A multi agent system based control scheme for optimization of microgrid operation

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2016

Foo, E. Y. S. (2015). A multi agent system based control scheme for optimization of microgrid operation. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/65876>

<https://doi.org/10.32657/10356/65876>

**NANYANG
TECHNOLOGICAL
UNIVERSITY**

A MULTI AGENT SYSTEM BASED
CONTROL SCHEME FOR OPTIMIZATION
OF MICROGRID OPERATION

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2016**

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School Electrical and Electronic Engineering

A thesis submitted to the Nanyang Technological University
in partial fulfilment of the requirement for the degree of
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ABSTRACT

Traditional power systems employ centralized control techniques to manage the entire power network. These networks are usually known to be passive because power flows radially from the utility grid to the load. With the deregulation and restructuring of the power industry coupled with increasing penetration of renewables and other traditional generators such as Distributed Generators (DGs) at the microgrid level, the way power flows within the network changes. This type of network is known as active networks because power can flow bi-directionally either from the utility grid to the microgrid or vice versa. As a result, centralized control may not be able to effectively manage the DGs at the microgrid level because it is cost inefficient and may prove challenging to control DGs in the microgrid. Therefore, another type of control known as decentralized or distributed control is proposed as an alternative to centralized control. The objective is to show that the microgrid can be effectively managed in a distributed manner while the economic benefits of the microgrid are maximized simultaneously.

In this thesis, Multi-Agent System (MAS) which is a type of distributed control is proposed for microgrids. The main idea is to utilize agents to solve large complex tasks. Agents are designed such that they exhibit intelligence and can make informed decisions without the intervention of a central controller. In addition, agents are adaptable to changes in environment and they can adjust to any disturbances or changes in the microgrid. One implementation of MAS is using the Java Agent DEvelopment framework (JADE) to simulate and monitor agent activities. Furthermore, JADE complies with IEEE's Foundation of Intelligent and Physical Agents (FIPA) standards and can be readily used for agent implementation. The extension of JADE for MATLAB/Simulink which is known as multi agent control simulation JADE extension (MACSimJX) was also used to simulate real-time microgrid implementations.

The first part of this thesis presents the design and implementation of user-defined agents in the proposed microgrid market clearing algorithm. A single-sided bidding mechanism is considered in the first part of the study. Agent objectives and a list of different test cases

are defined in the simulation study. The agent-based concept is implemented in a basic microgrid setup. The simulation results show that the revenue and load costs of the respective Generation Agents (GAs) and Load Agents (LAs) vary based on the agent objectives. In addition, the transactions are either biased towards the GAs or LAs. Therefore, another new agent objective is required to promote unbiased transactions between the GAs and LAs and this is discussed in the next part of this thesis.

The second part of this thesis extends the work done in the first part. It presents the use of IEEE FIPA compliant agent platform which include JADE and MACSimJX to coordinate distributed market operations and simulated real-time implementations. In particular, it considers the dynamic operation of a microgrid in Matlab/Simulink simulation environment while the market clearing engine which runs in JADE considers the average integrated MWh for each hourly interval. Both the t-domain dynamics of MW generation and bus voltages as well as market clearing price for each hourly interval are simulated. Furthermore, a double-sided bidding mechanism is considered. The scheduling and dispatch of DGs and loads in the microgrid are done based on a proposed market clearing algorithm. It models a market scenario where each energy seller or each energy buyer is represented by an agent that aims to maximize the benefits according to the defined agent objectives while ensuring the smooth operation and proper execution of microgrid operations under the simulated real-time environment. This is realized through agent interaction and coordination between MACSimJX and JADE agents. Three different agent objectives are defined which aim at maximizing the benefits of energy sellers and/or buyers through energy trading which considers LMP as part of the trading process. Each agent objective and the impact of marginal loss factors are analyzed. In addition, a list of agents is developed to verify the functionality of the proposed MAS approach. This approach is tested on a 7-bus microgrid system and further verified on an IEEE 14-bus power system. Simulation results show that maximizing the benefit for both energy buyers and sellers promotes unbiased transactions between them while ensuring the proper operation of the entire microgrid system. All these illustrate the applicability of MAS in the distributed management of microgrid operations.

Acknowledgements

This research is only possible with the guidance and assistance rendered by several individuals who have committed their time and effort over the duration of this study.

First of all, I would like to express my sincere gratitude to my supervisor, Associate Professor Gooi Hoay Beng, for his professional guidance and patience offered during this period. Through his constant encouragement and interactive discussions, he has greatly influenced my thoughts and has stimulated me to think deeper. His deep insight into problems and valuable industry experiences have been of great help in this research. I am really thankful to him for giving me this opportunity to conduct my PhD studies under his supervision where he has inspired and supported me tremendously in numerous ways.

I would also like to sincerely thank my co-supervisor, Professor Chan Siew Hwa for his encouragement and support during my study. His professionalism and enthusiasm in research has always been my source of inspiration for spurring me on.

I am also thankful to the technical staff of Laboratory for Clean Energy Research for the assistance and support provided by Mr. Foo Mong Keow, Thomas and Mdm. Chia-Nge Tak Heng. I would also like to especially thank Dr. Chen Shuaixun and Dr. Tan Kuan Tak for their constructive discussion and support throughout my research studies. This research work is supported in part by the Agency for Science, Technology and Research (A*STAR) under the Microgrid Energy Management System project of Intelligent Energy Distribution Systems (IEDS). I am also grateful to Energy Research Institute at NTU (ERI@N) for awarding me the research scholarship and giving me the opportunity to pursue a fulfilling graduate study.

Finally, I would like to thank my parents, especially to my mum and friends who have emotionally encouraged and supported me in various ways. Their encouragement is my constant source of strength during the research study.

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ABBREVIATIONS

ACL	-	Agent Communication Language
AE	-	Agent Environment
AGC	-	Automatic Generation Control
AID	-	Agent Identifier
AMS	-	Agent Management System
API	-	Application Programming Interface
A*STAR	-	Agency for Science, Technology And Research
ATF	-	Agent Task Force
CCHP	-	Combined Cycle Heat and Power
CEC	-	California Energy Commission
CERTS	-	Consortium for Electric Reliability Technology Solutions
CFP	-	Call For Proposal
CHP	-	Combined Heat and Power
CREATE	-	Campus for Research Excellence And Technological Enterprise
DER	-	Distributed Energy Resource
DF	-	Directory Facilitator
DG	-	Distributed Generation
Discos	-	Distribution Companies
DOE	-	Department of Energy
EMA	-	Energy Market Authority
EPGC	-	Experimental Power Grid Center
ESCo	-	Energy Service Company
ESS	-	Energy Storage System
EU	-	European Union
FIPA	-	Foundation for Intelligent Physical Agents
Gencos	-	Generation Companies
GUI	-	Graphical User Interface
IEDS	-	Intelligent Energy Distribution System
IRG	-	Interdisciplinary Research Group

ISO	-	Independent System Operator
JADE	-	Java Agent DEvelopment framework
KIF	-	Knowledge Interchange Format
KQML	-	Knowledge Query and Manipulation Language
LaCER	-	Laboratory for Clean Energy Research
LMP	-	Locational Marginal Price
LV	-	Low Voltage
MACSim	-	Multi Agent Control for Simulink
MACSimJX	-	Multi Agent Control for Simulink with Jade eXtension
MAS	-	Multi-Agent System
MG-EMS	-	Micro Grid Energy Management System
MCP	-	Market Clearing Price
MT	-	Microturbine
MV	-	Medium Voltage
NEDO	-	New Energy and Industrial Technology Development Organization
NTU	-	Nanyang Technological University
NTUA	-	National Technological University of Athens
PCC	-	Point of Common Coupling
PQR	-	Power Quality Reliability
PV	-	Photovoltaic
R&D	-	Research and Developement
RD&D	-	Research, Development and Demonstration
RED	-	Relative Electrical Distance
RMA	-	Remote Management Agent
SCADA	-	Supervisory Control And Data Acquisition
TCP/IP	-	Transmission Control Protocol / Internet Protocol
Tradecos	-	Trading Companies
Transcos	-	Transmission Companies
UPS	-	Uninterruptable Power Supply
U.S.	-	United States
WT	-	Wind Turbine

CHAPTER 1 INTRODUCTION

The advancement in communication and control, increased environmental awareness and volatile fuel prices have formed an emerging trend of Distributed Generation (DG) installations at the distribution voltage level. DGs can be either dispatchable conventional units or non-dispatchable renewable energy sources. Dispatchable DGs are generally used in applications which mainly include standby power, peak shaving, grid support and standalone operation [1]. Furthermore, more emphasis is placed on the use of renewable technologies to reduce the carbon footprints of consumers in recent years. Incentives are also given to households which install photovoltaics (PVs) and wind turbines (WTs) in a continuous effort to promote the use of renewable technologies [2]. As a result, this has generated a significant interest in the research of microgrids.

With the anticipated increase in DG penetration at distribution voltage levels, the supply of electricity is also expected to gradually shift away from centralized generation to a more distributed form of generation [3, 4]. Consequently, this has transformed traditionally regulated power generation into restructured entities [5]. Existing electrical networks will also see a transition from passive to a more active type of network [6] which gives rise to challenges in managing power flow and stability issues within the network [7-14]. Furthermore, the integration of DGs has become an important aspect for successful operation of microgrids among other operational and technical challenges faced [15-17].

Likewise, the power market also underwent a transformation during the deregulation of the power industry. In the past, power utilities were either owned by the government, co-operatives or private companies which were mostly regulated by the government [18]. In addition, the operation and control of these utilities were mainly centralized. Under this structure, the power market was monopolized by the government which ensured that the cost of delivering electricity be low and the reliability of electricity supply be maintained. However, economists have long questioned the effects of monopolized regulation and argued that the structure was inefficient and that it greatly discouraged regulated firms from operating efficiently with respect to the cost of service regulation. It was during the

1970s which saw the deregulation of transportation and financial services and in 1980s, the wholesale market for natural gas in Western economies has shown that deregulation could result in efficiency gains and a significant reduction in price. This coupled with the recent development of new DG technologies have gradually broken down the traditional regulatory approach and have paved way for new deregulated approaches. Furthermore, the non-discriminatory open access in transmission concept was created which states that transmission utilities are required to provide third party equal access to their own transmission lines. This concept allowed competition between two or more parties which subsequently called for different forms of structural unbundling in the power industry.

Although centralized approach proved to be successful in managing conventional power system operations, it may face difficulties in managing active networks where power can flow bi-directionally within the network. The integration and centralized management of numerous small scale DGs at distribution voltage levels may also pose problems since they may not be economically viable to implement. They are considered part of the major limitations of the centralized approach which calls for other alternative approaches in managing the emerging DGs. Several forms of the decentralized/distributed approach were proposed to better manage power system operations with the inclusion of numerous DGs at distribution voltage levels. They range from hierarchical to a fully decentralized type of structure. In addition, the decentralized/distributed approach offers several desirable advantages such as supporting plug-and-play features, potential for future power system expansion, increased system reliability, reduction in computation burden of a central server and lower infrastructure costs. In this way, it is expected that the distributed approach can overcome the limitations of centralized approach and can efficiently manage microgrid operations when more DGs are expected to integrate with the existing networks in future.

1.1 Introduction to Microgrids

Microgrids [19-21] are small scale low/medium voltage (LV/MV) networks connected to an existing electrical network via the point of common coupling (PCC). It primarily consists of a cluster of controllable loads, energy storage systems (ESSs) [22] which include batteries, flywheels and ultracapacitors that are controlled through the use of power

electronic converters and a combination of renewable and conventional distributed energy resources (DERs) such as photovoltaics (PVs), wind turbines (WTs), hydro generating units, fuel cells [23-26], combined cooling heat and power units (CCHPs), microturbines (MTs), gas turbines and diesel engines that operate in a coordinated manner to supply reliable electricity and reduce energy prices [27, 28]. In addition, microgrids are expected to improve power quality [29], reduce transmission losses, provide system reliability and enable integration of DGs and renewable sources [30]. An IEEE standard [31] which provides a set of guidelines for the interconnection of DERs was also established. Furthermore, microgrids have the capability to operate in either grid connected or islanded mode [32, 33]. In grid connected mode, microgrids aim at satisfying demand through local generation. Excess or deficit power in a microgrid can be absorbed or supplied by the grid respectively. In islanded mode, power balance within the microgrid must be observed between generation and demand in order to maintain system frequency and stability.

In terms of implementation, microgrid related research and development (R&D) activities involving ongoing pilot projects and research related experimental setups which serve as a testbed for microgrid R&D have been widely reported in many countries. In Singapore, a SGD\$1.32 million microgrid energy management system (MG-EMS) project funded by the Agency for Science, Technology And Research (A*STAR) was completed by a team of researchers at Nanyang Technological University (NTU) in July 2011 [34]. A schematic illustrating the 0.4kV microgrid and the MicroGrid Energy Management System (MG-EMS) developed in Laboratory for Clean Energy Research (LaCER) at NTU is shown in Figure 1-1. The primary objective of this project was to design and develop software algorithms, control schemes and hardware prototypes which are responsible for the monitoring, control and decision-making in the management of microgrids. In addition, the web based MG-EMS is also expected to perform several functions which mainly include the prediction of total consumer loads, economic scheduling of DERs, active management by rescheduling the real and reactive power, improving energy efficiency and thermal energy utilization at distribution level. In addition, another SGD\$38 million experimental power grid center (EPGC) was also built as a research unit within the Agency for Science, Technology and Research (A*STAR) to support the development of next generation grid technology. The core focus of EPGC's research is on challenges and issues related to

intelligent power distribution, penetration of renewable technologies and plug and play DERs. In addition, the construction of a 1-MW experimental microgrid testbed located in Jurong Island was also completed in November 2011 [34].

Figure 1-1: Overview of NTU microgrid architecture developed in LaCER [35]

In the European Union (EU), a number of microgrid research, development and demonstration (RD&D) projects were extensively studied where two major research efforts were dedicated in particular to microgrids. The first major microgrid project, “*Microgrids: Large Scale Integration of Micro-Generation to Low Voltage Grids*” was successfully completed and funded at €4.5 million by the Consortium which was led by National Technical University of Athens (NTUA) together with fourteen partners from seven EU countries, including the various European utilities, manufacturers, research institutions and universities. The project offered several technical solutions which basically include [27]:

- Agent based control algorithms for hierarchical and distributed systems,

- DER modeling using steady-state and dynamic analysis in inverter-dominated microgrids,
- Intelligence requirements and interface response of DERs, and
- Operating philosophies for interconnected and islanded microgrids.

