A Practical Particle Swarm Optimized Sliding Mode Controller for an AC-DC Boost Converter

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Abstract— An effective technique for the control of non linear systems is the use of sliding mode controller. Sliding mode controller can be used for the improvement of static and dynamic performance of both linear and non-linear systems. This paper presents the designing and implementation of a sliding mode controller for an AC-DC boost converter. The sliding surface is designed according to the requirement of the considered system. The sliding surface parameters are optimized for improved performance using particle swarm optimization. This optimized sliding mode controller helps in getting the required output voltage and also yields good line and load regulation.

Index Terms— AC-DC Boost Converter, Lyapunov, Particle Swarm Optimization(PSO), Sliding Mode Controller(SMC), Sliding Surface, Voltage control.

1. INTRODUCTION

CONVERSION, control and conditioning of electric power is mainly done using power converters. For getting high system reliability, control of these power converters is essential. Common linear converter systems are controlled using PID controllers [1]. These PID controllers can also be used for the control of nonlinear DC-DC converter systems [2]. But these controllers fail to give required performance in case of large disturbances. Hence a new control technique is to be introduced for non-linear systems for their effective performance in conditions of large parameter variation.

Sliding mode control is an effective technique for the control of non-linear systems [3]. They are mainly designed to give a stable performance during non-linear mode of operation. The sliding mode control approach is recognized as one of the efficient tools to design robust controllers for complex high order nonlinear dynamic systems operating under uncertainty conditions. The major advantage of sliding mode is low sensitivity to system parameter variations and disturbances which eliminates the necessity of exact modeling. Sliding mode control enables the decoupling of the overall system motion into independent partial components of lower dimension and as a result reduces the complexity of feedback design.

Analysis and design of sliding mode controller for voltage and current control is studied in this paper. The sliding surface is designed for both output voltage and input current control. The existence condition and stability conditions are checked for this designed surface. The sliding surface parameters can be optimized for more accurate results. Optimization can be done using the different optimization techniques like genetic algorithm, particle swarm optimization etc [4],[5]. Here the sliding mode parameters are optimized using particle swarm optimization. Sliding mode voltage control can be easily implemented using microcontrollers. In case of voltage and current control microcontroller control becomes difficult and much complicated. Hence this can be implemented using control desk DSPACE [6]. In this paper the results are simulated and the voltage control is validated using hardware implementation.

2. OVERVIEW OF MATHEMATICAL BOOST CONVERTER MODEL

A simple AC-DC boost converter circuit is shown in Fig.1. A diode bridge rectifier converts the AC input to DC. This DC voltage is boosted to a higher reference value by a boost converter with the switching of switch. When the switch is ON (u=1), the inductor current increases and hence energy is stored in the inductor.

Simultaneously the capacitor supplies the load. This is mode 1. When switch is OFF (u=0), the energy stored in the inductor is supplied to the load in addition to the input. This is mode 2. By circuit analysis, the output voltage and inductor current dynamics is given by:

$$\begin{aligned} C\frac{dv_0}{dt} &= (1-u)i_L - i_0 \\ L\frac{di_L}{dt} &= v_{in} - (1-u)v_0 \end{aligned} \tag{1}$$

where C,L – capacitance and inductance of the converter,

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$\frac{dv_0}{dt}, \frac{di_L}{dt}$ - rate of change of output voltage and rate of change of inductor current, u – switching state, v_{in}, i_L - input voltage and inductor current, v_0, i_0 - output voltage and current.

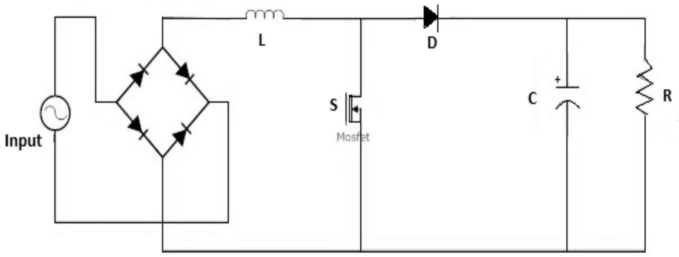


Fig. 1.AC-DC Boost Converter

In order to obtain improvement in power factor, the input current is to be made in phase with input voltage. This can be achieved by comparing the actual current through the inductor with a reference current. The output voltage control can be implemented by comparing the output voltage with a reference value.

