Investigation on Performance of Controllers for Three Level PFC Converter for Wide Operating Range

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***Abstract*—Single phase single-stage three level AC-DC power factor correction converters are commonly used as switch mode power supplies in telecommunication systems to provide effective power conversion with good operating performance. This paper deals with the comparative analysis of the converter response with four different control techniques, namely proportional integral and derivative controller (PID), fuzzy Logic controller (FLC), sliding mode controller (SMC), and average current controller (ACC) for wide operating conditions. Necessary analytical equations are derived to observe the dynamic behavior of the converter. Simulations are done with MATLAB/Simulink, and the responses of the PID, FLC, SMC, and ACC are compared for line and load regulations. It is observed that the average current control technique yields better transient and dynamic response than the other three control techniques. The effective performance of the ACC is validated through experimentation.**

***Index Terms*—fuzzy control, PI control, sliding mode control, switching converter, system performance.**

I. INTRODUCTION

Since recent years, switch mode power supply (SMPS) has been playing a vital role in telecommunication systems, PCs, battery chargers etc. In telecom equipment, energy conversion is made possible using SMPS in an effective manner under various operating conditions. Designing of SMPS can be done with two power factor correction (PFC) techniques: active PFC and passive PFC.

Active power factor correction technique has two methods: two-stage PFC method and single stage power factor correction (SSPFC) method. Two stage PFC converters become complex and difficult to design with passive elements [1-3]. Due to complex structure, SMPS has lower efficiency at all operating conditions. To overcome these issues, SSPFC has been considered for discussion in this paper. SSPFC converters with discontinuous mode of operation are widely used only for low power application due to excessive voltage stress that appears across the converter switches [4-6]. This voltage stress can be reduced by balancing the voltage across DC-link capacitors. The improved dynamic performance of the buck- boost power factor correction converter with hybrid controllers is examined for various operating conditions [7-8].

Dynamic performance of DC-DC converter is analyzed with conventional PI (proportional and integral) and fuzzy logic controllers under different operating conditions [9-10]. Disturbance rejection and better dynamic response are achieved by using PI controller, FLC, and SMC for DC-DC converters. Among these three controllers, sliding mode controller ensures better dynamic performance for line variations and load variations [11]. Output voltage can be effectively regulated by proper tuning of PI controller and FLC to achieve better operating characteristics than fixed frequency SMC of the buck converter [12]. DC-DC converter is implemented in real time to obtain improved response under non-linear conditions [13-14]. Detailed comparative analysis has been carried out with PI and sliding mode controllers under line and load changes for DC-DC converter and super lift Luo converter [15-16]. High efficiency, lower voltage stress and ZVS operation are ensured with the balancing of DC link capacitor voltages in bridgeless AC-DC converter topology. Switching and conduction losses are diminished by removing the diode bridge rectifier and ensuring ZVS operation by balancing DC link capacitor voltages over wide operating ranges [17]. Average and indirect current control techniques provide better performance under various operating conditions than PI, FLC and SMC in power converters. Better dynamic response is achieved using current controllers for DC-DC converter topologies [18-23]. Comparative analysis of output performance is carried out in forward and fly back converter topologies [24].

Based on the above literature, it is understood that PID, FLC, SMC, and ACC controllers have played a vital role in achieving better dynamic response from DC-DC converter topologies. With respect to single stage three-port full-bridge PFC converter, conventional PWM and phase shift modulation have been proposed in [25]. However, as there is no proper literature found with regard to the controllers for AC-DC power factor correction converters, the authors propose these four controllers in this paper. The performance analysis carried out recommends the selection of an effective controller for wide line and load variations.

This paper is structured as follows: in Section 2, the working of three-level AC-DC PFC converter is presented in brief. Section 3 describes the proposed control techniques for the SSPFC converters. Section 4 discusses the simulated results followed by comparative analysis at length. In section 5, hardware realization is presented.

II. BRIEF ON THREE LEVEL AC-DC POWER FACTOR CORRECTION CONVERTER CIRCUIT

Single-stage three level AC-DC PFC converter shown in Fig. 1, is the combined topology of an AC-DC PFC circuit

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with three level converter [6]. Two independent controllers are incorporated in single converter itself to carry out the power factor correction and DC-DC regulation as well. The auxiliary diodes D_{x1}, D_{x2}, and D_{x3} are used to obtain power factor correction at the input side. D_{x1} is an auxiliary diode that provides boost operation at the input side. These diodes are responsible for providing a freewheeling path for the primary current when energy transfer happens. The DC-link capacitors (C_1) and (C_2) are designed to balance half of the DC link voltage at steady state condition in such a way that they reduce voltage stress across the converter switches. The output voltage is regulated using Schottky rectifier with output side passive filter to reduce ripple content with low noise level.

