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Original scientific paper

Direct Power based Sliding Mode Control of AC-DC Converter with Reduced THD

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Abstract: Direct Power based Sliding Mode (DPSMC) control for controlling single phase AC-DC pre regulator assuring unity power factor and stable output voltage under load variation is proposed in this paper. Direct Power Based Control (DPC) commonly applied for three phase circuits, is combined with Sliding mode control (SMC) to control and regulate the single-phase AC-DC pre regulator. The proposed DPSMC apart from being simple to design and robust to parameter variations also helps in reducing the line current distortion inherent to AC-DC Converters. The design of the proposed power based sliding mode control along with its existence condition is discussed. The performance of the proposed method over conventional sliding mode control is assessed through computer simulations and the feasibility of the proposed controller is confirmed through experimental implementation carried out with the help of LabVIEW and sbRIO FPGA development board.

Keywords: AC-DC Converter; Direct Power Control; Sliding Mode Control; THD; Non Linear Controllers

1 INTRODUCTION

AC-DC converters find a wide range of application in our day-to-day life in homes in the form of chargers, LED based lighting, etc. Conventional AC-DC converters use a diode rectifier followed by a DC link capacitor drawing a non sinusoidal AC line current from the supply, injecting higher order harmonics into supply mains and result in the reduction of power factor [1]. With the emerging use of AC-DC converters at the consumer end, strict regulations such as IEC 61000-2-2, have been imposed to regulate the Power factor of these devices [2].

To mitigate the above problem, power factor pre-regulator circuits are widely used, which introduces a boost converter in between the diode rectifier and the load. Power factor pre- regulator topology, remains to be an ample choice for low power applications where the power transfer is unidirectional, because of its simplicity of design and control [3].

Many linear as well as non-linear control strategies have been proposed in literature, to control the output voltage and to regulate the power factor of these converters. Model based linear Average Current mode control proposed in [4] seems to work fine under predefined operating points, but its performance gets deteriorated with variable load conditions. Feed forward current mode control [5, 6], mitigates the problems with averaged mode control by generating a duty cycle in proportion to the supply voltage and the desired output, but suffers from duty ratio saturation at converter start up and slow response to load variations. Digital controllers proposed in [7, 8] have faster response to load variations, but are complex to implement.

In recent days, because of the nonlinear characteristics of AC-DC converter introduced by the switching action of the switch, Non linear control methods like hysteresis control, fuzzy control and Sliding mode control are widely used to control and regulate these converters. Fuzzy mode controllers proposed in [9] and [10] are robust, but the accuracy and performance of the controller is highly dependent on the selection of number of fuzzy variables and fuzzy logic rule base. The real-time implementation of the controller is limited due to its tedious fuzzy rule tuning and its need for significant computational resources.

Sliding mode controller (SMC) initially used for the control of Variable structure systems, is gaining importance in the field of power electronics because of its robustness to disturbances [11, 12]. Chattering problem predominant in sliding mode control is minimized by using fixed switching frequency sliding mode control as proposed in [13]. However, the performance of the controller depends on the selection of sliding variables and the dynamic response is highly dependent on the sliding mode constant as proposed in [14].To overcome the above difficulty a Rotating sliding mode control employing a time variable slope based sliding surface has been proposed in [15]. Even though the dynamic response of the converter is improved, it takes time for the tracking error to become zero.

To improve the dynamic response and to reduce the settling time, PID controller based SMC replacing the sliding mode constant with PID controller parameters has been proposed in [16]. Even though the performance is better, the performance of the controller is still dependent on the tedious tuning of PID parameters and requires tedious tuning algorithms and optimization techniques as proposed in [17, 18]. The DPSMC proposed here not only being simple to implement and robust to disturbances, it overcomes the problems in the selection of sliding co-efficient, which is evident with the sliding mode control.

Direct Power control (DPC) previously used for Direct flux control of Induction motor is emerging as an attractive control strategy for the control of grid connected Three Phase converters because of its simplicity, robustness and fast dynamic response [19]. By [20], DPC directly regulates the Instantaneous Active and Reactive power of a three-phase circuit by the proper selection of switching states. [21] & [22] have proposed the feasibility of applying DPC to switched mode three phase power converters by using an outer PI controller and an inner Fuzzy based switching state selector to select the switching states of the converter. All these DPC methods proposed in the literature aim at the regulation and control of three phase converter circuits and a very little emphasis is given to the control of single-phase systems. DPC could be extended to control and regulate single-phase systems.

In this paper, a Direct Power based sliding mode Control (DPSMC) for the control and regulation of single-phase AC-DC power factor pre-regulator is proposed. The proposed control strategy consists of a DPC based outer loop controller generating the reference current for the inner current loop SMC controller. The proposed control, apart from being simple, provides a robust output under disturbances with reduced line current distortion. Section II presents the system modelling and the control objective along with the traditional PI based sliding mode control as proposed in [16]. The DPSMC proposed is discussed in section III, followed by its existence condition and the sliding mode load estimator. Section IV provides the comparative simulation results of the proposed control strategy over the traditional SMC. Simulation results are justified by the hardware experimentation results of the proposed control method in section V followed by the conclusion.