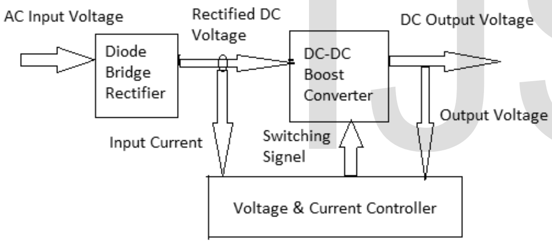


Fig. 2. Block diagram of closed loop control of Converter

3. MODELING OF SLIDING MODE CONTROLLER

The sliding mode controller has two objectives: 1. To regulate the output voltage to a reference value. 2. To give the input current a rectified sinusoidal waveform shape in phase with that of the voltage v_{in}.

The first step of modeling a sliding mode controller is the selection of a sliding surface. As the control objective includes two parameters, the sliding surface can be taken as

$$S = \lambda_1 (v_0 - V_{ref}) + \lambda_2 (i_L - i_{ref}) \tag{2}$$

The general power equation is given as

$$P = V_{rms}.I_{rms} = v_0 i_0 = \frac{V_M I_M (1-\cos 2\omega t)}{2} \tag{3}$$

In the above equation, $I_M = I_{ref}$ and $v_0 = V_{ref}$. Hence equation (3) is modified as:

$$\frac{V_M I_{ref}}{2V_{ref}} = \frac{i_0}{(1-\cos 2\omega t)} = \frac{v_0}{R(1-\cos 2\omega t)} \tag{4}$$

Now from equation (4), the reference current is obtained as:

$$I_{ref} = \frac{2v_0 V_{ref}}{V_M R(1-\cos 2\omega t)} \tag{5}$$

Thus the actual current reference for the inductor current is formulated as:

$$i_{ref} = I_{ref} \,|\sin \omega t\,| \tag{6}$$

The above equation (6) defines the instantaneous reference current. This reference current helps the sliding mode controller to improve the power factor of the system by providing the required controller action based on the current error.

3.1.Existence Condition

The existence of sliding mode around the switching surface is guaranteed by the existence condition. The existence condition is given as: $S\dot{S} < 0$ as $S \to 0$.

This implies that S and $\dot{S}$ will tend to zero as $t \to \infty$. This shows that the system dynamics remains on the sliding surface. The equilibrium point can be chosen as the origin. The voltage error and the current error are taken as the state variables x_1 and x_2.Now, the model of sliding mode controlled boost converter can be written in state space as

$$x_1 = v_0 - V_{ref}$$

$$x_2 = i_L - i_{ref}$$

On substituting these variables in equation (1), the state equations are obtained as:

$$\begin{aligned} C\frac{dx_1}{dt} &= (1-u)(x_2 + i_{ref}) - (\frac{x_1 + V_{ref}}{R}) \\ L\frac{dx_2}{dt} &= v_{in} - (1-u)(x_1 + V_{ref}) \end{aligned} \tag{7}$$

Replacing the value of i_{ref} from (6) in the sliding surface equation (2), we get

$$S = \lambda_1 (v_0 - V_{ref}) + \lambda_2 (i_L - I_{ref}\,|\sin \omega t\,|)$$

$$= \lambda_1 (v_0 - V_{ref}) + \lambda_2 (i_L - \frac{2 v_0 V_{ref}}{V_M R(1-\cos 2\omega t)}) \qquad (8)$$

