Chapter 2

Background and Literature Review

The research work reported in this thesis owes its background study and concepts from various resources that exists in literature. Some of these contributions that are significant to microgrid small signal analysis and relevant for present analysis have been summarized in this chapter. The various sections have been organized in accordance to the reported literature pertaining to the objectives of the thesis study as given in the previous chapter.

2.1 Mathematical Modelling of Microgrid Systems

The development of a small signal model of such microgrid systems is crucial for its analysis and control while maintaining small signal stability with the various segregated electrical components interconnected. Different small signal microgrid models for AC microgrids exist in the literature [9-15] with the difference in the choices of state variables of the state space model. The 36^{th} order model of a microgrid system in autonomous mode with two DGs interconnected with their load and line dynamics has been obtained in references [9-12]. The droop controlled inverter dynamics with the current controller, power controller and voltage controller has been mathematically formulated and their complete state space representations have been obtained. The system dynamics of each DER in a microgrid system is represented by 15 states [10], offering limited analytical insights.

The mathematical model of both grid-tied and autonomous configurations of AC microgrid are given in [13] where the optimal values of circuit parameters are evaluated by PSO algorithm in pre-defined number of iterations. The different control strategies and the detailed mathematical analysis of microgrid components is given in the reference [14]. A 17^{th} order state space model for grid-tied microgrid in current control model has been obtained in [15] with a certain change in the selection of state variables. In practical power systems, uncertainties may occur due to the network parameters, load dynamics, line dynamics or noise in communicating links. Small system perturbations affect the system by particularly altering certain low-frequency dynamics. System stability under these forms of variations is given in reference [16] wherein the variations in the low-frequency eigenvalues has been analyzed. This theory of state perturbation has been utilized in this work for stability considerations in eigenvalue analysis and to study their impact on small signal stability for both full order and reduced order system.

The AC microgrid state space model considered in this work has been taken from reference [10] and [17] for the microgrid in autonomous mode and grid-tied mode respectively. This state space consists of 36 state variables for the microgrid in autonomous mode and 15 state variables for microgrid in grid connected mode. These models are further deployed for the application of MOR to complex practical systems.

In the present work, the small signal modelling of DC microgrid system has been obtained with a different approach, i.e., the PV-fuel cell based microgrid system is mathematically modelled by obtaining the nonlinear equations of power components and control dynamics with droop and MPPT controllers individually so as to emphasize the different time scales in the system modelling. The work on DC microgrid that exists in literature [18-21] is more focussed on the energy management strategy and the subsequent modelling has been done in that respect. To the authors best knowledge, detailed small signal modelling of DC microgrid has not been reported in literature, thus, an effort has been made in order to obtain a cumulative state space representation of overall system from mathematical formulation of individual components. The small signal model developed in this work takes the concept from different instances in literature, modelling the different parts of the overall microgrid model. For example, the simplified PV cell dynamics from reference [22] has been considered and the detailed nonlinear state space model of fuel cell from [23], consisting of electrical as well as chemical/electrochemical states. This has been done to focus on the concept of fast-slow dynamics which results due to presence of the varied time scales. An approximate model of fuel cell consists of a single electrical state variable representing voltage across a capacitor form from the charge decomposition on the electrodes which is generally used in such mathematical formulations is given in reference [24]. This is also known as 'double-charge effect'. Additionally the battery model with droop control is obtained from [25] and the aggregation of different feasible load combinations are depicted by an equivalent load model comprising of Constant Resistive Load (CRL) and Constant Voltage Load (CVL) [26] has also been considered.

The control strategies involved in this work are limited to MPPT and droop control for accurate fulfilment of load power through regulation of converter duty cycle ratio. A decentralized modified droop control ensuring both accuracy in current sharing and voltage restoration for each converter model has been utilized for effective load power sharing [27-28]. MPPT controller tracks the maximum power points of a PV array by adjusting the converter duty cycle [29]. A droop control in combination with MPPT controller has been explored to meet the load requirements in the system. Thus, the resultant state space model of the overall DC microgrid system for our analysis, with the two renewable sources PV array and fuel cell has been developed in the view of timescale separation.

