Design and Analysis of Multi-Device Interleaved Boost Converter Driving an Induction Motor

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Abstract. Electric vehicles are the future of mobility solutions. The electric vehicles are driven by an electric motor with the help of a power electronic interface. The power electronic interface needs to be designed in an efficient way both in mechanical and electrical aspects. This paper proposes the concept of design, simulation and analysis of a 10 kW Multi-Device Interleaved DC-DC Boost Converter (MDIBC) to drive a 4 kW Induction Motor. The motor is driven from the MDIBC through an inverter with SPWM technique. The variation in DC link voltage due to motor is controlled and stabilized to give a constant DC of 400 V. MDIBC consists of semi-controlled switches topology excited by Phase Shifted PWM technique to reduce the ripple current in interleaving inductors. The dual loop control methodology using PI controller is adopted to reduce the ripple in input inductor current and DC link voltage. The open loop simulation and closed loop simulation are done in MATLAB Simulink environment. The simulation results show that the overshoots and steady state error in inductor currents and output voltage are reduced in addition with reduction in current and voltage ripples.

1. Introduction

Vehicles running now rely on internal combustion engines for mobility. Electric vehicle is the need of hour as the fuel availability is reducing faster than forecasted. Deployment of electric vehicle into consumer market is important and vehicle manufacturers are in research of electric vehicle efficient technologies. The automotive sector encountered a revolution in its drive train technology in the past years. Introduction of Electric Vehicle (EV) technology with the use of battery and electric motor proved they are superior to ICE and eco-friendly. The Electric Motor drives the wheels of an EV. Electricity is generated and transmitted over a wide area and it is normally an AC voltage. The motor in EV on road requires the help of battery as a major source of its power. Battery has to be recharged once used. Thus, the DC–DC converter has to be more efficient. Various DC–DC converter topologies have been in research in the past years [5]. Among which the Multi-Device Interleaved DC-DC Bidirectional Converter (MDIBC) has low input current ripples, low output voltage ripples, low electromagnetic interference, bidirectional feature, high efficiency and a reliable topology [6]. This converter can be employed to vehicles driven by high power motors.

The MDIBC proposed in this work is designed, simulated and analysed for current and voltage ripples at the input inductor and output capacitor respectively. The MDIBC proposed works in unidirectional mode, from DC source to the load, the induction motor. Two inductors interleave phases of
the boost converter. MDIBC consists of eight switches with four switches per channel, two smoothing inductors and a filter capacitor. Among which four are MOSFET switches driven by Phase shift PWM technique with a switching frequency of 20 kHz. A 200V to 400V converter is designed and controlled. The 4kW squirrel cage induction motor is chosen as the electric motor. Interleaving boost inductors and the filter capacitor are calculated and checked for correctness using open loop simulation. Later a closed loop PI controlled dual loop controller was employed to regulate less ripple inductor current and a constant output across the DC link.

Electric vehicles require a DC-DC converter which is reliable with reduced filter size, low voltage ripple and low current ripple and provide a better battery performance and also with high efficiency [1]. Thus, a controlled DC-DC converter is necessary to perform the power conversion. The control algorithm proposed so far with diodes fed to R load is for uni-directional purpose. The motor drive when connected across the capacitor, ripples in DC link voltage are observed along with discontinuous input inductor current. The transients caused in MDIBC during the load variations causes transients in drive motor and would produce high torque oscillations. Thus it is necessary to maintain a constant DC link voltage by implementing a dual loop control strategy. The existing research work developed have ripples in the DC link voltage whenever the motor drive is connected. Also the mathematical modelling has further increased the complexity in control strategy. The control adopted in the proposed work smoothen the DC voltage without any complex mathematical modelling and reduces the voltage ripples.

