Preface

This book studies the distributed control of microgrids. Microgrids are small-scale power networks that are exploited to supply local loads in small geographical spans. Microgrids have various applications such as remote villages, hospitals, universities and educational institutes, police stations, business and residential buildings, shipboard power systems, military bases, ships. The microgrid concept, with its local control and power quality support, potentially allows for reliable and predictable operation of renewable energy generators and for scalable addition of new generation and loads. Conventionally, microgrids are spanned on the traditional AC distribution networks that supply AC loads. These microgrids with AC electrical infrastructure are called AC microgrids. Recently, DC microgrids have also gained much attention due to their advantages. DC microgrids exploit a DC electrical infrastructure. This book applies techniques from distributed cooperative control of multi-agent dynamical systems to synchronization, power sharing, and load balancing problems arising in AC and DC electric power microgrids. Distributed networks of coupled dynamical systems have received much attention over the years because they occur in many different fields including biological and social systems, physics and chemistry, and computer science.

In Chap. 1, an introduction on microgrids and distributed control of multi-agent systems is provided. Chapter 2 introduces AC microgrid with focus on its control. An inverter-based distributed generator (DG) consists of primary power source (e.g., battery), voltage source converter (VSC) and the power, voltage and current control loops. The control loops assign and regulate the output voltage and the frequency of the VSC. The dynamics of the DG can be expressed in the form of a nonlinear state space equation. A systematic derivation for the relevant equations for primary control is given. A basic introduction to secondary and tertiary control is also given. Later, dynamic models are developed for voltage-controlled voltage source inverters (VCVSI) and current-controlled voltage source inverters (CCVSI). Finally, the objectives for primary and secondary controllers in DC microgrid are introduced.

Chapter 3 discusses distributed cooperative control of multi-agent systems. Graph theory is introduced which is used to represent the communication structure of a multi-agent-based system. Later, consensus in multi-agent systems is introduced, and it is shown how it can be used in multi-agent-regulating problems and multi-agent synchronization problem. A general analysis on multi-agent systems with variable graph structure and nodes with vector states is done. Finally, the concepts of synchronization are applied to electric circuits.

In Chap. 4, the design and principles of distributed secondary control of AC microgrids are discussed. The secondary control in microgrid is a tracking synchronization problem in which the leader node (one of the DGs) tracks the desired value, while the other nodes synchronize their outputs with that of the leader. For example, if it is desired to control the voltage of the microgrid, then the reference voltage is provided only to the leader node. The leader conveys its information to its neighbors who further convey their information to their neighbors. This chain of exchange of information ensures that all the DGs are aware of the reference voltage and their primary controller brings their voltages to the reference values. Similarly, the frequency of individual DGs can be synchronized. Chapter 4 provides a detailed information on how the concepts of cooperative control can be applied to solve the problem of voltage regulation and frequency synchronization in microgrids. Moreover, it is shown how the cooperative secondary frequency controller also shares the active power among the DGs based on their power ratings.

As mentioned before, the DGs are interfaced with microgrid via voltage source inverters. Depending upon the requirement, a VSI may be designed as voltage-controlled voltage source inverters or current-controlled voltage source inverters. The control structure of a VCVSI ensures regulated voltage and frequency, while the control in CCVSI regulates the active and reactive power delivery. In Chap. 5, a multi-objective distributed control framework is designed for AC microgrids. To achieve the multiple goals, secondary controller has two separate control layers: First control layer controls the VCVSIs which control the output voltage and frequency of the DGs, whereas second control layer controls the CCVSIs that manage the flow of active and reactive power. In addition to multi-objective distributed control framework, Chap. 5 discusses adaptive distributed voltage control techniques in AC microgrids. The adaptive distributed voltage control compensates for the nonlinear and uncertain dynamics of DGs and, hence, obviates the control design challenges caused by the nonlinear dynamics of DGs. The controller is fully independent of the DG parameters and the specification of the connector by which each DG is connected to the microgrid. Therefore, the controller can be deployed on any DG regardless of the DG parameters and the connector specifications, and its performance does not deteriorate by the change in DG parameters (e.g., due to aging and thermal effects). The adaptive voltage controller appropriately responds to the changes in the system operating condition, without any manual intervention, and adjusts the control parameters in real time.

Droop control, which is inspired from the governors in synchronous generators, are implemented virtually in inverter-based DGs. Droop control is popular due to its simplicity but it is ineffective in the presence of nonlinear loads, and its reactive power sharing ability is poor when there are unequal bus voltages. To address these issues, a droop-free distributed controller is designed for AC microgrids. To design a droop-free controller, each DG is equipped with a voltage regulator, reactive power regulator, and active power regulator. Each DG exchanges information of its voltage and normalized active and reactive power with their neighbors. The voltage regulator at a DG uses the voltage measurements (its own and neighbors) to estimate the grid voltage using a voltage estimator. This estimate is then compared against the required voltage, and the error is passed through a PI controller to synchronize the voltage to the required voltage. Similarly, using the principles of cooperative control, active and reactive power can be shared among all DGs based on their power ratings.

Similar to hierarchical control structure in AC microgrids (inspired by the traditional power grids), the same concept is implemented in DC microgrids. For a DC microgrid, the main objectives are global voltage regulation and proportional load sharing. These objectives can be met using similar control strategies that were employed in AC microgrids. The primary controller is augmented with a distributed secondary controller at each DG. The secondary controller consists of a voltage regulator and a current regulator. The voltage regulator estimates the grid voltage from the measurements of its neighbors and updates its voltage such that its voltage is equal to the voltage grid. When this process is performed at all DGs, voltage regulation is achieved. A noise-resilient voltage observer is designed such that it can estimate the grid voltage from the voltage information of a limited number of DGs. The voltage observer uses the principle of dynamic voting protocol to perform the voltage estimation. To ensure that the load is distributed proportionally, a current regulator compares its normalized currents with its neighbors and adjusts the current such that the normalized current of all DGs are equal. Equal normalized current of all DGs ensures that each DG is loaded based on its rating. The global dynamic model and details of the controller are provided in Chap. 7.

Chapter 8 discusses the utilization of power buffers to improve the stability of DC microgrids when the loads are volatile due to limited generational inertia and damping. Power buffer is a power electronic converter with a large storage component that can decouple the dynamics of distribution network and the load. During transients, the buffer can use its stored energy to supply the load and prevent the disturbance from reaching the distribution network. In traditional power grids, central storage units are used to balance the supply and demand, but they are slow and expensive. A power buffer, on the other hand, is fast and efficient and can be installed at the load terminal. Typically, power buffers are controlled individually to serve local loads, but their efficiency can further be improved if the buffers operate collectively to serve neighboring loads. To achieve a cooperative operation of power buffers, a communication module is provided that enables the buffers to exchange information with their neighbors. In this way, in case of load changes, the buffer at that node along with the neighboring buffers can supply the required load. This collective response from the buffers increases the damping of the microgrid.

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