Chapter 3 : Closed Loop Current Mode DC\DC Boost Converter

3.1 Introduction

DC/DC Converter efficiently converts unregulated DC voltage to a regulated DC voltage with better efficiency and high power density. Linear power regulator fails in terms of efficiency and high power density and that's the reason for its narrowed application. A DC/DC converter of high power is used nowadays mostly in the field of renewable energy and Telecom applications. Using a basic buck and boost converter, several other converters are derived and each one of them has their own strategy of functioning, merits and demerits [57]. DC/DC converters being a switched power supply are used in situations where a high efficiency is necessary and the dissipation of heat poses a problem.

The most common converter in non-isolated circuit is of the boost converter [58]. Basic DC/DC step-up (boost) is discussed and its mathematical modelling is done using Matlab/Simulink. Later in chapter 4, the same DC/DC converters are paralleled and an appropriate control strategy is used for harvesting of renewable DC energy. These DC/DC converter being modular; can be scaled to high power for residential, commercial applications by utilizing the green renewable energy. However, the analyses, design, and control of modular converters is a difficult task.

3.2 Basic description of DC/DC boost converter

The step-up (boost) and step-down (buck) converter consists of a DC input voltage source (V_s), inductor, filter capacitor, controllable switch (Q), diode (D) and load resistance (R). The buck converter's output voltage is always lower than input voltage and the output voltage of boost converter is always greater than the input DC voltage.

If the switch operates with a Duty ratio D, the DC Voltage gain of the boost converter is given by $M = \frac{V_o}{V_s} = \frac{1}{1-D}$, where Vo is the output voltage and D is the duty ratio of the pulse width modulation (PWM) signal used to control the metal–oxide–semiconductor field-effect transistor (MOSFET) switching states.

Only the boost convertor is considered and its schematic diagram is shown in Figure 2.1(a). The portion of the switching period over which the inductor current of the converter is never zero is called continuous current mode (CCM) and when the inductor current is zero during switching period the converter is said to be operating in discontinuous current mode (DCM) [59].

Here the parasitic resistance of inductor, capacitor and source is not taken into account. These parasitic resistances degrade the gain of the converter. The voltage gain of the converter is monotonically increasing function, but it falls sharply as the duty cycle reaches to unity because of these parasitic resistances. If the inductor and source resistance are considered then the output voltage of this converter is given by equation (3.1)

$$V_0 = \frac{V_S}{1-D}\left[\frac{1}{1+\left\{\frac{r_L+r_S}{R(1-D)^2}\right\}}\right]\ldots \quad (3.1)$$

where r_L and r_S is inductor and source parasitic resistance and R is the resistive load. In CCM mode, the rate of change of current during the switching period is constant and this ripple current is given by the equation (3.2) given as,

$$\partial_i = \frac{D(1-D)^2 RT_s}{L}\ldots \quad (3.2)$$

The converter's output voltage ripple depends on charging and discharging rate of the capacitor and the load on it. It has first order roll-of with the switching frequency. Voltage ripple is given by equation (3.3),

$$\partial_v = \frac{DT_s}{RC}\ldots \quad (3.3)$$

3.3 Basic operation of boost converter

In CCM mode, when the switch is ON, the diode is reversed biased and polarity of left side of the inductor is positive. The inductor being an energy storing device starts storing energy due to the flow of current in clockwise direction.

When the switch is OFF, polarity of left side of the inductor is reversed due to decrease in current because of high impedance and as a result the supplied input voltage and voltage across inductor will be added up. This is the reason for output voltage of boost converter is always higher than the input voltage. The circuit diagram of the Boost converters is shown in Figure 3.1.

