Chapter 1

Introduction

The increasing population and their standard of living in fast developing countries is expected to push the global energy demand by more than a quarter to 2040.The concept of sustainable future relies on renewable energy resources to fulfil the demands of society with comfort, shelter and future security[1]. Moreover, the rapid replacement of large fossil fuel power stations by distributed energy resources requires reconfiguration of the existing distribution and transmission models used by the energy industry. Microgrids appear as a solution to this problem by interconnecting such distributed resources in urban communities or remote locations providing power to off-grid networks. Microgrid as a controlled element within the energy distribution and generation systems can operate either as separate unit or supply power to the main grid. Small signal analysis of energy systems is crucial to small signal stability under nominal operating conditions. Stability of a linearized model also called small signal model indicates that the operating condition is stable for small system variations. This thesis investigates the following design aspects of microgrid systems: modelling, small signal analysis and order reduction. The main contribution of this research work is the reduced order modelling and control of complex microgrid system through optimization based methods. These objectives have been fulfilled by the deployment of two of the popular swarm intelligence techniques; PSO and ABC optimization, and the segregation of slow-fast states. The rest of this chapter discusses the motivation for the research that has been carried out, the main objectives and the organization of the thesis.

1.1 Motivation

Microgrids as solution to increasing energy requirements.

The first power plant constructed in 1882 by Thomas Edison called the Manhattan Pearl Street Station was a microgrid configuration, as the central grid system was not developed till that time. Around 58 DC microgrids were developed by him till 1886. Perhaps, the systematic research and development programs started with Consortium for Electric Reliability Technology Solutions (CERTS) in the United States and the MICROGRIDS project in Europe. CERTS was developed in 1999 and has been recognized as the originator of the modern day grid-connected microgrid system [2]. It envisioned a microgrid that could incorporate multiple DERs yet present itself to the existing grid as a typical customer or small generator, in order to remove perceived challenges to integrating DERs. The key strategies were to remove dependence on high speed communication and to enhance the 'plug and play' system such that redesigning of the architecture is not required on removal or addition of a Distributed Energy Resource (DER) [3]. This turned to be economical and flexible in terms of placement of microgrid structures. Microgrids were even visualized as the building blocks of the more enhanced smart grid or 'Super Grids'.

Recently, the increasing electricity demands, depletion of fossil fuels and their associated environmental hazards emerged as the key issues leading to the deployment of inexhaustible energy resources for power generation and utilisation [4]. The integration of renewable energy resources to the main grid to meet the load requirements, became a viable option with development of Microgrids. It is defined in [5] as "a cluster of loads, Distributed Generation (DG) units and Energy Storage Systems (ESSs) operated in coordination to reliably supply electricity, connected to the host power system at the distribution level at a single point of connection, the Point of Common Coupling (PCC)". It can be said to be an interconnection of several Distributed Energy Resources (DERs) such as photovoltaic, fuel cells, wind turbines etc., to meet the load demands either in grid connected mode or autonomous mode. The definition wordings from the U.S. DOE MEG and the CIGRE 6.22 WG are given below [6];

According to the U.S. Department of Energy Microgrid Exchange Group, "A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode."

CIGRÉ C6.22 Working Group, Microgrid Evolution Roadmap defines microgrid as; "electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while is landed."

CIGRÉ C6.22 Definition Qualifiers are given below;

"Generators covers all sources possible at the scales and within the context of a microgrid, e.g. fossil or biomass-fired small-scale combined heat and power (CHP), photovoltaic modules (PV), small wind turbines, mini-hydro, etc."

"Storage Devices includes all of electrical, pressure, gravitational, flywheel, and heat storage technologies. While the microgrid concept focuses on a power system, heat storage can be relevant to its operation whenever its existence affects operation of the microgrid. For example, the availability of heat storage will alter the desirable operating schedule of a CHP system as the electrical and heat loads are decoupled. Similarly, the pre-cooling or heating of buildings will alter the load shape of heating ventilation and air conditioning (HVAC) system, and therefore the requirement faced by electricity supply resources."

"Controlled loads, such as automatically dimmable lighting or delayed pumping, are particularly important to microgrids simply by virtue of their scale. Inevitably in small power systems, load variability will be more extreme than in utility-scale systems. The corollary is that load control can make a particularly valuable contribution to a microgrid."

Lawrence Berkeley National Laboratory (LBNL) in [2] identified the superiority of microgrids over the existing grid networks due to the following dominant features as below.

Autonomy: The ability to work in autonomous mode with generation, load and storage allows microgrid to compensate the growing energy demands and the voltage-frequency issues by using the recent advanced techniques.

