3.1 INTRODUCTION

The non isolated cascaded and switched coupled inductor based bidirectional converter has less conduction losses due its simple winding structure. Moreover, this technique has the ability to attain maximum conversion ratio by changing the winding ratio. But the energy stored in inductor produces a potential spike in switches. The voltage clamping technique is utilized to recover the stored energy so that the potential stress on switches is reduced significantly. A multilevel with cascaded capacitor techniques has been presented to achieve lower stress on power device. This chapter discusses the design of switched coupled inductor based non isolated bidirectional DC to DC converter. The work in this chapter has been published in first paper as given in list of publication.

3.2 SWITCHED COUPLED INDUCTOR BASED CASCADED NON ISOLATED BIDIRECTIONAL DC to DC CONVERTER

The existing bidirectional converter technique has more voltage stress, energy loss due to leakage inductance, and less step-up ratio. Switched coupled inductor based cascaded NBDC was projected for solving the above-said problem and also used for voltage gain enhancement. This converter operated with soft switching, continuous inductor current and fixed switching cycle. It is stated that the coupled inductor performance could be improved by the switched coupled inductor. It is used to achieve the high voltage gain ratio with moderate duty cycle. The cascading structure is used for improving the efficiency of the conversion.

3.2.1 Circuit description

The proposed converter is illustrated in Fig. 3.1 performs the bidirectional operation. In the given circuit, the current flowing through the positive terminal of the L₁ & L₂ inductor is considered as positive. The current
flows through the switches $T_{11}$ and $T_{12}$ are positive, when it flows through their respective drain terminal of switches. The current flows through the $T_a$ switch is positive, when it is flowing from the source to drain. The cascaded capacitors ($C_1$, $C_2$,.....$C_n$) and diodes ($D_1$, $D_2$,...$D_n$) are added to the cascading circuit, which allows the current in a particular direction. The capacitors and the diodes are used for improving the performance of the converter.

Fig. 3.1 Proposed switched coupled inductor based cascaded non-isolated bidirectional DC to DC converter

In boost mode, the $T_{11}$ acts as the boost switch and diode across switch $T_{12}$ acts as a freewheeling diode. During buck mode, $T_{12}$ acts as the main switch whereas diode across $T_{11}$ acts as a freewheeling diode. In both modes, switch $T_a$ is utilized to create resonant for soft switching. The cascaded arrangement of a series connection of capacitors and diodes enhance the performance of the converter. The presence of switched coupled inductor promotes a high conversion ratio. The mathematical derivation of output voltage in both modes are given as follows,

$$V_{boost} = V_i \left[ 1 + \frac{T_{on}}{T_{off}} \cdot N \right] + \sum_{m=1}^{2} L_m \frac{di_m}{dt} + \sum_{m=1}^{n} \frac{1}{C_m} \int i_2(t) dt + \sum_{m=1}^{n} \frac{k_{m}}{q} + \frac{V_{low}}{1-D_k} \tag{3.1}$$

where,
N=N₂/N₁-Turns ratio under boost mode

In this mode, N₂ winding should be greater than N₁ winding

Vᵢ - Input Voltage

Lₘ - Mutual Inductors, where m=1,2……n

Cₘ - Capacitors, m=1,2…. n

k - Boltzmann constant

Tₘ - Absolute Temperature of the P-N junction diode, m=1,2……n

q - Magnitude of Charge on an Electron

D₁ - Duty Ratio of switch T₁₁

Correspondingly, the output voltage during buck mode is given in equation (3.2).

\[
V_{buck} = V₁ \left[ 1 + \frac{T_{on}}{T_{off}} K \right] + \sum_{m=1}^{2} Lₘ \frac{dlₘ}{dt} + \sum_{m=1}^{n} \frac{1}{Cₘ} \int i₂(t) dt + \sum_{m=1}^{n} \frac{kTₘ}{q} + V_{high} + \frac{nV_{low}}{1 - D}
\]

(3.2)

where,

K=N₂/N₁ buck mode’s turns ratio.

Under this mode, N₂ winding should be fewer than N₁ winding

Vₜₐₜ - High voltage side

D - Duty Ratio of switch T₁₂

The operating modes of proposed converter for both modes such as boost and buck operation is presented in section 3.2.2 and 3.2.3.
3.2.2 Boost mode of operation

It has eight modes in one switching cycle and its equivalent circuit is given in Fig. 3.2. In boost operation, switch $T_{11}$ acts as the main switch, and the diode across switch $T_{12}$ acts as freewheeling diode. The switched coupled inductor gives high conversion ratio, and the cascading of the circuit improves the efficiency of the system.

