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Sliding Mode Control of Wide input Wide output DC-DC Boost Converter

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Abstract: Coupled inductor based DC-DC converters are used into achieve high step up(or)step down voltage gains. Most of these converters use fixed frequency pulse width modulation technique for controlling the output voltage. Many configurations are available for step up and step down DC-DC conversion operation, out of the available converter configurations the model proposed in [1] is considered for analysis purpose for which a control circuit based on sliding mode controller is proposed for implementation. This sliding mode controllers are non-linear controllers and found to be suitable for switching operations and references are provides sufficient literature about the stable operation of converter circuits. The performance of this converter is studied for different loads with indirect sliding mode controller. And case studies verified with the help of MATLAB SIMULINK software.

Keywords: Wide input wide output (WIWO), Sliding Mode Control (SMC), Indirect Sliding Mode Control, Coupled Inductor, DC-DC Converter, PWM Controller.

1. INTRODUCTION

For many applications such as high intensity discharge lamp ballasts for automobile headlamps, fuel-cell energy conversion systems, solar-cell energy conversion systems, and battery backup systems for uninterruptible power supplies requires DC–DC converter with a high step-up voltage gain. Theoretically, a high step-up voltage gain with an extremely high duty ratio can be achieved by dc–dc boost converter [1]–[3]. However, in practice power switches, rectifier diodes, and the equivalent series resistance (ESR) of inductors and capacitors limit step-up voltage gain to limited values. A serious reverse-recovery problem is due to the extremely high duty-ratio in dc-dc boost converter. To overcome this recovery problem so many topologies have been introduced and to provide a high step-up voltage gain without extremely high duty-ratio [4]-[24].

A simple structure with a high step-up voltage gain and an electrical isolation is dc-dc fly back converter but active switch in this converter suffers with high voltage stress due to the leakage inductance of the transformer. To minimize the voltage stress and to recycle the energy of the leakage inductance, few energy regeneration techniques are introduced[4]-[6].In these techniques, coupled-inductor technique can provide high voltage gain with a low voltage stress on the active switch of converters, and high efficiency without the problem of high duty ratio ratio[7]-[15].

In the past research on the transformer less dc-dc converters are happened, these include cascade boost type[16],the quadratic boost type[17],the voltage-lift type[18]–[20], the capacitor-diode voltage multiplier type[21],[22],and the boost type integrating with switched-capacitor technique [23]. These techniques are all complex and are having high cost. The modified boost type with switched inductor technique is shown in Fig.1 [24].It has very simple structure because only one power stage is used in this converter. However, this converter has two issues (1) During the switch-on period, three power devices exist in the current-flow path and during the switch-off period, two power devices exist in the current-flow path and (2) The output voltage is equal to the voltage stress on the active switch.

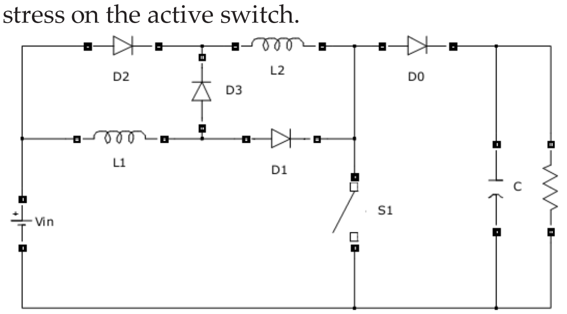

Figure 1: Transformer less dc–dc high step-up

converter

A transformer less dc–dc high step-up converter is proposed in this paper, as shown in Fig.2, compared with the converter in [24], the proposed converter has the following merits:
1) During the switch-on period two power devices exist in the current flow path and during the switch-off period, one power device exist in the current flow path. 2)The voltage stresses on the active switches are less than the output voltage; and 3)Under the same operating conditions, including input voltage, output voltage, and output power, the current stress on the active switch during the switch-on period is equal to the half of the current stress on the active switch of the converter in[24].