Stability: Due to the dependence of the control laws on frequency droops and voltage levels at the terminal of interconnected devices, the microgrid network operation is stable irrespective of the uncertainty in the main grid.

Compatibility: The compatibility of the microgrids with the existing utility grid networks, helps enhance the existing configurations and the otherwise stranded utility assets.

Flexibility: Expansion and growth rates of involved resources do not have to follow any precise forecasts. They are also technology neutral, thus are capable of operating with a combination of renewable and non-renewable energy resources.

Scalability: Microgrids can be scaled for higher power generation and consumption by allowing the parallel as well as modular operation of multiple generation, storage and load devices.

Efficiency: Energy management goals – including economic and environmental – can be optimized in a systematic fashion.

Economics: Droop frequency control techniques in microgrids programming through standard operating protocols for economic decision making.

Peer-to-Peer Model: Microgrids present a modernised platform that is a true peer-to-peer model which can function as standalone module, independent of size, scalability, peers or expansion rates.

The most significant feature of microgrids is that it is locally controlled system. It can operate both in isolated and grid-integrated configurations [6]. Microgrid operating in autonomous mode can be intentional or unintentional [5]. Intentional islanding may occur during scheduled maintenance or when quality of power supplied from main grid is undesirable. An unintentional islanding may on the other hand, occur due to unknown system faults which are to be analysed for safety of the equipment and resources. Islanded or autonomous microgrids are utilised in remote microgrid applications for electrification of inaccessible and remote geographic areas. In grid-tied mode, microgrid being connected to the main grid can supply power for grid operations or consume deficient power from the main grid.

Challenges with microgrid systems.

The microgrids present a number of challenges in their proper implementation which needs to be addressed for the design of control and protection schemes while maintaining the required level of reliability in microgrid operation. Some of the challenges in microgrid protection and control are [4];

Bidirectional power flows: Integration of DERs at low voltage levels may cause power flow in opposite direction leading to faults in current and voltage control, failure of protection schemes and unknown power flow patterns.

Stability concerns: Interaction of the individual control strategies of the DGs involved requires a detailed small signal stability analysis. In addition, a smooth transition between the two microgrid modes requires complete analysis of transient stability.

Modelling issues: The modelling of microgrids is different from the conventional power systems and needs to be revised for proper analysis.

Low inertia: Such a characteristic in microgrids provide an enhanced dynamic performance but may lead to large frequency deviations in autonomous mode without proper control equipment.

Uncertainty: A high level of synchronization is required between the different DERs operating in the microgrid system for its economical and reliable operation. The uncertainty of parameters such as load, supply that occur due to reduced number of loads and correlated variations in energy resources appears as a major challenge in proper microgrid operation and power sharing.

Thus an efficient control mechanism is required by the microgrid system to overcome the above mentioned challenges and provide proper output voltages and currents with effective power sharing.

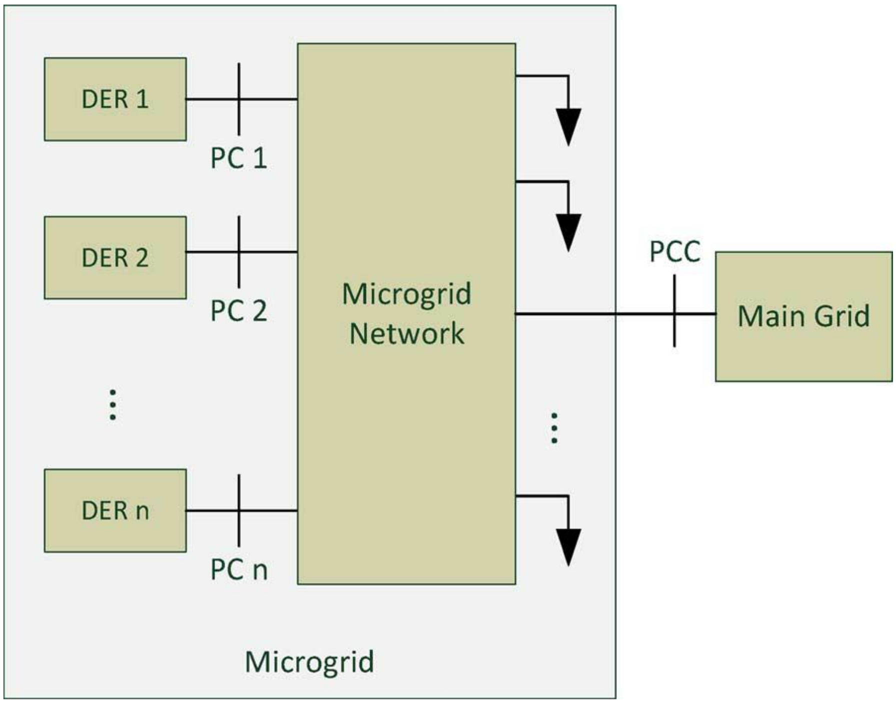

Figure 1.1. *Schematic diagram of a generic multiple-DER microgrid [5].*

Complex microgrid configurations with multiple DERs.