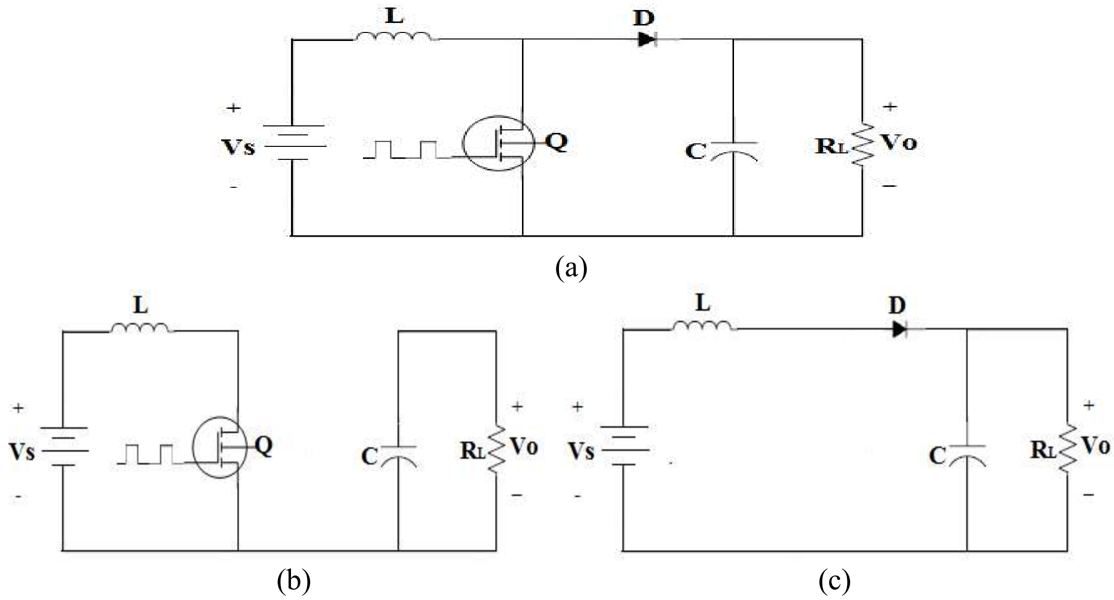

Figure 3.1 Step-up (boost) converter (a) equivalent circuit, (b) equivalent circuit when switch-on and (c) equivalent circuit when switch-off

3.4 Selection of components and design of inductor for boost converter

The component values tabulated in Table 3.1 are implemented in the hardware for making DC boost converters. Two inductors namely L_1 is used in converter 1 and L_2 is used in converter 2. Diode and capacitance used in both converters are same and switching PWM is of 18.2 kHz. Diode used here is a Schottky diode for quick reverse recovery operation.

Table 3.1 Design parameters of boost converter.

Component Values	**Boost converter values**
Input DC voltage, V_s	19.2 V
Output DC voltage, V_o	48.2 V
Switching frequency, F_s	18.2 kHz
Inductance, L_1, L_2	18.2 µH, 30.2 µH
Capacitance, C	94 µF
Diode, D	1N5401

3.4.1 Design of inductor for boost converter

The design inductor is a vital for stable operation of boost convertor. Here a T 94-2 iron powder core is used. The choice of inductor value is made from the acceptable ripple current at maximum input voltage and at the minimum duty cycle of PWM switching [60]. The boost convertor's operation in CCM or DCM mode depends on the inductor value which is given by equation (3.4)

$$L = \frac{[V_o - V_{in(\max)}] * V^2{}_{in} * T_s}{2 * P_{in} * V_o} \quad \dots \tag{3.4}$$

and the required number of turns is is given by equation (3.5), where A_L is Inductive index.

$$\left[\frac{\text{desired L (nH)}}{A_L(\frac{nH}{N^2})}\right]^{1/2} \dots \tag{3.5}$$

The inductor for converter-1 is 18.2 μH and convertor-2 is 30.2 μH for 9.6 W and 7.2 W as input power respectively. Designed inductor core's electrical properties are given in Table 3.2.

Table 3.2 Design parameters of inductor for the step-up converters.

