MULTI-AGENT SYSTEM FOR CONTROL AND MANAGEMENT OF DISTRIBUTED POWER SYSTEMS

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ABSTRACT

The operation of modern power systems that focus on smart grid has become complicated with the introduction of distributed generation, load control, market operation, complex distribution networks and vehicle to grid interconnection. Smart grid represents a vision of the future power systems and integrates advanced sensing technologies, control methodologies and communication technologies into existing electricity grid at transmission and distribution levels. Hence, new control and management paradigms and technologies that are different from the traditional methodologies are necessary for the operation of modern power systems.

In this dissertation, a decentralized control and energy management architecture based on intelligent Multi-Agent System (MAS) is proposed for the operation of modern distributed power systems. Intelligent multi-agent system is a distributed Computational Intelligence (CI) technique that has been applied to solve several power system problems such as market operation, condition monitoring, fault diagnosis, power system restoration and protection. This technology has a great potential to solve problems in the control and management of modern power systems that implement smart grid techniques. In order to validate and evaluate the effectiveness of the proposed multi-agent system, several simulation studies on the control and management of modern distributed power systems were carried out.

This dissertation mainly focuses on the following aspects.

- A decentralized control and energy management architecture that is very much suitable for the smart grid development is proposed with intelligent multi-agent system approach.

- Multi-agent simulation platform is developed for the control and energy management of distributed power systems based on IEEE FIPA standards using JADE.
- Simulation studies on the control and management of distributed power systems with microgrids and integrated microgrids operating in different types of environments were carried out. Several algorithms were developed and implemented to optimize the functions of control and management.
- A real-time multi-agent system was developed to carry out real-time simulation studies on microgrid energy management. The real-time simulation studies were tested and validated with a Real Time Digital Simulator (RTDS).
- Novel methodologies are proposed for optimal sizing and placement of distributed energy resources in distributed power systems. Most of the simulation systems and case studies carried out in this dissertation were optimally found out using these proposed methodologies.
- Finally, management of distributed energy storage system and plug-in hybrid electrical vehicles was carried out for opening up the future research opportunities in context of distributed smart grid.

The outcome of the various simulation studies show that the developed multi-agent system handles the interaction among the control entities, provides a two-way communication channel for the entities in the distributed power systems, and makes some decisions locally to provide more reliable electricity supply to customers. Decision making of agents, in the multi-agent system which were developed using mathematical and computational intelligence techniques, show the applications and effectiveness of computational intelligence techniques for smart grid development. Furthermore, the real-time simulation studies on the smart microgrid at the

distribution network level show that multi-agent system can also handle real-time dynamic events while implementing smart grid techniques for the future power systems.

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LIST OF ABBREVIATIONS

ACL	Agent Communication Language
AID	Agent Identifier
AMS	Agent Management Service
CA	Contingency Analyser
CESS	Composite Energy Storage System
CI	Computational Intelligence
DER	Distributed Energy Resource
DESS	Distributed Energy Storage System
DF	Directory Facilitator
DG	Distributed Generation/Distributed Generator
DMS	Distribution Management System
DNO	Distribution Network Operator
DSM	Demand Side Management
EA	Evolutionary Algorithm
ES	Evolutionary Strategy
EV	Electrical Vehicle
FIPA	Foundation for Intelligent Physical Agents
GPI	Global Performance Index
IEDS	Intelligent Energy Distribution System
IEEE	Institute of Electrical and Electronics Engineers
ISO	Independent System Operator

JADE	Java Agent Development
JNI	Java Native Interface
LC	Local Controller/Load Controller
LMP	Locational Marginal Price
LP	Linear Programming
LR	Lagrangian Relaxation
LREA	Lagrangian Relaxation with Evolutionary Algorithm
MAS	Multi-Agent System
MCP	Market Clearing Price
MGC	Microgrid Controller
MO	Market Operator
MODERN	Modular Distributed Energy Resource Network
MSC	Micro Source Controller
MTS	Message Transport Service
OPF	Optimal Power Flow
PHEV	Plug-in Hybrid Electrical Vehicle
PX	Power Exchange
RMA	Remote Monitoring Agent
RTDS	Real-Time Digital Simulator
RTU	Remote Terminal Unit
SC	Schedule Coordinator
SCADA	System Control And Data Acquisition
SE	State Estimator

CHAPTER 1

INTRODUCTION

1.1. Overview

Power industry is experiencing technological innovations all around the world to provide electricity and related services to customers at the lowest prices, through the introduction of competition in power industry [1,2]. Restructuring of power systems is achieved through gradual transition from centralized power generation to distributed power generation [3-6]. Distributed Generation (DG) [4,7-9] encompasses any small-scale electricity generation technology that generates and provides electric power close to the consumers' premises. With the introduction of distributed power generation, demand side management, market operation, complex distribution networks, and many interconnections among distributed power systems and sub systems, the operation of modern distributed power systems have become extremely complicated. Therefore, new control and management paradigms and various techniques that are different from those used in the past are necessary for the operation of modern distributed power systems.

The main objective of this dissertation is to design, develop and simulate intelligent Multi-Agent Systems (MAS) [10] that enable control and energy management of distributed power systems. This includes the development of control and management algorithms, optimal sizing and placement of Distributed Energy Resources (DER) [4,5], the implementation of smart grid techniques [6,7] and management of distributed power systems.

This chapter is organized as follows. Section 1.2 describes the distributed power system control. Section 1.3 briefly explains the smart grid and its main characteristics.

Section 1.4 provides an overview of distributed power systems. Section 1.5 presents details about the control and management of distributed power systems. Section 1.6 proposes an approach for the control and management of distributed power systems. Section 1.7 provides the main objectives of this dissertation. Section 1.8 provides the main contributions of this dissertation. Section 1.9 outlines the organization of this dissertation.

1.2. Power System Control

Currently, electric power systems are evolving from an entirely centralized architecture to a decentralized architecture [3-6]. This evolution towards the smart grid [7,11,12] requires novel control and management methodologies which must be capable of adapting to new requirements such as highly distributed nature of power grid, ability to run in islanded mode, intermittency of renewable energy sources and two-way communication channel between power system elements [5].

The overall performance of distributed power systems is affected by the way that each individual elements in network is operated and how it interacts with the other elements. Therefore, efficient distributed control and management techniques should be developed with a proper coordination strategy among the power system elements. The power system control can be classified as centralized control system and decentralized control system based on the responsibilities and the coordination strategy provided to the controllers in the system.

1.2.1. Centralized Control System

Traditionally, power systems were operated centrally [1,13]. Even today, most of the power systems around the world are controlled and managed centrally. Centralized operational frameworks are implemented with local controllers together with a centralized Supervisory Control and Data Acquisition (SCADA) system [1,13,14].

The central controller is the main responsible element in the control system, which determines actions and commands through the SCADA system. Figure 1.1 shows the schematic representation of a centralized control system.

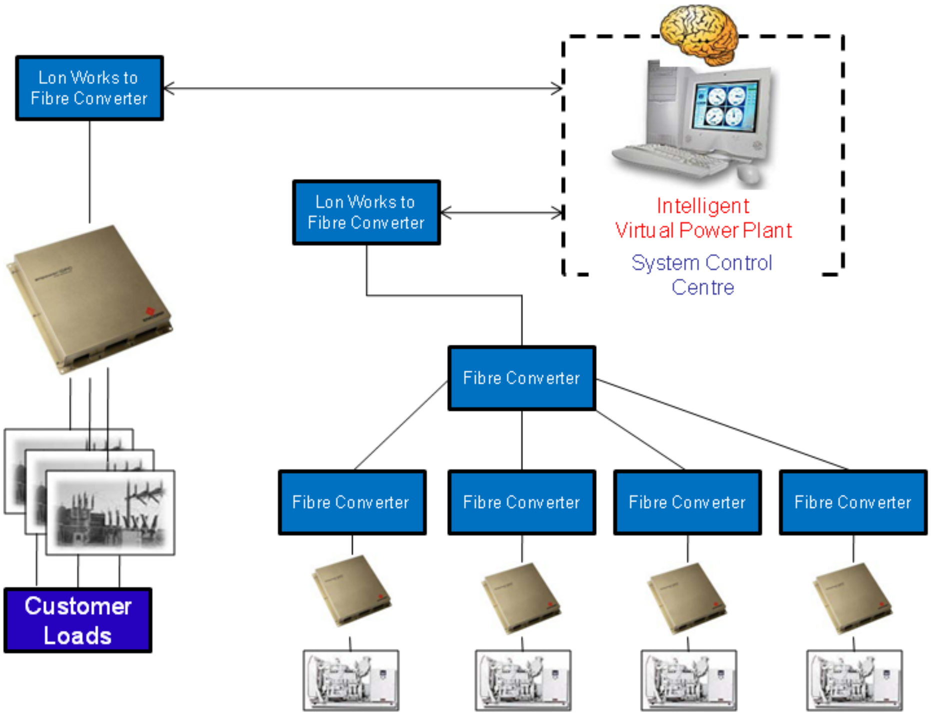


Figure 1.1. Schematic representation of a centralized control system

In centralized control systems [13,14], local controllers follow orders of the central controller. The central controller maximizes the power system values, and optimizes the power system operation. It uses the electricity market prices to determine the amount of power that can be delivered from each source and also performs demand side management actions to the controllable loads. It might use simple forecasts loads and power production capabilities of distributed energy resources.

1.2.2. Decentralized Control System

Modern power systems [1,7], though highly versatile, have become complicated. Their operation is carried out based on electricity markets [15,16] where energy sources can have different owners and objectives. In order to participate in the electricity market, energy sources need to take a few local autonomous and goal-oriented decisions. Furthermore, energy sources also provide ancillary services to the power grid for reliable operation besides supplying power to distribution networks. Therefore, energy sources should have a certain degree of intelligence. These behaviours of controllers can be included in decentralized control and management architectures. Figure 1.2 shows the typical representation of a decentralized control system for the operation of modern power systems.

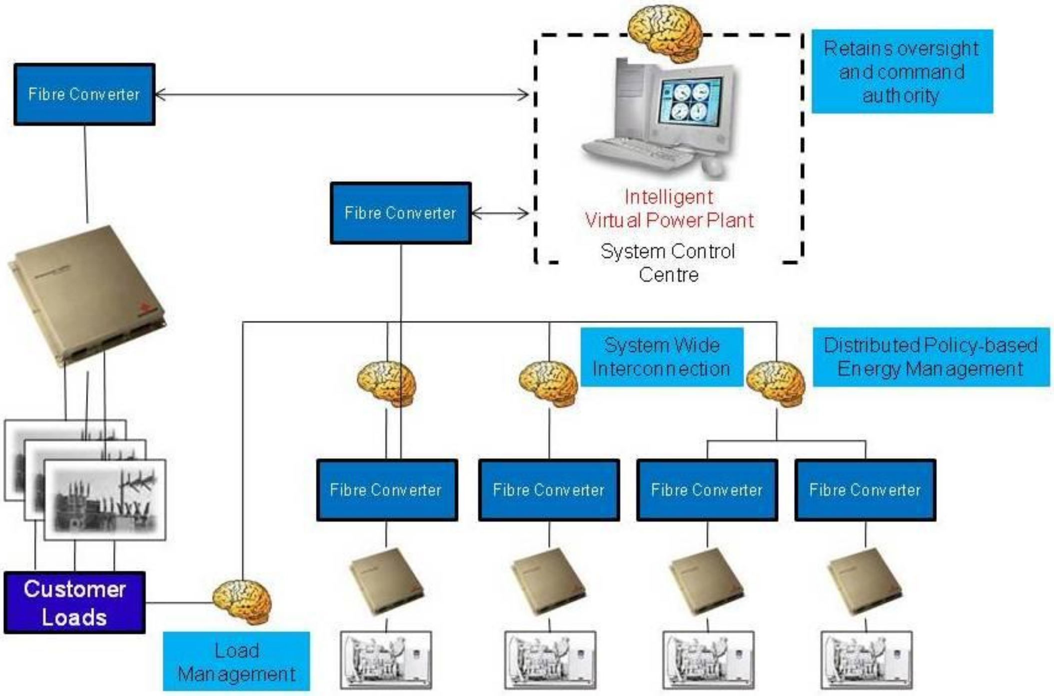


Figure 1.2. Schematic representation of a decentralized control system

In decentralized control systems [15-17], the main responsibility is given to local controllers of power system elements. The local controllers can autonomously coordinate with other entities to optimize their operations in order to satisfy their individual and system requirements. These decentralized control systems can be developed with distributed computational intelligence techniques [10,18].

1.3. Smart Grid

Smart grid [7,11,12] a vision of the future power systems, which is influenced by economical, political, environmental, social and technical factors. Smart grid integrates advanced technologies and methodologies into current power systems at transmission and distribution levels in order to supply electricity in a smart and user friendly manner. Smart grid techniques [7,11,12] can be divided into two main categories: smart grid techniques for deployment of smart metering infrastructure that allows customers to communicate with electricity providers in a two-way fashion and smart grid techniques for the advancement of transmission and distribution networks. According to the modern grid initiative report by the department of energy, United States [12,19], the main characteristics of smart grids are consumer friendliness, hack proof self-healing, attack resistance, ability to accommodate all types of generation units and storage elements, high power quality and efficient operation by involving electricity markets in the power industry.

Smart grid can be implemented by applying sensing, measurement and control devices together with two-way communication between electricity production, transmission, distribution and consumption parts of the power systems [5,6]. Two-way communication is necessary for users, operators and automated devices in order to respond dynamically to changes in the power grid. Some of the key characteristics of a smart grid such as high penetration of distributed power generation, demand side management and market based operation have already been implemented in many distributed power systems, whereas the other characteristics of smart grid are expected to be implemented very soon [5,7].

Even though smart grid is defined by above characteristics, most of these characteristics belong to the traditional power systems as well. In order to differentiate smart grid and traditional power grid clearly, Table 1.1 compares the main characteristics of a smart grid and a traditional grid.

Table 1.1. Comparison of a smart grid and a traditional grid

Characteristics	Smart Grid	Traditional Power Gird
Integrating generation and storage elements	Many distributed energy resources, plug-and-play convenience, focus on more renewable energy sources	Dominated by big central generation, several difficulties for integrating elements
Consumer participation	Informed, involved and active customers with demand responses, distributed generation and vehicle to grid connection	Informed and non-participative
Electricity market evolution	Mature, well-integrated wholesale markets, growth of new electricity markets for consumers	Limited wholesale markets, not well integrated, limited opportunities for consumers
Resiliency	Resilient to attacks and natural disasters with rapid restoration capabilities (i.e. self healing)	Vulnerable to natural disasters and malicious acts of terror
Asset optimization	Greatly expanded data acquisition of grid parameters, focus on prevention, minimize impact to consumers	Little integration of operational data with asset management
Power quality	Priority with variety of power quality/price options, rapid resolution of issues	Focus on outage, slow response to power quality issues
Responsiveness	Automatically detects and responds to problems, focus on prevention, minimizing impact to consumer	Responds to prevent further damage, focus is on protecting assets following fault

Smart grid is not a single destination that happens at once; rather it is a journey that evolves gradually. Furthermore, smart grid does not happen in a particular order. Smart grid cannot be achieved without distributed intelligent methodologies and multi-party interactions. With the introduction of smart grid techniques, the operation of modern power systems has become extremely complicated. Therefore, this is the time for power system researchers to find out suitable technologies for sensing, measurement, control and communication, appropriate methodologies for design, development and implementation and optimization algorithms for the control and management functions of modern power systems.

1.4. Distributed Power Systems

Distributed Generation (DG) [4,7-9] encompasses any small-scale electricity generation technology that generates and provides power close to the customers. The size of distributed generation varies from a few kilowatts to a few megawatts. Today, there is growing interest in distributed generation, particularly as on-site generation for business and homeowners, which provides better power quality, high reliability and fewer environment problems. Distributed generation technology is often lumped with distributed storage, and the combination is referred to as Distributed Energy Resource (DER) [5] that represents a modular electrical generation or storage installed at customer site. Distributed generation is operated in parallel with the utility system or islanded from the utility system. Technological advances in distributed generation have resulted in small-scale generation that is cost-competitive with larger power plants. Compared with traditional large-scale power generation, distributed generation is less expensive, flexible and environmentally friendly power source. These features make it more competitive in the energy market [1,5].

In general, distributed generation [4] can make use of energy derived from wind, solar, geothermal, bio-power or fossil fuels. Typically, distributed generation technologies available include wind turbines, photovoltaic panels, fuel cells, combustion turbines and combustion engines. Several of these technologies offer clean, efficient and cost-effective electric energy. In general, economics of electrical power systems depend on capital costs, operating efficiencies, fuel costs as well as operational and maintenance cost. The distributed generation technologies are considered compatible with other merchant power generation options, and are utilized in smart grid environment. Each technology has its own strengths and weaknesses. Some of these technologies can be combined together to form a hybrid system that is cost-effective system, and supplies as a continuous source of power. Environmental friendly and renewable energy technologies such as wind turbines and photovoltaic systems, and clean and efficient fossil-fuel technologies such as gas turbines and fuel cells are new generating technologies that encourage the utilization of distributed generation. These renewable generators usually have small size, and can be easily connected to distribution grids.

The modern power systems are becoming more distributed. Therefore, it is necessary to come up with a distributed operational architecture for the control and management of modern power systems. There are few concepts and architectures that are already exist in the industry. Microgrids and integrated microgrids are some of the existing innovative control and management concepts in distributed power systems. Currently, these operational concepts are mostly used as test beds for research and development of smart grid techniques.

1.4.1. Microgrid

Microgrid [8,20,21] is a low voltage distributed electrical power networks comprising various distributed generators, storage systems and controllable loads, which can be operated either as a grid-connected system or an islanded system. Figure 1.3 shows the schematic diagram of a microgrid.

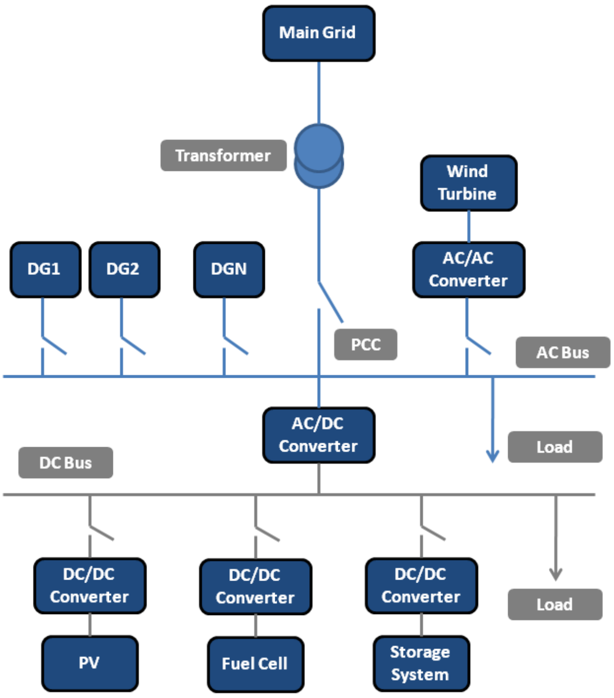


Figure 1.3. Schematic diagram of a microgrid

From the grid's point of view, microgrids can be considered as controllable entities within the electrical power system that behave as aggregated loads or sources of power and also provide ancillary services to the supporting networks which depend on the status of both the microgrid and the main distribution grid. From the customers' point of view, microgrids are similar to traditional distribution networks that provide electricity to the customers. Microgrids enhance local reliability, reduce emissions, improve power quality and potentially lower the cost of energy supply. This denotes the capability of a microgrid in the smart grid development at distribution level.

1.4.2. Integrated Microgrid

Recently, interest in microgrids and renewable energy resources has increased significantly, and more microgrids are being implemented in distributed power systems. An innovative control and management architecture, called integrated microgrid [6,15] is proposed in this dissertation. Integrated microgrid has ability to control and manage many microgrids within its architecture. Integrated microgrid is a distributed electrical power network, which has several microgrids interconnected with each other. Figure 1.4 shows the schematic diagram of an integrated microgrid.

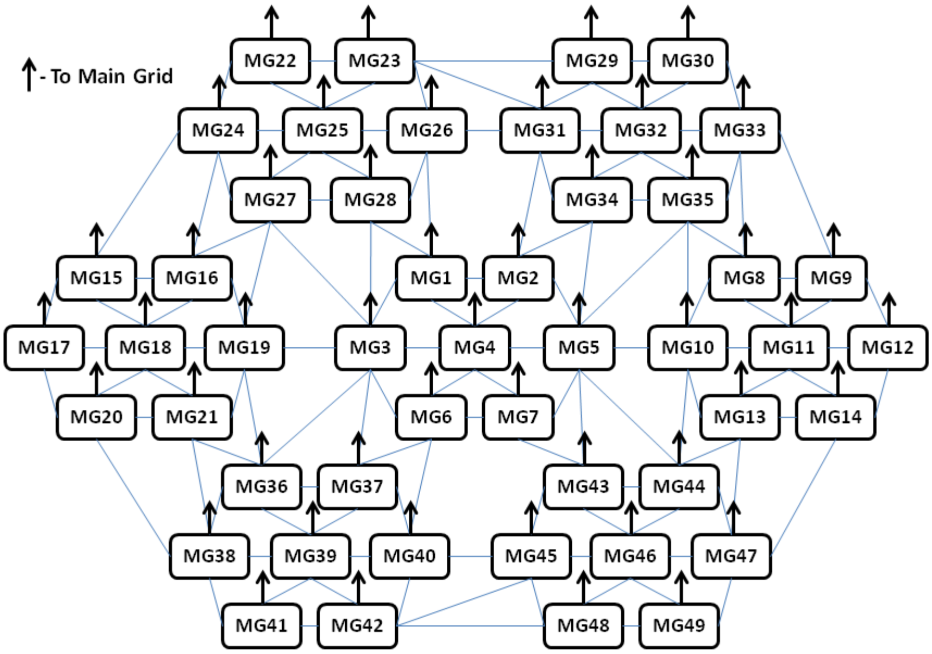


Figure 1.4. Schematic diagram of an integrated microgrid

Each microgrid in an integrated microgrid could contain different types of loads and energy sources, and can be operated with different sets of rules and policies [1,6,15]. Therefore, proper resource sharing among the microgrids is needed, so that more benefits than what is achievable by single microgrids can be achieved. In addition, electric power grids are expected to guard themselves against man-made and natural disasters. This can be achieved by resiliency and autonomous re-configurability of the power systems for which many microgrids have to be placed at distribution networks.

1.5. Distributed Power System Control and Management

Distributed power systems can be operated either as grid-connected systems or as islanded systems. The network controllers [17,20,22] are responsible in ensuring that micro sources work properly at predefined operating points, or even at slightly different from the predefined operating points, the operating limits of the micro sources are satisfied. The control system also handles the power exchanges between the distributed power system and the main distribution system, disconnection and reconnection processes, market participation, and heat utilization for local installations. In addition, the control system must have black-starting capability in the islanded mode operation. The control system in distributed power systems can be classified as local control system, centralized control system and decentralized control system according to the decentralization of responsibilities and functions assigned to the controllers [17].

Some of the typical functions which should be handled by the energy management in the distributed power systems are forecasting of electrical load and heat demand in the system, forecasting of power production capabilities of renewable energy sources in the system, generation scheduling, emissions calculations, demand side management and security assessment. Control and management functions [17,20] of distributed power systems basically depend on the mode of operation.

In the islanded mode, due to unavailability of the utility grid, two additional requirements must be fulfilled: Power balance between generation and demand of the system and control of voltage amplitude and frequency of the installation. Due to the non-controllable nature of renewable energy sources, controllable micro sources such as engine generator, fuel cell and energy storage system are responsible for ensuring power balance by absorbing or injecting the power difference between renewable generation and local load demand. When there is sufficient energy, the energy management system has to control the output power of controllable micro sources to maintain the frequency and voltage of the distributed power system. On the other hand, if the power from the micro sources is not enough to feed the local load demand, the energy management system detaches non-critical loads in the distributed power system. In addition, the distributed power system should be able to handle the control functions such as islanding from the main grid, synchronizing with the main grid and black starting.

In the grid-connected mode, power balance between generation and demand as well as the frequency and voltage of the distributed power system are guaranteed by the utility grid. Thus, the distributed power system can operate as a power generator or as a power load, and filters active power transferring between the distributed power system and the main distribution system.

1.6. Proposed Control and Management Methodology

The traditional Energy Management System (EMS) [5,13] in power systems consists of three components: System Control And Data Acquisition (SCADA) system, State Estimator (SE) and Contingency Analyser (CA). SCADA system serves both as a data gathering system as well as a device control system. Data is collected from generation plants and substations through field Remote Terminal Units (RTUs), and fed into master stations integrated in the control room of each control area. State estimator is used in the control room to improve the accuracy of the raw sampled data with the help of mathematical processing so as to make it consistent with the electrical system model. The resulting information for equipment voltages and loadings is used in software tools such as contingency analyser to simulate various conditions and outages to evaluate the reliability of the power system.

The current control and management approach [5,7] of distributed power systems uses a central Supervisory Control And Data Acquisition (SCADA) system and several small distributed SCADA systems. This approach is no longer sufficient for various control operations of future smart grid with millions of controllable appliances because they will have to work efficiently on a large scale distributed system. Therefore, an approach that can provide adaptable local control and intelligent decision making is required. This can be achieved through distributed control, monitoring and management [5]. Intelligent multi-agent system approach [10,12] is one of the most suitable technologies for implementing such functionalities and is thus proposed for the control and management of distributed power systems in this dissertation.

Multi-Agent System (MAS) [10] is a distributed computational intelligence technique that emphasizes the joint behaviour of agents with some degree of autonomy and complexity arising from their interactions. Though generalized multi-agent platform could be used for solving different problems, it is a common practice to design a tailor made multi-agent architecture according to the application. Multi-agent systems are capable of combining the various advantages of computational intelligence techniques into a single framework thereby attaining a superior performance. Furthermore, multi-agent system can also be used to model competitive, cooperative or coordinating the behaviours of the system.

The potential of solving complex problems of a distributed nature motivates the use of multi-agent system approach in a smart grid. Multi-agent system not only provides a common communication interface for all elements but also takes autonomous distributed intelligent control and decisions. Moreover, a multi-agent system can be used as a flexible, extendable and fault tolerant control and management system. Recent studies show that applications of multi-agent system have been applied for the management of microgrids and other kinds of distributed power systems [16,23-29]. But most of these multi-agent systems only deal with one or two smart gird techniques, wherein some of them are not implemented with any industrial standards [30,31]. In order to develop industrialized multi-agent systems for the operation of distributed power systems, it is necessary to make unique and feasible standards, tools and design methodologies.

1.7. Main Research Objectives

The main objective of this dissertation is to develop a distributed multi-agent system for the control and management of distributed power systems. The energy management system mainly handles the control and management of any power system. Forecasting of electrical load and heat demand and power production capabilities of renewable energy sources, economical generation scheduling including emissions calculations, demand side management and security assessment are some of the main functions of distributed energy management. Among these functions, generation scheduling and demand side management functions need much interaction and local decision making of many entities. Hence, these two managerial functions are considered in this dissertation for validating the multi-agent system approach for the control and management of distributed power systems.

The performance of the multi-agent system mainly depends on decision making modules of the agents and coordination strategies among the agents. The objectives of this dissertation also include development and implementation of the decision making modules of the agents using mathematical and computational intelligence techniques. This dissertation mainly concentrates on the agents that involve for carrying out the following functions of energy management system.

- Day-ahead generation scheduling
- Real-time supply-demand matching
- Demand side management

As modern distributed power systems intend to have distributed storage systems and integrated plug-in hybrid electrical vehicles, this dissertation also seeks to provide a multi-agent system platform for managing distributed power systems with these innovative integrations.

1.8. Main Research Contributions

The main contribution of this research is the conceptualization, development and application of a distributed multi-agent architecture to simulate the control and management of distributed power systems. The significant contributions of this dissertation are given below.

- The development of distributed multi-agent system platforms for control and management of distributed power systems in Java Agent Development Environment (JADE).
- The development of computational intelligence and mathematical algorithms for decision making of the agents in multi-agent systems. These include generation scheduling and demand side management of microgrids and integrated microgrids operating under different rules and policies.
- The multi-agent systems were interfaced with Power World simulator and Real-Time Digital Simulator (RTDS) for confirming the control and management without violating any technical constraints.
- The development of a real-time multi-agent simulation platform for validating real-time control and management of a microgrid in RTDS.
- Proposed novel methodologies for optimal sizing and placement of distributed energy resources for distributed power systems.
- Explored emerging research opportunities such as intelligent management of distributed energy storage system and plug-in hybrid electrical vehicles.

The developed multi-agent systems produced promising results from various simulation studies which were conducted on microgrids and integrated microgrids operating with different rules and policies. This research constitutes a partial effort on the development and implementation of smart grid techniques in distributed power systems using the multi-agent system technology.

1.9. Dissertation Outline

The rest of this dissertation is organized as follows.

- Chapter 2 provides a literature review for the research that includes a review of proposed multi-agent system technology and its background information.
- Chapter 3 proposes a multi-agent system for the control and management of distributed power systems and formulates some of the functions of energy management of distributed power systems such as generation scheduling and demand side management.
- Chapter 4 provides simulation studies on the operation of microgrids in competitive and cooperative environments as well as simulation studies on the operation of integrated microgrids in grid-connected and islanded modes.
- Chapter 5 provides the development of real-time multi-agent platform for control and management of a microgrid using a RTDS.
- Chapter 6 provides the expansion of the multi-agent system for the management of plug-in hybrid electrical vehicles and intelligent short-term management of a distributed energy storage system.
- Chapter 7 proposes novel methodologies for optimal sizing and placement of distributed energy resources for distributed power systems.
- Chapter 8 concludes this dissertation, and provides future research on the field of the dissertation.

CHAPTER 2

BACKGROUND AND RELATED WORK

2.1. Overview

The evolution towards decentralised architecture requires new highly distributed methodologies for control and management of the modern power systems. Multi-Agent System (MAS) [10] is one of the potential methodologies. In the multi-agent system approach, the power system is considered and modelled as a collection of distributed entities called agents which inturn present power system elements and evolve in a given environment. A certain degree of distributed or collective intelligence can be achieved through the interaction of these agents to reach their goals.

This chapter is a review of applications of multi-agent system used for power system and distributed energy management published in the literature. It has a number of concepts and experiments used by researchers to apply this promising methodology. The remaining chapter is organized as follows. Section 2.2 provides the background about the multi-agent system technology. Section 2.3 provides the background about the design and development of multi-agent systems. Section 2.4 reviews several publications in which the multi-agent system has been used for solving the power system problems. Section 2.5 reviews several publications in which the multi-agent system has been used for the development of smart grid. Section 2.6 summaries the chapter.

2.2. Multi-Agent System

Multi-agent system is a loosely connected network of distributed intelligent hardware and software agents that interact with each other. The interaction of agents can be designed such that the multi-agent system achieves a global goal. Although each agent is an intelligent entity, it is not enough for an individual agent to achieve the global goal in a large-scale complex system. Multi-agent system approach can be used to model a large-scale complex power system as a group of geographically distributed, autonomous and adaptive intelligent agents. Each agent has only a local view of the power system, but agents as a whole, can perform control and management schemes for the entire system through the autonomous interaction of the agents.

The fundamental element of a multi-agent system is an agent. According to Wooldridge [10], an agent is a piece of software or a hardware entity that is situated in an environment and is able to autonomously react to changes in the environment. The environment is simply everything external to the agent. Wooldridge's basic definition of an agent [10] is similar to that of Russell and Norvig [32]. Wooldridge extends the concept of an agent to an intelligent agent by defining flexible autonomy. Flexible autonomy of an intelligent agent is defined by characteristics such as reactivity, pro-activeness and social ability.

- Reactivity is the ability of an agent to recognize any changes in its environment, and takes actions for the changes based on its knowledge.
- Pro-activeness is the ability of an agent to express its goal oriented behaviours.
- Social ability is the ability of an agent to interact with the other intelligent agents.

The following sections have briefly reviewed the main characteristics and advantages of the multi-agent system technology.

2.2.1. Characteristics of Multi-Agent System

Some of the main characteristics of intelligent agents [10,32] are explained here to show the potential of the multi-agent system approach for control and management of distributed power systems [20,22].

- Agents have a certain level of autonomy. Agents can take decisions driven by a set of tendencies without a central controller or commander. The autonomy of each agent is related to its resources. For example, in the case of charging a battery bank, it can charge when the price of electricity is low, or the state of charge is low. Thus, the corresponding local agents decide when to charge battery bank based on their own rules and goals.
- Agents are capable of acting in an environment. This means that agents are capable to change their environment through their actions. For instance, an agent that controls a storage unit changes power settings of other production units, adjacent bus voltages and security level of the system.
- Agents can communicate with each other. For instance, agents controlling micro sources communicate with the market operator, distributed network operator and the other agents to negotiate bids of electricity to operate an electricity market.
- Agents can interact among distinct conceptual entities such as different control subsystems and plant items. For instance, an agent controls a microgrid while taking into account of thermal unit constraints.
- Agents can represent their environment partially. For example, a generator agent knows only the voltage level of its own bus, and could be used to estimate what is happening in other buses. However, the agent does not have the information about the other elements and the system as whole.
- Agents have certain behaviours and tend to satisfy their objectives using their resources, skills and services. The way that an agent uses its resources, skills and services is defined by its behaviours. As a consequence, the behaviours of each

agent are formed by its goals. For instance, an agent that controls a storage system aiming to provide uninterruptible supply to the load has different behaviours from that of another storage system in the system.

2.2.2. Advantages of Multi-Agent System

The multi-agent system approach has several distinct advantages over the traditional approaches for control and management of distributed power systems [15,16,20,23-31]. Multi-agent system enhances the overall system performance specifically along the dimensions of computational efficiency, reliability, extensibility, maintainability, flexibility and robustness. Some of the important advantages of the multi-agent system approach are briefly explained as follows.

- Unit autonomy: This is a basic characteristic of an agent in which each unit behaves autonomously in its environment based on its individual goals.
- Reduced the need of large data manipulation: In a multi-agent system, information is processed locally in the agents and only knowledge is exchanged with other agents. In this way, the amount of information exchanged is limited.
- Increased reliability and robustness of control systems: In a multi-agent system, if one of the controller agents fails, the other controller agents adapt to the situation and continue the system operation.
- Openness of the system: Multi-agent system allows manufacturers of distributed energy resources to embed a programmable agent in the controller of their equipment according to certain rules. In this way, the required “plug and play” capability for installing future distributed energy resources and loads is provided.
- Learning of agents: Agents update their rules based on the effectiveness of the rules to provide better performance.

Multi-agent system technology, a potential method to realize above benefits can be used to model distributed energy resources and implement distributed coordination among them.

2.3. Multi-Agent System Development

This section briefly reviews the literature for design methodologies of multi-agent system, available multi-agent system architecture, design methodologies of an intelligent agent, available industrial standards for development of multi-agent systems, agent communication languages, ontology design, available multi-agent system platforms and technical challenges and problems posed for the development of multi-agent system in power system engineering.

2.3.1. Multi-Agent System Design

There are several methodologies available in the literature for designing multi-agent systems [33-37], but their fundamental is often the same. The design methodologies have emerged for the specification and design of multi-agent systems by developing or extending traditional software engineering approaches and knowledge engineering approaches. For example, MAS-CommonKADS [33] is an extended methodology of CommonKADS knowledge engineering approach, and DESIRE [35], MaSE [36] and Gaia [37] are developed from object-oriented approaches. In addition, some other methodologies, recommendations and tools [16,23-25] are also available for designing and implementing multi-agent systems for power engineering.

Generally, a multi-agent system design has three phases such as conceptualization, analysis and design. The problem to be solved is specified in the conceptualization phase, analyzed in the analysis phase and the results from the analysis phase are used to produce agents and their communication strategy. Figure 2.1 shows the typical stages of multi-agent system design.

Each stage of this design methodology produces outputs that are used in the subsequent stages of the design process. The methodology begins with the specification of the system requirements and capturing the knowledge needed to fulfill those requirements. During the task decomposition stage, the specification of requirements and knowledge captured in the previous stage are transformed into a hierarchy of tasks and subtasks. After task decomposition, the ontology that is the vocabulary for the agent communication is designed. The stage of agent modeling uses the task hierarchy and ontology to identify a group of autonomous agents with the abilities to perform the tasks. An agent can encapsulate one or more tasks, and each task in the hierarchy must be attributed to at least one agent. At this stage, the outcome is a set of agents and specific tasks that the agents should perform. The methodology also identifies the tasks which can be attributed to legacy systems and hence new code needs to be generated. Once the agents have been identified, interactions of the agents must be defined. Hence, the final stage is to design and provide interaction of agents and control functionalities of the agents.

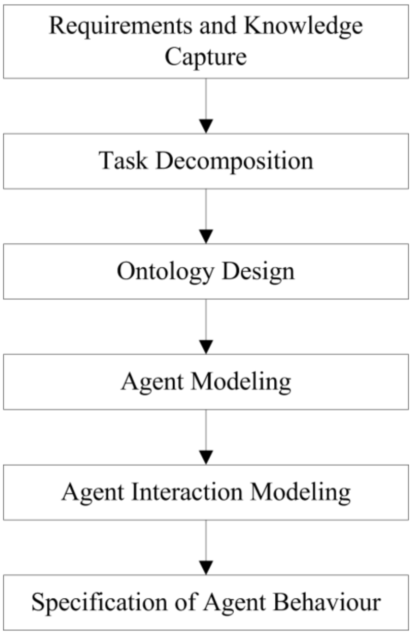


Figure 2.1. Design stages of multi-agent system

Most of the multi-agent system design methodologies referenced in the literature, share one common feature - they begin with particular problem to solve using the multi-agent systems. In such an approach, the behaviours of the multi-agent system is design-directed rather that emergent. The multi-agent system has been built with all the necessary interactions of agents to achieve the goals of the agents and the multi-agent system. If multi-agent systems are truly open, the interactions of an agent with other future agents should also be considered. However, such a top-down approach can lead to a rigid agent structure, wherein agents are less socially able and flexibly autonomous than desired values. Some consideration should be given to the type of agent communication possible to engage in rather than specific communication protocol required for the task at hand. The current methodologies do not guarantee fully flexible and extensible solutions. Therefore, careful consideration should be made to the type of communication each agent can engage in as this is the key when asserting flexibility and extensibility of agents.

2.3.2. Multi-Agent System Architecture

Power system management demands a great degree of intelligence from agents. In order to manage a variety of power systems, different multi-agent system architectures are possible. However, most of the studies show a basic structure based on two or three hierarchical layers [20,25]. Three-layered multi-agent system architecture is shown in Figure 2.2.

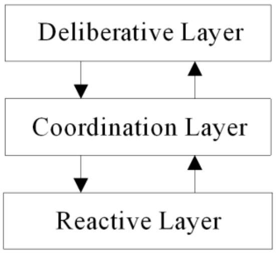


Figure 2.2. Layered architecture of multi-agent system

The bottom layer has agents controlling power system elements such as generators, loads and storage systems. These agents have rule based decision making systems to react in real time. The intermediary layer has area or zone operator agents in charge of coordinating the elements of the previous layer. These agents optimize the operation of the areas by dispatching energy between generators and loads. The top layer has a distribution network or microgrid operator agents, which coordinates several areas to optimize global operations.

Due to the growing nature of this field, several other types of architectures coexist in the literature. For example, agents are categorized into two types in [38]: traditional agents like generator and load agents and ancillary agents used for forecasting, trading, planning and other roles. A management type is added in [22]. In Rumley et al. [39], three different types of agents are used: feeders, loads and neutral agents. In Pipattanasomporn et al. [40] and Feroze [41], four types of agents are used: distributed energy resource, control, user and database agents. In [42], other types of agents such as bulletin board, weather forecasting, monitoring, price aggregation and manager agents are added besides buyer and seller agents. A particular architecture named ABCDIR (Agent-Based Control of Distributed Infrastructure Resources) based on many types of agents and groups of agents called globs and coops, is presented in [27]. There are a few other types of agents and agent architectures also used in this field [29,43,44].

As the multi-agent approach is relatively new in power systems and due to its growing nature in this field, researchers are designing and developing multi-agent systems according to their preference. Hence, most of the multi-agent systems are not designed or implemented with any industrial standards [30,31]. In order to focus more on the applications of the multi-agent system for power system development, it is necessary to bring the researchers together by proposing unique and feasible standards to develop multi-agent systems for power systems. The proposing standards should obey the existing power engineering standards and the software development standards. It is not possible to analyse multi-agent system architectures and their developments in detail without proposing firmed standards.

2.3.3. Intelligent Agent Design

An agent can be conceptualized as a black box which sends and receives messages, and interacts with its environment autonomously. However, the functionality of engineering multi-agent systems means that the developer needs different agent design options or agent anatomies and their characteristics so that they can select the best appropriate agent anatomy required for their applications.

There are several approaches such as Belief Desire and Intention (BDI) agents [10], reactive agents, agents with layered architectures [10] and agents implemented using model-based programming [45] in the literature to build individual autonomous intelligent agents. BDI approach is based on mental models of an agent’s beliefs, desires and intentions. It considers agent to have beliefs about itself, other agents and its environment, desires about future states and intentions about its own future actions. Reactive agents are normally associated with the model of intelligence. The fundamental property of reactive agents is that they do not perform reasoning through interaction with environment. Instead, they react to inputs from their environments and messages from other agents based on the pro-activeness of the agents. Several layered agent anatomies are discussed in the literature [5,33-39]. As an example, agents developed in JADE [46] platform tends to consist of three basic layers: a message handling layer, a behavioural layer and functional layer. This anatomy is shown in Figure 2.3.

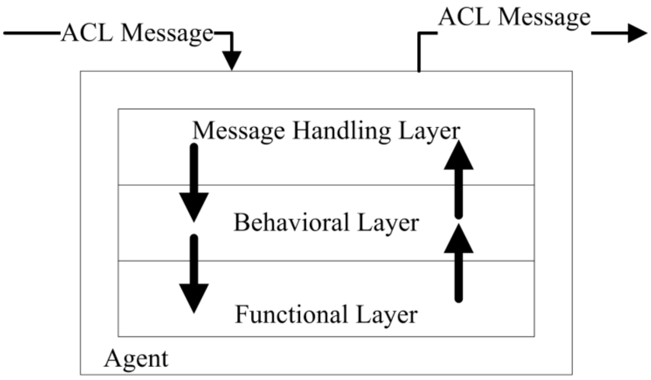


Figure 2.3. Layered agent anatomy [46]

The functional layer represents the core functional attributes which are the actions of agent to perform. The behavioural layer provides control, when an agent carries out specific tasks. When the functional layer produces new data, the behavioural layer instructs the message handling layer to inform interested agents of the new data. Similarly, the action taken by an agent in response to the receipt of a new message is decided in the behavioural layer. The message handling layer is responsible for the sending and receiving of messages from other agents, implementing the relevant Agent Communication Language (ACL) and ontology parsers as well as the functionalities for the control of conversations with other agents.

2.3.4. Multi-Agent System Platform

There are number of multi-agent system platforms like JANUS [47], JADE [46], ZEUS, Skeleton Agent and Mad Kit [40] available in the literature for developing multi-agent systems. However, judicious selection is required to ensure long-term compatibility and robustness for real-time and online applications. A good platform should have flexible, extendable and open architecture with excellent adherence to existing standards. Furthermore, agents should be able to interact with each other irrespective of the platform they run on. Most of these platforms offer functionalities that simplify the programming and the use of a multi-agent system. For an example, existence of directory services is useful for listing agents and their abilities. JADE is the most commonly used Java-based platform for the type of applications dealt in this thesis. JADE itself supports FIPA [48] standards, and has a good documentation of the framework. Some researchers and developers have developed their own framework as well [39,44].

In this research, JADE [46] framework that complies with FIPA standards for intelligent agents is used. JADE is also used as the runtime environment in which agents execute, thereby masking from the agents the underlying complexity of the operating system or network. Agents can span between multiple computers, or be on one computer, yet for the implementation, the code for sending and receiving messages is the same. The JADE runtime in turn executes within a Java Virtual Machine (JVM). An agent lives in a container and a collection of containers make up a platform. A platform encompasses all the containers within an agent system and therefore can span between multiple computers.

This research project uses JADE libraries which are utilized to implement agents, behaviours and ontology. These were implemented directly as extensions of corresponding JADE classes. Similarly, standard FIPA-SL [48] content language was adopted for communication of agents. As JADE provides the flexibility to develop a new ontology together with extension of JADE ontology, a set of ontologies have been created to structure information transferred among agents. Concepts, predictors and agent actions are the basic components of ontology. Concepts, as the name suggests, model the domain concepts such as microgrid, distributed resources and features of each element. Predicates specify the concept relationships, which can be evaluated as true or false such as the status of all distributed energy resources and loads. An action is a type of concept specifically for communication, where agents discuss an event happening, for instance: ON/OFF of production unit, or charging or discharging state of storage system.

2.3.5. Industrial Standards

IEEE Foundation for Intelligent Physical Agents (FIPA) [48] standards are become the mostly accepted standards for development and management of multi-agent systems. FIPA agent management reference model [48] is shown in Figure 2.4, which allows agents to communicate with each other by defining a standard for messaging and creating two directory concepts: an Agent Management Service (AMS) and a Directory Facilitator (DF).

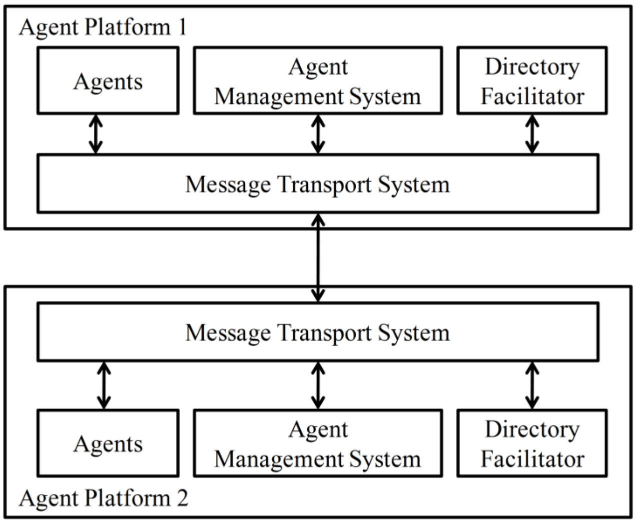


Figure 2.4. FIPA agent management reference model [48]

Agent Management Service (AMS) is responsible for managing the agent platform, which maintains a directory of Agent Identifiers (AIDs) and agent states. AMS has a list of registered agents, and behaves like white pages. DF provides the default yellow page services in the platform, which allows the agents to discover the other agents in the network based on the services they wish to offer or to obtain. Finally, Message Transport Service (MTS) that is responsible for delivering messages among agents provides services for message transportation in the agent system.

2.3.6. Agent Communication Languages

A number of different methods for inter agent communication have been developed in literature such as ARCHON [49] and blackboard [50] system. One of the first Agent Communication Languages (ACL) to be used by different researchers across different fields is Knowledge Query and Manipulation Language (KQML) [51]. In recent years, KQML has been superseded by FIPA-ACL. FIPA-ACL has its roots in speech act theory, and incorporates many aspects of KQML [48]. These languages define how messages are to be written. A FIPA-ACL [48] message contains 13 fields: Performative, Sender, Receiver, Reply-to, Content, Language, Encoding, Ontology, Protocol, Conversion-id, Reply-with, In reply-to and Reply-by.

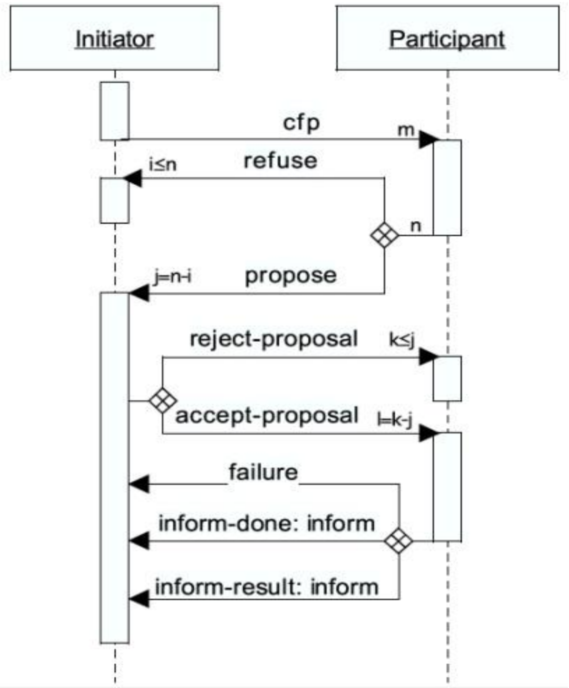


Figure 2.5. Interaction of agents for FIPA contract-net protocol [48]

The first and only mandatory field in the message is the Performative field that defines the type of communicative act or speech act. By classifying the message using a Performative, FIPA-ACL ensures that recipients understand the meaning of a message in the same way as the sender, removing any ambiguity about the message's content. Some of the Performative are agree, cancel, confirm, failure, inform, query if, request and propose. FIPA specifies communicative protocols that define the type of message content and the flow of messages expected by each agent during specific classes of communication acts [48]. FIPA Request, FIPA Query, FIPA Auction English, FIPA Auction Dutch and FIPA Brokering are some of the standard protocols. In addition, FIPA allows creating user defined protocol based on some standards [48]. Figure 2.5 illustrates the flow of messages specified by FIPA for a contract-net protocol.

2.3.7. Ontology Design

The content of a message between agents comprises two parts: content language and ontology. The content language defines the syntax or grammar of the content. The semantics or lexicon is drawn from the ontology. Ontologies provide a way to structure information for several agents in the multi-agent system to understand the semantics of knowledge and agree upon the terminologies used in agent communication.