2.2 Reduced Order Modelling of Microgrid Systems

Several methods have been explored to reduce the dimensionality of large power systems, some of which are discussed in [30], [16]. As far as the microgrid systems are concerned, reference [31] reduces a sixth order islanded microgrid to fourth order by retaining the very fast dynamics in the response. In [32], a reduced order DC microgrid model has been developed with small signal approximation and its stability is analyzed with change in component values. The method proposed in this work is applicable to any general interconnecting structures of sources and loads. On the contrary, due to the two time scales in microgrids, thirty-sixth order microgrid has been reduced to fifteenth order by singular perturbation method in [17]. Reference [33] reduced a ninth order small signal model of microgrid to its fifth order approximation using singular perturbation and kron method. Aggregation method and certain mixed methods have been used to reduce the order of these power systems in [16], [34]. Balanced truncation (BT) technique has been applied to large power systems in [35] using a number of matrix calculations. The presence of steady state error in BT reduced order model is quite frequent. On contrary to the methods being adopted in literature for MOR technique, a simpler yet equally effective MOR technique is Dominant pole technique, which preserves the larger time constants in reduced order models, as the faster dynamics die out early and do not affect the system much[34]. The improvisation of the MOR can further be achieved by application of Particle Swarm Optimization (PSO) algorithm, in the lieu of formulation of appropriate objective function in terms of the reduction error minimization because of the high flexibility and design accuracy.

Similarly, the literature reported for order reduction of grid connected microgrid systems consists of several significant contributions some of which have been reported here. A structure preserving reduced order model is obtained for the grid-tied system in [37] where system dynamics were retained by preserving system components. Nonlinear reduced order model for low voltage microgrid has been derived for AC microgrids in [38]. Balanced Truncation (BT) is based on elimination of least controllable or least observable states as in [39]. It may however, lead to steady state errors in system behavior or even a numerical instability when dealing with larger systems. A 12th order grid-tied model has been reduced to a 2nd order model by balanced truncation in [40] such that the reduced order model closely replicates the original system. The 15th order grid-tied microgrid has been reduced to its 8th order approximation using the singular perturbation approach in [17].

In this work, a modern MOR technique based on the separation of slow and fast states, termed as timescale separation, has been obtained for the DC microgrid model in state space. Two timescale separation of linear and nonlinear control system owes its background study in [41] where slow and fast dynamics was grouped based on system characteristics such as time constants, loop gains, inertia etc. This concept was applied in electrical power networks such as, transmission networks and wind power networks, by internal balanced realization of linear systems [42] with the reduced model obtained through identification of dominant modes. Singular perturbation theory in AC microgrid structures as in [32], [43], and [44] was based on grouping of fast and slow responses by determination of small model parameter ε for all states. The location of system eigenvalues also studied this modal dominance in terms of different system time constants involved. Reduced order modelling of DC microgrid through grouping of DGs with similar time constants in a multi-DG system was reported in [26] subsequently reducing system complexity. Although the time constants were identified based on system components, an equivalent source model was considered. In continuation to the previous concept, a three time scale model was developed for an AC microgrid in [45] based on the relative eigenvalue loci. This droop based inverter interfaced DGs evaluated model parameter ε for order reduction of linearized system based on singular perturbation theory. The concept of time-scale based separation with preservation of nonlinearity implemented in this work is most recently applied in converter modelling in [46] by 'peel-off and add back' criterion. According to this criterion, a reduced model was obtained by retaining slow submodel and adding the most significant information from fast sub model. Stability concerns in the system modelling were realized through eigenvalue analysis followed by system linearization. In the light of the above concept, the present work focusses on reducing the complexity of the autonomous PV-fuel cell based DC microgrid by adopting timescale separation principle, where a wide range of timescales from millisecond to several seconds exists due to the slower chemical-electrochemical processing in fuel cell. To completely retain the high nonlinearity in slower states that do exist in fuel cell system, it is kept intact, in the reduced order system model. The procedure followed for analysis is discussed in detail in Chapter 3.