**Mode 0: ($t < t_0$)**

In this mode, the boost switch $T_{11}$ is on. The switched coupled inductor switch $D_{s1}$ is off and $D_{s2}$ is on, the inductor $L_{m1}$ current increases and at the same time $L_{m2}$ gets energized. The energizing of the $L_{m2}$ inductor is done by magnetizing coupling between the mutual inductors $L_{m1}$ and $L_{m2}$. The current flows from the left to the right side in $L_{m2}$ and the current circulates from the right to the left side through the 1:1 transformer. The voltage equation in this mode is given in equation (3.3).

$$V_{\text{boost}} = V_i \left[ 1 + \frac{T_{en}}{T_{\text{eff}}} \times N \right] + L_1 \frac{di_1}{dt} + \frac{V_{\text{leak}}}{1-D_1} \quad (3.3)$$
Fig. 3.2 Equivalent circuit of Mode 0 to Mode 7 during boost operation
Mode 1: \((t_0 < t < t_1)\)

At \(t_0\) switch \(T_{11}\) is off and capacitor \(C_{s1}\) across switch \(T_{11}\) starts charges. This path is similar to the same path of mode 0. At \(t = t_1\), the switched coupled inductor switch \(D_{s1}\) is turned off and \(D_{s2}\) is turned on. The voltage equation in this mode is given in equation (3.4).

\[
V_{\text{boost}} = V_i \left[ 1 + \frac{T_{\text{on}}}{T_{\text{off}}} \times N \right] + L_2 \frac{d i_3}{d t} \quad (3.4)
\]

Mode 2: \((t_1 < t < t_2)\)

Initially, the body diode \(T_a\) becomes forward biased, switch \(D_{s1}\) is on and \(D_{s2}\) is off. In this mode, the input current gets diverted to inductor \(L_1\) to \(L_2\), and the current in \(L_1\) charges the capacitors \(C_1,C_2,...,C_n\) using the body diode. Finally, the input current has been completely transferred from \(L_1\) to \(L_2\), so that no current is observed by the working components, i.e. \(L_1, T_a, C_1,C_2,...,C_n\) and \(C_{s1}\). The voltage equation in this mode is given in equation (3.5).

\[
V_{\text{boost}} = V_i \left[ 1 + \frac{T_{\text{on}}}{T_{\text{off}}} \times N \right] + \sum_{m=1}^{2} L_m \frac{d l_m}{d t} + \sum_{m=1}^{n} \frac{1}{C_m} \int i_2(t) dt + \sum_{m=1}^{n} \frac{kT_m}{q} + \frac{V_{\text{low}}}{1 - D_1} \quad (3.5)
\]

At the end of this mode, the charges in the capacitors reaches to the maximum as given in equation (3.6).

\[
V_{ei} = I_{\text{input}} Z, \quad i = 1,2,...,n \quad (3.6)
\]

where \(I_{\text{input}}\) is the input current and

\[
Z = \sqrt{\frac{L_1 + L_2}{C_1 + C_2 + \ldots C_n}}
\]
Mode 3: \((t_2 < t < t_3)\)

At \(t=t_2\), capacitor \(C_{s2}\) across the switch \(T_{12}\) is fully discharged, and the diode of the switch \(T_{12}\) start conduction. At this time the converter act as the standard boost converter. Now current through the inductor \(L_{m1}\) decreases and charges \(L_{m2}\) due to mutual inductance between \(L_{m1}\) and \(L_{m2}\). At \(t=t_3\), switch \(D_{s1}\) is off and \(D_{s2}\) is on. The potential equation in this mode is given in equation (3.7).

\[
V_{\text{boost}} = V_i \left[ 1 + \frac{T_{\text{on}}}{T_{\text{off}}} \star N \right] + L_2 \frac{d i_2}{dt}
\] (3.7)

Mode 4: \((t_3 < t < t_4)\)

In mode 4, \(T_{11}\) is on sometimes before the time \(t_3\), the body switch \(T_a\) is on with ZCS. The discharging process is done at this time, the capacitors \(C_1, C_2, \ldots, C_n\) discharge through \(C_1, C_2, \ldots, C_n\) - \(L_1\) and \(L_2\). At \(t = t_4\) the switch \(D_{s1}\) is off and \(D_{s2}\) is on. The operation of this mode is described by the equation (3.8).