When a multi-agent system is developed in JADE [46], ontology can be used as a class hierarchy of concepts, predicates and agent actions. Concepts are expressions that indicate entities with a complex structure that can be defined in terms of role or property. Concepts represent agents that are relevant to particular operation. E.g. Switch and Load. Predicates are expressions that say something about status or relationship of concepts. These can be true or false. E.g. Islanded and GridConnected. Agent actions indicate actions that can be performed by agents. For example, SwitchIn and SwithOut are used by PCC to request a switch agent to connect or disconnect the corresponding switch.

Currently different developers of multi-agent systems for power systems try to develop application oriented ontologies. This provides several different ontologies in power systems. Although the ontologies are different, power systems tend to capture common concepts, such as microgrid, load and generator. The problem is that the way these concepts are represented in the ontologies is different. In other words, the agents speak the same language but do not share a common vocabulary.

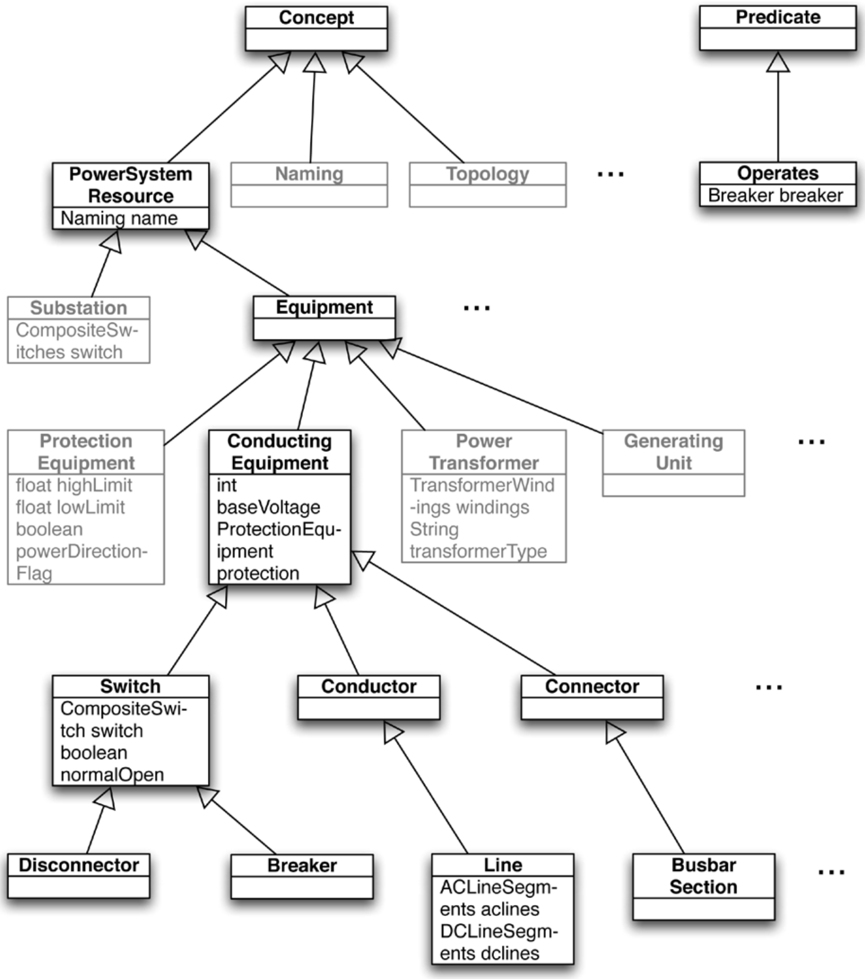


Figure 2.6. Class hierarchy of a part of an upper ontology based on CIM [31]

This problem can be overcome by using of a common upper ontology for power systems. Multi-agent system developers can then extend the upper ontology for their applications. The upper ontology for power systems should be made based on power engineering standards, such as IEC 61850, CIM [5] and IEC 61400-25 [5]. This may provide data models that can be used as a foundation for an upper ontology. An upper ontology [31] based on CIM is available at IEEE MAS working group web site. Figure 2.6 shows the class hierarchy of a part of an upper ontology based on CIM [31].

2.3.8. Technical Challenges and Problems

It is important to identify the key technical problems and challenges in the development of multi-agent systems for power systems, and how to overcome them. The challenges include selection of multi-agent platforms, designing of intelligent agents, agent communication languages and ontologies, industrial standards and security of multi-agent systems.

Selection of multi-agent platforms is an important challenge because there are number of multi-agent system platforms that exist in the literature. A good platform should be flexible, extensible and open adhering to standards. A proper designing of intelligent agents for power system applications is also a challenging task because there are several agent architectures available in the literature. Intelligent agents should be designed in such a way that they express their unique characteristics such as reactivity, pro-activeness and social ability.

Developing and following a set of common international standards for multi-agent system design is necessary. Agent communication languages and designing of ontologies should be based on common standards. On the other hand, it is very difficult to interconnect several multi-agent systems together in future. At this moment, IEEE FIPA standards are followed by most of the multi-agent system developers but still they have not become de facto standards. A key aspect of using agent-based technology is that all agents within power engineering applications should be able to cooperate and interoperate. This aspect should be independent of the individual developer but based on the power engineering community standards.

Therefore, the community must agree on the adoption of appropriate agent communication language standards.

Security of multi-agent systems is another area which cannot be overlooked. It is a key concern due to the peer to peer nature of the multi-agent system. If agents join with an agent community, there must be measures in place to determine the level of trust between agents and the security of messaging. It is even more significant when there are mobile agents are involved in the system.

2.4. Applications of Multi-Agent System in Power Systems

This section focuses on the review of applications of the multi-agent system approach for control and energy management of power systems. It provides the active applications areas of the multi-agent system approach in power systems and related applications.

2.4.1. Modern Power System Operation

Novel and advanced control and managerial methodologies are necessary for the operation of modern power systems. Multi-agent system as a modelling approach could be beneficial to operate modern power systems, energy markets, overall energy networks and energy utilization. Even though the overall system is very complex, it can be modelled by the interaction of simple entities.

Multi-agent system approach for modelling has already been investigated to energy marketplace simulations, where agents represent suppliers, brokers, generators and customers [52-58]. Planning of power transmission system [59] is another area, where multi-agent system modelling has been successfully used. A simulation application uses an agent to provide simulated data to the rest of the agents in the multi-agent system for the analysis of what-if scenario in control of shipboard electrical systems [60]. This is similar to the data driven simulation and poses new problems regarding the dynamic real-time interaction of agents and the real world. More recently, agent technology has been suggested for the integration and coordination of different entities in modelling software packages [61].

Application of multi-agent system for power distribution systems is another emerging research area [16,24-29,62] in modern power systems. This includes distributed energy resource scheduling, power system restoration, active distribution networks operation and microgrid control management. Management and control of active complex distribution networks face a number of challenges such as the scalability and flexibility of solutions. Multi-agent system approaches are proposed by a number of researchers as an alternative to centralized power system management and control. Decision-making regarding network restoration, reconfiguration, dispatch of generation and management of loads can be locally managed by distributing the management and control functionalities using intelligent agents. Local decision-making would require agents capable of taking actions such as monitoring local conditions, controlling switchgear and other plant and coordinating with other regions of the network.

2.4.2. Monitoring and Diagnostic Functions

Multi-agent system approach is an excellent tool for collecting and manipulating distributed information and knowledge. Currently, power engineers use multi-agent system for the management and interpretation of data for a wide variety of monitoring and diagnostic functions such as condition monitoring and post-fault diagnosis.

Condition monitoring [63-66] of equipment and plant items offers a number of challenges such as gathering data from a variety of sensors and interpreting the data to extract meaningful information. This requires the use of multiple algorithmic and intelligent system-based approaches. Approaches combine the evidence and information from different interpretation algorithms to generate an overall diagnostic conclusion, deliver diagnostic information in the correct format to relevant engineers, and automatically alter power system and plant settings based on the condition of the plant. Multi-agent system allows the combination of data from all sources in a flexible manner by delegating the tasks of monitoring each source by an intelligent agent.

Multi-agent system is one of the best suitable technologies for post-fault diagnosis [67] of power system faults. When operational engineers investigate the causes and impact of power system faults, they employ a number of data sources. These include data from SCADA, digital fault recorder data and travelling-wave fault locator data. In a similar fashion to the condition monitoring problem discussed previously, automation of the analysis of such data provides essential decision support to operational engineers. Research into the application of intelligent systems for the analysis of power systems data has produced a variety of tools and techniques for analysing individual data sources. Multi-agent system can be used to integrate legacy data analysis tools in order to enhance diagnostic support for engineers.

2.4.3. Power System Protection

Protection and fault management systems are important parts of the automation process in power systems. This should include the knowledge about failure modes and their causes and provide information about the presence of faults in the processes as soon as possible. This task involves timely detection of an abnormal event, diagnosing its causal origins and then taking appropriate supervisory control decisions and actions to bring the process back to a normal, safe, operating state or, at least, with minimal process operation degradation.

The multi-agent system technology has been investigated for the protection of power system by several research groups [68-72]. It is a good option to create a distributed, modular and collaborative fault management system for the industrial processes [73]. Multi-agent system coordination for system protection is presented in [74] consists of relay agents, distributed generator agents and equipment agents. The agents communicate with each other within the same agent society or within different agent societies. For an example, a distributed generator agent communicates with relay agent to provide connection status. An innovative Fault Tolerant Networked Control System based on Multi-Agent Systems (FTNCS-MAS), is proposed in [75] with a framework involving simultaneously decentralized and centralized topology. Extensive research in protection and fault management has been done in the area of power system protection and shipboard power system protection [76-78].

2.4.4. Reconfiguration and Restoration

An efficient switching operation scheme that restores power systems to an optimal network configuration is referred to as power system restoration. The problem can be formulated as an optimization problem, where the objective is to maximize the supply of power to as many loads as possible. There are many algorithms and methodologies that exist in the literature. Even though most of the restoration techniques applied in the literature are centralized, some decentralized approaches with the intelligent multi-agent system approach exist. Nagata et al. in [79,80] obtained interesting results with multi-agent system approach for power restoration problem. The authors propose a multi-agent architecture, classifying agents into upper and lower level agents. The negotiation process under specific fault scenarios is discussed. This paper proposes a decentralized multi-agent system implemented with FIPA compliant language and interfaced with power system simulation software. There are few research works on the applications of multi-agent system for power distribution networks and power system restoration [81] and reconfiguration of shipboard power systems [82].

2.5. Applications of Multi-Agent System in Smart Grid Development

The developing tools that are flexible enough to enable the integration of the control strategies, aggregation of micro source models and simulations with disturbances is a part of the research in smart grid development. Multi-agent system is one of the promising technologies to model the operation of smart grid, which has been already applied to solve some problems in the smart grid development. This section focuses mainly on the review of multi-agent system approach for the development of a smart grid. In particular, it covers modelling of distributed energy resources, marketing, operation of microgrids, computer-based simulation studies and studies on real systems in context of distributed control and energy management of smart grid.

2.5.1. Distributed Energy Resource Modeling

The development of adequate models of Distributed Energy Resources (DER) [4-6] and power electronic interfaces [11,83] is necessary for simulating the operation of a smart grid. Modeling of smart grid can be done in a way that each distributed energy resource in the system is represented as an autonomous intelligent agent that provides a common communication interface for all the other agents representing the other components in smart grid. Intelligent modeling of distributed energy resources provides distributed intelligence which can be used to develop smart grid techniques. To study the performance of a smart grid, proper dynamical and steady-state models of each components are necessary [5,11,83].

2.5.2. Energy Market

In recent years, many countries around the world have modified their electricity supply frame and constructed different types of electricity market. Smart grid encourages more customer participation. Enabling market environment among distributed energy sources and customers is one of main characteristics of smart grid.

The multi-agent system provides a platform for modelling autonomous decision making entities in a de-centralized fashion, which allows the implementation of market based operation of smart grid. Multi-agent system technology as a useful tool, offers to construct agent-based market simulators for electricity marketing. These models have hinted at the potential of multi-agent system models for the analysis of electricity markets [52-58].

2.5.3. Microgrid Operation

Smart grid is expected to evolve into small and interconnected local grids. These local grids are called microgrids, and simply consist of energy sources and loads connected to a low voltage electrical network. The deregulation of the electricity markets in many countries allows entry and exit of energy producers at any scale into the market easily. This encourages the development of low power renewable energy resources and distributed generators in a decentralized way.

Microgrids can operate in two ways: either connected to the main grid or in islanded mode. The relative simplicity of these microgrids makes them an interesting choice to run tests for new control concepts like multi-agent system. Rahman et al. [23] presents a new concept based on microgrids: Intelligent Distributed Autonomous Power Systems (IDAPS), where demand is supply-driven instead of the contrary for today's grid. They represent an elementary grid structure that is representative for most of the grid control issues. Microgrids can also integrate thermal generation with electricity production as presented in [84,85].

2.5.4. Computer-Based Simulation Studies

In most studies in the literature of smart grid development, the scale of smart grid is limited to a few interconnected microgrids or a single one. Most of these microgrids are made of all or some of the following components: photovoltaic, micro-turbines, small wind turbines, loads and battery storage. Operation of microgrids were carried out with multi-agent system by several researchers [16,23-25,83-86]. Negotiations are carried out every hour and results show that prices tend to increase when the weather is bad or not windy.

Pipattanasomporn et al. [40] and Feroze [41] simulate a simple microgrid to analyse the behaviour of the microgrid in case of a connection fault. Rahman et al. [23] describes a simulation based on data from the microgrid on Virgina Tech's campus. A web service is used for interfacing a Matlab/Simulink model of loads and generators with the multi-agent system. Philips et al. [27] present their tests on a military four-tent microgrid, consisting of several controllable generators and loads. Tests are run with Matlab/Simulink and the implementation of the multi-agent system. Rumley et al. [39] compare their results with results from Nagata et. al [79] and find satisfying results. In [87], a field test is run with five different installations gathered into a virtual power plant. A large network containing 154 buses and 9 generators, which is much more complex than the other structures, is used in [44] and extensive tests are run on the proposed algorithms.

2.5.5. Studies on Real Test Systems

Computer-based tests are essential, but real studies are required to validate the proposed algorithms. In the literature, there are few studies that were carried out on the applications of multi-agent system for smart grid development [17,42]. Dimeas and Hatziargyriou [21,22,62], describe a multi-agent system installed on the Greek island of Kythnos within the Microgrids and MOREMicrogrids European projects. The choice of this location is because of a new rule that regulates operational and technical aspects of energy production, by providing equality between private and public generation means, competing on the same energy market. This microgrid there is made of photovoltaic, battery banks and a diesel generator. It uses a single phase AC for power transport, PLC and RS485 for data transport and powers 12 houses and is controlled by a multi-agent system. Current, voltage and frequency are monitored by an Intelligent Load Controller (ILC) developed during the project. Due to the isolation of the microgrid, intelligent load shedding allows to distribute the load shedding to several houses instead of just one.

2.6. Summary

This chapter focuses on the applications of multi-agent system technology in decentralized control and management of power industry today and future. It shows that multi-agent system is a very promising technology for the modelling and operation of modern power systems. Multi-agent system technology is emerging as a new paradigm for controlling and managing energy in modern grids such as microgrids and smart grids. Moreover, no real alternative appears to offer equivalent results with a similar infrastructure especially in terms of data volume and computational power. However, much work still has to be done in this field, although the performance of multi-agent systems is interesting and allows new functionalities to be added to the system operation. Trading and meta-heuristic algorithms are the most popular for now, but innovative solutions based on the concepts of distributed optimization and emergence might appear in the future. An appropriate degree of decentralization will also have to be found as a full decentralization or a full centralization would probably not be optimal. Large scale tests should also be run, but will require high computational power in order to simulate an entire grid and validate the multi-agent system. Other problems linked to multi-agent system technologies, like data security, ontologies and platforms are also raised by several researchers. Once these problems are solved, precise standards will have to be developed in order to allow a large scale deployment of multi-agent systems in the industry. It is concluded that intelligent multi-agent system technology has significant potential benefits for facilitating many decentralized control strategies, system modelling and better performances in modern power management.

CHAPTER 3

PROPOSED MULTI-AGENT SYSTEM FOR DISTRIBUTED POWER SYSTEMS

3.1. Overview

This chapter proposes the multi-agent system approach for the decentralized control and management of distributed power systems. Detailed information about the proposed multi-agent system, the proposed control architecture and their development and implementation are provided. Further, this chapter formulates generation scheduling problem and demand side management problem of microgrid energy management mathematically. The proposed multi-agent system was used for several simulation studies on the operation of microgrids in context of distributed smart grid management. The details about the simulation studies are provided in the next chapter.

The remaining chapter is organized as follows. Section 3.2 proposes a multi-agent system for distributed power systems. Section 3.3 provides the implementation of the multi-agent system. Section 3.4 provides the interfacing details of power system simulators with the multi-agent system. Section 3.5 provides the background information of demand side management problem of distributed power systems and formulates a day-ahead load shifting technique mathematically. Section 3.6 provides the background information of generation scheduling problem of distributed power systems and formulates a day-ahead generation scheduling of microgrids and integrated microgrids operating under different configurations and policies. Section 3.7 provides the development of decision making modules of the key agents. Section 3.8 summaries the chapter.

3.2. Proposed Multi-Agent System

In this dissertation, distributed multi-agent system architecture is proposed for the control and management of distributed power systems which consist of many microgrids. By representing each important element in the distributed power systems as an autonomous intelligent agent or a group of intelligent agents, multi agent modeling of distributed power systems is designed. A schematic diagram of the proposed system is shown in Figure 3.1.

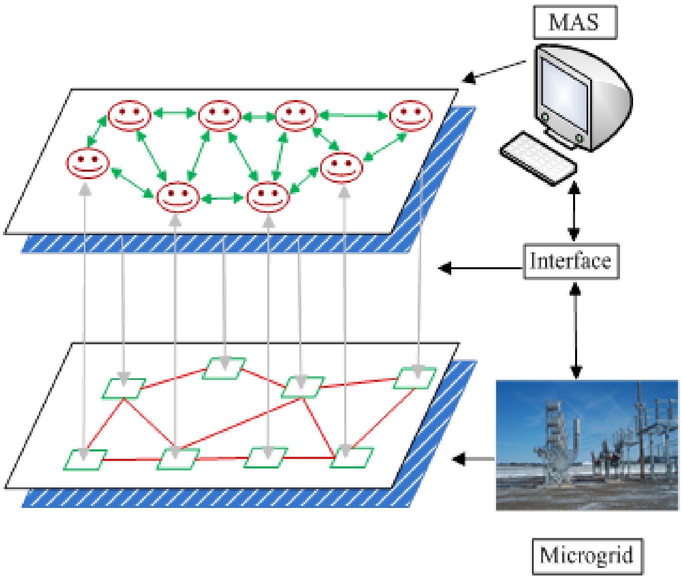


Figure 3.1. Schematic diagram of MAS - Microgrid

3.2.1. Proposed Control Architecture

It is important to integrate micro sources into low voltage grids, and optimize their operation [16,20] by considering their relationship with the other sources in microgrids and medium voltage networks. A distributed control strategy that comprises three critical control levels is proposed for the operation of distributed power systems with microgrids [20]. Figure 3.2 shows such control architecture.

At the bottom level, there are local Micro Source Controllers (MSC) and local Load Controllers (LC). Each micro source has a local micro source controller which has the autonomy to perform local optimization of active and reactive power production of the micro source. Similarly, each controllable load has a local load controller which provides load control capabilities according to the instructions from demand side management system or microgrid controller.

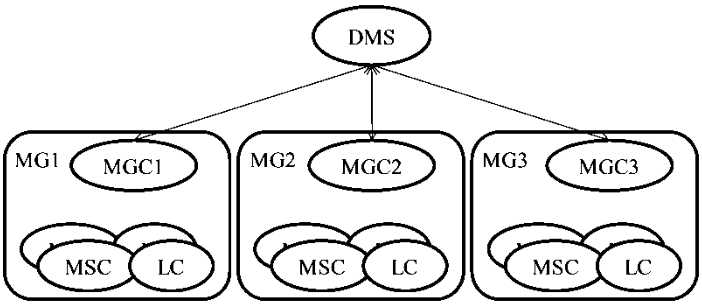


Figure 3.2. Control architecture for distributed power system with microgrids

Microgrid Controllers (MGC) exist above local controllers. Microgrid controllers are responsible for forecasting of load demand and power production capabilities and to optimize the operation of microgrids by coordinating the local controllers properly. Distribution Management Systems (DMS) are at the top most level in the distributed power system control architecture. Distribution management systems work together with the microgrid controllers and ensures that the overall distributed power system operates economically and securely. Distribution management systems consist of functional elements such as Distribution Network Operators (DNO) and Market Operators (MO). Distribution network operators are similar to Independent System Operator (ISO) [1] for deregulated power systems and are responsible for technical operation of low and medium voltage networks, where microgrids exist. Market operators are similar to Power Exchange (PX) [1] for deregulated power systems and are responsible for electricity market operation in the networks.

The proposed control architecture is implemented on the multi-agent system such that power production outputs of local distributed generators are maximized, and power exchanges among the microgrids as well as power exchange between the main distribution grid and the integrated microgrid are optimized.

3.2.2. Proposed Multi-Agent System Architecture

Each microgrid is an autonomous entity in distributed power systems, which is modeled as an intelligent agent, Microgrid Agent (MGA). Each generating unit and load have the ability and intelligence to communicate with the microgrid agent, and work together to solve control and management problems in the microgrid. It also plays a part in the control and management of distributed power systems.

In this research, a layered multi-agent system architecture [10,46] that is shown in Figure 3.3, is proposed for the microgrid agent.

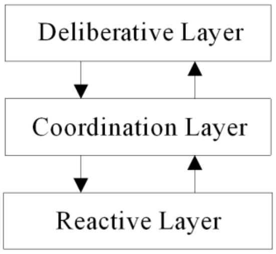


Figure 3.3. Layered structure for a microgrid agent

The bottom layer is the reactive layer which performs pre-programmed actions that need to respond immediately for very short-term planning. This layer is distributed at every local substation, and interfaces with the middle layer. The reactive layer consists of a number of reactive agents that can handle the microgrid from a local point of view to achieve fast and adaptive control.

The middle layer is the coordination layer which identifies triggering events from the reactive layer based on heuristics. A triggering event is allowed to the deliberative layer which is the top level layer only if it exceeds a preset threshold. This layer also analyzes the commands, and decomposes them into actual control signal and sends them to the agents in the bottom layer.

The deliberative layer prepares higher-level commands such as generation scheduling, contingency assessment and self-healing by considering current information from the coordination layer. A number of cognitive agents are placed in the deliberative layer that can analyze and monitor the entire system from a wide area point of view.

Each agent is endowed with certain communication capabilities. The communication among agents is at knowledge level that is quite similar to human communication. This kind of agent communication guarantees the openness and flexibility of multi-agent system. All communication among agents can be implemented through a dedicated intranet with potential access through the internet. Agents belonging to the different layers can communicative with each other and the agents on the same layer can exchange their information.

The coordination layer compares system models continuously between the deliberative layer and the reactive layer because agents in the deliberative layer do not always respond to the current situation of the microgrid. Besides, it updates the current system model, and checks whether commands from the deliberative layer are matched with the status of the system. When a command does not align with real-world model, the coordination layer will ask the deliberative layer to modify the command. Sometime, events from the reactive layer contain too much information for the deliberative layer to process, or commands from the deliberative layer might be too condensed for the agents in the reactive layer to implement. In such a situation, the deliberative layer must send many control commands to the reactive layer at the same time.

The agents in the reactive layer perform very short-term planning while the agents in the deliberative layer can plan for both short-term and long-term. The agents in the deliberative layer can inhibit control actions and decisions initiated by the reactive layer for wide area control purposes. For instance, a generation agent may decide, based on its local view to trip the generator. However, if reconfiguration agents in the deliberative layer based on the global view decide to block tripping action, then the action of the generation agent will be inhibited. The deliberative layer does not always respond to the current state of the power system. Thus decision made by the deliberative layer might be inconsistent with current power system conditions. Therefore, the coordination layer continuously updates and stores the current state of the power system and verifies the plan from the deliberative layer with the current state of the power system. This coordination layer also examines the importance of events and signals received from the reactive layer.

3.2.3. Agents in Multi-Agent System

Each agent has a set of rules and tools associated with its actions and goals. Even though each agent is different in behaviours, it can be placed into a common frame. In this research, a generic architecture for the intelligent agent is proposed, which is shown in Figure 3.4.

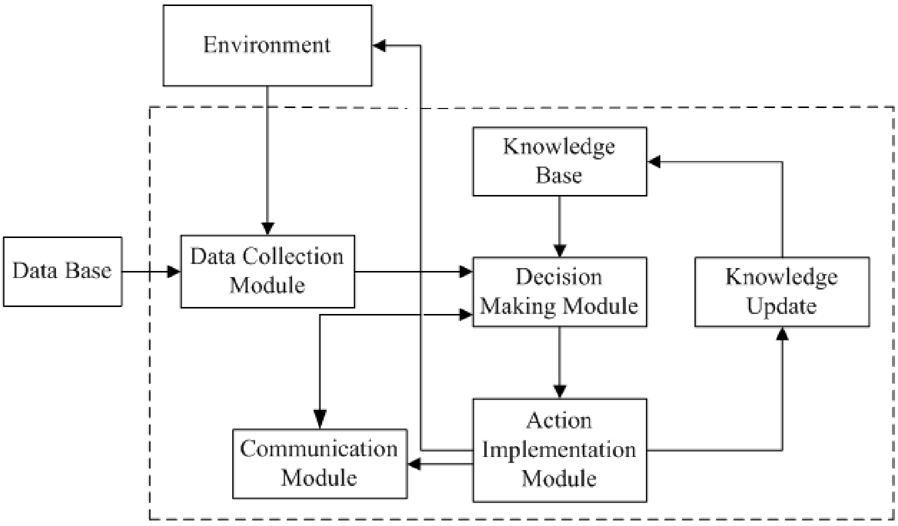


Figure 3.4. Generic architecture of an intelligent agent

The knowledge base of each agent is implemented mainly using rule-base systems, and agent communication is implemented according to IEEE FIPA [48] standards. The decision making modules of intelligent agents are implemented using computational intelligence techniques and mathematical tools. JADE [46], a FIPA compliant multi-agent system platform is selected to develop the multi-agent system.

The proposed multi-agent system for control and management of distributed power systems with many microgrids consists of several types of agents namely, Distributed Generator Agent (DG Agent), Load Agent (Load Agent), Renewable Energy Source Agent (RES Agent), Storage system Agent (Storage Agent), MicroGrid Manager Agent (MGM Agent), Schedule Coordinator Agent (SC Agent) and administrative agents. In addition, the software platform has a distributed database which keeps track of data and information of all the available agents in the platform, and their tracks and capabilities. A brief description of the main agents that are incorporated in the multi-agent system is given below.

- MGM Agent: This is main agent responsible for controlling and managing the microgrid. Monitoring, scheduling and managing the distributed energy resources and performing demand side management are some of the main functions of this agent. MGM Agent activates SC Agent in response to balance supply and demand for a period.
- SC Agent: SC Agent is activated by MGM Agent when generation scheduling is necessary for a period. This agent negotiates with DG Agents and Load Agents to decide the economic schedule for that period.
- DSM Agent: This agent is responsible for demand side management of the system. In this research, this agent runs a day-head load shifting technique optimized by Evolutionary Algorithm (EA) and does load shedding or load

curtailment dynamically whenever it is necessary and possible.

- DG Agent: This agent is responsible for monitoring, controlling and negotiating its power level and status. This agent has fixed data such as unit name, minimum and maximum power levels, and fuel cost coefficients, and variable data such as power setting and status.
- RES Agent: Renewable energy sources are mathematically modeled in this agent who is responsible for monitoring, controlling and negotiating its power level. This agent is interfaced with the main database to get meteorological data necessary for calculating forecasted power output of the renewable energy sources.
- Load Agent: This agent is capable of monitoring, controlling and negotiating power level of load and its status. It has flexibility to accept commands from DSM Agent and MGM Agent.
- Storage Agent: This agent manages energy storage elements such as fuel stack, electrolyzer and battery banks in the system and provides the best schedule of the storage elements with optimum energy density and power density. This agent monitors State Of Charge (SOC) of storage system and responds based on the current state of charge and/or commands from MGM Agent.
- PWS/RTDS Agent: It represents power system network in Power World simulator/Real-Time Digital Simulator and integrates into the multi-agent system.
- Model Update Agent: It updates the current real-world model of the system, and checks whether the plans or commands from the deliberative layer are consistent with the current status of the system. For an example, distributed energy resources can connect or disconnect from the microgrid at any time. This agent pays attention to the information provided by the distributed energy resources.

- Command Interpretation Agent: This agent decomposes the commands from the deliberative layer into control signals that will be transmitted to the reactive layer.
- PX/MO Agent: PX Agent acts as a middle mediator among various market participants and ISO Agent. Market participants will submit their bids to the pool. PX Agent performs scheduling through SC Agent. SC Agent will determine a schedule using the market clearing engine. For any particular day schedule, PX Agent will also scan for any violation bids. If any violated bids are received, PX Agent disseminates the information to the relevant market players.
- ISO/DNO Agent: ISO Agent in this framework performs the roles of a regulatory body. ISO Agent seeks to ensure the authenticity of the bids and the stability of the network. Bids are checked for violations and acted upon accordingly. ISO Agent would conduct these checks with the help of a rule-based engine. In addition, network simulations are carried out for the schedules to ensure stability of the network with a power system simulator.

3.2.4. Security Manager Agent

This agent is an overall central information security hub which provides all encryption, decryption, encryption keys generation, issue of digital certificates and other security related services to the multi-agent system. All agents have to register with this agent to make use of the security services in the network. As all message transmission is done through Secured Socket Layer (SSL) protocols, agents which do not register with this agent will have no access to the secured socket layer service. Thus they will not be able to communicate with any other agents in the network.

Authorized agent will have a valid ID in the agent world, and this ID is used to register with the security manager agent. In this development, security architecture for intelligent agents is employed in the network as shown in Figure 3.5.

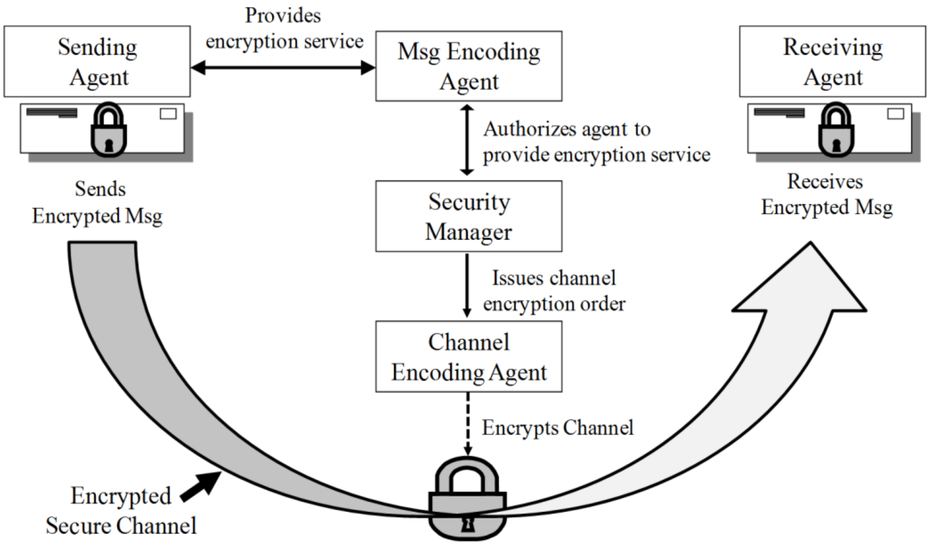


Figure 3.5. Security architecture of an agent world

Security manager agent has exclusive access to message encoding agent and channel encoding agent, which are mainly responsible for providing encryption of messages and secure channel to all agents. All agents that wish to send messages across the network will have to engage their service in encrypting the message and choose the channel which they are going to send it through. The agents need to contact the security manager agent, upon the authentication. Message encoding agent will provide encryption service for the sending agent after receiving encryption order from the security manager agent, and channel encoding agent will encrypt the message channel between the sending and receiving agent after receiving encryption order from security manager agent. When a message is successful encrypted, sending agent will send the encrypted message through the encrypted channel.

This architecture provides double redundancy in communication security. For any hacker, it is needed to break encryption of the channel and then the message. This is difficult to achieve for the following reasons:

- The encryption process is done by two separate entities (i.e. Message encoding agent and channel encoding agent). Unlike systems with only one encrypting entity where all encryption are done centrally, it takes twice the effort to search or guess a key.

- The channel encryption provides dual level of security. Every time a message is sent between two agents, a new secured channel is established. The encryption key used to establish the secured channel is always different. Since the channel encryption is always different, the key value for decryption is also always different. This makes it even harder for unauthorized interception of messages to succeed.

3.3. Implementation of Multi-Agent System

The proposed multi-agent system was implemented in JADE platform, which is interfaced with two power system simulators: Power World simulator and Real Time Digital Simulator (RTDS). The multi-agent system uses the power system simulators to confirm that there is no technical violation during the simulation of the distributed power system. The multi-agent system was implemented according to IEEE FIPA [48] standards. JADE is also a FIPA compliant multi-agent system platform, which supports a certain style of agent implementation.

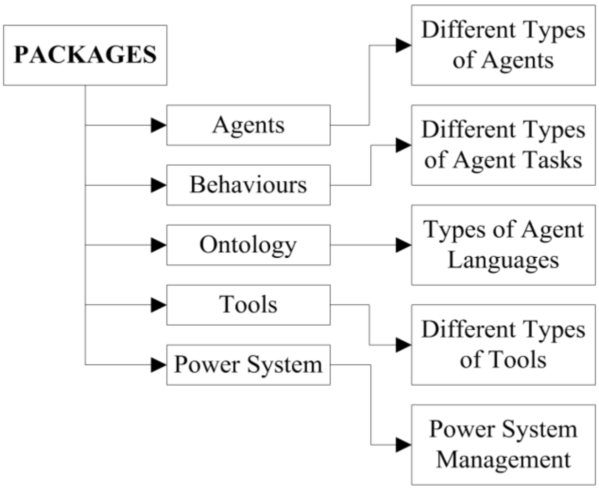


Figure 3.6. Structure of software packages

A layered architecture was employed for designing of intelligent agents in JADE that allows three basic layers namely message handling layer, behavioural layer and functional layer. The functional layer embodies the core functional attributes of the agent, the behavioural layer provides control of an agent when specific tasks are carried out, and the message handling layer is responsible for the sending and receiving of messages, and implementing the relevant agent communication language and ontology. Generic software packages have been designed and developed within the multi-agent system platform. Figure 3.6 shows the developed software packages.

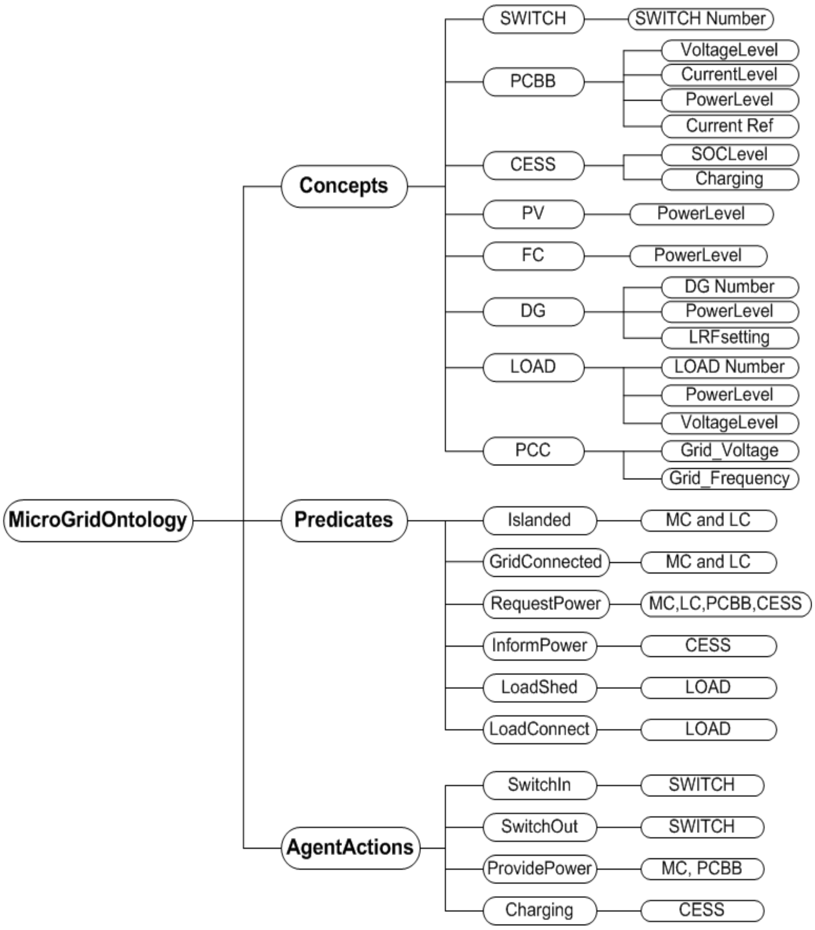


Figure 3.7. MicroGridOntology

The main software packages in the multi-agent platform are agents, behaviours, ontology, tools and power system. The agent package consists of different types of agents, and the behaviour package contains tasks assigned to the agents. The ontology package specifies a set of vocabulary for agent communication, and the tools package has a collection of tools which are used by the agents for the operation. Finally, the power system package comprises of data structures used to represent the state of the distributed power systems. Contents of these packages will be described in the other chapters of this thesis. Here, the ontology package is described briefly.

Defining an appropriate ontology that specifies the message content of agent language is an important part of multi-agent system design. Ontology provides a way to share common understanding of information among agents. Agents communicate by exchanging messages and ontology is used to structure the messages. Typically, content of the message complies with content language and ontology. In this research, MicroGridOntology that is shown in Figure 3.7 has been developed for the operation of microgrids.

3.4. Interface with Power System Simulators

Distributed power systems were modeled in power system simulators which were interfaced with the multi-agent system. The power system simulators confirm the operation of the distributed power systems without any technical violation. In this research, Power World simulator [88] was used for day-ahead simulation studies, and Real-Time Digital Simulator (RTDS) [89] was used for real-time simulation studies.

3.4.1. Power World Simulator

Power World simulator is commercial power system simulation software which has the capability to simulate detailed and serious engineering analysis. It is very user-friendly and highly interactive software. Its graphical user interface can be used to explain the power system operation easily even to non-technical audiences. In this research, this simulator is used for day-ahead simulation studies on the distributed power systems.

One add-on in Power World simulator called "SimAuto" can be used to interface the simulator with any external software. It works on the principle of COM object. Unfortunately, Java does not support COM object directly. In this research, Java and Power World simulator were interfaced with each other via interfacing software EZ Jcom [90]. EZ Jcom is a commercial tool to extract interface information for COM objects and generate Java classes for accessing the objects. These Java classes talk with COM objects via an intermediate DLL known as a Java Native Interface (JNI) [90] DLL. A schematic diagram of the interface is illustrated in Figure 3.8.

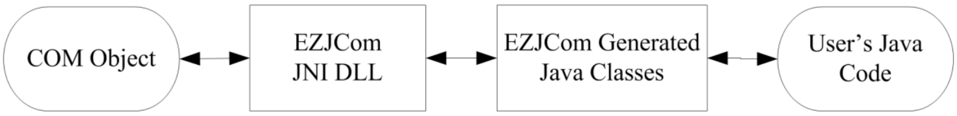


Figure 3.8. Interface between Power World Simulator and MAS (Java)

3.4.2. Real-Time Digital Simulator

The Real-Time Digital Simulator (RTDS) [89] is a special purpose power system simulator to study electromagnetic transient phenomena in real-time. The RTDS comprises both specially designed hardware and software. RTDS hardware is based on Digital Signal Processor (DSP) and Reduced Instruction Set Computer (RISC) and utilizes advanced parallel processing techniques in order to achieve the computation speeds required to maintain continuous real-time operation. RTDS software includes accurate power system component models required to represent many of the complex elements which make up physical power systems. The overall network solution technique employed in the RTDS is based on nodal analysis. Dommel's solution algorithm [89] is used in virtually all digital simulation programs designed for the study of electromagnetic transients. RTDS software also includes a powerful and user friendly Graphical User Interface (GUI), referred to as RSCAD, through which the user is able to construct, run and analyze simulation cases.

The RTDS is currently applied to many areas of development, testing and studying such as protective relaying schemes, integrated protection and control systems, control system for HVDC, SVC, synchronous machines, and FACTS devices, general AC and DC system operations and behaviour, interaction of AC and DC systems, interaction of various electrical installations, distributed power generations, demonstration and training.

3.4.2.1. RTDS Hardware

Unlike analogue simulators which outputs continuous signals with respect to time, digital simulators compute the state of the power system model only at discrete instants in time. The time between these discrete instants is referred to as the simulation time step. Many hundreds of thousands of calculations must be performed during each time step in order to compute the state of the system at that instant. The temporary transient class of studies for which the RTDS is most often used requires a simulation time step to be in the order of 50μs to 60μs. By definition, in order to operate in real-time, a 50μs time step would require all computations for the system solution be completed in less than 50μs of actual time. In order to realize and maintain the required computation rates for real-time operation, many high speed processors operating in parallel are utilized by the RTDS.

3.4.2.2. RTDS Software

Software for the RTDS is organized into a hierarchy containing three separate levels: high level graphical user interface, mid level compiler and communications and the low level WIF multi-tasking operating system. The RTDS user is exposed only to the high level software with the lower levels being automatically accessed through higher level software. The high level RTDS software comprises the RSCAD family of tools. RSCAD is a software developed to provide a fully graphical interface to the RTDS.

3.4.2.3. Component Model Libraries

Icons in the RSCAD that represent all available RTDS models are stored in one or more libraries. Several libraries have been included in the RSCAD Software installation. In general the libraries supplied by RTDS Technologies are split into the several categories such as power system components, control system components, IEEE generator control components, complex control components and load flow components/single line diagrams.

3.4.2.4. Interface with RTDS

In this research, the RTDS was used for real-time simulation studies on distributed power systems. Java and RTDS were interfaced via TCP/IP. A distributed power system was developed in RSCAD/RTDS, and “ListenOnPort” and “ListenOnPortHandshake” commands were used to instruct RTDS-RUNTIME to listen script commands generated from an external program. ListenOnPort script command allows a way for an external program to control RSCAD by sending script commands over a TCP/IP connection. This interface is illustrated in Figure 3.9.

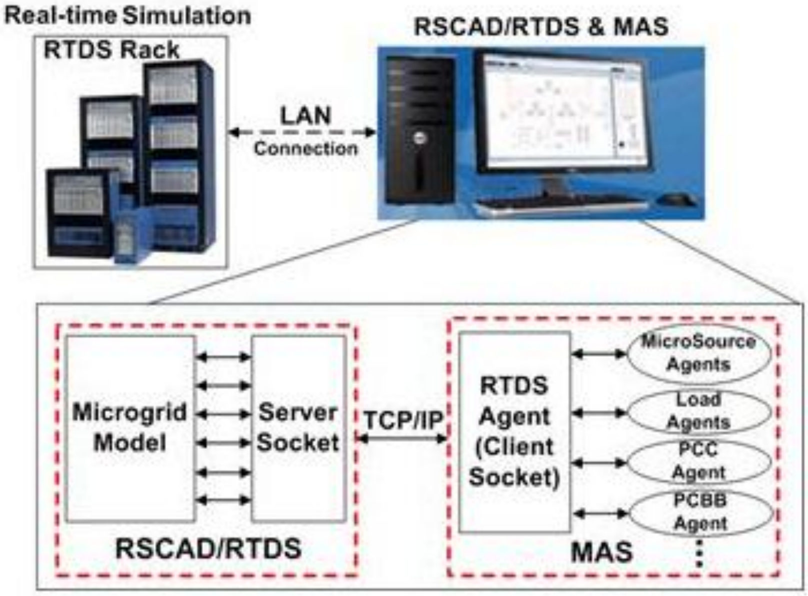


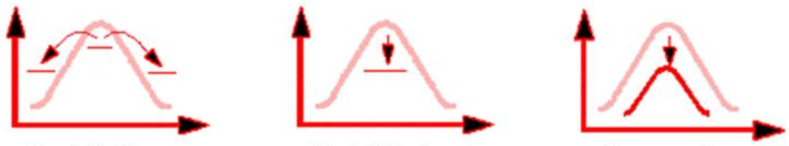
Figure 3.9. Interface between RTDS and MAS (Java)

3.5. Proposed Demand Side Management

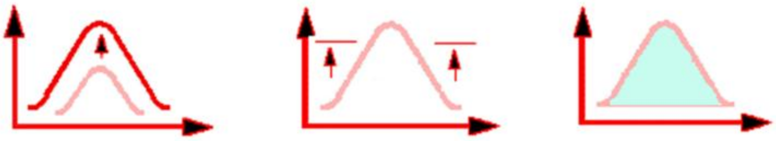
Demand side management [91,92] is one of the important functions in power system management, which allows customers to make informed decisions regarding their energy consumption and helps the energy providers reduce the peak load demand and reshape the load profile. Demand side management focuses on utilizing power saving technologies, electricity tariffs, monetary incentives and government policies to mitigate the peak load demand instead of enlarging the generation capacity or reinforcing the transmission and distribution network.

3.5.1. Demand Side Management Techniques

The load shapes which indicate the daily or seasonal electricity demands of industrial, commercial or residential consumers between peak and off peak times can be altered by means of six broad techniques [91-93]: peak clipping, valley filling, load shifting, strategic conservation, strategic load growth and flexible load shaping. Generally, these are the possible demand side management techniques that can be employed in future power systems. These six demand side management techniques are illustrated in Figure 3.10.



Load Shifting Peak Clipping Conservation



Load Building Valley Filling Flexible Load

Figure 3.10. Demand side management techniques

Peak clipping and valley filling techniques focus on reducing the difference between the peak and valley load levels mitigate the burden of peak demand and increase the security of the smart grid. Peak clipping [91] is a direct load control technique to make reduction of the peak load demands, whereas valley filling constructs the off-peak demand by applying direct load control.

Load shifting [91] is widely applied and the most effective load management technique in current distribution networks. Load shifting takes advantage of time independence of loads and shifts loads from peak to off-peak time. Strategic conservation [91] aims to achieve load shape optimization through application of demand reduction methods directly at customer premises. The distribution management system has to consider this for long-term implications of demand reduction on network planning and operation.

Strategic load growth [91-93] optimizes the daily responses in case of large demand introduction beyond the valley filling technique. It is based on increasing the market share of loads supported by energy conversion by storage systems or distributed energy resources. This issue occurs in planning and operations in order to balance the increasing demand by constructing necessary infrastructure that accompanies load growth. The future power systems have to provide the necessary infrastructure for strategic load growth.

Flexible load shape [91-93] is mainly related to reliability of the distributed power systems. Distributed management identifies the customers with flexible loads which are willing to be controlled during critical periods in exchange for various incentives. Studies have to be conducted to identify the anticipated load shape which includes demand side management activities forecasted over the planning horizon.

3.5.2. Demand Side Management in Smart Grid

The transformation of today’s grid towards the smart grid opens new perspectives on demand side management. First, a significant part of the generation in smart grid is expected to come from renewable energy resources such as wind turbines and photovoltaic systems [91]. The intermittent nature of these renewable energy sources makes power dispatch in a smart grid challenging. Such a scenario necessitates the use of load control methodologies. The operation of smart grid requires a two-way communication between the central controller and various system elements. Therefore, the demand side management strategies can make use of the communication infrastructure. The last but not the least, criteria for deciding the optimal load consumption can vary widely. It could be maximizing the use of renewable energy resources, maximizing the economic benefits, minimizing the amount of power imported from the main grid and/or reducing the peak load demand.

3.5.3. Proposed Load Shifting Technique

A demand side management technique [91] that schedules connection of each shiftable device in a way that brings the total load consumption as close as possible to the objective load consumption is proposed in this dissertation. The problem is mathematically formulated as follows.

Minimize,

$$\sum_{t=1}^{N} (Pload(t) - Objective(t))^2 \tag{3.1}$$

where, $Objective(t)$ is the value of the objective curve at time t, and $Pload(t)$ is the actual consumption at time t.

$Pload(t)$ is given as follows.

$$Pload(t) = Forecast(t) + Connected(t) - Disconnected(t) \tag{3.2}$$

where, $Forecast(t)$ is the forecasted consumption at time t, and $Connected(t)$ and $Disconnected(t)$ are the amount of loads connected and disconnected at time t during load shifting respectively.

The term $Connected(t)$ has two parts: increment in the load due to shifted devices to time t, and increment in the load at time t due to the devices scheduled before time t, which precede to time t. $Connected(t)$ is given by the following equation.

$$Connected(t) = \sum_{i=1}^{t-1}\sum_{k=1}^{D} X_{kit}.P_{1k} + \sum_{l=1}^{j-1}\sum_{i=1}^{t-1}\sum_{k=1}^{D} X_{ki(t-1)}.P_{(1+l)k} \qquad (3.3)$$

where, X_{kit} is the number of devices of type k that are shifted from time step i to t, D is the number of types of devices, P_{1k} and $P_{(1+l)k}$ is the power consumed at time steps 1 and $(1 + l)$ for device type k respectively, and j is the total duration of consumption of device from type k.

The $Connected(t)$ is illustrated graphically in Figure 3.11.

