Chapter 6

Conclusion and Scope of Future Work

6.1 Introduction

In order to address the various challenges of transformerless hybrid converters (THCs), such as inability to operate in wide operating range of D and M_i, non-minimum phase property, common mode leakage current, shoot-through problem and requirement of deadtime circuit, a transformerless minimum phase hybrid converter (TLMPHC) is proposed in this work. While investigating the proposed TLMPHC, it has been observed that the TLMPHC operates only in the operating condition of $D + M_i \leq 1$, which results into a trade-off between the DC gain and better quality of AC output voltage. Further, it has been observed that the TLMPHC is not suitable for higher power applications, since the coupled inductor coils (L_1 and L_2) of TLMPHC charge and discharge simultaneously. For achieving $D + M_i \geq 1$ operating condition (wide operating range of D and M_i) along with all the advantages of TLMPHC in a single THC, the concept of interleaved converters has been incorporated with the proposed TLMPHC. The newly developed THC is termed as transformerless interleaved hybrid converter (TLIHC). In this way, two different transformerless hybrid power electronic converters are proposed in this thesis.

The circuit operation and analysis of the TLMPHC has been carried out in stand-alone mode, whereas the operation of TLIHC has been carried out for both stand-alone and grid connected modes. In this chapter, the conclusions of the work carried out in the previous chapters are summarised. Also, the scope of future research in this area is discussed.

6.2 Conclusions

In this thesis, transformerless boost derived type hybrid converter TLMPHC and transformerless boost derived interleaved type hybrid converter TLIHC are proposed for PV based residential and microgrid applications. The TLMPHC is developed by replacing the controlled switch of a boost converter by a modified voltage source inverter to obtain both DC and AC outputs simultaneously in the operating condition $D + M_i \leq 1$. A pair of magnetically coupled inductor coils and a DC link capacitor is used in TLMPHC to achieve the minimum phase property. In order to achieve wide operating range of D and M_i ($D + M_i \geq 1$) along with all the features of TLMPHC, the developed TLMPHC has been incorporated with a conventional DC-DC boost converter to develop the TLIHC. The controlled switch of the DC-DC boost converter in TLIHC controls the value of D and the controlled switches of TLMPHC controls the value of M_i. The proposed TLIHC can operate in both $D + M_i \geq 1$ and $D + M_i \leq 1$ conditions. In both of the proposed topologies, a pair of magnetically coupled inductor coils is present in the input side to achieve continuous input current with lesser ripple. The performance of proposed TLMPHC and TLIHC are investigated through simulation and experimental studies in this work.

A hybrid unipolar based SPWM technique has been developed to achieve zero total common mode voltage during the entire switching cycle of TLMPHC and to regulate the power flow between the AC and DC loads. Further, due to the presence of magnetically coupled inductor coils and DC link capacitor, the stored energy of DC output capacitor (C_0) is not discharged to the DC load during the shoot-through state (i.e., switch-on state of conventional DC-DC boost converter). So, there is no right half-plane zero (RHPZ) in the control-to-DC output voltage transfer function of TLMPHC and hence the minimum phase property has been achieved. The power losses in the various elements of the proposed TLMPHC have been calculated. However, from the circuit operation point of view, it can be observed that the proposed TLMPHC can operate only in the operating range $D + M_i \leq 1$. So, in each operating conditions of TLMPHC, there is a compromise between the DC voltage gain and AC output voltage quality. Further, it can also be observed that the coupled inductor coils (L_1 and L_2) of TLMPHC are in the charging mode during the shoot-through state and in discharging mode during the non-shoot through state. So, it is not suitable for high power applications. To take care of these issues along with all the advantages of TLMPHC, another THC termed as TLIHC has been developed by introducing the concept of interleaved converters incorporated with the proposed TLMPHC in this work.

