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

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,

\[ \partial t = \frac{D(1-D)^2 R T_S}{L} \ldots \]  

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-off with the switching frequency. Voltage ripple is given by equation (3.3),

\[ \partial v = \frac{D T_S}{R C} \ldots \]  

### 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.

<table>
<thead>
<tr>
<th>Component Values</th>
<th>Boost converter values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input DC voltage, $V_s$</td>
<td>19.2 V</td>
</tr>
<tr>
<td>Output DC voltage, $V_o$</td>
<td>48.2 V</td>
</tr>
<tr>
<td>Switching frequency, $F_s$</td>
<td>18.2 kHz</td>
</tr>
<tr>
<td>Inductance, $L_1, L_2$</td>
<td>18.2 $\mu$H, 30.2 $\mu$H</td>
</tr>
<tr>
<td>Capacitance, $C$</td>
<td>94 $\mu$F</td>
</tr>
<tr>
<td>Diode, $D$</td>
<td>1N5401</td>
</tr>
</tbody>
</table>
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)

\[
L = \frac{[V_o - V_{in(max)}] \cdot V^2_{in} \cdot T_s}{2 \cdot P_{in} \cdot V_o} \quad \ldots
\]  

(3.4)

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

\[
\left[ \frac{\text{desired } L \text{ (nH)}}{A_L \left( \frac{\text{nh}}{N^2} \right)} \right]^{1/2} \quad \ldots
\]

(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>
<thead>
<tr>
<th>Inductor</th>
<th>Inductance</th>
<th>Core part No</th>
<th>Wire gauge</th>
<th>No.of turns</th>
<th>Max. ( I_{pk} )</th>
<th>Core ( A_L )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_{L1} )</td>
<td>18.2 μH</td>
<td>T 94-26</td>
<td>21</td>
<td>47</td>
<td>1.2 A</td>
<td>8.4</td>
</tr>
<tr>
<td>( I_{L2} )</td>
<td>30.2 μH</td>
<td>T 80-6</td>
<td>23</td>
<td>52</td>
<td>0.8 A</td>
<td>10</td>
</tr>
</tbody>
</table>

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

\[
\begin{align*}
\frac{di_L}{dt} &= \frac{1}{L} (Vs) \\
\frac{dv_o}{dt} &= \frac{1}{C} \left( -\frac{v_o}{R} \right), \quad 0 < t < dT, Q: \text{ON} \ldots \quad (3.6)
\end{align*}
\]

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

\[
\begin{align*}
\frac{di_L}{dt} &= \frac{1}{L} (Vs - Vo) \\
\frac{dv_o}{dt} &= \frac{1}{C} \left( \frac{I_L}{R} - \frac{v_o}{R} \right), \quad dT < t < T, Q: \text{OFF} \ldots \quad (3.7)
\end{align*}
\]

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.
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.

![DC\DC Boost converter with current mode control](image)

**Figure 3.3** DC\DC Boost converter with current mode control

The choice of this method in this work is due to 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].
3.7 Proposed closed loop parallel boost converter using CMC UC 3843 controller

The closed loop CMC boost converter schematic is shown in Figure 3.4 and two such converters are paralleled and connected to a common resistive load as shown in Figure 3.5. The controller IC uses a part of PV module power for its functioning and no external supply is required for its operation. In controller ICs the sub harmonic instability of the current-mode converter is improved by avoiding the extreme duty ratios [69] or using programmed compensation ramp to be mixed with a reference current.

![Figure 3.4](image.png)

Figure 3.4 Closed loop Step-up converter using current mode controller IC (UC3843)

To reduce the stress on switching component during transient period, an optimum number of MOSFETs can be paralleled so that complexity in interconnections is avoided and on-state resistance \( (R_{ds(ON)}) \) of MOSFET is reduced to half of single MOSFET resistance [70, 71] as shown in figure 5. These paralleled MOSFETS when hard triggered synchronously, it helps
with the flow of twice the current through the converter inductor and this helps in the modular design of the converter [72].

Here two such similar converters are paralleled with cable resistance consideration and tested with varying irradiance on PV modules which are current source. The schematic diagram and its experimental setup are shown in Figure 3.5 and Figure 3.6 respectively. G1 and G2 as shown in the Figure 3.5 are the feedback for the paralleled DC\DC converters. In Figure 3.5, $R_{27}$ and $R_{48}$ represent the cable resistances and it is fixed in simulation as well as in experimental work.

![Figure 3.5 Paralleled step-up converter with cable resistance interfaced with PV modules](image)

Figure 3.5  Paralleled step-up converter with cable resistance interfaced with PV modules
paralleled Step-up converter with resistive load
The main objective of this work is to integrate several renewable energy sources using power electronic components and investigate how the power contribution from each source occurs under varying parameters. Here the role of control theory plays a vital role in the regulation of voltage and current sharing between the converters in parallel.