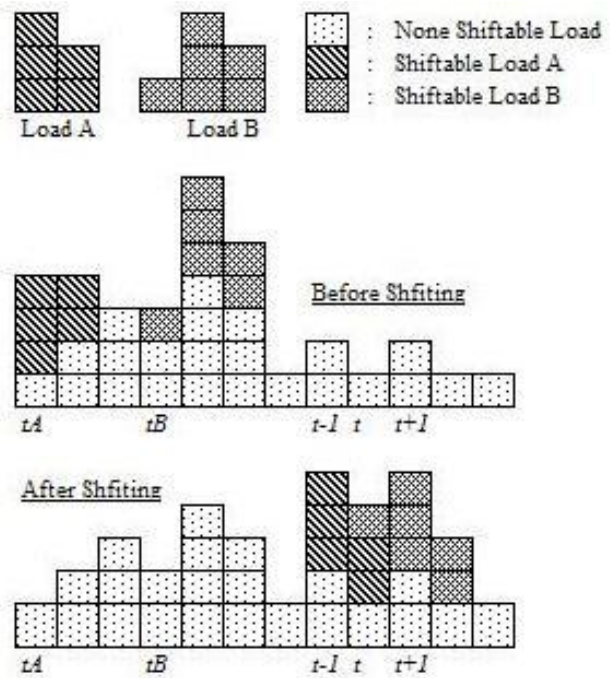


Figure 3.11. Illustration of $Connected(t)$

Similarly, the term $Disconnected(t)$ consists of two parts: decrement in the load due to delay in connection times of devices that were supposed to begin their consumption at time step t, and decrement in the load due to delay in connection times of devices that were expected to start their consumption at time steps that precede to time t. $Disconnected(t)$ is given by the following equation.

$$Disconnected(t) = \sum_{q=t+1}^{t+m} \sum_{k=1}^{D} X_{ktq} . P_{1k} + \sum_{l=1}^{j-1} \sum_{q=t+1}^{t+m} \sum_{k=1}^{D} X_{k(t-1)q} . P_{(1+l)k} \tag{3.4}$$

where, X_{ktq} is the number of devices of type k, which are delayed from time step t to q, and m is the maximum allowable delay.

The $Disconnected(t)$ is illustrated graphically in Figure 3.12.

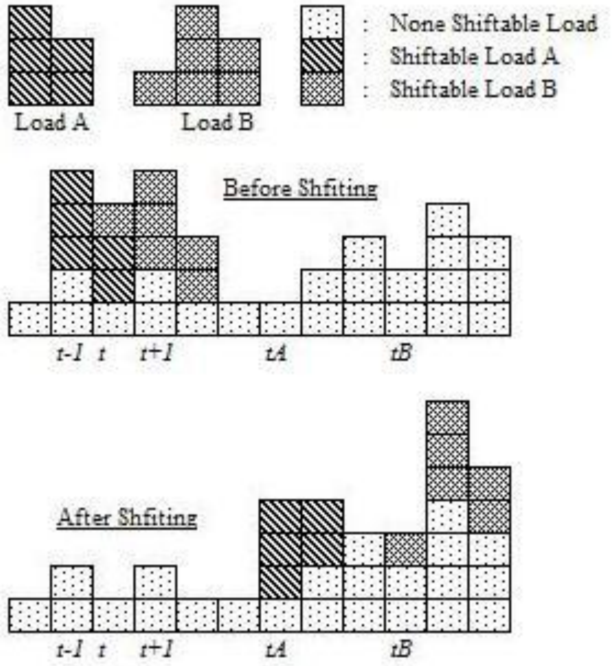


Figure 3.12. Illustration of $Disconnected(t)$

This minimization problem is subject to the following constraints.

1. The number of devices shifted cannot be a negative value.

$$X_{kit} > 0 \qquad \forall i, j, k \tag{3.5}$$

2. The number of devices shifted away from a time step cannot be more than the number of devices available for control at the time step.

$$\sum_{t=1}^{N} X_{kit} \leq Ctrlk(i) \tag{3.6}$$

where, $Ctrlk(i)$ is the number of devices of type k available for control at time step i.

3.6. Proposed Generation Scheduling

Generator scheduling [13] can be defined as the scheduling of power production from generation units over a daily to weekly time spectrum while considering various generator constraints and system constraints. The objective function includes costs associated with energy production, and start-up and shut-down decisions along with possible profits. The resulting problem is a large scale nonlinear optimization problem. Generator scheduling problem can be divided into two sub-problems [13]: Unit Commitment (UC) and Economic Dispatch (ED). The unit commitment problem decides ON/OFF statuses of generators over the scheduling period whereas the economic dispatch problem finds out the operating power levels of the committed generators based on the operating cost of the generators.

Modern distributed power systems comprise many number of distributed generators [13,94,95]. As number of generation units increases, the generation scheduling problem grows exponentially and hence the computation time would be excessive. The number of units is likely to increase further in the near future. In addition, in the modern restructured environment, small improvement in generation scheduling solutions can result significantly in payments to bidders. Therefore, the generation scheduling problem has a very important role in the energy management of distributed power systems. The following sections give mathematical formulation for generation scheduling problem of microgrid and integrated microgrid mathematically.

3.6.1. Cooperative Microgrid Environment

The schematic diagram of a microgrid is shown in Figure 3.13 which would help understand the problem formulation clearly. Day-ahead generation scheduling problem of a cooperative microgrid in both grid-connected mode and islanded mode is mathematically formulated in the following sections.

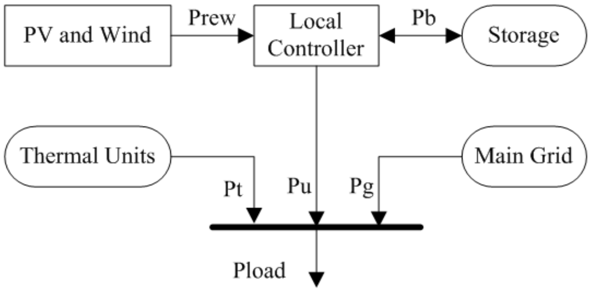


Figure 3.13. Schematic diagram of a microgrid

3.6.1.1. Grid-Connected Mode Operation

The microgrid maximizes the corresponding revenues by exchanging power with the main distribution grid. Consumers are charged for their power consumption at open market prices. Day-ahead scheduling of a grid-connected microgrid can be mathematically formulated as follows.

Maximize

$$\sum_{t=1}^{T} Profit(t) = Revenue(t) - Expenses(t) \tag{3.7}$$

where, T is the number of time steps in the scheduling period.

If the sum of power produced by microgrid sources is not enough or is expensive to cover its local loads, power $Pg(t)$ is bought from the upstream network and sold to the consumers at the same price. Each microgrid maximizes its profit which is given as follows.

$$Profit(t) = \left[MP(t) \times Pg(t) + MP(t) \times \sum_{i=1}^{N} P_i(t)\right] - \left[\sum_{i=1}^{N} bid(P_i(t)) + MP(t) \times Pg(t)\right] \tag{3.8}$$

where, $MP(t)$ is the open market price, $P_i(t)$ is the power production of ith source, N is the number of sources that offer bids for power production, $bid(P_i(t))$ is the bid from ith source at time t.

As microgrids are low power networks distributed over small areas, the power brought from the upstream networks was sold to customers in the microgrids at same price, but it can be sold at any price by the microgrid manager based on its business and operational strategies.

This maximization problem is subject to the following system constraint.

$$Pg(t) + \sum_{i=1}^{N} P_i\,(t)\ \geq P_l(t) \tag{3.9}$$

where, $P_l(t)$ is the internal load demand of the microgrid.

1. Further, the maximization problem is subject to the following technical limits.

   $$P_u(t) + P_T(t) = P_l(t) \tag{3.10}$$

   where, $P_u(t)$ is the renewable-battery power, and $P_T(t)$ is net power from the distributed generators at time t.

2. The renewable-battery power balance is given as follows.

   $$P_{Rew}(t) - P_b(t) - P_u(t) = 0 \tag{3.11}$$

   where, $P_{Rew}(t)$ is total renewable power, and $P_b(t)$ is battery power at time t.

3. The upper limit of renewable-battery system is given as follows.

   $$P_u(t) < P_u^{max} \tag{3.12}$$

   where, P_u^{max} is the maximum renewable penetration to the microgrid.

4. Total renewable power is calculated as follows.

   $$P_{Rew}(t) = P_{pv}(t) + \ P_{wind}(t) \tag{3.13}$$

   where, $P_{pv}(t)$ is total photovoltaic power, and $P_{wind}(t)$ is total wind power at time t.

5. Photovoltaic power output depends on solar radiation and surrounding temperature. This functional relationship is given as follows.

   $$P_{pv}(t) = f\big(G_a(t), T_a(t)\big) \tag{3.14}$$

   where, $G_a(t)$ is the total insolation on photovoltaic system, $T_a(t)$ is the ambient temperature at photovoltaic system at time t.

6. Wind power output depends on wind speed at the turbine. This functional relationship is given as follows.

   $$P_{wind}(t) = f\big(V_w(t)\big) \tag{3.15}$$

   where, $V_w(t)$ is the wind speed at wind plant at time t.

7. Battery bank can store or provide power up to its charging/discharging power ratings. This is represented as follows.

   $$|P_b(t)| < P_b^{max} \tag{3.16}$$

   where, P_b^{max} is the maximum battery power.

8. State of charge of battery bank is calculated as follows.

   $$C(t) = C(t-1) + \left[\frac{\Delta t \, \eta_b(t)}{V_b(t)} \left(P_{Rew}(t) - P_u(t)\right)\right] \tag{3.17}$$

   where, $C(t)$ and $C(t-1)$ represent the battery charges at time t and $(t-1)$ respectively, $\eta_b(t)$ is the battery efficiency at time t, and $V_b(t)$ is the voltage at battery terminals at time t.

9. The upper and lower limits for state of charge of battery bank are given below.

   $$C_{min} < C(t) < C_n \tag{3.18}$$

   where, C_n and C_{min} are the nominal and the minimum limits respectively.

10. Battery bank can have an expected state of charge at the end of an operational period, and has an initial state of charge for the period. These set of constraints are represented as follows.

$$C(t)|_{t=0} = C_s \tag{3.19}$$

$$C(t)|_{t=N_t} = C_f \tag{3.20}$$

where, C_s is the initial state of charge, and C_f is the final state of charge.

In addition, the maximization problem is subject to following constraints [94,95] of distributed generators.

11. Unit generation limits

$$P_i^{min} \leq P_i(t) \leq P_i^{max} \tag{3.21}$$

where, P_i^{min} and P_i^{max} are the minimum and the maximum generation limit of unit i respectively.

12. System spinning reserve requirements

$$\sum_{i=1}^{N} I_i(t) P_i^{max} \geq P_T(t) + P_R(t) \tag{3.22}$$

where, $P_R(t)$ is the spinning reserve at time t and $I_i(t)$ is the ON/OFF status of unit. $I_i(t)$ is 1 for ON and 0 for OFF.

13. Thermal unit minimum starting up/down times

$$\begin{aligned} &\left(T_{i,on}(t-1) - T_{i,Up}\right)\left(I_i(t-1) - I_i(t)\right) \geq 0 \\ &\left(T_{i,off}(t-1) - T_{i,Down}\right)\left(I_i(t-1) - I_i(t)\right) \geq 0 \end{aligned} \tag{3.23}$$

where, $T_{i,on}(t)$ is the continuously on time of unit i up to time t, $T_{i,up}$ is the minimum up time of unit i. $T_{i,off}(t)$ is the continuously off time of unit i up to time t, $T_{i,Down}$ is the minimum down time of unit i and $T_{i,cold}$ is the cold start time of unit i .

14. Ramp rate limits

$$\begin{aligned} &P_i(t) - P_i(t-1) \leq UR_i \\ &P_i(t-1) - P_i(t) \leq DR_i \end{aligned} \tag{3.24}$$

where, UR_i and DR_i are the ramp up and ramp down rates of unit i respectively.

3.6.1.2. Islanded Mode Operation

In this section, the day-ahead scheduling of an islanded microgrid is mathematically formulated. The microgrid minimizes the total operational cost while satisfying the internal loads to the maximum possible extent. The operational costs of renewable energy sources and storage system are almost negligible. Therefore, the objective of the operation is to minimize the Total Operational Cost (TOC) of the thermal units in the microgrid, which can be mathematically written as follows.

Minimize,

$$TOC = \sum_{i=1}^{N} \sum_{t=1}^{T} \left[I_i(t) F_i\big(P_i(t)\big) + ST_i(t)(1 - I_i(t-1)) I_i(t) \right] \tag{3.25}$$

where, $P_i(t)$ is the power generation of unit i at time t, $I_i(t)$ is the ON/OFF status of unit i at time t (ON = 1 and OFF = 0), and $F_i(P_i(t))$ is the fuel cost of unit i at time t. $F_i(P_i(t))$ is given as follows.

$$F_i(P_i(t)) = a_i + b_i P_i(t) + c_i P_i(t)^2 \tag{3.26}$$

where, a_i, b_i and c_i represent the fuel cost coefficients of unit i.

$ST_i(t)$ is the start-up cost of unit i at time t, which is given as follows.

$$ST_i(t) = \begin{cases} ST_{hi} & if\ T_{i,off}(t) \leq T_{i,Down} + T_{i,cold} \\ ST_{ci} & if\ T_{i,off}(t) > T_{i,Down} + T_{i,cold} \end{cases} \tag{3.27}$$

where, ST_{hi} is the hot start-up cost, ST_{ci} is the cold start-up cost, $T_{i,off}(t)$ is the continuous off time of unit i at time t, $T_{i,Down}$ is the minimum down time of unit i and $T_{i,cold}$ is the cold start-up time of unit i.

This minimization problem is subject to several constraints.

The internal load demand of the microgrid should be equal to the power from the sources in the microgrid. The constraint is written as follows.

$$P_u(t) + \sum_{i=1}^{N} P_i\,(t) = P_l(t) \tag{3.28}$$

In addition, the minimization problem is subject to other constraints as given in the problem formulation of microgrid in grid-connected mode from equation 4.10.

3.6.2. Competitive Microgrid Environment

In this section, the generation scheduling problem of a competitive microgrid is proposed based on the PoolCo market model [1,96]. Here, the PoolCo market model is first briefly described and the market operation is proposed for the competitive microgrid. In this case, there is no difference in market operation for grid-connected mode or islanded mode. In the grid-connected mode, the main grid is considered as a market player with a bidding quantity which is equal to power transmission capacity of the interconnection link between the microgrid and the main grid and a bidding price which is equal to the main market price.

3.6.2.1. PoolCo Market

The main objective of the electricity market is to decrease the cost of electricity through competition. Several electricity market [1,2] models exist in the industry. These market models would differ in terms of marketplace rules and governance structure. Generally, they can be classified into three types [1,2] such as PoolCo model, bilateral contract model and hybrid model.

PoolCo market model is a marketplace where power generating companies and consumer companies submit their bids. The market operator uses a market clearing tool to find the market clearing price and accepted bids for each hour. Bilateral contract model is a negotiable agreement between sellers and buyers about the power supply and consumption. It is very flexible because negotiating parties can specify their own contract terms and conditions. Finally, the third market model is the hybrid model which is a combination of PoolCo and bilateral contract models. In this model, customers can either negotiate with suppliers directly for power supply agreements or accept power from PoolCo at market clearing price.

A typical PoolCo market model is chosen for generation scheduling of a competitive microgrid. PoolCo model consists of competitive independent power producers, vertically integrated distribution companies, load aggregators and retail marketers. It does not own any part of generation or transmission utilities. The main task of PoolCo is to centrally dispatch and schedule generating units within its jurisdiction. The operating mechanism of PoolCo model is described in Figure 3.14.

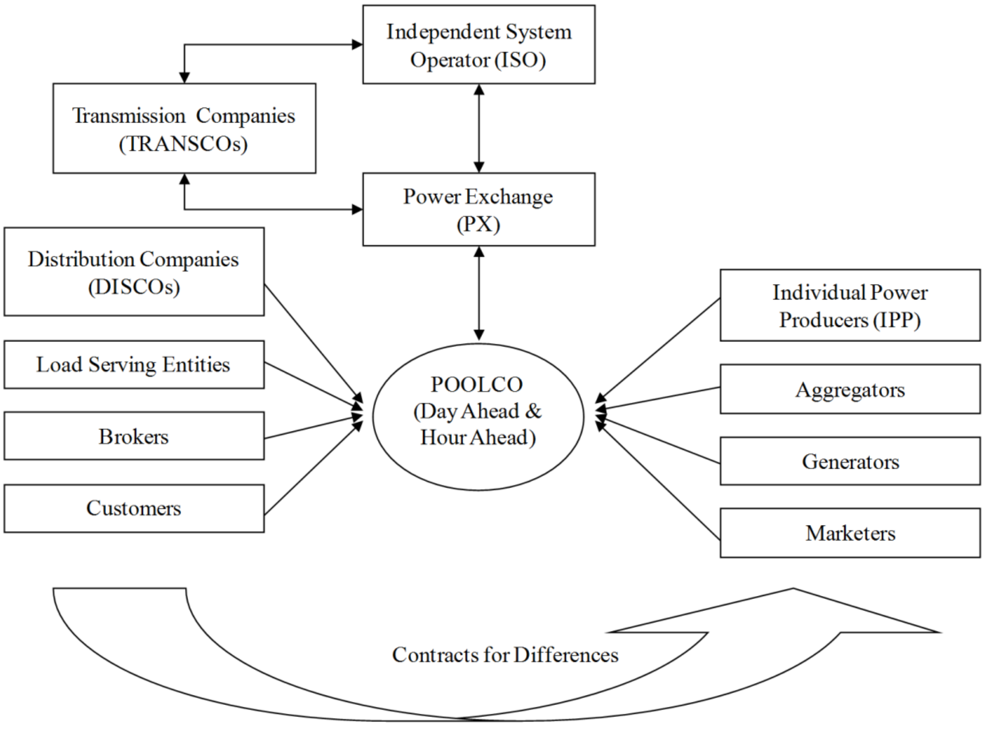


Figure 3.14. PoolCo market model

In a PoolCo market, buyers (i.e. loads) submit their bids to buy power from PoolCo and sellers (i.e. generators) submit their bids to sell power to PoolCo. All generators have the right to sell power to PoolCo, but they can not specify their customers. During PoolCo operation, each player will submit their bids to PoolCo which is provided by power exchange. Power exchange sums up these bids and matches the demands and the supplies. Power exchange then performs economic dispatch to produce a single spot price for electricity for the whole system. This price is called Market Clearing Price (MCP) which is the highest price in the selected bids of the particular hour. Winning generators pay for their successful bids at market clearing price, and successful loads purchase electricity at market clearing price. A PoolCo market clearing algorithm is graphically described in Figure 3.15.

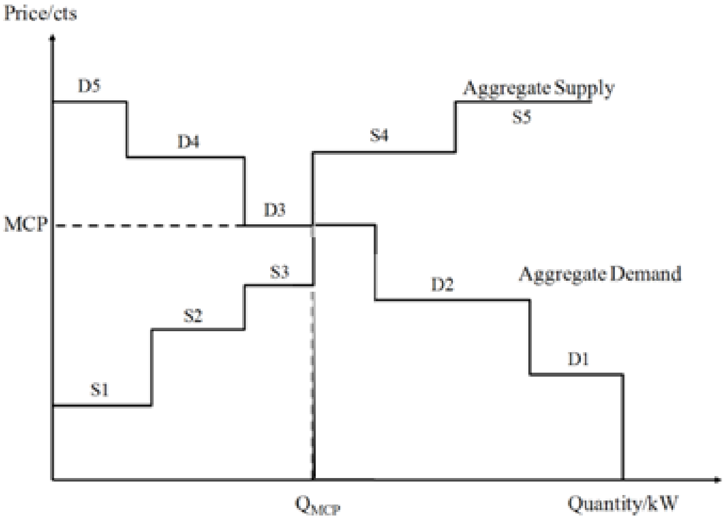


Figure 3.15. PoolCo market clearing algorithm

Generators compete for selling power to PoolCo. If bids submitted by generators are too high, they have a low possibility to sell their power. Similarly, loads compete for buying power from PoolCo. If bids submitted by load agents are too low, they have as low possibility to get power. In this market model, generators bidding with low cost and load bidding with high cost would essentially be rewarded.

3.6.2.2. Proposed Market Operation

The proposed market [96] for competitive microgrid is shown in Figure 3.16. ISO and PX handle the market operation which can be a day-ahead market or an hour-ahead market [1,2,5]. In a day-ahead market, sellers bid a set of supplies at various prices and buyers bid a set of demands at various prices for 24-hour window. PX determines market clearing prices and market clearing quantities for each hour, and ISO finalizes the scheduling without any violation of network limits. An hour-ahead market is similar to a day-ahead market, except the total scheduling period is an hour instead of 24 hours.

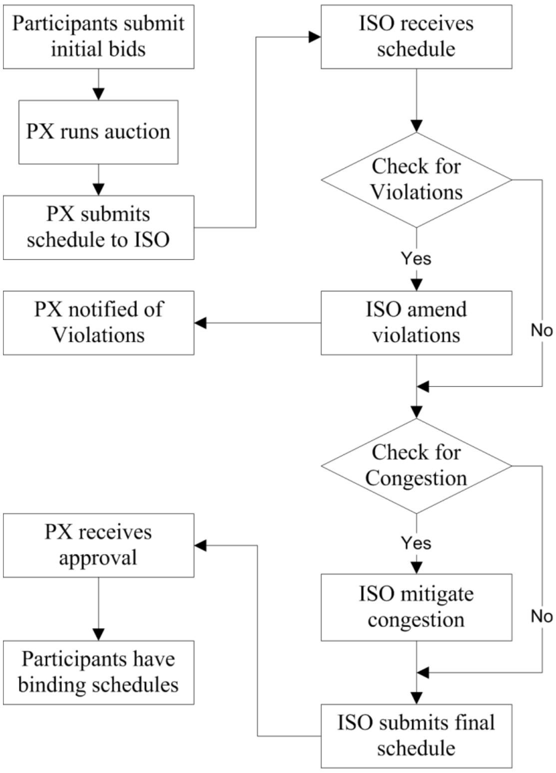


Figure 3.16. Proposed market operation

3.6.3. Integrated Microgrid Environment

Currently, many microgrids are being implemented in the modern distributed power systems. Integrated microgrid [6,15] environment provides a platform to control and manage many microgrids within its architecture. It has a distributed network of microgrids which are interconnected with each other and operated with different sets of rules and policies [1,6,15] too. In addition, they can be connected with the main distribution grid also. According to the proposed control architecture, microgrids can be operated as a control entity in whole distributed power systems. They can participate in the power system market based on the available resources.

3.6.3.1. Bidding Strategy of Microgrid

A bidding strategy is proposed for microgrids to participate in the main power system market. The price signals from microgrid manager reflect the payment asked by the microgrid for producing power from its sources. Similarly, the price signals from lump load controllers reflect the amount to be paid for load shedding respectively. Lump local controllers derive the bidding prices and quantities from the predetermined operational cost functions and their operating points. The microgrid controllers find their bids on the operational cost functions of power sources in the microgrids and the internal load demands of the microgrids. The bidding prices depend on the above factors as well as the other factors such as market forecasting and preferences of the owners.

Methodology for finding bidding quantities can be extended from the bidding strategy [1] of a single thermal unit, which is given as follows.

Bidding curve of a generator [1,15] with a quadratic cost function $C(P) = a + bP + cP^2$ is given as follows.

$$m = \frac{\rho_g - b - 2cP_O}{c(P - P_O)} - 1 \tag{3.29}$$

where, the slope m defines the bidding strategy. $m = 0$ is for bidding at incremental cost, and $m = 1$ is for bidding at marginal cost. P_O represents the sum of quantity of bilateral contact and its own load demand. In this chapter, since bilateral contracts were not considered, this represents only the latter. In this chapter, $m = 1$, bidding at marginal cost strategy is considered. Furthermore, it is considered that each microgrid and lumped load have market price forecasting facilities. The bidding price is taken as the individual forecasted market price. Therefore, the corresponding available power at each individual generator is calculated by the following equation.

$$P = \frac{\rho_g - b - 2cP_O}{c(m+1)} + P_O \tag{3.30}$$

Bidding Quantity (BQ) of the microgrid can be calculated as a sum of the total available power of all generators in the microgrid. Bidding Price (BP) of the microgrid is same as the forecasted market price of the microgrid.

3.6.3.2. Islanded Integrated Microgrid Operation

In this section, an operational scheme [15] is proposed for a day-head scheduling of islanded integrated microgrids. Figure 3.17 shows the proposed operational scheme.

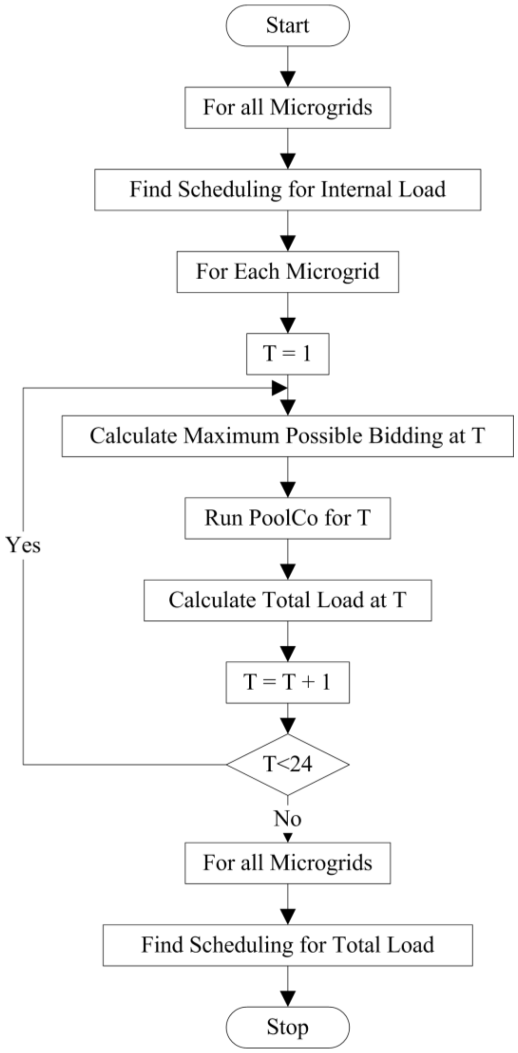


Figure 3.17. Proposed scheduling for islanded integrated microgrid

The proposed scheduling scheme has three stages. The first stage is to schedule each microgrid individually to satisfy its internal load demand. The PoolCo market model is used in the next stage and it involves finding the best possible bids for exporting power to the outside network and competing in a wholesale energy market. The final stage is to reschedule each microgrid individually to satisfy the total load demand which is the addition of the internal load demand and the load demand from the results of the wholesale energy market. The proposed algorithm which is described in SC Agent is used to schedule the microgrids individually at the first and the final stages.

3.6.3.3. Grid-Connected Integrated Microgrid Operation

In this section, an operational scheme [6] is proposed for the day-head scheduling of grid-connected integrated microgrids. The proposed operational scheme is shown in Figure 3.18.

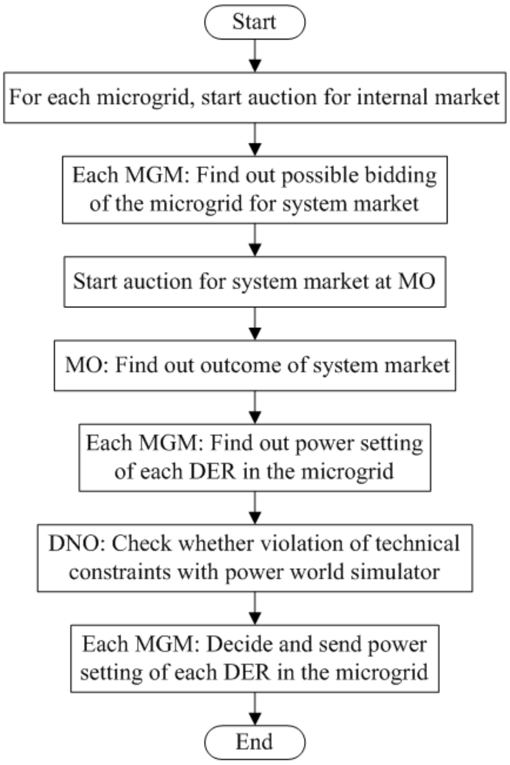


Figure 3.18. Proposed scheduling for grid-connected integrated microgrid

This operational scheme starts with opening the internal energy market in each microgrid. Each microgrid finds out the maximum possible bids that can be submitted to the main power system market for forecasted market prices for the corresponding periods. Market operator runs a market clearing algorithm which was developed in this project and reaches to the outcomes.

Calculation of optimal power transferring among the microgrids as well as between the main distribution grid and the integrated microgrid are important factors in the market clearing algorithm. These are found out by forming a Power Transferring Matrix (PTM), and optimizing the possible power transferring between the microgrids. A power transferring matrix is shown as follows.

$$PTM = \left\{ \begin{array}{cccccc} Supply/Demand & MG_1 & MG_2 & MG_3 & \ldots & MG_n \\ MG_1 & X_{11} & X_{12} & X_{13} & \ldots & X_{1n} \\ MG_2 & X_{21} & X_{22} & X_{23} & \ldots & X_{21} \\ MG_3 & X_{31} & X_{32} & X_{33} & \ldots & X_{31} \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ MG_n & X_{n1} & X_{n2} & X_{n3} & \ldots & X_{nn} \\ MG_{n+1} & X_{n+11} & X_{n+12} & X_{n+13} & \ldots & X_{n+1n} \end{array} \right\} \qquad (3.31)$$

where, X_{yz} is the possible power transferring from microgrid y to microgrid z for the forecasted marker price at the time of operation. It is calculated by the proposed bidding strategy.

$$\begin{array}{ll} 0 \leq X_{yz} \leq \infty & , y = z \\ 0 \leq X_{yz} \leq X_{yz}^{max} & , y \neq z \end{array} \qquad (3.32)$$

All microgrids have high priority to satisfy their internal load demands as much as possible. X_{yz}^{max} is the power transfer capability which is determined by the characteristics of the interconnection link between the microgrids.

The above optimum power transferring problem is solved by Vogel's approximation (UV) method [97]. By knowing the possible power transferring among the microgrids, the available power for each microgrid can be estimated. For example, P_t^{ava} is the available power for microgrid z at hour t can be found as follows.

$$P_t^{ava} = \sum_{i=1}^{N} X_{ij} \tag{3.33}$$

where, N is the number of microgrids in the integrated microgrid.

Once available power for each microgrid is calculated, the next stage of the operational scheme is to schedule each microgrid individually to satisfy its internal load demand. Similar to the islanded integrated microgrid, the proposed algorithm which is described in SC Agent is used to schedule the microgrids individually. Finally, Power World simulator confirms the operation of the system without any technical violations. This decides the final power settings of distributed energy resources and their actual buying or selling prices.

3.7. Development of Decision Making Modules

Decision making is an important module in the proposed intelligent agent architecture. This section provides the development details of decision making modules of the main agents that involve in demand side management and generation scheduling of distributed power systems. These agents were used for simulating the test systems in this dissertation by including additional functions and alteration based on the types of simulation systems and their behaviours.

3.7.1. SC Agent

During the simulation of a microgrid, Schedule Coordinator (SC) Agent is activated by the Microgrid Manager (MGM) Agent. SC Agent then schedules distributed energy resources to satisfy the load demand of the microgrid. An algorithm was proposed [94,95] to schedule the microgrid and was implemented in the decision making module of the SC Agent.

The proposed algorithm has three steps. The first step is to set up an initial feasible solution for unit commitment of thermal units, where necessity of the total thermal energy for the system is minimized. The second step is to solve the unit commitment problem. A hybrid algorithm (i.e. LREA) [94,98] that combined Lagrangian Relaxation (LR) with Evolutionary Algorithm (EA) is used to solve the unit commitment problem. The final step is to optimize the renewable energy sources-thermal units dispatch based on the results of the unit commitment problem.

First, an initial feasible solution for thermal unit commitment is found by minimizing the total thermal energy necessity for the system.

Minimize

$$ET = \sum_{t=1}^{T} \left(P_l(t) - P_u(t)\right) \tag{3.34}$$

where, ET is equivalent thermal system.

Subject to, the all unit and system constraints as given in the problem formulation.

This minimization problem is solved by Dynamic Programming (DP). Now, the net power demand for the thermal units at each time can be found as follow.

$$P_T(t) = P_l(t) - P_u(t) \tag{3.35}$$

The second step is to solve thermal unit commitment problem which minimizes the total production costs over the scheduling horizon.

Minimize

$$TOC = \sum_{i=1}^{N} \sum_{t=1}^{T} \left[I_i(t) F_i\left(P_i(t)\right) + ST_i(t)(1 - I_i(t-1)) I_i(t)\right] \tag{3.36}$$

Subject to, the all thermal unit constraints as given in the problem formulation.

This minimization problem is solved by LREA (i.e. Lagrangian Relaxation (LR) and Evolutionary Algorithm (EA)). Lagrangian Relaxation (LR) which is widely accepted methodology for generation scheduling solves the unit commitment problem by ignoring the coupling constraints temporarily and solving the problem as if they did not exist. Lagrangian relaxation decomposition procedure is based on the dual optimization theory. It generates a separable problem by integrating some coupling constraints into the objective function through functions of the constraint violation with Lagrangian multipliers which are determined iteratively. Instead of solving the primal problem, one can solve the dual by maximizing the Lagrangian function with respect to the Lagrangian multipliers, while minimizing with respect to the unit commitment control variable. The principal advantage of applying Lagrangian relaxation is its computational efficiency. The execution time of Lagrangian relaxation will increase linearly with the size of the problem. The Lagrangian relaxation method allows the utilization of parallel computing techniques for single unit commitment sub problems with a small CPU time. However, Lagrangian relaxation decomposition procedure is dependent on the initial estimates of the Lagrangian multipliers, and on the method used to update the multipliers. In order to obtain a near-optimal solution, Lagrange multiplier adjustments are needed to be managed skillfully. In addition, the Lagrangian relaxation method often encounters difficulties as more complicated constraints are considered. The inclusion of a large number of multipliers could result in an optimization problem that is more difficult and even impossible to solve as the number of constraints grows and various heuristics are embedded in the Lagrangian relaxation algorithm.

Evolutionary Algorithm (EA) is a general purpose stochastic and parallel search method, which can be used as an optimization technique for obtaining near-global optimum. This algorithm is inspired from genetics and evolution theories of natural selection and survival of the fittest. It is iterative procedure acting on a population of chromosomes, each chromosome being the encoding of a candidate solution to the problem. A fitness which depends on how well it solves the problem is associated with each chromosome. The objective function involves penalty term to penalize those potential solutions in which the problem constraints are not fulfilled. The objective function translates into a fitness which determines the solution's ability to survive and produce offspring. New generations of solutions are obtained by a process of selection, cross-over, and mutation. During the evolution process, new generations should give increasingly fitter solution and evolve toward an optimal solution.

In this dissertation, a hybrid algorithm combined with Lagrangian Relaxation (LR) and Evolutionary Algorithm (EA) is proposed to solve the concern problem. This is shown in Figure 3.19.

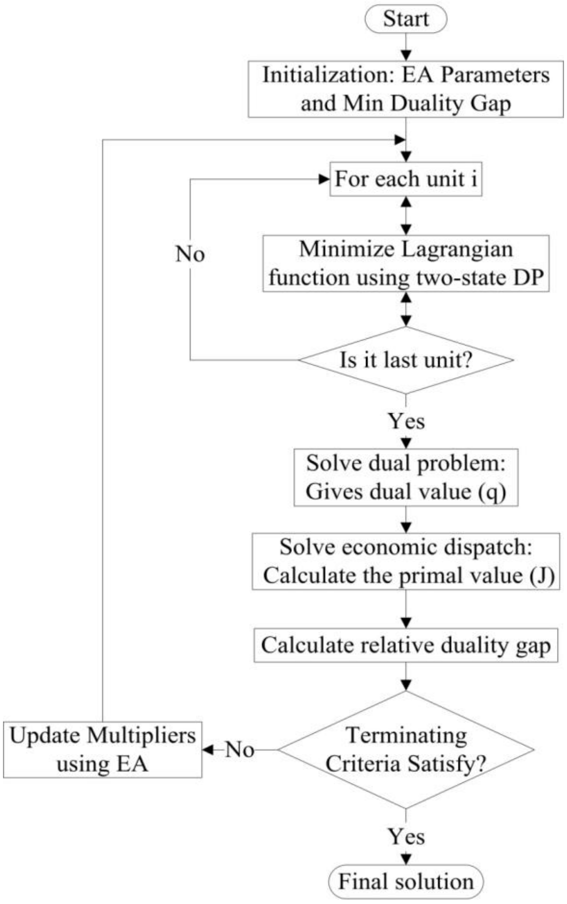


Figure 3.19. LREA for thermal unit commitment problem

This methodology incorporates evolutionary algorithm into Lagrangian relaxation to update Lagrangian multipliers and improve the performance of Lagrangian relaxation method. The evolutionary algorithm combines the adaptive nature of the natural genetics or the evolution procedures of organs with functional optimizations. Lagrangian Relaxation with Evolutionary Algorithm (LREA) method consists of a two-stage cycle. The first stage is to search for the constrained minimum of Lagrangian function under constant Lagrangian multipliers by two-state dynamic programming. The second stage is to maximize the Lagrangian function with respect to the Lagrangian multipliers adjusted by evolutionary algorithm.

The final step is to optimize the renewable-thermal dispatch based on the results from thermal unit commitment problem.

Minimize

$$TOC = \sum_{i=1}^{N} \sum_{t=1}^{T} \left[I_i(t)^* F_i\big(P_i(t)\big) + ST_i(t)(1 - I_i(t-1)^*) I_i(t)^* \right] \tag{3.37}$$

where, $I_i(t)^*$ is the ON/OFF status of thermal unit i at time t from the results of thermal unit commitment problem.

Subject to, the all unit and system constraints as given in the problem formulation.

This minimization problem is solved by Dynamic Programming (DP). The results give the scheduling of all units in the system.

3.7.2. DSM Agent

Demand side management of the future power systems is needed to handle a large number of controllable devices of several types. Besides, each type of controllable load can have different consumption characteristics and several heuristics which is spread over a few hours. Therefore, a suitable algorithm that should be proposed for the problem needs to handle these complexities. Linear programming and dynamic programming are commonly used algorithms [99-101] in this field though both cannot handle such complexities. As this dissertation proposes a strategy for a future grid with large number of devices from several types, dynamic programming is not a good technique too.

Currently, evolutionary algorithms show their potential for solving complex problems [18]. They have several advantages over the traditional mathematical algorithms besides providing near optimal results. Hence, in this dissertation, a heuristic based evolutionary algorithm [91] is proposed for the decision making module of Demand Side Management (DSM) Agent. The proposed algorithm not only adapts the heuristics in the problem but also provides an efficient and effective solution to the problem.

One of the main advantages of the proposed algorithm [91] is flexibility for constructing and developing algorithm which cannot be afforded by any other conventional approaches. The flexibility even allows implementing the lifestyle of customers while carrying out load control so that it minimizes inconvenience of the customers. Certain loads may have higher priority over the others. These types of priorities can also be included into consideration by the algorithm so that they are shifted to the appropriate times according to their importance. Another main advantage of the proposed algorithm is the ability to handle large number of controllable devices of several types. The size of the problem affects only in length of the chromosomes of the evolutionary algorithm.

The particular problems taken in this dissertation have characteristics such as connection times of devices can only be delayed and not brought forward. This is given in the problem formulation as below.

$$X_{kit} = 0 \qquad \forall i > t \tag{3.38}$$

The contract options stipulate the maximum allowable time delay of all devices, and limit the possible number of time steps such that devices can be shifted to. Thus,

$$X_{kit} = 0 \qquad\qquad (t - i) > m \tag{3.39}$$

where, m is the maximum permissible delay.

Taking all above factors into consideration, the maximum number of time steps N that devices can be possibly shifted to is calculated by the following equation.

$$N = \left((24 - m) \times m + \sum_{n=1}^{m-1} n \right) \times k \tag{3.40}$$

where, k is the number of different types of devices.

The chromosome of the evolutionary algorithm will give the final solutions to the problem. A binary chromosome is used. The length of the chromosome is directly related to the number of time steps N, which is given by the following equation.

$$k = N \times B \tag{3.41}$$

where, B is the number of bits required to represent the number of devices that are shifted to each time step.

The main stages of the proposed evolutionary algorithm are shown in Figure 3.20.

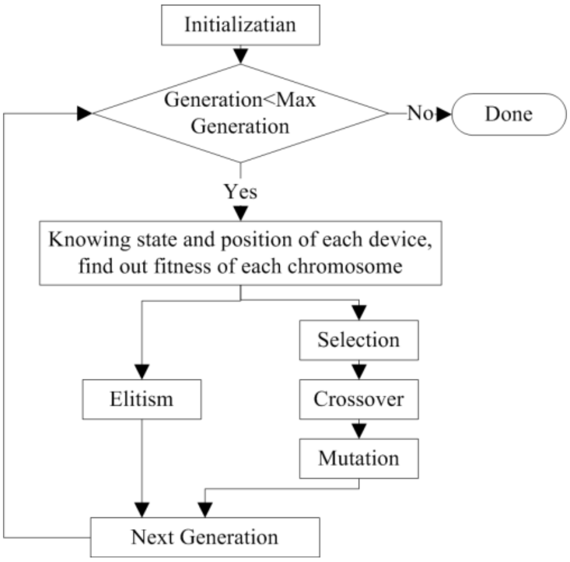


Figure 3.20. Proposed evolutionary algorithm

A population of chromosomes is randomly initialized at the beginning. A fitness function is chosen such that the algorithm makes the final load curve as close as to the objective load curve, which is given as follows.

$$Fitness = \frac{1}{1 + \sum_{t=1}^{T}(PLoad(t) - Objective(t))^2} \tag{3.42}$$

While the algorithm is progressing, new populations of chromosomes are produced from the existing populations by genetic operators: crossover and mutation. A large crossover rate ensures the faster convergence of the solution. Very large mutation rate may result in loss of good solutions from previous generations, and would stop the algorithm with premature convergence. The best crossover rate and mutation rate were found out for this problem by simulating the system for several times. Best crossover rate and mutation rate were found out as 0.9 and 0.1 respectively. In addition, elitism is used to prevent the loss of good solutions that may emerge early on. A tournament method is used as the selection technique. The algorithm is terminated when the stipulated number of generations is reached or when the change in fitness value does not vary more than a tolerance limit as the number of generation increases. Some of the main information and the parameters are given below.

- The chromosome is an array of bits. Calculation of length of the chromosome has been given above.
- Fitness function has been defined in equation 3.42.
- Population size of 200 is used for the test case.
- Single point crossover is used. Crossover rate of 0.9 is used for the test case.
- Binary mutation is used. Mutation rate of 0.1 is used for the test case.
- Stipulated number of generations is set as 500 in the test case.

- Termination criteria: Stipulated number of generations is reached, or when the magnitude in the change in fitness value does not vary more than a tolerance limit 10^{-10} for 50 subsequent generations.
- Simulation time is about 6 hours for the test case. It is acceptable as it solves a day-ahead demand side management strategy which will be carried out in 24 hours before the time of operation.

3.7.3. Security Agent

Steady-state security [1-3,13] concerns the operation of the system satisfying voltage constraints and power flow limits. A critical consideration in this case is the overloading of interconnecting lines between microgrids and the upstream distribution network. Dynamic security concerns the system operation under a number of contingencies within and above it. For microgrids, a seamless transition between the interconnected mode and the islanded mode is an important issue. Security considerations can be expressed as additional constraints of the optimization problems. In this research, Security Agent ensures the steady-state security of the microgrid operation with the help of Power World simulator [88].

Steady-state security for operation of distributed power systems is confirmed by the Power World simulator at the final stage of scheduling. Power World simulator confirms the operation of power generation without any technical violations in the system. Additionally, it decides the final power settings of distributed energy resources and their electricity prices. The actual electricity prices will be same as the market/bidding prices if there is no technical violation in the system, or it will be same as the Locational Marginal Price (LMP) [1,2] if there is any technical violation.

3.8. Summary

This chapter proposes the multi-agent system approach for the decentralized control and management of distributed power systems. Further, it provides development and implementation details of the multi-agent system and also provides information and details about the proposed multi-agent system, the proposed control architecture and their implementations. Among functions of energy management system, generation scheduling and demand side management functions need the interaction and local decision making of many entities. Hence, these two managerial functions are mathematically formulated in this chapter to validate the multi-agent system approach for the control and management of distributed power systems.

CHAPTER 4

DAY-AHEAD SIMULATIONS OF DISTRIBUTED POWER SYSTEMS

4.1. Overview

This chapter presents various simulation studies on the developed multi-agent system for the control and management of microgrids in cooperative and competitive environments. The developed multi-agent system is then further extended for the control and management of distributed power systems with integrated microgrids. Various simulation studies were carried out on the developed multi-agent system for demonstrating the effectiveness and capability of the proposed multi-agent system for the operation of microgrids and integrated microgrids.

The remaining chapter is organised as follows. Section 4.2 provides simulation studies on a microgrid in a competitive environment. Section 4.3 provides simulation studies on microgrids in a cooperative environment. Section 4.4 provides simulation studies on the operation of a grid-connected integrated microgrid. Section 4.5 provides simulation studies on the operation of an islanded integrated microgrid. Section 4.6 summarizes the chapter.

4.2. Competitive Microgrid Operation

This section presents simulation studies on a microgrid in a competitive environment, where utilities are not necessary to meet any system requirements, but the focus is to maximize individual profits. The number of generating units committed to the system is increased when the market price is higher. When more number of generating units are introduced in the market, more profit can be achieved by producing higher amount of power. In this dissertation, PoolCo market model [1,2] is used to provide the competitive environment in the microgrid.

4.2.1. Multi-Agent System Launching

The developed multi-agent system is launched via an agent launch pad [96]. This is shown in Figure 4.1. All administrative agents such as PoolCo Manager Agent, Security Manager Agent, Power System Manager Agent, ISO Agent, PX Agent and Schedule Coordinator Agent, and market player agents such as Buyer Agents and Seller Agents are launched and activated.

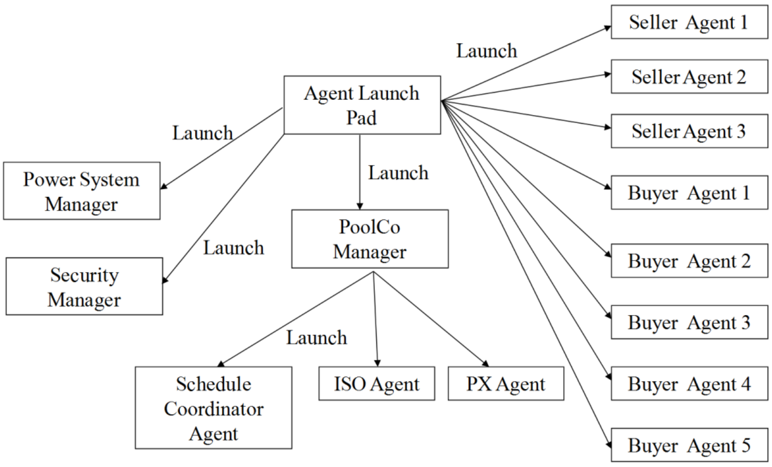


Figure 4.1. Initialization of multi-agent system

4.2.2. Registering with Directory Facilitator

After the agents are launched and activated, they execute their threads to initialize their capacities, load requirements and bids by obtaining data from the corresponding databases. Once all parameters of the agents are properly initialized, each agent automatically registers with Directory Facilitator (DF). This process is illustrated in Figure 4.2. Once the agents are registered with the directory facilitator, agents query the directory facilitator for a list of agents and their services in the network using certain search constraints. These search constraints which are usually types of services or agents names. Seller Agents send a query to the directory facilitator on all Buyer Agents and PoolCo Manager Agent. Buyer Agents send a query to the directory facilitator on all Seller Agents and PoolCo Manager Agent. The directory facilitator responds with a list of agents and their physical addresses that match with the search constraints.

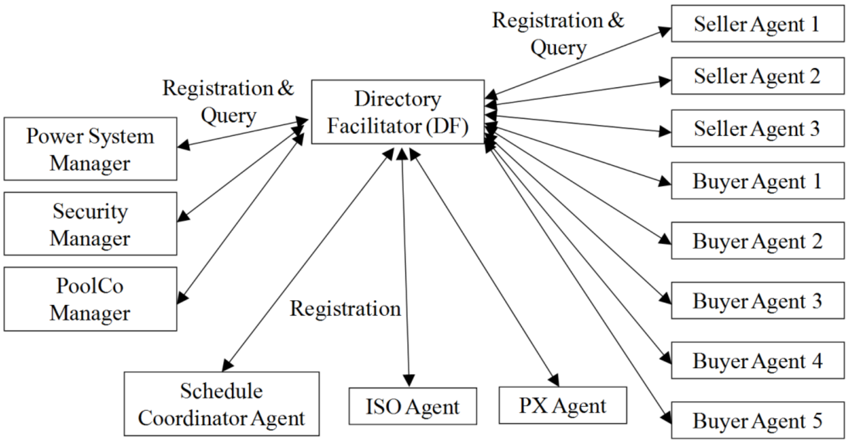


Figure 4.2. Registration and query of agents

4.2.3. Registering with Security Services

After retrieving the necessary directory list of various agents in the network, each agent contacts the Security Manager Agent for allocation of security ID keys which are used for the encryption and SSL algorithm engine.

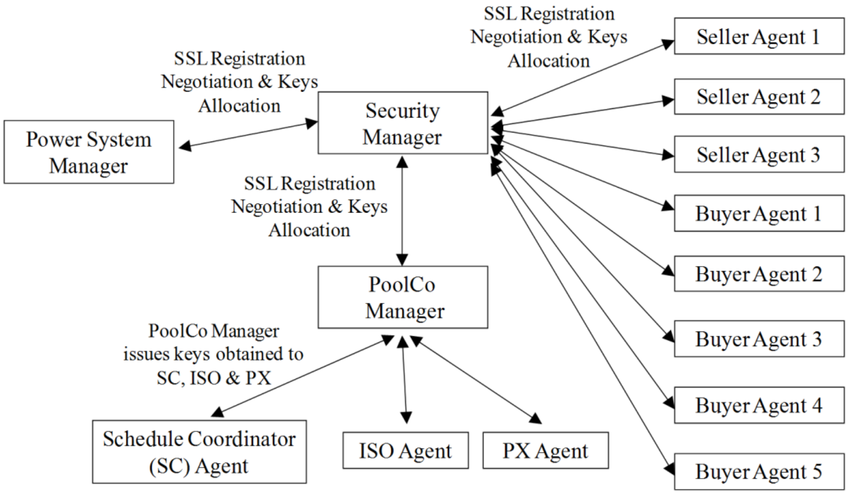


Figure 4.3. Role of Security Manager Agent

This process is shown in Figure 4.3. Once the agents are registered for the security services, further communication is encrypted.

