Abstract

Motivated by the growing concerns over climate change and carbon emissions caused by excessive utilization of fossil fuels, the global energy sector is transitioning towards the adoption of clean energy sources such as solar photovoltaics (PV), wind, small hydro etc. The concept of microgrids (MG) has become an emerging trend as it facilitates large-scale penetration of renewable energy sources (RES) based distributed energy resources (DERs) and increased incorporation of information & communication technology (ICT). Since RES based generation systems inherently produce intermittent output characteristics, therefore, their integration in electrical systems results in greater challenges for the system operator, in terms of system stability and operation. Apart from having intermittent characteristics, renewable energy sources (RES) generation systems are interfaced through power electronics converters which have zero or low inertia. Such proliferation of power electronics devices reduces the overall system inertia in the network, which makes the system frequency and voltage more susceptible to instability issues. Accordingly, this thesis focuses on integration of smart infrastructure for real-time monitoring and information processing, and further develops fast and robust control strategies for reliable operation of microgrid while countering the effect of real-time uncertainties.

Smart buildings and homes are building blocks of the smart grid that enable interaction between utility and consumers in multiple ways such as real-time energy monitoring, demand response, demand-side management etc. A smart building unit includes the integration of numerous engineering technologies such as electrical power network with robust control and reliable two-way communication infrastructure with intelligent software and hardware systems. In view of this, firstly, this thesis develops a smart energy metering solution and an appliance control device for advanced monitoring and control infrastructure in smart grid environment. It upgrades the non-automated smart energy metering and appliance control to an IoT-enabled intelligent energy management system. It also reduces the peak load and overall energy consumption of a building by switching off non-essential appliances.

The real-time electrical parameters information acquired from smart energy metering solution is further utilised for development of an online algorithm for non-intrusive load monitoring (NILM) which helps system operator for the purpose of network support and demand response applications in an increasingly uncertain distribution network. Accordingly, this thesis further focuses on development of a multi-layered convolutional neural network (CNN) based NILM for load monitoring in smart buildings, through precise identification of appliances and their operational
schedules during real-time operation.

Owing to the increased penetration of distributed RES, the system frequency and voltage stability are increasingly susceptible to disturbances under uncertain environments. In this regard, a fast and robust auxiliary control for voltage and frequency regulation has been integrated to the existing conventional controllers, which improves the system performance without additional computational burden. A single-input and single-output linear disturbance observer-based control has been proposed to regulate system frequency and voltage within prescribed under uncertain environment. Furthermore, the performance of the proposed control have been evaluated under noisy load and communication delays.

This thesis further focuses on utilization the information of appliance switching through appliance control board in an energy internet environment. In this regard, a multi-timescale coordinated control scheme has been proposed to optimally control inverter-based resources in different timescales. Accordingly, a two-stage stochastic optimization framework has been developed for optimal operation of battery energy storage system (BESS) and voltage source converters (VSC) in hour-ahead and intra-hourly timescales, to counteract the effects of

uncertainties in solar photovoltaic (PV) and load. Additionally, a novel real-time coordination framework has been developed for fast frequency control, triggered by appliance switching/scheduling information through energy internet. Thus, real-time control is implemented as a pre-disturbance preventive action, appropriately acting with the load switching event. Furthermore, the proposed real-time frequency control is developed as a coordination strategy for primary regulation by adaptive VSC control and recovery control by the grid.

Virtual synchronous generator (VSG) is an emerging approach for grid-forming inverters that imparts stability to low-inertia microgrids. In view of this, an adaptive VSG concept has been proposed to enhance system stability in islanded microgrids. Accordingly, a two-layered coordinated control strategy for optimal operation of renewable energy sources (RES) integrated microgrids has been developed. At the first layer, a voltage control scheme has been developed for radial distribution networks through reactive power support using inverter-based resources. The second layer develops an adaptive approach for VSG parameter tuning for frequency regulation in islanded networks, considering load and generation uncertainty. Accordingly, a bi-level optimization model has been developed, wherein the first level evaluates robust VSG parameters, and the second level develops a stochastic programming model for adaptive tuning of VSG parameters to counteract the effects of network uncertainties during islanding.

Performance of the control and optimization strategies developed in this thesis have been verified through extensive simulations on standard data sets and test systems. Furthermore, effectiveness of the proposed control approaches have been validated on hardware-in-loop simulation on OPAL-RT and laboratory-scale hardware experimental setup.