2 SYSTEM MODEL AND CONTROL OBJECTIVE

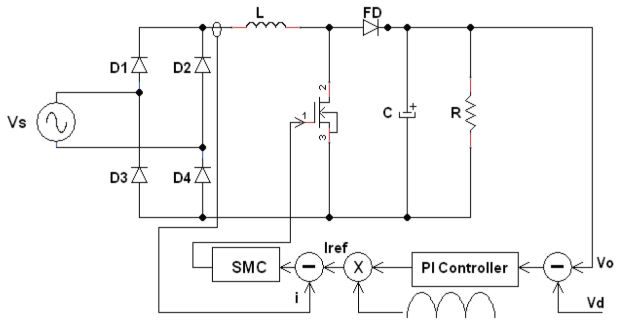


Figure 1 Traditional PI based SMC

Fig. 1 gives the model of the AC-DC pre regulator circuit selected along with the traditional PI based SMC controller. The circuit selected is a simple diode rectifier, followed by a boost converter. To get the desired output voltage with a sinusoidal line current, which is in phase with line voltage, the controller controls the switch position. Eq. (1) gives the behaviour of the circuit proposed,

$$L\frac{\mathrm{d}i(t)}{\mathrm{d}t} = v_{\mathrm{r}}(t) - uv_{\mathrm{o}}(t), \quad C\frac{\mathrm{d}v_{\mathrm{o}}(t)}{\mathrm{d}t} = ui(t) - \frac{v_{\mathrm{o}}(t)}{R}. \tag{1}$$

where $v_s = V_m \cdot \sin \omega t$ is the input AC supply; $v_r(t)$ is the full wave rectified voltage available at the output of full bridge rectifier, $i(t)$ - being the current through the inductor and $v_o(t)$ being the output DC voltage. u is the control signal defining the position of the switch and is given by Eq. (2),

$$u = 1 \text{ Switch in On - state}, \quad u = 0 \text{ Switch in Off - state}. \tag{2}$$

2.1 Control Objective

The controller is designed to meet the following control objectives: 1) The converter should draw a sinusoidal line current which is in phase with the line voltage guaranteeing a unity power factor at AC mains 2) Output DC voltage Vo should be greater than the input supply voltage V_s ensuring boost operation

Because of the non-minimum phase behaviour of the proposed converter circuit with respect to output voltage, the controller regulates the output voltage indirectly by forcing the converter input current to track a desirable current profile.

2.2 Traditional PI based SMC

In case of Traditional SMC, an outer PI based Voltage loop controller generates the reference current signal i_{Ref} for the inner SMC based current loop controller as depicted in Fig. 1. Eq. (3), gives the sliding surface selected

$$S = i - i_{\mathrm{Re}f} \tag{3}$$

with the control signal given by Eq. (4)

$$u = sign(S), \quad S < 0,\ u = 1, \quad S > 0,\ u = 0 \tag{4}$$

where $i_{\mathrm{Ref}} = \beta \sin \omega t$, with β being the output of outer loop PI controller and is given by

$$\beta = k_{\mathrm{p}}(V_{\mathrm{d}} - v_{\mathrm{o}}) + k_{\mathrm{i}}\int (V_{\mathrm{d}} - v_{\mathrm{o}})\,\mathrm{d}t \tag{5}$$

where k_p and k_i are the gain constants of the PI Controller, derived based on the small signal model of the converter under nominal operating conditions.

From Eq. (5), the performance of the traditional SMC is highly dependent on the values of k_P and k_i. As the gain constant values are selected for some nominal condition, the performance of the traditional SMC deteriorates under wide load disturbances and a lot of tuning has to be done in selecting a perfect gain constant to get a better performance as proposed in [2].

DPSMC overcomes the above difficulties of traditional SMC by generating the reference current signal i_{Ref} by the outer loop Direct power based Controller (DPC) based on input – output power balance providing a better performance under a wide range of operating conditions.

3 DIRECT POWER BASED SMC

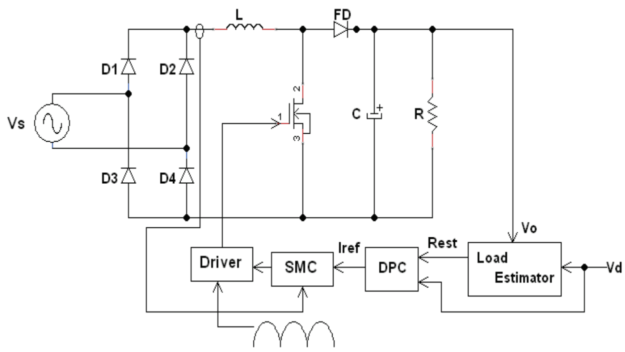


Figure 2 Proposed control structure

Fig. 2 gives the converter model along with the proposed control structure. The DPSMC proposed, aims at achieving unity power factor by forcing the line current to follow the reference current signal i_{Ref} that is in phase with line voltage using the inner loop SMC current controller, with the desired reference current generated by the outer DPC, based on disturbances.

$$i_{Ref} = I_d \sin \omega t \tag{6}$$

where i_{Ref} is the reference current waveform and I_d is the desired current profile generated by the outer loop DPC.

3.1 Proposed DPSMC Controller

As per the Instantaneous power theory, the power converter operates at unity power factor if the power consumed by the converter is purely equivalent to Active power component.

To make the power consumed by the converter equivalent to active power component, the outer loop DPC generates the reference current profile i_{Ref}, by equating the Active power components of Input and output at steady state and the converter is forced to follow the i_{Ref} by the inner loop SMC thus forcing the reactive power component to zero.