4.2.4. Coordination of Agents

The agents coordinate among themselves to satisfy the load demand of the microgrid. Simple coordination strategy based on contract-net protocol is provided for simulating the PoolCo market. Contract-net protocol [48] is a simple negotiation without allowing any counter proposals. Figure 4.4 shows the overall communication between the agents for the operation of a competitive microgrid.

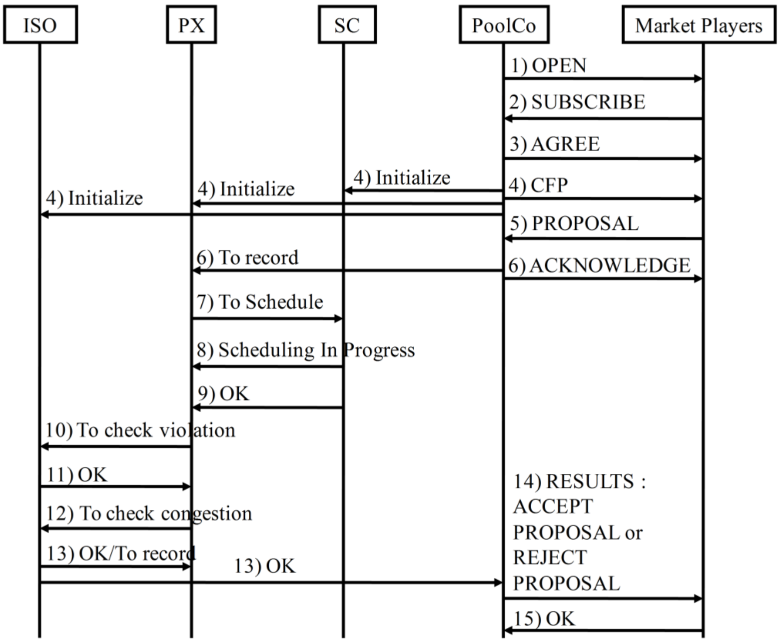


Figure 4.4. Interaction of agents for competitive microgrid operation

As shown in the figure, when PoolCo Manager Agent is ready to communicate with all player agents, it broadcasts an OPEN message. All player agents who wish to take part in the current round of bidding, respond by sending a SUBSCRIBE message to subscribe the PoolCo Manager Agent. PoolCo Manager Agent closes the subscription window after everyone in the network has subscribed or when the subscription date and time have expired. Then the PoolCo Manager Agent issues an AGREE message which indicates that all agents who have signed up for subscription confirm their subscriptions. When the AGREE message is received, they record this correspondence in their internal databases. After sending out the AGREE message, the PoolCo Manager Agent also updates its own internal database and proceeds to prepare a call for proposal broadcast. Once it prepares the Call For Proposal (CFP) message, it sends the message to all subscribers. Upon receiving the CFP message, the player agents prepare their bids if they are interested to participating in this round.

These submissions of bids and replies from the PoolCo Manager Agent are legally binding contracts. The Buyer Agents who submitted bids are legally obliged to buy the quantities of power at the proposed prices. The same things are applicable for the Seller Agents too. Agents, who are interested in submitting bids, have access to their internal bidding records. They prepare the necessary parameters like price and quantity of electricity to buy or offer in the market and the parameters are encoded as a bid object. When the encoding is completed, they send a PROPOSAL message to the PoolCo Manager Agent with a bid object enclosed. When the PoolCo Manager Agent receives the PROPOSAL message, it re-directs the message to the PX Agent for recording. The PoolCo Manager Agent only closes the proposal window after all agents in the network have submitted their proposals or date and time for the proposal window have expired. The proposal expiry date is default by one day from the time the PoolCo Manager Agent sent out the CFP message. After the proposal window is closed, the PX Agent processes the bids and sends them to the SC Agent. Once they are received, the SC Agent sends a message to the PoolCo Manager Agent to notify as scheduling in progress.

SC Agent has a market clearing algorithm, which clears the market for the time. SC Agent finds out a single spot price at the market equilibrium. This price is called as

Market Clearing Price (MCP). It also calculates the quantity of electricity transacted at this price. The PX Agent also finds out the successful Buyer Agents and Seller Agents in the round based on MCP and quantity of electricity transacted. The entire set of results is then sent to the ISO Agent to check for any violation of bids and/or any network congestion for the scheduling. If any bidding is violated or the scheduling is congested, the ISO Agent takes necessary actions.

4.2.5. Mitigating Violation and Congestion

If a scheduling is congested, the ISO Agent would employ Power World simulator to mitigate the congestion. Power World simulator uses Optimal Power Flow (OPF) which is to minimize the operational cost of the system with respect to both equality and inequality constraints of both the system and the units in the system. Once congestion has been mitigated, a new network schedule and relevant network information are extracted from the Power World simulator. Figure 4.5 shows the network diagram of the microgrid modelled [96] for simulation studies in this section.

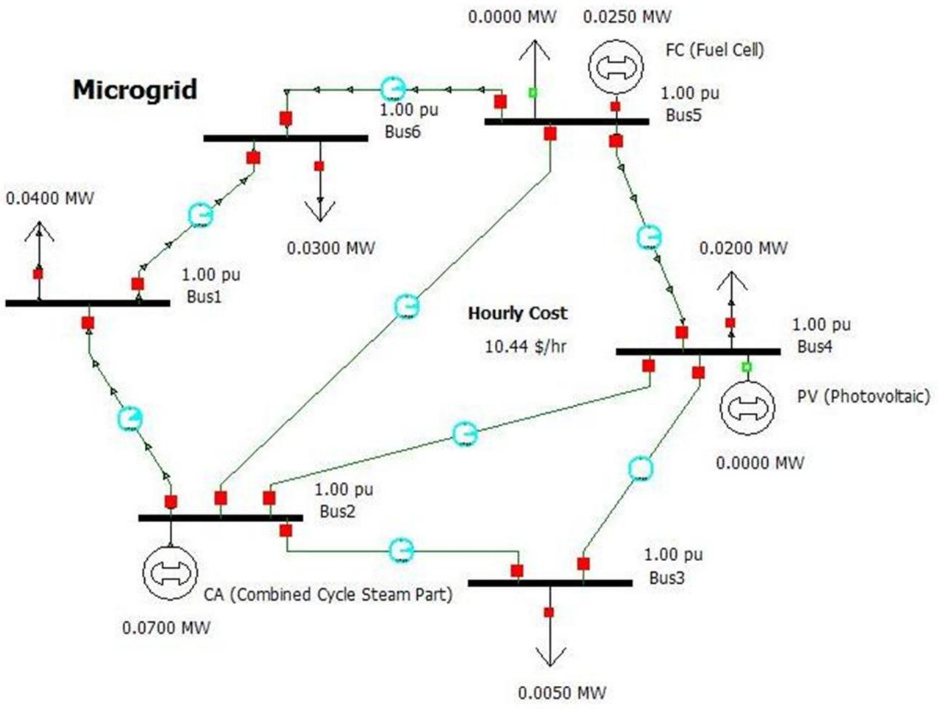


Figure 4.5. Network diagram of the microgrid

Later, a set of data comprising of MCP, quantity of electricity transacted, list of successful and unsuccessful Buyer Agents and Seller Agents is sent to the PoolCo Manager Agent. After receiving the data, the PoolCo Manager Agent extracts out the relevant information and sends to the Power System Manager Agent so that it can update the state of the power system. The PoolCo Agent extracts the list of successful bidders from the data and sends an ACCEPT PROPOSAL message to successful bidders embedded with details of the successful bids. The PoolCo Agent also extracts the list of unsuccessful bidders from the data and sends a REJECT PROPOSAL message to unsuccessful bidders. All bidders are notified of their bidding outcomes at the end of every round of bidding. Agents who receive an ACCEPT PROPOSAL message records their successful bid object and update their internal records. Then, they send an OK message to the PoolCo Manager Agent to acknowledge the contract. Agents who receive a REJECT PROPOSAL message records their unsuccessful attempt and make changes to their internal records.

The whole process is for one time slot. In case of a day-ahead market, there will be a 24-hour slot. Agents usually submit a complete set of 24 bids to the market.

4.2.6. Simulation Studies

The following scenarios [96] of double sided bidding in the PoolCo market were carried out on the developed multi-agent system for the operation of a competitive microgrid. The network diagram of the microgrid is shown in Figure 4.5.

- Scenario 1 is a case, where excess demand is available at MCP. This scenario is illustrated in Figure 4.6.
- Scenario 2 is a case, where excess supply is available at MCP. This scenario is illustrated in Figure 4.7.

- Scenario 3 is a case, where supply and demand are equal at MCP. This scenario is illustrated in Figure 4.8.

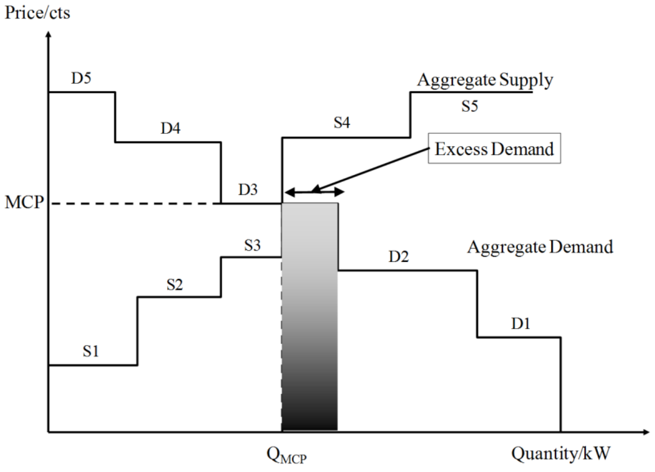


Figure 4.6. Excess demand at MCP

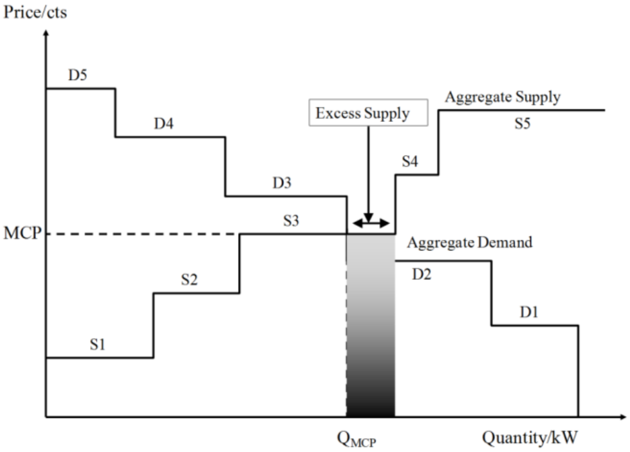


Figure 4.7. Excess supply at MCP

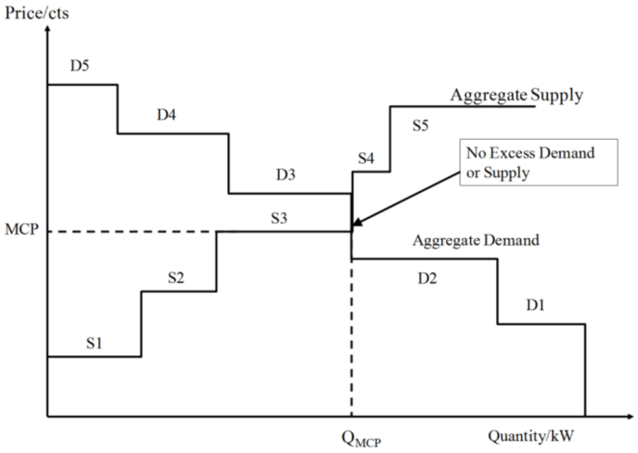


Figure 4.8. Perfect matching of supply and demand at MCP

4.2.7. Simulation Results

Table 4.1 provides numerical results for the above scenarios. In scenario 1, at the market equilibrium, the bidding quantity of Load 1 is 10kW, whereas the successful market output is only 5kW. Therefore, additional 5kW power is necessary for Load 1.

Table 4.1. Simulation results

Agents	Scenario 1				Scenario 2				Scenario 3			
	Input		Output		Input		Output		Input		Output	
	P	Q	P	Q	P	Q	P	Q	P	Q	P	Q
Pgen 1	11	70	11	70	11	70	11	65	11	70	12	70
Pgen 2	12	20	0	0	12	20	0	0	12	20	0	0
Pgen 3	10	25	11	25	10	35	11	35	10	20	12	20
Load 1	11	10	11	5	11	10	11	10	11	10	0	0
Load 2	12	20	11	20	12	20	11	20	12	20	12	20
Load 3	10	10	0	0	10	10	0	0	10	10	0	0
Load 4	14	30	11	30	14	30	11	30	14	30	12	30
Load 5	13	40	11	40	13	40	11	40	13	40	12	40

P- Price in cents and Q- Quantity in kW

Here, the excess demand of 5kW is available at the market equilibrium. In scenario 2, at the market equilibrium, the bidding quantity of Pgen 1 is 70kW, whereas the successful market output is only 65kW. Therefore, 5kW power is available at Pgen 1. Here, the excess supply 5kW is available at the market equilibrium. In scenario 3, at the market equilibrium, the bidding quantity of Load 2 is 20kW, and the successful market output is also 20kW. Here, the supply and the demand are exactly matched at the market equilibrium.

Remote Monitoring Agent (RMA) can be run in the JADE runtime environment. Agents in the framework can be monitored and controlled from RMA. The other graphical tools such as the dummy agent, the sniffer agent and the introspector agent, which are used to monitor, debug and control multi-agent system programming can be activated from the RMA. Figure 4.9 shows a screen snap which demonstrates the developed multi-agent system. In this figure, a sniffer agent is activated, where communication between the agents for a simulation study can be observed.

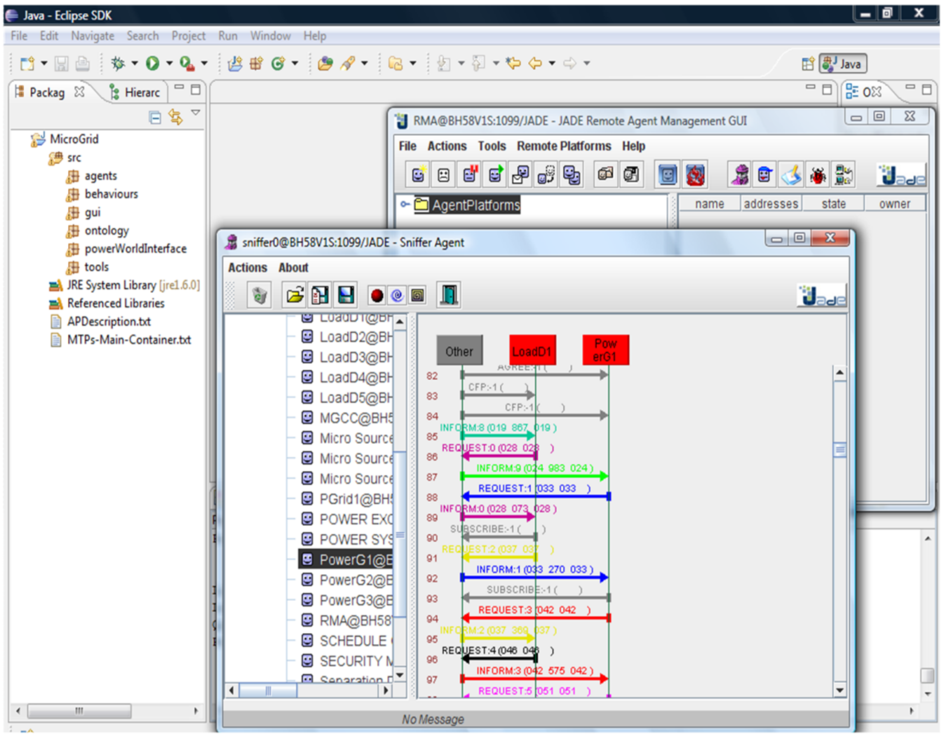


Figure 4.9. Demonstration of multi-agent system

4.2.8. Discussions

In this section of research, the developed multi-agent system was used to simulate the operation of a microgrid in competitive environment. PoolCo market model was used to create the competitive environment in the microgrid. The simulation studies demonstrate the successful development and implementation of the multi-agent framework, feasibility and effectiveness of the multi-agent platform to model energy markets and roles of ISO and PX in particular for carrying out energy markets.

A market that has an inelastic demand operates normally as long as the supply offers exceed the current demand. When the available offers exceed the demand, an intersection exists between demand and supply curves and the market clearing price can be determined [2]. However, if an imbalance occurs between the supply and demand, problems may arise. An imbalance can be due to an unanticipated increase in demand, which could be due to weather and planned or forced outages in supply or/and transmission facilities. In these cases, there is no intersection between the supply and demand curves. Such a situation may result in a price park or a sudden change. In this case, a price cap (i.e. ceiling) can be imposed by PoolCo or ISO to limit the increase in energy prices. The price tends to increase to high levels because unusual measures need to be taken to restore the balance between supply and demand. The balance is usually restored by either shedding loads which sets the market clearing price at the price gap or alternatively by obtaining additional supply sources which could be offered at this maximum price or close to it. To the contrary, the problem of restoring the balance between supply and demand is much easier when the demand is elastic. Because of elastic demand, the increase in price would cause the demand to decrease and a new balance point is established that would reflect the need of customers for energy and their desire to manage energy costs.

4.3. Cooperative Microgrid Operation

This section provides various simulation studies on different types of microgrids in a cooperative environment, where utilities are necessary to meet system requirements and maximize their profits. The scheduling of generators basically depends on open market prices.

4.3.1. Coordination of Agents

The developed multi-agent system is launched, and agents are registered with directory facilitator, then for security services. In this environment, agents interact cooperatively to achieve the system goals. The interaction of agents and the respective messages for a day-ahead scheduling are shown in Figure 4.10.

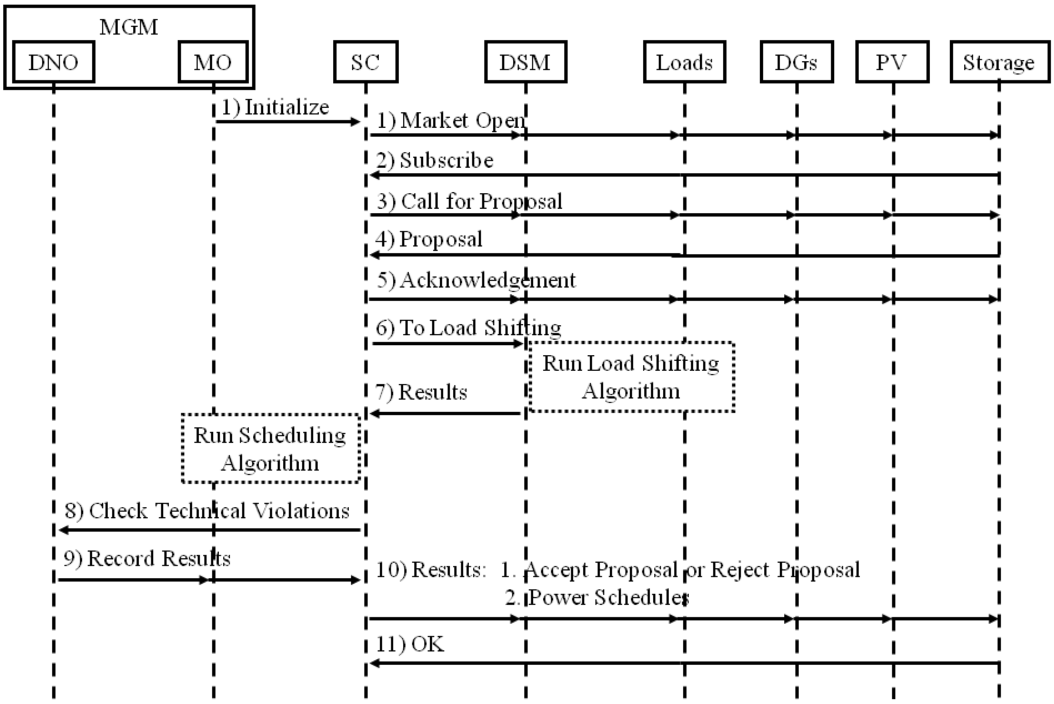


Figure 4.10. Interaction of agents for cooperative microgrid operation

4.3.2. Simulation Studies

Simulation studies were carried out on the developed multi-agent system for three different types of microgrids. Each type has different customers namely residential, commercial and industrial. The network diagram of each microgrid is given in the corresponding sections [6]. They operate at a voltage of 410V. Each interconnection link including the link between the microgrid and the main distribution grid has a resistance of 0.003pu, a reactance of 0.01pu, and maximum power transfer limit of 500kVA. Length of the links in the residential microgrid, commercial microgrid and industrial microgrid is 2km, 3km and 5km respectively. These network diagrams were come up with experience of the experts worked in MODREN project, but they are not optimized networks which can be optimized in the future research.

In these simulation studies, the main objective was to reduce the utility bills of these microgrids. Therefore, an objective load curve was chosen which is inversely propositional to wholesale electricity market prices. The same market prices were applied to all microgrids.

Table 4.2. Forecasted load demands and wholesale energy prices

Time	Wholesale Price (ct/kWh)	Hourly Forecasted Load (kWh)		
		Residential Microgrid	Commercial Microgrid	Industrial Microgrid
8hrs-9hrs	13.00	729.4	923.5	2045.5
9hrs-10hrs	10.29	713.5	1154.4	2435.1
10hrs-11hrs	12.47	713.5	1443.0	2629.9
11hrs-12hrs	20.79	808.7	1558.4	2727.3
12hrs-13hrs	26.42	824.5	1673.9	2435.1
13hrs-14hrs	27.75	761.1	1673.9	2678.6
14hrs-15hrs	13.81	745.2	1673.9	2678.6
15hrs-16hrs	17.91	681.8	1587.3	2629.9
16hrs-17hrs	15.42	666.0	1558.4	2532.5
17hrs-18hrs	10.83	951.4	1673.9	2094.2
18hrs-19hrs	9.63	1220.9	1818.2	1704.5
19hrs-20hrs	6.87	1331.9	1500.7	1509.7
20hrs-21hrs	9.35	1363.6	1298.7	1363.6
21hrs-22hrs	15.44	1252.6	1096.7	1314.9
22hrs-23hrs	15.19	1046.5	923.5	1120.1
23hrs-24hrs	10.87	761.1	577.2	1022.7
24hrs-1hrs	9.65	475.7	404.0	974.0
1hrs-2hrs	8.11	412.3	375.2	876.6
2hrs-3hrs	7.25	364.7	375.2	827.9
3hrs-4hrs	8.10	348.8	404.0	730.5
4hrs-5hrs	9.14	269.6	432.9	730.5
5hrs-6hrs	8.13	269.6	432.9	779.2
6hrs-7hrs	9.34	412.3	432.9	1120.1
7hrs-8hrs	8.35	539.1	663.8	1509.7

Simulations studies were carried out with a maximum allowable delay of 12 hours. It is known that the longer the delay, the better the performance of demand side management strategy because the possible number of loads subjected to load shifting increases. Hence, the results will be improved. Forecasted hourly wholesale electricity prices [102] and load demands of the microgrids are given in Table 4.2.

The maximum load demands of residential microgrid, commercial microgrid and industrial microgrid in this study are 1.5MW, 2 MW and 3MW respectively. In a typical day, valley hours of load consumption will be before the peak hours. If load shifting window is from 0 hr to 24 hrs, the peak load cannot be shifted to valley hours. In order to avoid this circumstance, control period is changed from 8 hrs of current day to 8 hrs of the following day for demand side management.

Table 4.3 contains normalized data of wind power and photovoltaic power production [15,94] which were calculated from the models proposed in Chapter 9. Normalized power production of a renewable source is the ratio of power output from the source to the power rating of the source. Forecasted wind speed, solar radiation and atmospheric temperature were taken from the meteorological department [103].

Table 4.3. Forecasted hourly normalized power production of RES

Hour	Wind Power	PV Power	Hour	Wind Power	PV Power	Hour	Wind Power	PV Power
1	0.0860	0	9	0.4450	0.6358	17	0	0.2546
2	0.1465	0	10	0.4726	0.6780	18	0.0040	0.2122
3	0.2449	0	11	0.2674	0.8131	19	0	0.1528
4	0.1829	0	12	0.1927	0.8469	20	0	0.0680
5	0.3780	0.0935	13	0.0995	0.8300	21	0.0062	0.0425
6	0.6424	0.2123	14	0.0426	0.8468	22	0.0100	0
7	0.9835	0.2547	15	0.0062	0.6779	23	0.0100	0
8	0.6282	0.4666	16	0.0053	0.5933	24	0.0344	0

Table 4.4. Distribution of loads in the system

Bus	Microgrid	Load (%)	Bus	Microgrid	Load (%)
1	Industrial Microgrid	35.0	15	Residential Microgrid	5.0
2	Industrial Microgrid	10.0	16	Residential Microgrid	5.0
3	Industrial Microgrid	7.5	17	Residential Microgrid	7.5
4	Industrial Microgrid	15.0	18	Residential Microgrid	7.5
5	Industrial Microgrid	20.0	19	Residential Microgrid	7.5
6	Industrial Microgrid	12.5	20	Residential Microgrid	7.5
7	Residential Microgrid	7.5	21	Commercial Microgrid	15
8	Residential Microgrid	7.5	22	Commercial Microgrid	10
9	Residential Microgrid	7.5	23	Commercial Microgrid	15
10	Residential Microgrid	7.5	24	Commercial Microgrid	15
11	Residential Microgrid	7.5	25	Commercial Microgrid	10
12	Residential Microgrid	7.5	26	Commercial Microgrid	10
13	Residential Microgrid	10.0	27	Commercial Microgrid	15
14	Residential Microgrid	5.0	28	Commercial Microgrid	10

A significant part of power generation for microgrids is expected to come from renewable energy resources. The unpredictability of renewable sources makes the dispatch of microgrids more challenging. In this situation, load control is very desirable and in some cases a real necessity. A common way to safely operate a small isolated microgrid, where renewable power generation is significant, is to provide some storage system which stores energy when there is excess energy in the system, and provides power when power is needed in the system.

All three microgrids are parts of a smart integrated microgrid. The distribution of loads and installed capacities of the sources in the microgrids are given in Table 4.4 and Table 4.5 respectively [6,104]. Each microgrid in the smart grid has different types of controllable devices. The details of devices and types of devices in each microgrid and their characteristics are given in following sections.

Table 4.5. Installed capacities of distributed energy resources

Microgrid	Unit Type	Minimum Power (kW)	Maximum Power (kW)
Industrial Microgrid	Fuel Cell (FC)	60	120
Industrial Microgrid	Micro Turbine (MT) 1	30	120
Industrial Microgrid	Diesel Generator (Die. G) 1	50	350
Industrial Microgrid	Micro Turbine (MT) 2	120	600
Industrial Microgrid	Diesel Generator (Die. G) 2	40	120
Industrial Microgrid	Photovoltaic (PV)	0	864
Industrial Microgrid	Wind Turbine (WT)	0	280
Industrial Microgrid	Battery Bank	0	1000kW & 5000kWh
Residential Microgrid	Fuel Cell (FC)	30	60
Residential Microgrid	Micro Turbine (MT) 1	15	60
Residential Microgrid	Diesel Generator (Die. G) 1	30	210
Residential Microgrid	Micro Turbine (MT) 2	60	300
Residential Microgrid	Diesel Generator (Die. G) 2	20	60
Residential Microgrid	Photovoltaic (PV)	0	432
Residential Microgrid	Wind Turbine (WT)	0	140
Residential Microgrid	Battery Bank	0	600kW & 3000kWh
Commercial Microgrid	Fuel Cell (FC)	35	70
Commercial Microgrid	Micro Turbine (MT) 1	20	80
Commercial Microgrid	Diesel Generator (Die. G) 1	40	280
Commercial Microgrid	Micro Turbine (MT) 2	80	400
Commercial Microgrid	Diesel Generator (Die. G) 2	30	90
Commercial Microgrid	Photovoltaic (PV)	0	576
Commercial Microgrid	Wind Turbine (WT)	0	140
Commercial Microgrid	Battery Bank	0	600kW & 3000kWh

4.3.2.1. Residential Microgrid

The network diagram [6,104] of the residential microgrid which serves mostly the residential customers is given in Figure 4.11.

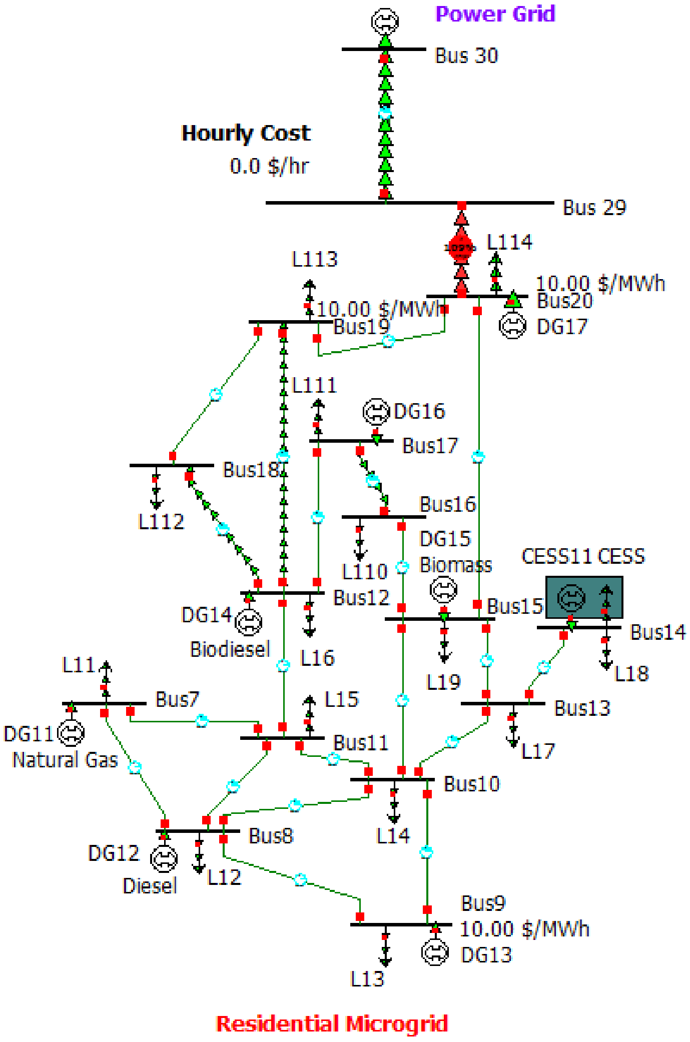


Figure 4.11. Network diagram of the residential microgrid

The devices subjected to control in the residential microgrid typically have small power consumption ratings and short durations of operation. Table 4.6 shows device types that are subjected to load control in this microgrid and their consumption patterns [91]. There are over 2600 controllable devices available in this microgrid from 14 different types of devices.

Table 4.6. Data of controllable devices in the residential microgrid

Device Type	Hourly Consumption of Device (kW)			Number of Devices
	1st Hour	2nd Hour	3rd Hour	
Dryer	1.2	-	-	189
Dish Washer	0.7	-	-	288
Washing Machine	0.5	0.4	-	268
Oven	1.3	-	-	279
Iron	1.0	-	-	340
Vacuum Cleaner	0.4	-	-	158
Fan	0.20	0.20	0.20	288
Kettle	2.0	-	-	406
Toaster	0.9	-	-	48
Rice-Cooker	0.85	-	-	59
Hair Dryer	1.5	-	-	58
Blender	0.3	-	-	66
Frying Pan	1.1	-	-	101
Coffee Maker	0.8	-	-	56
Total	-	-	-	2604

4.3.2.2. Commercial Microgrid

The network diagram [6,104] of the commercial microgrid which serves mostly the commercial buildings and customers is given in Figure 4.12. The devices subjected to control in the commercial microgrid have consumption ratings slightly higher than those in the residential microgrid. The consumption patterns [91] of the loads under the control are given in Table 4.7. There are over 800 controllable devices available for control in this microgrid from 8 different types of devices.

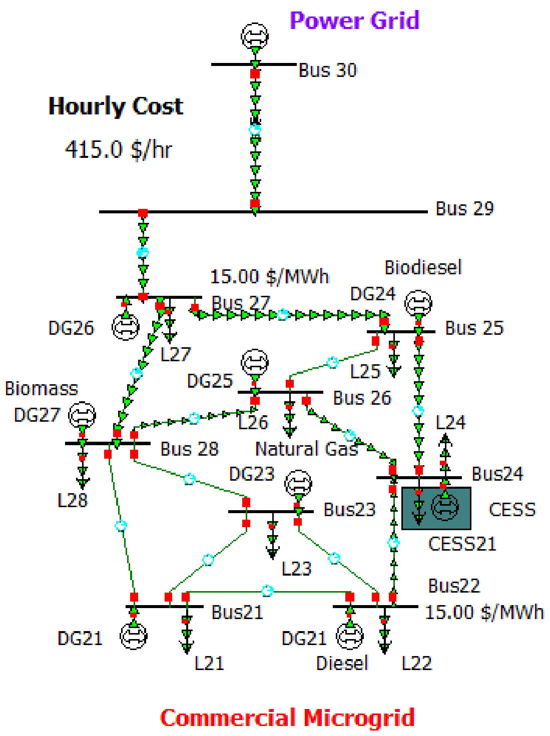


Figure 4.12. Network diagram of the commercial microgrid

Table 4.7. Data of controllable devices in the commercial microgrid

Device Type	Hourly Consumption of Device (kW)			Number Devices
	1st Hour	2nd Hour	3rd Hour	
Water Dispenser	2.5	-	-	156
Dryer	3.5	-	-	117
Kettle	3.0	2.5	-	123
Oven	5.0	-	-	77
Coffee Maker	2.0	2.0	-	99
Fan/AC	3.5	3.0	-	93
Air Conditioner	4.0	3.5	3.0	56
Lights	2.0	1.75	1.5	87
Total	-	-	-	808

4.3.2.3. Industrial Microgrid

The network diagram [6,104] of the industrial microgrid which serves mostly the industrial parks and buildings is given in Figure 4.13.

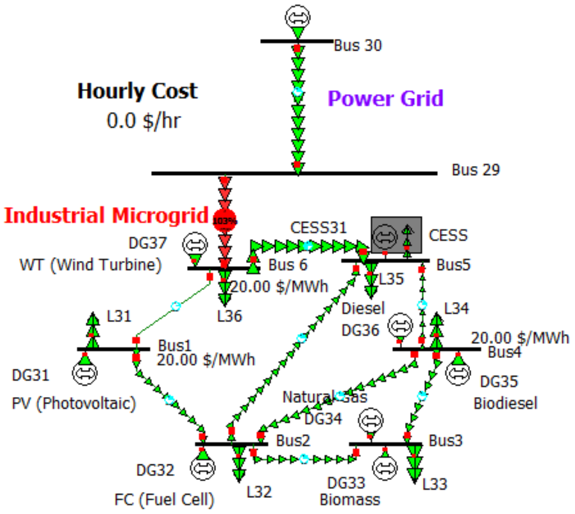


Figure 4.13. Network diagram of the industrial microgrid

Most of the industrial loads are critical and cannot be subjected to load control. The control periods of the devices are similar to those in previous cases. The consumption patterns [91] of the devices are given in Table 4.8. There are over 100 controllable devices available in this microgrid from 6 different types of devices.

Table 4.8. Data of controllable devices in the industrial microgrid

Device Type	Hourly Consumption of Device (kW)						Number Devices
	1st Hour	2nd Hour	3rd Hour	4th Hour	5th Hour	6th Hour	
Water Heater	12.5	12.5	12.5	12.5	-	-	39
Welding Machine	25.0	25.0	25.0	25.0	25.0	-	35
Fan/AC	30.0	30.0	30.0	30.0	30.0	-	16
Arc Furnace	50.0	50.0	50.0	50.0	50.0	50.0	8
Induction Motor	100	100	100	100	100	100	5
DC Motor	150	150	150	-	-	-	6
Total	-	-	-	-	-	-	109

The number of devices available for control in the industrial microgrid is the smallest among all three microgrids. However, the devices have the largest consumption ratings and the longest consumption periods among all three microgrids. The reason for small number of devices available for control can be attributed to reality.

4.3.3. Simulation Results

Simulation studies were carried out on above microgrids. Interaction among distributed energy resources in the microgrid, and interaction between the microgrid and the main grid are the crucial tasks for better development of design and control schemes for microgrids. This research proves that the multi-agent system is one of the best promising approaches to handle the interaction between the elements, and also shows that microgrids at the distribution level provide more reliable supply to the customers.

4.3.3.1. Residential Microgrid

The results obtained from the DSM Agent for the residential microgrid are given in Figure 4.14 and the generation scheduling of the microgrid is given in Figure 4.15.

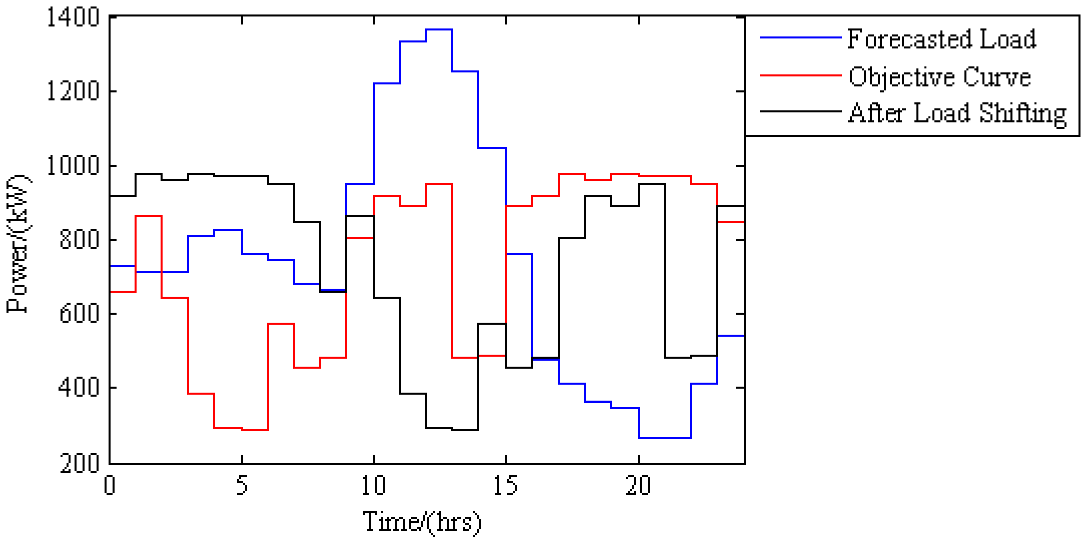


Figure 4.14. DSM results of the residential microgrid

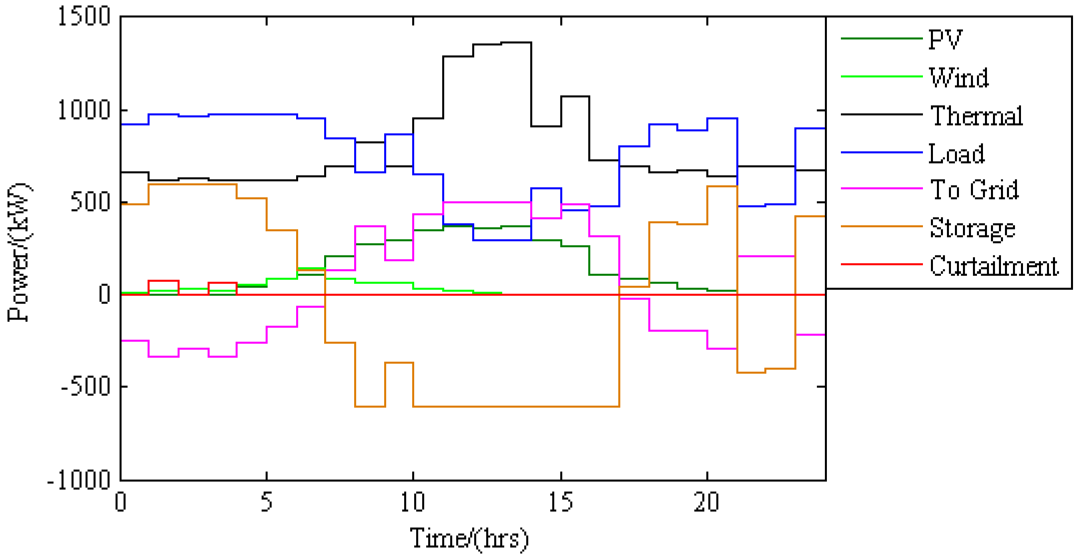


Figure 4.15. Generation scheduling of the residential microgrid

The utility bill of the residential microgrid without demand side management strategy is $2302.90 for the day; whereas, it is $2188.30 with demand side management strategy. There is about 5.0% reduction in the operational cost.

4.3.3.2. Commercial Microgrid

The results obtained from the DSM Agent for the commercial microgrid are given in Figure 4.16, and the generation scheduling of the microgrid is given in Figure 4.17.

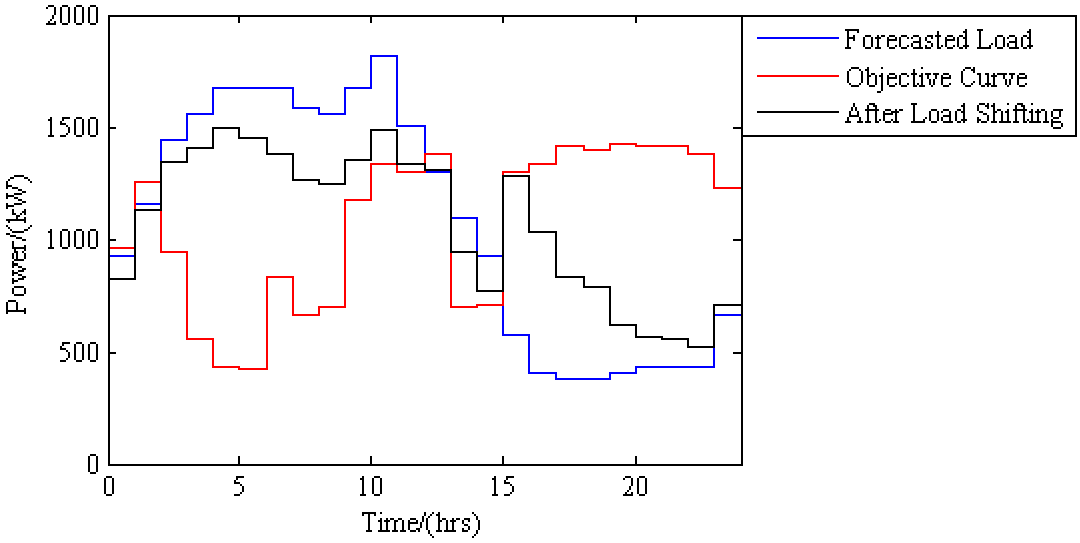


Figure 4.16. DSM results of the commercial microgrid

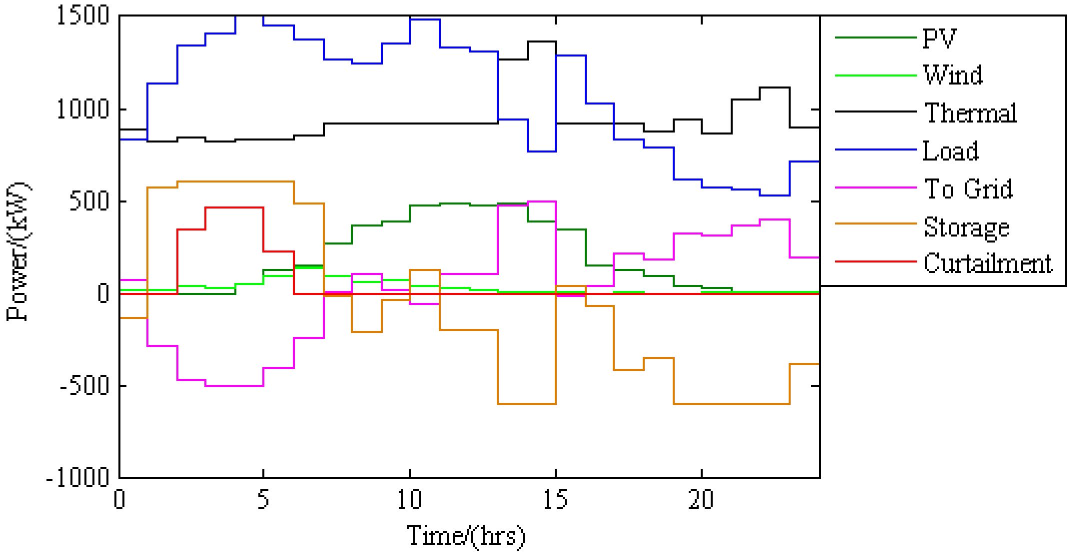


Figure 4.17. Generation scheduling of the commercial microgrid

The utility bill of the commercial microgrid without demand side management strategy is \$3636.60 for the day; whereas, it is \$3424.30 with demand side management strategy. There is about 5.8% reduction in the operational cost.

4.3.3.3. Industrial Microgrid

The results obtained from the DSM Agent for the industrial microgrid are given in Figure 4.18, and the generation scheduling of the microgrid is given in Figure 4.19.

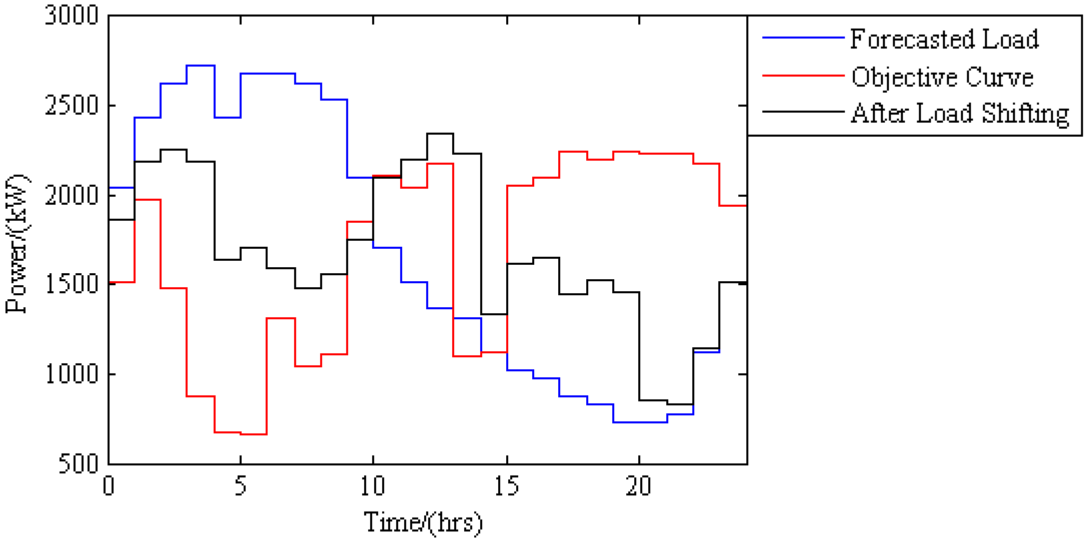


Figure 4.18. DSM results of the industrial microgrid

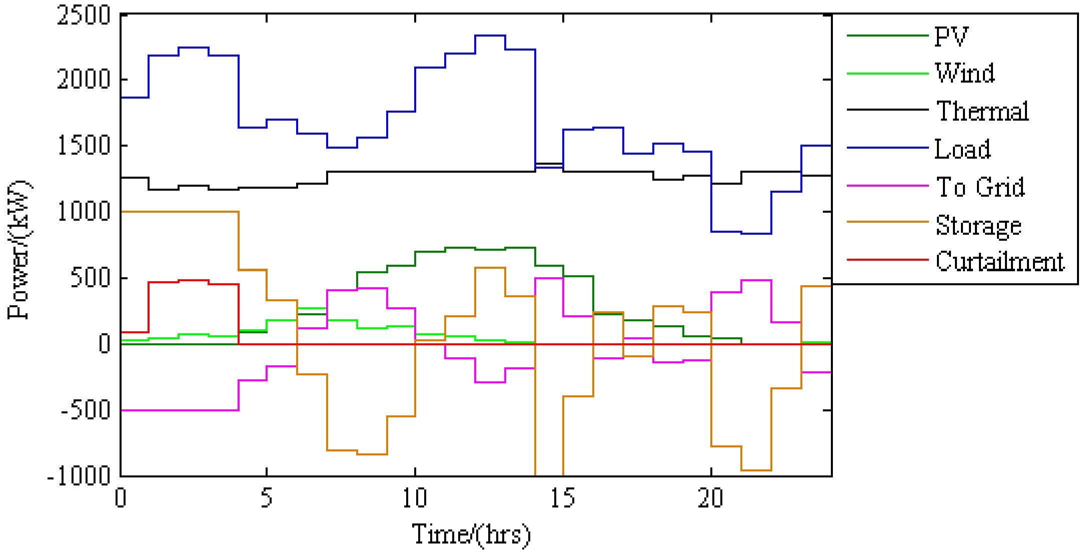


Figure 4.19. Generation scheduling of the industrial microgrid

The utility bill of the industrial microgrid without demand side management strategy is $5712.00 for the day; whereas, it is $5141.60 with demand side management strategy. There is about 10% reduction in the operational cost.

4.3.4. Discussions

It is observed that the proposed demand side management strategy has managed to bring the final consumption closer to the objective load curve in all three cases. The proposed algorithm for the load shifting has handled the larger number of controllable loads of several types, and adopts all heuristics in the smart grid. Table 4.9 summarizes simulation results from the demand side management.