These proposed dc–dc converters utilizes switched- inductor technique, in which during the switch-on period two inductors with same level of inductance are charged in parallel and during the switch-off period these are discharged in series, to achieve high step-up voltage gain without the extremely high duty ratio. The operating principles and steady-state analysis are discussed in the following sections. Some conditions are assumed to analyze the steady- state characteristics of the proposed converters and these are as follows:

1) All components are ideal and the ON-state resistance $R_{DS(ON)}$ of the active switches, the forward voltage drop of the diodes, and the ESRs of the inductors and capacitors all are ignored. 2) All capacitors are sufficiently large and voltages across the capacitors can be treated as constant.

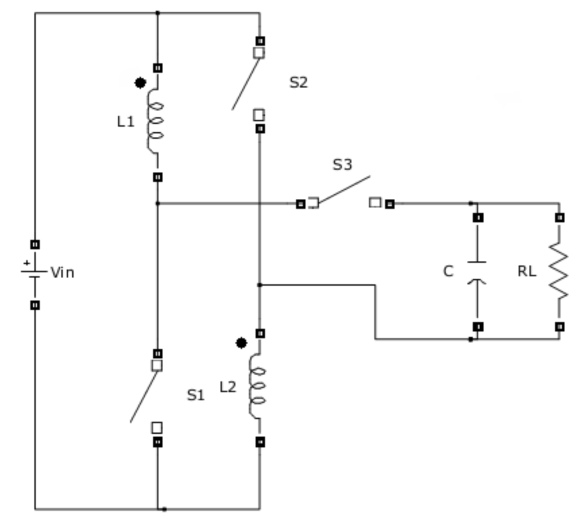

Figure 2: Proposed high step up dc-dc converter

Fig.2 shows the circuit configuration of the proposed converter, consisting of two active switches (S_1 and S_2) two inductors (L_1 and L_2) with the same level of inductance, one output diode Do and one output capacitor Co. Switches S_1 and S_2 are controlled simultaneously with one control signal. The operating principle and steady- state analysis of CCM are presented in detail as follows

2. BOOST CONVERTER MODEL

Entire operation of the circuit proposed in Fig.2 is divided into two modes.
Mode 1: Switches S_1 and S_2 are ON and Diode D_0 is OFF and value of switching function u is 1. During this mode the two windings of coupled inductor are connected in parallel. In this mode of operation coupled inductor stores energy. Load Voltage and Current through inductor are given by

$$\frac{dV_0}{dt} = -\frac{V_0}{RC}u \quad \text{……..(1)}$$

And

$$\frac{di_L}{dt} = \frac{2V_{in}}{(1+k)L}u \quad \text{……..(2)}$$

Mode 2: Switches S_1 and S_2 are OFF and Diode D_0 is ON and value of switching function u is 0. The two windings of the coupled inductor are connected in series and energy stored in coupled inductor is delivered to the load.

Expressions for voltage across load and Current through the inductor are given by

$$\frac{dV_0}{dt} = -\frac{V_0}{RC} + \frac{i_L}{C} - \frac{i_L}{C}u \quad \text{.........(3)}$$

And

$$\frac{di_L}{dt} = -\frac{1}{2L(1+k)}V_0 + \frac{V_{in}}{2L(1+k)} + \left[\frac{V_0}{2L(1+k)} + \frac{3V_{in}}{2L(1+k)}\right]u$$

.........(4)

Combining equations (1), (3) and (2),(4) will give state model of proposed configuration

$$\frac{dV_0}{dt} = -\frac{V_0}{RC} + \frac{i_L}{C} - \frac{i_L}{C}u - \frac{V_0}{RC}u \quad \text{......... (5)}$$

And

$$\frac{di_L}{dt} = -\frac{1}{2L(1+k)}V_0 + \frac{V_{in}}{2L(1+k)} + \left[\frac{V_0}{2L(1+k)} + \frac{3V_{in}}{2L(1+k)} + \frac{2V_{in}}{L(1+k)}\right]u \quad \text{---------(6)}$$

The state model of proposed configuration is

$$\begin{bmatrix} \frac{dV_0}{dt} \\ \frac{di_L}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-1}{RC} & \frac{1}{C} \\ \frac{-1}{2L(1+k)} & 0 \end{bmatrix} \begin{bmatrix} V_0 \\ i \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{2L(1+k)} \end{bmatrix} V_{in} + u \begin{bmatrix} \frac{-1}{RC} & \frac{-1}{C} \\ \frac{1}{2L(1+k)} & 0 \end{bmatrix} \begin{bmatrix} V_0 \\ i \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{7}{2L(1+k)} \end{bmatrix} V_{in}u$$

3.SLIDING MODE CONTROLLER (SMC)

Two types of sliding mode control (SMC) techniques are available for DC-DC converters. One is called the direct SMC scheme, other is known as indirect SMC scheme.