Under steady state conditions, Active power component of input is equivalent to the Input DC power component and is given by Eq. (7),

$$\begin{aligned}\left\langle IP\right\rangle_{DC} &= \left\langle v_s i_{Ref}\right\rangle_{dc} = \left\langle V_m \sin \omega t \cdot I_d \sin \omega t\right\rangle_{dc} = \\ &= \left\langle V_m I_d \sin^2 \omega t\right\rangle_{dc} = \frac{V_m I_d}{2}.\end{aligned} \tag{7}$$

Similarly, the output DC component is given by Eq. (8)

$$\left\langle OP\right\rangle_{DC} = \left\langle v_o i_o\right\rangle_{dc} = \left\langle v_o^2 / R\right\rangle_{dc} = \frac{V_o^2}{R}. \tag{8}$$

Equating Eq. (7) and Eq. (8), and solving for I_d,

$$I_d = \frac{2V_o^2}{V_m R}. \tag{9}$$

From Eq. (9), it is evident that the desired current I_d is dependent on the converter parameters V_o – desired output voltage, V_m peak value of supply voltage and the value of load resistance R and the performance of the proposed DPSMC depends on accurately sensing the above parameters.

Because of the practical difficulty in accurately sensing load resistance R, the value of load resistor is estimated using a sliding mode based load estimator and its design is also discussed later in this paper.

3.2 SMC based Inner Loop Control

DPSMC uses an inner loop SMC controller to force the inductor current follow the desired reference current profile. The first phase in the design of the sliding mode controller is the selection of sliding surface, such that system trajectory when forced to the surface will have the desired dynamics. The following sliding surface is selected to force the inductor current to follow the reference current i_{Ref}.

$$S = i - i_{Ref}. \tag{10}$$

With control signal u given by

$$\begin{aligned}&u = sign\,(S)\\ &S < 0, u = 1\\ &S > 0, u = 0\end{aligned} \tag{11}$$

Around the Sliding line S = 0, inductor current i and the reference current i_{Ref} would be equal, thus forcing the system to the desired dynamics, $v_o = V_d$ and $i = i_{Ref}$, and thus assuring zero reactive power component.

3.3 Existence condition of DPSMC

Existence condition guarantees the presence of sliding mode around the sliding line. For the sliding mode to exist the following condition needs to be satisfied

$$S\dot{S} < 0 \tag{12}$$

Lyapunov method is used to derive the existence condition of the proposed DPSMC. For the existence of proposed DPSMC, the first derivative of Lyapunouv function selected should be negative definite. The following Lyapunov function is selected for the analysis purpose,

$$V = \frac{1}{2}S^2 \tag{13}$$

and its first derivative is given by Eq. (14)

$$\dot{V} = S\dot{S} \tag{14}$$

where

$$\begin{aligned}\dot{S} &= \frac{d}{dt}\left(i - i_{Ref}\right) == \frac{v_r - uv_o}{L} - \omega I_d \cos \omega t = \\ &= \frac{v_r}{L} - \omega I_d \cos \omega t - \frac{uv_o}{L}\end{aligned} \tag{15}$$

or simply

$$\dot{S} = \varphi - \frac{uv_o}{L} \tag{16}$$

and

$$\varphi = \frac{v_r}{L} - \omega I_d \cos \omega t \tag{17}$$

With the upper band of φ is given by Eq. (18),

$$\varphi = \frac{V_m}{L} + \omega I_d. \tag{18}$$

For the existence of sliding mode control, first derivative of Lyapunov function should be negative definite that is

$$\dot{V} < 0$$
$$\Rightarrow |S|\left(\varphi - \frac{v_o}{L}\right) < 0 \tag{19}$$
$$\Rightarrow v_o > L|\varphi|$$

Substituting Eq. (18) in Eq. (19), the sufficient condition that ensures the existence of the proposed sliding mode is given by

$$v_o > V_m + \omega L I_d. \tag{20}$$

Sub Eq. (9) in Eq. (20), and solving for v_o, gives the minimum value of v_o that needs to be selected for the existence of sliding mode control and is given by

$$v_o > \frac{V_m\left(R - \sqrt{\left(R^2 - 8\omega LR\right)}\right)}{4\omega L}. \tag{21}$$

Eq. (21), gives the lower bound of v_o that needs to be met for the existence of sliding mode control and the proposed control algorithm. From Eq. (21), it is evident that the existence of the proposed DPSMC depends mainly on the circuit components and the desired output voltage.

3.4 Sliding Mode based Load Estimator

From Eq. (9), it is evident that for achieving the design objectives, it is necessary to find the value of load resistor R accurately. This section is devoted to the design of sliding mode based load estimator.

From Eq. (1), the dynamical model of the Estimator is given by

$$C\frac{d\hat{v}_o}{dt} = ui - \frac{\hat{v}_0}{R_n} - V_{eq}, \tag{22}$$

$\hat{v}_0$ is the output voltage estimate, estimated by observing the current, V_{eq} being the equivalent injection applied during sliding mode and R_n being the nominal value of load resistance.

The first derivation of the estimation error e_{v_o} is given by,

$$\dot{e}_{v_o} = \dot{v}_o - \dot{\hat{v}}_o = \left(\frac{v_o}{R_e} - \frac{\hat{v}_o}{R_o}\right)\cdot\frac{1}{C} - V_e. \tag{23}$$

R_e is the estimated Load resistance value. On achieving sliding motion,

$$e_{v_o} = 0, \dot{e}_{v_o} = 0$$
$$\dot{e}_{v_o} = \frac{1}{C}\left(\frac{v_o}{R_e} - \frac{\hat{v}_o}{R_n}\right) - V_e = 0 \tag{24}$$
$$\Rightarrow R_e = \frac{R_n v_o}{(CR_n V_e + \hat{v}_o)}$$

With $V_e = sign(e_{v_o})$, Eq. (24) gives the estimate of load resistance obtained by the sliding mode estimator.

4 SIMULATION RESULTS

To prove the effectiveness of the proposed control method over the traditional SMC, dynamic and steady state performance analysis of the converter with the traditional SMC and proposed DPSMC is done through Matlab/Simulink simulations. Tab. 1 gives the parameter values used for the simulation purpose.