The second major project, “*More Microgrids: Advanced Architectures and Control Concepts for More Microgrids*” was funded at €8.5 million by a second Consortium which was led by NTUA consisting of various manufacturers and power utilities based in Europe. The main objectives [27] for this project include:

- Developing alternative control strategies using next-generation information and communication technologies,
- Technical and commercial integration of multiple microgrids with upstream distribution management systems that focuses on operation of decentralized energy and ancillary service markets, and
- Standardizing technical and commercial protocols to allow ease of installing DERs with plug-and-play capabilities.

Several EU demonstration sites which showcase pilot microgrid installations were also reported [27]. The first demonstration site is located in Kythnos Island, Greece where the microgrid primarily consists of a 10kW PV system, 53kWh battery bank, 5kW diesel genset and several residential loads and focuses on controlling the battery and PV converters. The second pilot installation is in the Netherlands located in Continuum’s MV/LV facility. This microgrid comprises some residential loads and a 315kW grid-tied PV system and aims to manage PV power during peak and off-peak hours and the power quality of the microgrid during islanded operation. The third demonstration site is located in Germany under the MVV residential demonstration at Mannheim-Wallstadt where the microgrid is composed of a 30kW PV system with some residential loads and is aimed at engaging customers in load management. Other installation activities are also taking place in Denmark, Italy, Portugal and Spain.

In the United States (U.S), there was a modest expansion of the microgrid research program which was supported by the U.S. Department of Energy (DOE) and the California Energy Commission (CEC). One of the well known U.S microgrid which was built by the Consortium for Electric Reliability Technology Solutions (CERTS) in 1999 to investigate the implications of emerging technologies, regulatory-institutional, economic and environmental influences on power system reliability. The CERTS microgrid has been proven to work well in both simulation and bench testing of a laboratory scale test system in order to demonstrate the technical feasibility of the system [27]. Furthermore, an energy manager design funded by CERTS was also proposed for microgrids [36]. In addition, a US\$4 million microgrid energy management framework managed by General Electric was co-funded by DOE to develop and demonstrate the viability of microgrids [37, 38].

In Canada, microgrid research activities are mostly based on medium voltage (MV) networks. These projects are usually done in collaboration with the electric utility industries, manufacturers and stakeholders in integration and utilization of DERs. The main objectives of the microgrid projects include:

- Development of control algorithms and protection schemes for autonomous operation,
- Investigating the impacts of high DER penetration in existing power systems, and
- Exploring the effects of communication technologies in host microgrid and DER operations.

In addition, further collaborations with the electric utility industries were made to conduct field tests and experiments on several aspects [27] such as

- Autonomous operation of microgrids for remote areas,
- Grid-connected microgrid operations,
- Planned islanding operation of microgrids, and
- Developing MV test line for testing prototypes and performance evaluation.

In Japan, the government has set targets to increase the contribution of renewable sources such as solar and wind power into its existing national grid. In 2003, three proposed microgrid projects located in Aomori, Aichi and Kyoto Prefectures were initiated by the New Energy and Industrial Technology Development Organization (NEDO) to study the integration of renewable energy sources into existing distribution networks. In addition, NEDO also sponsored the demonstration in Sendai on the multiple Power Quality Reliability (PQR) services which aims to show that multiple power quality levels can be simultaneously supplied by the microgrid and to compare the cost benefit analysis of multiple PQR services with conventional uninterruptable power supply (UPS) equipment. There are also future collaborations between Shimizu Corporation and University of Tokyo to develop a microgrid control system consisting of a 90kW and 350kW natural gas gensets, four 100kW electric double layer capacitors and a 200kW NiMH battery bank [27].

1.2 Microgrid Control Architectures

Control architecture of a power system can be broadly classified into two distinctive categories which are centralized and decentralized controls. The main difference between the two types of control lies in the management of tasks and responsibilities given to the respective controllers. In a dynamic microgrid where DGs and loads typically have different ownerships, variations in generation and demand raise challenges in forecasting. They result in high levels of uncertainties. In addition, information on power quantity and cost function of DGs and loads is also not readily known [39]. Therefore, appropriate control schemes and coordination strategies are necessary for efficient microgrid operations.

1.2.1 Centralized Control

The main idea of centralized control is using a central processing unit to collect, consolidate and process all the measurement data from various devices in order to make control decisions. A fully centralized control architecture usually consists of a dedicated central controller which executes a range of functions such as gathering data, performing

calculation and optimization and determining control actions for all units. In addition, all of these functions are done at a single point which requires an extensive communication infrastructure for the central controller and controlled units to interact.

Figure 1-2 illustrates an example of a centralized control approach which may be used to control the DERs and other devices in the microgrid. In this figure, the Energy Service Company (ESCO) serves as a Supervisory Control And Data Acquisition (SCADA) to control microgrid operations. Its main objective is to perform decision-making functions which may include load forecasting, state estimation, unit commitment, economic dispatch, automatic generation control (AGC) and security monitoring. ESCo retrieves information from the measurement and control devices in the microgrid and processes these data values using the decision-making modules. After processing the data, ESCo will subsequently send the corresponding control signals back to the microgrid to implement the decisions made by the decision-making module.

Figure 1-2: Overview of a centralized control approach [40]

One main advantage of adopting the centralized approach is that the microgrid operator has a broader observability of the network. This implies that network parameters such as bus voltages, currents, frequencies, real and reactive power flows will be known. Therefore, the system operator can have a full global view of the microgrid and can monitor specific sections within the microgrid if required.

However, one major disadvantage of implementing the centralized approach is the costs of communication infrastructure. For every DER or storage device connected to the microgrid,

a corresponding set of control equipment to control the device must also be installed and synchronized with the main microgrid server. This is particularly undesirable as most of the DERs and energy storage devices are small in capacity and thus it may not be economically feasible to individually control and govern each component at the microgrid level. Furthermore, due to the need for processing large amounts of information at a single point simultaneously, centralized control is unable to exhibit the plug-and-play feature which is required in a dynamic microgrid setup. Consequently, this restricts power system expansion and poses limitations on planning of power systems among other factors [41]. Although there are disadvantages associated with centralized control, it can, however, offer broader observability of microgrid operations and greater knowledge for making control decisions as part of its tradeoffs [42]. Generally, centralized control is more suited for standalone power systems which need to maintain critical supply and demand balances in a slow changing infrastructure with large generating units.

1.2.2 Decentralized Control

Decentralized or sometimes known as distributed control can be categorized into several different types ranging from hybrid to a fully decentralized control. The main difference between these control types lies in the responsibilities given to the controllers at various nodes within the microgrid. Figure 1-3 provides an overview on the operating principle for the decentralized control approach. In this case, the ESCo provides basic ancillary services such as load forecasting, state estimation and security monitoring. Economic dispatch, scheduling and unit commitment are not included into the functions of ESCo because these functions will be realized by the distributed controllers in the microgrid. The main role of ESCo is to retrieve price information and policies from the utility grid. Together with the decision making modules, this information is then sent to the clients (or agents) residing in the microgrid where trading and negotiation will take place between the clients to obtain the dispatch schedule for the respective DERs and storage devices. One observation from this control architecture is that there is no single central processing server to implement control decisions for all the local controllers. In this manner, information exchange between ESCo and clients can be minimized.

Figure 1-3: Overview of decentralized approach [40]

A fully decentralized control typically consists of many local controllers where each controller controls a single unit. These controllers only gather local information about the unit under control and is neither fully aware of system level parameters nor control actions from neighboring controllers [43]. This means that local controllers have limited knowledge on their immediate surroundings and can only make informed decisions based on information obtained by interacting with neighboring controllers. However, in a system where the presence of strong coupling between various operating units requires a minimum level of coordination, a fully decentralized control is unable to achieve stable operation based on local information alone. As a result, a hybrid form of control known as hierarchical control [44-49] is proposed in Figure 1-4 for the microgrid due to the presence of numerous controllable devices and stringent performance requirements [50, 51].

Figure 1-4: Example of a hierarchically controlled microgrid

The decentralized control approach also offers several key benefits and they are described as follows:

- System openness and scalability – This approach allows the expansion of power networks through its inherent plug-and-play properties. The architecture is also flexible. This enables DERs to be integrated with the existing power networks with minimal changes to the control operations.
- Non computational intensive – Since complex tasks are broken down and accomplished through smaller simpler tasks, there is no need for a central super computer which can lower the implementation costs.
- Minimal information exchange with central server – This approach utilizes the peer-to-peer concept where local controllers are treated as peers where they interact with each other to accomplish their tasks. In this way, it can lower implementation costs because it does not require an expensive central server to manage the distributed operations.

In general, decentralized control is applicable for grid-connected microgrids comprising of many fast changing DGs with different ownerships.

1.3 Restructuring of the Power Industry

During the last few decades, the power industry scene has undergone major restructuring which can be seen in many countries around the world. Traditionally, utilities were predominantly monopolistic and vertically integrated but this structure is gradually giving way to a new competitive environment where generation and distribution companies can trade freely and have non-discriminatory access to the power network [18]. This transformation is commonly termed as *deregulation*. A direct consequence of this is the introduction of deregulated energy markets [52-61]. The objective of this market is to consider energy as a commodity that can be freely traded and the energy price can be set according to demand and supply at a particular period of time.

As a result of deregulation, several new entities were created in the electricity market sector [18]. The first entity introduced is the generation companies (Gencos) which are power generation companies who compete among themselves to sell power. Following that, there are distribution companies (Discos) which purchase power from the wholesale market and sell it to consumers. In addition, there is another group of transmission companies (Transcos) which own the transmission network and direct power flow from Gencos to Discos. The transactions that take place in deregulated electricity markets are done through wholesale power markets which basically consist of a power exchange and several power trading companies (Tradecos). Finally, other services that are required for the secure and reliable operation of the power network are provided by an Independent System Operator (ISO). In addition, the ISO also overlooks electricity market operation and is accountable for the security and reliability standards in the power network.

The transition from regulation to deregulation contained several complexities and many issues which need to be addressed. This is because of the unique characteristics inherent in the power industry which hinders its successful commercialization [55]. The following peculiarities of electricity are discussed below while designing electricity markets:

- Energy storage issues – There is currently no cost effective ways for storing energy on a large scale. This means that demand and supply need to be balanced

instantaneously. The power imbalance in the system has to be also promptly balanced through some technical means.

- Congestion management – The law of physics have a greater influence on the flow of electricity within the power network than commercial contracts. Satisfying all contracts may cause congestion in certain parts of the system.
- Provision of ancillary services – The generation of energy and the provision of ancillary services are interdependent in order to ensure that the power system is stable and secure. These ancillary services may include frequency regulation, operating reserves and reactive power compensation which are to be provided by the same and other generating units.
- Scheduling and dispatching generating units – There is a need to plan ahead the scheduling of generating units and dispatch them in real time because electricity travels quickly through transmission and distribution lines.

The architecture for electricity markets is more complicated compared to other commodity markets due to the peculiarities in electricity as described previously. Experts also could not arrive at a common agreement for designing the architecture of electricity markets despite many years of operating experience. In many parts of the world, electricity markets do not follow a common standard design because of the wide diversification in their architectures. Electricity markets can be divided into several submarkets which are classified into different categories depending on certain criteria. One common criterion used to classify electricity markets is to identify the type of product being traded. Based on this criterion, electricity markets are classified as follows:

- Energy market – This market primarily deals with energy trading. The Market Clearing Price (MCP) is computed from the submitted bids of the energy buyers and energy sellers.
- Transmission market – This market deals in the transmission rights which is auctioned by the ISO. The transmission rights authorize the user to inject or consume power from the transmission grid.
- Ancillary service market – This market basically deals with ancillary services such as frequency regulation, reactive power compensation and various forms of

reserves. The ancillary services provided by the ancillary service providers are to be procured by the ISO.

Likewise, the electricity submarkets can be classified based on the degree of coordination as described in the following:

- Bilateral market – In this market, energy buyers and energy sellers enter into a bilateral contract for the purchase and sale of power at an agreed price. This can be done directly between sellers and buyers or through a broker. This type of market is highly decentralized which limits the role of the ISO to verify the availability of transmission capacity before completing any transactions.
- Pool market – In this market, the ISO receives the submitted bids from generators and loads and performs dispatch on them. This type of market is highly centralized where the ISO has a larger role to play. In addition, the Locational Marginal Price (LMP) is determined by the ISO by maximizing the social welfare of the generating and load entities.

In addition, there are also other types of submarkets which include brokered, dealer and exchange markets. In terms of architecture, these submarkets are also ranked according to their hierarchy. Bilateral markets are classified as having a highly decentralized structure followed by brokered markets, dealer markets, exchange markets and finally, pool markets being the most centralized structure [18].

Furthermore, electricity submarkets can be categorized [18] based on the time of operation which is described in the following:

- Forward market – This market primarily handles long term and short term bilateral contracts. Long term contracts are defined as procuring electricity over a long time span which may range from several months to several years. Conversely, short term contracts are defined as procuring electricity over a short time span which may range from a few days to several weeks.
- Spot market – This type of market is typically either day ahead which schedules resources at every hour on the following day or hour ahead which schedules

resources for any deviation from the day ahead schedule. In addition, energy and ancillary services may be traded in this market.

- Real-time market – The generation and demand in a power system must be balanced in real-time to ensure its reliability during normal operation. However, there are instances when the real-time generation and demand deviate from the spot market and forward market scheduling. To address this issue, real-time markets are developed in order to meet the power balancing requirements in real-time.

Therefore, the three submarkets described above address energy trading and ancillary services based on the time of operation. Chronologically, forward markets will be the first submarket to award the contracts to successful bidders followed by the spot market and finally, the real-time market to continuously balance the generation and demand of the power system during the actual delivery period.

1.4 Research Motivation

The proliferation of renewable energy has changed the way energy is distributed and consumed. The evolution in smart grid applications and energy management systems has also gained momentum in recent years to better manage energy in a cost-effective manner in view of rising oil prices. In Singapore, the Energy Market Authority (EMA) is currently reviewing its existing regulatory framework to facilitate the deployment of renewable sources and their integration into the current electricity market [62]. In addition, the energy policy in Singapore also emphasized on fostering greater competition in the power market to ensure electricity prices remain competitive. Several initiatives were recently announced in 2013 in which one of them highlights the introduction of electricity futures market to complement the existing spot market. Another initiative was also proposed which introduces a demand response scheme to allow consumers to curtail demand when electricity prices are high and is expected to commence in 2015. The primary objective of these initiatives is to foster a competitive electricity market structure which empowers consumers with more choices and for end users to create a diversified portfolio for electricity and demand to reduce volatility.