2.3 Optimization Algorithms

The error function in reduce order modelling of microgrid systems to a simplified lower order equivalent can be minimized by agent-based Swarm Intelligence (SI) techniques [47] in the form of the fitness function of the particles. Although the error objective function can be in the form of Integral Square Error(ISE), Integral Absolute Error(IAE), Integral Time weighted Absolute Error(ITAE), etc., a more standard norm based objective function such as L_1 norm, H_2 norm, H_∞ norm or mixed norm, has been considered in this analysis. The robustness in SI techniques due to the multi-agent, self-organisation, adaptive and distributed control features increases their potential for application in practical optimization problems. Two of the most commonly applied SI algorithms that are considered in the present analysis are: Particle Swarm Optimization **(**PSO) and Artificial Bee Colony (ABC).

2.3.1 Particle Swarm Optimization and Artificial Bee Colony

PSO was developed by Eberhart and Kennedy in mid 1990s as an effective optimization tool and has been widely used in various field of engineering [48-50] since its advent. This algorithm has been reported to be used in various optimization based problems in the literature [51-53]. In the present analysis, the mixed approach to MOR of the microgrid model consists of dominant pole and PSO algorithm for achieving a reduced order equivalent which replicates the original model. The amalgamation of these two techniques not only simplifies the reduction process but also utilizes the advantages of both of them [54]. This algorithm has also been utilised for tuning the controller parameters in Chapter 6 due to its adaptive nature.

Around a decade after the invention of PSO, Karaboga developed a mathematical formulation from the "particular intelligent behaviour of honeybee swarms", called the Artificial Bee Colony algorithm [53-59]. He compared its efficiency with other similar algorithms such as Genetic Algorithm, differential evolution, Particle Swarm Optimization and Evolutionary Algorithms in [60] with various test functions. Its faster convergence rate and fewer control parameters make it a suitable method for reduced order modelling of complex microgrid systems. The three essential components of optimal foraging leading to collective intelligence in honeybee swarm are food sources, employed foragers and unemployed foragers. The quality of a food source depends on the food concentration, nearness to the nest and the ease in extraction. All these factors are included in an objective function that is used by bees to evaluate the source fitness. ABC algorithm is derived from the behaviour of three types of bees: Employed bees, Onlooker bees and Scout bees [55-57] such that their functions vary.

2.3.2 Mixed Sensitivity Objective Function

In order to address the impact of uncertainty due to stochastic and intermittent renewable resources in microgrid systems, a mixed H_2 and H_∞ norm, can be formulated to solve the two-fold objective of reduced tracking error and increased robustness. Such an objective function formulation for optimization algorithms, in context of minimization of norms with metaheuristic and bio-inspired optimization techniques exists in literature [61-62]. Mixed sensitivity approach for objective function formulation owes its concept from [63] with gives a detailed study of the system norms with their utility in system design. The reference [64] derives an optimal H_2/H_∞ controller using Orthogonal Stimulated Annealing algorithm for MIMO systems. The mixed optimal controller architecture and its mathematical significance has been discussed. Similar optimal controllers through Intelligent Genetic Algorithm has been derived in the reference [62]. The present analysis utilise the mixed sensitivity norm as objective function in swarm intelligence algorithms for reduced order modelling of the higher order microgrid state space models.