\[
V_{\text{boost}} = V_i \left[ 1 + \frac{T_{\text{on}}}{T_{\text{off}}} \star N \right] + \sum_{m=1}^{2} L_m \frac{di_m}{dt} + \sum_{m=1}^{n} \frac{1}{C_m} \int i_2(t) \, dt + \sum_{m=1}^{n} \frac{k_{\text{q}}}{q}
\] (3.8)

The capacitor voltage is given in equation (3.9).

\[
V_{C_i} = I_{\text{input}} Z, \quad i = 1, 2, \ldots, n
\] (3.9)

where, \(I_{\text{input}}\) is the input current and

\[
Z = \sqrt{\frac{L_1 + L_2}{C_1 + C_2 + \ldots + C_n}}
\]

Mode 5: \((t_4 < t < t_5)\)

This mode of operation lies between \(t_4\) and \(t_5\). At this stage switch \(T_a\) and switch \(D_{s1}\) are off and \(D_{s2}\) is on. The capacitor \(C_{s1}\) starts discharging and the voltage across the \(C_{sa}\) rises, due to the reduction of voltage to zero across \(C_{s1}\). The inductor \(L_1\) accommodates additional current in switched
coupled inductor \( L_{m1} \), so that the voltage equation is similar to the equation (3.8).

**Mode 6**: \((t_5 < t < t_6)\)

At \( t_5 \), the capacitor \( C_{s1} \) is completely discharged. The diode across \( T_{11} \) starts conducting and \( T_{11} \) is turned on with ZVS. The potential equation in this mode is given in equation (3.10).

\[
V_{\text{boost}} = V_i \left[ 1 + \frac{T_{on}}{T_{off}} \times N \right] + \sum_{m=1}^{2} L_m \frac{dI_m}{dt} 
\]

(3.10)

**Mode 7**: \((t_6 < t < t_7)\)

At \( t = t_6 \), \( T_{11} \) is on; \( L_1 \) current direction is reversed and current is transferred from inductor \( L_2 \) to switch \( T_{11} \). When the current is completely transferred, this mode of operation will be completed and mode 0 operation of this converter starts again at time \( t = t_0 \). The voltage equation in this mode is given in equation (3.11).

\[
V_{\text{boost}} = V_i \left[ 1 + \frac{T_{on}}{T_{off}} \times N \right] + \sum_{m=1}^{2} L_m \frac{dI_m}{dt} + \frac{V_{\text{low}}}{1-D_2} 
\]

(3.11)

The time required for complete current transfer in this mode is given by the following equation (3.12).

\[
t_{c1} = \frac{I_{\text{input}} (L_1 + L_2)}{V_{\text{input}} \frac{V_{\text{high}}}{n}}
\]

(3.12)

where, \( t_{c1} \) is the time at which current completely transferred from inductor \( L_1 \) to \( L_2 \) and ‘n’ is coupled inductor turns ratio. The timing diagram of converter in boost mode for one cycle is illustrated in Fig. 3.3. It has eight modes of operation and time ranges from \( t_0 \) to \( t_7 \).
3.2.3 Buck mode of operation

It has eight operational modes, in which the switch $T_{12}$ acts as a buck switch and diode across switch $T_{11}$ acts as the freewheeling diode. The operating modes are illustrated in Fig. 3.4 and its explanations are given below.

Mode 0: ($t < t_0$)

During this mode, converter acts as the standard switched coupled inductor PWM buck converter. At this time the main switch $T_{11}$, the switched coupled inductor switch $D_{s4}$ is on and switch $D_{s3}$ is off. The current through the inductor $L_{m2}$ increases at the same time $L_{m1}$ gets energized through mutual coupling. The energizing of the $L_{m1}$ inductor is done by the magnetization coupling between the mutual inductors $L_{m1}$ and $L_{m2}$. The voltage equation in this mode is given in equation (3.13).

$$V_{\text{buck}} = V_{i} \left[ 1 + \frac{T_{\text{on}}}{T_{\text{eff}}} \times K \right] + L_{2} \frac{di}{dt} + V_{\text{high}} + \frac{nV_{\text{in}}}{1-D}$$  (3.13)
Fig. 3.4 Equivalent circuit of Mode-0 to Mode-7 during buck operation