Due to the anticipated increase in penetration of Distributed Energy Resources (DERs) at the microgrid level, control and management are necessary to ensure smooth and stable operation of microgrids. However, traditional centralized intelligence approaches proved to be inadequate to cope with the increasing growth of DERs due to the lack of flexibility and extensibility [63]. Moreover, centralized control was initially designed to handle large generation units. With numerous DERs appearing in the power network, it is difficult or nearly impossible to control the entire system by a single central controller adopting a top-down approach [64, 65]. If such a controller is implemented, it would require increased cost for communication infrastructure and introduce added complexity in the centralized control supervisor.

Similarly, power market operations and distribution networks become increasingly complex as the power industry moves towards decentralization [66]. The presence of DERs at distribution voltage levels will inevitably change the way power flows within the network causing it to change from a passive to an active one. Consequently, centralized Supervisory Control and Data Acquisition (SCADA) which was originally designed for traditional passive networks may be inadequate to cope with the high penetration of DERs and complex control decisions [63]. In addition, the assumptions applied to conventional power systems may not be valid for active distributed systems which raise challenges in the operation of microgrids [39]. The main issues regarding integration of DERs are also highlighted in [67-70] which primarily include:

- The need for scheduling and dispatch of DGs under supply and demand uncertainties,
- Design of new market models that enables competitive participation within a microgrid,
- Development of market and control mechanisms which exhibits plug-and-play for seamless integration of DERs,
- Cooperation and control which are distributed and realized with minimal information exchange with the central controller, and
- Communication networks which are based on standard components such as TCP/IP protocol.

Most of the above mentioned issues can be addressed by providing an agent platform with a common communication interface in the distributed system [71]. This can be realized by MAS which has been widely proposed as a feasible approach for managing distributed systems because it can effectively handle complex systems operations by decomposing complex tasks into simpler tasks to accomplish its goals [72-74]. The extension of MAS into microgrid applications is also evident in [74-91] where various research activities ranging from agent based market operation, fault protection strategies, DG control schemes, coordination control strategies, optimization strategies and distributed energy management systems to real time implementations.

MAS is a form of decentralized control which exhibits distributed intelligence by employing software entities or agents to communicate, negotiate and optimize microgrid operations. As opposed to the centralized approach, MAS uses a bottom-up approach to manage and optimize microgrid operations so that communications and complexity of the microgrid are kept to minimal. In addition, proposed guidelines and requirements on the use and applications of MAS in power systems are discussed in detail [92, 93]. Key motivation for proposing MAS in power systems basically lies in its inherent benefits such as flexibility, scalability, autonomy and reduction in problem complexity among other factors.

Therefore, the motivation of this thesis is to develop an agent based distributed control scheme for optimizing microgrid operations. The integration of DGs into the distribution grid will ultimately change the way power flows within the network. This calls for a need to better manage the power flow as well as market operations. In addition, the DGs and loads may have different ownerships and operating objectives which may result in conflicting goals among themselves. A local competitive microgrid market is proposed and developed in this thesis which considers the individual objectives of each participant. The impacts of different operating objectives for DGs and loads are also examined and discussed. This can help cater to the needs of individual power producers (IPPs) and price conscious consumers so that they can satisfy their respective objectives and at the same time, help to drive down local energy costs and maximize the overall benefit of the microgrid.

1.5 Objectives of the Research

In this thesis, the research focus is to examine how the microgrid can be best managed based on price-sensitive generation sources and loads. A multi agent based optimization control scheme based on a hierarchical architecture is proposed to investigate how such a proposed scheme can be adapted to best fit the operation needs of microgrids while maximizing their revenue when connected to upstream networks. Three main objectives have been identified and are described as follows.

The first objective in this thesis is to design and build a multi agent system (MAS) platform for microgrid operations. The MAS platform is designed to perform the following:

- Execute market operations for microgrids using the proposed market clearing algorithm;
- Simulate agent interaction and coordination based on different agent objectives,
- Send real-time control signals to the generators and loads in order to regulate their power set points;
- All the above actions are coordinated through a series of agent communication and coordination.

The second objective is to investigate how different market mechanisms and agent objectives will affect microgrid operations. Two types of market mechanisms will be considered: 1) A single side bidding whereby generators are allowed to bid and, 2) a double side bidding whereby both generators and loads are allowed to bid. Besides, the agent objectives are categorized into two types i.e. cooperative and competing. By studying the market outcomes based on different agent objectives, the optimal market results and agent objectives can be evaluated.

The final objective is to implement the outcome of the market operations on a simulated real-time environment in order to verify the proper operation of the microgrid. The microgrid is modeled in Matlab/Simulink environment and the agents are communicating to the Matlab/Simulink models via MACSimJX. The microgrid is simulated for a 24-hour period where the market clears every hourly. The output active power and voltage

waveforms for the generators and loads will be analyzed to evaluate the performance of the agent based control scheme for microgrids.

1.6 Organization of Thesis

This thesis is organized into five chapters. The current chapter, which is Chapter 1, provides an introduction to the deregulation and restructuring of the power industry. The concept of microgrid and various microgrid control schemes are introduced. Trends in microgrid technologies and recent developments are also reviewed. It also reviews the problems and challenges faced when employing conventional centralized control in microgrids and the need for distributed controls in the management of microgrids. A hybrid form of control, also known as hierarchical control, and its architecture for microgrids are introduced. The research motivation, objectives and organization of this thesis are also discussed.

Chapter 2 provides a literature review on Multi Agent Systems and its application in microgrid operations. The agent theory, concepts and architecture are introduced and described in detail. In addition, the IEEE Foundation for Intelligent Physical Agent (FIPA) standard for agents is introduced. This provides standards for agent design and implementation. The Java based agent framework is subsequently introduced that provides an IEEE FIPA compliant platform for agent implementation. This framework is further extended to Matlab/Simulink using multi agent control for simulink with JADE extension (MACSimJX) and its working principle and architecture are also presented.

Chapter 3 presents a preliminary agent design for microgrid operation. It discusses the use of JADE to simulate agent control for scheduling and dispatch of DGs in a microgrid based on market pricing. A list of agents that are developed and customized according to the requirements of the microgrid has been discussed. In addition, the functions of these agents are described in detail. Agent implementation in JADE relies on agent communication and message exchanges in order to fulfill their objectives. In the simulation studies, agent communication is demonstrated through the trading and negotiation process. Simulation studies have been done to analyze the performance of the customized agents under grid

connected mode of operations. Simulation results have shown that the agents developed are capable of performing decentralized microgrid control operations.

Chapter 4 presents a proposed Multi Agent System approach for integrating microgrid market operations and DER implementations. In this approach, each DG or price-sensitive load is modeled as an energy seller or energy buyer respectively and is represented by an agent which participates in a microgrid energy market. Each agent aims at maximizing the benefits according to the defined agent objectives while ensuring the smooth operation and proper execution of microgrid operations under a simulated real-time environment. The results from simulation studies demonstrate the effectiveness in employing multi agent system to perform coordinated actions between market operations and DER implementations in the distributed management of microgrids.

Chapter 5 provides conclusion, contributions of this thesis and suggestions on future works with regards to the research of multi agent systems for distributed microgrid operations.

CHAPTER 2 INTRODUCTION TO MULTI AGENT SYSTEM (MAS)

A multi agent system (MAS) typically consists of a collection of two or more objective-oriented agents interacting with each other to solve complex problems in a distributed manner. The term agent refers to either a software abstraction, idea or concept containing methods and objects which provide an intuitive way to describe complex software entities that are able to act with a certain level of autonomy to complete some designated tasks. An agent may also be defined in terms of its behavior but several authors have proposed different variation of agent definitions in the past. Although the agent definition varies from different sources, there are several key concepts which are common among these agent definitions and they are 1) sociability, 2) autonomous, and 3) reactivity. Based on these key concepts, an agent can then be defined as either a software or hardware entity operating in an environment with a certain level of autonomy, knowledge and specified goals.

A more general definition of an agent is also provided in [94] which basically defines an agent as an autonomous entity that can either communicate with other agents or solve problems on its own in an embedded environment. In addition, agents are able to control its internal state and outputs. They can also operate without external human intervention. Figure 2-1 illustrates a general MAS framework conceptually. In this figure, each agent is equipped with the relevant tools such as sensors and actuators to obtain local data and provide control signals to the equipment respectively. In addition, agents may also interact with each other by exchanging messages in order to achieve specified objectives.

Inherently, MAS offers several desirable key features which include 1) the ability to parallel process, 2) scalability, 3) modularity, 4) flexibility, 5) extensibility, 6) reliability and 7) the capability to represent, model and control distributed systems which make MAS the ideal candidate for a wide range of engineering applications. In the past few decades, MAS has been widely applied in many areas which include traffic and transport optimization, aircraft controls, robotics, medicine, commerce, congestion control and power systems control. The main objective of MAS is to solve complex dynamic problems

by decomposing complex tasks into simpler and manageable ones which translate into reduced problem complexity and computational burden.

Figure 2-1: A general multi agent system framework

The extension of MAS into power engineering applications is also detailed in [92, 93] which discuss proposed guidelines and requirements on the use of MAS applications in power systems and the possible research areas where MAS can be applied. A MAS based framework for microgrids is also discussed in [95, 96]. Examples where MAS can be applied to power systems include power system protection, condition monitoring, market trading simulations, energy management systems, automation and implementation. Furthermore with the emergence of smart grids and microgrids, recent research activities are significantly focused on the integration of renewable technologies, controlling and scheduling of DERs, demand response management and distributed market operations for the optimized operation of smart grids and microgrids.

In [97], MAS was used to simulate multiple microgrid market scenario involving load and generation agents with and without energy storage systems. MAS was also implemented in energy market simulation using risk-based continuous double auction algorithm [98]. The application of MAS in power market environment for microgrid operations is also discussed in [99]. In [100], MAS was applied to microgrids to participate in ancillary service markets. The proposed auction algorithm which solves asymmetric assignment problems is discussed in [101]. In [74], MAS implementation for operation of a microgrid is presented. The MAS design and implementation of microgrids for seamless transition

from grid-connected to islanded mode in MATLAB/Simulink environment is discussed in [75, 102].

2.1 Autonomous Agents

MAS is made up of many agents interacting with one another to achieve a common goal. Each agent is specifically assigned with tasks and responsibilities and is required to communicate with other agents to achieve its objectives. In addition, agents are also expected to have self autonomy and exhibit intelligence which is one of the important characteristics of intelligent agents. This means that agents should be capable of deciding the next course of action for the equipment they are controlling without any form of major intervention from either the owner or the main central server. It is particularly useful in the context of microgrids because with numerous DERs connected to the microgrid network, control operations will not be delayed if any DER fails to respond. Agents should also be able to adjust accordingly to different circumstances. Some important key attributes of agents are listed [103, 104] as follows:

- *Social ability* - Since agents have partial or no knowledge of the entire network, agents are required to communicate with one another to achieve their objectives. Through communication with neighboring agents, each agent can continuously update itself with relevant information.
- *Reactivity* - Agents are programmed in such a way that they can respond and adapt to any changes in the environment without much delay. For instance, if any DER agents goes offline due to either a fault or maintenance, neighboring agents can be notified and subsequently make minor adjustments in their behaviors to ensure that the system continues to operate smoothly.
- *Pro-activeness* - Agents alone cannot achieve their objectives unless they take the initiative to interact with other agents. In order to accomplish their objectives, agents should exhibit goal-directed behaviors and actively engage in interaction with other agents.

- *Reliability* - Agents are not allowed to intentionally provide false or misleading information that can potentially corrupt the integrity of the information exchanged between agents.
- *Mobility* - Agents are able to migrate from one host platform to another without requiring a major overhaul to the existing system. This property is desirable because when a client computer is scheduled for maintenance, agents can temporarily migrate to another client without causing any downtime for the equipment it is controlling.

Agents are the fundamental building block which drives MAS applications. They are particularly effective when they work together in groups because they can potentially improve systems operating on artificial intelligence. Therefore, it is important to understand and appreciate the underlying principles of agent theory for agent design and development. Various agent theories which attempt to capture different aspects of intelligent behaviors are discussed in [94]. In the following sections, some agent theories which attempt to capture different aspects of intelligent behaviors that can result in varying degrees of intelligence are discussed.

2.1.1 The theory of intention

One possible way for an agent to achieve a task is by providing it with a set of intentions. It is closely affiliated to the goal-directed, purposeful and behavior inherent in living organisms. P. R. Cohen and H. J. Levesque [105] believe that six properties need to be satisfied for any theory which discusses intentions and they are described as follows:

- Intentions create problems where agents need to find ways of achieving them.
- New intentions must not overlap and/or conflict with existing intentions.
- Agents are goal-oriented and will attempt to try again until they succeed in achieving their intentions.
- Agents believe that the intentions given to them are achievable.

- Agents always believe in the success of their intention where failure is not an option.
- Agents cannot foresee the consequences of their intentions.

In addition, they [105] believe that agents have persistent goals if two criteria are met as follows:

- The goal will ultimately become true even though it is not true at present.
- Before deciding to drop any goals, agents believe that the goal is either satisfied or will never be satisfied [106].

Agents that have intentions can be interpreted as having a strong motivation to achieve a certain desired state. This means that agents have to find ways to change a current state into a desired future state. In the context of control systems, the future state can be seen as a setpoint for the controller which it constantly wants to achieve. While it is desirable for agents to have intentions, they must also be intelligent enough to recognize whether an objective is impossible to achieve. This is because agents will exhibit obsessional behaviour if they try to achieve an objective that is impossible which will lead to unproductive outcomes that is undesirable.

2.1.2 The Possible Worlds Model

Another possible way for an agent to achieve its tasks is by developing a set of solutions based on its own beliefs. J. Hintikka [107] developed this model as a means to represent the knowledge and beliefs held by agents. This model works well with the intention theory because it considers the methods and/or strategies required to accomplish objectives. The strategies are known as worlds in this model and are represented in a system using classical propositional logic. The theory of this model states that the set of possible strategies developed for any given situation is dependent on the beliefs and information that is processed by the system. This means that the effectiveness of the strategies will increase with more system information and thus improving the chances of accomplishing any given

objectives. However, a limitation of this model is when system information is fixed and predetermined resulting in a closed knowledge and belief system.