Inductor	**Inductance**	**Core part No**	**Wire gauge**	**No.of turns**	**Max. I_{pk}**	**Core A_L**
I_{L1}	18.2 μH	T 94-26	21	47	1.2 A	8.4
I_{L2}	30.2 μH	T 80-6	23	52	0.8 A	10

The output capacitor used in boost converter is 94 μF and input capacitor is of 940 μF. The choice of capacitor value depends mainly on the equivalent series resistance (ESR) as the converter's efficiency is influenced. Hence, ESR value of the capacitors used should be small or it can be achieved by paralleling capacitors [61].

3.5 Mathematical Model of Boost Converter

The set of differential equations which aid in mathematical modelling of DC/DC boost converter is helpful in representing the waveforms of the modelled circuit and it is known as state-space modelling [62].

The Boost converter's state space equation (3.6) when the switch is ON is shown here

$$\begin{cases} \frac{di_L}{dt} = \frac{1}{L}(Vs) \\ \frac{dV_O}{dt} = \frac{1}{C}\left(-\frac{Vo}{R}\right) \end{cases}, 0 < t < dT, Q: ON \ldots \tag{3.6}$$

And during the switch OFF mode the state space equation (3.7) obtained will be as shown by

$$\begin{cases} \frac{di_L}{dt} = \frac{1}{L}(Vs - Vo) \\ \frac{dV_O}{dt} = \frac{1}{C}\left(I_L - \frac{Vo}{R}\right) \end{cases}, dT < t < T, Q: OFF \ldots \tag{3.7}$$

Based on above mathematical equations, the Simulink modeling of boost converter was used for simulation. Two similar boost converters with closed loop proportional-integral (PI) controller were paralleled for the purpose of power sharing with and without cable consideration. The Simulink simulation result is discussed in detail in Chapter 4.

Here the hardware implementation of closed loop paralleled boost converter is discussed. In this work, the unregulated voltages of the PV modules due to variation of insolation and temperature, is input to this DC\DC converter for getting a constant voltage as output. The high voltage gains of DC/DC converters help in attaining large quality power production from renewable sources [63, 64].

In order to regulate a constant output voltage, several control techniques are available in the literature. In this work a current mode control is chosen for its advance features and easy implementation as discussed in the following sections.

3.6 Analog control techniques: Voltage mode control Vs. Current mode control

The conventional analog control methods used industries are the voltage mode and current mode control for closed loop DC\DC converter operation. Both techniques are analog based and are implemented in compact ICs.

3.6.1 Voltage mode control of DC/DC converter

Voltage mode control (VMC) is a single loop controller and therefore it is easy in implementation. This method is used in research and industry for simple control of DC converters. In this method, the measured value and the reference voltage are compared to generate the control voltage [65]. Then the control voltage is compared with fixed frequency sawtooth waveform to determine the duty ratio as shown in Figure 3.2.

This switching duty ratio maintains the average voltage across the inductor and eventually the output voltage remains close to its reference value.