Table 1 Simulation parameters

Supply voltage V_m	6 V
Desired output voltage v_o	12 V
Nominal power output	20 W
Inductor	2 mH
Capacitor	2200 µF
Switching frequency	20 kHz

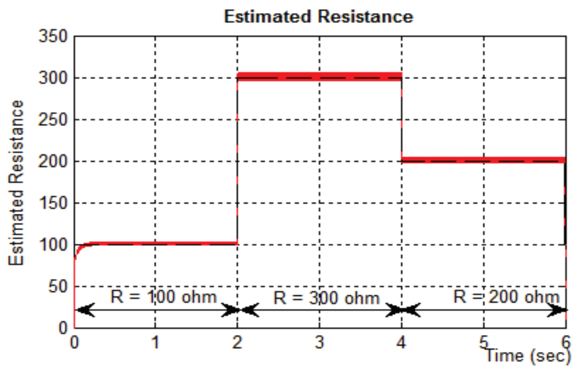


Figure 3 Estimated load resistance

Table 2 Simulation result of converter under SMC and DPSMC

Simulation Parameters			SMC					DPSMC				
V_s (V)	V_d (V)	R (Ω)	T_r (s)	T_s (s)	PO (V)	PU (V)	%THD	T_r (s)	T_s (s)	PO (V)	PU (V)	%THD
5	12	100	0.4	1.1	13.4	11.5	3.38	0.3	1	12.2	11.9	1.21
8	12	100	0.05	0.8	13.2	11.8	5.65	0.1	0.6	12.2	11.7	2.04
6	12	100	0.08	1.0	13.4	11.8	6.93	0.2	0.8	12.1	11.9	2.81
6	12	200	0.08	1.0	14.0	11.5	5.54	0.12	0.7	12.1	11.9	1.33
6	12	300	0.08	1.1	14.1	11.4	5.72	0.14	0.75	12.2	11.8	1.73
6	14	100	0.2	0.8	16.0	13.5	7.70	0.3	0.8	12.1	11.9	1.34
6	8	100	0.05	0.4	8.5	7.8	7.13	0.05	0.4	12.1	11.9	1.46
6	10	100	0.05	0.7	11.0	9.8	7.53	0.05	0.6	12.1	11.8	1.88

T_r, T_s – Rise time and settling time of output voltage; PO, PU – Peak overshoot and peak undershoot of output voltage

4.1 Performance of Sliding Mode Estimator

Fig. 3 gives the performance of the sliding mode based load estimator and it could be seen that the estimator tracks the change in load accurately thus making the proposed control algorithm feasible.

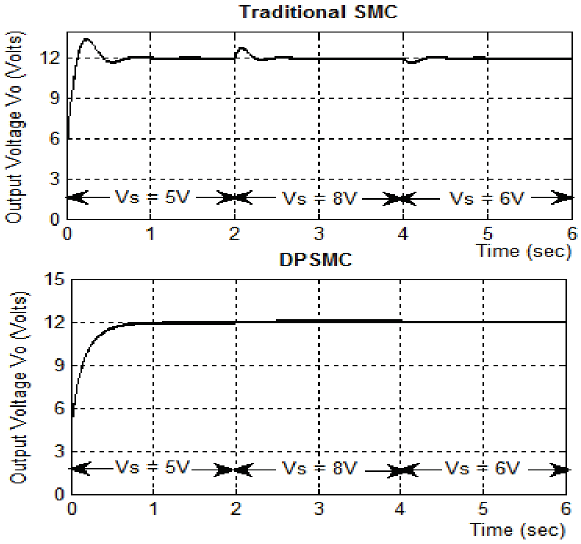


Figure 4 Output voltage with input disturbance

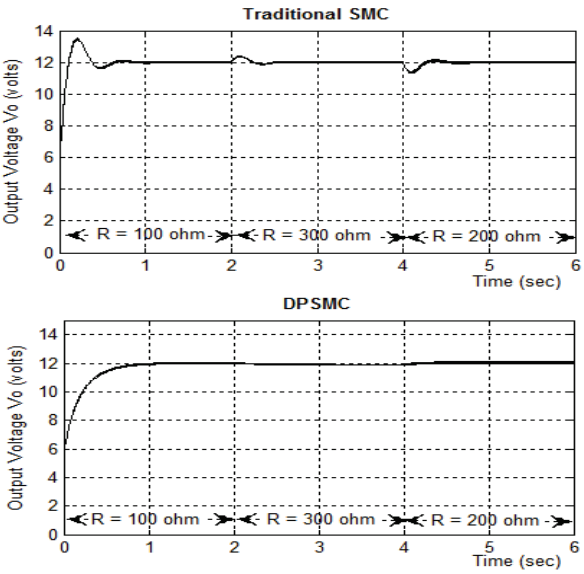


Figure 5 Output voltage with load disturbance

4.2 Performance under Disturbances

Fig. 4, Fig. 5 and Fig. 6, give the output voltage waveform of the converter controlled by Traditional SMC and by proposed DPSMC, with disturbances in supply voltage, load, and with changes in desired voltage.

Tab. 2 gives the results of simulation under various conditions. From the simulation results, it is observed that the voltage output of the converter under DPSMC is free from Peak Overshoot and undershoot which is evident in traditional SMC. This reduces the stress experienced by the load connected at the output of the converter. Apart from being robust to disturbances, the dynamic and steady state performance of the converter under DPSMC is improved and is better compared to its counterpart.