This problem can be solved if the system is capable of obtaining new relevant knowledge to better improve strategies. This implies that the system must have the ability to monitor its performance and learn from past experience. In addition, C. R. Robinson [94] also suggested that language played an important role in the thinking and reasoning process of agents which could possibly manipulate information stored in the memory and could think about the consequences of their actions before executing the strategies. Therefore, the prediction of future events and creation of better strategies can be done through the use of language which appears to be important in learning concepts and the abstraction of rules.

2.1.3 Belief Desire Intention (BDI) Model

Currently, this is the one of the more popular theories in agent based systems proposed by A. S. Rao and M. P. Georgeff [108]. The theory in this model is derived from the intention theory and is based on the branching concept of time. The primary motivation behind this theory is to investigate how beliefs about the future will affect the desires and intentions of agents. This implies that the agent will abandon a particular objective if it has beliefs about the future that the objective is impossible to accomplish. Hence, this addresses the issue of obsessional behavior previously discussed in the intention theory.

2.1.4 The Knowledge and Action Theory

This theory was proposed by R. Moore [109] which takes into account information that an agent needs to know before taking any actions. The logical structure of this theory considers the case when agents have incomplete information on how to go about accomplishing their goals and provide procedures for them to search for additional information which they require.

2.1.5 Miscellaneous Theories

Other theories worth mentioning can be found in [110-113]. In [111], M. Wooldridge developed a set of formalisms to describe a generalized model of a MAS. In [112], E. Werner created an agent based system which uses the working principle of game theory, economics, philosophy, situation semantics and situated automata theory. In [113], M. Singh developed a set of formalisms in branching time framework using beliefs, intention, communication and knowledge.

However, there is one common problem among these theories. They only address specific behavioral features and functional attributes performed by agents. This implies that a more comprehensive theory is needed to cover every aspect of agent behaviors and functional attributes which will result in a system with higher degree of intelligence and is particularly desirable in the design of MAS. However, such a theory has yet to be developed. But over the years, developments in agent architectures have incorporated some aspects of these theories which are discussed in the subsequent sections.

2.2 Agent Architectures

This section discusses the contribution of agent theories in the structuring of software based MAS. While many different agent architectures have been discussed in [94], three commonly used agent architectures are selected and described in the following sections in order to illustrate the implementation of agent theory in agent architectures.

2.2.1 Deliberative-based Agents

An agent architecture is known to be deliberative or cognitive if it consists of an explicitly represented symbolic model of the world. In this architecture, decisions are made through logical reasoning which is based on symbolic manipulation and pattern matching. Agents having this architecture will be able to consider alternative ways of solving a given problem which may also include tapping on knowledge gained from past experiences.

2.2.2 Reactive-based Agents

This architecture can be defined as having no memory to make decisions. This means that reactive agents are designed such that the choice of action is situationally determined i.e. they are programmed to perform certain actions based on a particular environmental condition [114]. Agents respond immediately to changes in the environment by making decisions based on the limited available information at that time. The primary advantage of a reactive over a deliberative agent architecture is that it has a faster response time and implementation is relatively easier. On the other hand, the disadvantage of reactive based agent architecture is that the agent intelligence is limited because of the limited amount of information available during decision making. In addition, several well known examples of reactive agent architectures such as the subsumption architecture, Pengi, situated automata and agent network architecture can also be found in [94] which describes each of them in detail.

2.2.3 Hybrid-based Agents

This architecture is developed based on the combination of deliberative and reactive properties mentioned previously. Typically, this architecture consists of many layers where agents residing in the lower layers are assigned reactive behaviors which are responsible for short term decision making. On the other hand, agents residing in the upper layers have cognitive behaviors which are responsible for guiding the system towards the long term goals. In [94], C. R. Robinson suggested that in terms of abilities, hybrid agents were considered the most versatile among other architectures. Furthermore, several examples of hybrid agents such as procedural reasoning system, touring machines, COSY and inteRRaP are also described in detail.

2.3 Structure of an Agent

A typical agent structure is shown in Figure 2-2 which illustrates an example of a layered architecture of an intelligent agent. An agent basically has a three-layered architecture which includes the message handling layer, behavioral layer and the functional layer [115].

In the message handling layer, whenever an agent communication language (ACL) message is either received or sent by the agent, this layer is responsible for facilitating the flow of these ACL messages by implementing the relevant ontology parsers as well as maintaining functional control of conversations with other agents.

Figure 2-2: Layered architecture of an agent [116]

In the behavioral layer, it essentially controls and instructs when an agent is supposed to carry out specific tasks. For instance, whenever new information is produced in the functional layer, the behavioral layer will instruct the message handling layer to inform other interested agents. Likewise in response to incoming ACL messages, the behavioral layer will decide whether to take any actions with regards to the contents of the message. In the functional layer, it basically controls the core intelligence of the agent. This layer comprises core functional attributes which specify the type of actions that the agent can perform as well as analyze the contents of the ACL message. Therefore, the message processing of an agent is to receive messages via the message handling layer which is later passed on to the behavioral layer and is finally transferred to the functional layer for analysis before any new messages can be sent out of the agent.

In terms of agent programming, the JADE framework described in Section 2.6.2 provides the essential codes and classes necessary in order to get an agent online and running. As mentioned previously, most of the underlying JADE framework which is used for agent implementation is deliberately hidden from the user to reduce the complexity of the development cycle as well as to enable users to focus more on the logical aspects of the system. In addition, users working in JADE are also interested in going straight into some form of agent template in order to program user-defined functions for their agents. JADE

also provides an application programming interface (API) which is essentially a library detailing various classes and functions whose input and output parameters are specified. In this library, users are able to search for properties that they want their agent to exhibit which may include agent behaviors, communication methods and interaction among agents.

An example of agent code template is shown in Figure 2-3. The structure of this template can be classified into several different parts. The code begins by importing different libraries of functions from the API. Subsequently, the agent class name and type are declared followed by two main methods which are `setup()` and `takedown()`. The `setup()` method initializes the initial conditions and agent behaviors required in order to run the agent. Within the `setup()` method, there is a section for adding new inner classes that contains various agent behaviors. Behaviors are broadly classified into three different categories as described in the following:

- *One-shot behavior*: Agents having the one-shot behavior properties will execute their behavior once when instructed and is a one-time event.
- *Cyclic behavior*: Agents having cyclic behavior will execute their behavior upon receiving incoming messages. This type of behavior will only be triggered when an event such as an incoming message occurs and will only stop upon termination of the agent.
- *Ticker behavior*: Agents with the ticker behavior basically will exhibit this behavior once at every periodic interval which is pre-defined by the programmer. This type of behavior does not require an external event to trigger and it will persist until the agent terminates.

Whenever an agent is active, it will constantly check its own list of behaviors for activity and if no behaviors are available for execution, the agent is considered to be in a state of idling. Users may use this set of behaviors to create customized behaviors by inserting the desired agent function and communication codes under the respective customized behaviors. Lastly, the `takedown()` method handles the removal of this agent from the system. Once the user has completed writing the agent code, it has to be compiled before implementation. After which, the agent can be readily executed from the JADE runtime

environment and users can follow the detailed tutorials in [117] to operate the agent based system.

```
import jade.lang.acl.*;
import jade.core.Agent;
import jade.core.behaviours.*;

public class AgentTemplate extends Agent {
    protected void setup() {

        addBehaviour(new AgentBehaviour1());
        addBehaviour(new AgentBehaviour2());

        Object [] args = getArguments();
        if (args != null && args.length > 0) {
            //Initialization tasks
        }
        else {
            takedown();
        }
    }
    protected void takedown() {
        //Perform shutdown tasks
    }

    Class AgentBehaviour1 extends OneShotBehaviour {
        public void action() {
            ACLMessage msg = receive();
            if (msg != null) {
                //Process incoming message contents
            }
        }
    }

    Class AgentBehaviour2 extends OneShotBehaviour {
        public void action() {
            ACLMessage msg = receive();
            if (msg != null) {
                //Process incoming message contents
            }
        }
    }
}
```

Figure 2-3: Agent code template containing methods and classes

An agent's localized knowledge base is located in the agent behavior class of the agent code template in Figure 2-3. It contains the rules and behaviors necessary to govern its decision-making process. An agent's internal process flowchart is shown in Figure 2-4

which illustrates the states involved when decisions are made. Whenever an agent is initialized by the agent platform, it may be programmed to display a user-friendly Graphical User Interface (GUI) and register itself with the Directory Facilitator (DF). After successfully registering itself with the DF, the agent will continuously look for subscribed ACL messages which require processing. Based on the message information, an agent may act according to the rules and behaviors that are programmed by the user.

Figure 2-4: Agent process flowchart

In the agent termination module, the agent will continuously check its status. An agent is considered to be active if there are no instructions to terminate itself. Otherwise, an agent is considered to be in a state of inactivity (i.e. its services are no longer required) where it will deregister itself from the DF and close its GUI and all its services. After an agent has shut down, the agent platform will be notified. The whole process is repeated for subsequent newly created agents.

2.4 Foundation for Intelligent Physical Agent (FIPA)

FIPA is an international non-profit association of companies and organizations producing specifications for agent technologies [118]. This set of standards is formed to achieve a high level of interoperability in complex systems and to integrate agent technologies with non-agent technologies. Originally, FIPA was formed as a Swiss based organization in 1996 to produce standards and specifications for agent based systems. Since its founding, FIPA played a vital role in the development of agent standards and has promoted many

initiatives which contributed to the growing presence of agent technology. In addition, current internet and web technologies and related specifications originally came from ideas developed in FIPA. In March 2005, FIPA committee members voted to join the IEEE Computer Society to expand agent standards into a wider context for software development. Since then, FIPA has been officially accepted as part of the IEEE Computer Society's standards committee and is currently setting the standards for agent development for agent based systems.

Among the many FIPA specifications and standards currently in place, there is one particular specification that is fundamentally required in any agent based system. In this specification, three important roles were identified to describe the reference model of an agent platform as shown in Figure 2-5. The first role requires the Agent Management System (AMS) to be set up so that supervisory control can be done on the agent platform. The agent platform must also maintain a list of directories for active agents and is required to handle the life cycle of these agents. The next role requires the Agent Communication Channel (ACC) which is the default basic agent communication method to offer reliable, orderly and accurate message routing services. ACC is also responsible for the interoperability between FIPA compliant agent platforms. The last role requires the DF agent to be present so that yellow page services can be provided to agents residing on the agent platform.

Figure 2-5: FIPA compliant agent platform reference model

2.5 Agent Interaction and Communication

In order for agents to achieve their goals and objectives, they need to interact and communicate with each other. These agent interactions are derived from high level agent communication languages (ACLs) [119] which are languages where agent communicative acts are expressed. ACL is also a form of language used by agents to exchange messages. Previously, some of the commonly used agent languages which include the knowledge query and manipulation language (KQML) and knowledge interchange format (KIF) have been developed. O. Shehory [120] also suggested four different agent interaction paradigms which have existed and they are mentioned below:

- *Peer-to-Peer interaction* - informational messages can be directly shared between agents without the need for a centralized client-server model.
- *Broadcast* - informational messages are sent to all agents residing on the agent platform.
- *Multicast* - informational messages are sent to an intended group of agents.
- *Generative communication* - informational messages generated by agents are put on a blackboard where it is available for other agents to read.

However, there is one issue regarding agent communication, i.e. since agents can be created by different developers, there is a possibility of ambiguity and confusion arising from agent communication. It is only in recent years that agent communication standards have been developed by FIPA which is currently known as FIPA-ACL. This standard has since been used by MAS developers for building agent based systems. In addition, FIPA joined the IEEE Computer Society in 2005 which resulted in the establishment of the IEEE FIPA ACL standard. This standard ensures that agents running on different platforms are able to understand and interpret messages. It is also primarily based on the speech-act theory and defines agent messages as a representation of actions or communicative acts also known as performatives [121]. A standard set of performatives can be found in the FIPA communicative act library specification [122, 123]. It displays a list of commonly used performatives as shown in Table 2-1. The FIPA-ACL message template was also created under this specification and is shown in Figure 2-6.

Table 2-1: FIPA Performatives

Performative	Description
<i>Accept-proposal</i>	Accepting previously submitted <i>Propose</i> message in order to perform an action.
<i>Agree</i>	Agreeing to perform a <i>Request</i> action made by other agents.
<i>Cancel</i>	Canceling a previous <i>Request</i> action made by other agents.
<i>Cfp</i>	Issues call for proposals from other agents.
<i>Confirm</i>	The sender confirms the integrity of the message contents to the receiver.
<i>Disconfirm</i>	The sender does not agree with the integrity of the message contents that is sent to the receiver.
<i>Failure</i>	Tell other agents that a previous <i>Request</i> action has failed
<i>Inform</i>	Let other agents know about something
<i>Inform-if</i>	Only <i>Inform</i> other agents <i>if</i> statement is true
<i>Inform-ref</i>	Similar to <i>Inform-if</i> but ask for value of expression
<i>Not-understood</i>	Tell the sender that the recipient do not understand the message
<i>Propagate</i>	Ask another agent to forward message to other fellow agents
<i>Propose</i>	Agent send a deal proposal. This is used in response to <i>cfp</i> .
<i>Proxy</i>	The sender asks the receiver to send an embedded message to selected agents denoted by a given description.
<i>Query-if</i>	Asking another agent if a given proposition is true.
<i>Query-ref</i>	Asking another agent for a referred object by a referential expression.
<i>Refuse</i>	Refusing to perform an action and provide a reason for the refusal.
<i>Reject-proposal</i>	Rejecting a proposal in order to perform other actions during negotiation.
<i>Request</i>	The sender requests the receiver to perform certain actions.
<i>Request-when</i>	The sender only wants the receiver to perform certain actions if some given proposition is true.
<i>Request-whenever</i>	The sender wants the receiver to perform certain actions when current and subsequent proposition becomes true.
<i>Subscribe</i>	Act of requesting a persistent intention in order to notify the sender of a reference value as well as any changes in reference value.

In a typical message template, only certain essential parameters such as receivers, communicative act, content and conversation id are necessary for basic agent communication. Under the receivers section, programmers are required to specify target recipients of this message by stating Agent IDentifier (AID) names for the respective recipients in this section. In addition, to ensure only intended recipients receive this message, the conversation id section is specified by providing a name for this section. As a result, recipients who only provide their AID names but not the conversation id will not receive the intended message. Therefore the conversation id parameter acts as an additional

confirmation for agents so that the intended messages will not be sent to the wrong agents. The communicative act parameter indicates the type of performatives used to categorize the message type and can be easily traced by the sniffer agent to track this message. Referring to Table 2-1, examples of performatives that are commonly used are *call for proposal (CFP)*, *accept_proposal*, *refuse*, *inform*, *request* and *query*. Lastly, the content parameter contains information about the message and can be deciphered by the recipient upon receiving this message. The content of the message is the only source of information that agents can acquire from other agents to update their knowledge database as well as making well informed decisions.