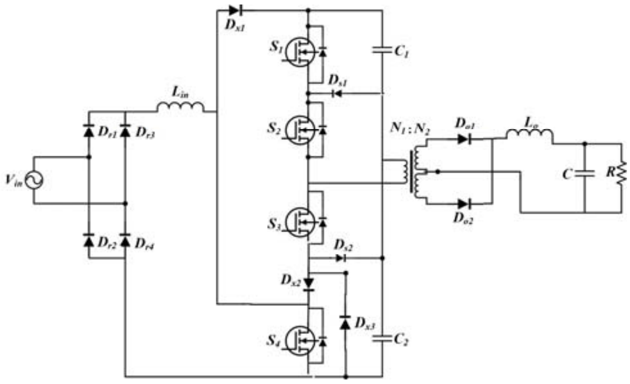

Figure 1. Single Phase Single Stage Three Level full bridge AC-DC Converter

This converter operates under discontinuous conduction mode as desired [6]. Discontinuous input current is considered here to ensure high power factor and improved dynamic performance under various operating conditions.

III. Controllers for Three Level AC-DC PFC Converter

Control structure of three level AC-DC PFC converter consists of outer and inner loop controllers for output voltage and input current as shown in Fig. 2. Inner current loop is designed to improve power quality parameters, and outer control loop ensures regulated output voltage with improved steady state and dynamic responses under wide operating conditions.

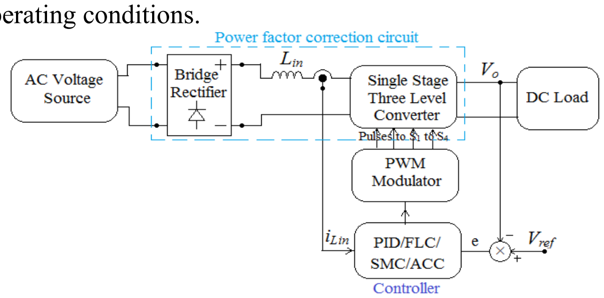

Figure 2. Block diagram for Single Stage Three Level full bridge AC-DC Converter with four different control methods

In this paper, four different control techniques are designed with voltage controller and current controller to achieve good dynamic responses under various operating conditions. Each control strategy has its very own ups and downs to overcome the issues arising from the converter. From each controller, the resultant switching signals are fed to drive the converter switches.

A. *PID Controller*

One of the most commonly used classical controllers is PID controller. Desired control signal is generated from feedback control of output parameters such that error signal can be minimized to approximately zero. Error signal is generated from the compared result of actual output with reference. The initial gains of controller have been found using Ziegler Nichols method and then tuning has been done by trial and error method. Tuned gain values are K_p=0.001, K_i=10, and K_d=10.

B. *FLC Controller*

Experts' thinking and mathematical principles are the main driving forces in fuzzy logic controller to solve the problems in non-linear systems. FLC stabilizes the converter system against wide range of non-linear conditions by choosing proper linguistic variables. FLC is designed with three different stages, namely fuzzification, fuzzy inference, and defuzzification for each loop using the control algorithm. Control algorithm depends on the expert's knowledge to interpret the best solution for the converter system under variations in line side and load side.

TABLE I. CONTROL RULES FOR FUZZY LOGIC CONTROLLER

de \ e	NH	NL	MIN	PL	PH
NH	MIN	NL	NH	NH	NH
NL	PL	MIN	NL	NL	NH
MIN	PH	PL	MIN	NL	NH
PL	PH	PL	PL	MIN	NL
PH	PH	PH	PH	PL	MIN

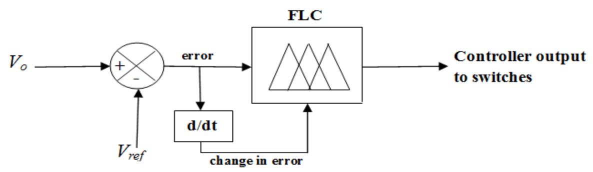

Figure 3. Schematic diagram for FLC for three level PFC AC-DC converter

Actual output parameters are compared with the reference value at each interval to determine the actual error and change in error as shown in Fig. 3. Simulation is done with Matlab/Simulink with five triangular membership functions, namely NH (Negative High), NL (Negative Low), MIN (Minimum), PH (Positive High), and PL (Positive Low) which are used as linguistic input variables to obtain the desired output. The rule base developed for FLC control loop is listed in Table I.

C. *Sliding Mode (SM) Controller*

Non-linear control techniques have been intended to obtain the satisfactory converter performance even under non- linear conditions present in the system. Sliding Mode Control (SMC) is the efficient non-linear controller among all other non-linear control methods for variable structure system. Designing of sliding mode controller has three states, namely, hitting state, existence state, and stability state to reach the stable equilibrium point at the sliding manifold. SMC is designed with one outer voltage and inner current loops. General form of modeling equation of the converter is given by

$$\dot{v} = Av + Bu + D \tag{1}$$

The following three basic equations are framed with state variables to design the sliding mode controller under DCM operation.

$$x_1 = V_o - V_{ref} \tag{2}$$

$$x_2 = V_{c1} - V_{c1ref} \tag{3}$$

$$x_3 = V_{c2} - V_{c2ref} \tag{4}$$

The following control law is necessary to verify the hitting state of the SMC with assumed state variables (x_1, x_2, and x_3),

$$u = \begin{cases} 1 \rightarrow u_B = 0 \rightarrow S \rangle 0 \\ 0 \rightarrow u_B = 1 \rightarrow S \langle 0 \\ 0 \rightarrow u_B = 0 \rightarrow S \langle 0 \end{cases} \tag{5}$$

