Chapter 6

Conclusion and Scope of Future Research

6.1 Introduction

The previous chapters present three advanced control strategies to improve the power quality of the grid-tied PV system along with an improved methodology for deriving the capability curve. The schemes and methodology presented in the thesis is used to estimate the reactive power limit at maximum power point (MPP) conditions, reduce the grid current harmonics, eliminate the active and reactive power oscillations and enhance the low voltage ride through (LVRT) capability of the grid-tied PV system under distorted grid voltages, grid faults and weak grid conditions. This chapter presents the conclusion of the research work carried out in the previous chapters and subsequently gives the scope for future research.

6.2 Conclusion

In this thesis, three advanced control strategies and an improved methodology are proposed to provide the reactive power limits and improve the power quality of the grid-tied PV system. The power quality of the grid-tied PV system is improved by taking care of grid current harmonics, power oscillations during unbalanced and weak grid conditions and low voltage ride through (LVRT) during grid faults. The improved methodology tackles managing the reactive power of the grid-tied PV system by developing a P-*Q* capability curve at MPP conditions. The first advanced control strategy is designed for the grid-tied PV system which simultaneously mitigates current harmonics and active and reactive power oscillations during distorted grid voltage conditions. The second advanced control strategy proposed in this thesis is used to simultaneously reduce grid current harmonics and eliminate active and reactive power oscillations during distorted grid voltages without a PLL block in the control structure. In the third control strategy, the simultaneous enhancement of LVRT during grid faults and reduction of current harmonics during weak grid are achieved without a PLL block in the control structure.

In the improved mathematical methodology, the *P-Q* capability curve of the grid-tied PV system is evaluated at MPP conditions. The *P-Q* capability curve is used to improve the management of reactive power of the grid-tied PV system under MPP conditions under different atmospheric conditions. The presented capability curve provides the reactive power limits for the current controller of the grid-tied PV system.

An integrated PLL-based advanced control strategy is proposed in this work to reduce the grid current harmonics and minimize active and reactive power oscillations for a grid-tied PV system under distorted grid voltage conditions. The proposed control strategy consists of an advanced proportional multi resonant (APMR) controller and a grid voltage sag (CGVS) compensator. The APMR controller has two compensators which are proportional resonant compensator (PRC) and multiple resonant harmonic compensators (RHC). The PRC is used to track the fundamental component of grid current with zero steady-state error, and the RHC is used to attenuate the selected grid current harmonics. To overcome the issues of conventional PMR controller such as infinite gain at resonant frequency, narrow bandwidth, difficulty in digital implementation and sensitivity to grid frequency deviation, the proposed APMR controller is designed by modifying the control structure of the conventional proportional multi resonant (CPMR) controller. The modification is done by including a damping factor (ξ) in the transfer function of the CPMR controller. Due to these modifications, the proposed APMR controller achieves wider bandwidth, finite gain at the resonant frequency and is less sensitive to grid frequency deviation. The frequency response analysis of the proposed APMR controller has also been discussed in this thesis. The optimal values of the control parameters of the APMR controller are obtained from the bode diagram of the APMR controller. The active and reactive power oscillations due to unbalanced grid voltages are eliminated by integrating a CGVS with the APMR controller. The CGVS is designed by including a band-reject filter (BRF) in the PLL loop to eliminate the active and reactive power oscillations. Further, an adaptive step size INC (ASINC) maximum power point tracking (MPPT) algorithm is implemented with the proposed control strategy to achieve faster-tracking speed and better MPP tracking accuracy under variable environmental conditions. A scaled-down experimental prototype is developed for a 3.8 kW PV power module. The proposed control strategy is implemented using the OPAL-RT OP 4510 real-time digital simulator in the digital domain. It is validated from the experimental results that the proposed advanced control strategy is more effective in reducing the grid current harmonics and eliminating the power oscillations as compared to the conventional CPMR control strategy. Further, the proposed control strategy's frequency adaptability is superior as compared to the CPMR control strategy.