Figure 2-6: ACL message template

Besides these core FIPA specifications, other specifications such as agent-software integration, agent mobility, agent security, ontology service and human-agent communication are also laid out by FIPA but these specifications are, however, outside the scope of this research work because they are considered ancillary and are not required for basic agent simulation. More information on these specifications can be found in [124].

2.6 Java-Based Agent Framework

2.6.1 The Java Language

In order to design and develop agents for MAS applications, prior review was done to determine the most suitable programming language and multi agent framework. C. R. Robinson [94] reported that the Java programming language was considered to be the most appropriate programming language due to several reasons. One key reason is because there exists numerous Java-based agent frameworks which are already readily available on the internet. This implies that instead of having to redesign agent methodologies and agent handling procedures from scratch, more effort can be channeled into the development and integration of agents to solve problems since obtaining a general level of understanding for the existing frameworks will suffice. Other desirable attributes of using Java are mentioned below which include:

- *Portability.* Programs written in Java are easily portable across many platforms. This means that users do not need to rewrite the same program in another language and this implies a reduction in implementation time.
- *Real-time.* The Java language inherently has numerous real-time features. Although there are currently some issues which are related in real-time such as not having direct hardware accessibility, these issues will be addressed in a future release known as Real-time Java.
- *Object oriented.* This means that systems designed using the object oriented approach will last longer and have lower maintenance costs because the system processes are encapsulated. In addition, such systems have better reliability and more flexibility. Codes can also be readily reused and this reduces development time.
- *Detailed documentation.* The documentations describing useful applications of Java are comprehensive.
- *Strong network communication support.* This attribute is particularly important in multi agent based systems because agent communication is essential in order for MAS to work.

Therefore, it is clear that systems built using Java exhibit many advantages and there is also a possibility of such systems to be widely applied in future projects. This subsequently led to the search for the most appropriate Java based multi agent framework. A general Java based multi agent framework is basically a set of program codes written in Java language containing methods that generate agents after compilation. It is also required that the multi agent framework be flexible and contain libraries that can be reused and provide sufficient error handling mechanisms during agent implementation. In addition, technical support from developers and reliability of agent programming codes are some of the other requirements needed in multi agent frameworks.

Currently, many research activities involving agent design and development are done for various MAS applications. Developing a multi agent framework from scratch can be tedious and time consuming. Therefore, it is necessary to search the Internet for Java based multi agent framework which meets all the requirements mentioned above. A review of the several multi agent frameworks [94, 125] was done and the description for each agent construction tool is summarized in Table 2-1 as follow:

Table 2-2: Java-based Multi Agent Frameworks

Name of Framework	Description	
JADE	URL Developer Architecture Communication Product support License	http://jade.tilab.com/ TILab, CSELT S.P.A., University of Parma FIPA-compliant for interoperable multi agent systems Java message parsing using Contract Net Protocol Active mailing list Free (Open source program)
Jack	URL Developer Architecture Communication Product support License	http://aosgrp.com/ Agent Oriented Software Primarily reactive that is based on BDI. Adopts a specific communication language Online forums Commercial license required
JESS	URL Developer Architecture Communication Product support License	http://www.jessrules.com/jess/index.shtml Ernest Friedman-Hill at Sandia National Laboratories in Livermore, CA Deliberative expert system shell NA Through a mailing list Free for academic use, licensed for commercial use

Cougar	URL Developer Architecture Communication Product support License	http://www.cougaar.org/ DARPA funded project since 1996 Two level agent interaction, reusable component framework Java based message representation Online forums Free (Open source program)
Zeus	URL Developer Architecture Communication Product support License	http://sourceforge.net/projects/zeusagent Advanced Applications & Technology Department of British Telecommunication labs Java-based agent component library, agent building tool and a suite of utility agents Standard agent communication language (ACL) Unknown Free (Open source program)
Voyager	URL Developer Architecture Communication Product support License	http://www.recursionsw.com/ Recursion Software Inc. Service oriented architecture Java-based message representation Online portal Commerical product
Agent Builder	URL Developer Architecture Communication Product support License	http://www.agentbuilder.com/index.html Acronymics, Inc Java-based toolkit and run-time system Knowledge Query and Manipulation Language (KQML) Mailing list Trial and commercial license
Madkit	URL Developer Architecture Communication Product support License	http://www.madkit.org Multi agent development kit (MADKIT) Modular, scalable multi agent platform built upon Agent, Group, Role (AGR) organization model Peer-to-peer based mechanism Developer support through forums Free (Open source program)
Retsina	URL Developer Architecture Communication Product support License	http://www.cs.cmu.edu/~softagents/retsina_agent_arch.html Software Agents Lab at Carnegie Mellon University's Robotics Institute Functional based architecture Peer-to-peer interactions Unknown Unknown

Among the available toolkit mentioned above, JADE was selected for this research because it complies with the core IEEE FIPA specifications and meets all the requirements which are necessary in implementing a normative Java based multi agent framework.

2.6.2 Java Agent Development Framework (JADE)

JADE was originally developed by Telecom Italia Lab (TILab), a R&D group which was formerly known as Centro Studi E Laboratori Telecomunicazioni (CSELT) in Italy to address the issue of the lack of support for developing agent based systems [117]. It is a Java based multi agent framework and provides users with the capability to develop agent based applications for interoperable multi agent systems which complies with IEEE FIPA specifications. The intention of JADE is to simplify the development process while making sure it adheres to standard compliance through an extensive set of system services and agents. Furthermore, JADE exhibits numerous inherent features found in distributed systems. Most of JADE's complexities are hidden from users enabling more focus on logical aspects of the system. This allows users to zoom straight into solving problems without having to fully understand how JADE operates internally such as agent transport, encoding, parsing and agent life-cycle. In addition, JADE provides a runtime agent environment, a requirement for agents to operate, a graphical interface to monitor agents as well as an extensive library of classes with methods based on FIPA standards. JADE also utilizes object oriented abstractions to develop FIPA-compliant agent applications and can provide a convenient distributed platform which is suitable for microgrid control and monitoring operations.

JADE can be illustrated as a distributed platform consisting of a main and several peripheral containers as shown in Figure 2-7. Each container is an instance of the runtime environment by JADE. Whenever a new agent platform is created, the main container comprising AMS and DF agents will have to be initialized first. This is in accordance to one of the specifications stated by FIPA. Once the main container has been initialized, peripheral containers containing user-defined customized agents can subsequently be created on client computers which are connected to the same network. If another agent

platform intends to join the existing network, a new main container along with AMS and DF agents are required to be initialized before this agent platform is allowed to connect to the existing network.

The communication network used in JADE will be via the Transmission Control Protocol/Internet Protocol (TCP/IP) for agents to communicate and exchange information with one another. From this setup, it is observed that a distributed platform is created and is most suited for microgrid application. In addition, the nature of this architecture exhibits system openness which effectively supports the Plug-and-Play capability and is particularly scalable without much modification to the existing control scheme. This is considered desirable in the microgrid context as each peripheral container can be represented as either a DER, energy storage or a consumer so this architecture can support microgrid operations without much reconfiguration on the system control architecture.

Figure 2-7: JADE control architecture

JADE's communication architecture is based on the peer-to-peer concept where peers are considered as agents [117]. It allows each agent to dynamically discover other agents and communicate with them according to this peer-to-peer paradigm. The JADE environment can also evolve dynamically with agents that may appear and disappear in the system according to the requirements of the application environment. In addition, JADE has the capability to parallel execute agent behaviors by using its own class of libraries. JADE also inherently has two special agents which are the DF and AMS that facilitate agent

communication shown in Figure 2-8. The DF keeps track of all current agents and allows these agents to search for other agents whose services are required via the *yellow page* service. The AMS controls the platform and has the ability to create or destroy agents under the *life cycle management* service. Other services such as the *message transport* service and *white page* service also ensure that agent coordination is based on common signaling.

Figure 2-8: Services provided by a FIPA compliant platform [117]

There are two ways in which JADE can be executed for agent simulation as shown in Figure 2-9. The first method requires users to execute the commands from the windows command prompt shell which displays simulation status in the form of plain text without much information on the activities of the active agents. The other method of executing JADE is by calling the Remote Management Agent (RMA) which displays a graphical working environment of JADE. RMA is JADE's default Graphical User Interface (GUI) agent and is usually called upon to display the software environment in a more systematic way. With this graphical environment, users can easily monitor active agent statuses from the main window and invoke JADE's sniffer agent which tracks message exchange between active agents or open the DF catalog to see the list of agents currently registered to the network.

From Figure 2-8 and Figure 2-9, it is clear that JADE is able to provide the necessary tools for an agent platform to be online and running within a short time frame. The JADE agent platform is further supported by the large collection of classes which is readily available to

users. This library of classes is created and refined over the years by the original developers to meet the basic FIPA requirements needed in a multi agent system. It is also a result of the user community which had rigorously applied the multi agent framework under many different case studies.

Figure 2-9: JADE's simulation environment

In terms of technical support, JADE provides active support through the use of mailing lists where users can subscribe to for assistance. The email histories are also archived and made available online for other users in the forums to answer common JADE-related programming problems. Up till today, JADE has been widely applied in a spectrum of areas which include urban and aircraft traffic control, travel industry support, manufacturing and robotics.

2.7 Integration between Simulink and Agents

2.7.1 Multi Agent Control for Simulink (MACSim)

Simulink is currently one of the most powerful and popular tools available for performing simulations. Although it is effective for running simulations, it does not provide the tools required to set up a proper agent based framework. To address this issue, Simulink offers added functionalities through the use of S-function blocks. This conveniently allows programs to be written in other programming languages such as C++ and Java which can

then be encapsulated in Simulink and used when required while still running in the respective native languages.

Even though the S-function block allows agents that are programmed in other languages to run in Simulink, another inherent problem exists. The S-function block can only handle single thread of execution which implies that it is not able to cope with multiple threads of execution. This means that the S-function block becomes unstable if many concurrent processes run at the same time. However in a multi agent system, running many processes simultaneously is a functional property and is a basic requirement which needs to be satisfied. Therefore in order to implement MAS in Simulink, a program known as multi agent control for Simulink program (MACSim) was developed in [126]. By taking advantage of the S-function capability in Simulink as a medium to pass data to/from a completely external program, MACSim makes the development of agent based systems plausible.

MACSim is primarily programmed in C++ which includes a wrapper that allows interaction with Java written programs. It has the capability to parallel process data items and adopts a client-server architecture as shown in Figure 2-10. The client side resides in Simulink through the use of the S-function while the server side is located in another separate program. The communication link between the server and client is achieved by using named Windows pipes. This type of architecture enables synchronization to be achieved because the MACSim server program is decoupled from Simulink and therefore has the capability to perform multi threaded executions which overcomes the limitations of the S-function and allows parallel processing which is much required in agent based systems.

Figure 2-10: Client-server architecture of MACSim [127]

2.7.2 Multi Agent Control for Simulink with JADE eXtension (MACSimJX)

In order to specifically integrate JADE with Simulink, C. R. Robinson et al. [127] have further extended on the functionalities on the MACSim server to enable JADE to interact with Simulink. This extension is known as Multi Agent Control for Simulink with JADE eXtension (MACSimJX). Under this extension, two new terms are introduced as shown in Figure 2-11. The first term is the agent environment (AE) which works as an interface between Simulink and JADE agents. The second term is called the agent task force (ATF) which is basically a group of agents working together to collect data from Simulink and perform some associated tasks on it. More descriptions on MACSimJX, AE and ATF are subsequently given in the following subsections 2.7.2.1 and 2.7.2.2.

MACSimJX as the name suggests, is an extended model built on MACSim which receives simulation data from Simulink via MACSim and the data is then passed on to the corresponding agents for processing in JADE. Tasked with objectives to accomplish, these agents perform certain actions such as optimizing the incoming data. After the data items have been processed by the agents, it is then sent back to Simulink along the same communication channels for implementation.

Figure 2-11: Outline of MACSimJX complete model [127]

2.7.2.1 Agent Environment (AE)

The agent environment, which interfaces JADE agents and Simulink contains the necessary foundation work required for any agent based model using Simulink and JADE.

It is also responsible for the handling and passing of data between Simulink and JADE. In addition to data handling, C. R. Robinson [94] also suggested that the AE must be able to meet several other key requirements which are described as follows:

- Monitor all active agents and facilitate the dynamic creation and termination of agents.
- Synchronize with Simulink.
- Able to provide current input and time step data upon request.
- Ability to track changes made by agents and store these data items systematically which are sent to Simulink when ready.
- Broadcast messages to subscribed agents

Among the classes that make up AE, two of them are particularly important. They are the AgentServer and the AgentCoordinator which are shown in Figure 2-12. Both of them serve as a link between Simulink and ATF. They are also considered to be agents because it is easier to communicate with the JADE framework. The AgentServer uses the *runServerBehaviour* class to form a communication channel with Simulink by utilizing the methods available in MACSim. It then links up Simulink with the AgentCoordinator agent. In addition, it is tasked to shut down all agents whenever MACSimJX is closed by the user.

Figure 2-12: Outline of the Agent Environment [127]

The AgentCoordinator automatically registers its services with DF when it is set up so that it can provide updates to agents whenever new data is received. It also starts up AgentServer and initializes the ATF as part of its set up. The AgentCoordinator uses the *monitorBehaviour* class to manage the communication links with agents which are interested in receiving the incoming data. Furthermore, it broadcasts incoming data from Simulink to agents subscribed to its service. After the JADE agents have completed their tasks, the processed data is sent back to the AgentCoordinator which is then passed on to Simulink.

2.7.2.2 Agent Task Force (ATF)

The agent task force is another important component in the MACSimJX model. It primarily consists of agents jointly working on incoming data from Simulink to achieve their objectives. These agents inherently have the `setup()` and `takedown()` methods as well as customized behaviour functions developed by the user. From Figure 2-13, it can be seen that agents are able to communicate among themselves within the task force and also with the AgentCoordinator from AE.