Existence state of the SMC provides the desired path for sliding state variables to satisfy the local reachability condition in each subinterval. The general form of existence condition is given below:

$$\lim_{S \to 0} S\dot{S} < 0 \tag{6}$$

The specific existence conditions for the SMC for the three level AC-DC PFC converter under DCM are given below:

$$\dot{S}_{S \to 0} = K^T Ax + K^T Bv_{S \to 0} > 0 \tag{7}$$

$$\dot{S}_{S \to 0} = K^T Ax + K^T Bv_{S \to 0} < 0 \tag{8}$$

where, $K^T = [K_1\ K_2\ K_3]^T$ – sliding coefficient matrix

Existence condition leads the state variables to follow the reference sliding path to reach the stable equilibrium point. Stability of the converter system is assured by proper designing of control law and sliding variables to get better dynamic response against line and load variations. Stability of the system is verified by the following sliding plane equation:

$$S = K_1 x_1 + K_2 x_2 + K_3 x_3 \tag{9}$$

where, S is Instantaneous state trajectory. K_1, K_2, and K_3 are tuning parameters being tuned by iterative method to improve steady state and dynamic responses of the converter system. Iterative procedure is repeated until satisfactory response from the converter system has been obtained. Simulation part is done and verified with Matlab/Simulink. Sliding coefficients are computed by iterative procedure (K_1=500, K_2=2.5, and K_3=2.5).

D. Average Current Controller

Accurate control of average input and output currents is achieved by average current control. Also, this method assures higher noise immunity compared to other three control methods. Hence, for medium and low power applications, average current control method is a suitable solution to achieve better power quality parameters and dynamic response of converter system against line and load variations. In this control method, both input and output currents are sensed and controlled using current sensing elements. In inner and outer control loops, the error signals are generated by comparing both actual output voltage and inductor current with their reference values. Generated error signals are processed and controlled through PI controllers with proper tuning of gain constants to drive the converter switches.

Simplified small signal equations for the converter are derived as follows:

$$L_{in}\frac{d(I_{Lin} - \tilde{i}_{Lin})}{dt} = [(V_{in} + \tilde{v}_{in}) - \frac{1}{n}(V_o + \tilde{v}_o)][1 - (D_1 + \tilde{d}_1) - (D_2 + \tilde{d}_2)] \tag{10}$$

$$C_1\frac{d(V_{c1} - \tilde{v}_{c1})}{dt} = (I_{Lin} + \tilde{i}_{Lin})[1 - (D_1 + \tilde{d}_1) - (D_2 + \tilde{d}_2)] - \frac{(V_o + \tilde{v}_o)}{nR} \tag{11}$$

$$C_2\frac{d(V_{c2} - \tilde{v}_{c2})}{dt} = (I_{Lin} + \tilde{i}_{Lin})[1 - (D_1 + \tilde{d}_1) - (D_2 + \tilde{d}_2)] - \frac{(V_o + \tilde{v}_o)}{nR} \tag{12}$$

Rearranging the above equations using small signal analysis, the following is obtained

$$G_{ic}(s) = \frac{V_o(1 - D_1 - D_2)R - sL_{in}I_{Lin}nR}{nR(1 - D_1 - D_2)^2 + s^2 L_{in}nRC + snL_{in}} \tag{13}$$

Transfer function of inner current loop is obtained by substituting the designed values of R, L_{in}, $n=N_1/N_2$ and C ($C=C_1+C_2$) in the above equation.

IV. SIMULATION RESULTS

Simulation parameters for the three level AC-DC converter are shown in Table II. Switching frequency of the converter has been chosen to be above 20 kHz due to inherent nature of this converter.

TABLE II. SIMULATION PARAMETERS

Parameter	Symbol	Value
Source Voltage	V_{in}	110 V-260 V
Output Voltage	V_o	48 V
Inductor	L_{in}	50 µH
Capacitors	C_1,C_2	2200 µF
switching frequency	f_s	50 kHz
Efficiency	η %	92 %

Simulation of three level PFC AC-DC converter is done with PID controller, FLC, SMC and ACC. Simulation of the converter with four controllers has been implemented and evaluated against changes that occur in line side and load side.

A. Transient Parameters: Comparison of proposed controllers

Fig. 4 shows the output response with transient parameters for each type of controller. Here, transient parameters like delay time (t_d), settling time (t_s), rise time (t_r), peak time (t_p) and maximum peak overshoot (M_p) are considered for comparative analysis of the four controllers. From Fig. 4(a), performance of the converter with PID controller is quite slow with large settling time of 58 ms with an overshoot of 8 V under sudden changes that occur in the line side. These transient parameters are quite not acceptable with standard values. To improve these values, other three controllers are introduced.

Fig. 4(b) indicates the transient response of fuzzy logic controller for the converter. By applying fuzzy theory, performance of the converter is improved with improved settling time of 8 ms and overshoot of 0.4 V as against PID controller. Similarly, Figs. 4(c) and (d) clearly indicate that the output response of the SMC and ACC are well settled and suitable for low and medium power applications with improved values of transient parameters compared with PID and FLC controllers. Hence, it is inferred that the ACC has better transient response than the other three control methods.