2.4 Controller design for Hybrid Microgrid System

The differential equations for the mathematical modelling of the interlinking converter for AC to DC conversion operation has been obtained from reference [65], while considering the basic concept of current through input inductors and the voltage across output capacitor as state variables in d-q frames. The main aim of this work is to control the filter current and dc link voltage of the IC model through proper switching pulses at the bridge switches. A subsequent controller design for this converter model can be derived from the concepts that exist in literature. Such as, a voltage controlled modified droop based control methodology for the converter system in [66] determines the P-f characteristics solely on voltage measurements and hence gives a better voltage quality. It derives its concept from AC microgrid systems. An Improved Particle Swarm Optimization (IPSO) master controller strategy in [67] controls the IC and thus, helps in efficient power sharing and controlling the various renewable energy resources connected to the various AC-DC loads. The reference [68] gives a mathematical model of the controller designed for the converter system. The current control part of the droop based controller utilises the LQR control technique so as to achieve a current regulation with inherit robustness and speed. In addition to this improvisation, an LMI based approach for current control is given in reference [69] which augments the performance by enhancing its robustness to parametric uncertainties and load perturbations. A more complex decentralized coordination control scheme for suppressing the circulating currents with separate inner and outer control loop is described in reference [70], with more emphasis on power sharing and current regulation.

A small signal analysis with state space realizations of the control design problem is more crucial from the perspective of a control engineer. In this work, PID, FOPID and loop shaping controller has been designed for the state space plant model with a proper selection of controller parameters and weight functions for the output and error signals. An analysis of H-infinity controller for pneumatic servo system and four rotor hover vehicle has been given in [71-72] with the comparison of PID and Ziegler Nicholas method. The weights in the controller design are tuned according to the sensitivity and complementary sensitivity plots in a number of repetitions. Reference [65] has developed a mathematical H-infinity controller for AC to DC Voltage Source Converter system using the Riccati equation approach. Moreover, a simplified H-infinity based loop shaping controller is designed for a grid-connected single-phase PV system in [73] with proper weight selection on trial and error basis. The design constraints for controller design have been analysed with a reduction in controller order.

In this analysis, the adaptive tuning of variable parameters of PID, FOPID and H-infinity loop shaping controller by deployment of the optimization algorithms: PSO and ABC algorithm for the interlinking converter state space model has been obtained to achieve the two fold objective of robustness and performance. Noise attenuation and robustness of hybrid microgrid system to uncertainties can greatly be enhanced by proper selection of the tuning parameters in controller design. The objective function in optimization also plays a key role in this regard.

2.5 Eigenvalue Analysis and Stability

The Eigenvalue analysis in power system applications has been discussed in detail in the book reference [74]. The various illustrations in this reference with the detailed participation factor analysis gives the concepts of eigenvalue analysis and has been utilised in this work. The reference [75] also demonstrates the participation factor study in the inverter based microgrid systems with the small signal and large signal evaluation. The analysis in this thesis determines the state variables associated to the eigenvalues through participation matrix so as to determine the states retained in the reduced order models by dominant pole retention techniques. This analysis also determines the stability of the microgrid system w.r.t. the location and nature of the state space eigenvalues.

Eigenvalue analysis of complex systems is most frequently used to determine the singular values from the linearized system matrices. The above methodology constituting linearization of nonlinear systems leads to a significant trade-off between simplicity and accuracy, which implies certain important information being compromised with reduction of computational burden. In this context, an effort is made to retain non-linearity followed by system behavioural analysis in order to investigate stability. The detailed nonlinear control techniques has been discussed in the book [76]. In this work, a nonlinear stability analysis has been evaluated for DC microgrid system with mathematical formulation of stability in two steps: (1) Application of center manifold theory leading to evaluation of asymptotic stability of unforced system; (2) Input to State Stability based on mathematical analysis leading to system convergence for any bounded external input.

2.6 Summary

This chapter discusses a brief review of the existing concepts in literature that are essential for the present analysis work. The key contributions in the mathematical modelling of microgrid systems and their order reduction are discussed in this chapter. The significant work in literature pertaining to robust controller design and stability considerations are also included in this chapter.