-* AC–DC power conversion, boost converter, sliding mode control (SMC), interleaving, L-C filter, power factor correction (PFC). Rrection; PI controller; Fuzzzy logic control; Sliding Mode Control.**

1. INTRODUCTION

Nowadays, the control systems for many power electronic appliances have been increasing widely. Crucial with these demands, many researchers or designers have been struggling to find the most economic and reliable controller to meet these demands. The idea to have a control system in dc-dc converter is to ensure desired voltage output can be produced efficiently as compared to open loop system. The usage of electronic equipments is increasing rapidly in the daily life according to consumer or industrial needs. All these electronic equipments have power supplies that obtain required energy from utility grid [1-2]. These electronic systems generally use one or more switched mode power supplies (SMPS) that draw a non-sinusoidal current. This causes current and voltage distortions that affect other equipments connected to the same power grid, thus, lowering the capability of the power source[3-4]. In order to overcome these problems, new standards have been developed for limiting the harmonic content of the input current. Manufacturers should find solutions for meeting the requirements of these standards. In the general usage, different load groups are supplied by different phases. If one of the phases is loaded with nonlinear loads, unbalanced currents flow through the neutral line of star configuration. These unbalanced currents cause heating and power loss in the conductors and voltage distortion and electromagnetic compatibility (EMC) problems occur.

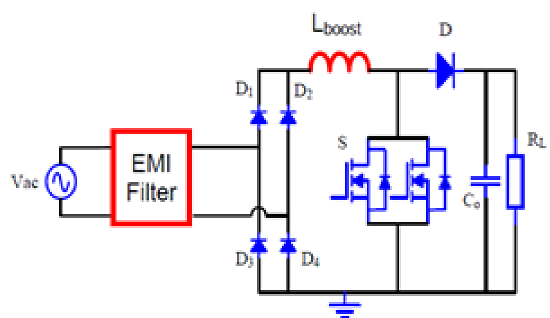


Fig. 1 Single-phase rectifier boost topology for PFC application..

Moreover the harmonic content of this pulsating current causes additional losses and dielectric stresses in capacitors and cables, increasing currents in windings of rotating machinery and transformers and noise emissions in many products, and bringing about early failure of fuses and other safety components. Harmonics can affect other devices that are connected to the same system.

DC-DC converters are non-linear in nature hence the design of controller is most challenging task for DC-DC converters. The general control principle for power electronic converter is shown in figure 2.

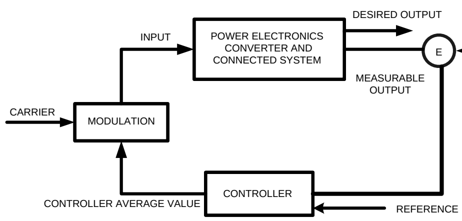


Fig.2. General control principle for a power electronic converter

There are linear and non-linear controllers. Non-linear controllers are more accurate as compared to linear controller [3]. In traditional controller, application of linear control theory based on linearised model. A linear control method fails to respond properly to any variation in the operating point and load disturbance. To overcome these issues, nonlinear controllers can be used which are more robust and have faster dynamic response [4]. There are many non-linear control schemes, such as fuzzy logic control, current-mode control and PI control proposed for DC-DC converter. Due to simple and model free implementation PI control and fuzzy logic control can be applied with satisfactory results [4]. Out of this controller PI control is powerful method which able to makes the system very robust. The system with PI control avoided effects of modeling uncertainties, fluctuations and disturbance of parameter and load variations. The advantages of PI controller are robustness and stability [4]. Due to this reason PI control technique has gained popularity in the applications involving converter and inverters [5].