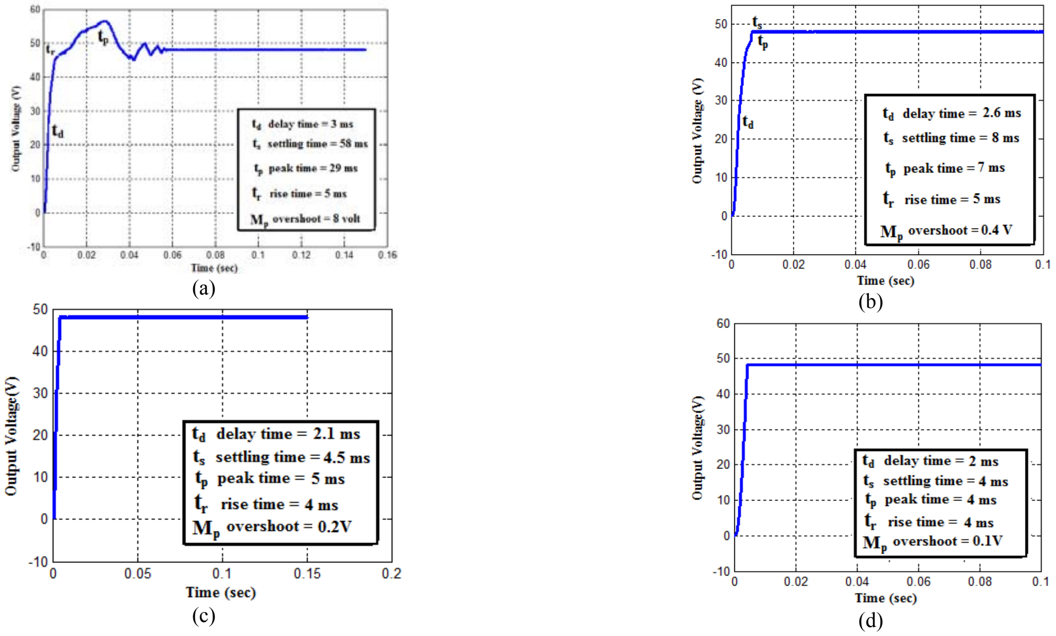

Figure 4. Transient parameters comparison of three level AC-DC converter with (a) PID, (b) FLC, (c) SMC, and (d) ACC controllers

Fig. 5 clearly shows the overall comparative chart with respect to transient parameters for the converter with four different control techniques. From this chart, it could be concluded that ACC has better transient response than the other three methods under various operating conditions.

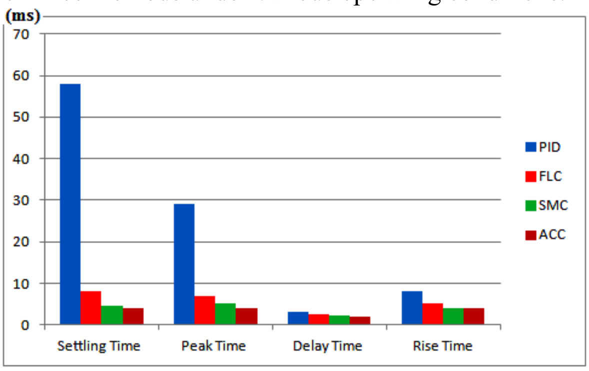

Figure 5. Transient parameters comparison with four control methods

B. Comparative Analysis of the proposed controllers

1) Case.1: Wide Variations Occur in Line Side

Fig. 6a shows the changes in the output voltage due to variations in the input voltage (ranging from 220 V to 180 V to 150 V) for PID controller. From this figure, it is inferred that output voltage is severely affected by sudden changes that occurred in the input side and hence, the settling time of the output voltage is too large to settle down. This effect limits the applications of the converter.

Fig. 6b indicates the response of the output voltage when sudden changes occur in the input side voltages from 220 V-180 V-150 V for FLC controller. Here, the effect of line voltage on output response is quite smaller than the PID controller. Comparatively, FLC has better output response than PID. Likewise, Figs. 6(c) & (d) show the output response of the sliding mode controller (SMC) and the average current controller (ACC) for three level AC-DC converter. These two figures clearly show that the output voltage is well settled during sudden changes occurring in the line side. Output response of SMC and ACC are well settled unlike the PID and FLC. Better performance is achieved with average current controller during line voltage disturbances.

Fig. 7 shows the output response variations with supply voltages for four controllers. From Fig. 7(a), output voltage is analyzed with PID controller for various values of source voltage. Based on the results, it can be seen that the performance of the converter is not satisfactory with PID controller under changes that occur from low to high line voltage conditions. FLC is the optimal controller to get better transient and dynamic performances during high line voltage condition than low line input voltage in comparison to the PID controller as shown in Fig. 7(b). Figs. 7(c) and 7(d) show the output response of SMC and ACC for low and high line voltage conditions. Comparatively, ACC has improved transient and dynamic response against various values of line voltages ranging from 110 V to 300 V.