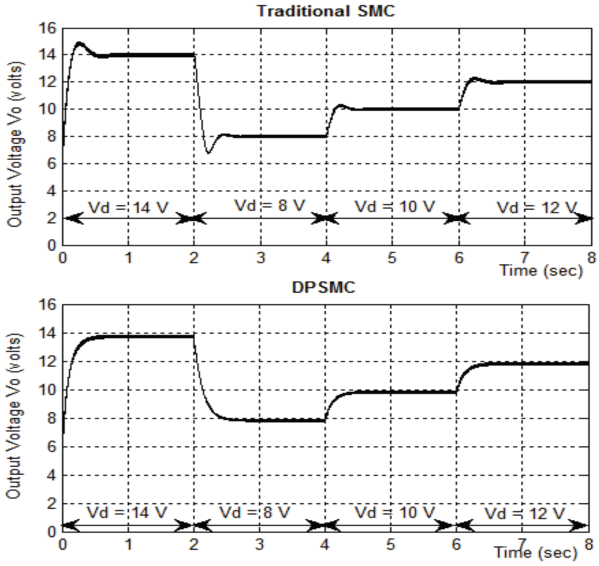


Figure 6 Output voltage with change in desired voltage

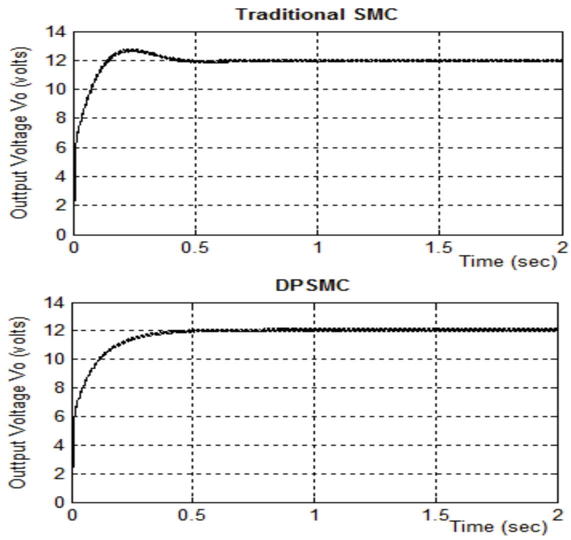


Figure 7 Output voltage under nominal condition

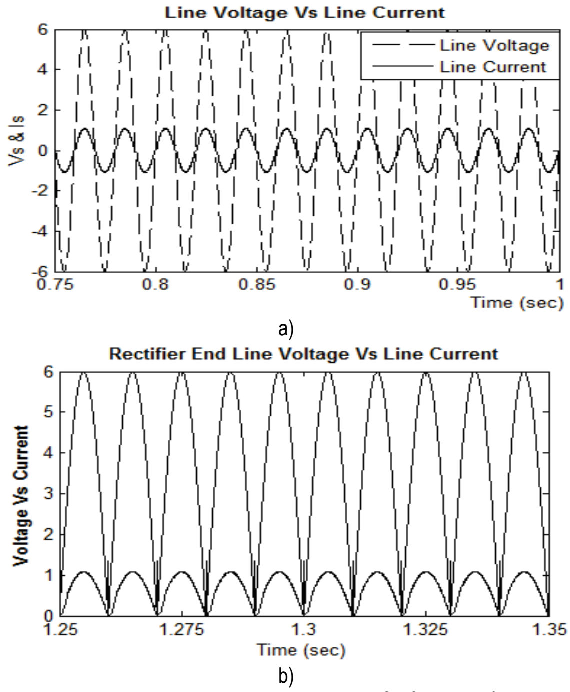


Figure 8 a) Line voltage and line current under DPSMC; b) Rectifier side line voltage and current

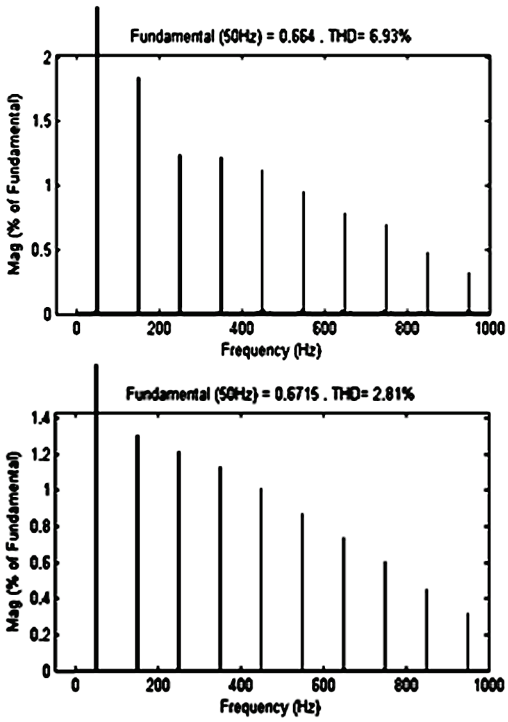


Figure 9 Line current THD under nominal condition

4.3 Performance under Nominal Condition

Fig. 7 gives the output voltage waveform of the converter under nominal operating condition. Fig. 8a (line voltage V_s line current) and Fig. 8b (voltage and current waveform at rectifier end) give the voltage and current of the converter under DPSMC

Fig. 9 gives the THD of line current of the converter under both the control methods. From Figs. 8 and 9, it is evident that DPSMC assures a unity Power Factor with reduced line current THD. From the simulation results it is evident that the proposed DPSMC improves the performance of the converter with a reduced line current THD. The same is verified by using a laboratory prototype AC-DC converter.

5 HARDWARE RESULTS

Implementation of the proposed DPSMC in real time is carried out with the help of LabVIEW, Sb-Rio FPGA development board and NI USB myDAQ devices. The control logic is implemented in the Sb-Rio FPGA development board with 40 MHz clock and USB-myDAQ is used to acquire and generate the visual display of data acquired. ACS712 current sensor is used to sense the line current.