Conventionally, PI, PD and PID controller are most popular controllers and widely used in most power electronic closed loop appliances however recently there are many researchers reported successfully adopted Fuzzy Logic Controller (FLC) to become one of intelligent controllers to their appliances [6]. With respect to their successful methodology implementation, control closed loop boost converter and opened loop boost converter will compare the efficiency of the converters. This kind of methodology implemented in this paper is using fuzzy logic controller with feed back by introduction of voltage output respectively. The introduction of voltage output in the circuit will be fed to fuzzy controller to give appropriate measure on steady state signal. The fuzzy logic controller serves as intelligent controller for this propose. This Methodology can be easily applied to many dc-dc converter topologies such as Buck, Boost and Buck-Boost. The power sources have quite low –voltage output and requires series connection of voltage booster to provide higher output voltage. DC-DC Boost converter is generally used to further boost the voltage to the required level [6]-[8]. Other booster converter such as Boost, Buck, Boost series resonant full bridge and push-pull are not recommended due to objectionable ripples in the current flowing out of the renewable energy sources [9]-[12]. In traditional controller, application of linear control theory based on linearised model. A linear control method fails to respond properly to any variation in the operating point and load disturbance. To overcome these issues, nonlinear controllers can be used which are more robust and have faster dynamic response [13]-[16]. There are many non-linear control schemes, such as fuzzy logic control, current-mode control and PI control proposed for DC-DC converter. Due to simple and model free implementation PI control and fuzzy logic control can be applied with satisfactory results [9]. Out of this controller PI control is powerful method which able to makes the system very robust. The system with PI control avoided effects of modeling uncertainties, fluctuations and disturbance of parameter and load variations. The advantages of PI controller are robustness and stability [17]. Due to this reason PI control technique has gained popularity in the applications involving converter and inverters [18]-[19].

During electronically extreme thermal excursions it become to develop a high temperature, high power density and high efficiency electrical power system which can be reliably function. To fulfill this requirement interleaved boost converters have been studies in recent years due to their potential to improve power converter performance in terms of efficiency, size, conducted electromagnetic emission and transient response [20]-[23]. The power system can have high voltage step up and smaller ripple at the output voltage and output current. Interleaved boost converter has low switching loss and faster transient response [24]-[26].

High power density, high conversion efficiency, high power factor, and low total harmonic distortion (THD) are the desired features expected from onboard plug-in electric vehicle (PEV) battery chargers [27]–[28]. Fig. 1 shows the general power electronic architecture of a typical onboard PEV battery charger. The system consists of a front-end ac/dc converter used for rectification at a unity power factor and a second stage dc/dc converter responsible for battery current regulation and providing galvanic isolation [29],[30]. A comprehensive topological survey of the currently available PEV charging solutions has been presented in [4]. A boost converter is a common front-end PFC interface due to its simple structure, good THD reduction performance, and unity power factor operation capability [31]-[32]. However, the volume of the converter tends to increase with the increase in charging power. Moreover, high RMS current in the dc-link capacitors would generate high power loss and significantly reduce the capacitor's lifetime, leading to capacitor failures. In addition, the required inductance value to reduce the ripples in the input current for better THD performance would considerably increase as the charging power increases [34]. This results in a large-volume inductor core and wire size. Compared with a single-phase boost PFC converter, the interleaved boost topology has the benefits of reduced overall volume and improved power density [35]. In the dc/dc isolation stage, resonant converters are preferable at high-voltage and high-power PEV battery charging applications.

II.DC TO DC BOOST CONVETER

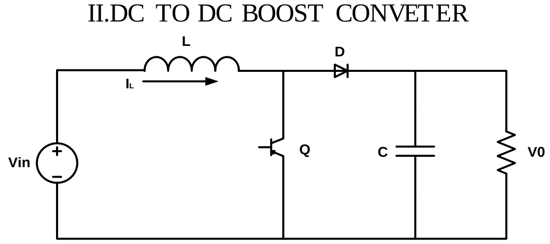


Fig.3. DC-DC Boost Converter

Fig. 3 shows a DC–DC boost converter. It consists of a DC input voltage source (Vin), a controlled switch (Sw), a diode (D), a filter inductor (L), a filter capacitor (C), and a load resistor (R). The equations describing the operation of the converter can be written for the switching conditions ON and OFF, respectively as