Rearranging we get

$$S = (\lambda_1 - \frac{2.\lambda_2.V_{ref}.|\sin \omega t|}{V_{SM}.R.(1-\cos 2\omega t)}) v_0 - \lambda_2 i_L - \lambda_1 V_{ref}$$

Substituting for i_L and v_0, we can write the equation in the coordinate form (x_1, x_2) as

$$\begin{aligned} S &= (\lambda_1 - \frac{2.\lambda_2.V_{ref}.|\sin \omega t|}{V_{SM}.R.(1-\cos 2\omega t)}) x_1 \\ &+ (\lambda_1 - \frac{2.\lambda_2.V_{ref}.|\sin \omega t|}{V_{SM}.R.(1-\cos 2\omega t)}) V_{ref} \\ &+ \lambda_2 x_2 + \lambda_2 i_{ref} - \lambda_1 V_{ref} \end{aligned}$$

Substituting $(\lambda_1 - \frac{2.\lambda_2.V_{ref}.|\sin \omega t|}{V_{SM}.R.(1-\cos 2\omega t)}) = \lambda_1^{'}$

$$S = \lambda_1^{'} x_1 + \lambda_2 x_2 \qquad (9)$$

The switch has two states (u=0,1). Replacing the value of u in the state equation (7), the boundaries of the sliding area can be obtained as

$$\begin{aligned} & x_1(-\frac{\lambda_1^{'}}{RC} - \frac{\lambda_2}{L}) + x_2 \frac{\lambda_1^{'}}{C} + \lambda_2 (\frac{v_{in}}{L} - \frac{V_{ref}}{L}) \\ & -\lambda_1^{'} (\frac{V_{ref}}{RC} - \frac{i_{ref}}{C}) < 0 \rightarrow (\dot{S} < 0) \qquad (10) \\ & \frac{-\lambda_1^{'} x_1}{RC} - \lambda_1^{'} \frac{V_{ref}}{RC} + \lambda_2 \frac{v_{in}}{L} > 0 \rightarrow (\dot{S} > 0) \end{aligned}$$

Since the origin is taken as the equilibrium point and to ensure the existence of the sliding surface around this point, the condition to be satisfied is given as $(x_1 = x_2 = 0)$:

$$-\lambda_1^{'} \frac{V_{ref}}{RC} + \lambda_2 \frac{v_{in}}{L} > 0$$

Or,

$$\frac{\lambda_1^{'}}{\lambda_2} < \frac{RC.v_{in}}{V_{ref}.L} \qquad (11)$$

This means that the condition given in equation (11) is to be satisfied for the system sliding surface to exist at the origin.

3.2 Stability Condition

The stability of the system can be ensured by directing the system dynamics to the equilibrium point when it is in the sliding mode. From the state space model in equation (7), the commutation surface in equation (9) and $\dot{S} = 0$, we get the value of control to be applied to the system so that the system slides over the sliding surface. This is given by

$$u_{eq} = 1 - \frac{(v_{in}/L) - (\lambda_1^{'}(x_1 + V_{ref})/\lambda_2 RC)}{(x_1 + V_{ref})/L - \lambda_1^{'}(x_2 + i_{ref})/\lambda_2 C} \qquad (12)$$

Substituting the control in the state space model equation (7) and setting S=0, the dynamics of x_1 at the sliding region is given as:

$$\frac{dx_1}{dt} = \frac{v_{in}(i_{ref} - (x_1 \lambda_1^{'}/\lambda_2)) - (x_1 + V_{ref})^2 / R}{C(V_{ref} + x_1) - L(i_{ref} - (x_1 \lambda_1^{'}/\lambda_2))(\lambda_1^{'}/\lambda_2)} \qquad (13)$$