**Mode 1:** \((t_0 < t < t_1)\)

At \(t_0\), the switch \(T_{12}\) is off and there is a rise in voltage across the switch \(T_{12}\), which is limited by using the capacitor \(C_{s2}\). The switched coupled inductor switches \(D_{s3}\) and \(D_{s4}\) are similar to the mode 0. The capacitor \(C_{s1}\) charges with the help of current flowing through the inductor \(L_2\) and starts to flow through the capacitors \(C_1, C_2, ..., C_n\). Also in this mode, input current starts to deliver to the inductor \(L_1\) and the capacitance \(C_{s1}\) across the switch \(T_{11}\) starts discharging. The voltage in this mode is given in equation (3.14).

\[
V_{buck} = V_i \left[1 + \frac{T_{on}}{T_{off}} \times K\right] + \sum_{m=1}^{n} \frac{1}{C_m} \int i_2(t) \, dt + \sum_{m=1}^{n} \frac{k_i}{q} \quad (3.14)
\]

The voltage across the capacitor is given in equation (3.15)

\[
V_{ei} = I_{input} Z_1 \sin \omega t, \quad i = 1, 2, ..., n
\]

\[
Z_1 = \sqrt{\frac{L_2}{C_1 + C_2 + ... + C_n}}
\]

\[
\omega = \sqrt{\frac{1}{L_2 (C_1 + C_2 + ... + C_n)}}
\]
Mode 2: \( (t_1 < t < t_2) \)

At \( t_1 \), capacitor \( C_{s1} \) across the switch \( T_{11} \) is fully discharged, the switch \( D_{s4} \) is off and \( D_{s3} \) is on at the time \( t = t_1 \) and the current passes through the body diode \( T_a \). At \( t_2 \) the capacitor ‘\( C_{s1} \)’ across the switch is charged and the current passing through the capacitors branch \( C_1,C_2,...C_n \) is stopped. The voltage equation in this mode is similar to the equation (3.14).

Mode 3: \( (t_2 < t < t_3) \)

At \( t_2 \) current flowing through auxiliary components is stopped. At this time the proposed converter acts as the standard switched coupled inductor PWM buck converter and the switched coupled inductor switch remains in the previous mode condition. The \( L_{m1} \) current decreases and negative voltage appears across the inductor \( L_{m1} \). At this time the high voltage side energy is transmitted to the low voltage side which is given in (3.16)

\[
V_{\text{buck}} = V_i \left[ 1 + \frac{T_{on}}{T_{off}} \times K \right] + L_1 \frac{di_1}{dt}
\]

Mode 4: \( (t_3 < t < t_4) \)

At \( t_3 \), \( T_{12} \) is on. Sometimes, little earlier than \( t_3 \), the body switch \( T_a \) is turned on with ZCS. The discharging process is done at this time, the capacitors \( C_1,C_2,...C_n \) discharges through the inductors \( L_1 \) and \( L_2 \). The switched coupled inductor current continues to decrease. At the end, the switch \( D_{s4} \) is off and \( D_{s3} \) is on. The operation of this mode is described in equation (3.17).

\[
V_{\text{buck}} = V_i \left[ 1 + \frac{T_{on}}{T_{off}} \times K \right] + \sum_{m=1}^{2} L_m \frac{di_m}{dt} + \sum_{m=1}^{n} \frac{1}{C_m} \int i_2(t) \, dt + \sum_{m=1}^{n} \frac{kT_{m}}{q} \quad (3.17)
\]

Mode 5: \( (t_4 < t < t_5) \)

At \( t_4 \), \( T_a \) switch is off and \( D_{s3} \) is on. During this mode the capacitor \( C_{s2} \) starts discharging and the voltage across the \( C_{sa} \) increases, due to the reduction of voltage across the \( C_{s2} \) to zero.
**Mode 6: \((t_5 < t < t_6)\)**

The capacitor \(C_{s2}\) is completely discharged at \(t=t_5\). The body diode of the switch \(T_{12}\) starts conducting in this mode and \(T_{12}\) is on due to conduction of body diode. This mode voltage equation is given in equation (3.18).

\[
V_{suck} = V_i \left[ 1 + \frac{T_{on}}{T_{eff}} \times K \right] + \sum_{m=1}^{2} L_m \frac{di_m}{dt} 
\]  
(3.18)

**Mode 7: \((t_6 < t < t_7)\)**

At \(t_6\), \(T_{12}\) is on; the current direction of the inductor \(L_1\) is reversed and the current is transferred from inductor \(L_2\) to switch \(T_{12}\). The current is completely transferred to the switch \(T_{12}\). Then the converter enters into the mode 0 operation at time \(t=t_0\). This mode voltage equation is given in equation (3.19).