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

$$\frac{dv_0}{dt} = \frac{1}{C}(-\frac{v_0}{R}) \tag{2}$$

And

$$\frac{di_L}{dt} = \frac{1}{L}(V_{in} - v_0) \tag{3}$$

$$\frac{dv_0}{dt} = \frac{1}{C}(1 - \frac{v_0}{R}) \tag{4}$$

Combining (1)-(4) gives

$$\frac{di_L}{dt} = \frac{1}{L}(V_{in} - uv_0) \tag{5}$$

$$\frac{dv_0}{dt} = \frac{1}{C}(u - \frac{v_0}{R}) \tag{6}$$

Where 'u' is the control input which takes 1 for the ON state of the switch and 0 for the OFF state.

III.INTERLEAVED PFC BOOST CONVERTER

Interleaved boost converter can be simply obtained by operating three boost converters operating 1200 out of phase. The input current is the sum of three inductor currents IL1, IL2 and IL3. Because the inductor ripple current is out of phase, they cancel each other and reduce the input ripple current produce by inductor of boost converter.

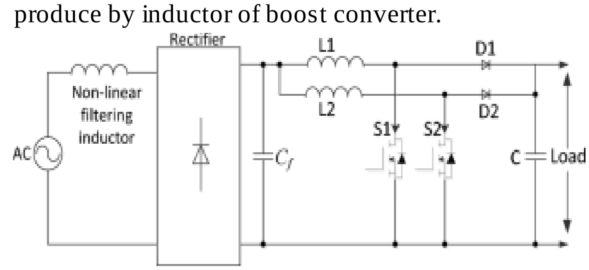


Fig.4 interleaved boost converter topology

The output capacitor current is the sum of the three diode currents, I1+ I2+ I3 minus Dc output current, which reduces the dc- output capacitor ripple Iout as a function of duty cycle

The design aspects of Interleaved Boost Converter are given in the below section:

A. Boost Ratio

The boosting ratio of the converter is a function of the duty ratio. It is same as in conventional boost converter. It is defined as

$$Vdc/\ Vin = 1/1\text{-}D$$

Where Vdc is the output voltage, Vin is the input voltage and D is the duty ratio.

B. Input Current

The input current can be calculated by the input power and the input voltage.

$$Iin = Pin/Vin$$

Where Pin is the input power, in is the input voltage

C. Inductor current ripple peak –to-peak amplitude

The inductor current ripple peak-to-peak amplitude is given by.

□I L1, L2, L3=VinD/fswL

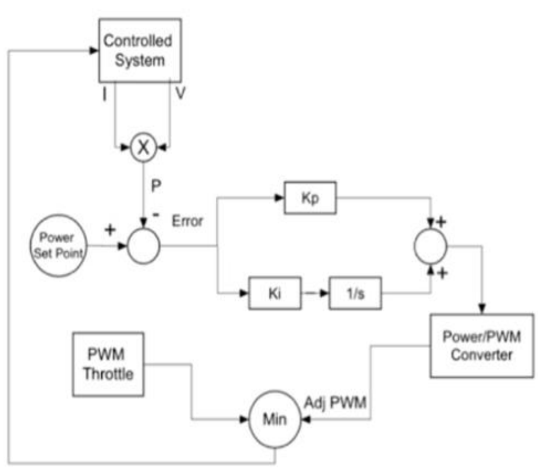
Where fsw is the switching frequency, D is the duty cycle, Vin is the input voltage and L is the inductance.

Interleaved boost converter is employed to reduce input and output a voltage ripple which reduces the size of filters since the output current spitted into N parts it reduces the I2R losses and inductor loss which leads to higher efficiency [6].

IV. PI CONTROL

A common aspect for all the converter topologies is the presence of a control signal implemented by using switching devices.

So that the control variable u only takes values 0 switch is open (closed) or 1 switch is closed (On).



Fig,5 PI control loop and PWM signal

The objective is to steer the time varying load voltage y to a reference value y(t). According to strategy we define two PI surface.