Considering a Lyapunov $V = \frac{1}{2} x_1^2$ function and taking its derivative, we get

$$\dot{V} = x_1 \dot{x}_1$$

Substituting for $\dot{x}_1$ from (13), we get

$$\dot{V} = -x_1^2 \frac{v_{in}(\lambda_1^{'}/\lambda_2) + 4V_{ref}(v_0 + V_{ref})/Rx_1}{C(V_{ref} + x_1) - L(i_{ref} - (x_1 \lambda_1^{'}/\lambda_2))(\lambda_1^{'}/\lambda_2)} \qquad (14)$$

The condition for $\dot{V}$ to be negative is

$$\begin{aligned} & C(V_{ref} + x_1) - L(i_{ref} - (x_1 \lambda_1^{'}/\lambda_2))(\lambda_1^{'}/\lambda_2) > 0 \\ & \Rightarrow x_1 > \frac{(LV_{ref}^2/RE)(\lambda_1^{'}/\lambda_2) - CV_{ref}}{C + L(\lambda_1^{'}/\lambda_2)^2} \qquad (15) \end{aligned}$$

By considering the sliding region given by equation (10) and the existence condition by equation (11), the condition given in equation (15) is always satisfied. And hence according to the theorem of Lyapunov stability, the system is globally asymptotically stable.

4. PARTICLE SWARM OPTIMIZATION

Particle Swarm Optimization (PSO) is one recent technique that has been used with great success in the Computational Intelligence arena. It is an unconstrained optimization technique.

In this paper the gains λ_1 and λ_2 of sliding controller are found out using online iterative particle swarm optimization. Thus PSO optimizes the values of the sliding parameters to get optimal performance. Thus the objective of the PSO is to determine the values of parameters that ensure that the system will intercept the sliding part of commutation surface, regardless of the operating point. The objective function is derived from the sliding surface equation.

5. SIMULATION RESULTS

The simulation is done in MATLAB. The simulink model is as shown in figure. The switching frequency can be applied upto 20kHz. The outputs are obtained as in the figure. The specification of the power circuit is as given below:

Output voltage $V_0 = 33V$
Input voltage $V_s = 24V$
Load resistance $R = 210\ \Omega$
Input inductance $L = 10$ mH
Output capacitor $C = 470\ \mu$F