Table 4.9. Operational cost reduction with DSM

Microgrid	Cost without DSM ($)	Cost with DSM ($)	Percentage Reduction (%)
Residential Microgrid	2302.90	2188.30	5.0
Commercial Microgrid	3636.60	3424.30	5.8
Industrial Microgrid	5712.00	5141.60	10.0

The approach has successfully managed to achieve the objective behind it in all three microgrids. Typically, demand side management results will be better when number of devices available for control increases. However, this may not be true in these simulation studies because complexities of the devices under control pose restrictions. Even though the number of devices available for control is the least in the industrial microgrid, the percentage reduction in the operational cost is the highest among all microgrids. On the other hand, the residential microgrid has the highest number of devices available for control in terms of quantity and variety, but the percentage reduction in the operational cost is not much as it is expected. These happened because the power consumptions of devices are high in the industrial microgrid and very low in the residential microgrid. In addition, a small load shifting of high power devices will give a huge saving to the customers.

In a smart grid, benefits of customers will improve with better contract options taken up by customers with utilities. Customers can reimburse by making the contract options. The amount of reimbursement taken by customers through such contract schemes depends on how much inconvenience is willing to undertake by the customers. In case of the residential microgrid, level of tolerance is high for most of the devices. This means that generally the customers have no preference in time when the loads have to be consumed. On the other hand, in case of the commercial and the industrial microgrid, level of tolerance is very low.

Not only demand side management provides benefit to the end users but also it provides advantages to the utilities. One of the main advantages to the system is the reduction in the peak load demands. Table 4.10 shows the peak load demands with and without the demand side management strategy for each microgrid. It is shown that the proposed demand side management strategy reduces the peak load demand of each microgrid. Reduction in the peak load demand increases the grid sustainability by reducing the overall cost and carbon emission levels. Furthermore, this will lead to avoiding the construction of an under-utilized electrical infrastructure in terms of generation capacity, transmission lines and distribution networks.

Table 4.10. Peak demand reduction with DSM

Microgrid	Peak Load Without DSM (kW)	Peak Load With DSM (kW)	Peak Reduction (kW)	Percentage Reduction (%)
Residential Microgrid	1363.6	1114.4	249.2	18.3
Commercial Microgrid	1818.2	1485.2	333.0	18.3
Industrial Microgrid	2727.3	2343.6	383.7	14.2

The reduction in peak load demands would provide huge cost savings for generation companies. Normally, costly generators will be turned on to provide power during the peak load demands. Therefore, when system peak load demand reduces, the operational cost of generators will be reduced substantially. This would also result in increasing reserve generation capacity of the system. Figures 4.15, 4.17 and 4.19 show the generation scheduling of residential, commercial and industrial microgrids respectively. The industrial microgrid spends $252.15, and the commercial microgrid spends $157.52, whereas, the residential microgrid saves $345.82 for the scheduling day. As a whole, the smart grid saves $103.70 without any unsatisfied demand during the scheduling day.

Table 4.11 shows the cost saving of each microgrid from generation companies point of view and unsatisfied load demand of each microgrid. The results show that demand side management is indeed beneficial to both consumers and the utility companies. In the simulation studies, customers achieve from 5% to 10% of saving and generation companies archive a substantial saving by generation scheduling. In addition, transmission companies achieve from 15% to 20% reduction in the network congestion.

Table 4.11. Additional saving from generation scheduling

Microgrid	Additional Saving by DSM ($)	Unsatisfied load (kWh)	
		Without DSM	With DSM
Residential Microgrid	120.34	0	0
Commercial Microgrid	393.81	0	0
Industrial Microgrid	443.36	346.34	0

The above simulation studies are a part of a real power system. The actual cost savings and peak reduction for the real power system will be much higher when the proposed strategy is applied to the real power system. The above simulation studies are just examples to show how the proposed demand side management strategy and proposed generation scheduling methodology could be applied for smart grid operation.

The proposed demand side management strategy is a generalized technique based on load shifting. The inputs to the problem are: control period (i.e. number of time steps), discrete model of devices' load consumption pattern, power consumption at each time step and uncertainties. The simulation results show that proposed day-ahead demand side management strategy provides substantial savings and several advantages for the operation of smart grid. It is also necessary to develop real-time demand side management techniques such as load curtailment, load shedding and load shifting for the real-time operation of a smart gird [91].

4.4. Grid-Connected Integrated Microgrid Operation

Figure 4.20 shows the schematic diagram of an integrated microgrid [6], which contains three microgrids namely residential, commercial and industrial microgrids, and interconnected with each other. This integrated microgrid was used for the simulation studies in this chapter. The operation of an integrated microgrid can be formulated as the operation of single microgrids together with the interaction of the microgrids. The problem formulation and the operational scheme for operation of integrated microgrids are given in Chapter 3.

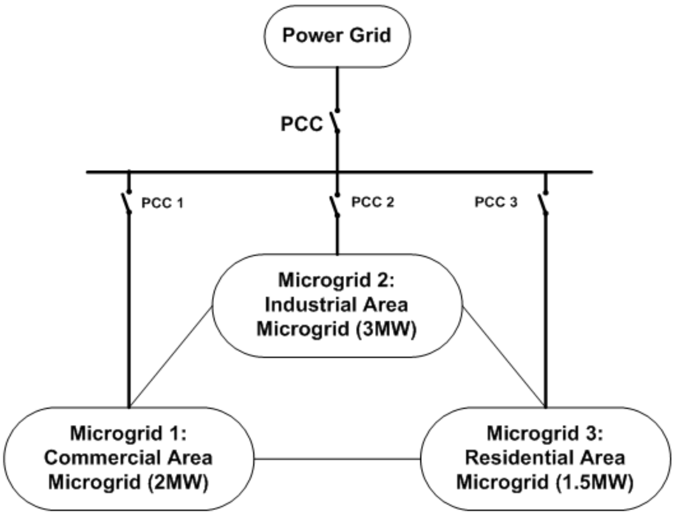


Figure 4.20. Schematic diagram of an integrated microgrid

4.4.1. Coordination of Agents

According to the proposed control architecture, Distribution Network Operator (DNO) and Market Operator (MO) handle the operation of integrated microgrids. The distribution network operator and the market operator behave similar to ISO (Independent System Operator) and PX (Power Exchange) in deregulated power systems respectively. In a day-ahead market [1,2,5], distributed generators bid for a set of supplies at various prices, and loads bid for a set of demands at various prices for a 24-hour window. Market clearing prices and market clearing quantities are determined for each hour based on their bids.

The market operator handles the market operation and schedules supplies and demands with the help of the distribution network operator. The distribution network operator finalizes the schedules without any technical violations of the electrical network. In this multi-agent system, intelligent agents represent individual autonomous entities, and interact with other agents proactively. Interaction of agents and respective messages for the day-ahead scheduling based on the proposed operational strategy are shown in Figure 4.21.

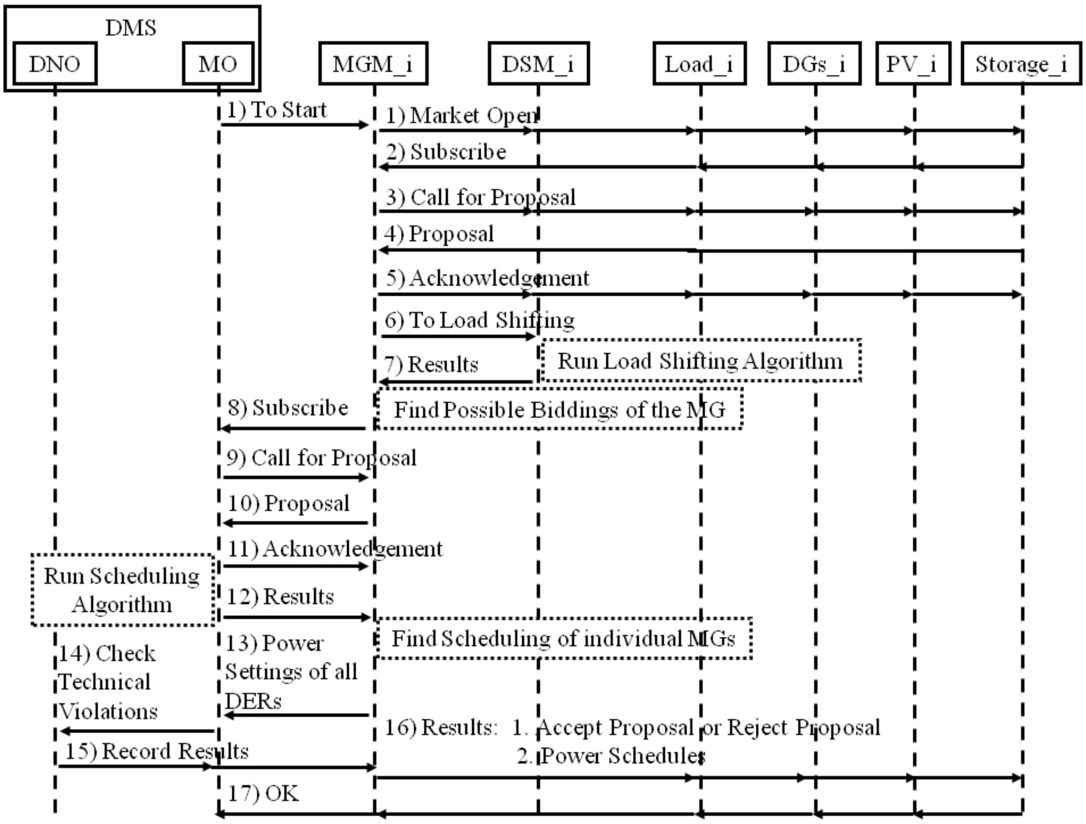


Figure 4.21. Interaction of agents for grid-connected integrated microgrid

4.4.2. Simulation Studies

Simulation studies were carried out on an integrated microgrid [6,104] which contains three microgrids: a 3MW industrial microgrid, a 2MW commercial microgrid and a 1.5MW residential microgrid, and interconnected with each other in a distributed power system. The residential microgrid serves an area that contains primarily residential customers, the industrial microgrid serves an area with several workshops and factories, and the commercial microgrid serves commercial consumers. A schematic diagram of the integrated microgrid is shown in Figure 4.20. Figure 4.22 shows the electrical network of the integrated microgrid.

This integrated microgrid is the combined distributed power system of the three microgrids used in the simulation studies in Chapter 5. The entire electrical network operates at 410V. Interconnection links including the ones between the microgrids and the main distribution grid have a resistance of 0.003pu, a reactance of 0.01pu and maximum power transferring limit of 500kVA. Length of the interconnection links in the residential microgrid, commercial microgrid and industrial microgrid is 2km, 3km and 5km respectively.

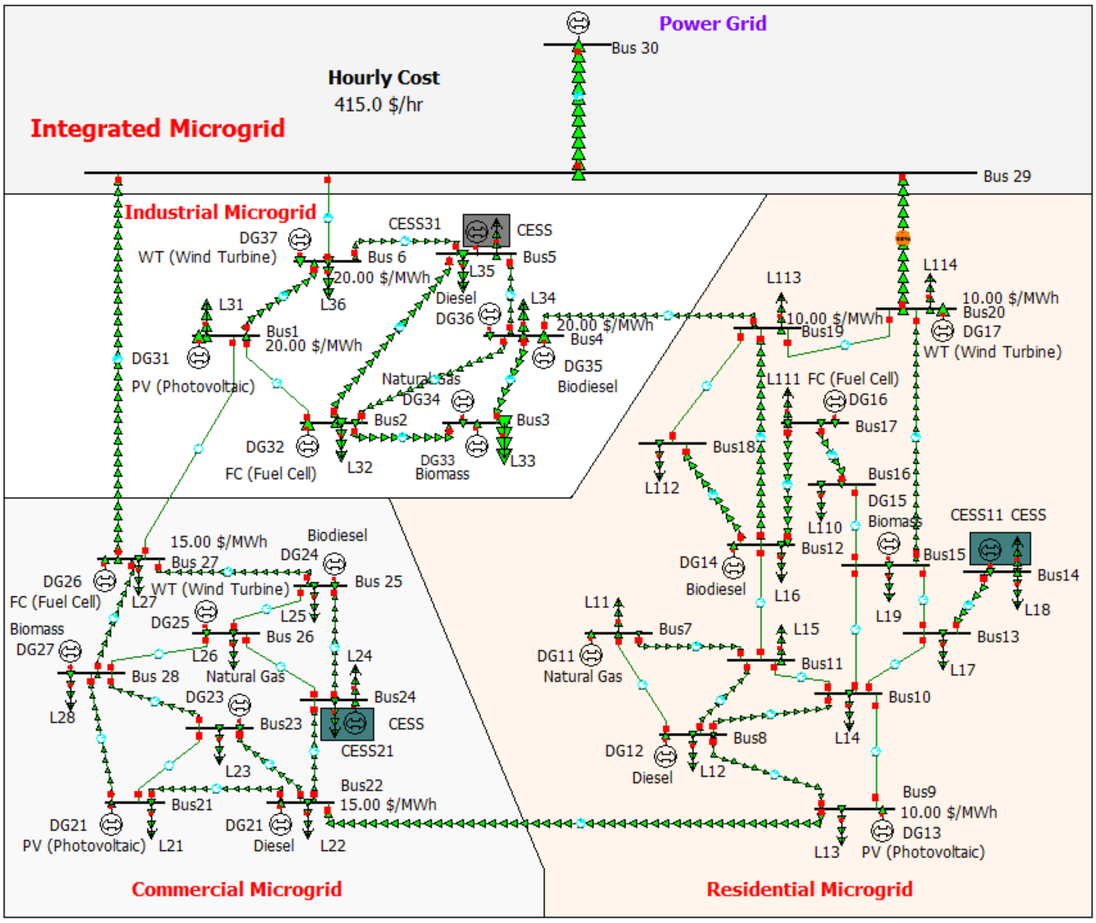


Figure 4.22. Electrical network diagram of the integrated microgrid

Various Distributed Generators (DG), such as the Micro Turbine (MT), Diesel Generator (Die. G), Fuel Cell (FC), Wind Turbine (WT) and Photovoltaic (PV) systems together with the storage system are installed in all microgrids. The placements of the distributed generators are shown in the electrical network diagram [6,104]. The distribution of load demands and the installed capacities of distributed generators are given in Table 5.4 and Table 5.5 respectively.

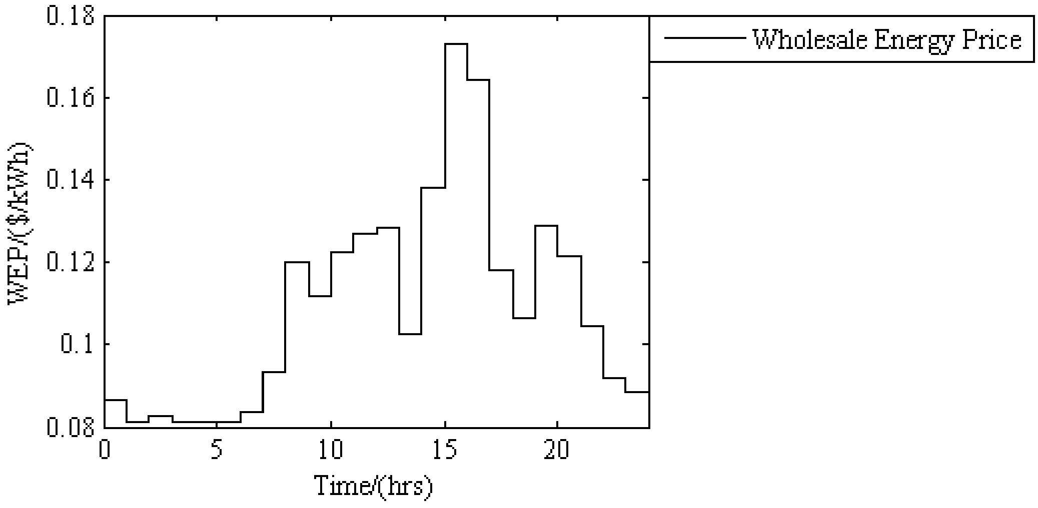


Figure 4.23. Hourly wholesale energy prices

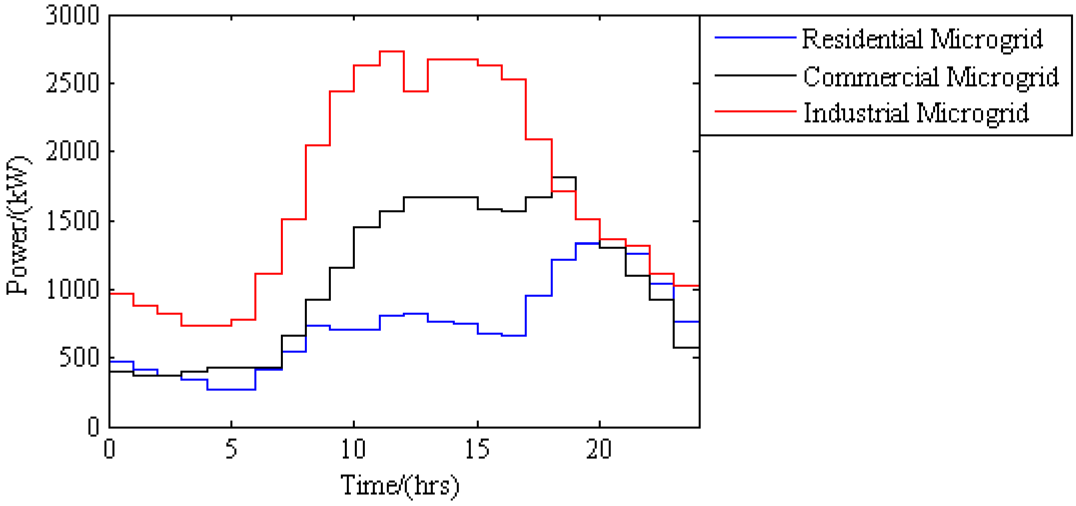


Figure 4.24. Hourly forecasted load demands

All distributed generators produce power at unity power factor, and power factor of each load is unity. Wind power and PV power productions that have been determined from the models proposed in [105] are given in [94]. A typical day, 30 March, 2009 was chosen for the simulation studies. Hourly wholesale energy prices [102] and typical load demand profile of each microgrid are given in Figure 4.23 and Figure 4.24 respectively.

4.4.3. Simulation Results

Simulation studies were carried out on the system for 24-hour period of the day. The devices subjected to load control are from different types, and have different power consumption ratings and patterns. There are over 2600 controllable loads in the residential microgrid from 14 types of devices, over 800 controllable loads in the commercial microgrid from 8 types of devices and over 100 controllable loads in the industrial microgrid from 6 types of devices available. The details about the controllable loads can also be found in the previous chapter [6].

The resultant load demand profiles obtained from load shifting by the demand side management agent (DSM Agent) are given in Figure 4.25.

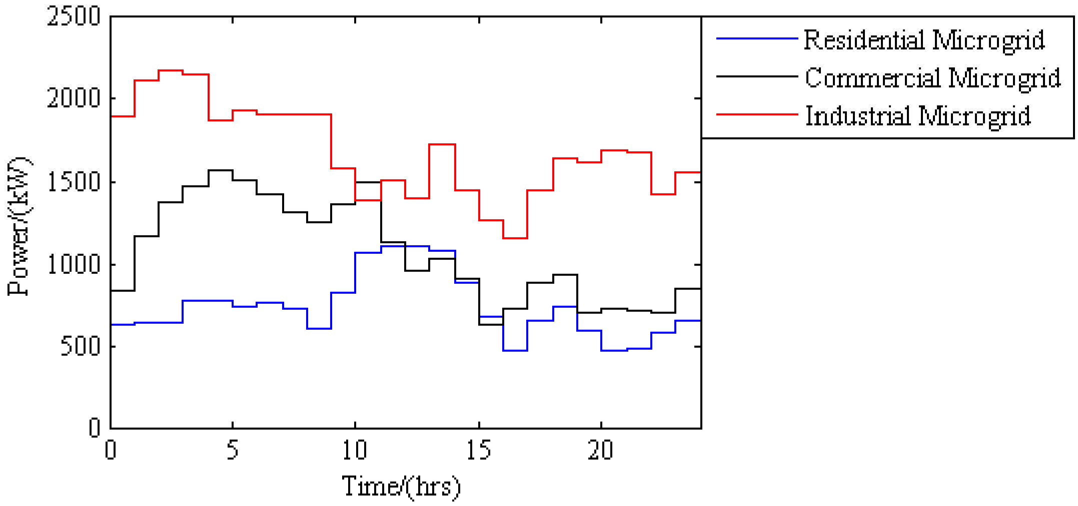


Figure 4.25. Load demands after load shifting

The system has achieved additional profits about 6.0% from the residential microgrid, 7.3% from the commercial microgrid, and 16% profit from the industrial microgrid by load shifting. Once DSM Agent has calculated the optimal load demand profiles, the schedule coordinator agent (SC Agent) starts coordination among the other agents for generation scheduling.

Figure 4.26 shows power exchange among the microgrids, and power exchange between the main distribution grid and the integrated microgrid.

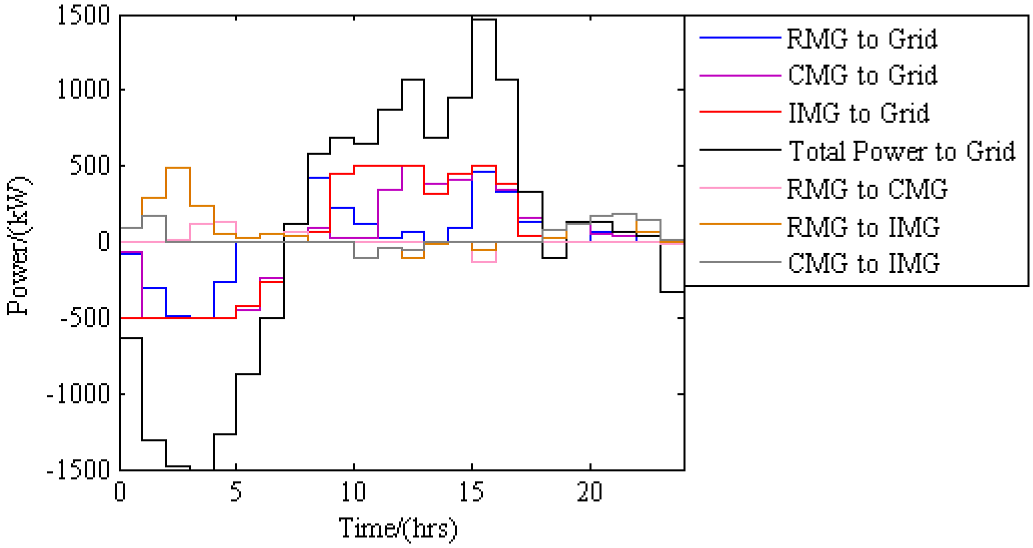


Figure 4.26. Power exchanges among the control entities

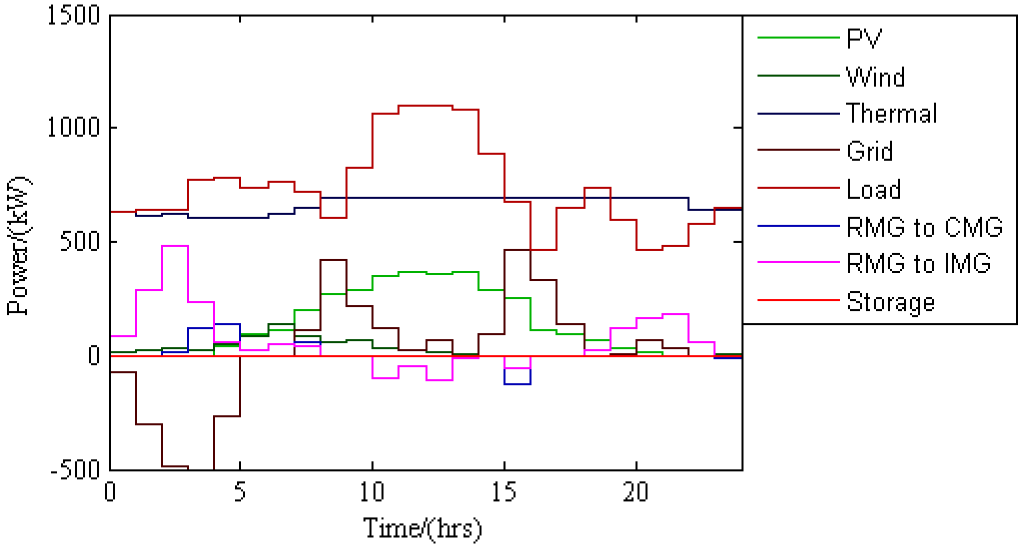


Figure 4.27. Generation scheduling of the residential microgrid

The integrated microgrid receives power from the main distribution grid from 0hr to 7hrs, from 18hrs to 19hrs, and from 23hrs to 24hrs, and it supplies power to the main grid for the rest of the time. From 3hrs to 4hrs, the power exchange between the main distribution gird and the integrated microgrid is the maximum of 1500kW.

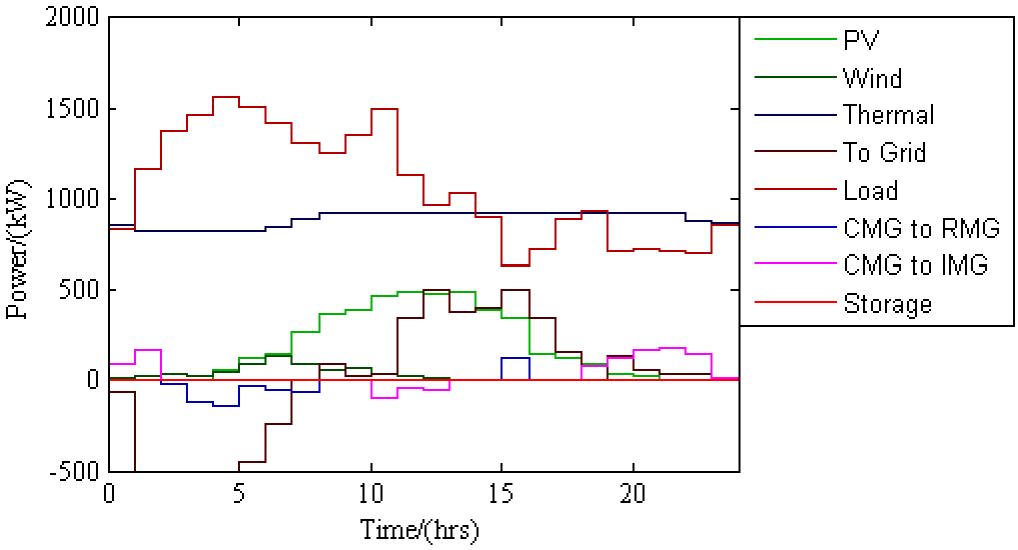


Figure 4.28. Generation scheduling of the commercial microgrid

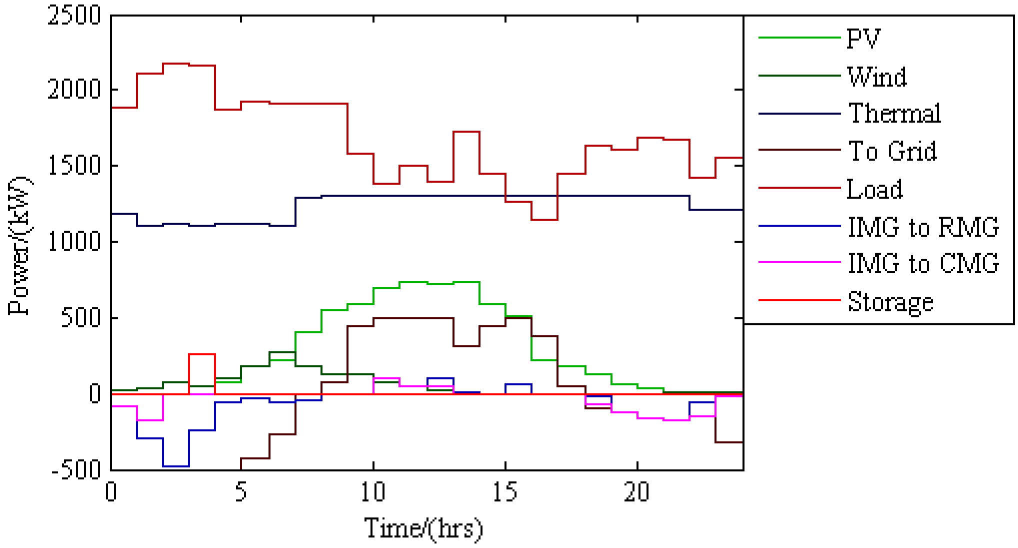


Figure 4.29. Generation scheduling of the industrial microgrid

Figures 4.27, 4.28 and 4.29 show power settings of energy sources such as photovoltaic system, wind turbine, storage system and the other distributed generators, power exchanges among the microgrids, and power exchange with the main distribution grid for the residential microgrid, the commercial microgrid and the industrial microgrid respectively.

As it can be seen from the results, during the simulation of the system over the 24-hour period, the multi-agent system has optimized the operation of integrated microgrid. In this period, the industrial microgrid spends $252.15, and the commercial microgrid spends $157.52, whereas, the residential microgrid saves $345.82. As a whole, the integrated microgrid spent only $103.70 without any unsatisfied demand during the scheduling period.

4.4.4. Discussions

This section presents the simulation studies on the developed multi-agent system for the operation of a grid-connection integrated microgrid. The proposed control scheme maximized the power production output of local distributed generators, and optimized power exchanges among the microgrids as well as power exchange between the main distribution system and the integrated microgrid. Simulation studies carried out on the developed system demonstrate the effectiveness of the proposed multi-agent system for the operation of an integrated microgrid.

In order to demonstrate the effects of interconnection links among the microgrids at distribution level, another study was carried out on the integrated microgrid without interconnection links among the microgrids. During the operation, the multi-agent system has optimized the operation of integrated microgrid while minimizing the unsatisfied demand in the system. From this study, it is found out that the industrial microgrid spends $525.34 and the commercial microgrid spends $153.32, whereas, the residential microgrid saves $345.63. As a whole system, the integrated microgrid spent only $333.03 with an unsatisfied demand of 912.2kWh during the simulation period. Therefore, interaction among control entities such as microgrids, distributed energy resources and the main distribution grid are needed to handle carefully in the development of design and control schemes for integrated microgrids.

4.5. Islanded Integrated Microgrid Operation

This section presents some simulation studies on the developed multi-agent system for the operation of an islanded integrated microgrid [15]. Figure 4.30 shows a schematic diagram of an islanded distributed power system with microgrids and lumped loads, which was used for the simulation studies in this section.

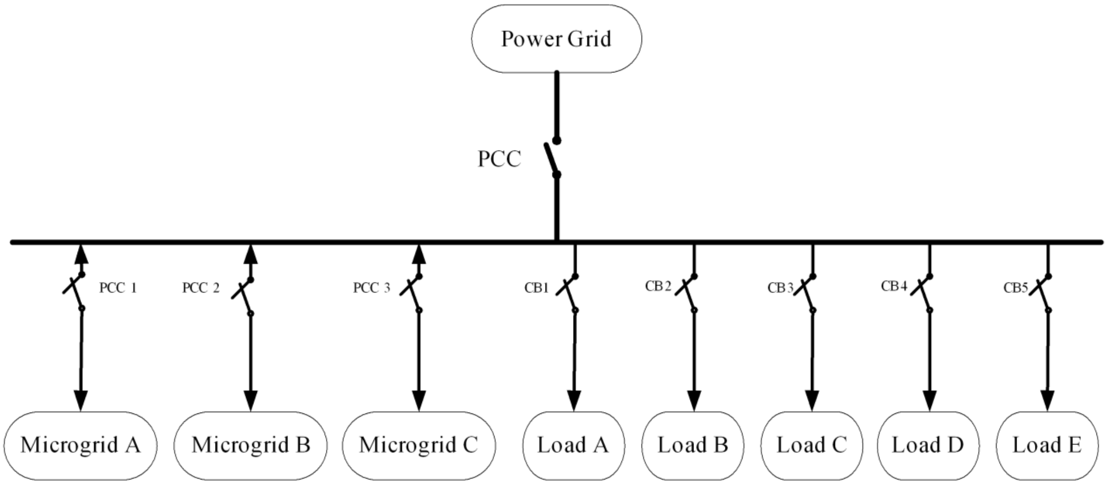


Figure 4.30. Schematic diagram of an islanded distributed power system

4.5.1. Coordination of Agents

Similar to the operation of the grid-connected integrated microgrid, distribution network operator and market operator handle the operation of the islanded distributed power system too. Distributed generators bid a set of supplies at various prices, and loads bid a set of demands at various prices for a 24-hour window. Market clearing prices and market clearing quantities are determined for each hour based on their bids.

Intelligent agents interact with other agents proactively. Interaction of agents and respective messages for a day-ahead scheduling based on the proposed operational strategy are shown in Figure 4.31.

Using the proposed bidding strategy, each microgrid finds the maximum possible bids that can be submitted to the main power system market for the forecasted market prices on corresponding periods. The main power system market for the islanded distributed power system is proposed with PoolCo energy market, where electricity business among the microgrids and lumped loads is carried out. PoolCo market provides a competitive environment among these control entities.

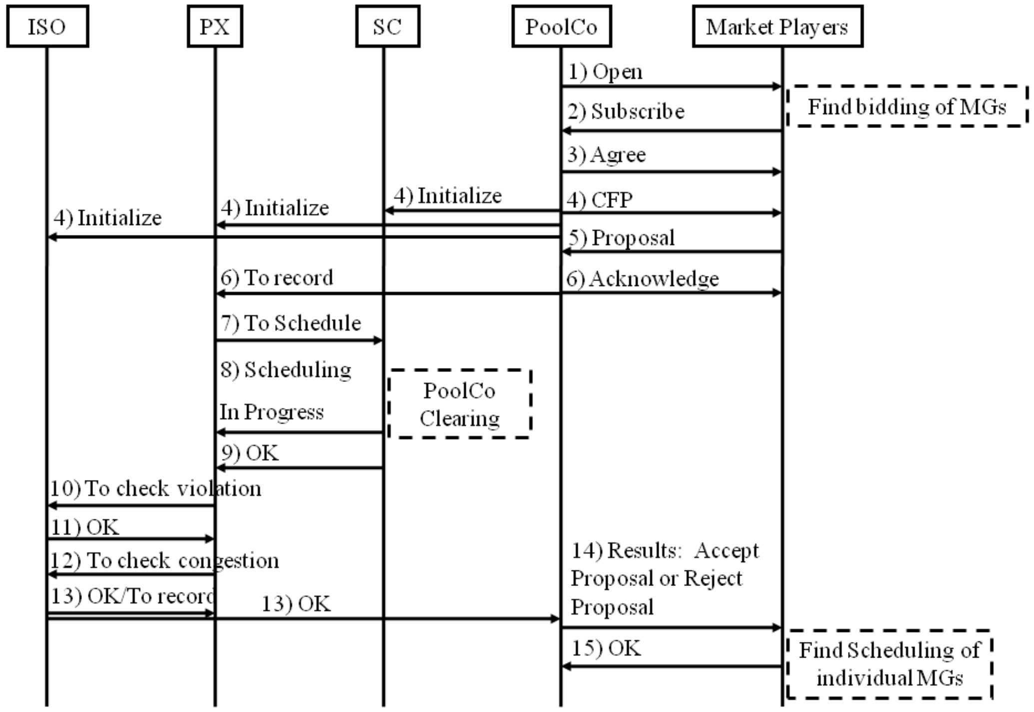


Figure 4.31. Coordination of agents for islanded integrated microgrid

Each microgrid and lumped load submits their bids to the market, where these bids are summed up, and matched the interested loads and supplies. Market operator performs the economic dispatch and produces a market clearing price at each time. Winning microgrids are paid market clearing price for their successful bids while successful bids of loads are obliged to purchase electricity at market clearing price. The typical PoolCo market clearing algorithm as explained in [1,2] is proposed and implemented on the multi-agent system. At the final stage of scheduling, each microgrid is rescheduled individually to satisfy their total load demands which are the addition of internal load demands and the load demands from the results of the wholesale energy market. The same algorithm that was used for scheduling of microgrid in the grid-connected integrated microgrid was used here for scheduling of each microgrid.

4.5.2. Simulation Studies

The simulation system [15] consists of three microgrids and five lumped loads. A schematic diagram of the system is shown in Figure 4.31. Figure 4.32 shows the electrical network [15] of the distributed power system.

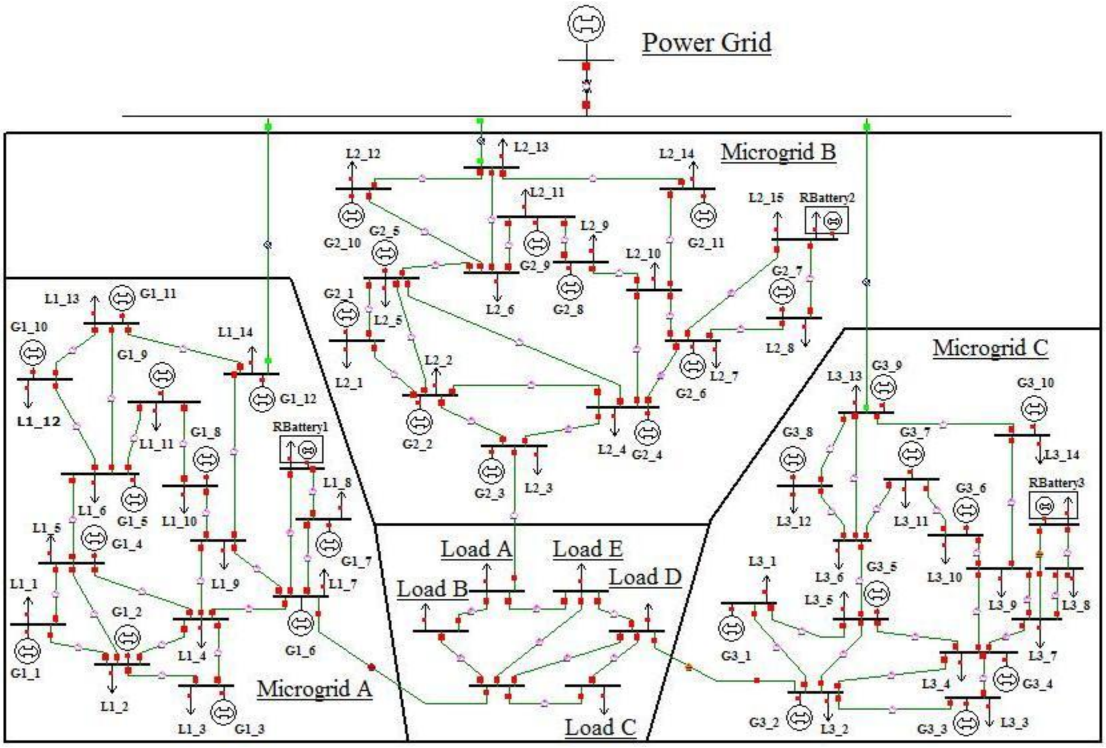


Figure 4.32. Electrical network diagram of the distributed power system

This network diagram is taken from an Indonesian power grid. The entire electrical network operates at 410V. Interconnection links including the ones between the microgrids and the main distribution grid have a resistance of 0.003pu, a reactance of 0.01pu and maximum power transferring limit of 500kVA. Length of the interconnection links is 5km.

Each microgrid operates as an independent power producer and each lumped load has individual load management system. While satisfying the own load demand, each microgrid bids in the energy market to sell electricity to outside the microgrid. Each microgrid and lumped load has facilities to forecast hourly demands and market prices. Details of distributed energy resources in each microgrid are given in Table 4.12, and details of distributed generators (i.e. DG units in Table 4.12) are given in Table 4.13. In this case study, all the unit and system constraints expect ramp up and ramp down rates as given in the problem formulations are considered.

Table 4.12. Details of DERs in the microgrids

Parameters	Microgrid A	Microgrid B	Microgrid C
Maximum Load	2MW	1.5MW	1MW
DG Units	Unit 1 - Unit 12	Unit 2 - Unit 12	Unit 3 - Unit 12
PV Systems	3×360kWp	2×360kWp	1×360kWp
Wind Plants	3×140kWp	2×140kWp	1×140kWp
Maximum Renewable Penetration	1000kW	750kW	500kW
Battery Bank	1×500 kW, 2.5MWh	1×500 kW, 2.5MWh	1×500 kW, 2.5MWh

Simulation studies were carried out on a typical day. Figure 4.33 shows the forecasted load demands, and Figure 4.34 shows forecasted market prices for each microgrid and lumped load. Bidding Quantities (BQ) of each microgrid and lumped load that are calculated according to the proposed bidding strategy are given in Figure 4.35.

Table 4.13. Data of thermal units

Parameters	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
Maximum Power (kW)	410	410	270	270	140	140
Minimum Power (kW)	100	100	50	50	25	25
a (cts/hr)	65	60	45	41	40	38
b (cts/kWh)	15.20	15.30	16.60	16.50	18.50	18.76
c (cts/kW^{2}hr)	0.00052	0.00061	0.0021	0.00211	0.0042	0.0053
Minimum Up Time (hr)	5	5	3	3	2	2
Minimum Down Time(hr)	5	5	3	3	2	2
Hot Start-up Cost (cts)	550	500	450	460	800	750
Cold Start-up Cost(cts)	1100	1000	900	920	1600	1500
Cold Start Time (hr)	3	3	2	2	1	1
Initial Status (hr)	5	5	3	3	2	-2

Parameters	Unit 7	Unit 8	Unit 9	Unit 10	Unit 11	Unit 12
Maximum Power (kW)	90	90	65	65	45	45
Minimum Power (kW)	20	20	15	15	10	10
a (cts/hr)	38	35	30	24	18	15
b (cts/kWh)	26.70	26.90	29.71	29.92	26.20	26.79
c (cts/kW^{2}hr)	8	12	9	13	24	31
Minimum Up Time (hr)	2	2	1	1	1	1
Minimum Down Time(hr)	2	2	1	1	1	1
Hot Start-up Cost (cts)	360	350	280	285	200	205
Cold Start-up Cost(cts)	720	700	560	570	400	410
Cold Start Time (hr)	1	1	0	0	0	0
Initial Status (hr)	-2	-2	-1	-1	-1	-1

The reserves for the microgrids are considered as 10% of hourly internal load demands of the microgrids. Details about the battery bank, photovoltaic system and wind plant are given in [94]. The power from the renewable-battery system is calculated from the meteorological data for the day. Various constraints on generating units and system constraints discussed in [94,95] were included in the simulation studies.

Similar to the operation of a grid-connected integrated microgrid, the steady-state security is considered for the operation of islanded distributed power system with the help of Power World simulator at the final stage of the scheduling. Power World simulator confirms the operation of the system without any technical violations. Furthermore, it decides the final power settings and prices of the sources.

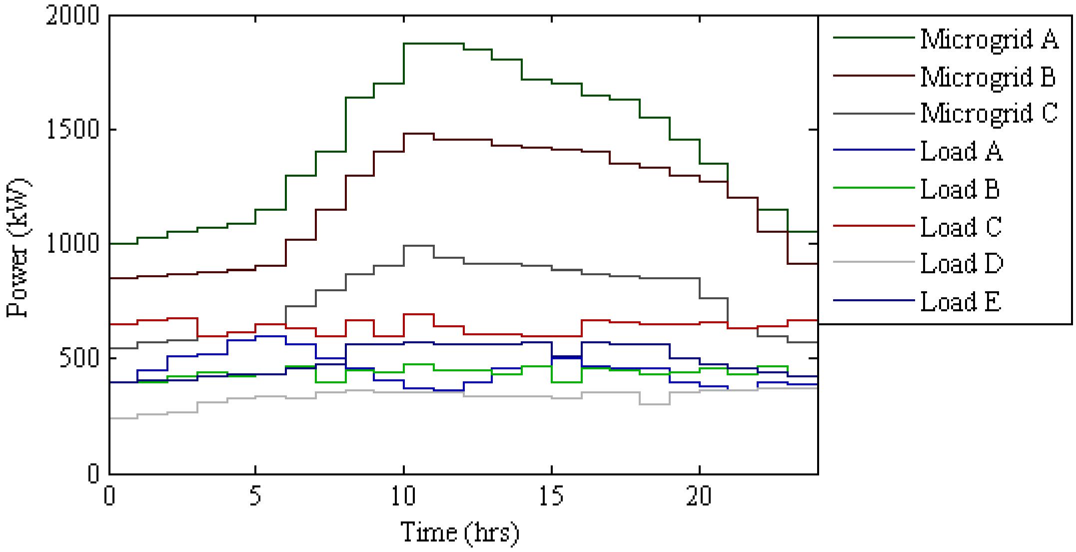


Figure 4.33. Forecasted load demands of each microgrid and lumped load

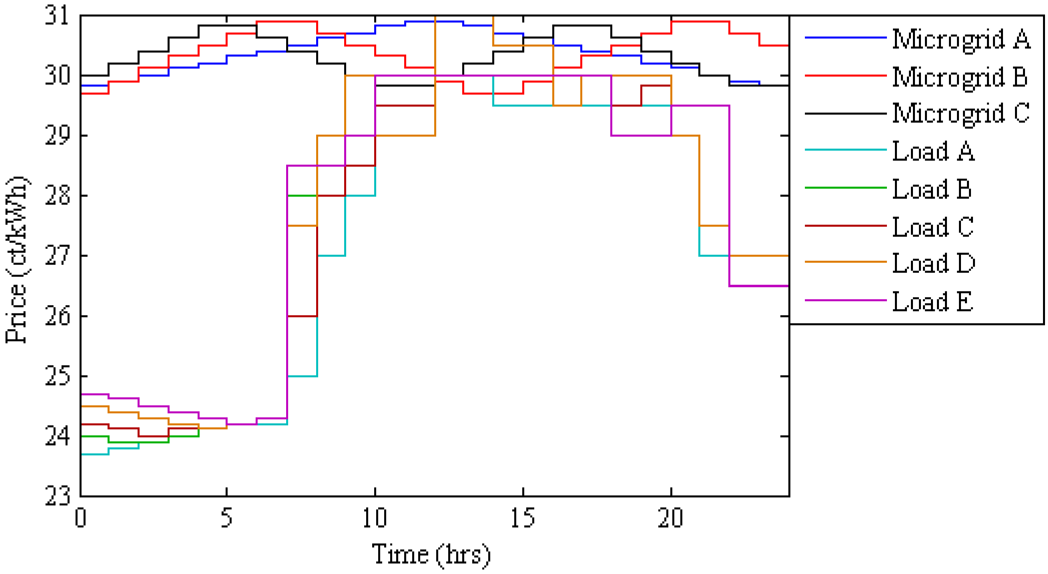


Figure 4.34. Forecasted market prices of each microgrid and lumped load

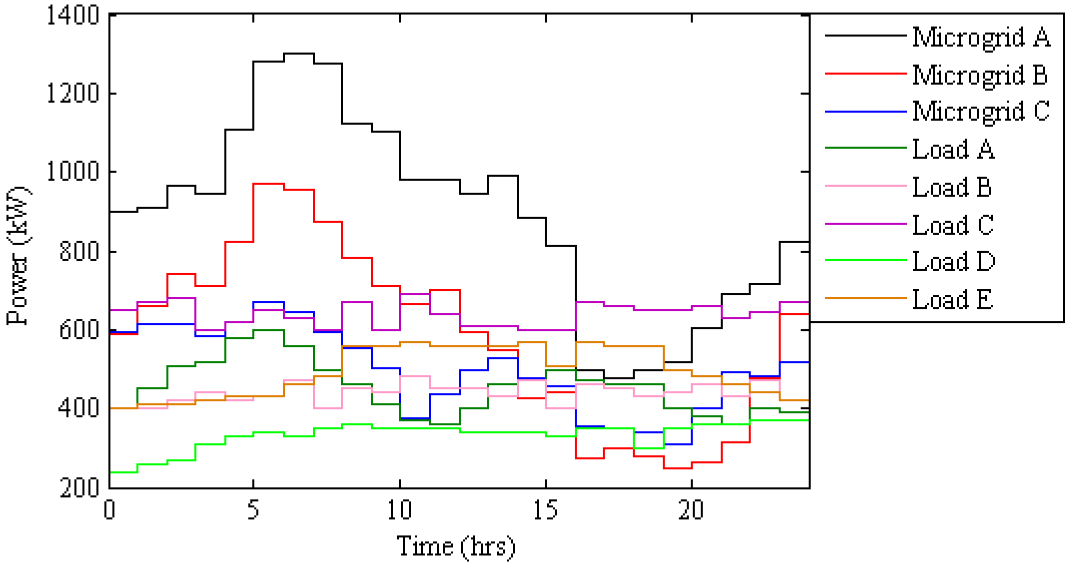


Figure 4.35. Bid Quantities (BQ) of each microgrid and lumped load

4.5.3. Simulation Results

Simulation studies were carried out on the above distributed power system. Scheduling at the system level is based on PoolCo market, where microgrids compete for selling power. If bids submitted by the microgrids are too high, they have low possibility to sell their power. Similarly, lumped loads compete for buying power. If bids from lumped loads are too low, they have a low possibility to get the required power. In such a model, low priced microgrid and high priced lumped load would essentially be rewarded. As each microgrid and lumped load have own market price forecasting, they bid at their forecasted market prices. Therefore, any market player succeeds in the energy market, if they have good forecasted market prices.

According to the proposed market clearing algorithm, successful bidding quantities of market players depend on the bidding quantities and bidding prices of all market players. One of the main objectives of this study is to propose an optimal operational strategy for an islanded distributed power system which contains several microgrids. The simulation results verify the optimal operation of the system.

Figures 4.36, 4.37 and 4.38 show the power settings of each distributed energy resources in microgrid A, microgrid B and microgrid C respectively.

