Chapter 9

Conclusion and Future Work

9.1 Conclusion

HEVs are next generation road transportation system which will improve the environmental conditions. With the huge demand of HEVs, it is imperative to have better solutions. The CPMSM is an alternative which is reported to have wider operating region. This feature is particularly due to the presence of additional DC stator field excitation which is not present in a conventional PMSM. The separate field winding, excited by DC voltage, controls the level of field weakening which allows the smooth operation of CPMSM over wider speed range. The work presented in this thesis summarizes the various prospective power electronic converter which can drive the CPMSM and other loads present in HEV. Firstly, the state of the art along with evolution of proposed DC-DC converter is explained. The operating modes of the proposed DC-DC converter are discussed with the steady state analysis. A high gain factor, $\frac{3-3d-d^2}{1-3d-d^2}$ is achieved using the proposed DC-DC converter. This specific feature of the proposed converter, assuages the voltage stress across the passive components and switches, as compared to contemporary converters having same gain. Moreover, for same gain, the proposed converter has lower conduction losses than contemporary converters due to reduced duty cycle. Eventually the converter is tested at duty cycle 0.16 and 43 V input voltage for 200 W power rating. A 200 V output voltage is obtained which is 10 V lesser as compared to the theoretical value due to forward voltage drop of diodes and switches. Based on the experimental results maximum 93.33% efficiency is reported.

Secondly, three classes of DC-AC Z source converter are validated. The development of first Z source converter started with steady state analysis of SBI in chapter 3. For wide variation of duty cycle, SBI exhibits undesirable operation due to the aberrant behaviour of inductor current. The mode in which aberrant behaviour of inductor current occurs is termed as NZ-DCM. This unique phenomenon is generalized in the sense that if a Z source inverter is having a combination of diode and capacitor across the voltage source inverter like SBI, then NZ-DCM will exist. For experimental study of NZ-DCM, a 370 W prototype is designed. It is found that SBI in NZ-DCM has higher THD(10% at d=0.22) for AC voltage and increased voltage stress across the inverter switches(200 V at d=0.22). The FCCM is introduced to mitigate NZ-DCM by interconnecting an antiparallel switch across the diode which eventually reduces the THD and voltage stress to 1% and 99 V, respectively. Therefore, modified SBI has better prospect to perform well under variable load conditions. Furthermore, in chapter 4, to lift the inverter gain, QMCAIS is reported having gain factor of $\frac{1}{1+d^2-d(2+K)}$. The gain of the QMCAIS can be increased by simply increasing the number of turns, therefore, QMCAIS is compact in size. The QMCAIS is validated experimentally. However, QMCAIS is suitable only when a suitable core is selected to minimize the leakage effect. Moreover, QMCAIS and other reported Z-source inverter till now has two level AC output voltage, which consequently requires huge filter size. This would lead to bulky system and ultimately cost would be increased. In order to address these problems, in chapter 5, an improved gain multilevel inverter is proposed which utilizes switched inductor approach. The proposed high gain MLI has five levels in phase voltages, which reduces the size of filter and hence system becomes compact with reduced cost. The two control techniques are developed for proposed MLI i.e. FST and UST/LST. These techniques are validated with no output filters. The proposed MLI is simulated at d=0.2 and m=0.8. The simulation results are in good accordance with the theoretical analysis. The FST mode has higher THD i.e. 90%. On the other hand, UST/LST produces only 42% THD. Hence, proposed MLI has better prospects than 2 level Z source converter.

Depending on the number of semiconductor devices involved, passive elements and filter size, the selection can be made among the three different proposed DC-AC converters. If the magnetic components are to be reduced in the circuit, then MLI is better solution. However, to have lesser number of semiconductor, SBI and its counterpart are the better alternatives. Moreover, where compactness is an important factor at increased cost, the coupled inductor has a better prospect.