Fig. 10 gives the real time implementation of the controller and Tab. 3, gives the list of parameter used for the real time implementation of the controller.

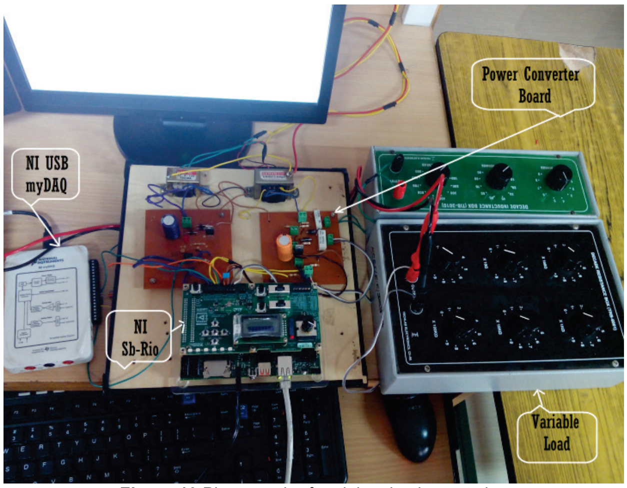


Figure 10 Photograph of real time implementation

Table 3 Real time implementation parameters

Supply voltage V_m	6 V
Desired output voltage v_o	12 V
Output Power	20 W
Inductor	2 mH
Capacitor	2200 µF
Switching frequency	20 kHz

5.1 Performance under disturbances

Figs. 11, 12 and 13 give the real-time output voltage of the converter controlled by DPSMC controller under disturbances in the form of change in supply voltage, change in load and change in desired output voltage. From the figures, it is evident that the real time output of the converter resembles the simulated output and it is clear that the proposed DPSMC is robust to disturbances.