A. Control loop

Current control loop as

1 = {(y,t)/ □i (y,t) = 0} i=1, 2

Where the PI function □i are

i (y,t) = □(y,t) - □i(t)

Where

(y,t) = y(t) – y

Is the tracking error and □i(t), i=1, 2

Is either

1(t) = □(y(0), 0)exp(c(t))

Or

2(t) =□1(t)+[□(y, t)|t=0 - □(y(0), 0)]t exp(c(t))

Is a correction function to keep the system state on the manifold since the initial time instant, as with □1

1|t=0=0

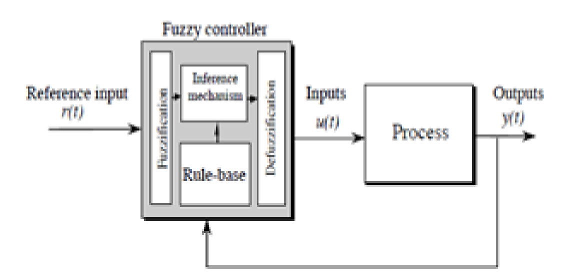
While when using □2

2|t=0=0, □2|t=0=0

Finally, c<0 is a constant defining the speed of recovery of initial mismatch between desired and actual voltage.

V. FUZZY LOGIC CONTROL

L. A. Zadeh presented the first paper on fuzzy set theory in 1965. Since then, a new language was developed to describe the fuzzy properties of reality, which are very difficult and sometime even impossible to be described using conventional methods. Fuzzy set theory has been widely used in the control area with some application to dc-to-dc converter system. A simple fuzzy logic control is built up by a group of rules based on the human knowledge of system behavior. Matlab/Simulink simulation model is built to study the dynamic behavior of dc-to-dc converter and performance of proposed controllers. Furthermore, design of fuzzy logic controller can provide desirable both small signal and large signal dynamic performance at same time, which is not possible with linear control technique. Thus, fuzzy logic controller has been potential ability to improve the robustness of dc-to-dc converters. The basic scheme of a fuzzy logic controller is shown in figure 2 and consists of four principal components such as: a fuzzyfication interface, which converts input data into suitable linguistic values; a knowledge base, which consists of a data base with the necessary linguistic definitions and the control rule set; a decision-making logic which, simulating a human decision process, infer the fuzzy control action from the knowledge of the control rules and linguistic variable definitions; a defuzzification interface which yields non fuzzy control action from an inferred fuzzy control action [4].



Fig,5 General fuzzy logic controller

The objective is to steer the time varying load voltage y to a reference value y(t). According to strategy we define two PI surface.

A. Fuzzy logic controller on the single phase AC to DC PFC Interleaved Boost converter

An analysis of single phase AC-DC interleaved boost converter circuit revealed that the inductor current plays significant task in dynamic response of boost converter. Additionally, it can provide the storage energy information in the converter. Thus, any changes on the inductor current may affect output voltage and output voltage will provide steady state condition information of converter. However, the three main parameters need to be considered when designing boost converters are power switch, inductor and capacitor. In this objective to achieve the desired output

voltage and the stability is by designing the power switch [6].

B. Analytical Expressions

There are few types of power switches in order to develop the design. The common power switches are BJT, power MOSFET, IGBT etc. Since the characteristics of the MOSFET are fast switching and voltage driven, they have been chosen for the power switching in this designing requirement. In this case, the parameters value of design requirement for the single phase AC to DC PFC Interleaved Boost converter is been set. The value of the parameter can be determined as illustrated in Table I below:

Parameter	Description	Value
V_{in}	Input Voltage	230 v
N	Number of phases	3
L	Inductance	2 mH
C	Capacitance	235 uF
R_0	Load Resistance	10578 ohm
f_{sw}	Switching Frequency	20 kHz

TABLE I. SIMULATION MODEL PARAMETERS

C. Fuzzy Logic Membership Function

The of single phase AC-DC interleaved boost converter is a nonlinear function of the duty cycle because of the small signal model and its control method was applied to the control of boost converters. Fuzzy controllers do not require an exact mathematical model. Instead, they are designed based on general knowledge of the plant. Fuzzy controllers are designed to adapt to varying operating points. Fuzzy Logic Controller is designed to control the output of boost dc-dc converter using Mamdani style fuzzy inference system. Two input variables, error (e) and change of error (de) are used in this fuzzy logic system. The single output variable (u) is duty cycle of PWM output [7].

