Chapter 7

Conclusion and Future Work

In the preceding chapters, the thesis discussed the analysis and modelling of the microgrid systems. The mathematical modelling of the AC microgrid and DC microgrid architecture, and their optimal MOR through the various modern methods based on optimization algorithms: PSO and ABC, and time-scale separation technique has been obtained. Further, the robust control and stability considerations for different types of microgrids has also been studied for its in-depth analysis. This chapter reflects on these contributions, discusses future scope in this area of reduced order modelling of microgrids and concludes.

7.1 Summary of Research Findings and Conclusion

This thesis has presented the application of reduced order modelling to microgrid systems. Recently, microgrid emerged as flexible architectures constituting various renewable DERs to meet the energy requirements in largely populated and fast developing countries. The small signal modelling and performance evaluation has become increasingly important because of various reasons. The Phase Locked Loop (PLL) synchronization and interfacing circuitry to connect the equivalent model of Distributed Generators (DGs) sources to ac loads and different buses is crucial. Even the power electronics converter which offers improved power quality and flexibility in control, poses threats to system stability due to their low-inertia as compared to other components, causing oscillations manifested due to network dynamics. As a matter of fact, the major concern in the reliable operation of a microgrid is small-signal stability. The limitations of these complex structures can be overcome by obtaining a simplified model while preserving the system significant characteristics. In this concern, the thesis tries to resolve this issue by optimal MOR to obtain lower order equivalent by deployment of the versatile optimization methods available for minimizing error in reduction process. The key contributions of the thesis have been presented below for AC microgrid as well as DC microgrid systems.

For the small signal analysis of AC microgrid, the main highlights of the research in this thesis work are;

- Implementation of MOR in Autonomous and Grid-tied Microgrid by dominant pole augmented by SI algorithms by reducing the L_1 error norm.
- Case study of certain perturbations on small signal model of grid-tied microgrid system to demonstrate its significant effect on smallest eigenvalues of the system. Impact of state perturbation to full order as well as reduced order microgrid structure
- Model order reduction of 36^{th} order autonomous mode and 15^{th} order grid-tied mode of microgrid to 9^{th} and 2^{nd} order model respectively, by conventional and swarm intelligence optimisation techniques: direct, balanced truncation, dominant pole with Particle Swarm Optimisation and Artificial Bee Colony algorithms.
- Evaluation of error subjected to step, ramp and impulse function for full order as well as reduced order.
- Calculation of eigenvalue sensitivity as well as various mode associated with the evaluation of participation matrix. Stability analysis through participation factor of all the state variables of full order system can determine the state influences retained in reduced order modelling when smallest eigenvalues are preserved as dominant poles.

- Dominance of optimization based MOR techniques as over other methods for this system in time as well as frequency domain as proved by ISE, ITAE, gain and phase margins. ABC optimization methods provides best optimized reduced order model for microgrid in Grid-tied mode.
- The responses from real time implementation of AC microgrid on Typhoon HIL 402 are compared to the reduced order system responses to demonstrate the effectiveness of reduced order modelling.

Similarly, in the DC microgrid analysis, the main contributions of this thesis work include the following highlights.

- Complete state space modelling of autonomous PV-fuel cell based DC microgrid system from mathematical model of individual components.
- Time-scale separation of states to identify the fast and slower system dynamics, for subsequent system MOR through preservation of slower subsystem as such and reducing the fast subsystem.
- Reduced order modelling of fast subsystem by PSO algorithm for optimization of mixed H_2 and H_∞ norm, with better noise rejection and increased robustness.
- Nonlinearity of the slow subsystem is retained in reduced order DC microgrid model by keeping it intact.
- Advanced Lyapunov based stability analysis involving Input to State Stability to ensure system stability with variations in uncontrolled inputs.

Another significant contribution of the present research apart from MOR is on the robust control of the interlinking converter in hybrid microgrid. It consists of the following main findings;

- Mathematical modelling of the interlinking converter and its augmented plant for controller design.
- Robust controller design for IC system through tuning based on two optimization algorithms; PSO and ABC.
- PID and FOPID controller design through parameter tuning by optimization.
- H-infinity loop shaping control strategy through a selection of weight functions by optimization with consideration of the loop shaping inequalities.
- Order reduction of optimal loop shaping controller without affecting its performance.
- A case study for comparison of the optimized controller responses.
- An eigenvalue analysis of open and closed loop system studying the stability of the system in time and frequency domains.

Thus, reduced order modelling of complex AC and DC microgrids has been successfully achieved by PSO and ABC optimization algorithms, i.e., the 36^{th} order autonomous AC microgrid, the 15^{th} order grid-tied microgrid and the 38^{th} order complex DC microgrid model has been simplified to their 9^{th} order, 2^{nd} order and 12^{th} order equivalents respectively. The efficiency in MOR of these systems has been proved by time-frequency simulations in MATLAB environment and real time implementation in Typhoon HIL 402 emulator. The stability and participation factor of original and reduced order models has been studied in terms of eigenvalue analysis. Further, robust controllers based on PID, FOPID and H_∞ Loop shaping control has been designed by parameter tuning via these adaptive algorithms to achieve enhanced control in case of system variations. The objective function formulations encompassing H_2/H_∞ norms ensures enhanced robustness and reduced tracking errors simultaneously.

7.2 Future Work

The main thrust of the future development in this area of research is on developing practical implementation of reduced order microgrid models so as to demonstrate their feasibility in real-systems. This thesis works on reduced order modelling as a theoretical concept and thus its practical model would be a significant future effort.

Further research can also extend the small signal analysis of microgrid architectures to general configurations consisting of numerous DERs deploying various renewable energy power resources and large-scale loads. Another area for potential future work is to incorporate parametric and stochastic uncertainties in microgrid models as to study the effect of intermittent renewable energy resources.

As such it provides very solid basis to conduct exploratory work. In particular new efforts can look at developing reduced order models based on latest optimization algorithms to explore their efficiency in comparison to the models based on ABC/PSO algorithms that have been obtained in this thesis. As far as the objective function formulation is concerned, a mixed norm error function can be enhanced to compensate for other design aspects such as reliabity.