With numerous DERs and loads interconnected in a microgrid system, the complexity of its small signal model increases greatly. Some arbitrary configuration of microgrid with *n* DERs is shown in Figure 1.1. Thus it is quite essential to analyse the small-signal model and with different controller parameters or filter constants, in order to enhance the system dynamics and ensure power quality within acceptable limits. As a matter of fact, the major concern to small signal stability is to maintain its reliability during operating time period. Another limitation to microgrid small signal analysis is the dimensional complexity due to the diversity of control strategy in DGs and components involved [7].

Complex system models offer limited analytical insights and are computationally expensive when applied to investigate the dynamics of large microgrids with many inverters. Another drawback is the design of high order controllers for such systems which are expensive in terms of computational time and mathematical complexity. Thus, the theoretical concept of Model Order Reduction (MOR) is indispensable to simplification of large complex systems. Further, it is a control engineering tool that aids in obtaining simplified system formulations while retaining the phenomena of interest, so as to decrease the system computational burden, execution time and memory requirements. The aim of order reduction techniques in the present work is the approximation of a complex higher order microgrid system by a simpler lower order model that achieves the required trade-off between accuracy and simplicity. Several MOR techniques have been applied to complex power system models, some of which are discussed in [8].

Thus, the development of an accurate small signal model of microgrid systems and their subsequent order reduction as well as stability considerations appear as the foremost tasks in the analysis and control of these modern energy systems. The in-depth study of these requirements from a control engineer perspective has been the driving force for the formulation of this research work. The motivation behind this research work has also been obtained from the existing literature in this area that has been reported till date. This literature survey has been discussed separately in Chapter 2 of this thesis.

1.2 Objectives

The research work in this thesis addresses the challenges in microgrid system analysis as discussed in the previous section and thereafter develops a modelling procedure suitable for control system analysis. The objectives of this thesis consists of the following tasks to be fulfilled for small signal analysis of both AC and DC microgrid systems in autonomous and grid-tied operating modes as given below.

- Mathematical modelling of the microgrid systems taking into account all the sources and loads with the control schemes. A complete state space representation of the system is obtained which accurately describes the system dynamical behaviour with time and frequency domain characteristics.
- Reduced order modelling of the complex state space models such that the reduced order equivalents demonstrate responses similar to the higher order models in both time and frequency domains within tolerable limits. Swarm intelligence optimization algorithms based MOR of the complex microgrid models with mixed sensitivity objective function to demonstrate their advantages over the traditional reduction techniques.
- Eigenvalue analysis of the full order and reduced order microgrid models for evaluation of the participating states and their corresponding stability considerations in the system design. This analysis characterises the system in time and frequency domains.
- Robust Controller design for the hybrid microgrid systems for achieving the tradeoff between robustness and performance. PID, FOPID and H_∞ loop shaping controller with adaptive parameter tuning via PSO and ABC algorithms are obtained for obtaining optimal performance index values.

1.3 Organisation of the thesis

The thesis has been divided into seven chapters to address all the above objectives of this research work. The organization of the thesis has been drafted as follows;

Chapter 1 constitutes the motivation behind the present work undertaken with the design objectives for the analysis. This chapter also includes the contents of the subsequent chapters.

Chapter 2 includes the background material and literature survey related to the present work.

Chapter 3 deals with the small signal modelling of the AC and DC microgrid system in autonomous and grid-tied mode. The mathematical formulation in terms of state equations for all the parts of the microgrid have also been dealt with.

Chapter 4 incorporates the reduced order modelling of the complex state space representations of chapter 3 such that a lower order equivalent model is developed which replicates the original system response. Swarm intelligence based optimization techniques are utilised for MOR of AC microgrid model whereas, timescale separation through robust optimization has been deployed in DC microgrid models for efficient MOR.

Chapter 5 presents the eigenvalue and stability analysis of the complex and reduced order microgrid models for AC and DC microgrid developed in the preceding two chapters for analysing the impact of state variables on the different oscillatory/non-oscillatory modes.

Chapter 6 consists of an adaptive controller design strategy by parameter tuning using PSO and ABC algorithms for the interlinking converter in hybrid microgrid configurations so as to enhance robustness and noise attenuation.

Chapter 7 concludes the main findings of the thesis and also discusses scope for future work.