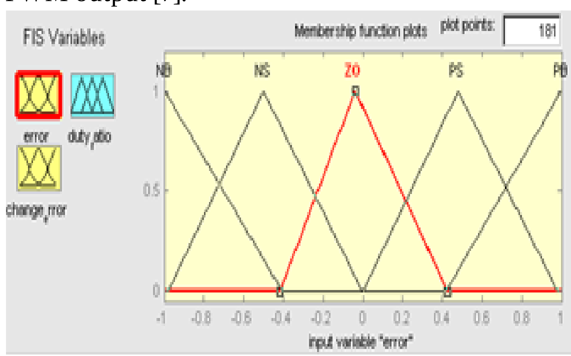


Fig.6: *The Membership Function plots of error.*

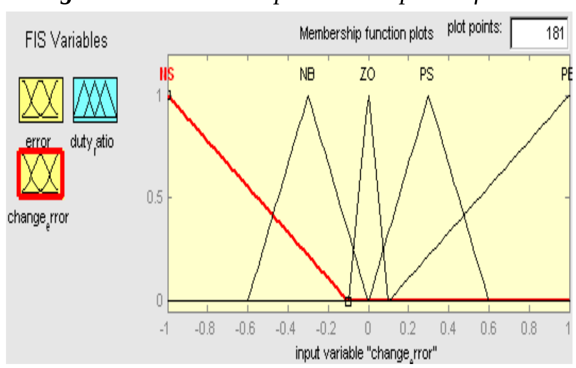


Fig 7: *The Membership Function plots of change error.*

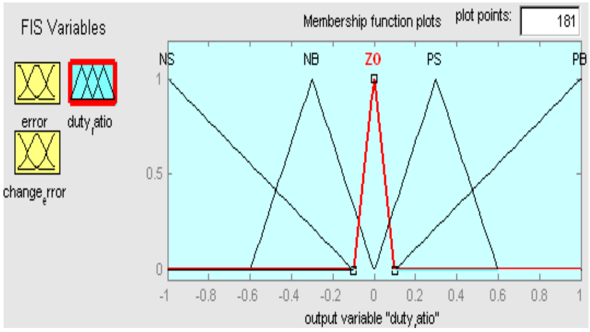


***Fig:8** The Membership Function plots of duty ratio.*

A. Fuzzy Logic Table Rules

The objective of this paper is to control the output voltage of the boost converter. The error and change of error of the output voltage will be the inputs of fuzzy logic controller. These 2 inputs are divided into five groups; NB: Negative Big, NS: Negative Small, ZO: Zero Area, PS: Positive small and PB: Positive Big and its parameter [8][9][10]. These fuzzy control rules for error and change of error can be referred in the table that is shown in Table II as per below:

(e) / (de)	NB	NS	ZO	PS	PB
NB	NB	NB	NB	NS	ZO
NS	NB	NB	NS	ZO	PS
ZO	NB	NS	ZO	PS	PB
PS	NS	ZO	PS	PB	PB
PB	ZO	PS	PB	PB	PB

TABLE II. SIMULATION MODEL PARAMETERS

VI. SLIDE MODE CONTROL

A. Control Law

u=1 = ON when S>0

0 = OFF when S<0

u is the state of power switch

S is the instantaneous state variable trajectory expressed as

$S=\alpha 1x1+\alpha 2x2+\alpha 3x3$

$\alpha 1$, $\alpha 2$, $\alpha 3$ are the control parameter

x1 current error

x2 voltage error

x3 integral of voltage & current error

x1= iref-iL

x2= Vref-βV0

$$\int (x1 + x2)dt$$

A common aspect for all the converter topologies is the presence of a control signal implemented by using switching devices.

So that the control variable u only takes values 0 switch is open (closed) or 1 switch is closed (On).