\[
V_{suck} = V_i \left[ 1 + \frac{T_{on}}{T_{eff}} \times K \right] + \sum_{m=1}^{2} L_m \frac{di_m}{dt} + V_{high} + \frac{nV_{low}}{1-D} 
\]  
(3.19)

The complete current transfer equation of this mode is given in equation (3.20)

\[
t_{c2} = \frac{I_{input}(L_1+L_2)}{V_{input} + V_{high}} \frac{1}{1-D}
\]  
(3.20)

where, \(t_{c2}\) is the time at which current is completely transferred from inductor \(L_1\) to \(L_2\). The timing diagram for one cycle is shown in Fig. 3.5. It has eight modes of operation and time ranges from \(t_0\) to \(t_7\).
The performance of the proposed circuit with multi levels is analyzed by implementing in MATLAB platform and compared with the existing method. The simulation results are explained in the following section 3.2.4.

### 3.2.4 Simulation results

The proposed method is implemented in the MATLAB platform. Fig. 3.6 illustrates the MATLAB simulation model of existing bidirectional converter and the Fig. 3.7 shows the MATLAB implementation model of this converter, which consists of capacitor cascading. The proposed circuit has the 5 levels of cascading, whose performance graphs are given in the following figures. The rating of component used in proposed converter is tabulated in Table 3.1.
Fig. 3.6 Existing bidirectional DC to DC converter model in MATLAB

Fig. 3.7 Proposed converter model in MATLAB

Table 3.1 Proposed converter parameters

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<th>S.No</th>
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<tr>
<td>2</td>
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### 3.2.4.1 Results in boost mode of operation

Fig. 3.8 represents the proposed converter in 5 level with different values of turns ratio ‘n’ (10, 12, 18, 20, 25). It is observed that the voltage conversion ratio depends on the turns ratio ‘n’ between mutual inductance L<sub>m1</sub> and L<sub>m2</sub>. If the turn’s ratio increases the conversion ratio also increases.

![Proposed converter in boost mode for 5 level](image-1)

**Fig. 3.8** Duty ratio versus voltage conversion ratio
The performance in boost mode (1 level, 3 level & 5 level) and the existing converter are analyzed and shown in the Fig. 3.9. The proposed converter performance is compared with the existing converter with coupled inductor turns ratio \( n=25 \) and found that proposed model gives the best conversion ratio while \( D \) (Duty ratio) ranges from 0.41 to 0.5.

![Boost mode operation of existing and proposed model](image)

**Fig. 3.9 Comparison of existing and proposed converter**

Fig. 3.10 represents the necessary values of \( L_1 \) to carry out ZVS turn on of switch \( T_{11} \) at low voltages 24 V and 30 V in boost mode. The sum of values of \( L_1 \) & \( L_2 \) and average load current are inversely proportional. The rating of inductances are found to be \( L_1 = L_2 = 1.5 \mu\text{H} \).
Fig. 3.10 Necessary values of \( L_1 \) to ensure the switch \( T_{11} \) to turn on at ZVS for different low voltages

The capacitor voltages corresponding to different input voltages (24 V & 30 V) are given in Fig. 3.11, which depends on the turn’s ratio ‘\( n \)’. When turns ratio of coupled inductor decreases, the voltage across boost switch \( T_{11} \) increases. Due to cascading technique the proposed topology has less voltage stress when compared to existing converter topology.

Fig. 3.11 Characteristics of capacitor voltage as a function of ‘\( n \)’ at different input voltages

43
Fig 3.12 shows the driving pulse for auxiliary switch $T_a$ and boost switch $T_{11}$ respectively. When switch $T_a$ and $T_{11}$ conducts, $T_a$ helps to create ZVS across switch $T_{11}$. Switch $T_a$ is turned on for few micro seconds before switch $T_{11}$ is turned on.

![Driving pulse for auxiliary switch $T_a$ and boost switch $T_{11}$](image1)

**Fig. 3.12 Driving pulse for auxiliary switch $T_a$ and boost switch $T_{11}$**

Fig 3.13 shows the driving pulse, drain current ($I_d$) and drain source voltage ($V_{ds}$) across boost switch $T_{11}$ respectively. From the figures it is found that value of drain current is 5 A and drain source voltage is almost zero. So power loss across switch is zero, even though the switch is turned on.