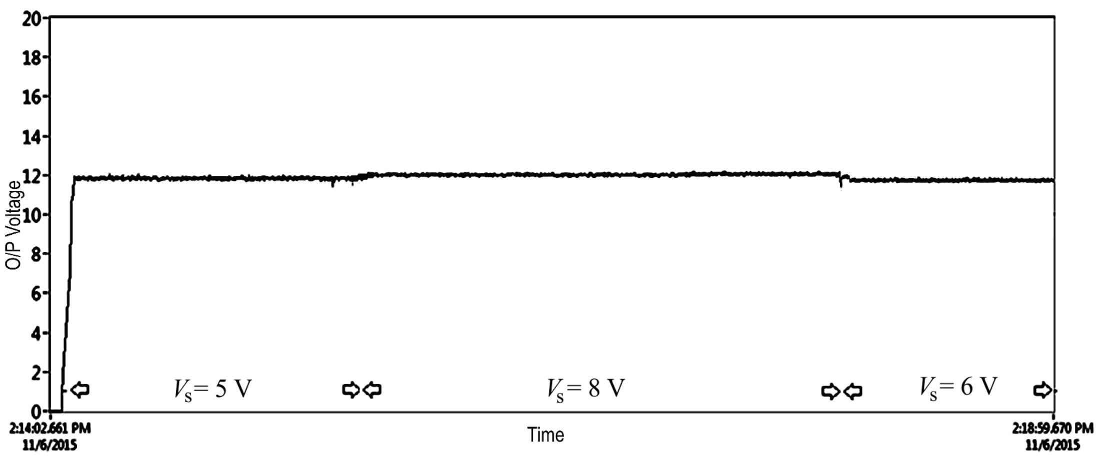


Figure 11 Output voltage under supply variations

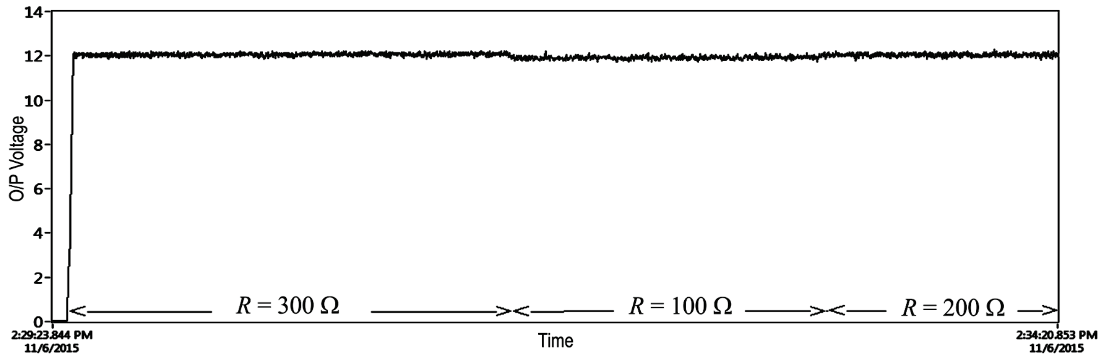


Figure 12 Output voltage under load variations

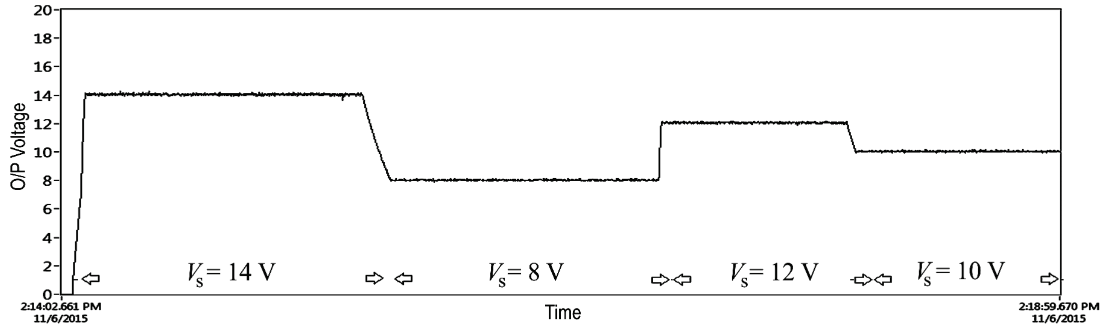


Figure 13 Output voltage with variable desired voltage

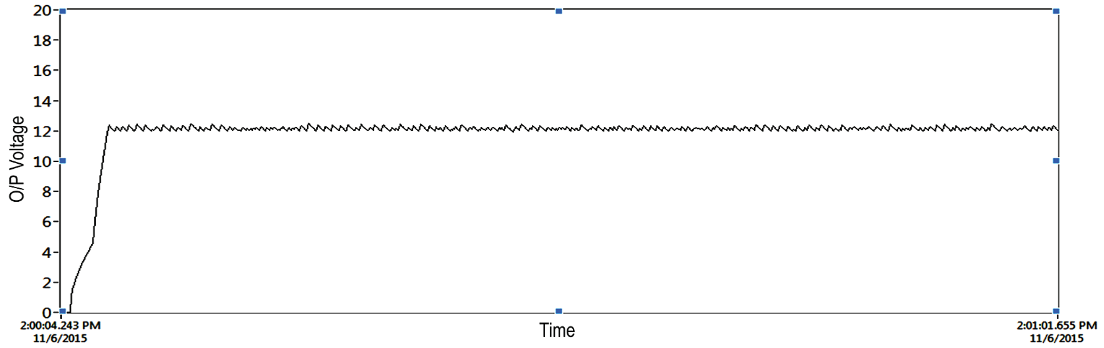
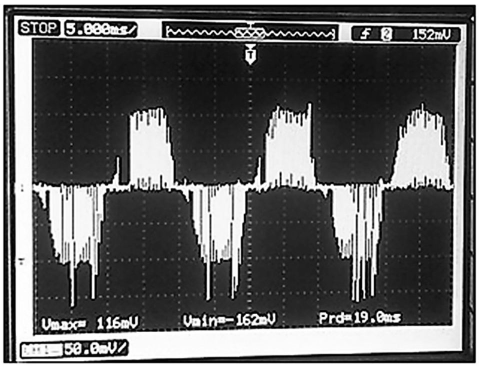
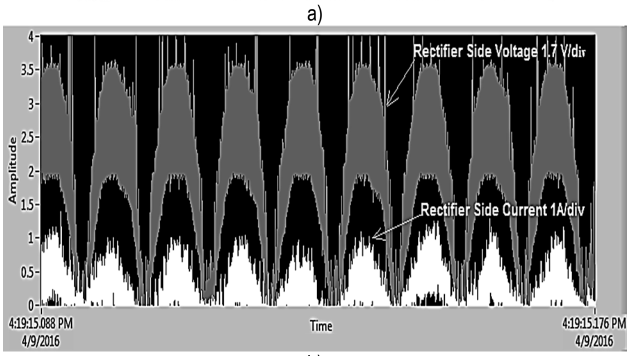


Figure 14 Output voltage under nominal condition



a)



b)

Figure 15 a) Line current waveform with DPSMC; b) Rectifier side voltage and current waveform with DPSMC

5.2 Performance under Nominal Conditions

Fig. 14, gives the real time output voltage waveform of the converter controlled by DPSMC under nominal operating condition as described in Tab. 3. Line Current versus line Voltage waveform of the converter controlled by DPSMC under nominal operating condition is given in Fig. 15a (Line Current) and Fig. 15b (Rectifier side voltage and current) along with the converters firing pulse in Fig. 16. Fig.14 gives the controller's ability to regulate the output of the converter to the desired output voltage without overshoot as depicted in the simulation results.

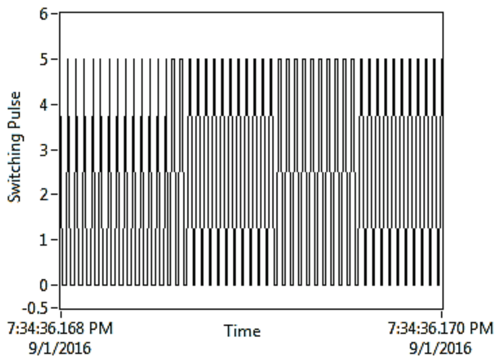


Figure 16 Converter Firing Pulse

6 CONCLUSION

In this paper, a direct power based sliding mode control has been proposed for the control of Single phase AC-DC power factor pre regulator circuit. The simulation results of the converter controlled by DPSMC have been justified through real time implementation. Both the simulation and hardware results have proved the feasibility of implementing DPSMC controller for the AC-DC power factor pre-regulator and the performance of the converter under proposed DPSMC is better compared to the traditional SMC.

7 REFERENCES

[1] Lin, Bor-Ren & Lu, Hsin-Hung. (2000). Single-phase power-factor-correction AC/DC converters with three PWM control schemes. *IEEE Transactions on Aerospace and Electronic Systems, 36*(1), 189-200. https://doi.org/10.1109/7.826321

[2] CISPR, International Special Committee on Radio Interference, http://www.iec.ch/emc/pdf/cispr_guide_2010.pdf (2010).