Figure 2-13: Outline of the Agent Task Force [127]

Each ATF is provided with its sub-package together with inner-packages for each agent type it utilizes. The agent package basically consists of the fundamental agent class as well

as the associated classes to complement it. Agents residing in the ATF are created by the AgentCoordinator. These agents have all the basic classes and methods required to operate and can be found in a typical agent template. The only difference that differentiates ATF agents from other agents is in the design of agent behaviours. ATF agents are designed to look out for three message types from the AgentCoordinator and they are listed as follows:

- *UpdateData* – Whenever an ACL message whose message ID containing the UpdateData parameter is broadcasted by the AgentCoordinator and it is received by the ATF agents, they will extract the data from the message content and process the extracted data. After processing the extracted data, a reply message is generated with message ID containing the ProcessedData parameter and message content containing the extracted data that will be sent to the AgentCoordinator.
- *DataAmended* – Whenever the AgentCoordinator receives messages whose message ID contains the ProcessedData parameter, the ATF agent will generate a reply message back to the message sender with message ID containing the DataAmended parameter and the message content stating a confirmation of data amended has been updated in its records. This process ends the message exchange sequence between the AgentCoordinator and ATF agents and the entire process will repeat when new data is received from Simulink.
- *Shutting Down* – Each agent receiving an ACL message with message ID containing the Shutting Down parameter is instructed to run its takedown() method and terminate themselves by deregistering and removing all its services from the DF. This usually occurs when the program is shut down by the user.

The three message types described above are usually the basic interactions between the AgentCoordinator and ATF agents. Furthermore, users may also introduce additional communication mechanisms to customize the way agents interact within the ATF and provide another degree of freedom to the users. In this thesis, ATF agents have been programmed to use the three basic message types mentioned above and also custom message types to interact with JADE agents for managing the coordinated market operation and implementation of the microgrid.

CHAPTER 3 PRELIMINARY AGENT DESIGN FOR MICROGRID MARKET OPERATION

3.1 Introduction

The first step for microgrids to effectively participate in the upstream or national energy market is to create a local energy market. Several types of market clearing mechanisms for microgrids have been previously proposed [97, 128-131]. For example in [129], a local market structure has been proposed to manage the market clearing mechanism for microgrid energy. The purchase and sale of energy in the microgrid electricity market is basically dependent on the supply and demand in the microgrid. In addition, the supply and demand of the microgrid are also used in setting the energy prices which is the MCP. Since the primary objective for introducing a microgrid electricity market is to reduce electricity prices, the energy prices determined from the microgrid's supply and demand should be lower than the utility grid selling price for the microgrid to benefit from such a market scheme.

In a typical electricity market, there are basically two options of bidding by generation bidders. They are described [129] as follows:

- Block generation bidding - In this bidding option, the amount of load demand awarded to generation bidders depend on several factors which include production cost estimates, variations in demand level, unit commitment costs and other economic considerations.
- Sealed bid auction - In this bidding option, generation bidders submit their bids to a pool operator to procure a certain amount of load which is forecasted by the pool operator. The objective of each generation bidder is to maximize its own benefits while the pool operator adopts a dispatch strategy which maximizes consumer welfare.

In addition, there are two general market clearing rules commonly used in real-time electricity markets and they are described as follows:

- Uniform/Single price – This rule is commonly applied in today's electricity markets. During market clearing, energy sellers will be paid for the sale of electricity based on MCP, regardless of whether they bid higher or lower than MCP. Similarly, energy buyers will pay for the purchase of electricity at MCP, regardless of whether they bid higher or lower than MCP. As a result, all bids to buy/sell energy will be priced at the marginal cost of the electricity.
- Discriminatory/Pay-as-bid – In this rule, energy sellers with the winning bid will be paid at their bid price. Similarly, energy buyers with the winning bid will pay at their bid price. In this process, every participant bids by guessing the cut-off price which is done by monitoring the market clearing results of the hourly bids over a 24-h period. However, this rule has a major drawback i.e. incorrect guessing of the cut-off price may result in increased cost that is above MCP. This may lead to a less efficient market clearing system which may not be desirable.

Based on the two market clearing rules mentioned above, S. Chowdhury [129] claimed that the uniform/single price rule is most suited for restructured electricity markets because it is believed that such a pricing rule will encourage participants to reveal their true cost which is beneficial to every participant. This will lead to a more efficient system which is desirable in the long run.

There are also two types of bidding mechanisms used in electricity markets i.e. the single side and double side bidding which are shown in Figure 3-1. The main difference between the two bidding procedures is the participation of consumers during the bidding process as well as the price elasticity of consumers. In single side bidding, generating units are allowed to participate in the energy market while consumers do not participate in the energy market and are considered to be fixed loads which need to be served regardless of market price. For double side bidding, both the generation as well as the consumer load participate in the energy trading market and are responsive to market price actions. In addition, generating units do not have any information on the current level of demand and consumers do not know the availability of energy in the microgrid. In both bidding mechanisms, it is generally considered that the generating units consist of Combined Heat and Power (CHP) units, renewable energy sources and diesel generators. It should be noted

that diesel generators are usually used as back-up units and consumer loads comprise a mixture of critical and non-critical loads where non-critical loads can be curtailed, if necessary, based on market price actions.

Figure 3-1: Single side and double side bidding curves

3.2 Problem Formulation

3.2.1 MCP (Single Side Bidding)

The main objective in this section is to propose a microgrid market structure which determines the MCP for the dispatch of a group of different DGs to satisfy a group of consumers. For each of the 24 hourly periods in a trading day, bids from suppliers and consumers are received in order to plot the corresponding aggregated energy supply curve and demand curve and the intersection between these two curves will determine the MCP at each hourly trading interval. In this chapter, a single-sided bidding market is considered which employs the uniform price market rule during the market clearing process.

Consider the power generated by the i^{th} generation bidder where the supply curve is approximated based on the fuel consumption data. It is expressed as:

$$p_{G,i} = \frac{c_{G,i}}{m_{G,i}} \quad (3.1)$$

where $p_{G,i}$ is the active power of the i^{th} generator; $c_{G,i}$ is the price for generating $p_{G,i}$; and $m_{G,i}$ is the gradient of the i^{th} supply curve and is commonly referred to as the bidding rate of the i^{th} generator in the subsequent sections.

Next, the total supply curve for N generation bidders can be found and is given as:

$$\begin{aligned}
 p_{G,Total} &= p_{G,1} + p_{G,2} + \dots + p_{G,N} \\
 &= \frac{c_{G,1}}{m_{G,1}} + \frac{c_{G,2}}{m_{G,2}} + \dots + \frac{c_{G,N}}{m_{G,N}} \\
 &= \sum_{i=1}^N \frac{c_{G,i}}{m_{G,i}}
 \end{aligned} \tag{3.2}$$

Since the load demand is considered to be constant in a single side bidding market, the total load demand in this case is denoted by D . At MCP, the common price is denoted as c_{MCP} and the total generation must be equal to the total load demand which is given as follows:

$$c_{MCP} \sum_{i=1}^N \frac{1}{m_{G,i}} = D \tag{3.3}$$

By rearranging and making c_{MCP} as the subject, the value of c_{MCP} can be found as given:

$$c_{MCP} = \frac{D}{\sum_{i=1}^N \frac{1}{m_{G,i}}} \tag{3.4}$$

The equation provided in (3.4) assumes that generation bidders have sufficient capacity for generation. If minimum and maximum generation capacity limits denoted by $p_{G,i,min}$ and $p_{G,i,max}$ are considered, then the total supply curve for N generation bidders is given as:

$$p_{G,Total} = \sum_{i=1}^N \frac{c_{G,i}}{m_{G,i}} \left[U(p_{G,i} - p_{G,i,min}) - U(p_{G,i} - p_{G,i,max}) \right] \tag{3.5}$$

where,

$$\begin{aligned}
 U(p_{G,i} - p_{G,i,min}) &= \begin{cases} 1, & \text{when } p_{G,i} \geq p_{G,i,min} \\ 0, & \text{when } p_{G,i} < p_{G,i,min} \end{cases} \\
 U(p_{G,i} - p_{G,i,max}) &= \begin{cases} 1, & \text{when } p_{G,i} \geq p_{G,i,max} \\ 0, & \text{when } p_{G,i} < p_{G,i,max} \end{cases}
 \end{aligned}$$

By equating (3.5) with D , the updated value of c_{MCP} can be found and is given as:

$$c_{MCP} = \frac{D}{\sum_{i=1}^N \frac{1}{m_{G,i}} \left[U(p_{G,i} - p_{G,i,min}) - U(p_{G,i} - p_{G,i,max}) \right]} \tag{3.6}$$

Hence, the MCP at each hourly trading interval is determined by (3.4). In the simulation study later on, a Price Agent (PA) was developed which employs the MCP algorithm presented earlier. The algorithm requests each Generation Agent (GA) and each Load Agent (LA) for the bidding rates of generation and demand curves respectively. Once MCP is computed, trading between the GA and LA can proceed for the current trading interval.

3.2.2 Cooperative and Competitive Pricing Strategy

In [85], I. Zabet and M. Montazeri discuss cooperative and competitive strategies for decentralized agent control. In the context of microgrids, a cooperative strategy aims at maximizing the benefits for the entire microgrid. This means that generation and load agents within the microgrid network will attempt to negotiate and satisfy the local microgrid load demand before importing/exporting power from the utility grid. As a result, minimal power will be bought from the utility grid since load demand is prioritized to be satisfied internally first before asking the utility grid for extra power. Thus, this arrangement reduces the amount of power bought from the utility grid. In terms of DER's energy pricing, Figure 3-2 shows that when the MCP obtained from (3.4) is below the utility grid's selling price, consumers will enjoy the lower costs of purchasing energy from the DGs within the microgrid. However, this strategy does not maximize the profit for the DGs because their main priority is to satisfy the microgrid internal load before selling any excess power back to the utility grid. The MCP in this strategy may fall below the grid's buyback price so this is why cooperative strategy does not yield a maximized profit for DGs.

In a competitive strategy, the objective of generation agents is to maximize profit for the DGs in the microgrid. Instead of satisfying local load demand, DGs are pricing their energy competitively with the utility grid's selling and buyback price in order to maximize their profit. This means that DGs will not prioritize local load demand as their main priority and any shortfall in unsatisfied load demand will be met by the utility grid. In terms of DG pricing, Figure 3-2 shows the acceptable range of MCP for competitive pricing which falls in between the grid's selling and grid's buyback prices. The reason for not permitting MCP to fall below the grid's buyback price is because in the event MCP

falls below the grid's buyback price, DG owners would benefit more by selling their energy to the utility grid at the grid's buyback price instead of selling energy to local microgrid loads at MCP. Based on the same argument, MCP is not permitted to go above the grid's selling price. This is because in the event DG owners price their energy above the grid's selling price, none of the load agents will purchase energy from the DG owners because the utility grid can offer a lower price. This will cause DG owners to sell their energy at the grid's buyback price which minimizes their profits. Therefore, DG owners may only price their energy within the acceptable range in order to stay competitive and maximize profits at the same time. Hence, depending on the generation agent objectives, DGs have the option to either adopt maximizing microgrid benefit or maximizing DG profit objective.

Figure 3-2: Cooperative and competitive pricing

3.2.3 Relative Electrical Distance (RED)

The Relative Electrical Distance (RED) concept in power systems basically refers to the relative locations of the load nodes with respect to generation nodes [132]. It has been widely used in power system to solve transmission cost problems [133, 134] and has been proven to be useful in determining the generation penalty factors accurately. Besides considering the total internal losses of the network to compute penalty factors, the relative electrical distance between generation and load may also be considered so that generation sources which are electrically closer to loads will not be heavily penalized even though they are expensive to generate. In order to accurately determine active transmission losses, network parameters such as admittance and impedance matrices, power injections at buses

and bus voltage variations are needed to calculate the loss sensitivity factors at each bus in the network. However, dispatch problems which consider losses are non-linear by nature and the computation time required will also increase as the size of the network increases.

The underlying idea behind the RED concept is to identify the location of the generation bus and load bus. Since RED is closely related to line impedance, it is reasonable to state that the transmission losses increase as RED increases. The electrical distance between generation bus and load bus can be computed by taking the absolute difference in relative electrical displacement between the generation and load bus. In a microgrid, DGs are typically small in capacity ($< 100\text{kW}$) so it would not be economically feasible for DGs to supply loads which are electrically far away from them since most of the power will be lost in the cables. In the simulation study, each generation agent and each load agent are assigned a relative electrical displacement, d , with respect to the point of common coupling (PCC) and the units are given in kilometers (km). In addition, the trading algorithm between generation agents and load agents considers the RED of each individual agent and prioritizes the negotiation sequence. This means that the load agents will initially search for the closest generation agent and after that if the load demand is still not met, the load agent will continue to search for the next closest generation agent. This sequence will carry on until either all generation agents have completely sold their available power or all the load demand of the load agents have been fully met.

Figure 3-3 illustrates the RED concept for both the generation as well as the load agents. Each generation agent and each load agent in this simulation have its own respective displacement from the PCC. During the trading process, generation and load agents will interact with each other in order to determine the absolute distance among themselves. The negotiation sequence will be such that priority is given to load agents that are electrically closer to generation agents. Since energy cost is handled by market clearing and all generation agents will be offering their price at MCP after market clearing, load agents searching for generation agents will only consider the RED of the generation agents as part of their algorithm. In this way, it can be interpreted that the trading algorithm can match the supply and demand while considering the RED between the generation and load agents.

Figure 3-3: Relative Electrical Distance (RED) concept

3.3 Agent Implementation

This section presents a list of user-defined agents developed in JADE. A brief summary on each agent's objective is summarized in Table 3-1. The GUI of each agent will also be shown in the subsequent sections and the corresponding agent behaviors are described.

3.3.1 Agent Functions and Objectives

A list of user-defined agents in Table 3-1 has been designed and developed to manage the power supply from energy sellers in meeting the needs of energy buyers as well as exchanging power with the utility grid. Agents are also required to perform energy trading and negotiation with other agents in order to achieve their tasks during the trading. Since the role of each agent is different, Table 3-1 summarizes the functionalities for the each of the respective agents.

In Table 3-1, a total of seven different agents were developed and their respective functions are described to understand their roles. In addition to the development of these user-defined agents, a GUI agent has been separately programmed and attached to each of the agents in Table 3-1. The GUIs can be found in Appendix A. The role of the GUI agent is to extract data from the user-defined agents and display the information in a user-friendly manner. Other functionalities such as the use of buttons to execute certain agent actions are also available on the GUI panel.