At a higher duty ratio, the parasitic elements of the basic components of the converter become dominating and alleviate the risk of high current and voltage stress and as a result the control and efficiency of conversion is aggravated [17]. The under voltage lockout (ULVO) of this PWM controller IC is 8.6 volts and it can be operated to 100% duty cycle [74].
3.8 Features and working of UC 3843 CMC controller

The controller UC3843 is a versatile IC and finds its applications in switched mode power supply (SMPS) [74]. There are several controller ICs such as TL494, UC384X and L6565 series available based on the mode of operations, namely voltage control mode, current control mode and green mode respectively. The voltage mode control method with PID tuned controller is used with three boost converters in parallel and the converters input power is from the same source, is discussed in [75].

The results obtained are higher efficiency, reduced ripple current/voltage and a stable system, but the cable resistance impact on the system is not considered. In another work, the effectiveness of interleaved boost converter using the sliding mode control is discussed with PSIM simulation [76] (Veerachary, 2005). The drawback of this system is that it cannot be operated under high frequency due to limitation of analog-digital converter’s (ADC) sampling frequency and operating frequency of the used switches.

3.8.1 UC3843 internal block description and their functions

Among mentioned control methods previously, UC3843 IC is used here for several reasons, the major being the two loops namely voltage and current loop implementation and MOSFETs triggering is easier without extra driver circuits. This current mode controller (CMC) IC UC3843 uses the voltage feedback from the output of the boost converter and the average inductor current like sawtooth waveform generated using auxiliary circuits and it is sensed at pin-3 of the IC and it gets added to the slope compensation voltage.
Using this compensation voltage, the average inductor current follows the control voltage. This process is called a current mode control method. The schematic diagram of the internal blocks of this IC is shown in Figure 3.7.

![Figure 3.7 Schematic diagram of the internal blocks of UC3843](image)

In boost convertor the average value of the inductor current ($I_L$) is equal to the DC input current ($I_{in}$). The output of the converter is set by the potentiometer to the desired output voltage. The latching PWM block generates the duty ratio according to the difference in voltage feedback and output compensation voltage and as per sensed current input. Resistor $R_T$ and capacitor $C_T$ are selected such that switching frequency is obtained for the designed inductor value and maximum obtained switching frequency is 250 kHz. $V_{cc}$ is the voltage for the operation of the internal blocks which is 5 volts obtained by voltage divider circuit. As per IC datasheet the range of $V_{cc}$ is 8.6 volts to 35 volts [77].

The dynamic response of the power converter is a significant parameter for measuring its performance [78, 79]. The closed loop current mode control converter schematic is shown in
Figure 3.8 and this pulse-width-modulated (PWM) IC uses the same power of photovoltaic module for its functioning and no external supply is required for its operation. To increase the efficiency of DC-DC power converter of the solar renewable sources the active snubber circuit can be employed [69]. A potentiometer \( R_2 \) is used to tune the desired output voltage as shown in Figure 3.8.

![Current mode controlled boost converter](image)

**Figure 3.8** Current mode controlled boost converter

![Waveforms of the boost converter in steady state CCM mode](image)

**Figure 3.9** Waveforms of the boost converter in steady state CCM mode
To reduce the stress on switching component during transient period, an optimum number of them can be paralleled so that complexity in interconnections is avoided and on-state resistance of MOSFET ($R_{ds\,(ON)}$) is reduced to half of single MOSFET resistance [80, 81]. Here in this work two MOSFETs in parallel are used and are synchronously switched.

These paralleled MOSFETs when triggered synchronously, its helps in flow of twice the current through the converter's inductor and this helps in modular design of converter [82]. The steady state waveform of a boost converter in continuous current mode is shown in Figure 3.9. In Chapter 5, two such similar converters are paralleled with cable resistance consideration and tested with varying irradiance on photovoltaic modules as a current source.

The main objective of this thesis is to integrate several renewable energy sources using power electronic components and investigate how the power contribution from each source occurs under varying parameters. Here the role of control theory plays a vital role in the regulation of voltage and current sharing between the converters in parallel.

The control IC UC3843 used in this work is a current mode control IC which uses the voltage as external loop feedback and sensed current as internal loop. This IC is a fixed frequency current-mode PWM controller. At higher duty ratio the parasitic elements of the basic components of the converter become dominating and alleviate the risk of high current and voltage stress and as a result the control and efficiency of converter is aggravated [72].

The under voltage lockout (ULVO) of this PWM controller IC is 8.6 volts and it can be operated to 100% duty cycle. Internally included circuits include a trimmed oscillator for precise duty cycle control, a temperature compensated reference, a current sensing
comparator, a high gain error amplifier and a high current totem pole output ideally suited for driving power Metal Oxide Semiconductor Field Effect Transistor (MOSFETs). The merits of current mode control method are as follow:

(a) The current control method is self protected from short circuit and control voltage is internally limited, so that even if external voltage is high, the output current is just close to maximum.