The objective is to steer the time varying load voltage y to a reference value y(t). According to strategy we define two PI surface.

B. Control loop

Current control loop as

$$\delta 1 = \{(y,t)/\ \delta i\ (y,t) = 0\} \qquad i=1,\ 2$$

Where the PI function δi are

$$\delta i\ (y,t) = \varepsilon(y,t) - \eta i(t)$$

Where

$$\varepsilon(y,t) = y(t) - y$$

Is the tracking error and $\eta i(t)$, i=1, 2

Is either

$$\eta 1(t) = \varepsilon(y(0),\ 0)\exp(c(t))$$

Or

$\eta 2(t) = \eta 1(t)+[\ \varepsilon(y,\ t)|t=0 - \varepsilon(y(0),\ 0)]t\ \exp(c(t))$

Is a correction function to keep the system state on the manifold since the initial time instant, as with η1

$$\delta 1|_{t=0}=0$$

While when using η2

$$\delta 2|_{t=0}=0, \quad \delta 2|_{t=0}=0$$

Finally, c<0 is a constant defining the speed of recovery of initial mismatch between desired and actual voltage.

V. SIMULATION RESULTS

The proposed converter parameters used in simulation are given in table I . The simulation of the interleaved PFC boost converter is carry out in the simulink/MATLAB. The reliability of the converter is checked by varying the magnitude of the input voltage. At the constant load the input current is change for the variation in the input voltage. The parameter of the converter is given in Table I.

Parameter	Description	Value
V_{in}	Input Voltage	230 v
N	Number of phases	3
L	Inductance	2 mH
C	Capacitance	235 uF
R_0	Load Resistance	10578 ohm
f_{sw}	Switching Frequency	20 kHz

TABLE I. SIMULATION MODEL PARAMETERS

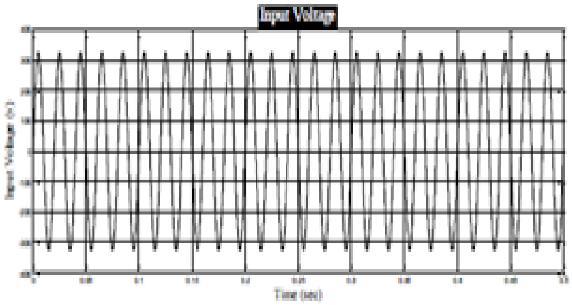


Fig. 4. Simulation waveform of input voltage

Fig. 4 shows waveform of single phase ac input voltage which is applied to rectifier.

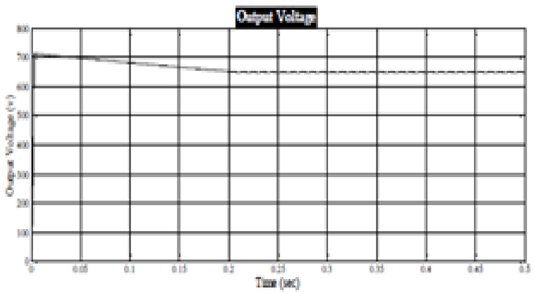


Fig. 5. Simulation waveform of output voltage

Fig. 5 shows waveform of output voltage of interleaved boost converter.

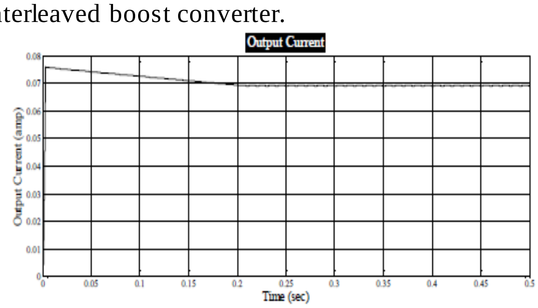


Fig. 6. Simulation waveform of output current

Fig. 6 shows waveform of output current of interleaved boost converter.