![Driving pulse, $I_d$ and $V_{ds}$ across switch $T_{11}$](image2)

**Fig. 3.13 Driving pulse, $I_d$ and $V_{ds}$ across switch $T_{11}$**
Fig 3.14 shows the driving pulse; drain current \( (I_d) \) and drain source voltage \( (V_{ds}) \) across and auxiliary switch \( T_a \) respectively. Graph indicates that drain current (ZCS) is zero and voltage is almost zero. So power loss is zero, even though the switch \( T_a \) is turned on.

![Graph showing driving pulse, \( I_d \) and \( V_{ds} \) across switch \( T_a \)](image)

**Fig. 3.14 Driving pulse, \( I_d \) and \( V_{ds} \) across switch \( T_a \)**

Fig 3.15 illustrates the current through inductor \( L_m \), \( L_1 \) and \( L_2 \) respectively. From the graph, the current through the inductor \( L_1 \) is 20 A which is used to boost the voltage in this mode.

![Graph showing current through inductor \( L_m \), \( L_1 \) and \( L_2 \)](image)

**Fig. 3.15 Current through inductor \( L_m \), \( L_1 \) and \( L_2 \)**
Fig. 3.16 shows the current through coupled inductor in primary and secondary respectively. Whenever primary coil of coupled inductor is energized, secondary coil receives energy due to mutual inductance between coupled inductor.

Fig. 3.16 Coupled inductor primary and secondary current

Fig. 3.17 illustrates the efficiency comparison between proposed converter and existing converter. It is observed that proposed converter has improved efficiency than existing bidirectional converter.

Fig. 3.17 Input voltage versus efficiency
Fig. 3.18 illustrates the graphical representation of the input versus output voltage for both existing and proposed converter. It is noticed that the proposed has higher potential gain than existing converter.

![Graph showing input voltage versus output voltage comparison between existing and proposed converter](image)

**Fig. 3.18 Input voltage versus output voltage**

Fig. 3.19 exhibits the comparison between existing and proposed converter with respect to input voltage and output power. From the graph the proposed bidirectional DC-DC converter has higher power output than existing bidirectional DC-DC converter.

![Graph showing input voltage and output power comparison](image)

**Fig. 3.19 Comparison of input voltage and output power**
Thus the performance of the both topologies with an input and output voltages of twelve volt and forty eight volt in boost mode are specified in the Table 3.2.

Table 3.2 Performance parameters in boost mode

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Existing Converter</th>
<th>Proposed Converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output power (W)</td>
<td>73</td>
<td>76</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>77.3</td>
<td>81.54</td>
</tr>
<tr>
<td>Voltage gain</td>
<td>3.6</td>
<td>3.75</td>
</tr>
<tr>
<td>Voltage conversion ratio</td>
<td>13</td>
<td>26</td>
</tr>
<tr>
<td>Switching losses</td>
<td>14 W</td>
<td>12 W</td>
</tr>
</tbody>
</table>

From the comparison Table 3.2, it is spotted that the proposed converter has improved efficiency ($P_{out}/P_{in}$) of 81.54%, voltage conversion ratio ($V_{high}/V_{low}$) is 26 and switching loss is 12 W in boost mode compared to the existing method. Hence, it is concluded that the proposed switched coupled inductor with cascaded circuit exhibits high voltage gain when compared to the existing coupled inductor converter.

3.2.4.2 Results in buck mode of operation

Fig. 3.20 shows voltage conversion ratio for various value of coupled inductor turns ratio '$n$' (10, 12, 18, 20, 25). From the figure it is observed that voltage conversion ratio reduces with decrease in turn ratio '$n$'.

![Proposed converter voltage conversion ratio versus duty ratio](image)
Fig. 3.21 illustrates the comparison between existing converter and proposed converter in buck mode when coupled inductor turn ratio n=25. This shows the proposed converter gives improved voltage conversion ratio compared to the existing converter and found that proposed model gives the best conversion ratio while D (Duty ratio) ranges from 0.5 to 0.76.

![Buck mode operation of existing and proposed model](image)

**Fig. 3.21 Existing and proposed converter comparison**

Fig. 3.22 shows the $L_1$ value to achieve ZVS across switch $T_{12}$ in buck mode at different voltages (24 V, 30 V). The sum of inductances $L_1$ & $L_2$ and average input current are inversely proportional to each other. Hence choice of inductance depends on input current in this mode. The value of inductances are $L_1=L_2=1.5$ μH.

