

# Abstract

The advent of enabling smart grid technologies has resulted in the proliferation of heterogeneous power generation networks. In this context, the concept of microgrids has gained popularity in recent years due to their ability to integrate renewable energy sources with the power system. As such, many industrial units are increasingly displaying characteristics similar to grid-connected microgrids. Moreover, large industrial parks such as Singapore's Jurong Island can also be considered as grid-connected microgrids with multiple energy streams. Consequently, the traditional day-ahead scheduling (unit commitment) problem solved in power systems needs to account for the increasingly heterogeneous nature of the generators. Furthermore, the deregulation of modern electricity markets has also introduced concepts such as demand side management which need to be accounted for by the scheduling problem. As such, there exists a need to formulate optimization models for modern energy systems which can account for the heterogeneity in the generation and the flexibility in the load. This becomes even more complex from the perspective of developing eco-industrial parks due to the presence of multiple energy streams.

This thesis primarily aims at developing optimal scheduling models for the participation of energy systems in the electricity market. The models developed in this thesis can be included as a part of an energy management system package. The energy systems in this thesis consider heterogeneous power generation sources including conventional combined cycle power plants, renewable energy sources and diesel generators. Apart from these, the presence of flexible elements such as battery energy storage systems, thermal energy storage systems, interruptible loads and schedulable loads make the energy management problem non-trivial. The energy system models in this thesis are developed using a component-wise approach to account for the intricacies involved in the operation of each individual component. The utility of the optimal scheduling problem formulations proposed in this thesis is primarily demonstrated through the prism of load management scenarios.

This thesis is broadly divided into four parts. The first part focuses on the development of accurate optimal scheduling models for the components which constitute the energy systems considered in the later chapters of the thesis. The hybrid systems based mixed logical dynamical modelling framework is used to develop optimal scheduling models of the gas turbines, steam turbines, boilers, diesel generators, battery energy storage systems, thermal energy storage systems and interruptible loads used in this thesis. The optimal scheduling models of the gas turbines, steam turbines and boilers include the power trajectories followed by these components while undergoing the hot, warm and cold start-up processes. The shutdown power trajectories are also included in the scheduling

models of the gas turbines, steam turbines and boilers. A detailed treatment of the modelling of an exemplar conventional fossil fuel based generating unit using the mixed logical dynamical framework is provided. The conventional generator scheduling model is subsequently used in a typical self-scheduling problem and a unit commitment problem involving five generators.

The second part of this thesis proposes a shipyard energy management system (SEMS) to optimize the cost of operating a typical shipyard drydock. The SEMS comprises three modules - load forecasting, contracted capacity optimization and optimal scheduling. The load forecasting module uses artificial neural networks (ANN) to generate short-term and medium-term load forecasts. Historical load demand data and ship arrival schedules are provided as inputs to the ANN. The inclusion of the ship arrival schedule as an input to the ANN enhances the accuracy of the load forecast. The optimal scheduling module minimizes the electricity cost incurred by the drydock operator. The optimal scheduling problem includes a pump scheduling optimization model which minimizes the uncontracted capacity cost incurred by the drydock operator. Illustrative case studies are performed using data from a local shipyard to demonstrate the efficacies of the proposed load forecasting and optimal scheduling modules.

The third part of the thesis enhances the features of the optimal scheduling module proposed in the aforementioned SEMS. The microgrid considered in this context comprises diesel generators, battery energy storage systems, renewable energy sources, flexible pump loads and interruptible loads. A two-stage energy management system architecture is proposed wherein an optimal, day-ahead scheduling problem similar to the SEMS is solved in the first stage. Subsequently, the results from the first stage are used to solve an optimal power flow problem in the second stage. This is done to account for the network losses and to verify the feasibility of the optimal schedule generated in the first stage with respect to the network constraints. Thereafter, the two stages are coordinated using an iterative procedure. The utility of the proposed optimization model is demonstrated using illustrative case studies.

The final part of this thesis proposes a detailed optimal scheduling model for an exemplar multi-energy system comprising combined cycle power plants (each constituted by one gas turbine and one steam turbine), battery energy storage systems, renewable energy sources, boilers, thermal energy storage systems, electric loads and thermal loads. The proposed model considers the detailed start-up and shutdown power trajectories of the gas turbines, steam turbines and boilers. Furthermore, a practical, multi-energy load management scheme is proposed within the framework of the optimal scheduling problem. The proposed load management scheme utilizes the flexibility offered by system components such as the flexible electrical pump loads, electrical interruptible loads and a lumped flexible thermal load to reduce the overall energy cost of the system. The efficacy of the proposed model in reducing the energy cost of the system is demonstrated in the context of a day-ahead scheduling problem using four illustrative scenarios.