2. Multi-Device Interleaved Boost Converter (MDIBC)

The Multi-Device Interleaved Boost Converter is a combination of boost converter, interleaved boost converter and multi-device boost converter [6]. The input inductor smoothen the input current. The number of inductors to be chosen depends on the number of phases of the converter. Six semiconductor switches are employed in the converter and the number of parallel devices is two. The two interleaving inductors are of same ratings. At a particular instant, if one inductor charges the other inductor discharges. The ripple in inductor current is twice that of the switching frequency. This is achieved by the method of phase shifting PWM. The phase shift angle depends on number of phases and number of parallel devices per phase [3]. The MDIBC is known for its less ripple factor, less filter size and low EMI. Thus the converter is highly recommended for low power motor electric vehicles. The battery being the primary source of power is taken as an ideal DC supply of 200V. The multi-device interleaved boost converter will produce the pulsed DC as output which is filtered out to a constant DC of 400 V. The six switch three leg inverter is used to drive the induction motor. A phase shift PWM needs to be applied to the inverter. The output voltage across the DC link is measured and the error in DC link voltage and input current are fed to the Dual loop PI controller during load variations and later a PWM generator produces phase shifted PWM’s with the appropriate duty cycle to activate the switches of MDIBC. The proposed block diagram is shown in Figure 1.

![Proposed block diagram](image-url)
2.1. MDIBC Topology

The proposed 10kW MDIBC is shown in figure 2. The input of 200V DC is boosted to 400V DC. The input supply is connected to two inductors constituting two phases. The inductor L1 and L2 are of same values. The inductor currents are complement to each other, when the current through inductor L1 is charging current then the current in L2 inductor will be discharging current, as shown in figure 3. The number of semi-conductor switches used is eight. Upper leg of the converter has four uncontrolled diodes and lower leg contains four controlled switches. The frequency of the switching pulses is 20 kHz and MOSFET switches are used. The relation between output and input voltage of the converter is given by equation 1. The switch used in the front as boost inductors are of same rating and the value of inductor can be calculated from equation 2. The capacitor value is given by equation 3 [5]. The calculated values of duty cycle, inductor and capacitor are mentioned in table 2.

\[
D = \frac{1}{n} \left(1 - \frac{V_{dc}}{V_o}\right) \quad (1)
\]

\[
L = \frac{(1-nD) \times V_o \times D}{p \times f_{sw} \times \Delta I_{L_{max}}} \quad (2)
\]

\[
C = \frac{V_o \times D}{p \times f_{sw} \times R \times \Delta V_o} \quad (3)
\]

![Diagram of MDIBC converter topology](image)

Figure 2. MDIBC converter topology

2.2. Boost Mode Operation of MDIBC

In boost operating mode, only one switch from upper leg and one switch in lower leg will be turned on simultaneously. As per the construction of boost converter, in MDIBC there exists two current smoothing inductors each for corresponding phase. The capacitor connected across the load reduces the ripple in the output DC voltage.

In figure 4(a), the current from source splits into two branches, through L1 and L2. At \( \delta = 0 \), the switch S1 is closed and current in iL1 returns to source. The branch current iL2 flows through D3 and D4, charges the capacitor and the load.

In figure 4(b), the current from source splits into two branches, through L1 and L2. At \( \delta = 90^\circ \) or \( T_s/4 \), the switch S3 is closed and current in iL2 returns to source. The branch current iL1 flows through D1 and D2, charges the capacitor and the load.
In figure 4(c), the current from source splits into two branches, through L1 and L2. At $\delta = 180^\circ$ or $T_s/2$, the switch S2 is closed and current through $i_{L1}$ returns to source. The branch current $i_{L2}$ flows through D3 and D4, charges the capacitor and the load.

In figure 4(d), the current from source splits into two branches, through L1 and L2. At $\delta = 270^\circ$ or $3T_s/4$, the switch S4 is closed and current in $i_{L2}$ returns to source. The branch current $i_{L1}$ flows through D1 and D2, charges the capacitor and the load.