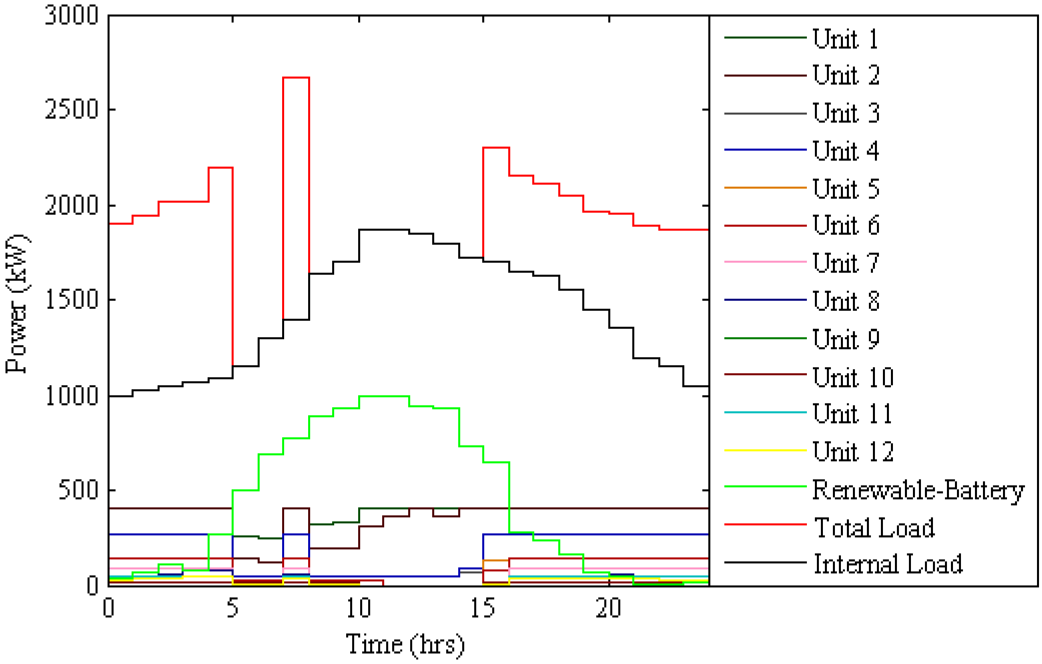


Figure 4.36. Power settings of DERs and load demand of the microgrid A

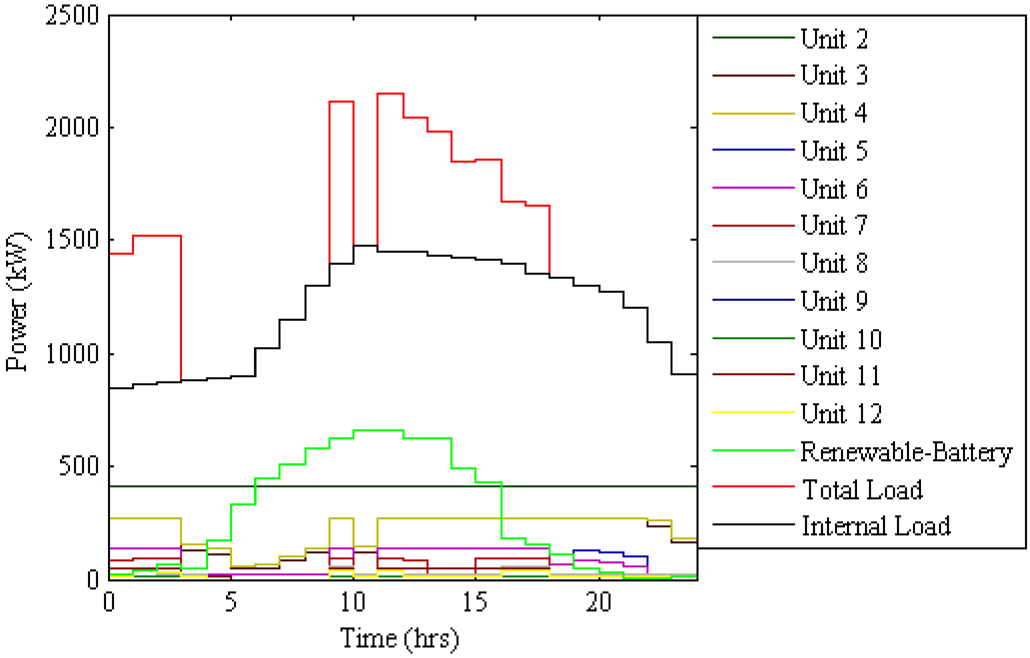


Figure 4.37. Power settings of DERs and load demand of the microgrid B

Figure 4.39 shows the market clearing prices and Figure 4.40 shows the Successful

Bidding Quantities (SBQ) which are the market outcomes from the PoolCo market.

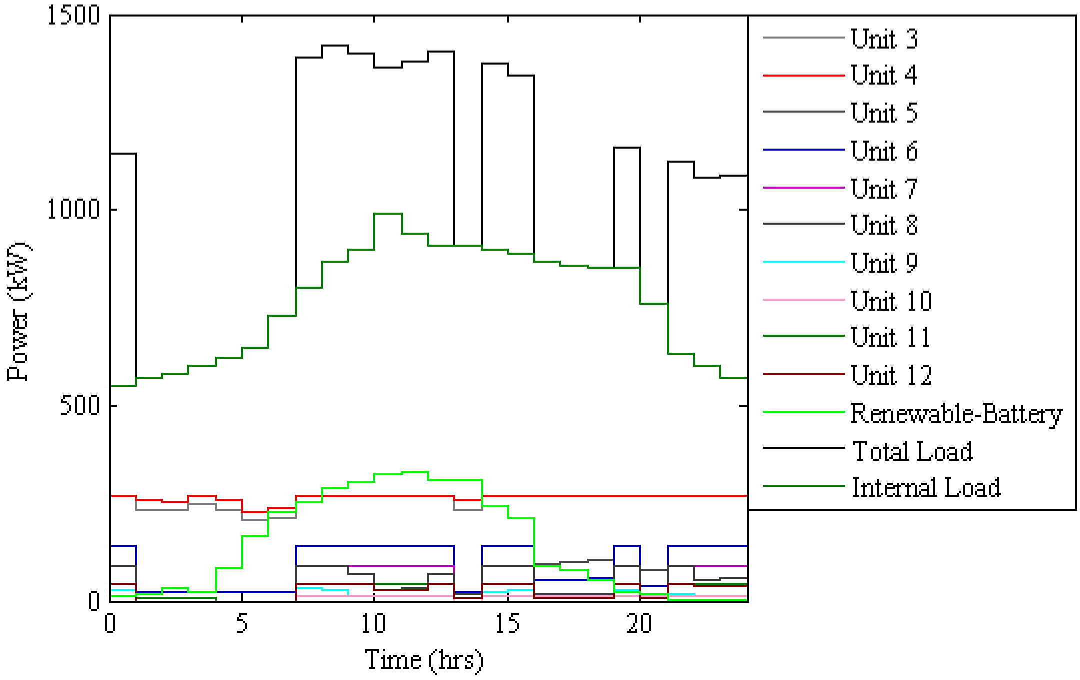


Figure 4.38. Power settings of DERs and load demand of the microgrid C

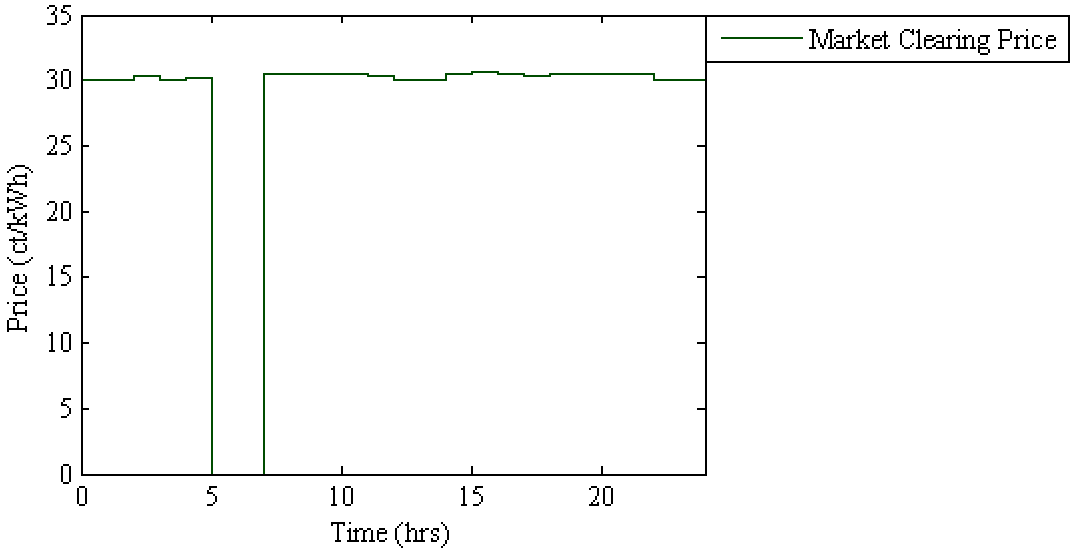


Figure 4.39. Market clearing prices

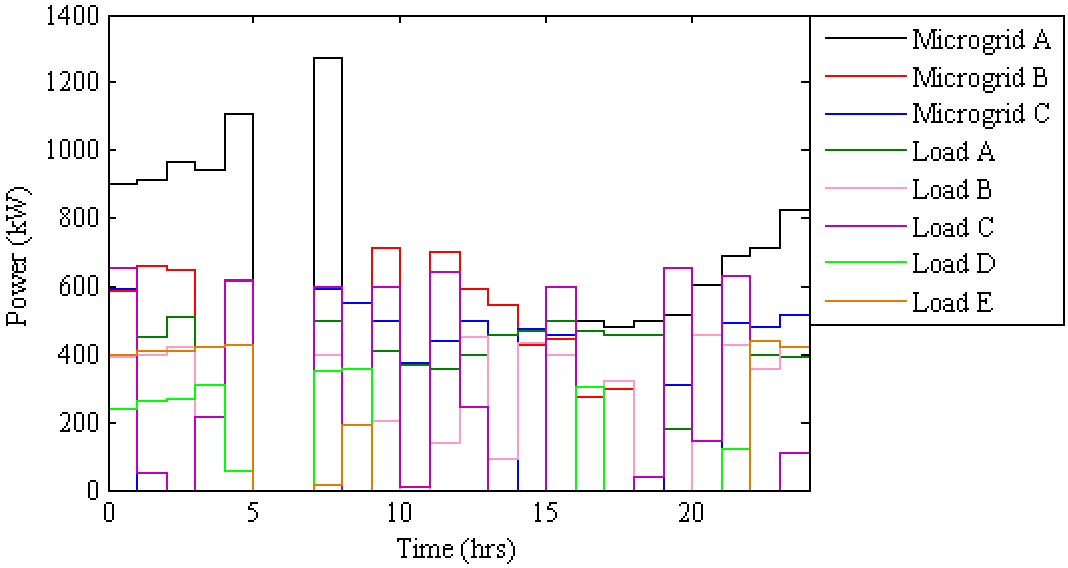


Figure 4.40. Successful Bid Quantities (SBQ) of each microgrid and lumped load

4.5.4. Discussions

As it can be seen from the results, no market player always succeeds throughout the 24 hour window. The successful market players are different from hour to hour, which are distributed among all market players. This reflects that none of the market players has accurate market price forecasting in this study. On the other hand, a market player can get success in all 24 hours. According to the proposed bidding strategy, bidding quantity of a microgrid depends on forecasted market prices, amount of internal load demand, initial states of distributed energy resources, and uncertainties and intermittent behaviours of the distributed energy resources.

Furthermore, market prices from 5hrs to 7hrs are zeros because there is no intersection of supply and demand curves in the main market. The development of the proposed market clearing algorithm does not consider this scenario. Therefore, it is necessary to do more research and development on the market clearing algorithm to handle this scenario also.

This simulation study is a prevalent case study in countries like Indonesia, Philippines and India, where mining industries are built in rural area. As there is no main power supply available in these areas, most of the power system companies compete to setup their microgrids in these areas.

Additionally, the future power systems will consist of several microgrids at the distribution level. Therefore, intensive research on design, development and implementation of distributed power systems with several microgrids is necessary. A study on extensive microgrids, which is part of a big electrical network, is critical for the development of control schemes not only for integrated microgrids but also for single microgrids.

This section presents multi-agent system approach for energy resource scheduling of an islanded distributed power system with distributed resources. The system consists of a set of microgrids and lumped loads, which are electrically connected and complemented by a communication system. The lumped loads represent the sum of loads in the areas, which are restricted by separate management authorities. The power system is successfully monitored, controlled and operated by means of the developed multi-agent system.

4.6. Summary

In this chapter, some of the smart grid characteristics were demonstrated clearly. In particular, market based operation of microgrids in cooperative and competitive environments were modelled with the multi-agent system. Some simulation studies were carried out on the operation of different types of microgrids operating under different types of environments. Then, the developed multi-agent system is extended for the operation of distributed power systems with integrated microgrids and some simulation studies were carried out for the operation of distributed power systems in grid-connected and islanded modes with realistic values of bids, market prices, load profiles and renewable power productions. Simulation results show that the multi-agent system maximized the power production output of local distributed generators, optimized power exchanges among the microgrids as well as power exchange between the main distribution system and the integrated microgrid and maximized the revenues for microgrid operators. It also shows that the multi-agent system provides a platform for the interconnection among the control entities to provide a reliable supply to the customers.

Interaction among distributed energy resources in the microgrid, and interaction between the microgrid and the main grid are the crucial tasks for better development of design and control schemes for microgrids. This research proves that the multi-agent system is one of the best promising approaches to handle the interaction among the elements and also shows that microgrids at the distribution level provide more reliable supply to the customers.

CHAPTER 5

REAL-TIME SIMULATIONS OF MICROGRID MANAGEMENT

5.1. Overview

This chapter presents the multi-agent system approach for the real-time control and management of a microgrid. The proposed real-time operational strategy is mainly focused on generation scheduling and demand side management. The schedule coordinator agent executes a two-stage generation scheduling: day-ahead scheduling and real-time scheduling. The day-ahead scheduling estimates hourly power settings of distributed energy resources from an energy market. The real-time scheduling updates the power settings of the distributed energy resources by considering the results of the day-ahead scheduling and feedback from the real-time simulation of the microgrid in Real-Time Digital Simulator (RTDS) [89]. Demand side management agent does the load shifting before the day-ahead scheduling and curtails load in real-time whenever it is necessary and possible.

The remaining paper is organized as follows. Section 5.2 proposes an operational architecture for the real-time simulation. Section 5.3 formulates the real-time supply-demand matching. Section 5.4 proposes a coordination strategy of the agents for the real-time simulation. Section 5.5 provides the simulation studies. Section 5.6 provides the simulation results and discussions. Section 5.7 summaries the chapter.

5.2. Proposed Operational Architecture

In this chapter, functions of microgrid management such as demand side management and generation scheduling were carried out with an intelligent multi-agent system.

Generator agents retrieve power scheduling information and send the set points to the generators. Two levels of generation scheduling system is used in this research: a day-ahead scheduling and a real-time scheduling. Demand side management agent performs load shifting and load curtailment techniques. The load shifting delays and connects the controllable loads effectively in accordance with some optimization criteria in a day advance. Load curtailment decreases the power consumption of the controllable loads dynamically during the real-time operation of the microgrid.

Figure 5.1 shows the schematic diagram of the proposed real-time operational architecture of a microgrid. The multi-agent system was developed in JADE, and was interacted with RTDS under real conditions via TCP/IP.

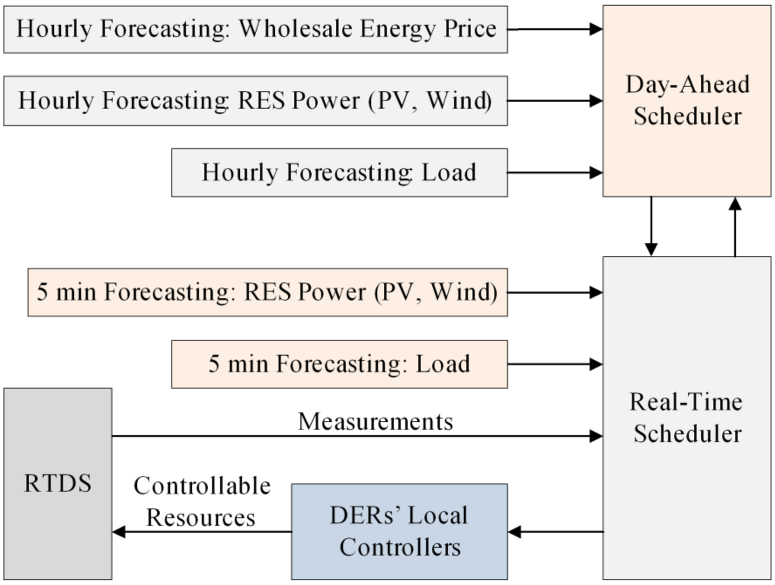


Figure 5.1. Proposed real-time operational architecture of a microgrid

Problem formulation of the proposed day-ahead hourly scheduling and load shifting technique of demand side management, and necessary background information have been discussed in Chapter 3. Problem formulation of the real-time supply-demand matching problem is given in the following section.

5.3. Real-Time Scheduling Problem

According to the proposed operational strategy, the real-time scheduling matches supply and demand of the microgrid in five minute intervals by taking the feedback from the real-time simulation of the microgrid in RTDS, and forecasted data of five minute intervals. This provides continuous matching of supply and demand in the microgrid.

According to the control architecture, real-time supply-demand matching is mainly monitored and controlled by the Storage Agent. When real-time matching goes beyond the capacity of the Storage Agent, the estimated error is calculated in each time interval, and adjustments of power settings of sources are assigned to each source proportional to their maximum generation capacities [12,28]. The adjustments of power setting ΔP_i^{Assign} made for source i is given by the following equation.

$$\Delta P_i^{Assign} = \frac{\left(P_i^{Max} - P_i^{Sch}\right)}{\sum\left(P_i^{Max} - P_i^{Sch}\right)} \times \sum P_i^{Sch} - P_i^{Mea} \tag{5.1}$$

where, P_i^{Sch} is the scheduled power, P_i^{Max} is the maximum power limit for the current market price, and P_i^{Mea} is the measured power from the simulation.

This is subject to the system constraints and unit constraints which are given in the day-ahead scheduling problem in Chapter 3. Whenever real-time matching goes beyond the capacity of both Storage Agent and other distributed sources, demand side management agent curtails the load to decrease the power consumption of the controllable loads if it is possible for the reliable operation of the microgrid.

5.4. Coordination of Agents

According to the proposed decentralized control architecture, the microgrid manager who has a Distribution Network Operator (DNO) and Market Operator (MO) handles the operation of the microgrid. First, the DSM Agent carries out load shifting according to the wholesale electricity prices to minimize the operational cost. Then, day-ahead scheduling is carried out based on the day-ahead microgrid market.

In the day-ahead scheduling, distributed generators bid for a set of supply powers for a 24-hour window. MO handles the scheduling based on the bidding and operating cost of generators. DNO finalizes the schedules without any violation of technical constraints. Finally, real-time scheduling is carried out as proposed in the chapter, the power settings of the distributed energy resources are adjusted according to the proposed real-time management strategy. Load curtailment is carried out by DSM Agent when it is necessary and possible for the reliable operation.

In this simulation platform, intelligent agents interact with other agents pro-actively. Interaction of agents and respective messages for the day-ahead generation scheduling and load shifting are shown in Figure 5.2.

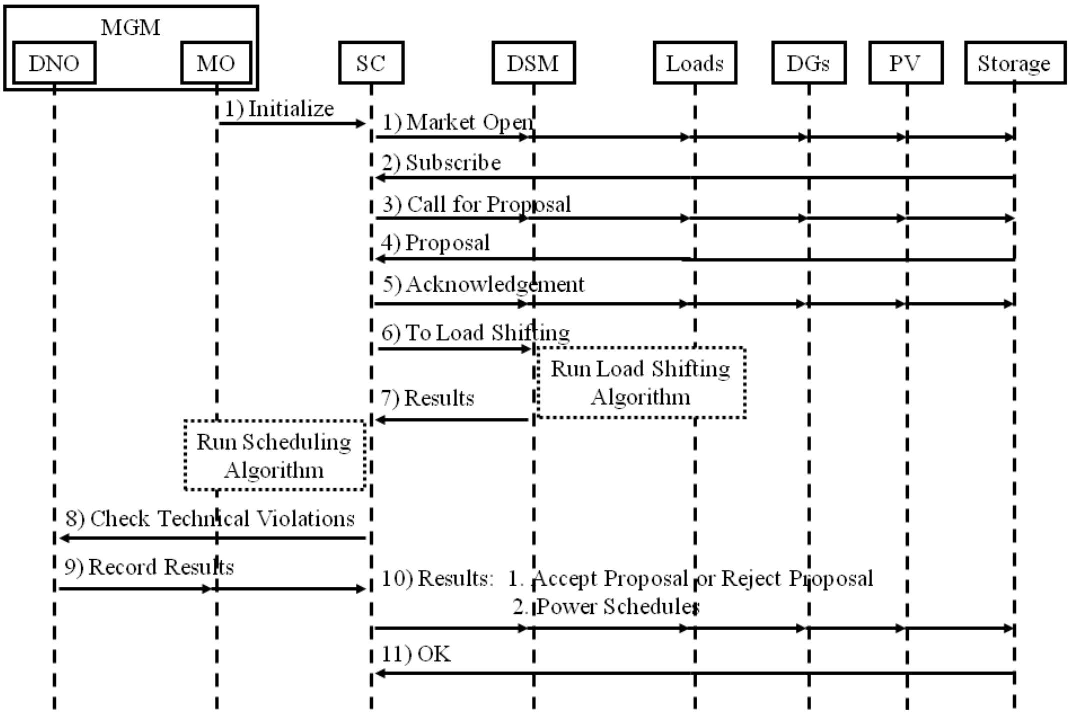


Figure 5.2. Interaction of agents for day-ahead scheduling

The above interaction runs only once a day before the day of scheduling. Interaction of agents and respective messages for the real-time generation scheduling and load curtailment are shown in Figure 5.3.

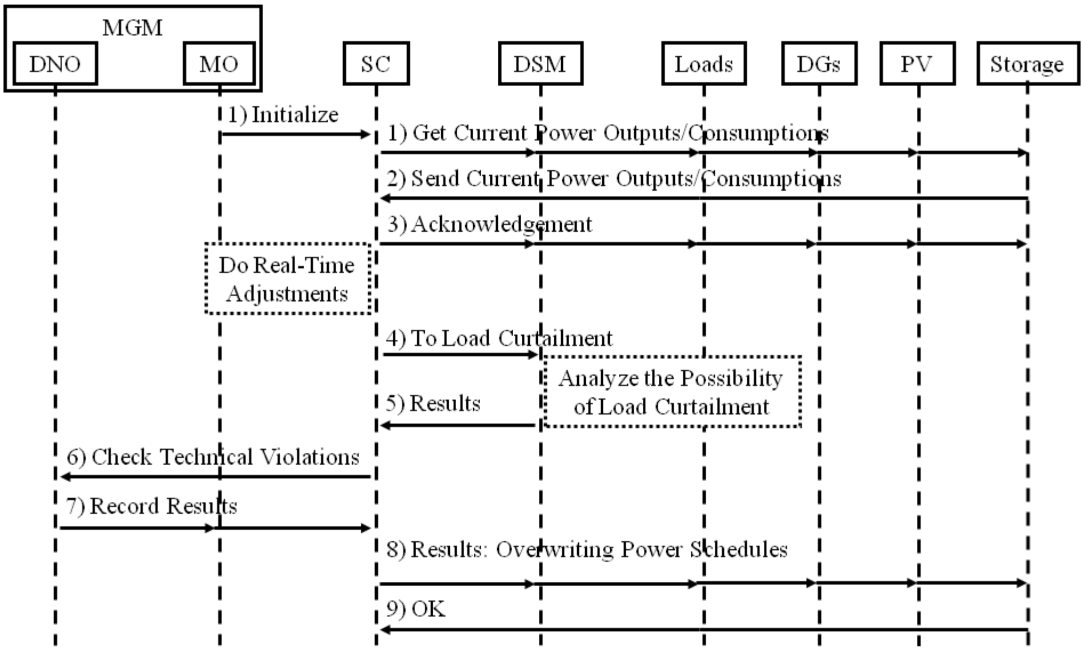


Figure 5.3. Interaction of agents for real-time scheduling

The above interaction runs in every five minutes while the microgrid is operating. In this chapter, apart from the implementation of multi-agent system, some of the best practices in Computational Intelligence (CI) techniques are also employed in decision making modules of the agents. For example, an Evolutionary Algorithm (EA) was developed in the decision making module of the DSM Agent [91].

5.5. Simulation Studies

Simulation studies were carried out on a 750kW residential microgrid [12]. The microgrid contains DERs such as a Photovoltaic (PV) system, a Fuel Cell (FC), three Distributed Generators (DG) (i.e. two Micro Turbines (MT) and one diesel engine) and a battery bank. Details of the distributed energy resources are given in Table 5.1. A schematic diagram of the microgrid is given in Figure 5.4, and the electrical network of the microgrid was modeled in RTDS, which is shown in Figure 5.5. Each power sources and power electronic building blocks [83] were modeled in details by the power electronic researchers who worked on this project. The power electronic building blocks are responsible for low level local control actions. The whole microgrid is operated in 410V. Maximum power transfer capability [12] of the interconnection link between the main grid and the microgrid is 100kVA.

Table 5.1. Details of the distributed energy resources

Unit Type	Minimum Power (kW)	Maximum Power (kW)	Operational Cost $(a + bP + cP^2)$		
			a	b	c
Fuel Cell	30	60	0.38	0.0267	0.00024
DG 1	50	200	0.40	0.0185	0.00042
DG 2	20	60	0.65	0.0152	0.00052
DG 3	20	140	0.30	0.0297	0.00031
PV	0	150	-	-	-
Battery	0	65kW, 650kWh	-	-	-

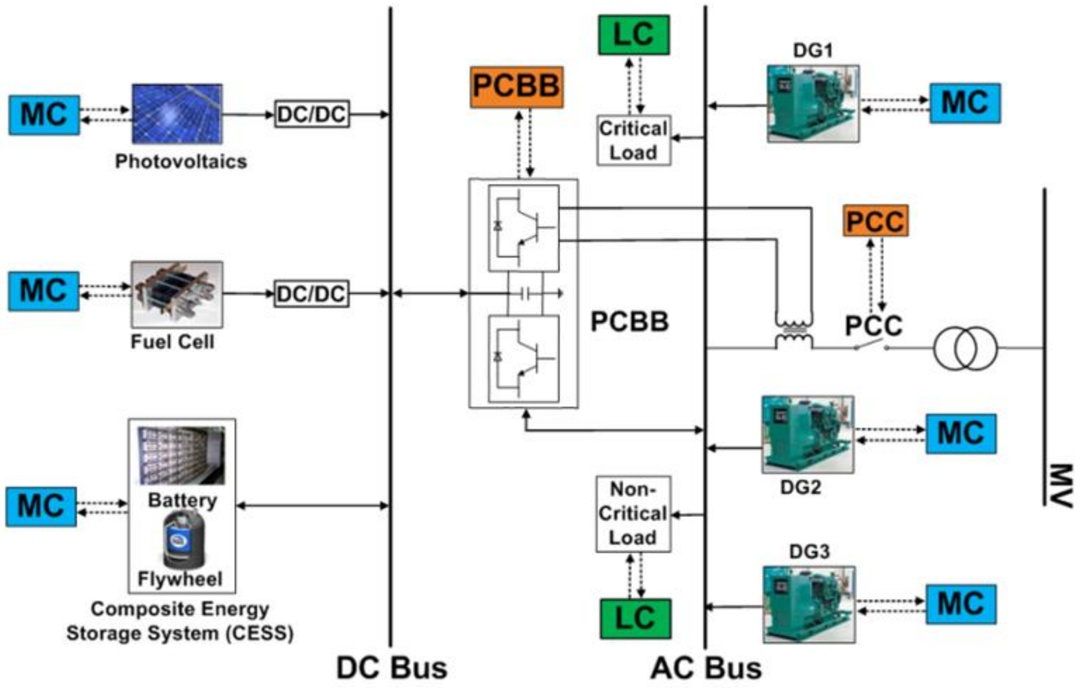


Figure 5.4. Schematic diagram of the microgrid

Simulation studies were carried out for a typical day in Singapore, March 30, 2009. Photovoltaic power production is calculated from the model given in RTDS library. Perfect forecasting of solar radiation, atmospheric temperature and load were considered for the simulation studies.

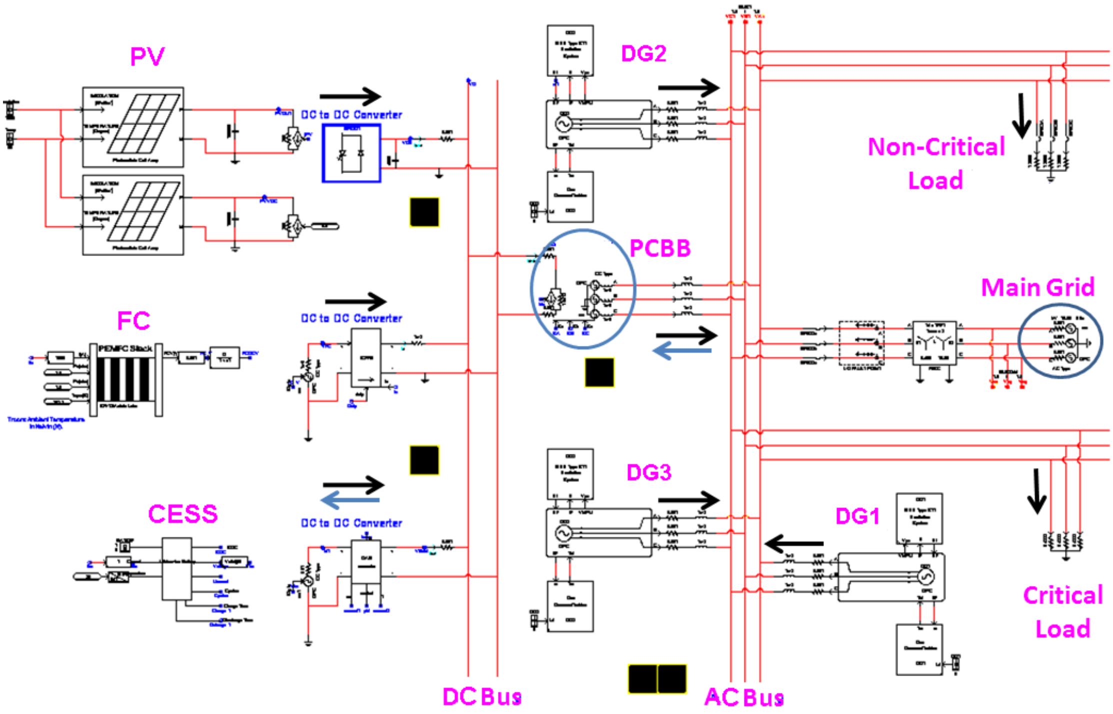


Figure 5.5. Electrical network diagram of the microgrid in RTDS

Forecasted hourly wholesale energy prices and load profile of the microgrid are given in Table 5.2. Battery bank has initial charge of 75%. The load contains 75% of critical load and 25% of non-critical load throughout. Both critical load and non-critical load are modeled as lumped loads in RTDS. The individual devices are not modeled separately.

Non-critical load contains several types of devices which are subjected to load control. These types of devices in the microgrid and their consumption patterns are given in Table 4.6. There are over 2600 controllable devices available in the microgrid from 14 different types of devices.

Table 5.2. Forecasted load demands and wholesale energy prices

Hour	Load (kWh)	Price (ct/kWh)	Hour	Load (kWh)	Price (ct/kWh)
1	457.7	8.65	13	345.2	26.82
2	336.5	8.11	14	320.6	27.35
3	274.9	8.25	15	333.2	13.81
4	272.6	8.10	16	316.8	17.31
5	245.3	8.14	17	291.3	16.42
6	233.7	8.13	18	413.8	9.83
7	274.6	8.34	19	539.8	8.63
8	291.0	9.35	20	557.2	8.87
9	315.7	12.0	21	557.1	8.35
10	362.4	9.19	22	535.0	16.44
11	320.0	12.3	23	437.8	16.19
12	350.0	20.7	24	447.3	8.87

5.6. Simulation Results

It is observed that the demand side management agent has managed to bring the final consumption closer to the objective load curve. The simulation results obtained from load shifting by the DSM Agent are given in Figure 5.6.

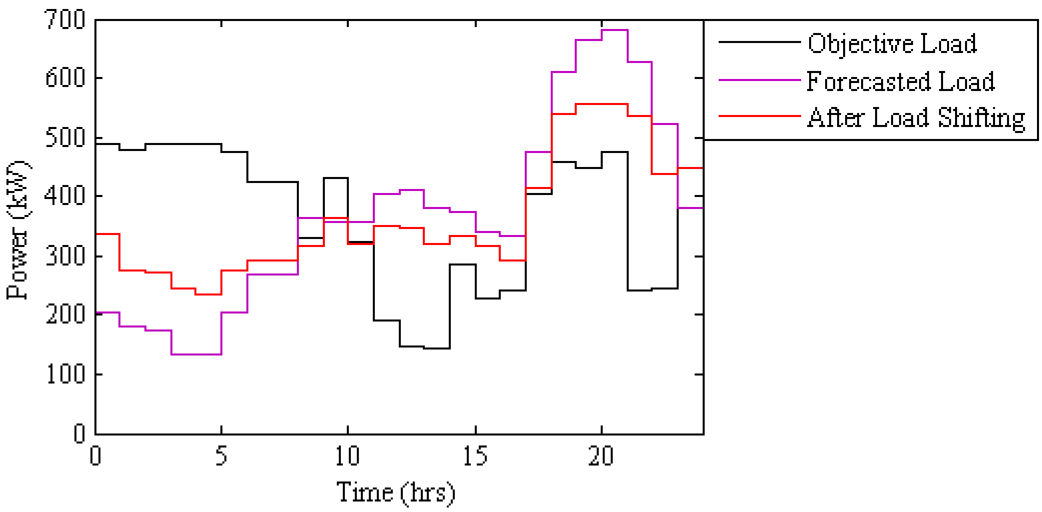


Figure 5.6. Load profile of after load shifting

The utility bills for the microgrid with and without load shifting are $1151.45 and $1094.15 respectively. Therefore, there is about 5.0% reduction in the operational cost by load shifting. Results of generation scheduling of the microgrid in grid-connected mode are given as follows.

5.6.1. Grid-Connected Microgrid Operation

Figure 5.7 shows outcome of day-ahead scheduling of the grid-connected microgrid for the day.

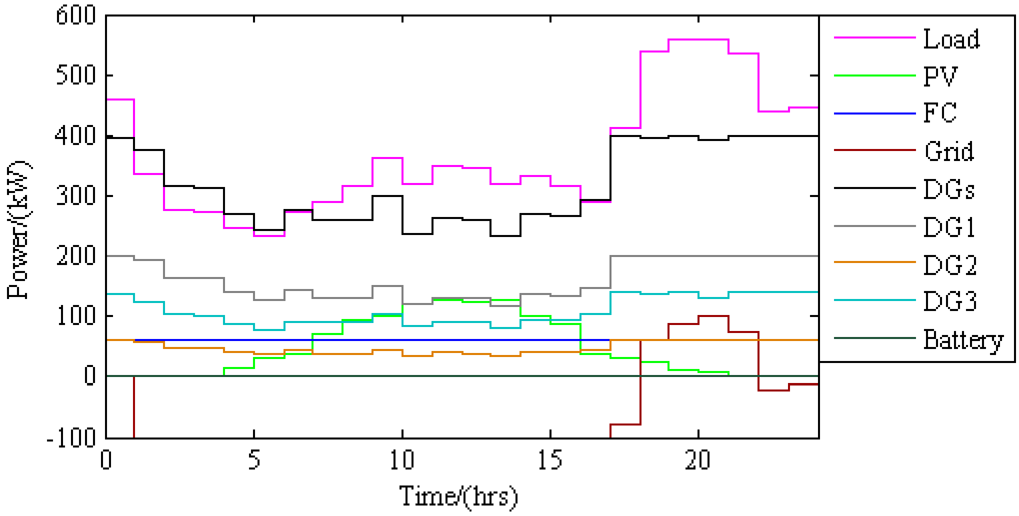


Figure 5.7. Day-ahead hourly schedule of the grid-connected microgrid

The microgrid receives power from the main grid from 18hrs to 22hrs, and it supplies power to the main grid for the rest of the day. The power exchange between the main gird and the microgrid is at its maximum of 100kW from 1hr to 17hrs. Furthermore, the power from the DGs are not met their maximum levels as the wholesale energy prices are not high in the period. Therefore, it is possible to supply even more power to the main grid if the power transfer capacity of the interconnection link is increased. Figure 5.8 shows the outcome of real-time scheduling of the grid-connected microgrid for the day. The results show that the real-time scheduling works as proposed, and maintains the stability of the microgrid. Four different situations can be clearly noticed in the figure.

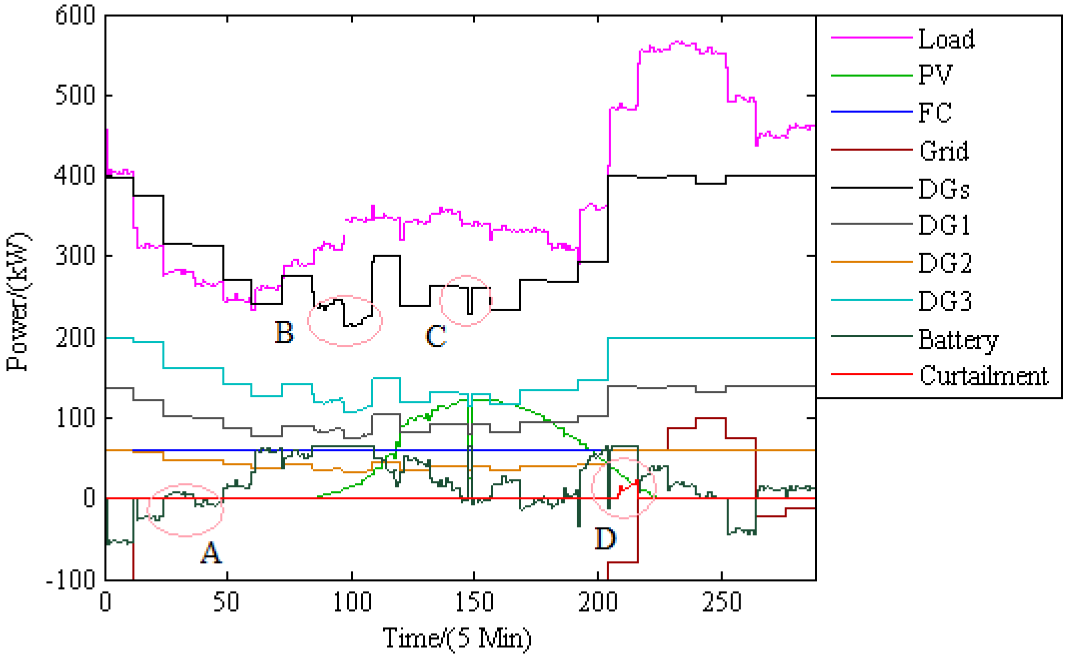


Figure 5.8. Real-time scheduling of the grid-connected microgrid

First, point A is a typical situation in real-time operation. As proposed, the load fluctuation is satisfied by the Storage Agent. Then, point B indicates that when the load fluctuation goes beyond the capacity of Storage Agent, it is satisfied by the available DGs for the market price on time. Then, point C is a situation when photovoltaic power drops due to some unexpected reasons such as cloud or shadow. In this case, it is managed by Storage Agent and DG Agents. Finally, point D is when the load fluctuation goes beyond the capacity of both Storage Agent and DG Agents, the microgrid has only option to call DSM Agent to do load curtailment or load shedding. In this case, DSM Agent has done some load curtailment.

5.6.2. Islanded Microgrid Operation

Figure 5.9 shows the outcome of day-ahead scheduling of the islanded microgrid for the day. The microgrid has tried to manage its internal load by its sources except at the peak demand period from 19hrs to 22hrs. During this period, DSM Agent has performed some load curtailment actions.

Figure 5.10 shows the outcome of real-time scheduling of the islanded microgrid for the day. The results show clearly that the proposed real-time scheduling maintains the stable operation of the microgrid even in the islanded mode. The four different situations as explained in the grid-connection mode can be seen clearly in this result also.

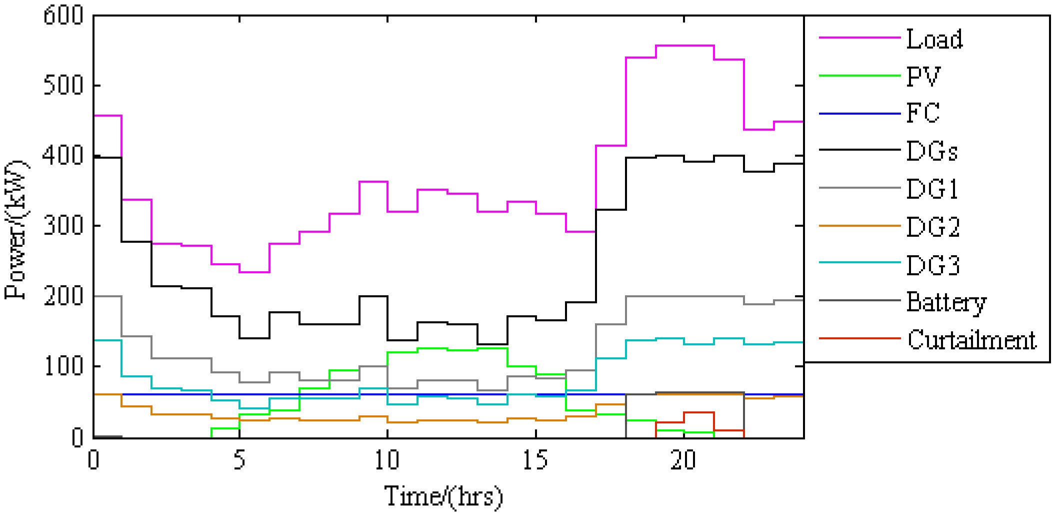


Figure 5.9. Day-ahead hourly schedule of the islanded microgrid

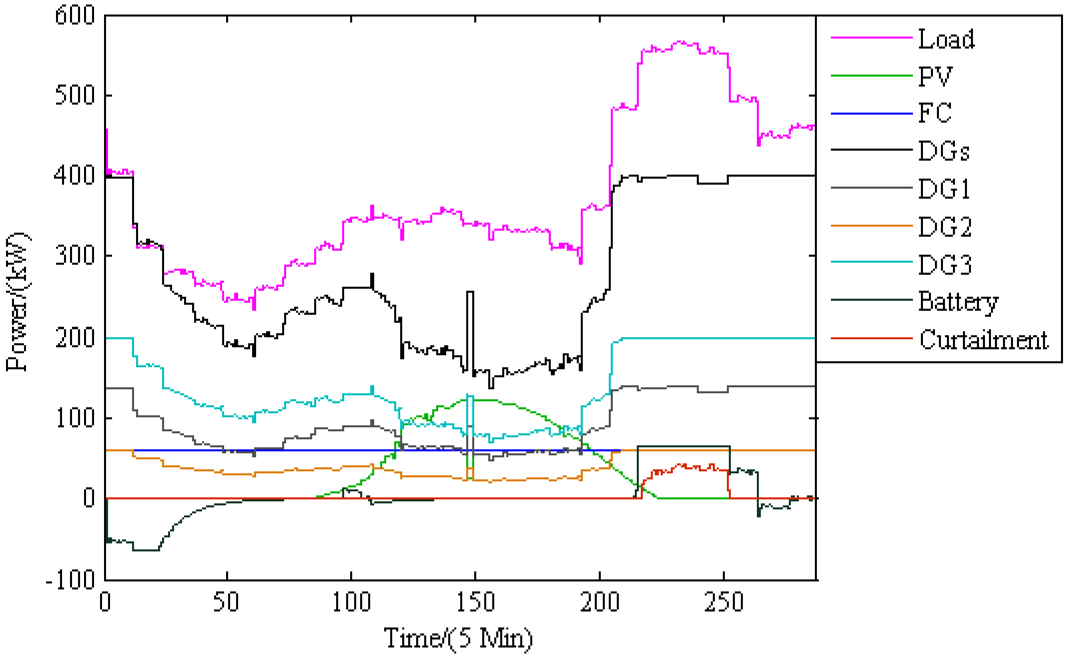


Figure 5.10. Real-time scheduling of the islanded microgrid

A distributed multi-agent system provides a common communication interface for all elements to interact each other for autonomous intelligent control actions. The multi-agent system maximizes the power production of local distributed generators, minimizes the operational cost of microgrid and optimizes the power exchange between the main power grid and the microgrid subject to system constraints and constraints of distributed energy resources. The outcome of simulation studies demonstrates the effectiveness of the proposed multi-agent system for the real-time simulation of microgrids.

5.7. Summary

This chapter presents the multi-agent system approach for the real-time simulation of a residential microgrid in both grid-connected and islanded modes under the real conditions with a RTDS. The real-time multi-agent system was developed in an open source IEEE FIPA compliant platform and a two-stage operational strategy was implemented on the multi-agent system. The outcome of the simulation studies demonstrates the effectiveness of the proposed control and management technique, and also shows the possibility of an autonomous built-in operation of a microgrid with a multi-agent system. The two stage scheduling described in the paper appears to be a useful tool for the proper management of a microgrid. The simulation studies have shown that the operational strategy is able to tackle both economical and technical objectives of the operation. The size of the microgrid is limited by the capabilities of the RTDS in the lab, but further developments of the scheduler for control and management of large scale distribution networks will lead toward actual smart grid development.

CHAPTER 6

MANAGEMENT OF PHEV AND DISTRIBUTED ENERGY STORAGE SYSTEMS

6.1. Overview

The intelligent multi-agent system that was developed for the operation of distributed power systems in this dissertation provides a platform for the modeling of autonomous decision making entities in de-centralized manner. It also provides plug and play capability. Therefore, the multi-agent system can be expanded to adopt distributed demand side management with Plug-in Hybrid Electrical Vehicle (PHEV) [106] and Distributed Energy Storage System (DESS) [107]. This chapter presents various simulation studies on these distributed energy resource management.

The remaining chapter is organized as follows. Section 6.2 presents simulation studies on the management of plug-in hybrid electrical vehicles. Section 6.3 presents simulation studies on the management of distributed energy storage system. Section 6.4 summaries the chapter.

6.2. Management of Electrical Vehicles

Electrical Vehicles (EVs) [106,108-111] have potential to increase the ability of residential customers to participate in demand response programs. Therefore, a new infrastructure that enables vehicles to participate in demand response programs is needed. Smart charging and discharging plans make lower the operational cost of electric vehicles and reduce the peak load demand of distributed power systems. In order to identify the best solution methodology, a decentralized multi-agent system [106,112] and a hybrid algorithm (EALP) [106] that combined Evolutionary

Algorithm (EA) with Linear Programming (LP) were developed for the management of a distributed power system with PHEVs.

6.2.1. Short-Term Management of EVs: Problem Formulation

The short-term energy management problem of electrical vehicles can be mathematically formulated as follows.

Minimize,

$$C_T = \sum_{t=1}^{T} \sum_{i=1}^{N} MP_t P_{it} \tag{6.1}$$

where, C_T is the total operational cost of the system, MP_t is the wholesale market price at time t, P_{it} is the power from the PHEV i at time t, N is the number of PHEVs in the system, and T is the number of time steps in the scheduling period.

This minimization problem is subject to the following constraints.

- Maximum power transferring limitations of interconnection links in the grid.
- Power limitations of the storage element in each PHEV. These limitations for PHEV i are written as follows.

$$\begin{bmatrix} Time/Parameters & t=1 & t=2 & t=3 & \dots & t=T \\ Lower\ limit & P_{i1}, min & P_{i2}, min & P_{i3}, min & \dots & P_{iT}, min \\ Upper\ limit & P_{i1}, max & P_{i2}, max & P_{i3}, max & \dots & P_{iT}, max \end{bmatrix} \tag{6.2}$$

- Energy limitations of the storage element in each PHEV. These limitations for PHEV i are written as follows.

$$\begin{bmatrix} Time/Parameters & t=1 & t=2 & t=3 & \dots & t=T \\ Lower\ limit & E_{i1}, min & E_{i2}, min & E_{i3}, min & \dots & E_{iT}, min \\ Upper\ limit & E_{i1}, max & E_{i2}, max & E_{i3}, max & \dots & E_{iT}, max \end{bmatrix} \tag{6.3}$$

- Departure times, arrival times and drive times of each PHEV.

The proposed EALP methodology is a centralized scheduler that includes all constraints of PHEVs and system constraints. It considers that PHEVs are able to gain the maximal electric driving. Nevertheless, a central scheduler is infeasible because of its characteristics such as incomplete information and poor scalability. The central scheduler is able to find out an optimal solution, but this solution strictly depends on exact data and behaviours of electrical vehicles. In reality, the exact data is not available at the time of simulation. For example, it is impossible to know the exact time when an electrical vehicle connects to the electric grid in advance. Although the problem is convex and therefore, it is solvable in polynomial time, the execution time is high due to the large number of variables. In this chapter, EALP is used to find out an optimal reference solution to compare the solution from the proposed multi-agent system approach.

6.2.2. Multi-Agent System for Electrical Vehicle Management

In the literature [12,25], the multi-agent system technology is used for the simulation of smart grid in the control and management architecture of microgrid and integrated microgrid. Currently, the multi-agent system approach is started to use for managing distributed power systems with PHEVs [106,112]. In this chapter, the multi-agent system approach is proposed for managing a distributed power system with PHEVs. The following section provides the details about the proposed multi-agent system.