In order to suppress the challenges of separate DC-DC and DC-AC converter, hybrid converters are reported in the thesis. These converters can supply power to both DC and AC load simultaneously. In chapter 6, BDHC is investigated under variable duty cycle and standalone mode, analytically. A boundary between CCM and NZ-DCM is presented which suggest that under high AC load conditions, the inductor current saturates at AC load current. A huge dip in DC link voltage is observed which worsens the converter performance in terms of high THD and high voltage stress across the switches. The FCCM is introduced to have the same operation as CCM which is capable to reduce THD. It also lowers the voltage stress across the passive elements and switches. In addition, the efficiency of the modified BDHC is reported which is around 89% at m=0.6 and d=0.3. To improve the gain of BDHC, a switched inductor arrangement is placed instead of single inductor, which is termed as hybrid L-ZSI(HLZSI). In HLZSI, the inductor charges in parallel while discharges in series, thereby, increasing the gain of the converter. Furthermore, the boundary condition between the CCM and NZ-DCM is derived. The HLZSI is operated in DCM to achieve higher voltage gain by using the antiparallel switch. For d=0.2 charging period and d_2=0.29 DCM period, the gain of the converter in DCM is 14 V higher as compared to CCM. This theory is generalized in the sense that if any Z source converter has input diode, then the converter can be operated in DCM to achieve higher gain. The converter is operated for resistive and inductive load at 10 kHz and 8 kHz switching frequencies, respectively. In resistive load, 14 V higher voltage is achieved while for inductive load 18 V higher voltage is obtained as compared to CCM. The efficiency of the converter is tested at different power level. The maximum efficiency is around 82.5% which can be increased by using diodes having lesser voltage drop. Finally in chapter 8, a buck boost derived hybrid converter is proposed which is suitable to step up or step down voltage at DC terminal. A boundary between CCM and NZ-DCM is derived for Buck Boost hybrid converter. The problem of NZ-DCM in Buck Boost derived hybrid converter became more intense due to zero voltage across the inverter switches. Modified Buck Boost is proposed to cure the problem of NZ-DCM, when converter is operated in FCCM using antiparallel switch. The converter is tested for 459 W power rating. This analysis is validated in simulation and experiment. A closed loop control strategy is established to regulate the AC and DC voltage and provide smooth control under load changes.

A high gain DC-DC converter, Coupled inductor ZSI, switched inductor MLI, Buck-Boost derived hybrid converter are the main contribution of this thesis. These proposed solutions are potential candidate for future HEV/Household/Industry applications. In particular, new phenomenon termed as NZ-DCM has two implications: high voltage stress across the switch and higher THD at AC terminal. It is suggested that converters should not operate in NZ-DCM. This could be avoided by either having FCCM or designing the converters such that they do not cross the CCM boundary.

9.2 Future work

A small change in duty cycle corresponds to huge change in voltage gain for high gain converters. In order to precisely control the voltage gain, controller requirement is the key challenge for High gain converters. Moreover, high gain converters has the problem of right half zero, therefore, it becomes difficult to track the reference quantity accurately. Conventionally, PI controllers are fulfilling the purpose at the cost of limited dynamic performance in terms of precise control on gain, tracking, and transient response. These problems could be avoided by introducing non linear control techniques such as sliding mode control and fractional order control.

Majority of the Z-source inverters are prone to operate in NZ-DCM, which is not desirable from performance point of view. However, NZ-DCM could be avoided at the cost of an extra switch. Therefore, one of the future challenge will be to have a better topology so that converter does not exhibit NZ-DCM, thereby, omitting the need of a dedicated switch. Moreover, as NZ-DCM is dependent on the ripple current, therefore, alternative control techniques may be explored which can minimizes the ripple current and hence avoid NZ-DCM.

For hybrid converters, if the DC gain is reduced then to increase the AC gain the modulation index has to be increased. However, modulation index and duty cycle can be varied in restricted range which limits the AC gain. Therefore, it may be possible that the boosted AC gain may not be sufficient to drive the load. This issue can be solved by modification in modulation technique. So, future research may be oriented to enhance AC gain in hybrid converters.

At last, in HEVs, compact structure of power converter is prime requirement. Wide band gap power devices may be considered for replacing existing silicon devices. The salient features in terms of high junction temperature, low switching losses and negligible reverse recovery current would allow reduction in thermal management unit and passive filters. Therefore, if these devices can be employed in the proposed DC-DC, the size of the proposed Z source inverter and hybrid converters can be further reduced and efficiency may be improved which would be beneficial for HEV.