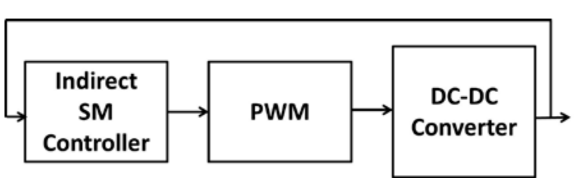

Figure 3: Block diagram of the indirect SMC scheme.

In direct SMC scheme output signal of the hysteresis circuit directly controls the switching of the power switch. Block diagram representation of indirect SMC is shown in fig.1. In indirect SMC scheme, the output of the SM controller is first compared with an external triangular waveform. Then the output signal of the comparator is employed to switch the converter switch. In this case, the control signal is not applied directly to the power switch. Indirect SMC is realized by changing the modulation method of the SM controller from hysteresis modulation to PWM, this scheme is also known as duty cycle control. Main advantage of PWM is that by fixing the frequency of the ramp, the frequency of the output switching signal will be constant, regardless of how the duty cycle varies with the variation of the control signal [20]. The SM controller design process aims at determining the switch position u, which generally has the form:

$$\begin{cases} u = 1 & \text{for } s(x) > 0 \\ u = 1 & \text{for } s(x) < 0 \end{cases}$$

Where s(x) is a smooth scalar function or instantaneous state trajectory given by

$$s = \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 = J^T x \quad \text{...... (1)}$$

For existence of SM operation, the reachability condition is

$$\lim_{s \to 0} s(x).\dot{s}(x) < 0 \quad \text{...... (2)}$$

To achieve such control in an indirect SMC a relation between direct SMC and duty cycle is required. The system trajectory of SMC is described by means of equivalent dynamics [25].

$$\dot{x} = Ax + Bu + D \quad \text{...... (3)}$$

Where u is equivalent control function [26], is the solution for u in the equation $\dot{s}(x) = 0$.

Control law that adopts a switching function is given by

$$u = \frac{1}{2}(1 + \mathrm{sgn}(s)) \quad \text{...... (4)}$$

4. DESIGN OF SLIDING MODE CONTROLLER

The objective of sliding mode control is to regulate the output voltage V_b to a reference voltage V_{ref}. The design of sliding mode controller for boost converter starts with the choice of sliding surface. As it is shown in [13], it is clear that direct surface V_0-V_{ref} can be tend to zero only if the current increases continuously . The output voltage generates the reference current from voltage error and controls inductor current via sliding mode.

This control of the output voltage of DC-DC converter meets the criteria of stability and existence of sliding mode. However, it is difficult to determine the gains of the voltage loop since sliding mode is a highly non linear method. In order to improve the performances of the controller, we proposed to study a control mode based on a sliding surface which involves output voltage.

The existence condition of sliding mode implies that both Sand $\dot{s}$ tend to zero when t tend to infinity, which means that the dynamics of the system will stay into the sliding surface. The existence condition of the sliding mode is $s\dot{s} < 0$ (when S→0) the fulfillment of this inequality ensures the existence of sliding mode around the commutation surface.

5. MODEL SIMULATION

After making the simplifications and applying the above mentioned conditions parameters of magnitude of the control voltage of PWM controller is found as

$$\left[\frac{1}{RC}\left(\beta V_0 - K_p\right) + V_0 + \frac{1}{\beta C} i_L\right] K > 1$$

Where K is a constant derived based on tail error method to eliminate steady state error. Where K is constant and is a function of load power.

With the available stability condition DC-DC boost converter circuit with nominal output voltage equal to 220V supplying a load of 200W from 12V input supply is modeled and simulated with the help of MATLAB SIMULINK.