![Value of $L_1$ to ensure the switch $T_{12}$ to turn on at ZVS](image)

**Fig. 3.22 Value of $L_1$ to ensure the switch $T_{12}$ to turn on at ZVS**
The voltage across the switch $T_{12}$ at different low side voltages such as 24 V, 30 V and 40 V respectively, depends on turns ratio ‘n’ is illustrated in Fig. 3.23. It indicates that when coupled inductor turns ratio decreases voltage across the switch $T_{12}$ decreases. Hence voltage across the switch is less in proposed converter.

![Graph showing voltage across switch $T_{12}$ for different values of $n$ at various low side voltages](image)

**Fig. 3.23 Voltage across the switch $T_{12}$ for different values of $n$ at various low side voltages**

Fig. 3.24 shows the driving pulse for buck switch $T_{12}$ and auxiliary switch $T_a$ respectively. From the figure, it is found that switches are turned on when gate voltage is applied to MOSFETs.

![Driving pulse for buck switch $T_{12}$ and auxiliary switch $T_a$](image)

**Fig. 3.24 Driving pulse for buck switch $T_{12}$ and auxiliary switch $T_a$**
Fig 3.25 shows the driving pulse, drain current ($I_d$) and drain source voltage ($V_{ds}$) across buck switch $T_{12}$ respectively. From the graph, it is found that when gate voltage is applied, drain current flowing through switch is 1 A and drain source voltage is zero. So switch is on at zero power loss.

![Graphs showing driving pulse, $I_d$ and $V_{ds}$ across buck switch $T_{12}$](image1)

**Fig. 3.25 Driving pulse, $I_d$ and $V_{ds}$ across buck switch $T_{12}$**

Fig 3.26 shows the driving pulse, drain current ($I_d$) and drain-source voltage ($V_{ds}$) across auxiliary switch $T_a$ respectively. From the graph, the $V_{ds}$ and $I_d$ flowing through $T_a$ is zero, hence it is on at ZCS.

![Graphs showing driving pulse, $I_d$ and $V_{ds}$ across auxiliary switch $T_a$](image2)

**Fig. 3.26 Driving pulse, $I_d$ and $V_{ds}$ across auxiliary switch $T_a$**
Fig 3.27 shows the current through inductor $L_m$, $L_1$ and $L_2$ respectively. From the graph, it is noted that current flowing through the inductance $L_1$ is 15 A. This is used to reduce the voltage in buck mode.

![Current through inductor](image)

**Fig. 3.27 Current through inductor $L_m$, $L_1$ and $L_2$**

Fig. 3.28 shows the current through coupled inductor in coil 1 and 2 respectively. The coupled inductor secondary current is 10 A and in primary of coupled inductor is 15 A. During buck mode, stored energy in secondary of coupled inductor is transferred to primary of coupled inductor due to mutual coupling between the windings.

![Current through coil 1 & 2](image)

**Fig. 3.28 Current through coil 1 & 2 of coupled inductor**
Fig 3.29 shows the efficiency comparison between existing converter and proposed converter. It also exhibits that proposed converter has higher efficiency of 91.49%.

![Efficiency Comparison Graph](image)

**Fig. 3.29 Input voltage versus efficiency**

Fig. 3.30 shows the graphical representation of the input voltage versus output voltage for both existing and proposed converter. From the graph it is found that voltage gain is reduced in buck mode so wide range of voltage gain is achieved due to the use of switched coupled inductor.

![Comparison Graph](image)

**Fig. 3.30 Comparison graph between input and output voltage**
Fig. 3.31 illustrates existing and proposed converter comparison with respect to $V_{in}$ and $P_o$. It is noted that the existing converter has lesser power output than proposed converter.

![Graph: Input voltage versus output power](image)

**Fig. 3.31 Input voltage versus output power**

Thus the overall performances comparison of both the topologies in buck mode is mentioned in Table 3.3.

**Table 3.3 Buck mode performance parameters**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Existing Converter</th>
<th>Proposed Converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output power (W)</td>
<td>78</td>
<td>75.9</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>89.3</td>
<td>91.49</td>
</tr>
<tr>
<td>Voltage gain</td>
<td>0.2207</td>
<td>0.2269</td>
</tr>
<tr>
<td>Voltage conversion ratio</td>
<td>1.31</td>
<td>1.35</td>
</tr>
<tr>
<td>Switching losses</td>
<td>12 W</td>
<td>9 W</td>
</tr>
</tbody>
</table>

From the comparison Table 3.3, it is found that the proposed cascaded converter has improved efficiency of 91.49%, voltage conversion ratio is 1.35 and switching losses is 9 W in buck mode of operation compared to the existing method. This comparison shows that the cascaded
converter topology could be more desirable than the conventional converter topology.