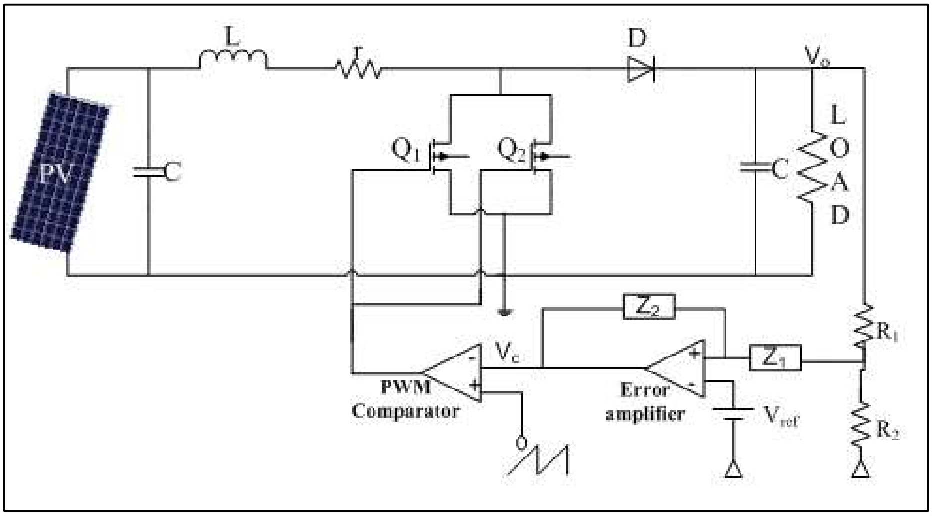

Figure 3.2 Boost converter with voltage mode control

This method inspite of easy implementation, it also has several disadvantages. They are i) when DC converters are connected in parallel with a common load, the reliability of control is poor. ii) The response time of control system is slow due to the higher order of switching cycles. iii) Poor reliability of switches. iv)It is inefficient in making the push-pull transformer to operate in center of linear region. Therefore, a better choice than this control is the control mode control which is described in next subsection 3.6.2 and in this work implemented in hardware and simulation.

3.6.2 DC\DC Boost converter with current mode control

Current mode control method is more complex than VMC as it is a dual loop control method. The current mode control (CMC) method used in this work is more superior to voltage mode control methods in terms of stability, response time and reliability [66]. The two loops are namely voltage and current control loop and the same is shown in Figure 3.3.

In this method, the output voltage V_o and the reference voltage V_{ref} are compared to generate reference current I_{ref}. This reference current I_{ref} is then compared with the sensed sawtooth waveform of current in terms of voltage to generate the control switching duty ratio [9].

The sensed inductor current tracks the reference current I_{ref} and the output voltage V_o equals the reference voltage V_{ref}. The only disadvantage of the control method is subharmonic oscillations which occur when the duty cycle exceeds the 50% duty ratio in the peak current mode control.

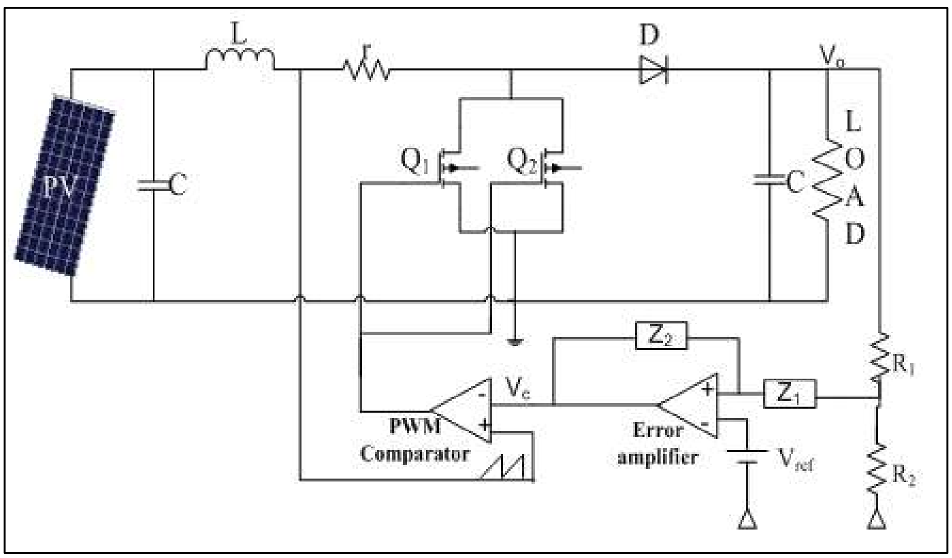

Figure 3.3 DC\DC Boost converter with current mode control

The choice of this method in this work is due several superior qualities of this technique.They are i) improved transient response, ii) better line regulation, iii) self protection features and iv) suitable for DC\DC converters operating in parallel mode. The dynamic response of the power converter is a vital parameter for measuring its performance [67, 68].