The proposed TLIHC exhibits three important characteristics, which are: reduced common mode leakage current, when the neutral point of the AC output voltage is grounded or the converter is grid integrated; simultaneous DC and AC outputs at an operating condition of $D + M_i \geq 1$ as well as $D + M_i \leq 1$ and elimination of RHPZ from the control-to-DC output voltage transfer function. The minimum phase behaviour of the proposed TLIHC has been validated for the operating condition $0.61 < D \leq 0.85$. As two switches (S_5 and S_6) of TLIHC are placed at the grid side to isolate the DC part and grid/AC part during the freewheeling period and also the dead-time of the switching pulses are eliminated, the quality of the AC output volage is improved. The observed THD value of TLIHC is within the specified limits of IEEE standards. Detailed mathematical modeling and steady-state analysis along with performance comparison of some similar topologies have been carried out to show the effectiveness of the proposed TLIHC. Similarly, to show the usefulness of TLIHC over TLMPHC, a comparison between TLMPHC and TLIHC has been carried out. The DC gain of TLIHC is increased by a factor of $\frac{1}{D}$ as compared to the conventional boost converters because of the presence of the DC link capacitor. The proposed TLIHC can operate at both unity power factor and non-unity power factor loads. The power losses in the various elements of the proposed TLIHC has been calculated to determine the efficiency of TLIHC. As, the conduction time is more for the least $R_{ds(on)}$ valued switches and vice-versa, the conduction loss is minimum in case of TLIHC. Similarly, the switching losses for the switches S_5 and S_6 are negligible as these two switches operate at lower frequency (50 Hz). This results into increase in efficiency of the proposed TLIHC. A comparative study in terms of DC as well as AC voltage gain, voltage and current stresses and efficiency with other conventional hybrid converters has also been carried out in this thesis. It can be concluded that although the proposed TLIHC has same voltage stress as that of conventional boost converters, however it has higher DC gain as compared the conventional boost converters.

The behaviour of the designed controller used in TLIHC along with its dynamic response has been verified to check its performance and robustness. The performance of the controller has been verified by changing various passive parameters (L_1, L_2 and C) of the proposed TLIHC. It can be observed that the controller is robust enough to tolerate $\pm$ 20 % variation in the designed value of passive parameter L_1 and L_2 and 23 % lower to 10 % higher variation of the designed value of C. Similarly, the performance of AC output side controller has been observed by varying the AC filter inductance value. Detailed mathematical modelling of AC side controller of TLIHC in terms of D-Q synchronous rotating frame control strategy has been discussed. All the circuit operating features of TLIHC, such as wide operating range of D and M_i simultaneously, minimum phase behaviour, well-regulated AC and DC output and minimization of common mode leakage current well below the safety limit have also been verified for the closed-loop operation. Further for dynamic load conditions, the cross-regulation behaviour of TLIHC has been verified.

For the grid integration of TLIHC, a $\frac{T}{4}$ delayed PLL technique has been implemented to synchronize the inverter output voltage with the grid. Detailed mathematical analysis for the state space model of synchronous reference frame control strategy has been carried out in this thesis. Further, the effect of step-down and step-up in D or DC reference voltage on grid current has also been discussed. The robustness of the controller has been checked by instantly stepping-up and stepping-down the grid current. Also, to check the functionality of DC side controller, the behaviour of coupled inductor currents, DC output voltage, DC link capacitor voltage and duty ratio has been verified during the step-up and step-down conditions of the grid current. For the grid integrated mode of TLIHC, a passive LCL filter has been designed to attenuate the harmonic currents injected into the grid. The FFT analysis of the grid current has been carried out to check the amount of harmonics injected into the grid current. All the circuit operating features of TLIHC has also been verified during the grid tied mode. Finally, the limitations and applications of the proposed TLIHC has been presented in this thesis.

6.3 Scope of Future Work

- The constant input DC source of proposed TLMPHC and TLIHC can be replaced by low voltage DC sources such as solar and fuel cells for the PV based residential microgrid systems.
- Controller design for the proposed TLMPHC can be further investigated for studying the dynamic behaviour in case of regulated outputs.
- The proposed TLIHC has some limitations like trade-off between DC link voltage (V_{inv}) and D, conditional minimum phase property ($0.61 < D \leq 0.85$) and higher DC gain either for $D < 0.4$ or $D > 0.6$, so further modification of the proposed TLIHC has to be done to overcome those limitations.
- The proposed TLMPHC and TLIHC are investigated for single-input and multi-output operations. Further modifications can be incorporated in these topologies for multi-input and multi-output operations.

- The proposed TLMPHC is investigated for stand-alone mode operation, so further the grid-connected mode operation of TLMPHC has to be done.
- The proposed TLMPHC and TLIHC are analyzed and verified for the reduction of common mode leakage current without EMI spectrum analysis, so further the common mode leakage current with EMI spectrum analysis has to be done to study the EMI behaviour for PV panel applications.
- The proposed TLIHC is investigated only for normal grid-tied mode operations. However, the scope of extending the present work in weak-grid scenario has to be done.