[3] Singh, B., Singh, B. N., Chandra, A., Al-Haddad, K., Pandey, A. & Kothari, D. P. (2003). A Review of Single-Phase Improved Power Quality AC-DC *Converters. IEEE Transactions on Industrial Electronics, 50*(5), 962-981. https://doi.org/10.1109/TIE.2003.817609

[4] Sun, J. (2004). On the Zero-Crossing Distortion in Single-Phase PFC Converters. *IEEE Transactions on Power Electronics, 19*(3), 685-692. https://doi.org/10.1109/TPEL.2004.826491

[5] Chen, M. & Sun, J. (2006). Feedforward Current Control of Boost Single-Phase PFC Converters. *IEEE Transactions on Power Electronics, 21*(2), 338-345. https://doi.org/10.1109/TPEL.2005.869746

[6] Ruzbehani, M., Zhou, L. & Mirzaei, N. (2010). Improvement of One-Cycle Controller Response with a Current Mode Controller. *Journal for Power Electronics, 10*(1), 21-26. https://doi.org/10.6113/JPE.2010.10.1.021

[7] Prodic, A., Chen, J., Erikson, R. W. & Maksimovic, D. (2002). Digitally controlled low-harmonic rectifier having fast dynamics responses. *Proc. IEEE APEC.*, 476-482. https://doi.org/10.1109/APEC.2002.989287

[8] Shin, Jong-Won, Hyeon, Byeong-Cheol and Cho, Bo-Hyung. (2009). Digital Control of a Power Factor Correction Boost Rectifier using Diode Current Sensing Technique. *Journal for Power Electronics, 9*(6), 903-910.

[9] Bouafia, Abdelouahab, Krim, Fateh & Gaubert, Jean-Paul. (2009). Fuzzy-Logic-Based Switching State Selection for Direct Power Control of Three-Phase PWM Rectifier. *IEEE Transactions on Industrial Electronics, 56*(6), 1984-1992. https://doi.org/10.1109/TIE.2009.2014746

[10] Cecati, C., Dell'Aquila, A., Liserre, M. & Ometto, A. (2003). A Fuzzy-Logic-Based Controller for Active Rectifier. *IEEE Transactions on Industry Applications, 39*(1), 104-112. https://doi.org/10.1109/TIA.2002.807227

[11] Tan, S. C., Lai, Y. M. & Tse, C. K. (2008). Indirect sliding mode control of power converters via double integral sliding surface. *IEEE Transaction on Power Electronics, 23*(2), 600-611. https://doi.org/10.1109/TPEL.2007.915624

[12] Tan, Siew-Chong, Lai, Y. M., Cheung, Martin K. H. & Tse, Chi K. (2005). On the Practical Design of a Sliding Mode Voltage Controlled Buck Converter. *IEEE Transactions on Power Electronics, 20*(2), 425-437. https://doi.org/10.1109/TPEL.2004.842977

[13] Abrishamifar, A., Ale Ahmad, A. & Mohamadian, M. (2012). Fixed Switching Frequency Sliding Mode Control for Single-Phase Unipolar Inverters. *IEEE Transactions on Power Electronics, 27*(5), 2507-2514. https://doi.org/10.1109/TPEL.2011.2175249

[14] Komurcugil, H. (2012). Rotating-Sliding-Line-Based Sliding-Mode Control for Single-Phase UPS Inverters. *IEEE Transactions on Industrial Electronics, 59*(10), 3719-3726. https://doi.org/10.1109/TIE.2011.2159354

[15] Yorgancioglu, F. & Komurcugil, H. (2008). Single-input fuzzy-like moving sliding surface approach to the sliding mode control. *Electrical Engineering, 90*(3), 199-207. https://doi.org/10.1007/s00202-007-0074-2

[16] Chen, Zengshi. (2012). PI and Sliding Mode Control of a Cuk Converter. *IEEE Transactions on Power Electronics, 27*(8), 3695-3703. https://doi.org/10.1109/TPEL.2012.2183891

[17] Amirahmadi, Ahmadreza, Dastfan, Ali & Rafiei, Mohammadreza. (2012). Optimal Controller Design for Single-Phase PFC Rectifiers Using SPEA Multi-Objective Optimization. *Journal of Power Electronics, 12*(1), 104-112. https://doi.org/10.6113/JPE.2012.12.1.104

[18] Nechadi, E., Harmas, M. N., Essounbouli, N. & Hamzaoui, A. (2016). Optimal Synergetic Control based Bat Algorithm for DC-DC Boost Converter. *IFAC-PapersOnLine, 49*(12), 698-703. https://doi.org/10.1016/j.ifacol.2016.07.792

[19] Malinowski, M., Kazmierkowski, M. P., Blaabjerg, F. & Marques, G. D. (2001). Virtual-Flux-Based Direct Power Control of Three-Phase PWM Rectifiers. *IEEE Transactions on Industry Applications, 37*(4), 1019-1027. https://doi.org/10.1109/28.936392

[20] Akagi, H., Kanazawa, Y. & Nabae, A. (1984). Instantaneous Reactive Power Compensators Comprising Switching Devices without Energy Storage. *IEEE Transaction on Industrial Application, 20*(3), 625-630. https://doi.org/10.1109/TIA.1984.4504460

[21] Huang, J., Zhang, A., Zhang, H., Ren, Z., Wang, J., Zhang, L. & Zhang, C. (2014). Improved Direct Power Control for Rectifier Based on Fuzzy Sliding Mode. *IEEE Transactions on Control Systems Technology, 22*(3), 1174-1180. https://doi.org/10.1109/TCST.2013.2273368

[22] Antoniewicz, P., Kazmierkowski, M. P., Aurtenechea, S. & Rodriguez, M. A. (2007). Comparative study of two predictive direct power control algorithms for three-phase AC/DC converters. *Proceedings European Conference on Power Electronics Application*, 1-10. https://doi.org/10.1109/EPE.2007.4417741

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