The PWM phase shift for the switching pattern for eight switches is achieved by the formula given in equation 4 [3]. Four pulses with delay time calculated by the switching time period PWM sequence is shown in figure 5. The order of switching the devices, current flow and pulse generation are as shown in figure 4 and figure 5 respectively. Four PWM pulses are generated using the PWM generator. The duty cycle is the same for all the switches [2]. The phase shift angle can be calculated from equation 4 [2]. The design consideration for number of phases, number of parallel devices is mentioned in table 1 and calculated value of $\delta$ is mentioned in table 2.

$$\delta = \frac{360^\circ}{(n \times p)} \quad (4)$$

Where, $\delta$ is the phase shift angle, $n$ is the number of parallel switches per channel, $p$ is the number of phases or channel.
3. Dual loop control of MDIBC
When the drive motor gets connected to the MDIBC there will be a discontinuous current flowing through the input inductor though the DC link voltage is ripple free. The current control in combination with the voltage control constitutes the dual loop control. The current control is the inner loop control and the voltage control is the outer loop control. The reference to the voltage controller is 400V. The error computed by the difference in reference voltage and measured voltage is fed to the PI controller. The output of voltage controller becomes the reference for the current controller. As there are two inductors in the front end, it is necessary to introduce two current controllers. Primarily the current reference is taken without connecting voltage controller. The parameters of the current controller are tuned such that the input current reaches the reference value. Then the voltage controller is connected to stabilize the DC link voltage. Figure 6 shows the block diagram representation of implemented Dual loop control.

4. Drive Train
The output of the MDIBC is fed to the three phase three leg MOSFET based voltage source inverter. Sinusoidal pulse width modulation technique is used to produce PWM pulses to the MOSFETS. Three pulses with a phase shift of 120° is generated for the HV leg switches and their complimentary pulses drive the gate of LV leg switches. The modulation index of the SPWM inverter is set to 0.8. The
output of the inverter is connected to the induction motor with specifications mentioned in table 3. The induction motor is well known for its robustness and low operational cost. The control of induction motor becomes easier when compared to other AC motors. In this work the motor is not connected to any load and thus the inverter with drive train acts as a load for MDIBC.

5. Design Specifications
This section provides information on design consideration, calculated values and parameters which are used for simulation of MDIBC.

| S.No. | Parameters                        | Values     |
|-------|-----------------------------------|------------|
| 1     | Input voltage, \( V_{in} \)       | 200 V      |
| 2     | Output voltage, \( V_o \)         | 400 V      |
| 3     | Output power, \( P_o \)           | 10 kW      |
| 4     | Switching frequency, \( F_{SW} \) | 20 kHz     |
| 5     | Inductor current ripple, \( \Delta I_L \) | 25% of \( I_o \) |
| 6     | Capacitor voltage ripple, \( \Delta V_o \) | 4% of \( V_o \) |
| 7     | Number of phases, \( n \)         | 2          |
| 8     | Number of parallel devices per phase, \( p \) | 2          |

Table 2. Converter parameters

| S.No. | Parameters         | Values |
|-------|--------------------|--------|
| 1     | Duty cycle         | 25%    |
| 2     | Inductors L1 and L2| 0.2 mH |
| 3     | Capacitor          | 40 \( \mu \) F |
| 3     | Phase shift angle (\( \phi \)) | 90° |

Table 3. Induction motor model parameters

| S.No. | Parameters         | Values     |
|-------|--------------------|------------|
| 1     | Rated power, \( P_o \) | 4 kW      |
| 2     | Frequency, \( f \)   | 50 Hz      |
| 3     | Stator resistance, \( s_s \) | 1.405 \( \Omega \) |
| 4     | Rotor resistance, \( r_s \) | 1.395 \( \Omega \) |
| 5     | Stator inductance, \( s_l \) | 5.839 mH |
| 6     | Rotor inductance, \( r_l \) | 5.839 mH |
| 7     | Mutual inductance, \( m \) | 0.1722 H |
| 8     | Inertia, \( B \)     | 0.0131 kgm² |
| 9     | Friction factor, \( J \) | 0.0029 Nms |
| 10    | No. of poles, \( P \) | 4          |

6. Simulation of MDIBC
This section discusses the implemented MATLAB simulation model of the proposed MDIBC converter and its controller strategy as per the calculated values of inductors and capacitors.

6.1. Open loop model
Input for MDIBC is given as a 200V DC supply. Diode and MOSFET constitutes the converter topology. The inductor at the front is the interleaving as well as boost inductor. The output across the
DC link will be ripple free. To check the correctness of the filter design, the open loop system is simulated as shown in Figure 7.