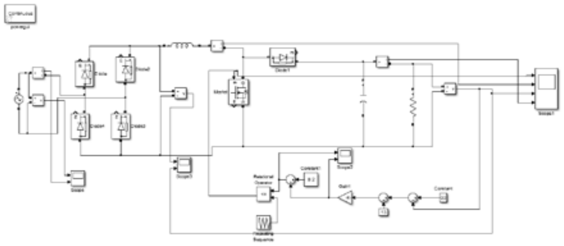


Fig. 3. Simulink model- voltage control

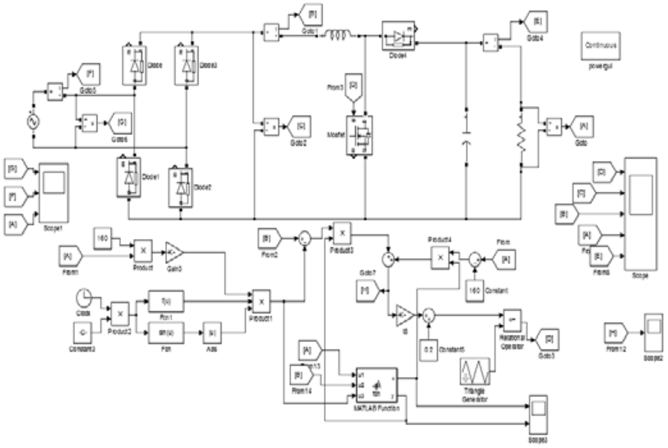


Fig. 4. Simulink Model-voltage and current control

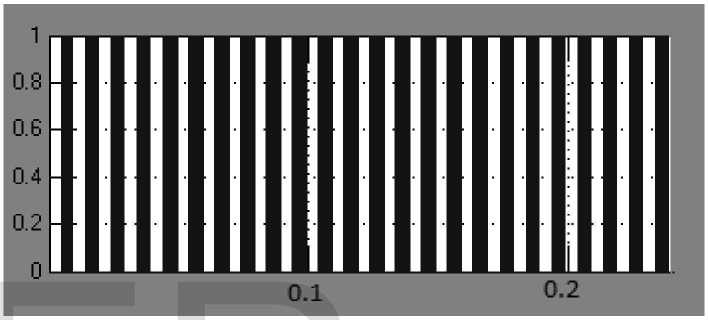


Fig. 5. Results of voltage control-Pulses

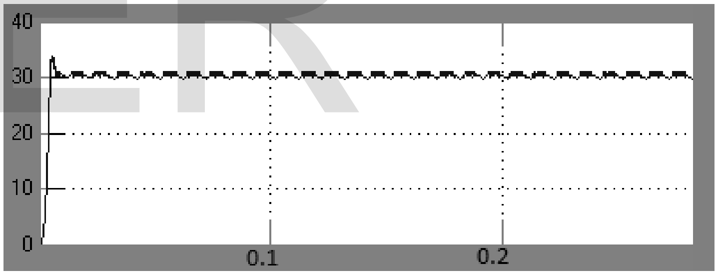


Fig. 6.Results of voltage control- Output Voltage

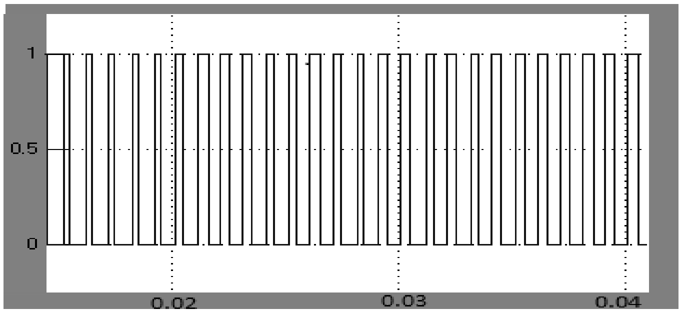


Fig. 6. Pulses of voltage and current control

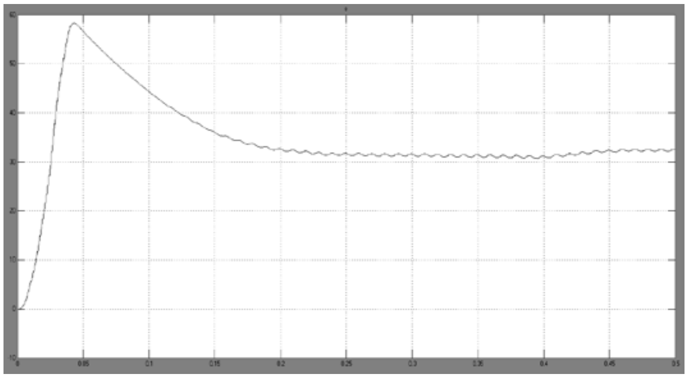


Fig. 7. Output voltage of voltage and current control

6. HARDWARE RESULTS

Closed loop voltage control of AC-DC boost converter is implemented using hardware setup. The specifications of power circuits are as in simulation setup. Sliding mode voltage control is implemented using microcontroller. A driver IC is used to drive the signal from the microcontroller. Regulators are used to provide the required voltages for the driver and microcontroller.

The input voltage given is 24V and the output reference is kept at 33V. The hardware results are obtained as in figure. The output voltage is obtained equal to 33V foe 24V input. When the input voltage is reduced to 16V, the pulse width varies and the output voltage is maintained constant. Similarly, when the input voltage is increased to 26V, output voltage remains constant.