Table 3-1: List of user-defined agent functions

Agent	Functions
Generation Agent (GA)	Collects information on DG's power setting, MCP, electrical distance from PCC, bidding rates and DG owner's objective to participate in the energy trading
Load Agent (LA)	Captures information on consumer load demands, electrical distance of the loads from PCC and MCP. It represents consumer loads to participate in the purchase of energy during the trading process
Monitor Agent (MA)	Requests status updates from GA and LA which are then displayed via the GUI
Grid Agent (GrA)	Collects information on the grid's energy prices which are then broadcasted to inform all other agents
Price Agent (PA)	Requests bidding rates from GA and LA. MCP is computed and broadcasted to GA, LA and CA
Aggregate Agent (AA)	Requests information from GA and LA. It then computes the microgrid's total and current available generation as well as total load demand and satisfied load
Control Agent (CA)	Captures information such as MCP, grid energy prices, total generation and load demand as well as net power exchange with GrA. It also initiates the beginning and the end of the trading session and performs a reset on all agents in preparation for the next trading hour

In addition to the functionalities described, two agent objectives are also defined for simulation study. The first objective is defined as the maximization of load benefits where agents will aim at minimizing the load costs of LAs. This means that the LAs will try to negotiate with either the GAs or the utility grid to obtain the lowest offer for satisfying its load demand. The second objective is defined as the profit maximization of GAs where agents aim at maximizing the revenue and profit of GAs. This means that GAs will try to negotiate with either the LAs or the utility grid to obtain the highest offer for selling its power. It also implies that if the utility grid buyback price is higher than the LA's offer, GAs will sell their power to the utility grid and the LAs will have to buy from the utility grid for that particular period. Therefore, depending on the agent's objectives the amount of revenue/profit received by GAs and the amount paid by LAs will vary. The results are discussed in Section 3.4.

3.3.2 Generation Agent

The primary function of the Generation Agent (GA) is to collect information from the DG owners and use the data to participate in the local microgrid energy market by communicating with other participating agents. Figure A-1 in Appendix A shows the GUI of a GA where certain parameters such as available power, incremental cost, electrical

distance from PCC, and agent objective are to be filled in by the DG owner. Other parameters such as agent identifier, grid prices, microgrid operating mode and MCP are automatically displayed on the GUI panel upon updating the GUI.

The lists of behaviors associated with Generation Agent (GA) are described as follows:

- Receive grid's energy prices behavior - This behavior is classified as *cyclic* and it constantly checks for messages sent from Grid Agent (GrA). Incoming messages received by this behavior inform GA on the grid's selling and buying energy prices which are shown on the GUI.
- Send bidding data and receive MCP behavior - This behavior is *cyclic* and constantly checks for messages sent from Price Agent (PA). This behavior targets two types of messages. The first type requests GAs to provide their bidding rate data to PA for computing the MCP value. After the MCP is calculated by PA, the second type of message is sent to GAs informing them on the current MCP value. Based on the GA's objective, it will then decide whether to sell its energy at MCP or at the grid's buying price.
- End current trading session behavior - This behavior is *cyclic* and constantly checks for two types of messages sent from Control Agent (CA). The first type of message is to receive the end trading signal from CA. Once this message is received, GA will settle any outstanding power by selling it back to GrA during grid connected mode of operation. The second type of message from CA is to inform GA that the current trading session is closed and it requests GA to reset its current database in preparation for the next trading session.
- Send status behavior - This behavior is *cyclic* and constantly checks for *request* messages from Monitor Agent (MA). Upon receiving the message from MA, the GA will create a *reply* message stating its current total and available power generation as well as its current bidding rate data.
- Send total and available generation behavior - This behavior is *cyclic* and constantly checks for messages from AA. Upon receiving the *request* message from AA, the GA will create a *reply* message stating its total generation and remaining available generation status to AA.

- Trading behavior - This behavior is *cyclic* and constantly checks for messages from Load Agent (LA). Upon receiving message requests from LAs, this behavior will first check the electrical distance between itself and LA. Secondly, this behavior will check whether it has sufficient generation to satisfy LA. If GA has insufficient generation, it will only supply whatever remaining generation to LA and request LA to search for other sources to satisfy its total load demand. Finally, this behavior executes the transaction between GA and LA on the energy settlement and update GA's remaining available generation for other subsequent LA's requests.

3.3.3 Load Agent

This agent represents consumers to participate in the local microgrid energy market to purchase energy. Figure A-2 in Appendix A illustrates the GUI of a Load Agent (LA) where the input parameters include load demand and electrical distance from PCC. Other parameters such as LA buying status, grid prices, load status and microgrid operating mode are automatically updated on the GUI upon refreshing.

The list of behaviors associated with this agent is described as follows:

- Receive grid price and microgrid status behavior - This behavior is *cyclic* and constantly checks for messages sent from GrA. Messages received contain information on the grid's selling price and operating mode of the microgrid.
- Send load demand data and receive MCP behavior - This behavior is *cyclic* and constantly checks for *request* messages from PA. Whenever a message is received from PA, it will create a *reply* message stating its load demand data so that PA can compute the MCP. After MCP is calculated, PA will send an *inform* message to LA containing MCP data which will be updated in the LA's GUI.
- Send status behavior - This behavior is *cyclic* and constantly checks for messages sent from MA. Upon receiving *request* messages from MA, this agent will create a *reply* message stating the LA's load demand level and amount of load being purchased currently.

- Send total demand and satisfied load demand behavior - This behavior is *cyclic* and constantly checks for *request* messages sent from AA. Upon receiving the *request* message, this agent will send a *reply* message to AA stating its total load demand and satisfied load demand to AA.
- Trading behavior - This behavior is *cyclic* and constantly checks for messages sent from CA. Upon receiving trading signal messages, this agent will automatically begin the current trading session by searching for GA to purchase energy. There are several message exchanges between LA and GA during trading. The first message searches for the nearest available GA to supply and the second *request* message checks for the next available GA if its demand is not fully satisfied by the previous GA. Another type of message received is to inform LA that the current trading session has ended and to request LA to settle any unsatisfied load demand with GrA in grid connected mode. The end trading message will inform LA to reset its current database in preparation for the next trading session.

3.3.4 Monitor Agent

This agent requests status updates from GA and LA and displays the information on its GUI. Figure A-3 in Appendix A shows a GUI snapshot of MA. This is a basic GUI displaying all active GAs and LAs currently participating in the trading session with their statuses displayed beside their respective agent identifiers. Thus through this agent, monitoring of GA and LA status can be done.

The list of behaviors associated with this agent is described as follows:

- Receive GA status behavior - This behavior is *cyclic* and constantly checks for messages sent by GAs. The messages contain information on every active GA which includes its total generation and remaining available generation status as well as its bidding rate data.
- Receive LA status behavior - This behavior is *cyclic* and constantly checks for messages sent by LA. The messages contain information on every LA which includes load demand and amount of power being purchased currently.

3.3.5 Grid Agent

This agent collects information on the grid's selling and buyback energy prices as well as the microgrid operating mode. Figure A-4 in Appendix A provides a GUI snapshot of Grid Agent (GrA). The GUI essentially collects inputs such as the grid's selling price and the microgrid status and automatically displays the information on the GUI panel. One point to note is that the grid's buyback price is automatically computed based on the grid's selling price. This is because the utility grid imposes an additional surcharge when the microgrid sells power back to the grid. Hence, the grid's buyback price is usually lower than its selling price.

The list of behaviors associated with this agent is described as follows:

- Update grid prices and microgrid status behavior - This behavior is classified as *one-shot* because it waits for the GUI before executing its updating routine. Upon receiving inputs from the GUI, this behavior will update GrA on the latest grid's prices and microgrid operating mode which are then displayed on the GUI panel when the Refresh button is used. It should be noted that the buttons created in the agent's GUI are designed to be manually triggered by the user in order to verify the functionality of the agent at each step in the algorithm. However in practice, the agent can be programmed to automatically execute certain actions at specific time intervals using the *cyclic* behavior.
- Broadcast grid prices and microgrid status behavior - This behavior is also *one-shot* as it has to wait for the GUI before broadcasting its information. Upon using GUI to update this agent, this behavior is simultaneously triggered to broadcast the updated information to GA, LA, PA, AA and CA.

3.3.6 Price Agent

The main function of the PA is to collect the bidding information from GA and LA in order to compute MCP for each hour trading session. Figure A-5 in Appendix A shows a snapshot of the agent's GUI. When the Compute and Broadcast MCP button is triggered, the agent will proceed to compute the MCP. This GUI does not require any GUI inputs to

function. When MCP is computed, its value will be displayed along with other parameters such as grid prices, microgrid operating mode and load demand.

The list of behaviors associated with this agent is described as follows:

- Receive grid's prices and microgrid status behavior - This behavior is *cyclic* and constantly checks for messages sent by GrA. Whenever GrA updates its selling and buyback prices, it will send a message to inform this agent. The connection status of the microgrid is also included into the message to inform PA on the operating mode of the microgrid.
- Compute and Broadcast MCP behavior - This behavior is *one-shot* because it requires users to press the Compute and Broadcast MCP button on the GUI before MCP can be computed. Once this behavior is triggered, it will request every GA for its bidding rate data and every LA for its load demand data. After that, it will compute the MCP and determine whether the MCP value is higher than the grid's selling price. If the MCP is higher than the grid's selling price, this agent will set MCP at the grid's selling price so that DGs can sell their energy to local consumers instead of consumers buying energy from the grid. After MCP is computed, it will correspondingly inform the GA, LA and CA.

3.3.7 Aggregate Agent

The main function of the AA is to consolidate all GAs and LAs in the microgrid and display the total microgrid generation and load demand in the GUI. Figure A-6 in Appendix A illustrates a GUI snapshot of the Aggregate Agent (AA). It requires GUI inputs in order to function. Whenever the update button is executed, it will begin aggregating data from the GAs and LAs and the updated data will be reflected on the GUI.

The list of behaviors associated with this agent is described as follows:

- Receive grid prices behavior - This behavior is *cyclic* and constantly checks for messages sent by GrA. When GrA updates its energy prices, a message will be sent to this agent where this behavior will be responsible for decrypting the message contents and update this agent accordingly.

- Receive GA status behavior - This behavior is *cyclic* and constantly checks for messages sent by GAs. When *request* messages are sent to GAs requesting for their generation status, GA will send a *reply* message to this agent where the message will be decrypted in this behavior. Message contents include GA's rated generation and remaining available generation. Once the generation statuses for all GAs have been collected, this agent will aggregate the data and display it on the GUI.
- Receive LA status behavior - This behavior is *cyclic* and constantly checks for messages sent by LA. Whenever this agent requests for LA's demand status, LA will send a reply message to this agent where it will be decrypted in this behavior. The contents of the message include each LA's total load demand and satisfied load demand data. After collecting data from all LAs, this agent aggregates the data and displays them in the GUI.
- End of current trading session and inform CA behavior - This behavior is *cyclic* and constantly checks for messages sent by CA. When the end of current trading session message is sent by CA, this behavior will receive the message and perform an internal update to collect current GA and LA statuses. The updated information is then sent back to CA containing all the GA and LA statuses after the current trading session.

3.3.8 Control Agent

This agent serves as a control for the operation of energy trading between GAs and LAs as well as recording the amount of microgrid power exchange with the utility grid. Figure A-7 in Appendix A shows a snapshot of the Control Agent (CA)'s GUI. This GUI displays parameters such as microgrid operating mode, grid prices, MCP, microgrid generation and load demand details. Users can press the update button on this GUI to update the microgrid parameters which will be subsequently reflected on the GUI. The Initiate Trade button tells this agent to start the current trading session by sending messages to GAs and LAs to inform them. This will trigger the start of the current trading session. When all GAs and LAs are done, the End Trade button is triggered to signal the end of the current trading session. During this time, GAs and LAs are required to settle their generation and load demand respectively and the final simulation results can be printed on the Windows

command prompt. The Reset Simulation button is triggered to prepare GAs and LAs for the next trading session.

The list of behaviors associated with this agent is described as follows:

- Receive grid prices and microgrid status behavior - This behavior is *cyclic* and constantly checks for messages sent by GrA. It looks for messages sent by GrA in order to update this agent on the grid's energy prices. The message contents include grid prices and microgrid operating status.
- Receive MCP behavior - This behavior is *cyclic* and constantly checks for messages sent by PA. After MCP is computed, PA will send a message to this agent and this behavior is responsible for obtaining the information. The updated MCP will be reflected in the GUI.
- Receive AA data behavior - This behavior is *cyclic* and constantly checks for messages sent by AA. When the Update button is triggered, it will send a *request* message to AA asking for the updated information. AA will send a *reply* message to this agent where it will be received by this behavior. Message contents include microgrid total generation and load demand status. CA then computes the net power flow from the microgrid and indicates whether a surplus or deficit in microgrid energy has occurred during the current trading session.
- Initiate trade behavior - This behavior is *one-shot* and is only triggered through this GUI when the Initiate Trade button is triggered. This signifies the start of the current trading session where it will inform all GAs and LAs to begin trading.
- End trade behavior - This behavior is *one-shot* and is triggered through the GUI when the End Trade button is triggered. It will send messages to all GAs and LAs informing them to settle any outstanding generation and load demand respectively. After which, CA will declare the end of the current trading session.
- Reset simulation behavior - This behavior is *one-shot* and is triggered when the Reset Simulation button is triggered. CA will send messages to all other agents telling them to reset their database in preparation for the next trading session.

3.3.9 Overview of Agent Interaction

Following the description of the previous seven user-defined agents, the agent interaction of these agents is shown in Figure 3-4. During the beginning of each trading session, the Grid Agent (GrA) will broadcast the grid price and microgrid status information to all the subscribed agents. After that, the Control Agent (CA) will announce the commencement of the trading session to the Generation Agent (GA) and the Load Agent (LA). Subsequently, the Price Agent (PA) will compute and broadcast the MCP by sending requests to the GAs and LAs to retrieve bidding information. Once MCP is known, the GAs and LAs will execute the trading algorithm which considers the RED among the agents as discussed previously.

Figure 3-4: Agent Interaction

At any time during the trading session, the Monitor Agent (MA) can send request messages to GAs and LAs to obtain their current status. When the end of trade signal is announced by CA, the GAs and LAs will settle any outstanding generation and load demand respectively with the utility grid. Subsequently, the Aggregate Agent (AA) will request for the GAs and LAs status and the information is passed on to the CA to confirm

that the current trading session has ended. The CA then informs AA, PA, GAs and LAs to reset their parameters in preparation for the next trading session.