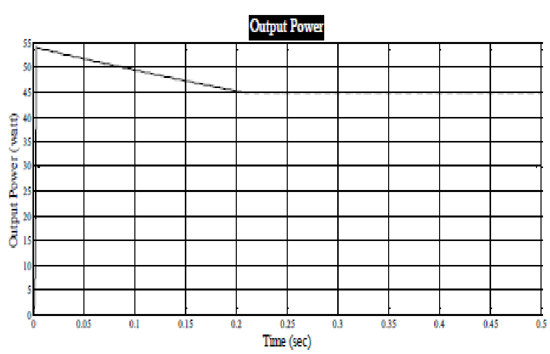


Fig. 7. Simulation waveform of output power

Fig. 7 shows waveform of output power of interleaved boost converter.

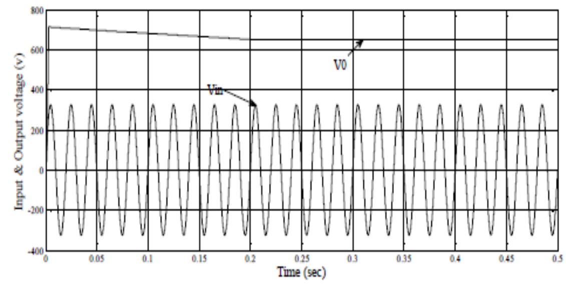


Fig. 8. Simulation waveform of output voltage for change in input voltage

Fig. 8 shows waveform of output voltage which remains unchanged as input voltage change of interleaved dc-dc boost converter.

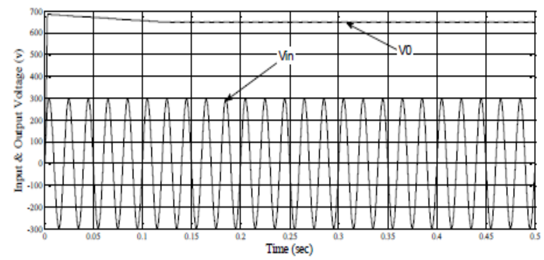


Fig. 9. Simulation waveform of output voltage for change in input voltage

Fig. 9 shows clearly as change input voltage output voltage does not change for same resistive load.

TABLE II. OUTPUT VOLTAGE AT DIFFERENT INPUT VOLTAGE

Input Voltage V_{in}	Load Resistance R	Output Voltage V_0
230 v	10578 Ω	650 v
220 v	10578 Ω	650 v
210 v	10578 Ω	650 v
200 v	10578 Ω	650 v

As change in the input voltage occurred due to due any uncertainty the output voltage remains unchanged. Output voltage remains stable which is clearly shown by simulation waveform and the values shown in Table. II

As per values shown in table III it is cleared that variations in the load parameters or any uncertainty output voltage remains same. As per values shown in table III it is cleared that variations in the load parameters or any uncertainty output voltage remains stable.

TABLE III. OUTPUT VOLTAGE AT DIFFERENT CONTROLLER

Input AC Voltage(V)	Output DC Voltage (V)		
	PI	Fuzzy	SMC
180	639	639	641

190	640	640	641
200	641	642	645
210	642	642	643
220	643	643	642
230	660	655	654
240	663	656	656
250	665	660	660

TABLE III. ERROR IN OUTPUT VOLTAGES BY DIFFERENT CONTROLLER

Input AC Voltage(V)	Error of Output DC Voltages (V)		
	PI	Fuzzy	smc
180	11	11	9
190	10	10	9
200	9	8	5
210	8	8	7
220	7	7	8
230	10	5	4
240	13	6	6
250	15	10	10

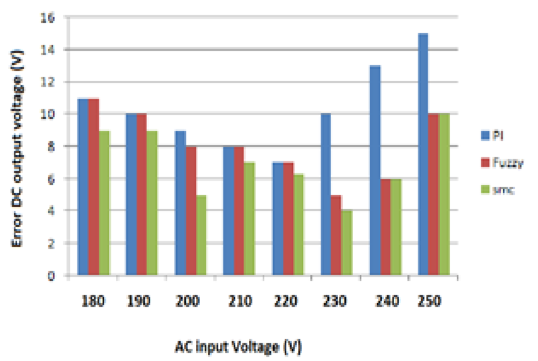


Fig. 15. Bar diagram of error in output by different controller

VI. EXPERIMENTAL SETUP

Fig. 14. Experimental setup of a PI control dc-dc interleaved boost converter

VII. EXPERIMENTAL RESULTS

The performance of the PI, Fuzzy logic and SMC controller is experimentally verified. The specification of the converter is the same as that used in simulation. The experimental results match the simulation very well. Also, it can be seen that the output voltage is a little less than or higher than the desired 650V in each circumstance, due to the parasitic parameters in the hardware circuit, which are neglected in simulation.