6.2.2.1. Agents in Multi-Agent System

The proposed decentralized multi-agent system consists of the following additional agents. PHEV agent (PHEV Agent) represents the software control of a PHEV, transformer agent (TF Agent) controls a transformer, load agent (Load Agent) represents the system load and power grid agent (Grid Agent) represents the main power grid. The schematic overview of the proposed multi-agent system is shown in Figure 6.1. The functions of the main agents in the multi-agent system are briefly provided as follows.

- PHEV Agent: Charge or discharge the storage element in a PHEV.

- TF Agent: Attend the loads of the transformer and prevent overloading.
- Load Agent: Get power from the main grid and allow demand side management actions.
- Grid Agent: Get or provide power to PHEV Agents and provide power to the Load Agents based on the system condition.

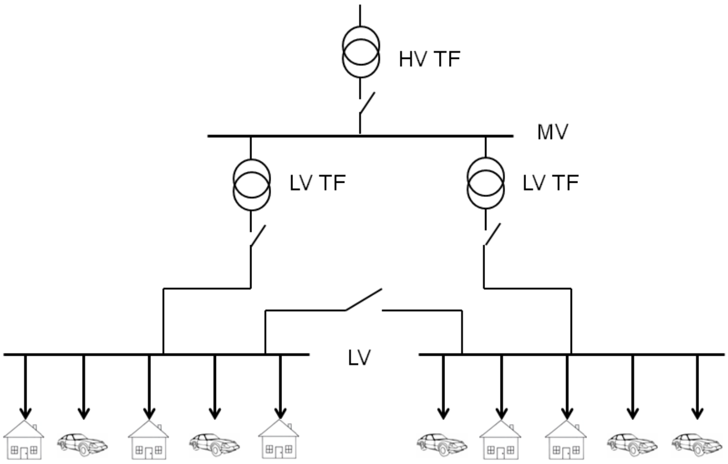


Figure 6.1. Schematic overview of the multi-agent system

Each agent has an individual goal and intends to achieve it. In order to achieve the system goal, the agents have to coordinate with each other. Even though the goals of agents are independent in the multi-agent system, they are not independent in real. For example, a PHEV with an empty battery cannot be charged in any time, because this may cause overloading a low voltage transformer. Therefore, a proper coordination strategy is needed to propose for achieving the system goal.

6.2.2.2. Coordination of Agents

A coordination strategy for a PHEV Agent is proposed for getting permission from a TF Agent for charging. This strategy is shown in Figure 6.2.

- PHEV Agent sends its intention to the connected TF Agents.
- TF Agents individually determine the charging power that attends the load at its

best.

- TF Agents negotiate with each other for a mutual charging power schedule that attends the best of PHEV Agent at the transformers.
- TF Agents at the low voltage announce the mutual agreed charging power schedule to PHEV Agent.

The PHEV Agents asynchronously send charging or discharging requests to the TF Agents at regular time intervals to keep the transformers informed of their intentions. Based on this coordination mechanism, a coordination strategy was developed. The strategy has a combined effect of energy limit and power limit of the batteries in the PHEVs. The energy limit and power limit of the PHEVs reserve an amount of energy and power when they connect to the power grid. The energy limit requires forecasted data. The TF Agents need forecasted data about the loads behind them and The PHEV Agents need data about the battery levels and the expected departure times. Power values can be estimated by data mining techniques, while the load can be forecasted by analysing the historical data.

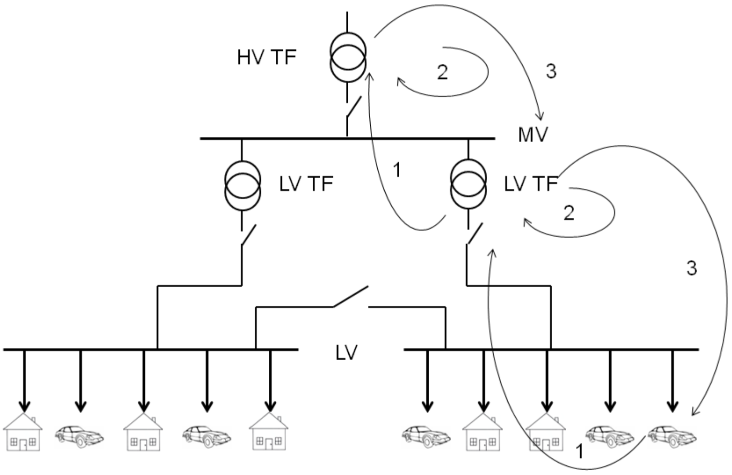


Figure 6.2. Coordination of agents for management of PHEVs

Figure 6.3 shows how a PHEV Agent requests its charging power. A request for charging or discharging is sent from the PHEV Agent to its connected LV TF Agent which forwards the request to connected HV TF Agent. This request contains the required energy and the expected departure time to leave. The successful power request will fall with the range between 0 and P_{max}^t.

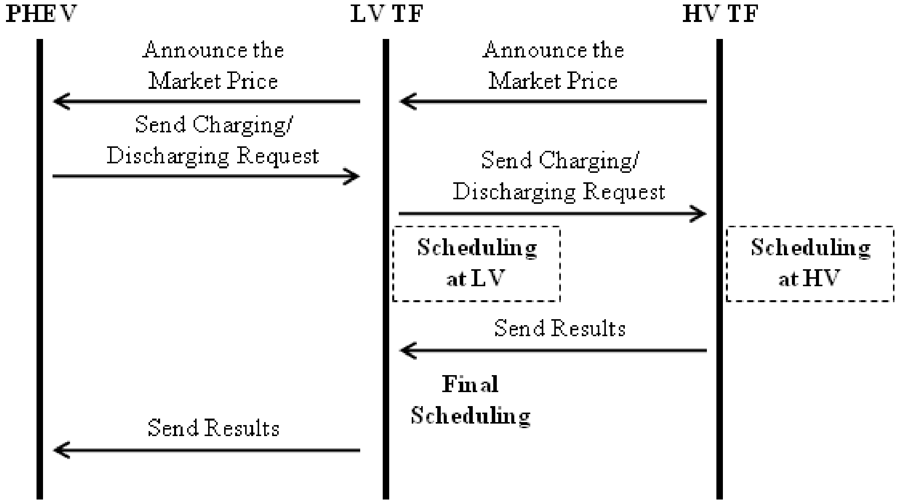


Figure 6.3. Messages among the agents for a request of charging

When it charges,

$$P_{max}^t = max\left(P_{min}, min\left(P_{max}, \frac{\left(E_{max} - E(t-1)\right)}{T}\right)\right) \tag{6.4}$$

When it discharges,

$$P_{max}^t = max\left(P_{min}, min\left(P_{max}, \frac{\left(E(t-1) - E_{min}\right)}{T}\right)\right) \tag{6.5}$$

The LV TF Agent and the HV TF Agent reserve the requested energy at the transformers and determine a feasible power for the PHEV Agent. The HV TF Agent sends its preferred power for the PHEV Agent to the LV TF Agent. The LV TF Agent, then calculates the average of the power which is allowed by the HV TF Agent. The allowed power is sent back to the respective PHEV Agent and the PHEV Agent can adapt its power accordingly.

PHEV Agents have to resend requests at regular time intervals to confirm their energy reservations. If an energy reservation is not confirmed, transformers will delete the reservation after the time is expired. This is the way, the agents adapt dynamically to unexpected behaviours of PHEVs. Reservation of energy may be different from scheduling because the arrival times of PHEVs are not known beforehand. Therefore, only reservation of energy can be done. The actual charging or discharging depends on the time when they arrive and connect to the grid.

6.2.3. Simulation Studies

Preliminary simulation studies [106] were carried out for a typical day in Singapore, Figure 6.4 shows the wholesale electricity prices of March 30, 2009. These simulation studies considered around 20% penetration PHEVs in the system.

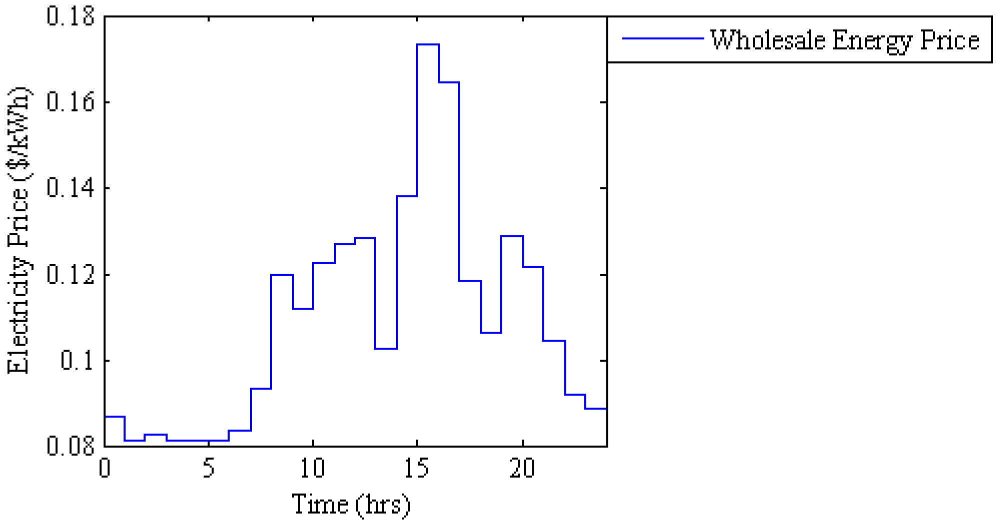


Figure 6.4. Wholesale energy prices

6.2.4. Simulation Results

Figure 6.5 shows the forecasted load profile and the resultant load profiles from proposed and the reference approaches for managing the distributed power system with PHEVs.

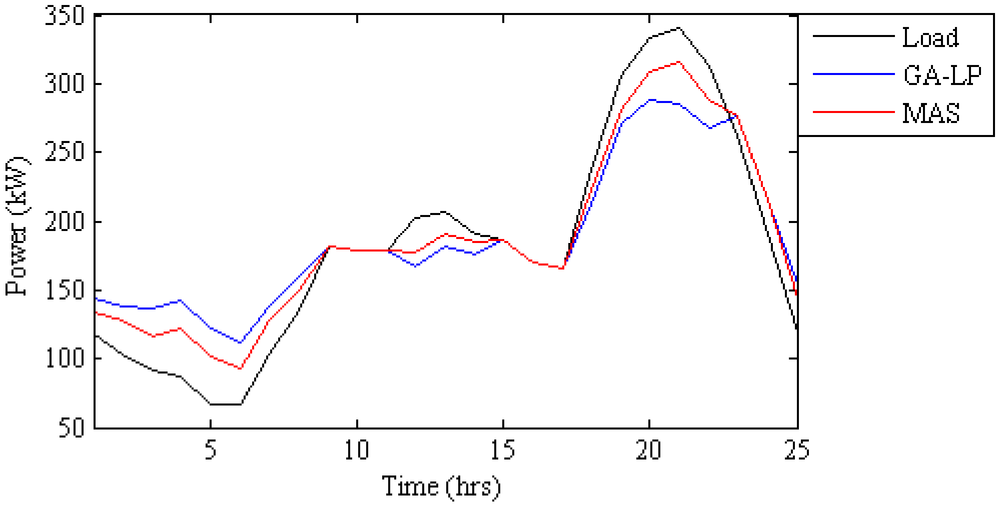


Figure 6.5. Forecasted load profile and the resultant load profiles

6.2.5. Discussions

In contrary to the central scheduler, the multi-agent system does not need exact data. Because PHEV Agents send their requests to TF Agents at regular time intervals and the TF Agents dynamically adapt information about the expected load. For example, when a PHEV leaves, no request is sent anymore, and pending reservations at TF Agents will be deleted. The adaptability of the multi-agent system is determined by the rate at which requests of PHEV Agents can be processed by TF Agents. If a request is sent by a PHEV Agent at first time, TF Agents have to reschedule. If a request from a PHEV Agent contains the same intentions as the last request, no rescheduling is needed. The coordination strategy responds fast enough to assure an adaptable system.

In this section, a multi-agent system is proposed for managing PHEVs in a distributed power system in context of a distributed smart grid. The solution from a distributed multi-agent system is compared with the solution from a centralized scheduler. The centralized scheduler manages PHEVs through EALP, which obtains an optimal way of charging or discharging of PHEVs, but it is unfeasible in practice. In the centralized scheduling, not all data about PHEVs are available for scheduling. Furthermore, centralized scheduling is not scalable. The developed multi-agent system shows its potential of solving the problem dynamically. The coordination strategy was developed according to the energy limits and power limits of PHEVs. The energy limit only uses prediction of loads, while the power limit doesn't use any forecast data. The system constantly adapts to new information through coordination among the agents. This part of the research is the first initiative for managing PHEVs by intelligent multi-agent system approach.

6.3. Management of Distributed Energy Storage Systems

Infrastructure of smart grid that should be able to utilize renewable energy sources requires Distributed Energy Storage Systems (DESS) with high power density and high energy density. Currently, some research works investigate energy management and dynamic control of distributed energy storage systems [107,113-117] to offer not only high power density and high energy density storage systems but also high efficiency and long-life energy storage systems. In this research, an intelligent energy management system is proposed to provide short-term requirements of distributed energy storage system in a smart grid. The energy management of the distributed energy storage system is mathematically formulated as a nonlinear mixed-integer optimization problem. A hybrid algorithm that combined evolutionary algorithm with linear programming [107] was developed to solve this optimization problem.

6.3.1. Distributed Energy Storage Systems

Energy storage system is an important energy source in smart grid, and a necessary element in the management of distributed renewable energy sources. Energy storage system is not only a technical solution for the network management and real-time load levelling, but also a mean of better utilizing renewable resources by avoiding load shedding or load curtailment. Coupled with local renewable energy generation, decentralized energy storage system could also improve power network sturdiness through a network of energy farms supplying a specific demand zone. Breakthroughs that dramatically reduce the costs of electricity, storage systems could drive revolutionary changes in the design and operation of the electric power system. Energy storage systems can reduce the peak load, improve the stability of electricity supply and eliminate power quality disturbances.

Figure 6.6 shows how the new electricity value chain is changing supported by the distributed energy storage systems.

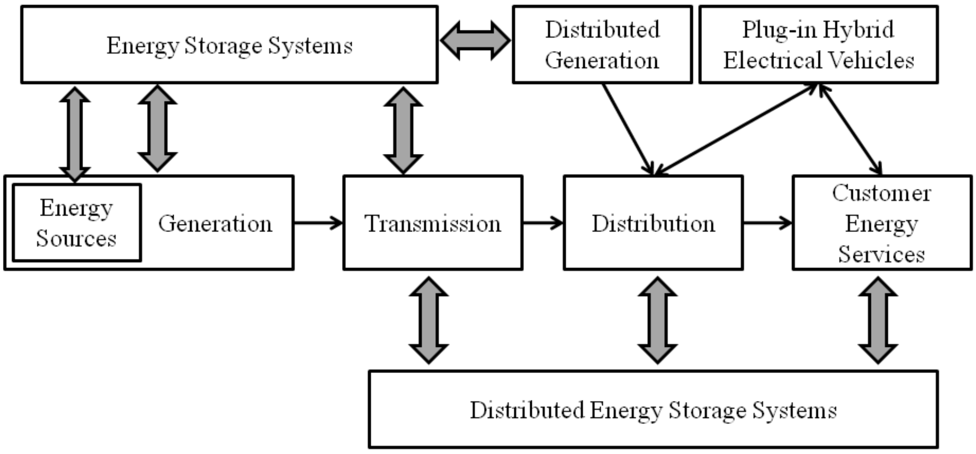


Figure 6.6. Distributed energy storage system in smart grid

Energy storage systems in combination with advanced power electronics have great technical roles, and lead to many technical and financial benefits. Some of them are summarized in the following section.

6.3.2. Storage Technologies, Technical Roles and Financial Benefits

Currently, various energy storage elements are available in the industry with different technologies, capabilities and applications [114,116]. These energy storage elements include pumped-hydro storage, compressed air energy storage, regenerative fuel cells, batteries, superconducting magnetic energy storage, flywheels, super capacitors, thermal energy storage systems and hydrogen energy storage systems.

Energy storage systems have several technical roles, and lead to many technical and financial benefits. Technical roles and functions [114,115] of electric storage systems in the smart grid includes grid voltage support, frequency support, grid transient stability, load Levelling and peak shaving, spinning reserve, power quality improvement, power reliability, ride through support and unbalanced load compensation. Financial benefits [114] of energy storage systems in the smart grid includes cost reduction of bulk energy arbitrage, revenue increased of central generation capacity, cost avoidance of ancillary services, revenue increased for transmission access and congestion, reduced demand charges, reduced reliability-related financial losses, reduced power quality-related financial losses, and increased revenue from renewable energy sources.

6.3.3. Proposed Operational Architecture for DESS

Typically, renewable power output and load demand have low frequency as well as high frequency fluctuations which are mutually independent in nature. To buffer out the low frequency oscillations and compensate for the intermittency of the renewable energy sources, high energy density storage system is required. To provide high frequency component of power and also to supply or absorb the high power transients, high power density storage system is required. But, both high energy density and high power density capabilities are not available in a single storage element. Hence, a distributed energy storage system comprising of both high power density and high energy density storage elements is proposed in this chapter. The block diagram of the interface of the proposed distributed energy storage system is shown in Figure 6.7. The architecture consists of a forecasting module and an optimization module. The energy storage elements are connected together through the grid. A two-communication infrastructure is also proposed among the energy storage elements and the optimization module.

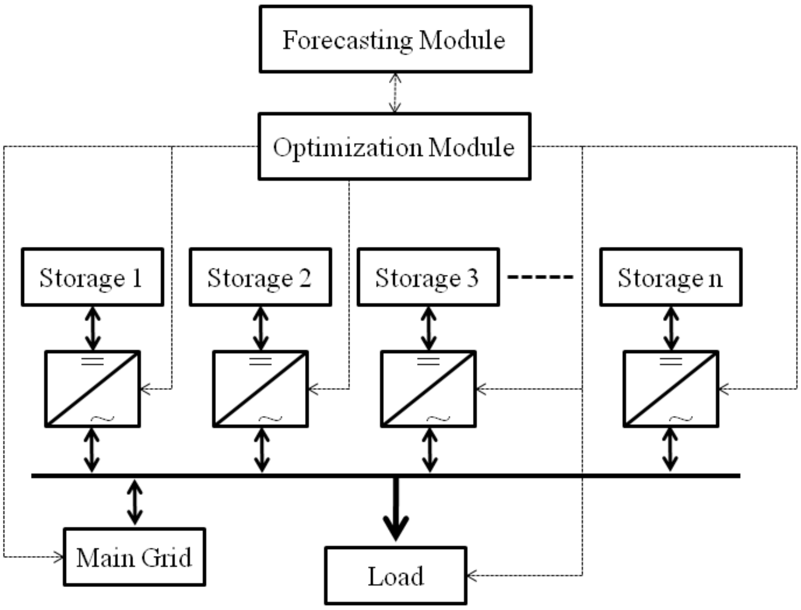


Figure 6.7. Proposed operational architecture of distributed energy storage system

Distributed energy storage system in a smart grid can be seen as an almost ideal energy storage system with the information of total stored energy. The distributed energy storage system can incorporate battery, ultra capacitor, flywheel, magnetic storage and others. Energy management system has to allocate sourcing or sinking energy of storage elements in the distributed energy storage system optimally. In [118], a cascaded control system for compensation of load dynamics and state of charge control for ultra capacitors in a microgrid application is used. A hybrid energy system comprising of battery and ultra capacitor is proposed in [119] for hybrid vehicles. In this scheme, ultra capacitor is used to satisfy the load transient requirements to improve onboard battery life cycle. The power converter configuration and energy management system is developed for this particular distributed energy storage system structure.

6.3.4. Short-Term Management of DESS: Problem Formulation

Short-term energy management of distributed energy storage systems can be mathematically formulated as follows. The variables that have to be optimized in the problem are the charging or discharging power levels of each storage element at each point of time.

Minimize,

$$C_T = \sum_{t=1}^{T} \sum_{i=1}^{N} MP_t P_{it} \tag{6.6}$$

where, C_T is the total operational cost of the system, MP_t is the wholesale market price at time t, P_{it} is the power from the storage element i at time t, N is the number of storage element in the system, and T is the number of time steps in the scheduling period.

This minimization problem is subject to the following constraints.

- Power balance: supply-demand matching.
- Power transferring limitations of interconnection links in the power grid.
- Power limitations of each storage element. These limitations of storage element i are written as follows.

$$\begin{bmatrix} Time/Parameters & t=1 & t=2 & t=3 & \dots & t=T \\ Lower\ limit & P_{i1}, min & P_{i2}, min & P_{i3}, min & \dots & P_{iT}, min \\ Upper\ limit & P_{i1}, max & P_{i2}, max & P_{i3}, max & \dots & P_{iT}, max \end{bmatrix} \tag{6.7}$$

- Energy limitations of each storage element. These limitations of storage element i are written as follows.

$$\begin{bmatrix} Time/Parameters & t=1 & t=2 & t=3 & \dots & t=T \\ Lower\ limit & E_{i1},min & E_{i2},min & E_{i3},min & \dots & E_{iT},min \\ Upper\ limit & E_{i1},max & E_{i2},max & E_{i3},max & \dots & E_{iT},max \end{bmatrix} \tag{6.8}$$

6.3.5. Proposed Methodology

Energy management of distributed energy storage systems has to satisfy both short-term and long-term requirements of the system. The short-term requirements are: constant voltage on bus bars, stability of distributed energy storage system and power quality. This includes sufficient response for incoming or outgoing power at DC ports. The long-term requirements are: high conversion efficiency, high storage efficiency and long life cycle. The short-term requirement of constant voltage on DC bus is taken care of by ultra-capacitor because ultra-capacitor is the storage that has highest power density. This means it can ensure fast dynamics performance. On the other side, ultra-capacitor has life-time of more than 500,000 cycles. Improvement of life-time is a serious problem in batteries but not in ultra-capacitors.

One of the long-term requirements is efficiency which includes power loss during conversions and power loss due to self-discharge, internal resistance, and other losses in energy storage system. Another long-term requirement is life cycle which indicates number of charging/discharging cycles before the storage system fails. This depends significantly on Depth-Of-Discharge (DOD). To ensure sufficient response for power demands, energy reserve and power reserve that show availability of storage system against deviations from predicted load profile are also used. For the optimization of long-term criteria, predicted load profile for distributed energy storage system is crucial, and is generated from predictive model based on historical data. To incorporate both predictive model and optimization, a hybrid algorithm which combined Evolutionary Algorithm (EA) with Linear Programming (LP) is used [107]. This is illustrated in Figure 6.8.

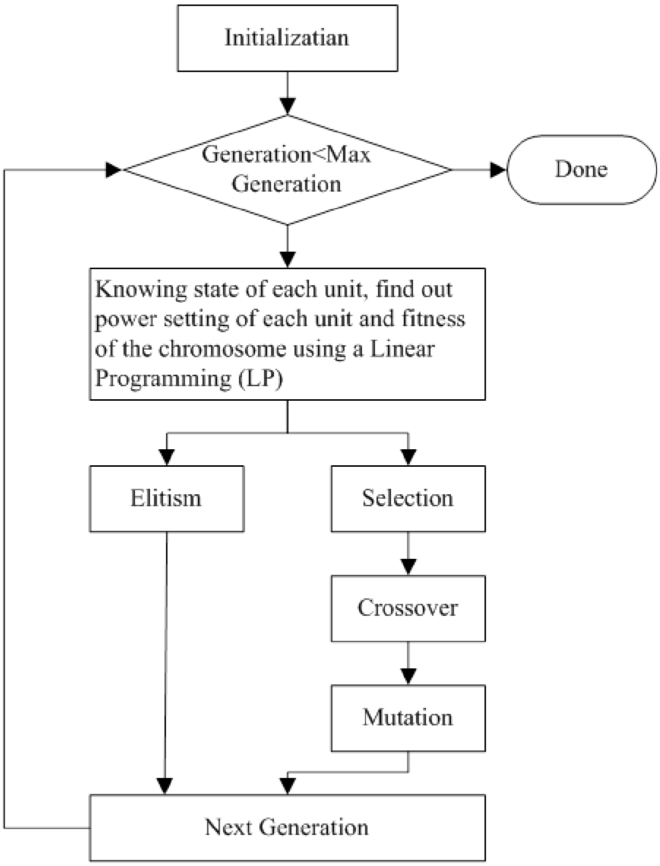


Figure 6.8. Proposed methodology for short-term management of DESS

In this project, the proposed algorithm evolved a randomly initial population. Evolution was characterized by the survival of the fittest, the reproduction ability based on the fitness and the genetic operators: cross-over and mutation. The length of the chromosome is $N \times T$. N is the number of storage elements and T is the number of time steps in the scheduling period. Binary chromosome is used, where '1' represents the charting state of the element, and '0' represents the discharging state of the element. The charging and discharging statues of the storage elements are decided by the evolutionary algorithm. Based on the state of each storage element at each time, the power setting of each storage element and fitness of each chromosome are found out by linear programming. The fitness of the chromosome is chosen such that the total operational cost of the system for the entire scheduling period is minimized.

6.3.6. Simulation Studies

Preliminary studies [107] were carried out for a distributed power system containing a distributed energy storage system which consists of 15 energy storage elements. The details of the storage elements are given in Table 6.1. The forecasted hourly system loads and wholesale energy prices of a day are given in Table 6.2.

Table 6.1. Details of the energy storage elements

Storage Element	Max. Power (kW)	Max. Energy (kWh)	Min. Energy (kWh)	Initial Energy (kWh)	Charging Efficiency (%)	Discharging Efficiency (%)
1-3	100	500	250	375	90	90
4-6	200	1000	500	750	90	90
7-9	300	1500	750	1125	90	90
10-12	400	2000	1000	1500	90	90
13-15	500	2500	1250	1875	90	90

Table 6.2. Forecasted hourly wholesale energy prices and system loads

Time (hr)	Wholesale Price (cts/kWh)	Load (kWh)	Time (hr)	Wholesale Price (cts/kWh)	Load (kWh)
1	8.65	118.93	13	12.82	206.13
2	8.11	103.08	14	10.25	190.28
3	8.25	91.18	15	13.81	186.30
4	8.10	87.20	16	17.31	170.45
5	8.14	67.40	17	16.42	166.50
6	8.13	67.40	18	11.82	237.85
7	8.34	103.08	19	10.63	305.23
8	9.35	134.78	20	12.87	332.98
9	12.00	182.35	21	12.15	340.90
10	11.18	178.38	22	10.44	313.15
11	12.27	178.38	23	9.19	261.63
12	12.69	202.18	24	8.87	190.28

The power transferring capacity between the simulation system and the main grid is 75kWh.

6.3.7. Simulation Results

The simulation outcomes are given in Figure 6.9 which shows the power settings of the energy storage elements.

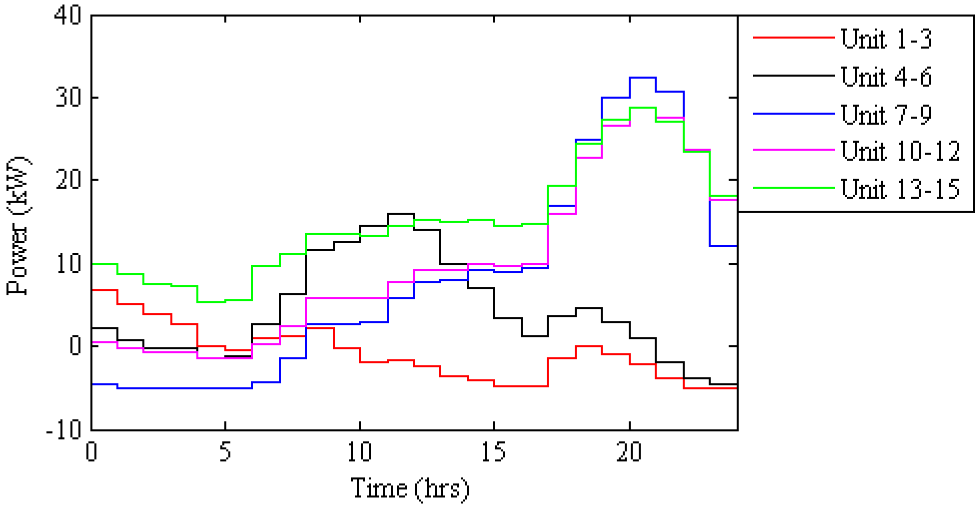


Figure 6.9. Power settings of the energy storage elements

The proposed intelligent energy management scheme flexibly shares the power among different energy storage elements. This is very important to ensure increased life of storage elements. The simulation results have shown that the distributed energy storage system can store, deliver and distribute power properly among energy storage devices following the optimization of the long-term requirements. In order to achieve full benefits, further realistic research is needed on the distributed energy storage systems in combination with advanced power electronics.

6.4. Summary

In this chapter, the multi-agent system approach was extended to adopt distributed demand side management with PHEVs. The proposed coordination strategy was developed according to the energy limit and the power limit of PHEVs. The system constantly adapts to new information through coordination among the agents. The simulation outcomes were compared with those from a centralized scheduler. This studies show the potential of solving the problem with decentralized multi-agent system. This is the first initiative part of the research on managing PHEVs with multi-agent system. Future research can be carried out from here.

This chapter also proposes an intelligent energy management of distributed energy storage elements in distributed power systems. The proposed intelligent management strategy can flexibly share the power among different energy storage elements. The strategy is validated by simulation results. Further research on the distributed energy storage systems in combination with advanced power electronics is necessary for the realistic implementation.

CHAPTER 7

OPTIMAL SIZING AND PLACEMENT OF DISTRIBUTED ENERGY RESOURCES

7.1. Overview

Optimal sizing and placement of Distributed Energy Resources (DER) is an important research problem for the advancement of distributed power systems. Optimal sizing of distributed energy resources involves in the selection of resources, and optimal placement of distributed energy resources involves in the design of network architecture. This chapter provides detail studies on these optimization tasks.

The remaining chapter is organized as follows. Section 7.2 provides optimal sizing of distributed energy resources for integrated microgrids. Section 7.3 provides optimal placement of distributed generators for a distributed power system. Section 7.4 summarizes the chapter.

7.2. Optimal Sizing of Distributed Energy Resources

Optimal sizing of distributed energy resources is a challenging task in the long-term planning of distributed power systems, which needs to consider a diverse criteria. Some of the important criteria are load type (i.e. residential, commercial or industrial), load priority (i.e. base load, backup load or peck load), operational mode (i.e. grid-connected or islanded), average load and available distributed energy resource technologies. Once, an appropriate distributed energy resource technology is selected, the subsequent criteria such as power rating, reliability, capital cost, installation cost, operational and maintenance cost, method of payment and life time of distributed energy resource are raised. Cost-benefit of distributed energy resources can be determined by comparing the electricity price of distributed generators with the electricity price of the main grid. In reality, cheap energy cost is not the sole objective, other objectives such as environmental friendliness and energy security are also needed to consider.

In the literature, several research works [120-125] have addressed different approaches for sizing of distributed generators such as wind generators, photovoltaic systems and storage elements. Some of them [120,121] have sized without using any optimization methodologies. Even though installation of each source and each microgrid are independent from each other, distribution network operators have right to limit the power ratings, and control the installation of sources and microgrids such that distributed power systems meet environmental and economic limits according to rules and policies of the government and the power system. In this section, a methodology based on evolutionary strategy is proposed for optimal sizing of distributed energy resources for integrated microgrids.

7.2.1. Problem Formulation

Figure 7.1 shows a distributed power system which consists of N_i number of microgrids. Each microgrid has N_j number of distributed energy resources. All microgrids are interconnected with each other, and interconnected with the main distribution grid. Optimal sizing of distributed energy resources for an integrated microgrid is mathematically formulated as a mixed-integer nonlinear minimization problem. This minimizes the sum of the capital cost and the annual operational cost of distributed energy resources subject to several constraints. This is written as follows.

Minimize,

$$C_T = \sum_{i=1}^{N_i} \sum_{j=1}^{N_j} C_{ij} N_{ij} + M_{ij} \tag{7.1}$$

where, C_T is the total cost which is the sum of the capital cost $(C_{ij}N_{ij})$, and the annual operational and maintenance cost (M_{ij}) of distributed energy resources, C_{ij} and N_{ij} are the capital cost and power rating of distributed energy resource j in microgrid i respectively.

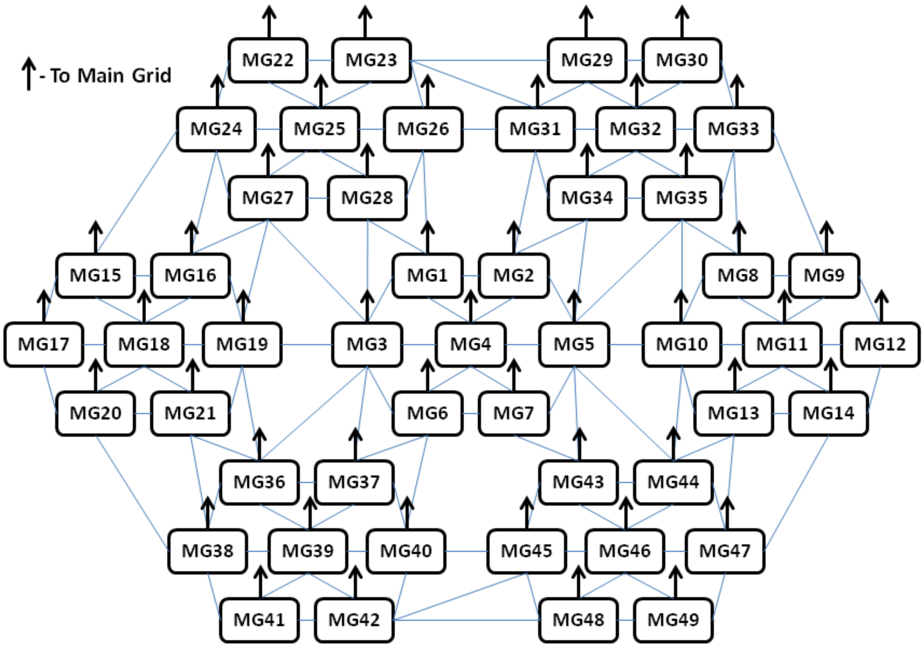


Figure 7.1. Schematic representation of an integrated microgrid

This minimization problem is subject to the following constraints.

$$E_{ij}^{min} \leq E_{ij} \leq E_{ij}^{max} \qquad \forall\, i, j \tag{7.2}$$

where, E_{ij}^{min} and E_{ij}^{max} are the minimum and maximum energy limits of distributed energy resource j in microgrid i respectively.

$$Em_{ij}^{min} \leq Em_{ij} \leq Em_{ij}^{max} \qquad \forall\, i, j \tag{7.3}$$

where, Em_{ij}^{min} and Em_{ij}^{Max} are the minimum and maximum emission limits of distributed energy resource j in microgrid i respectively. Typically, the minimum emission limit of distributed energy resource is zero, but it is set to Em_{ij}^{Min} for generalization of the problem formulation.

$$LOL_i \leq LOL_i^M \qquad \forall\, i \tag{7.4}$$

where, LOL_i and LOL_i^M are the fraction of loss of load of microgrid i and its maximum allowable limit respectively.

$$LOL \leq LOL^{Max} \tag{7.5}$$

where, LOL and LOL^{Max} are the fraction of loss of load of overall integrated microgrid and its maximum allowable limit respectively.

7.2.2. Modeling of Distributed Energy Resources

In this study, it is considered that enough fuel is available for the controllable sources which can provide required power within their limits at any time. On the other hand, power from the non-controllable sources depends on the meteorological data. Therefore, it is necessary to model non-controllable sources to know the available power at any time. It is preferred to use less complex model [94,116,126-128] of distributed energy resources without sacrificing the required accuracy because computational effort for function evaluation is the major time consuming task in this optimization. Following sections discuss the models chosen for photovoltaic panel, wind turbine and composite energy storage system in this study.

7.2.2.1. Photovoltaic System

Photovoltaic (PV) system converts sun light energy directly into electricity. Power output of photovoltaic system varies with operating voltage [126]. Usually, operators prefer to operate photovoltaic systems with Maximum Power Point Tracking (MPPT) system for getting the maximum power from the system. $P_{Max,t}$ is the maximum power output of a photovoltaic system at time t, which depends on the solar insolation and the atmospheric temperature at the time. The power output is expressed as follows.

$$P_{Max,t} = \frac{G_{a,t}}{G_{a,0}}\left[P_{Max,0} + \mu_{P_{Max}}(T_t - T_0)\right] \tag{7.6}$$

where, $G_{a,0}$ and $P_{Max,0}$ are the solar radiation and the maximum power output at standard module temperature T_0 respectively. G_a and $P_{Max,t}$ are the solar radiation and the maximum power generated at time t respectively. T_t is the module temperature. $\mu_{P_{Max}}$ is the temperature coefficient of the maximum power point.

Working temperature T_t depends exclusively on insolation $G_{a,t}$, ambient temperature $T_{a,t}$ and Normal Operating Cell Temperature ($NOCT$), which is given as follows.

$$T_t = T_{a,t} + G_{a,t}\frac{NOCT - 20}{800} \tag{7.7}$$

Therefore, the power output of a photovoltaic array is given as follows.

$$P_{Max,t} = N\frac{G_{a,t}}{1000} \times \left[P_{Max,0} + \mu_{P_{Max}}\left(T_{a,t} + G_{a,t}\frac{NOCT - 20}{800} - 25\right)\right] \tag{7.8}$$

where, N is the number of photovoltaic modules installed in the array.

7.2.2.2. Wind Turbine

Wind turbine converts kinetic energy of wind to electrical energy. Dynamic characteristics of wind turbine blades can be studied using aerodynamic coefficient curves [128]. Power derived by a wind turbine is given by the following equation.

$$P_{con,t} = \frac{1}{2}\rho_t A C_p(\lambda, \beta) V_{w,t}^3 \tag{7.9}$$

where, $P_{con,t}$ is the converted power, $C_p(\lambda, \beta)$ is a dimensionless aerodynamic power coefficient, $A = \pi R^2$ is the swept area of rotor disc, $V_{w,t}$ and ρ_t are the wind speed and the density of air at time t respectively.

This equation is often used to simulate the wind power generation in the field applications [128]. However, empirical models can be developed for wind turbines from the output characteristics provided by the manufacturers. In this study, an empirical model was developed for a wind turbine, which is expressed as follows.

$$P_{out,t} = \begin{cases} 0 & , \quad V_{w,t} < V_{ci} \\ aV_{w,t}^4 + bV_{w,t}^3 + cV_{w,t}^2 + dV_{w,t} + e & , \quad V_{ci} \le V_{w,t} < V_r \\ P_r & , \quad V_r \le V_{w,t} \le V_{co} \\ 0 & , \quad V_{w,t} > V_{co} \end{cases} \tag{7.10}$$

where, $P_{out,t}$ is the output power, V_w is the wind speed, P_r is the rated power, and V_{ci}, V_{co}, and V_r are the wind speeds at cut-in, cut-out and rated power respectively.

7.2.2.3. Composite Energy Storage System

Composite Energy Storage System (CESS) contains several types of energy storage elements such as flywheels, batteries and ultra capacitors. In this study, Composite energy storage system is empirically modeled as constant voltage source with power limit and energy limit.

The energy limit is measured by State Of Charge (SOC) which can be obtained by monitoring charging power $P_{c,t}$ and discharging power $P_{d,t}$.

$$SOC_{min} \le SOC_t \le SOC_{max} \tag{7.11}$$

where, SOC_t is the state of charge at time t. SOC_{min} and SOC_{max} are the minimum and maximum limits of stage of charge.

It is necessary to take care the undercharging and overcharging limits of composite energy storage system to have an enhanced life time for energy storage elements. This sizing problem provides the best energy and power rating of the composite energy storage system for each microgrid. Selection of individual energy storage elements should be done by analyzing their individual characteristics and manufacturing details.

7.2.3. Reliability Measures

Fraction of loss of load is used as the reliability measure in this study. Calculation of fraction of loss of load of a microgrid and an integrated microgrid is given as follows.

Total energy generated at time t from the renewable energy sources: wind turbine and photovoltaic system can be expressed as follows.

$$E_{R,t} = N_{PV}E_{PV,t} + N_{WTG}E_{WTG,t} \tag{7.12}$$

where, $E_{PV,t}$ and $E_{WTG,t}$ are the energy generated from the photovoltaic module and the wind turbine respectively. N_{PV} and N_{WTG} are the number of photovoltaic modules in the photovoltaic system and the number of wind turbines in the wind plant respectively.

If the sum of energy generated from wind plant and photovoltaic system is less than the load demand, the short of energy $E_{NR,t}$ to satisfy the load demand is generated from the other distributed generators.

$$E_{G,t} = E_{R,t} + E_{NR,t} \tag{7.13}$$

where, $E_{G,t}$ is the total energy generated by the sources except from the composite energy storage system.

If the sum of energy generated by all the distributed generators and the renewable energy sources exceeds the load demand, the excess energy is used to charge the composite energy storage system.

$$E_{B,t} = E_{B,(t-1)}(1-\sigma) + \left[E_{G,t} - \frac{E_{L,t}}{\eta_{inv}}\right]\eta_{bat} \tag{7.14}$$

where, $E_{B,(t-1)}$ and $E_{B,t}$ is the energy stored in the composite energy storage system at time $(t-1)$ and t respectively, $E_{L,t}$ is the load demand, η_{bat} is the round-trip efficiency of the composite energy storage system, η_{inv} is the inverter efficiency, and σ is the self-discharge rate of the composite energy storage system.

When the load demand is greater than the available energy generated, the composite energy storage system will be discharged by the amount that is needed to cover the energy deficit. This is expressed as follows.

$$E_{B,t} = E_{B,(t-1)}(1-\sigma) + \left[\frac{E_{L,t}}{\eta_{inv}} - E_{G,t}\right] \tag{7.15}$$

Loss of Power Supply (LPS) is the energy deficit which is not satisfied from the energy generated from all distributed energy resources. This can be written as follows.

$$LPS_t = E_{L,t} - \left[E_{G,t} + \ E_{B,(t-1)} - E_{Bmin}\right]\eta_{inv} \tag{7.16}$$

where, E_{Bmin} is the minimum energy needed to have in the composite energy storage system.

LOL is the fraction of the total load demand that is not supplied during simulation horizon. In other words, LOL is the ratio between the sum of all LPS_t to the sum of the load demand during the simulation horizon.

$$LOL = \frac{\sum_{t=1}^{T} LPS_t}{\sum_{t=1}^{T} E_{L,t}} \tag{7.17}$$

Interaction between the microgrids is very important to identify the best power transferring between the microgrids in integrated microgrids. In this research, it is modeled as similar to the transportation problem [97]. Each microgrid considers as both a supply center and a demand center. The Power Transferring Matrix (PTM) is written as follows.

$$PTM = \left\{ \begin{array}{cccccc} Supply/Demand & MG_1 & MG_2 & MG_3 & \ldots & MG_n \\ MG_1 & X_{11} & X_{12} & X_{13} & \ldots & X_{1n} \\ MG_2 & X_{21} & X_{22} & X_{23} & \ldots & X_{21} \\ MG_3 & X_{31} & X_{32} & X_{33} & \ldots & X_{31} \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ MG_n & X_{n1} & X_{n2} & X_{n3} & \ldots & X_{nn} \\ MG_{n+1} & X_{n+11} & X_{n+12} & X_{n+13} & \ldots & X_{n+1n} \end{array} \right\} \tag{7.18}$$

where, X_{yz} is the power from microgrid y to microgrid z.

The dimension of the power transfer matrix for an integrated microgrid with n microgrids is $(n + 1) \times n$, where the additional $(n + 1)^{\text{th}}$ row is allocated for the main power grid.

It is considered that all microgrids have high priority to satisfy their internal loads as much as possible. Therefore, the maximum allowable power transferring limit between microgrids is given as follows.

$$\begin{array}{ll} 0 \le X_{yz} \le \infty & , y = z \\ 0 \le X_{yz} \le X_{yz}^{max} & , y \neq z \end{array} \tag{7.19}$$

where, X_{yz}^{max} is the power transferring capacity of interconnection lines.

The power transferring between the microgrids is optimized by Vogel's approximation (UV) method [97]. By knowing the power transferring between microgrids, available energy $E_{m,t}^{i}$ for the internal load of each microgrid can be found out. For example, the available energy for microgrid z at hour t can be found out as follows.

$$E_{m,t}^{j} = \sum_{i=1}^{N} X_{ij} \tag{7.20}$$

where, N is the number of microgrids in the integrated microgrid.

When the available energy for a microgrid is more than the internal load demand of the microgrid, the composite energy storage system in the microgrid is charged as per equation (9.14). When the load demand is greater than the available energy, the composite energy storage system is discharged to cover-up the deficit as per equation (9.15).

The reliability measure LOL for the integrated microgrid is proposed as the fraction of the total load demand not supplied by the integrated microgrid during the simulation horizon. LOL of the integrated microgrid is written as follows.

$$LOL = \frac{\sum_{j=1}^{N} \sum_{t=1}^{T} LPS_{t}^{j}}{\sum_{j=1}^{N} \sum_{t=1}^{T} E_{L,t}^{j}}; \tag{7.21}$$

where, LPS_{t}^{j} and $E_{L,t}^{j}$ are the loss of power supply at time t in microgrid j, and the load demand at time t in microgrid j.

7.2.4. Proposed Methodology

The proposed methodology starts with identifying right design variables for integrated microgrids. The crucial design variables are number of photovoltaic modules, wind turbines, battery units, and power rating of other distributed generators for each microgrid in the integrated microgrid. The overall idea of the proposed methodology is given in Figure 7.2.

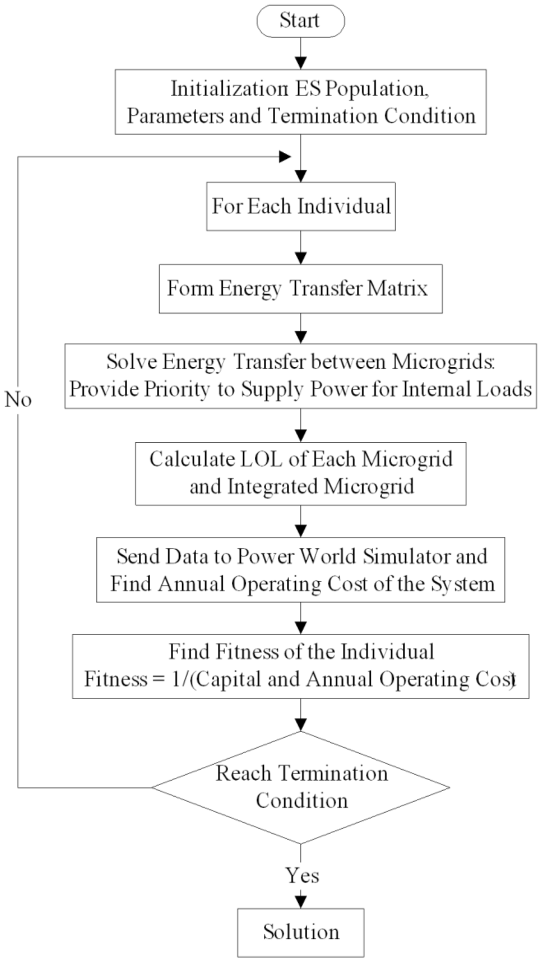


Figure 7.2. Proposed methodology for optimal sizing

Evolutionary Strategy (ES) [18,105] that works on an encoded representation of the solutions is proposed and developed to solve this problem. Each chromosome is a solution associated with an objective value. The objective value is the representative of the candidate solution's performance in relation to the parameter being optimized. It also reflects a candidate solution’s performance with respect to other potential solutions in the space. Based on the fitness values, number of individuals is selected and genetic operators (i.e. mutation and/or recombination) are applied to generate new individuals in the next generation. The best solutions generated in one generation become the parents for the next generation.

Evolutionary strategy is an iterative method and hence the process of selection and application of genetic operators is repeated until reaching the predefined convergence criteria. After convergence, the best solution obtained is represented by the best individual so far in all generations. In this project, typical $(\mu + \lambda)$ Evolutionary Strategy (ES) is used. The basic steps of the evolutionary strategy are given as follows.

1. Generate an initial population of λ individuals.
2. Evaluate each individual according to the fitness function.
3. Select μ best individuals called the parent population and discard the rest.
4. Apply genetic operator to create λ off springs from μ parents.
5. Go to step 2 until a desired solution has been found or predetermined number of generations have been produced and evaluated.

Initial population of chromosomes is randomly generated within the specified practical minimum and maximum bounds of decision variables. During the simulation, each chromosome is evaluated to find out the total cost, lost of load probability, energy and emission generated from each source in each microgrid. Total cost is the objective to optimize without violating energy, emission and reliability constraints. Power World simulator is used to find out the operational cost of the system. It calculates the sum of fuel cost and power transmission cost while considering power losses in the system. Power settings of each source and details of loads at each hour are sent to Power World simulator to find out the actual operating cost of the system. A fitness function is selected such that it minimizes the total cost. The fitness function is given as follows.

$$Fitness = \frac{1}{Total\ Cost} \tag{7.22}$$

The proposed methodology was used to size distributed energy resources for integrated microgrids operating under the different operational strategies.

7.2.5. Simulation Studies

The proposed methodology was used to size distributed energy resources in the integrated microgrid for MODERN project which was carried out by National University of Singapore [129] under IEDS program with the aid of A*STAR [130]. The interest is to size the resources for each microgrid optimally with reference to different operational strategies. The energy limits and emission limits for all distributed energy resources in the microgrids are taken from another work package of the project. That work package is completely dedicated to find out possible future energy source mixes for a particular country or a region [131] by considering the effects of economics, renewable energy penetration, emission, customer satisfaction, uncertainties and sustainability.

7.2.5.1. Simulation System

Schematic diagram of the integrated microgrid is shown in Figure 7.3. Each microgrid is built with different type of customers. Microgrid 1 (CMG) is for commercial type of customers, which has a peak load demand of 2MW, whereas, Microgrid 2 (IMG) and microgrid 3 (RMG) are belonging to industrial and residential types of customers respectively, whose peak load demands are 3MW and 1.5MW respectively. Energy limits for the integrated microgrid operating under different strategies are given in Table 7.1.