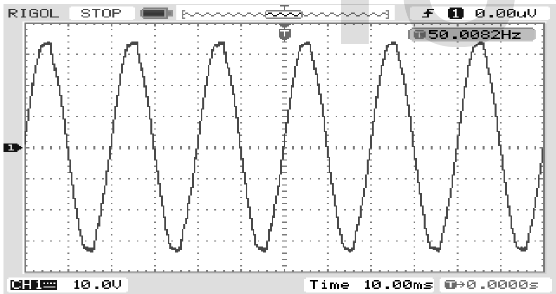
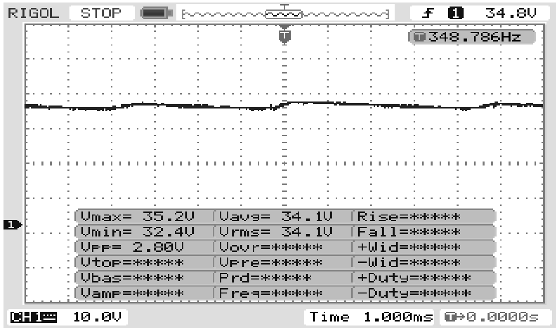
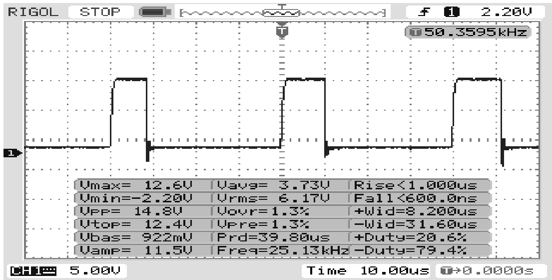


Fig. 8. Input voltage-24V



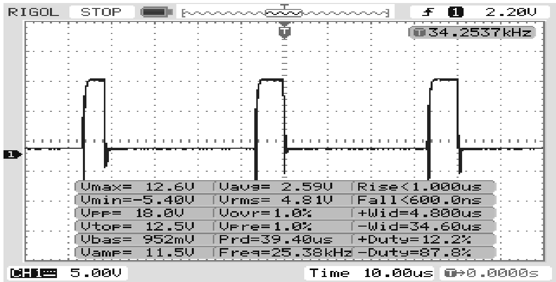
```
Vmax= 35.2V  Vavg= 34.1V   Rise=*****
Vmin= 32.4V  Vrms= 34.1V   Fall=*****
Vpp= 2.80V   Vovr=*****    +Wid=*****
Vtop=*****   Vpre=*****    -Wid=*****
Vbas=*****   Prd=*****     +Duty=*****
Vamp=*****   Freq=*****    -Duty=*****
```

Fig. 9.Output voltage



```
Vmax= 12.6V   Vavg= 3.73V      Rise<1.000us
Vmin=-2.20V   Vrms= 6.17V      Fall<600.0ns
Vpp= 14.8V    Vovr=1.3%        +Wid=8.200us
Vtop= 12.4V   Vpre=1.3%        -Wid=31.60us
Vbas= 922mV   Prd=39.80us      +Duty=20.6%
Vamp= 11.5V   Freq=25.13kHz    -Duty=79.4%
```

Fig. 10. Line regulation-Control pulse generated for 16V.



```
Vmax= 12.6V   Vavg= 2.59V      Rise<1.000us
Vmin=-5.40V   Vrms= 4.81V      Fall<600.0ns
Vpp= 18.0V    Vovr=1.0%        +Wid=4.800us
Vtop= 12.5V   Vpre=1.0%        -Wid=34.60us
Vbas= 952mV   Prd=39.40us      +Duty=12.2%
Vamp= 11.5V   Freq=25.38kHz    -Duty=87.8%
```

Fig. 11. Line regulation-Control pulse generated for 26V input

7. CONCLUSION

Sliding mode controller with two parameters, output voltage and inductor current is designed. An optimization algorithm is developed and implemented online to find out the optimal values of the parameters of the sliding surface. The optimization technique used is particle swarm optimization. Results show that the system gives stable performance for both steady state and transient conditions and gives a constant output voltage of 33V which is equal to the reference. Also output voltage control is implemented using microcontroller and the simulation results are validated using hardware results.

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