2) Case.2; Wide Variations Occurring in Load Side

Effect of load variations is clearly portrayed in Figs. 8, 9, and 10 for three level AC-DC converter using different types of controllers. Fig. 8 indicates that the output response of the converter changes with the change in the load ranging from 25% of full load to full load using PID controller. At light loading conditions, the output response has unacceptable dynamic response that leads to poor converter performance. In Fig. 9, output response of the converter using fuzzy logic controller is presented. It ensures that the output response is quickly settled with improved performance parameters as against the PID controller. Similarly, the output response is considered for the sliding mode controller and average current controller under various percentages of loading conditions as shown in Figs. 10(a) & (b). Based on the analysis, it can be stated that SMC and ACC have better performances even under light loading, heavy loading, and during load transition. The converter is investigated with each controller under different percentages of loading and the converter performance is examined as shown in Fig. 11.

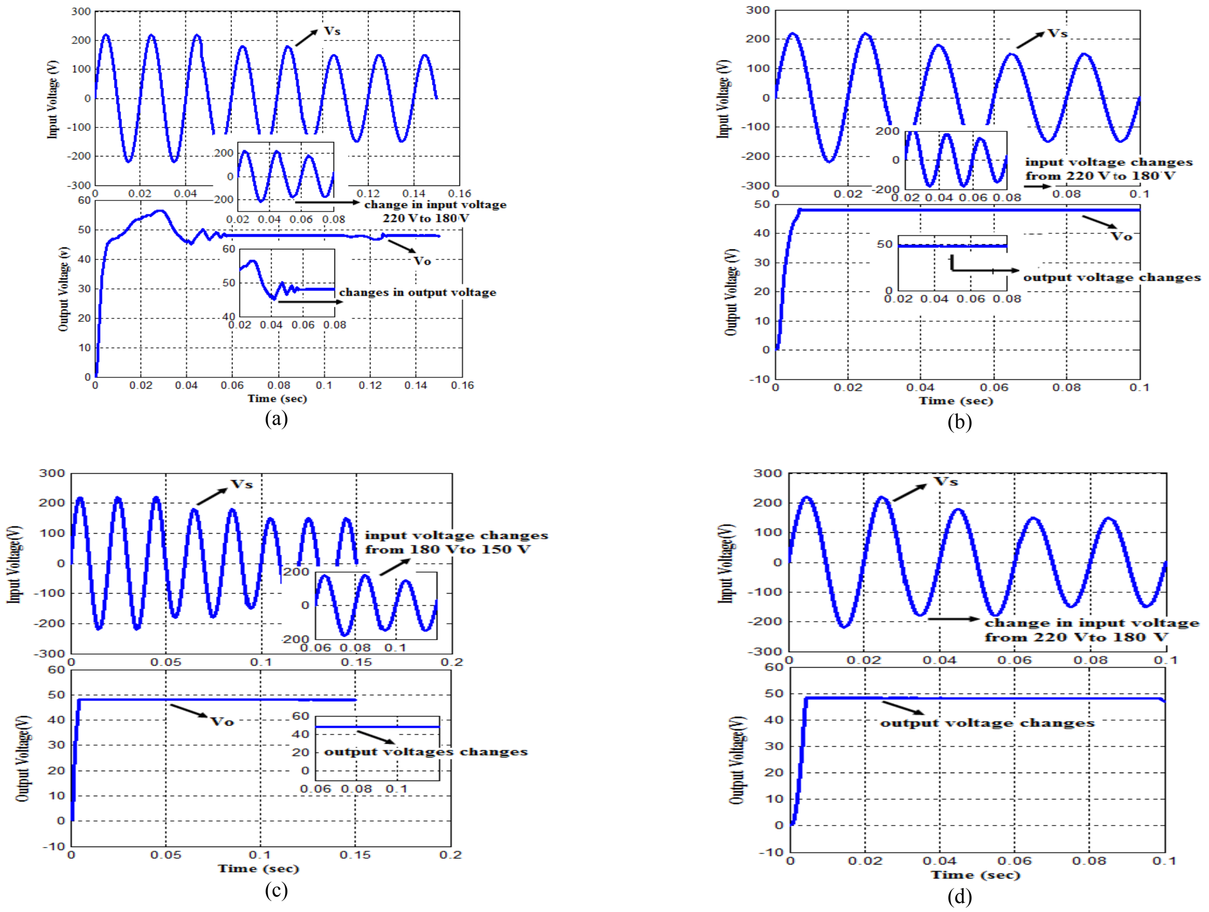

Figure 6. Response of output voltage for the changes occurring in input voltage from 220 V-180 V-150 V for (a) PID (b) FLC (c) SMC (d) ACC