(b) In technique, the overall transient response is improved and being the first order system, the design of feedback circuit is much easier.

(c) The switches in current control method are protected for over-current as the current threshold is internally limited to its maximum value. This factor attributes to improved switches reliability during start-up, transients and overload situations.

(d) This method is suitable in paralleled configured converters as single feedback circuit regulate the voltage. The equal load sharing is obtained because the parallel converters receive the same voltage.

(e) This technique is immune to noise as the circuit feeds the fixed current into load independent of the input and therefore the input transient does not require external feedback to correct the same.

3.9 Subharmonic elimination using the compensation ramp signal

The demerit of this technique is the sub-harmonics generation in boost converter operation. This sub harmonic instability of the current-mode converter is improved by avoiding the extreme duty ratios as well [83] and also by programming a compensating ramp signal.
The local feedback accounts for this instability in the current mode converter during the operation of converter’s duty ratio above 0.5. This is explained using steady state inductor current waveform as shown in figure 3.10. In steady state condition suppose the inductor current has a rising slope of $M_1$, falling slope of $M_2$ and $I_c$ be the control signal representing the current threshold [84], then 

$$\frac{M_2}{M_1} = \frac{D}{1-D} \ldots \quad (3.8)$$

If a perturbation of $\delta I_o$ occurs in the inductor current relative to the steady state at the beginning of the cycle, then after one period, the perturbation will propagate to $\delta I_1$ i.e.,

$$\delta I_1 = -\frac{M_2}{M_1} \delta I_2 \ldots \quad (3.9)$$

![Figure 3.10 Stability of Operating Point in Current mode Control method](image)

After $n$ periods, the error will be

$$\delta I_n = \left( -\frac{D}{1-D} \right)^n \delta I_o \ldots \quad (3.10)$$

Which clearly indicates the steady state is not stable for $D > 0.5$. This issue is overcome by adding an additional ramp $-M$ to the reference current.
By using this additional ramp \(-M\) to the reference current as shown in Figure 3.11, the perturbation after \(n\) cycle becomes

\[
\delta I_n = \left( -\frac{M_2 - M}{M_2 + M} \right)^n \delta I_0 \ldots \tag{3.11}
\]

An appropriate choice of the ramp slope \(M\) can thus cause this perturbation to disappear even if the duty ratio is greater than 0.5. The enhancement of inner loop stability and improvement in the transient recovery is attained by the correct slope choice of this compensating ramp.

For a variable operating point, a sophisticated program may be developed to achieve the compensation.

**Simulation Result**

The boost converter circuit of figure is simulated with same parameters and the result obtained confirms that it is operating in a discontinuous current mode. The inductor and
capacitor current waveforms at frequency 18.2 kHz are obtained from the simulation and it is shown in Figure 3.12.

![Waveforms of boost converter in DCM mode](image1.png)

**Figure 3.12** Waveforms of boost converter in DCM mode

![Load current and output voltage waveforms](image2.png)

**Figure 3.13** Load current and output voltage waveforms of boost converter in DCM mode

The regulated output voltage and load current obtained with resistive load of 600 Ω is shown in Figure 3.13. When the resistive load is drastically reduced to 12 Ω, the inductor current waveform shown in Figure 3.14, indicates that it is going in CCM mode, but this optimized resistive load alone will not result in CCM mode operation. The proper choice of inductor
value, switching frequency and duty cycle decides the mode of operation of the DC boost converter.

Figure 3.14 Waveforms of boost converter in CCM mode at 12 Ω load

Figure 3.15 Waveform of load current and output voltage in CCM mode

The Figure 3.15 shows the load current and output voltage of the boost converter whose voltage is regulated to the desired value. In chapter 5, two similar boost converters with $L_1=18.2 \, \mu\text{H}$ and $L_2=30.2 \, \mu\text{H}$ respectively, were implemented in parallel on hardware for investigating the power contribution from both the converters and the mode of operation.
By integrating few hundreds of watts of photovoltaic modules and small wind turbines to power conditioning devices such as these paralleled converters can suffice the everyday power consumption to at least DC light loads in every house of villagers which are remotely located and unreachable by the utility line. Here an attempt to power a light resistive load from photovoltaic module is done and how the contribution of the power takes place between the two boost converters in parallel is studied.

3.10 Summary

A basic about the operation of the DC\DC boost converter is studied. For the available voltage of PV modules, suitable inductors are designed for the boost converter and the details of it is given in table 3.2 Proper selection of diode, MOSFET and capacitance is made in order to operate the DC boost converter smoothly. Next among the varieties of the control algorithm, current mode control method is chosen for its advanced features and easy implementation. The drawback of CMC method and the solution of this drawback is discussed. Finally, the simulation results of the single DC boost converter using UC3843 PWM controller are presented. In chapter 4, another control technique which is widely used in industry, namely PID controller and its tuning by PSO algorithm is studied and implemented.

-------------------------------------------End of Chapter 3-------------------------------------------------