Parameters of the circuit are $L = 0.0011H$, with coefficient of coupling = 0.95, $C = 68\mu F$, operating frequency is equal to 20kHz. β is gain constant whose value is equal to $\frac{1}{2333.72}$

The converter is achieving a voltage gain approximately equal to 18.667.

Value K is determined based on trial and error method. Relation between K and P is established with the help of polynomial approximation. Its value is given by

$$K = \frac{2.081\times10^{-9}P^3 - 4.94\times10^{-6}P^2 + 6.603\times10^{-3}P + 0.1725}{\left(1.767\times10^{-7}P^2 + 8.548\times10^{-3}P + 0.08521\right)\times Ratio}$$

$$Ratio = \frac{K_p}{\beta}$$

P is the power delivered to the load.

Proposed circuit is simulated for different values of load power it has been observed that the system is exhibiting good regulation characteristics for the load power variations from 100W to 750W load regulation characteristic is shown in Table 1, along with the nominal output voltages and load currents.

S. No	Load Power (Watts)	Output voltage (Volts)	Load Current (Amps)	% Regulation
1	100	224.834	0.464	2.1976
2	150	223.805	0.693	1.7296
3	200	222.784	0.920	1.2655
4	250	221.771	1.145	0.8053
5	300	220.767	1.368	0.3489
6	350	219.772	1.589	-0.1036
7	400	218.785	1.8081	-0.5523
8	450	217.505	2.025	-0.9974
9	500	216.834	2.24	-1.4388
10	600	214.916	2.664	-2.3107
11	750	212.097	3.286	-3.5921
12	1000	207.547	4.288	-5.66

Table 1: Regulation estimation for the proposed converter for change in load power

Simulation diagram is shown in Fig.4, Subsystem modeling is shown in Fig.5,Load Voltage and load current, Voltage across switches S_1, S_2 and Current through diode , Voltage across D for load power P = 200Watts is shown in Fig.6, Fig.7 and Fig.8 respectively.

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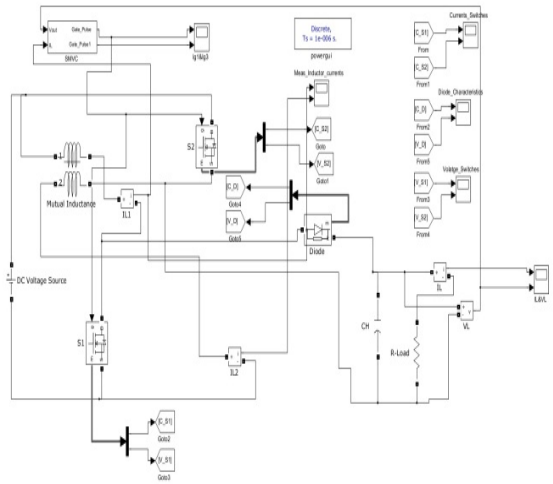