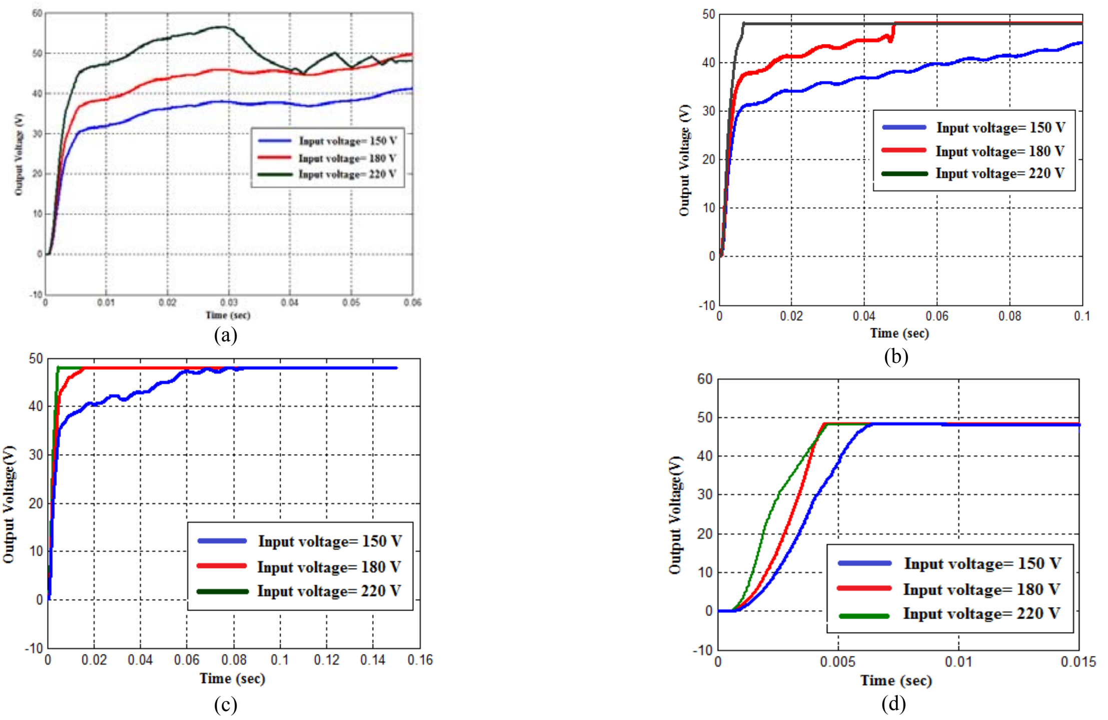

Figure 7. Performance of output voltage for various values of input voltage with four different controllers (a) PID, (b) FLC, (c) SMC and (d) ACC

Figs. 11(a) and (b) exhibit output response of the converter under different loading conditions with PID and FLC. In both controllers, during heavy load condition, stable operation of the converter is better than light load condition. Figs 12(a) and (b) reveal that the output response is well settled with SMC and ACC controller under light load and heavy load conditions and during load transition as well. Converter with ACC is suitable for low and medium power applications under different loading conditions with improved dynamic response.

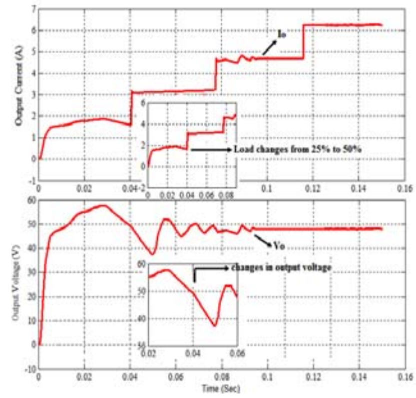

Figure 8. Response of output voltage for the changes that occur in load side from light load to full load for PID controller

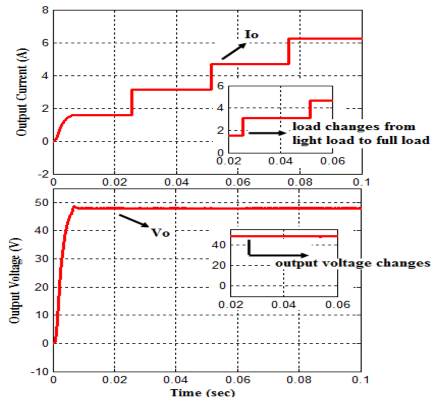

Figure 9. Response of output voltage for the changes occurring in load side from light load to full load for FLC controller

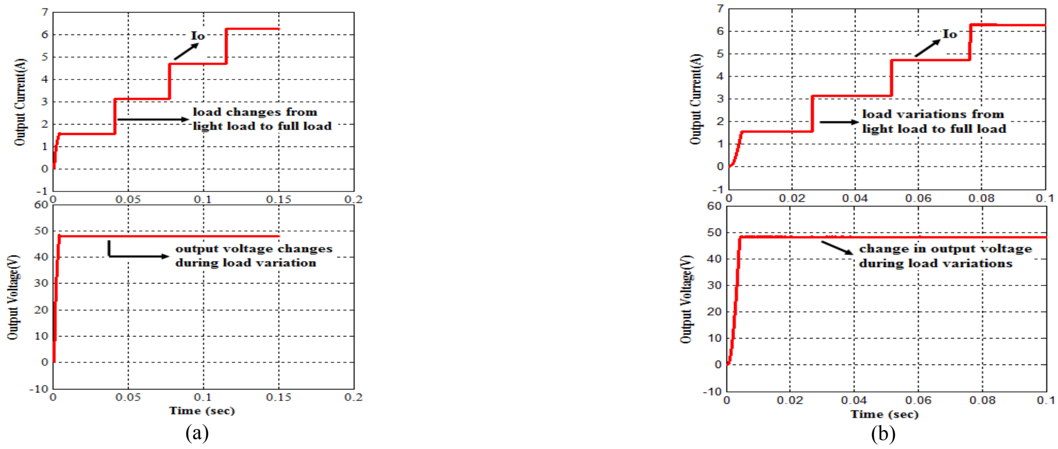

Figure 10. Response of output voltage for the changes occurring in load side from light load to full load for (a) SMC (b) ACC