![Open loop model of MDIBC](image)

**Figure 7. Open loop model of MDIBC**

### 6.2. Dual loop control model

For the closed loop control measured output voltage and input inductor currents are fed to the controller as shown in Figure 8.

![Closed loop dual control strategy](image)

**Figure 8. Closed loop dual control strategy**

### 6.3. Dual loop PI controller subsystem

Figure 9 shows the PI dual loop control implementation of the MDIBC. Figure 9 also shows the implementation of phase delay given to the MDIBC switches.

![Dual loop controller and PWM phase delay](image)

**Figure 9. Dual loop controller and PWM phase delay**
6.4. Drive train
Figure 10 shows the drive train subsystem with induction motor in figure 8.

![Drive train subsystem](image1)

Figure 10: Drive train subsystem

6.5. Voltage Source Inverter with SPWM
Figure 11 shows the implementation of Sinusoidal Pulse Width Modulation (SPWM) along with 3-phase three leg inverter.

![3-ph VSI fed by SPWM](image2)

Figure 11: 3-ph VSI fed by SPWM
7. Results and Discussion
This section discusses the observations captured on simulation of MDIBC with the specifications mentioned in table 1, 2 and 3.

7.1. Open loop output voltage
Figure 12 shows the DC link voltage. There is an observed overshoot up to 650 V and the system stabilizes at 5ms for 400 V.

![Figure 12. Open loop output voltage at DC link](image1)

7.2. Open loop inductor current
Figure 13 shows the current through the input inductor. It can be observed that the current overshoots up to 125 A and stabilizes at 5 ms around 25 A.

![Figure 13. Open loop inductor current waveform](image2)

7.3. Closed loop output voltage
Figure 14 shows the DC link voltage, it is observed that the overshoot is reduced to 460V and the system stabilizes at 15ms.

![Figure 14. Closed loop output of DC link voltage](image3)
7.4. **Closed loop inductor current**
Figure 15 shows the input inductor current at the stable system performance. The ripple gets reduced to 1.8A. And as the PI is tuned for better performance the average current is also reduced to 6A.

![Inductor Current L1 and L2](image)

**Figure 15. Closed loop inductor (L1 and L2) currents**

7.5. **Output voltage of 3-ph VSI**
Figure 16 shows the inverter line to line voltage with the average magnitude of 360V.

![Inverter line-to-line voltage](image)

**Figure 16. Inverter line to line voltage**
7.6. Motor Torque
Figure 17 shows the torque profile of the induction motor. The three phase stator currents are balanced at equilibrium state of 0.6s. The induction motor attains its stable speed of 1430 rpm. Also the steady state torque ripple ranges from 2.9 Nm to 4.1 Nm.

Table 4 presents the summary of observations in a tabulated format comparing the results of implementing dual loop control strategy with open loop system.

| S.No. | Parameter               | Open loop response | Closed loop response | Reduction |
|-------|-------------------------|--------------------|----------------------|-----------|
| 1     | Input current (average) | 25 A               | 5 A                  | 80 %      |
| 2     | Input current ripple    | 14 A               | 1.8 A                | 87.14 %   |
| 3     | Output voltage overshoot| 670 V              | 460 V                | 29.23 %   |

8. Conclusion
In this work the Multi-Device Interleaved Boost Converter is designed and simulated for an electric vehicle application. The load for the MDIBC is the inverter and drive train. Inductor ripple is found to be twice to that of the switching frequency. Increasing the switching frequency reduces the filter size further more. Number of phases can be increased for better ripple mitigation, though the number of switches gets increased. The open loop response with R load produces high instability for around 5ms. When the system is connected to the motor the input inductor currents becomes discontinuous. The DCM current is mitigated with the proper tuning of Dual loop PI control. The tuned system responses as per the graph shows that the DC link voltage is maintained with very less ripple such that the motor performance is achieved as expected. By the implementation of dual loop control strategy reductions in average input current, input current ripple and output voltage overshoot are obtained. The dual loop control strategy is implemented to obtain a better response for a motor load which is considered as EV motor.
9. References

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