3.3 EXPERIMENTAL RESULTS

The low voltage prototype model of proposed converter for 5 level is developed and it is shown in Fig. 3.32. The board consists of pulse generator circuit, driver circuit for MOSFETs, main switch $T_{11}$ and $T_{12}$, auxiliary switch $T_a$, cascaded capacitors and diodes, switched coupled inductor and switches such as $D_{s1}$, $D_{s2}$, $D_{s3}$ & $D_{s4}$ and load resistance. PIC microcontroller program for pulse generation is given in Appendix.1, which is compiled by using MPLAB software.

![Fig. 3.32 Prototype model of proposed converter](image)

The controller circuit for converter is shown in Fig 3.33. It has power supply section, PIC controller and opto-isolator section. The PIC16F877A controller is used for generating triggering pulse, applied to converter switches. The isolation between source and load is obtained by using Opto isolator. It is also used for amplification purpose.
The hardware rating of resonant capacitor, cascading capacitor and switching frequency, $V_{\text{low}}$, $V_{\text{high}}$ and $R_1$ are given in Table 3.4.

**Table 3.4 Component rating used in experimental setup**

<table>
<thead>
<tr>
<th>Components Name</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage (V)</td>
<td>12</td>
</tr>
<tr>
<td>Output voltage (V)</td>
<td>48</td>
</tr>
<tr>
<td>MOSFET switch</td>
<td>IRF8309, IRF3906</td>
</tr>
<tr>
<td>Inductor $L_1$ and $L_2$</td>
<td>1.5 uH</td>
</tr>
<tr>
<td>Resonant Capacitor $C_r$ and $C_1$</td>
<td>33 uF and 4 uF</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>66 kHz</td>
</tr>
<tr>
<td>Output Capacitor</td>
<td>470 uF</td>
</tr>
<tr>
<td>Output power</td>
<td>78 Watts</td>
</tr>
</tbody>
</table>

Fig. 3.34(a) shows the triggering pulses for switch $T_{11}$ and $T_{12}$. The zero voltage switching of main switch is represented in Fig. 3.34(b). Fig. 3.34(c) reveals the main switch voltage, current and pulse during turn on.
Fig. 3.34(a) Triggering pulse of switch $T_{11}$ and $T_{12}$

Fig. 3.34(b) ZVS operation of main switch

Fig. 3.34(c) Main switch pulse, current ($I_d$) and voltage ($V_{ds}$)
Fig. 3.35 shows the output voltage of 47 V in boost mode. During this mode, input voltage 12 V is boosted up to 47 V.

![Graph showing boost mode output voltage]

**Fig. 3.35 Boost mode output voltage**

Fig. 3.36 shows the output voltage of 11 V in buck mode. During this mode 48 V input voltage is reduced to 11 V.

![Graph showing buck mode output voltage]

**Fig. 3.36 Buck mode output voltage**

Experimental validation with simulation results is specified in Table 3.5.
Table 3.5 Simulation and experimental results

<table>
<thead>
<tr>
<th>Mode</th>
<th>Simulated value</th>
<th>Experimental value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage Input (V)</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Voltage Output (V)</td>
<td>48</td>
<td>47</td>
</tr>
<tr>
<td>Switching losses (W)</td>
<td>12</td>
<td>13.01</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>81.54</td>
<td>79</td>
</tr>
<tr>
<td>Buck</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage Input (V)</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>Voltage Output (V)</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>Switching losses (W)</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>91.49</td>
<td>89</td>
</tr>
</tbody>
</table>

### 3.4 SUMMARY

This chapter has dealt with the proposed switched coupled inductor based converter and is observed that the problems in the existing model could be sorted out by the proposed technique. The cascading purpose of this topology is to diminish the potential stress of the NBDC. The proposed method with 5 level is implemented in MATLAB Simulink and the output performance was analyzed. It shows that conversion ratio of the proposed method had improved well compared to existing method. The simulation result showed that the switching stresses and the switching losses of the proposed method had reduced. The comparative results proved that the proposed technique has the improved performance when compared to other techniques.

The prototype model of cascaded circuit is implemented using PIC controller and experimental values were validated with simulation results. However, it was necessary to maintain the output voltage of converter regardless of changes in the load or line voltage. Hence, closed loop control methods were being proposed to regulate output voltage of proposed converters in 5 level and it is discussed in the next chapter.