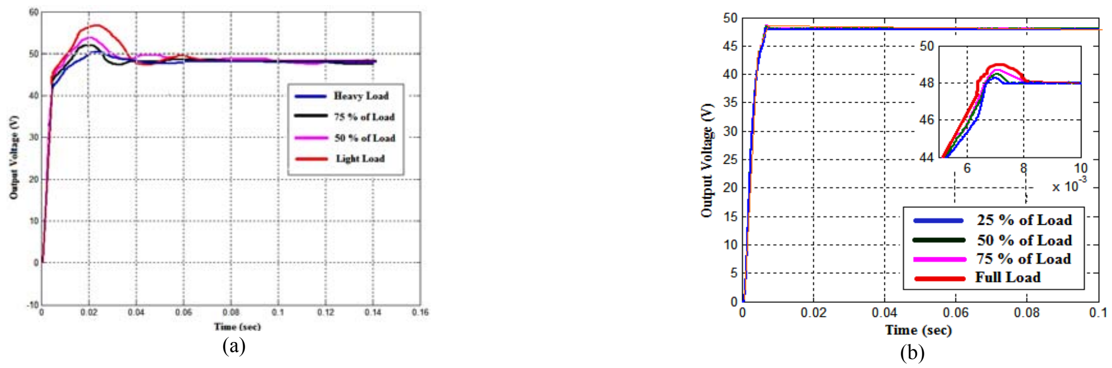

Figure 11. Performance of output voltage for various percentage of loading conditions for (a) PID controller, (b) FLC

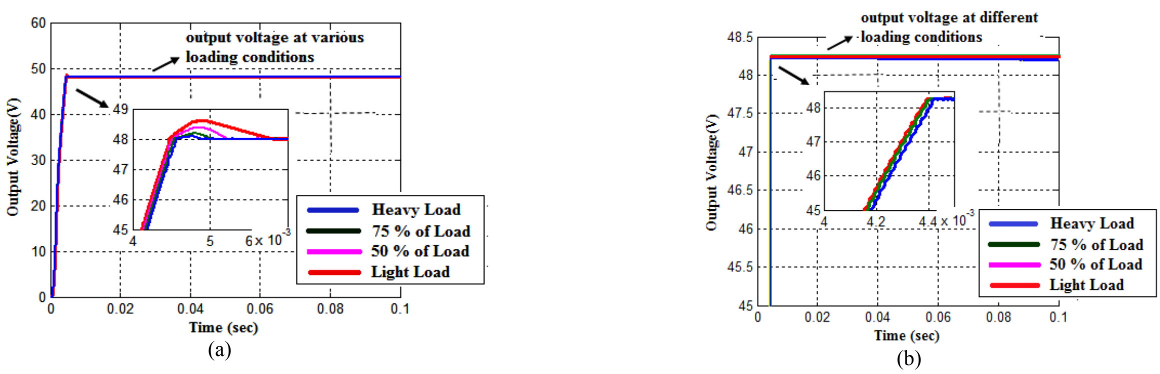

Figure 12. Performance of output voltage for various percentage of loading conditions for (a) SMC (b) ACC

V. Hardware Results

An experimental set-up was developed with the similar design values which were used in the simulation to integrate the theoretical results. Fig. 13 presents the photograph of the experimental set-up which was designed with high current rating MOSFET switches IRF460 and MBR20100. This prototype was controlled by using PIC16F887 and driver circuit of TLP250. From the controller circuit, output voltage and input current were sensed using average current control technique with two PI controllers. Sensed values were given to the driver circuit to generate the control signals for switches.

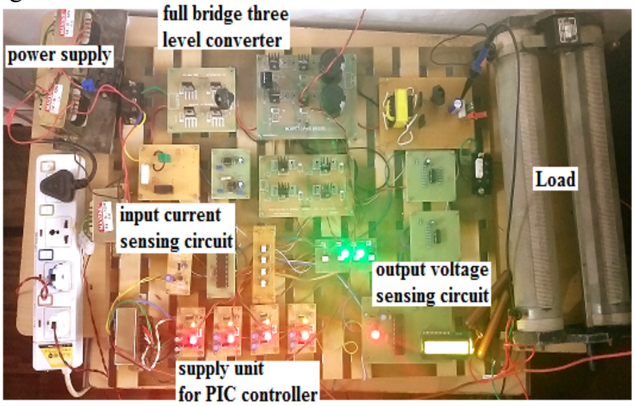

Figure 13. Image of experimental set-up

PIC micro controller supplies the appropriate control signals to the switches via driver circuit as shown in Figs. 14(a) & (b). Fig. 14(c) shows the sudden decrease in input voltage from 230 V to 180 V. To verify the stable operation of the converter response using average current control technique, a sudden decrease in input voltage was introduced. Fig. 14(d) indicates the small change of 0.3 V in the output response during sudden variations in the input voltage from 230 V to 180 V.