Figure 4: Simulation diagram of proposed model

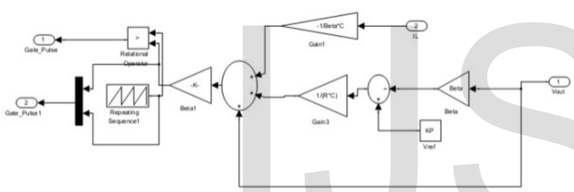

Figure 5: Subsystem representation for SMC

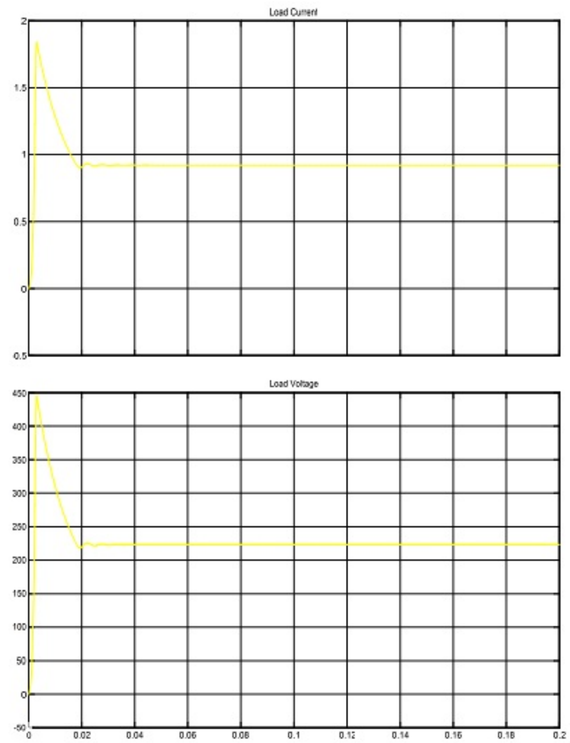

Figure 6: Load Current and Load voltage for P= 200W

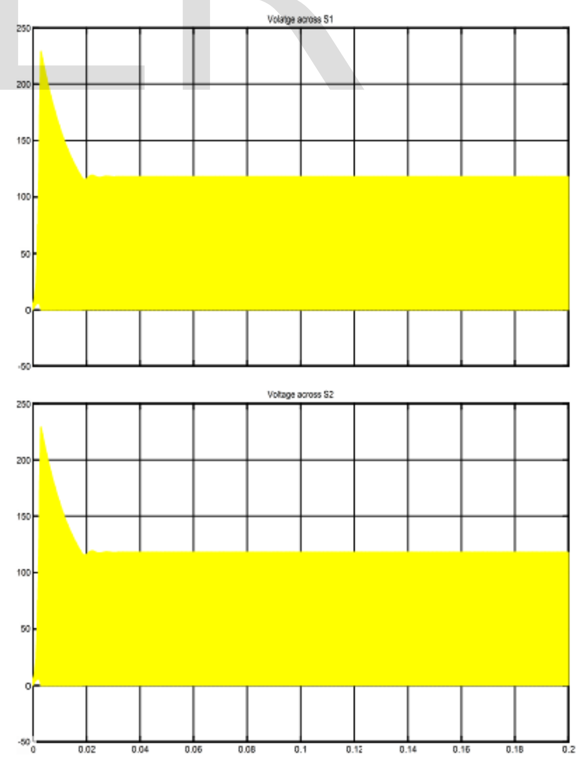

Figure 7: Voltages across Switches S_1 and S_2

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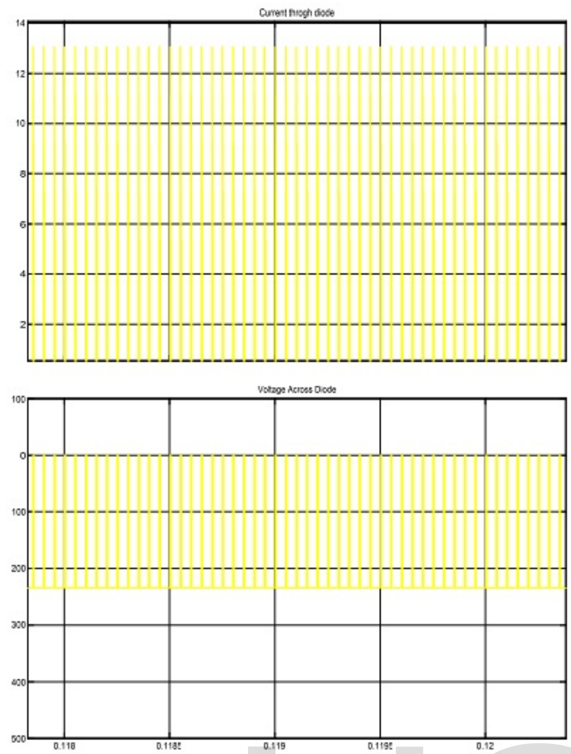

Figure 8: Current and Voltages of Diode D

6 . CONCLUSION

From simulation of the wide input wide output coupled inductor based DC-DC boost converter it has been observed that with the help of SMC it is possible to achieve good conversion gains which is not possible using convesional PWM technique. Moreover SMC are robust to system distrubances, in proposed analysis the system is working under sastifactory operating conditions for large varaiations in load power. In the proposed converter the maximum voltage gain achieved is 18.667 when load power is 100W, for which duty ratio of the converter is equal to 0.9 of the basic DC-DC boost converter.

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