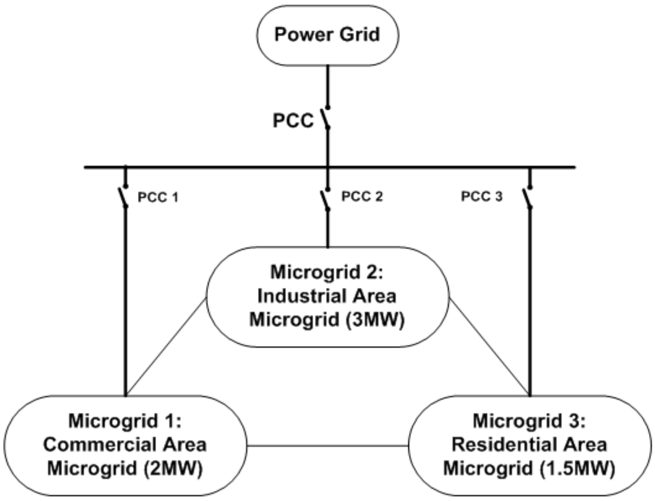


Figure 7.3. Schematic diagram of the integrated microgrid

Table 7.1. Average energy limits of distributed energy resources

DER (%)	Strategy 1			Strategy 2			Strategy 3		
	CMG	IMG	RMG	CMG	IMG	RMG	CMG	IMG	RMG
Wind	0.0	35.1	31.8	0.0	35.2	30.5	0.0	36.7	36.7
Solar	45.3	35.1	31.8	49.3	35.2	30.5	52.1	36.9	36.9
Hydrogen	24.7	11.7	2.4	15.8	11.3	9.8	3.4	0.0	0.0
Biomass	10.0	5.1	0.0	6.4	4.6	4.0	10.0	1.3	1.3
Biodiesel	10.0	6.7	24.3	10.0	6.7	25.2	9.5	0.0	0.0
NG	3.2	0.0	0.0	0.0	0.0	3.3	0.0	0.0	0.0
Diesel	6.8	6.3	9.7	9.5	6.3	10.0	0.0	0.0	0.0

Emission limits are only for diesel and natural gas units. 600 tons CO_2/MWh and 500 tons CO_2/MWh are the emission limits of diesel and natural gas units respectively for strategy 1. These values are 90% and 75% of the values of strategy 1 for strategy 2 and strategy 3 respectively. These data are recommended by energy source mix planning by work package 1 of MODERN project [131]. Proposing a methodology for sizing the sources is the main objective of this research. The energy limits and the emission limits are just inputs to the methodology. These can be any values from this part of the research, but it should be realistic for the real systems.

Figure 7.4 shows the comprehensive details of the electrical network [6,104] of the integrated microgrid. This network was found out by the experience of experts in the project team. The entire network operates at a low voltage (i.e. 410V). This network may not be an optimal network structure. The electrical data for the interconnection links are given in Table 7.2. The distribution of loads and generators are provided in Table 7.3.

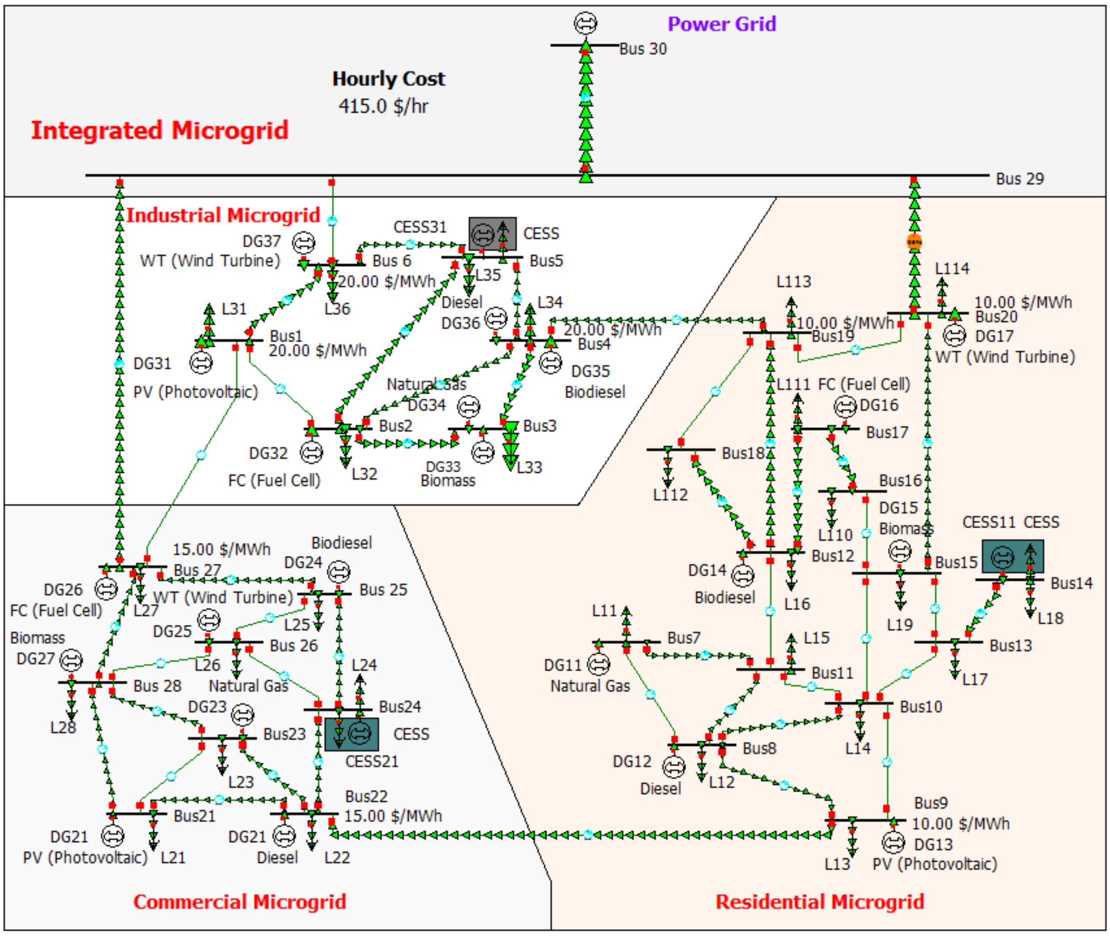


Figure 7.4. Electrical network diagram of the integrated microgrid

In this study, 140 kW wind turbines and 36W photovoltaic modules are considered as the basic elements of the renewable energy sources. The detail characteristics and data of these units can be found in [94].

Table 7.2. Data of interconnection links

Interconnection link	Resistance (pu)	Reactance (pu)	Power Flow Limit (kVA)	Length (km)
In Industrial MG	0.003	0.01	500	5
In Residential MG	0.00375	0.0125	500	2
In Commercial MG	0.0035	0.012	500	3
Among MGs	0.003	0.01	500	7.5
Between MG & Main Grid	0.003	0.01	500	10

Table 7.3. Distribution of loads and generators

Bus	MG	DER	Load (%)	Bus	MG	DER	Load (%)
1	IMG	PV	35.0	16	RMG	-	5.0
2	IMG	Hydrogen	10.0	17	RMG	Hydrogen	7.5
3	IMG	Biomass, Natural Gas	7.5	18	RMG	-	7.5
4	IMG	Biodiesel, Diesel	15.0	19	RMG	-	7.5
5	IMG	CESS	20.0	20	RMG	WT	7.5
6	IMG	WT	12.5	21	CMG	PV	15
7	RMG	Natural Gas	7.5	22	CMG	Diesel	10
8	RMG	Diesel	7.5	23	CMG	Natural Gas	15
9	RMG	PV	7.5	24	CMG	CESS	15
10	RMG	-	7.5	25	CMG	Biodiesel	10
11	RMG	-	7.5	26	CMG	WT	10
12	RMG	Biodiesel	7.5	27	CMG	Hydrogen	15
13	RMG	-	10.0	28	CMG	Biomass	10
14	RMG	CESS	5.0	29	Grid	-	-
15	RMG	Biomass	5.0	30	Grid	-	-

Composite energy storage systems with the following specification are considered as the basic elements for the energy storage. Maximum energy limit is 1000kWh, maximum power limit is 200kW, and charging and discharging efficiencies are 0.9

each. The minimum state of charge is 50%, and self-discharge rate per hour is 0.001%. In addition, it is considered that the maximum power point trackers, battery controllers and inverters have efficiencies of 100%. The number of wind turbines, photovoltaic modules and composite energy storage system required for the integrated microgrids are derived from the optimization. The meteorological data for the year, 2009 is taken as historical data from the meteorological department [103].

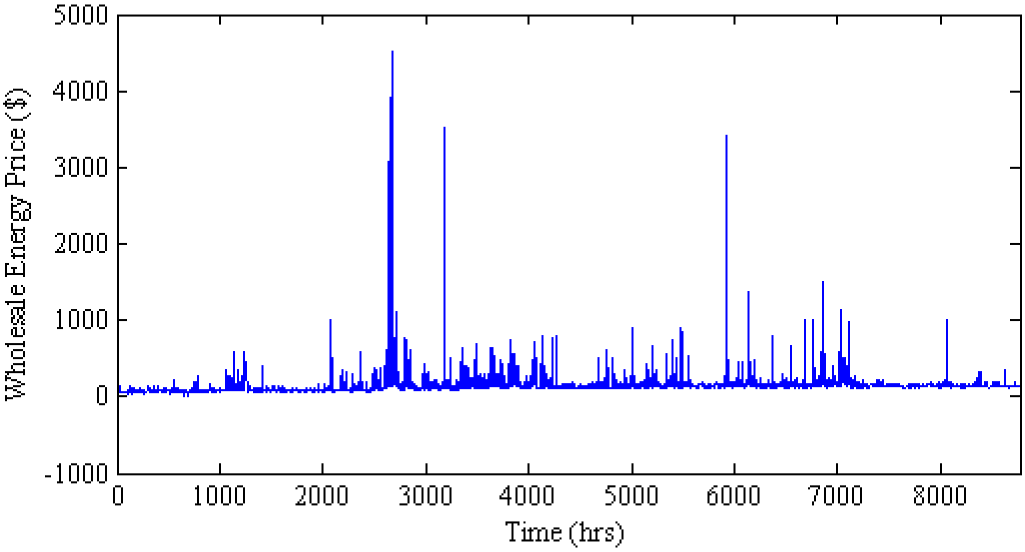


Figure 7.5. Hourly wholesale prices

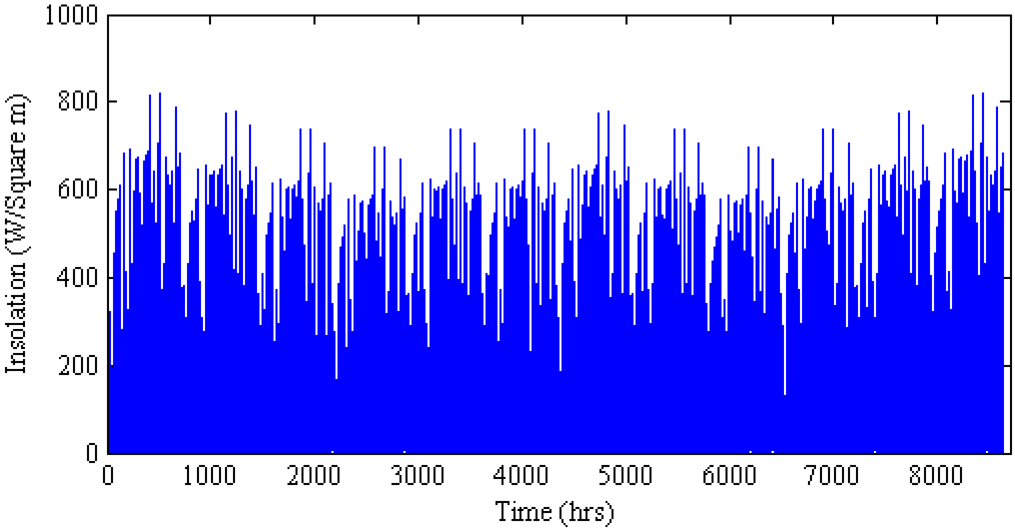


Figure 7.6. Hourly solar insolations

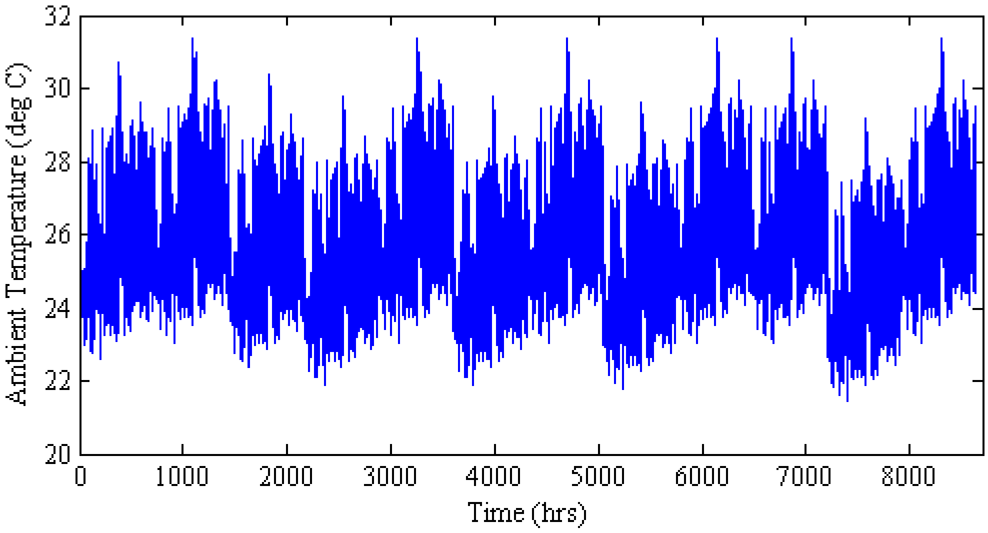


Figure 7.7. Hourly ambient temperatures

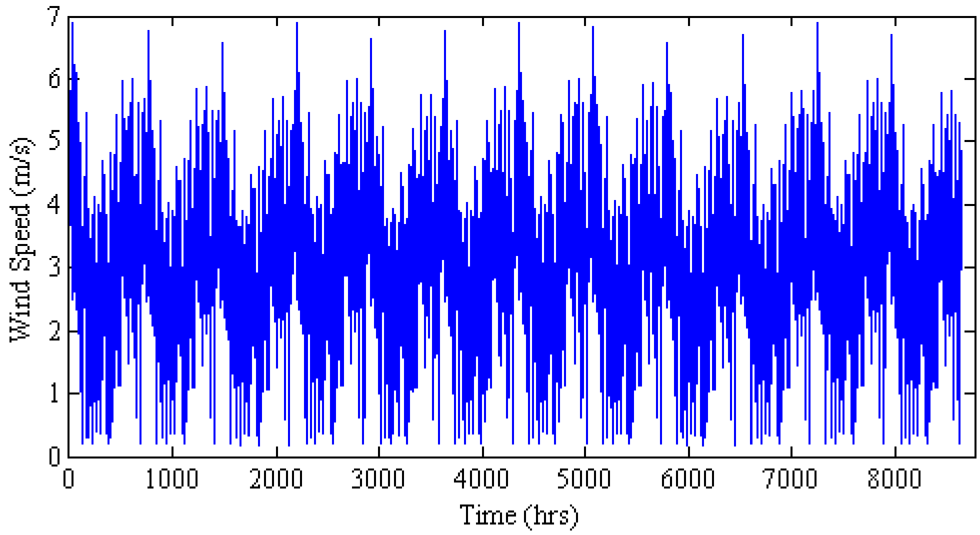


Figure 7.8. Hourly wind speeds

Figure 7.5 shows the hourly historical wholesale prices, Figure 7.6 shows the hourly historical solar insolations, Figure 7.7 shows the hourly historical ambient temperatures, and Figure 7.8 shows the hourly historical wind speeds. Table 7.4 contains the average capital cost [104,105] of each distributed energy resource in the integrated microgrid. Capital cost is the sum of cost associated with equipments and installation at particular location. Installation cost of distributed energy resources varies among technologies, especially less mature technologies faces wide variations. Typical installation costs are approximately 30% of the capital costs [104,105], however they could reach up to 100% for highly customized applications.

Table 7.4. Cost details of distributed energy resources

Technology	Equipment Cost ($/kW)	Installation Cost ($/kW)	Operational and Maintenance Cost ($/kW)	Fuel Cost (c/kW)
IC Engine Diesel	550	500	0.75	0.145
IC Engine Natural Gas	550	1000	1.10	0.085
Fuel Cell	6750	5500	0.75	0.025
Micro Turbine (BD)	900	1000	1.05	0.045
Micro Turbine (BM)	900	1000	1.05	0.035
Photovoltaic	5250	8000	1%†	-
Wind Turbine	2150	3000	2%†	-
CESS	1100	200	1%†	-

†Percentage of initial annual investment

Operational and maintenance costs of distributed energy resources have both fixed and variable cost components. Average operational and maintenance costs for each resource in the system are also given in the table. Fixed cost in operational and maintenance cost refers to labor cost, which is highly dependent on the operating cycle and staffing philosophy. Variable cost in operation and maintenance cost includes periodic inspection, repair works and replacement of system components, and required consumables in the plant. Average costs of the fuel sources are also given in the table.

7.2.5.2. Simulation Results

In these simulation studies, sizing of distributed energy resources for three different integrated microgrids was carried out. These integrated microgrids are differentiated based on the interconnection between the microgrids and interconnection with the main grid, which are briefly given below.

- Strategy 1: Islanded Microgrids - In this strategy, all microgrids in the integrated microgrid are operated in islanded mode, and remain self sustainable. Each microgrid operates independently.
- Strategy 2: Islanded Integrated Microgrid - In this strategy, all microgrids are interconnected with each other, but they are islanded from the main power grid.
- Strategy 3: Grid-Connected Integrated Microgrid - It is a prominent architecture of integrated microgrids where, all microgrids are interconnected with each other as well as connected with the main power grid.

One year hourly load, wind energy and photovoltaic energy are used for the simulations. It is considered that these hourly data are constants in each hour. Seasonal variations of the data are not considered due to the availability of limited data.

Table 7.5. Results for the integrated microgrids with strategies 1 and 2

DER	Strategy 1			Strategy 2		
	CMG	IMG	RMG	CMG	IMG	RMG
Diesel (kW)	140	210	110	155	240	120
Natural Gas (kW)	220	330	-	-	-	185
Fuel Cell (kW)	270	410	210	230	350	175
Biodiesel (kW)	220	330	170	250	370	185
Biomass (kW)	115	115	-	110	160	80
Photovoltaic (kW)	2304	3420	1728	2340	3492	1764
Wind Turbine (kW)	-	1400	700	-	1540	840
Battery Bank (kW)	800	1000	600	600	1000	400
Photovoltaic (units)	64†	95†	48†	65†	97†	49†
Wind Turbine (units)	-	10†	5†	-	11†	6†
Battery Bank (units)	4†	5†	3†	3†	5†	2†
LOL Achieved	0.005	0.004	0.002	0.006	0.001	0
Total Cost (x108$)	1.8532	2.7957	1.0113	1.4211	2.2344	1.5310

† refers to number of units

Predefined target reliability measures LOL_{Max} and LOL_{Max} are set to 0.01 each [132]. The best decisions recommended by the proposed methodology are tabulated in Table 7.5 for strategies 1 and 2, and in Table 7.6 for strategy 3.

Table 7.6. Results for the integrated microgrid with strategies 3

DER	CMG	IMG	RMG
Diesel (kW)	-	-	-
Natural Gas (kW)	-	-	-
Fuel Cell (kW)	25	-	-
Biodiesel (kW)	60	-	-
Biomass (kW)	75	110	55
Photovoltaic (kW)	2664	3996	2016
Wind Turbine (kW)	0	1540	840
Battery Bank (kW)	400	800	400
Photovoltaic (units)	74†	111†	56†
Wind Turbine (units)	-	11†	6†
Battery Bank (units)	2†	4†	2†
LOL Achieved	0	0.0003	0.0001
Total Cost (x108$)	1.2114	1.9341	1.3120

† refers to number of units

7.2.5.3. Discussions

Strategy 1 has islanded microgrids without any interconnections. This strategy simplifies the problem and efforts for the optimization because it does not have any interaction between the microgrids. The proposed evolutionary strategy outperformed as expected in this strategy. The optimum total cost is 5.66×108 dollars.

Strategy 2 is an integrated microgrid which does not have any connection with the main grid. This strategy aims to remain sustainable by sharing power between the microgrids. The optimum total cost is 5.18×108 dollars. This strategy has cost benefit of 8.5% compared to strategy 1. Here, total costs for CMG and IMG are less than that needed in strategy 1 because energy generation in CMG and IMG for strategy 2 is less than that for strategy 1. On the other hand, total cost of RMG increases substantially due to over exploitation of RMG to serve energy deficits in CMG and IMG.

Strategy 3 refers to an integrated microgrid with proper interconnection between the microgrids, and also connected to the main distribution grid. The optimum total cost is 4.46×108 dollars. This is 21% less than strategy 1, and 14% less than strategy 2 respectively. This cost benefits is mainly because of power import from the main power grid, which reduces the contribution of expensive distributed energy resources in the microgrids. The results show that diesel and natural gas are not recommended because these sources are expensive when GHG penalties imposed on them as per the work package 1 [131]. This also improvises the environmental benefits by stay away from the diesel and natural gas sources. Fuel cell and biomass are also not preferred by IMG and RMG because the energy imported cost is relatively cheaper than exploiting fuel cell and biomass sources.

With reference to the cost measure, energy and environmental benefits, integrated microgrid adopting strategy 3 is more prominent, and evident to provide energy at cheap cost with enhanced energy security. Even though proposed methodology investigates three integrated microgrids with seven distributed resources at each microgrid, it can be extended to any number of distributed resources with diverse types and technologies.

Proposed evolutionary strategy provides good convergence for all the cases. Figure 7.9 shows the convergence characteristic of the evolutionary strategy for strategy 3. Flexibility is the main advantage of the proposed methodology. The chromosome structure can be easily modified to adopt any size of problems. Sizes of distributed generators other than the renewable energy sources and storage systems obtained from the optimization are just numbers. In order to choose the available distributed generators, it is necessary to go for the nearest available ratings. It is also possible to select these from available ratings by the algorithm itself. Selection of vendors (i.e. types) for distributed generators can be added as additional genes in the chromosome if all data of each distributed generators are known.

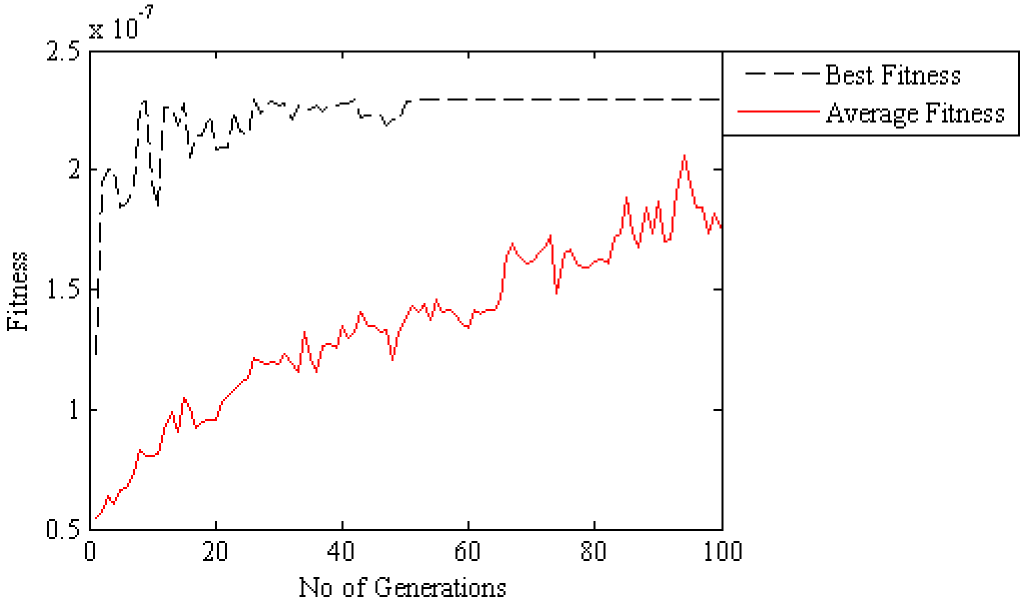


Figure 7.9. Convergence characteristic of ES for strategy 3

7.3. Optimal Placement of Distributed Generators

The placement and penetration of distributed generators in distributed power systems change the characteristics of the distribution systems, and have impacts on various technical parameters [133-137] of the systems. Therefore, it is necessary to place the distributed generators at the optimal point of the network such that it will make good changes to the network.

In this section, a methodology is proposed to find out the optimal locations for a predefined number of distributed generators. The proposed methodology can be used by distribution network operators to search for the available best sites among a large number of potential combinations, where a defined number of distributed generators can be strategically connected.

7.3.1. Global Performance Index

The penetration of generating sources in distributed power systems changes its characteristics, and impacts on various technical parameters such as real and reactive power losses, voltage profile, phase imbalance, fault current, current through lines, and harmonic currents [135,136]. If network structure is fixed, and all branches among nodes are known, level of impacts depends only on size and location of distributed generators. Therefore, proper locations and sizes of distributed generators in distributed power systems are important factors to obtain the maximum potential benefits from the distributed generation.

A Global Performance Index (GPI) [135] is a performance index used in this research to evaluate the collective impact on the technical parameters. It considers all impacts on the technical parameters of distributed power systems. Many indices related to involvement of distributed generation in system can be considered individually, but a global performance index has to be obtained to give a complete comprehensive evaluation of the system. The global performance index considers changes in the characteristics of distributed power systems, and impacts on various technical parameters of the systems. Some of them are briefly explained as follows.

- Indices of Real and Reactive Power Losses: Typically, real and reactive power losses will be reduced when distributed generation presents. The lower the values, the better the benefits in terms of loss reduction accrued to distributed generation location.

  Real power loss index is defined as follows.

$$I_{PL} = \frac{PL_{DG}}{PL} \tag{7.23}$$

Reactive power loss index is defined as follows.

$$I_{QL} = \frac{QL_{DG}}{QL} \tag{7.24}$$

where, PL_{DG} and QL_{DG} are the total real and reactive power losses of the system after including the distributed generation. PL and QL are the total real and reactive power losses of the system without distributed generation in the system.

- Voltage Profile Index: This index is the voltage deviation limit to ensure the rated voltage of each bus within the permissible limits. The lower this index, the better the network performance.

  The voltage profile index is defined as follows.

$$I_{VD} = Max\left[\frac{|V_i - v_i|}{V_i}\right] \qquad i = 1, 2, 3 \ldots\ldots\ldots\ldots n \tag{7.25}$$

where, V is the rated voltage at a bus, v is the voltage at the bus, and n is the number of buses in the system.

- Fault Level Indices: These indices are related to the protection and selectivity issues, since they evaluate the maximum short-circuit current variation among the scenarios with and without distributed generation. The greater the values of these indices means more contribution to the fault level, therefore, the protection issue of the system should be re-coordinated. Hence, the lower the index, the better the network performance.

  Three-phase short-circuit current index is defined as follows.

$$I_{SC3} = Max\left[\frac{SC3_{i,DG}}{SC3_i}\right] \qquad i = 1, 2, 3 \ldots\ldots\ldots\ldots n \tag{7.26}$$

Single phase short-circuit current index is defined as follows.

$$I_{SC1} = Max\left[\frac{SC1_{i,DG}}{SC1_i}\right] \qquad i = 1, 2, 3 \ldots\ldots\ldots\ldots n \tag{7.27}$$

where, $SC3_{i,DG}$ is the three-phase fault current value at bus *i* with distributed generation units, $SC3_i$ is the three-phase fault current value at bus *i* without distributed generation units, $SC1_{i,DG}$ is the single phase to ground fault current value at bus *i* with distributed generation units, and $SC1_i$ is single phase to ground fault current value at bus *i* without distributed generation units.

- Index of Current Capacity of Lines: As a consequence of supplying power near loads, power flows may reduce in some sections of the network, thus releasing more capacity, but in other sections, they may increase to level beyond distribution networks line limit. This index gives important information about the level of power flows through the network conductors regarding the maximum capacity of conductors. This index also gives the information about the need of system line upgrades. Low values of the index indicate more amount of available capacity.

  Current capacity of line index is defined as follows.

  $$I_{CC} = Max\left[\frac{s_i}{S_i}\right] \qquad i = 1, 2, 3 \dots\dots\dots\dots l \tag{7.28}$$

  where, s_i is the apparent power flow in a line, S_i is the power flow capacity of the line, and l is the number of lines.

- Harmonic Current Index: This index describes the total harmonic distortion in the presence of distributed generation units. Hence, the lower the index, the better the network performance.

  Harmonic current index is defined as follows.

  $$I_H = \sum_{i=1}^{n}\left(V_{THD_i} - V_{THD_{i,DG}}\right) \tag{7.29}$$

  where, $\boldsymbol{v_{THD_i}}$ is a voltage total harmonic distortion of bus *i* without adding distributed generation units, and $\boldsymbol{v_{THD_{i,DG}}}$ is the voltage total harmonic distortion of bus *i* with adding distributed generation units. The both values are per unit ratios from the summation of the total harmonic distortions all overall buses.

- Global Performance Index: The global performance index numerically describes the impact of distributed generation on the distributed network considering a given location and size. Close to zero value for the global performance index means higher benefits of distributed generation, and leads to the best location of distributed generation.

  The Global Performance Index (*GPI*) is defined as follows.

  $$GPI = w_1 I_{PL} + w_2 I_{QL} + w_3 I_{VD} + w_4 I_{SC3} + w_5 I_{SC1} + w_6 I_{CC} + w_7 I_H \tag{7.30}$$

  where,

  $GPI = w_i \in [0,1]$

  and

  $$\sum_{i=1}^{7} w_i = 1.0$$

The proposed global performance index considers all previously mentioned indices by strategically giving a weight for each one. The weighting factors are chosen based on the importance and criticality of the different loads and according to the objectives of the system operator. Logical and beneficially rules are taking into consideration when assigning the values of the weighting factors for the different operating cases. Indices that have a greater impact on improving system performance should have larger weights. The weighted normalized indices get their weights by translating their impacts in terms of cost. The cost may either be determined rigorously or through an engineering judgment. Regardless of the fact that one particular objective may get higher satisfaction on the cost than the others. It is desirable if the total cost decreases.

In this research, all the indices except the harmonic current index are used to form the global performance index. Table 7.7 shows the weight values used in the research for considering normal operation analysis. The values are near to that given in [138] after modifications for the new indices proposed and added in this work. However, these values may vary according to engineer's concerns and based on the system considered.

Table 7.7. Weight factors for indices

Indices	I_{PL}	I_{QL}	I_{VD}	I_{CC}	I_{SC3}	I_{SC1}	I_H
Weight Factors (w_i)	0.20	0.10	0.20	0.20	0.10	0.15	0.05

Figure 7.10 shows the steps in the proposed methodology. Simulation of power flow studies and short circuit studies were carried out using DIgSILENT power factory [139].

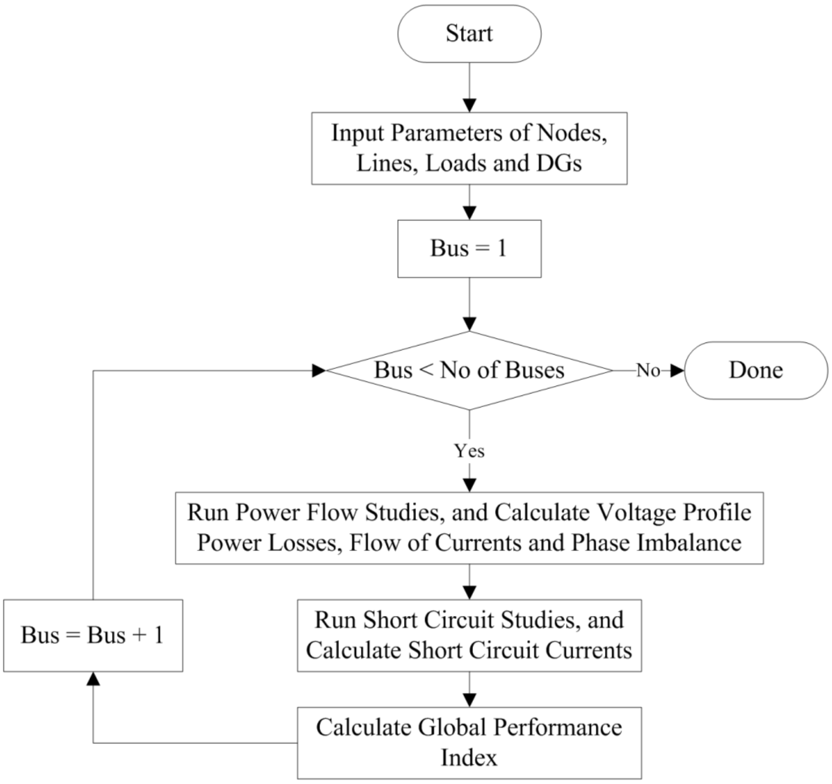


Figure 7.10. Flowchart of the proposed methodology

7.3.2. Simulation Study

IEEE 34 node distribution test feeder is used for simulation study, which is shown in Figure 7.11. Details about the test feeder can be seen in [140]. This study finds out the optimal location for distributed generators.

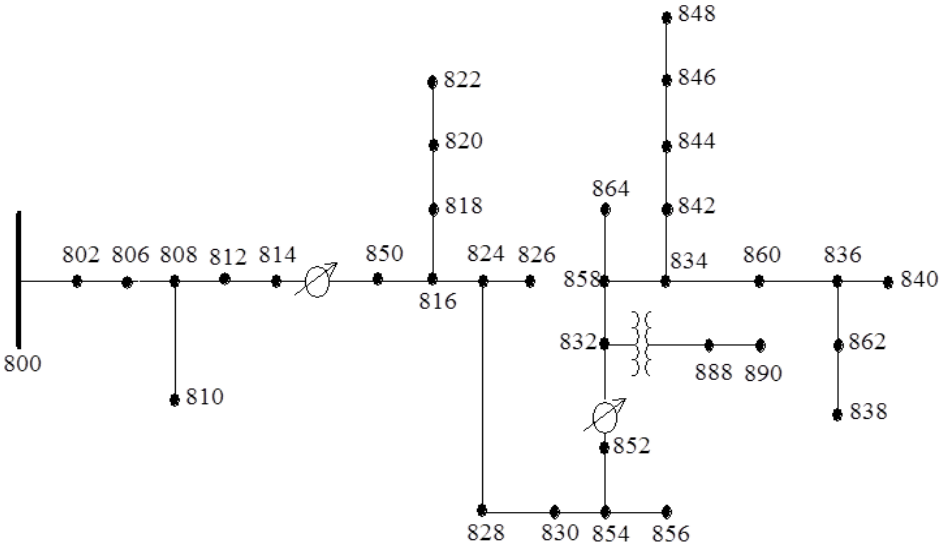


Figure 7.11. IEEE 34 node test feeder

Node 890 is selected as the best node for introducing three phase distributed generation. Special attention is required when distributed generation is placed at node 890 to adjust protective devices for the increased fault level. When introducing single phase distributed generation, attention should be taken in allocating the distributed generation among different phases such that statutory limit on phase imbalance is not violated.

This section analyses the changes by distributed generation, and studies the impacts on the technical parameters such as real and reactive power losses, voltage profile, phase imbalance and fault level by varying the penetration level and place of distributed generators. The project has delivered a flexible tool for optimal placement of distributed generation. This tool can be used for planning of any distributed power systems with any type of distributed generators.

7.4. Summary

Advanced optimization techniques and computational tools were developed for optimal sizing and placement of distributed generators. A novel methodology based on evolutionary strategy for optimal sizing of distributed energy resources is proposed for integrated microgrids. Three different operational strategies of integrated microgrids were considered in the simulation studies. Outcomes of the studies confirmed the workability of the proposed methodology. The proposed methodology is readily extendable for designing of integrated microgrids with any rules and policies. Some systems optimally sized using this proposed methodology were used for the simulation studies in various chapters of this dissertation.

Furthermore, the chapter investigates the changes and impacts on technical parameters of distributed power systems such as real and reactive power losses, voltage profile, phase imbalance, fault level, current capacity of lines, harmonic currents when distributed generation introduces in the power systems. A methodology is proposed for optimal placing of distributed generators, in which a global performance index was used to represent the combined impact on the technical parameters.

CHAPTER 8

CONCLUSIONS AND FUTURE WORK

In this final chapter, major findings of this research are summarized, their implications are discussed and areas for future research are suggested.

8.1. Overall Conclusions

This thesis presents the intelligent multi-agent system approach for control and management of distributed power systems for implementing smart grid functionalities. A FIPA complaint multi-agent system was developed and the proposed methodologies for the optimal control and management of distributed power systems were validated and demonstrated successfully. The outcomes of the various simulation studies show that the multi-agent system is a perfect platform for implementing the smart grid techniques and operating modern power systems.

The modern distributed power systems contain several microgrids that make the implementation of smart grid techniques at distribution network level simple. Interaction among distributed energy resources and interaction between microgrids and the main distribution grid are the crucial tasks for the better development of design and control schemes for distributed power systems. This research shows that the multi-agent system is one of the most promising approaches to handle the interaction among the control elements. It also shows that having many microgrids at the distribution network level provides highly reliable supply to customers. The proposed multi-agent system approach should be useful for many researchers in the academia and the industry to understand the design, development and implementation of agent-based technology for the development of smart grid and the operation of modern power systems.

8.2. Main Contributions

The main objective of this dissertation was to develop a distributed multi-agent system for control and management of distributed power systems. A FIPA complaint multi-agent platform was developed, the proposed methodologies for the optimal control and management of distributed power systems were implemented on the multi-agent system, and the developed multi-agent system was tested, validated and demonstrated successfully by several simulation studies. Some significant contributions made in the design front are given as follows.

- Development of a generalized distributed multi-agent platform for control and management of distributed power systems.
    1. It was developed based on IEEE FIPA standards in JADE.
    2. It was interfaced with two power system simulators: Power World simulator (via COM technology) for the simulation studies of day-ahead operation, and RTDS (via TCP/IP connectivity) for the simulation studies of real-time operation.
- Implementation of a hierarchical control scheme on the multi-agent system for maximizing the power production output of local distributed generators, and optimizing power exchanges among the microgrids and power exchange between the main distribution system and the integrated microgrid.
- Implementation of the decision making modules of the agents in the multi-agent system using mathematical and computational intelligence techniques. This dissertation mainly concentrates on the agents that involve in generation scheduling and demand side management functions.
    1. Evolutionary Algorithm (EA) was developed for the demand side management agent

    2. A hybrid algorithm (i.e. LREA) was developed for the generation scheduling agent

- Development of a dynamic multi-agent system for real-time simulation of a microgrid in the Real-Time Digital Simulator (RTDS).
    1. Collaboration with power electronic researchers made it much realistic.
    2. Power flow and power electronic interfaces were controlled dynamically.
- Development of simulation scenarios for control and management of distributed power systems such as microgrids and integrated microgrids.
- Development of advanced methodologies for the optimal sizing and placement of distributed energy resources for distributed power systems. The proposed methodologies were used to find out some of the simulation systems in this thesis.
- Extension of the proposed multi-agent system for management of plug-in hybrid electrical vehicles.
- Development of intelligent methodology for management of distributed energy storage systems.

8.3. Future Research Work

The modern power systems focus on smart grids which include the deployment of smart metering infrastructure and smart grid techniques for transmission and distributed networks. This research is one step towards the smart grid. Much more research works are needed for the full implementation of a smart grid.

This thesis proposes the intelligent multi-agent system approach for distributed power systems, which mainly focused on the development of some smart grid techniques and carried out some simulation studies on the developed platform. As the developed multi-agent system is scalable, extendable and easily reconfigurable, it could be expanded for further studies. Furthermore, research in the area of multi agent system applications for solving power system problems is being done by some researchers all around the world.

As the field of multi agent system for power systems is relatively a new field, it has several open avenues for research. Some of the recommendations for future research work are given below.

- Further insight is required to expand this research for including other smart grid techniques. Various simulation studies are needed on the multi-agent system for power systems operating with many smart grid techniques.
- It is necessary to have some interactions among power production companies in smart grid. Several gaming strategies can be followed by the companies to get success on their business. Therefore, intense research is needed on these types of interactions among the agents.
- Local controllers are needed to model the details with the power electronic concepts to do fast and adaptive control actions. This will lead to the research on comprehensive multi-agent system for the operation of distributed power systems.
- Research is needed on real power systems for testing and validating the real values of developed distributed control and energy management strategies.
- Research and alteration is needed to apply the developed distributed control and energy management strategies for current power systems.
- Advanced decentralised algorithms can be used for the development of fully decentralised control and management systems. In addition, comprehensive multi-objective control and management can be investigated.
- Self-healing is one of the main characteristics of a smart grid. The multi-agent approach has a huge potential to do decentralized monitoring, fault recognising

and restoring of power systems. Developing a self-healing power system is the biggest possible research opportunity in this field.

- Learning of agents is one of the main characteristics of multi-agent system. It can be used to operate a smart grid reliably even in uncertainties. Currently, the uncertainties are mainly handled by distributed energy storage system. Research is needed on learning of agents for power systems.

In addition, it is important to identify the key technical problems and challenges for the development of multi-agent system effectively within the field, and how to overcome them. The challenges include industrial standards and security of multi-agent system. Therefore, the future research is also necessary to focus on these areas.

APPENDIX

THE IDEAS FOR THE SIEMENS SMART GRID INNOVATION IDEA CONTEST

This section provides four innovative ideas which were submitted to the Siemens smart grid innovation idea contest, 2011 [141]. The ideas that are entitled "Multi-Agent System for Operation of a Smart Grid" and "Autonomous Distributed Power System Restoration" were awarded the first prize in the contest, and the idea that is entitled "Applications of Computational Intelligent Techniques for Implementing Smart Grid Concepts in an Integrated Microgrid" was featured in the top twenty list. Even though, the idea that is entitled "Distributed Demand Side Management of a Smart grid with PHEVs" was not awarded any rank, it received good respect from the audience and the members of the contest.

A.1. Idea 1: Multi-Agent System for Operation of a Smart Grid

Smart grid is made possible by applying sensing, measurement and control techniques with two-way communication between electricity production, transmission, distribution and consumption parts of the power grid. Two-way communication is necessary for system users, operators and automated devices to have the knowledge of grid condition in order to respond dynamically for the changes in grid. Current approach using a central SCADA system and several smaller distributed SCADA systems is no longer sufficient for large complex smart grid operations. An approach that provides adaptable local and decentralized control and intelligent decision making is required. Intelligent Multi-Agent System (MAS) is a promising technology for implementing such a control system because it provides a common communication interface for all elements and has the potential to provide autonomous intelligent control actions in a distributed nature. Intelligent multi-agent system provides a platform for modeling of autonomous decision making entities in decentralized fashion and can be used to implement smart grid concepts for the operation of modern power systems. This idea proposes an intelligent multi-agent system for operation of microgrids and other power distribution systems and implementing smart grid concepts in context of distributed smart grid. Some of the key benefits of this idea are: common communication interface for all elements and potential to solve complex problems in a decentralized manner. In addition, multi-agent system is capable of making intelligent decisions and can be used to implement flexible, extendable, fault tolerant control and management functions.

A.2. Idea 2: Autonomous Distributed Power System Restoration

When interruption of electric power supply is caused by a fault or a breakdown of any element in the power system, it is imperative to restore the power system promptly to an optimal target network configuration. It means that the power system should have self-healing characteristics. Possibility of restoration is depending on the type and the severity of the fault. Sometimes, it may not possible to restore immediately. In such a situation, distributed power system should work by parts independently to provide supply to customers as much as possible. Current power systems are becoming more complicated by the penetration of distributed generation and renewable energy sources. At the same time, customers require higher reliable electricity supply. Under these circumstances, it is mandatory to restore the power system quickly and safely. The problem of restoration after service interruption is a complex decision-making and control problem for power system operators. Typical power system restoration consists of two sequential steps with switching operations excepted: The first step is to determine an optimal configuration as a restoration target. The second step is to make up a sequence of restoration procedure to bring a faulted system into the thus obtained target system while maintaining a certain level of security. The configuration of distribution systems is quite different from local or bulk power systems. The common form of distribution system configuration is the radial-type because of the ease of operations. Conventionally, the determination of a target system for restoration and associated restorative control schemes are carried out by experts in the distributed power system control centre. However, computerized automation has gradually but steadily been promoted to improve distributed power system reliability. In general, the restoration problem may be described as a multi-objective, multi-stage, combinatorial, nonlinear and constrained optimization problem. The complexity of such a problem precludes the development of a generic method of determining restorative controls. To resolve this problem, various approaches have been investigated in the literature and few of them have been implemented for the objective of the support and automation of restoration schemes such as heuristics, expert systems, mathematical programming and soft computing. In an era of deregulation on energy polices, it is difficult to carry out power system restorations by the conventional approaches, since the coordination of all parties including independent power producers is required. Therefore, this idea is to investigate other possible methodologies to handle this situation. Intelligent Multi-Agent System (MAS) is a promising technology for implementing such a system because it provides a common communication interface for all elements, and has the potential to provide autonomous intelligent control actions in a distributed nature. Intelligent multi-agent system provides a platform for modeling autonomous decision making entities in decentralized fashion and can be used to implement an autonomous restoration system for distributed power systems.

A.3. Idea 3: Applications of Computational Intelligent Techniques for Implementing Smart Grid Concepts in an Integrated Microgrid

Smart grid represents the vision of the future power systems, which encourages integration of renewable energy sources, distributed generation and plug-in hybrid electric vehicles in distributed power systems. Smart grid adds complexity and challenges to various controllers at all levels of power grids. Therefore, new control and management paradigms and advanced computational methodologies are required for planning, optimization, fast control of power system elements, processing of field data and coordination across the grid. In this idea, an integrated microgrid that is an innovative architecture in which several microgrids are interconnected with each other for superior control and management of distributed power systems is proposed. Long-term planning of Distributed Energy Resources (DER) for the integrated microgrids can found out by a flexible evolutionary algorithm. Proper selection and optimal sizing of distributed energy resources are important optimization tasks involved in the long-term planning of integrated microgrids. Furthermore, the right coordination among distributed energy resources within a microgrid and proper harmony between microgrids and main distribution grid are critical challenges in the long-term planning. The design variables are needed to be optimized such that proposed integrated system provides reliable electricity at a cheap price. In addition, a decentralized Multi-Agent System (MAS) is proposed for the operation of the integrated microgrid. The multi-agent system can be designed, developed and implemented for the operation of an integrated microgrid according to the industrial standards. Decision making systems of the intelligent agents can be implemented with computational intelligent techniques and rule-based systems. For an example: A flexible Evolutionary Algorithm (EA) based on heuristics is proposed for decision making module of demand side management agent.

A.4. Idea 4: Distributed Demand Side Management of a Smart grid with PHEVs

Ability to accommodate all types of generation and storage options is one of main characteristics of a smart grid. Furthermore, demand response programs play a much important role in smart grids. Plug-in Hybrid Electrical Vehicles (PHEV) have the potential to increase the ability of residential customers to participate in demand response programs. Therefore, a new infrastructure that enables vehicle to charge in many places is needed. Smart charging and discharging plans will lower the operation cost of such electric vehicles and reduces peak load demand. To identify the best solution for the demand response program, different demand side management techniques are needed to research. Currently, power system researchers have started to propose intelligent Multi-Agent System (MAS) that provides a platform for modeling autonomous decision making entities in de-centralized fashion for the operation of smart grid. This approach is scalable and adaptable to incomplete and unpredictable information. Therefore, it has a great potential to solve this concern problem. This novel infrastructure enables vehicle to charge in many places. In addition, the same concept and approach can be used to management distributed energy storage systems also.

LIST OF AWARDS AND ACHIEVEMENTS

INTERNATIONAL AWARDS

[1] The 1st Prize Award Winner of Siemens Smart Grid Innovation Contest 2011. Awarded [141] on 15 September 2011, in Berlin, Germany. The winning entry is entitled "Multi-Agent System for Operation of a Smart Grid" and "Autonomous Distributed Power System Restoration". The prize comprises a plaque, a certificate, 5000 Euro cash and a paid trip to receive the prize.

[2] One of the contestants in Siemens Smart Grid Innovation Contest 2011, Call for Proposals. The following research proposals were accepted at the first round and full research proposals were submitted for the contest.

  [I] Black-Out Recovery: Concept and real time simulation to bring up power transmission and distribution systems with microgrid structures after a blackout again.

  [II] Energy Flow Dynamics: Prediction of real-time energy flow dynamics through data aggregation from Smart Grid and intelligent transportation systems.

LOCAL AND REGIONAL AWARDS

[3] The third prize award of the best research poster presentation in IEEE PES Graduate Student Workshop, Singapore, 2010.

[4] IEEE CIS Student Travel Grant Award (800 USD) and IEEE PES Conference Support Grant (400 SGD) for presenting a paper in IEEE Congress on Evolutionary Computation, New Orleans, USA, 2011.

[5] IEEE PES Conference Support Grant (800 SGD) for presenting a paper in IEEE International Conference on Sustainable Energy Technologies, Singapore, 2008.

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[1] T. Logenthiran, D. Srinivasan, and A. M. Khambadkone, "Multi-agent system for energy resource scheduling of integrated microgrids in a distributed system," *Journal of Electric Power Systems Research*, vol. 81, no. 1, pp. 138-148, 2011.

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[10] T. Logenthiran, D. Srinivasan, A. M. Khambadkone, and T. Sundar Raj, "Optimal sizing of an islanded microgrid using Evolutionary Strategy," *IEEE International Conference on Probabilistic Methods Applied to Power Systems*, pp.12-17, Singapore, 14-17 June 2010.

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