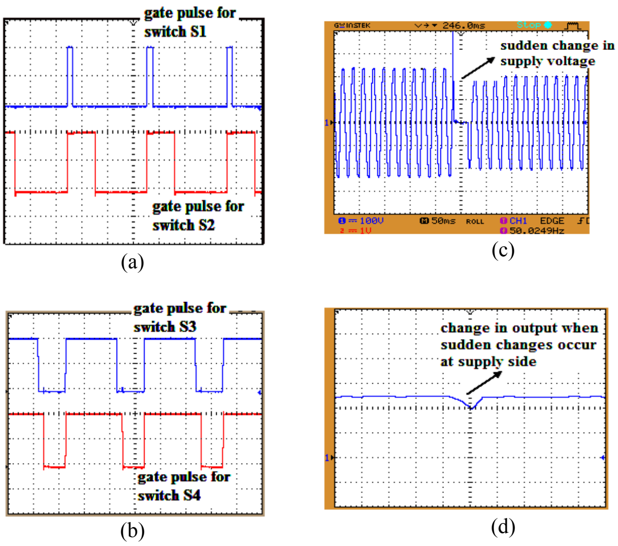

Figure 14. Experimental results (a) Generated control signals (X axis = 10 µs/div; S1 and S2: Y axis = 2 V/div) (b) control signals (X axis = 10 µs/div; S3 and S4: Y axis = 2 V/div) (c) sudden decrease in input voltage (X axis = 5 µs/div; Y axis = 100 V/div) (d) change in output voltage during sudden change in input voltage (X axis = 5 µs/div; Y axis = 20 V/div)

Similarly, Fig. 15(a) shows the sudden increase in input voltage from 180 V to 230 V to verify the stable operation of the converter. Fig. 15(b) indicates the small change in the output response during sudden variations in the input voltage from 180 V to 230 V. Fig. 16(a) represents the sudden increase in the load from 190 W to 250 W with respect to load current. Fig. 16(b) shows the well settled output response even under sudden change in the load value. These two experimental figures indicate that the output response of the converter is well settled even under wide variations occurring on line and load sides using average current control technique.

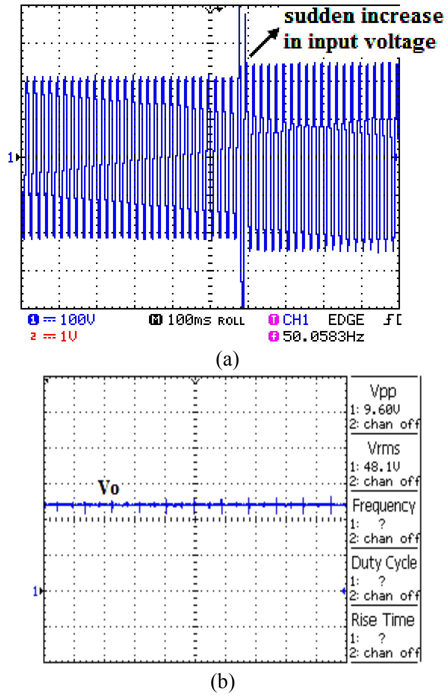

Figure 15. Experimental results (a) sudden increase in input voltage (X axis = 5 µs/div; Y axis = 100 V/div) (b) change in output voltage during sudden increase in input voltage (X axis = 5 µs/div; Y axis = 20 V/div)

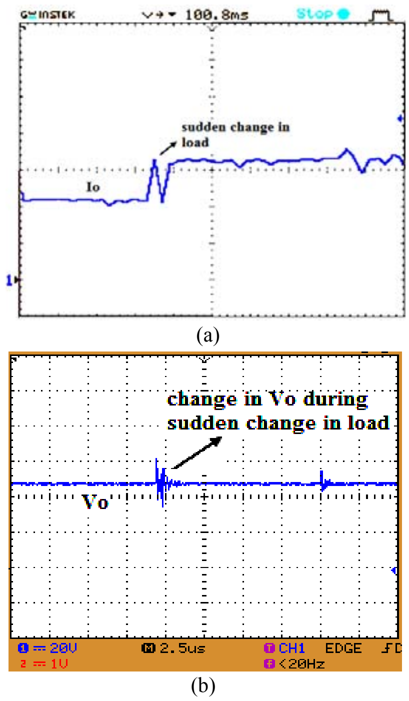

Figure 16. Experimental results (a) sudden increase in load 190 W to 250 W (X axis = 5 µs/div; Y axis = 2 A/div) (b) change in output voltage during sudden change in load (X axis = 5 µs/div; Y axis = 20 V/div)

VI. CONCLUSION

PID, FLC, SMC, and ACC based output voltage control of the single stage three level full-bridge AC-DC converter was investigated and compared under wide operating conditions. Time domain specifications were analyzed using four controllers and the results were compared with one another. Based on the comparative analysis, the ACC based controller was found to be more effective and efficient than PID, FLC and SMC to obtain transient and dynamic response for wide variations on line and load sides. The settling time obtained in the output voltage using ACC was 90% less than the PID controller and 70% less than FLC and SMC based controllers. Experimental set-up was built with ACC and the results were verified with simulated results.

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