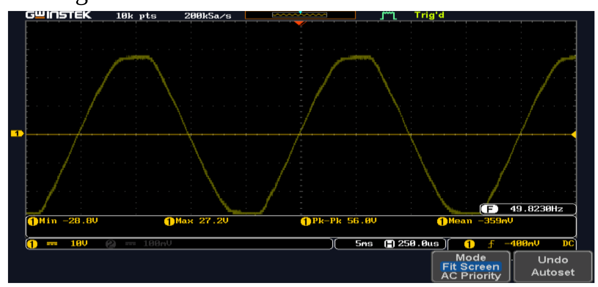


Fig. 16. Hardware Input voltage waveform

Simulation result and the hardware result are differ from each other as it is clearly seen from above result the some harmonics is present in the input of the 50Hz power supply.

The result is varying due to the above reasons. Moreover, it does not require the line voltage sensing, the multiplier, and the current loop compensation design owing to its beneficial characteristics in nature, which greatly simplifies control circuitry. The intrinsic features of the proposed method enable a current balancing between the interleaved modules by just letting them use the phase-shifted modulated carrier signals with the same amplitude. The operation principle has been presented and mathematically detailed.

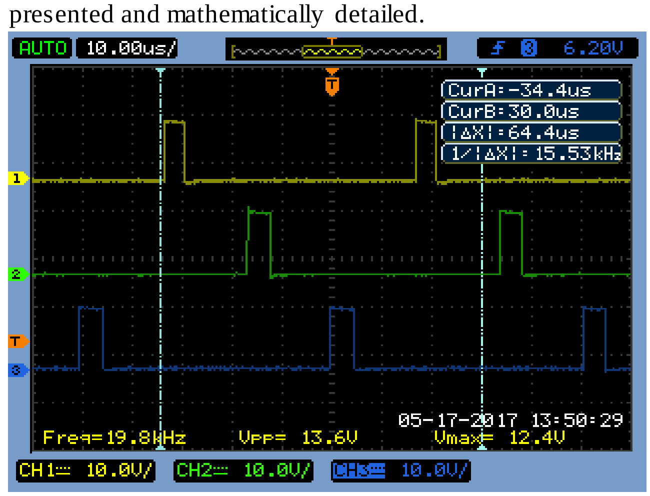


Fig. 16. Pulse generated in hardware

TABLE IV. OUTPUT VOLTAGE AT DIFFERENT INPUT VOLTAGE

Input Voltage Vin	Load Resistance R	Output Voltage V0
180 v	10578 Ω	641 v
190 v	10578 Ω	641 v
200 v	10578 Ω	645 v
210 v	10578 Ω	643 v
220 v	10578 Ω	642 v
230 v	10578 Ω	654 v
240 v	10578 Ω	656 v
250 v	10578 Ω	660 v

From above table output voltage for various input voltage values is given which is more or less than 650V due to the parasitic parameters in the hardware circuit.

VIII. CONCLUSIONS.

This paper presented a PI, Fuzzy logic and SMC controller of single phase ac-dc interleaved PFC boost converter. The various conditions are considered for testing the simulation results. After variation in the input voltage output voltage remains constant. Simultaneously by changing the resistive load in the system of simulation model does not effect on the output voltage.

Hardware results also shows the same expected results. Slight variations in the output voltage observed at the time of hardware experimentation. The simulation and hardware result shows that PI control is most robust and stable. This method which is proposed in this paper further may be investigated in other topologies of converters.

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