Although the proposed APMR control strategy reduces the grid current harmonics effectively, it requires a PLL block to synchronize the PV inverter to the grid. The PLL-based control strategy has poor frequency adaptability under grid frequency variations. Further, the computation burden on the controller increases due to Clark's and Park's transformation. To address these issues, the second advanced control strategy based on PLL-less scheme is proposed for the simultaneous reduction of grid current harmonics and power oscillations under distorted grid voltage conditions. Moreover, the proposed APMR controller is integrated with the PCRCG to mitigate grid current harmonics and power oscillations simultaneously. The PCRCG and APMR controller are implemented in the $\alpha\beta$ reference frame, thus eliminating the need of PLL and park transformation. Consequently, the synchronization task is embedded in the PCRCG, making the grid-tied PV system PLL-less or self-synchronizing. The frequency response analysis of the proposed APMR controller has been performed. A step-by-step design procedure to evaluate the optimal values of the APMR controller's coefficient is also discussed. The experiments are carried out to verify the feasibility and validity of the proposed control strategy on a 3.65 kW PV power module. The OPAL-RT OP-4510 real-time digital simulator executes the proposed control strategy. The experimental results validate the feasibility and outstanding performance of the proposed PLL-less control strategy with reduced grid current harmonics, eliminated power oscillations and faster frequency tracking time than the conventional PLL-based control strategy. Further, a comparative analysis is also discussed among the proposed PLL-less control strategy and the existing control strategies. It is observed that the performance of the proposed PLL-less control strategy is superior as compared to the existing control strategies with reduced computational burden, better harmonic reduction capability, negligible power oscillations and fast frequency adaptability.

The second advanced control strategy for the grid-tied PV system faces challenges to perform satisfactorily under grid faults and weak grid conditions. Considering this fact, the second advanced control strategy is modified so that the modified PLL-less control strategy successfully achieves enhanced LVRT operation under fault conditions, reduced grid current harmonics and negligible power oscillations simultaneously in the case of distorted and weak grid condition. The proposed PLL-less control strategy consists of an active power regulator (APR) with dynamic reactive power support (DRPS) controller, which enhances the LVRT capability of the grid-tied PV system during unbalanced grid faults.

Further, an advanced phase compensated multi resonant (APCMR) controller and the APR and DRPS controller reduce grid current harmonics under the distorted and weak grid conditions. Due to the wider bandwidth and finite gain at the resonant frequency, the proposed APCMR controller has superior current harmonics rejection capability as compared to the conventional PMR controller. Further, the frequency response analysis of the transfer function of the APCMR controller is discussed with variable grid impedance. The synchronization task and reduction of power oscillations are made by the coordinated operation of the APCMR controller along with the PCRCG. The proposed PLL-less control strategy is validated by conducting detailed experimental studies on a 4.3 kW laboratory prototype of the grid-tied PV system. The proposed PLL-less control strategy is operated on a real-time digital simulator OPAL-RT OP4510. A comparison between different existing control strategies is also discussed to bring out the uniqueness and effectiveness of the proposed PLL-less control strategy in terms of various features such as LVRT capability enhancement, harmonic current mitigation, power oscillations reduction and frequency adaptability improvement. It is observed that the proposed PLL-less control strategy has enhanced LVRT capability, reduced grid current harmonics, negligible power oscillations and better frequency adaptability as compared to the existing control strategies.

6.3 Scope For Future Research

Although several aspects for grid-tied PV systems have been investigated in this thesis, there are still other challenges that need to be addressed as a future extension of this work, which are:

- This thesis discusses the performance of the proposed control strategy with a single PV array. In the future, multiple PV arrays can be connected to the grid by some modification in the proposed control strategies.
- The proposed control strategies for the grid-tied PV system addressed in this thesis is limited to the two-level voltage source inverter. Extending the proposed control strategy to recently developed inverter topologies could be interesting.
- In the future, the analysis and mitigation of inter harmonics from the PV system should be addressed by some structural modification in the proposed control strategies.
- The control strategies proposed in this thesis can be developed further to make the grid-tied PV system capable anti islanding protection.

Besides the above points, as new power electronics topologies are continuously being explored. It is always essential to adopt these recent technologies and ensure that the control strategies discussed in this thesis can still be applied with certain modifications if required to improve the performance of grid-tied PV system.