3.4 Simulation Setup

3.4.1 Microgrid System

A microgrid setup is shown in Figure 3-5 to verify the functionality of MAS using JADE. In this setup, DGs and consumer loads connect to the microgrid through a 0.4kV main busbar using power converters and intelligent switches. A total of three DGs and two loads were considered in the simulation study. There is also an intelligent energy sensor located at the PCC to monitor the power exchange between the microgrid and utility grid. Computers controlling the corresponding power converters, intelligent switches and sensors are also connected via TCP/IP connection so that they are able to communicate with each other.

Figure 3-5: Basic microgrid setup

3.4.2 List of Test Cases

In order to perform simulation studies under different microgrid conditions, a list of test cases and description is created and shown in Table 3-2. These test cases state the possible events the microgrid may encounter during its normal operations. In the simulation studies, the microgrid operates in grid-connected mode for all test cases. The conditions that can be

varied are the net microgrid energy and agent objectives. During normal operations, power can be exchanged between the microgrid and the utility grid by either buying or selling power to the grid in order to maintain power balance within the microgrid.

Table 3-2: List of test cases and description

Test Case	Description
1	Net deficit of microgrid energy
2	Net surplus of microgrid energy
3	Zero net microgrid energy
4	MCP under different agent objectives

3.4.3 Generator and Load Details

Table 3-3 shows the detail of the GAs and LAs used in the simulation studies. The table depicts the minimum and maximum power fluctuations of both GAs and LAs and also defines the minimum and maximum bidding rate of GAs over a 24-hour period. The 24-hour bidding rates for GAs are also given in Table 3-4.

Table 3-3: Details of GA and LA

Agents	$P_{\min}$ (kW)	$P_{\max}$ (kW)	$m_{G,i,\min}$ (\$/kWh/kW)	$m_{G,i,\max}$ (\$/kWh/kW)
GA1	0	20	0.01	1
GA2	0	40	0.01	1
GA3	0	60	0.01	1
LA1	0	50	-	-
LA2	0	100	-	-

The GAs in the simulation studies represents various types of renewable and non-renewable technologies which may include solar PVs, wind turbines, fuel cells, gas turbines or CHP. The primary objective of the simulation study is to create an environment where the bidding rates and power outputs of the GAs varies throughout the simulation. For instance, GA1 has a DG capacity range of between 0kW and 20kW and a corresponding bidding rate range between \$0.01/kWh/kW and \$1/kWh/kW. The minimum bidding rate for the GAs should not be \$0/kWh/kW because it will immediately be dispatched and will not participate in the MCP computation process. Similarly, LA1 has a

load demand range between 0kW and 50kW and LA2 has a load demand range between 0kW and 100kW respectively.

Table 3-4: Bidding rates of GAs ($m_{G,i}$ in \$/MWh/MW) over 24-hour period

Hour	GA 1	GA 2	GA 3
0	0.105	0.11	0.111
1	0.222	0.159	0.106
2	0.187	0.202	0.198
3	0.12	0.17	0.131
4	0.08	0.101	0.112
5	0.212	0.136	0.364
6	0.323	0.278	0.241
7	0.132	0.316	0.414
8	0.222	0.095	0.167
9	0.087	0.171	0.145
10	0.103	0.077	0.118
11	0.123	0.104	0.084
12	0.137	0.112	0.151
13	0.141	0.094	0.118
14	0.094	0.114	0.138
15	0.176	0.141	0.129
16	0.158	0.139	0.171
17	0.143	0.086	0.156
18	0.134	0.101	0.118
19	0.082	0.126	0.114
20	0.126	0.076	0.131
21	0.124	0.106	0.071
22	0.116	0.132	0.106
23	0.108	0.163	0.142
24	0.184	0.195	0.212

The 24-hour generation and load demand profiles for the GAs and LAs are shown in Figure 3-6 and Figure 3-7 respectively. In Figure 3-6, three major peaks can be observed where the first peak occurs between hour 10 and hour 11 while the second peak occurs between hour 14 to hour 15. The third peak occurs between hour 17 to hour 18. These peaks represent a typical day where the afternoon and evening periods correspond to nominal situations when either the sunlight or the wind energy is the most abundant.

Figure 3-6: 24-hour GA generation profile

Figure 3-7: 24-hour LA demand profile

In Figure 3-7, the 24-hour load demand profile was extracted from historical data readings of the smart meters located in the NTU residential staff quarters. It is observed that the load demand profile exhibits several peaks during the afternoon and evening periods of the day. The total load demand curve remains consistently high between the afternoon and

evening periods and is relatively low during early morning and night hours. This coincides with the generation curve profile in Figure 3-6 where the two major peaks occur in the afternoon and evening periods. Data for the dispatch of GAs and LAs can also be found in Appendix A.

The relative electrical distance of the GAs and LAs with respect to the PCC is shown in Figure 3-8. It shows the position of every GA and LA with respect to the PCC. The position of the GAs and LAs are fixed during simulation for all the test cases listed in Table 3-2. During the simulation studies, the absolute distance between any GA and LA pairs will be determined via agent interaction and the trading will begin starting from the smallest absolute distance. It should be noted that the absolute distance is always a positive value and since the position of LA 1 and LA 2 are different, the absolute distance determined at LA 1 and LA 2 will be different with respect to the relative positions of the other three GAs.

Figure 3-8: GAs and LAs relative electrical distance during simulation studies

3.5 Results and Discussion

Agent simulation was implemented on the JADE simulation platform and the following simulation results are discussed and analyzed. Based on the agents' trading and negotiation algorithm, the 24-hour microgrid power flow results are shown in Figure 3-9. This figure consists of three curves which are denoted in blue, red and green curves. The first curve, denoted in blue represents the amount of microgrid power sold back to the utility grid while the second curve, denoted in red represents the amount of microgrid power bought from the utility grid in order to maintain power balance. The third curve which is denoted

in green represents the net microgrid power flowing out of the microgrid and is basically the difference between the first and second curves. The sign convention is defined such that negative values indicate a net power flowing into the microgrid and positive values indicate a net power flowing out of the microgrid. Thus, positive net microgrid power can be interpreted as the microgrid having an energy surplus and is selling power back to the utility grid while negative net microgrid power is interpreted as having an energy deficit and requires power to be bought from the utility grid in order to satisfy load demand within the microgrid.

Between hour 0 and hour 9, it simulates the situation described in Test Case 1 where the microgrid is experiencing more load demand than the microgrid local generation can produce. This means that the deficit power has to be bought from the grid in order to satisfy these loads. During this period, it is observed that no power is sold to the utility grid while some power is bought from the utility grid. This means that all GAs have sold their power to LAs and the remaining excess load demand is satisfied by purchasing power from the utility grid. It is also observed that the red curve is symmetrical about the x-axis due to the sign convention defined for the net microgrid power (i.e. green curve).

Figure 3-9: 24-hour microgrid power flow

Between hour 9 and hour 18, the situation described in Test Case 2 is simulated where the microgrid is experiencing a net surplus of power. It is observed that no power is bought from the utility grid while some power is sold to the utility grid during this period. This means that all LA load demand are satisfied by the GAs and the remaining excess GA generation is sold back to the utility grid. During this period, the green curve overlaps with the blue curve because both indicate that power is flowing out of the microgrid.

Between hour 18 to hour 24, the situation described in Test Case 3 is simulated where the microgrid is experiencing zero net microgrid power flow. During this period, there is no power sold and bought from the utility grid. This indicates that the power generated from the GAs equals the load demand of the LAs within the microgrid. Under such condition, trading and negotiation occurs only between the GAs and LAs and no transactions are made with the utility grid.

Next, Figure 3-10 illustrates the MCP under various agent objectives. The grid selling price and grid buyback price in this simulation study is set at \$4/kWh and \$3.4/kWh respectively. In this figure, three curves which are denoted by green, red and blue bars are presented. The first curve, identified by a blue bar, is the computed MCP curve which denotes the actual MCP calculated by PA. The second curve, identified by a red bar, is the maximization of load benefits curve. The third curve, identified by a green bar, is the maximization of GA profits curve. Numerical data of the MCP under various agent objectives can also be found in Appendix A.

In Figure 3-10, it is observed that there are periods when the computed MCP is above the grid selling price and several instances when it is below the grid buyback price. However for maximization of load benefits price curve, the clearing price is capped at the grid selling price but it is allowed to fall below the grid buyback price. The reason for the clearing price to cap at the grid selling price is to ensure that the price offered by GAs is at least the same or lower than the utility grid. For GAs adopting this strategy, they will follow this price curve to sell their power.

Figure 3-10: Energy prices under different agent objectives

Conversely, the price curve for maximization of GA profits restricts the clearing price such that it ranges in between grid selling and grid buyback price. The reason for this restriction is because it is more profitable for GAs to sell power back to the utility grid at the grid's buyback price if the computed MCP falls below that price. Therefore, GAs adopting this strategy will follow the price curve for maximization of GA profits and the clearing price will be capped at either the grid's selling or the buyback prices if the computed MCP exceeds the allowed price limit.

Table 3-5 shows the comparison in total revenue earned by each GA during the 24-hour period simulation. The values are extracted from Appendix A. In addition to the two agent objectives, the revenue for each GA in the base case is also provided. The base case describes the situation when there are no trading negotiations among agents. This means that the GAs can only directly sell their power to the utility at the grid's buyback price over the 24-hour period. From the table, GA1 records a revenue of \$908.16 while adopting the maximization of load benefits objective and \$980.56 while adopting the maximization of GA profits objective. It is evident that the maximization of GA profits objective yields a higher revenue compared to the maximization of load benefits objective. As explained earlier, the reason for the increase in revenue for profit maximization is because if the computed MCP is below the grid's buyback price, GAs are better off selling their energy to the grid to yield a higher revenue. Furthermore, GA1 records a revenue of \$941.80 in the

base case. It is observed that this value is higher than the revenue for maximization of load benefits. This is because under the maximization of load benefits objective, the price is allowed to fall below the grid's buyback price during certain periods while the base case allows GA to sell their power at the grid's buyback price over the 24-hour period. The same reasoning holds true for GA2 and GA3 correspondingly.

Table 3-6 shows the comparison in energy costs paid by each LA during the 24-hour period simulation. Likewise, the values have been extracted from Appendix A and the base case situation is described in the previous paragraph. From the table, LA1 records energy costs of \$2634.27 and \$2854.23 under the maximization of the load benefits and maximization of GA profits objective respectively. The results show that if GAs attempt to maximize their profits, then LAs will have to incur higher energy costs because they are required to buy power from the grid in order to satisfy the load demand. However if GAs adopts the maximization of load benefits objective, then the energy costs incurred by LAs will be reduced. The last column in Table 3-6 shows the energy costs incurred by the LAs in the base case. It is evident that the LA energy costs incurred in the base case are higher compared to the case when LAs are under either maximization of load benefits or maximization of GA profits objectives. This shows that the proposed agent-based microgrid market structure is able to reduce the energy costs of the loads and can provide more economical benefits if agents are allowed to interact.

Table 3-5: Comparison of GA revenues (\$) over 24-hour period

Agents	Maximization of load benefits	Maximization of GA profits	Base case
GA1	908.16	980.56	941.80
GA2	1,975.23	2,113.71	2,029.80
GA3	3,166.56	3,406.04	3,274.20

Table 3-6: Comparison of LA energy costs (\$) over 24-hour period

Agents	Maximization of load benefits	Maximization of GA profits	Base case
LA1	2,634.27	2,854.23	3,208
LA2	3,743.08	3,973.56	4,396

3.6 Summary

This chapter presents the application of MAS when running the proposed local microgrid market clearing algorithm using JADE. It basically provides a platform for agents to communicate and to perform the required market operations and monitoring tasks. Simulation was done in compliance with the IEEE FIPA standard through the use of JADE which uses the AMS and DF agents to manage the agent platform. It is found that the maximization of load benefits objective minimizes the profit of GAs while the profit maximization of GAs objective minimizes the benefits of LAs. This shows that the two agent objectives are biased to either the LAs or GAs. Therefore, a new agent objective is required to promote unbiased transactions between the agents. This is implemented and analyzed in the next chapter.

Under the proposed distributed agent-based control scheme, design and development of user-defined agents and their respective GUIs were created. Agent simulation was implemented on JADE to test the functionalities of the user-defined agents. During market trading, agents are programmed to consider the MCP, agent's objective and RED between each other as part of the criteria to perform power balancing and trading negotiations. The simulation results have shown that MAS is able to manage a distributed local energy trading market for DGs and loads to engage in negotiations while considering different microgrid conditions.

The simulation study in this chapter considers the single-side bidding mechanism of DGs and loads in the microgrid. In order to study the full market interaction between DGs and loads, a double-side bidding mechanism is required which will be covered in the next chapter. The simulation environment developed in this chapter primarily discusses the market interaction between agents which also serves as a reference for detailed studies in the next chapter where the t-domain dynamics of MW generation and bus voltage profiles are considered using the proposed microgrid market clearing technique.

CHAPTER 4 MUTLI AGENT SYSTEM FOR DISTRIBUTED MANAGEMENT OF MICROGRIDS

4.1 Introduction

As mentioned in Chapter 1, MAS is proposed for generation and demand scheduling and the LMP for various participants in the distributed microgrid energy market. Generator and load agents retrieve power scheduling information based on their incremental cost and price signals obtained from the proposed microgrid energy market. The power reference and load control signals are then sent to the generator and load correspondingly. The price signal refers to the Market Clearing Price (MCP) which is derived from the submitted bids of the generator and load. Subsequently, the derived MCP establishes the price reference in LMP among other variables where the participants will pay or be paid at that price. The amount that each generator or load agent receives or pays respectively depends on some objectives imposed on the agents.

4.2 Problem Formulation

4.2.1 MCP (Double Side Bidding) and Scheduling Problem

The idea of proposing a microgrid market structure is to encourage a competitive electricity market since DERs are considered more economical to generate electricity locally at least for a certain peak period compared to buying it directly from the main grid [77, 135]. In addition, a real-time market clearing technique is used to determine the MCP. The objective in determining MCP is to dispatch an aggregate of different types of DGs to an aggregate of different consumers. In Chapter 3, single side bidding was considered for the microgrid market bidding mechanism because it is assumed that consumers have no expertise to contribute effectively in the price mechanism. Therefore, most electricity markets consider consumers to be incapable of making rational market decisions and are simply represented as fixed loads which need to be satisfied. Therefore, active consumer participation in energy markets remains minimal. However, due to the advancement in

smart grid technologies and increasing consumer awareness, consumers are gradually better educated and thus have the necessary knowledge to contribute effectively in the price mechanism. Another reason that triggers consumer participation is because of increasing trend of electricity prices due to rising oil prices. Therefore in the subsequent simulation studies, a double side bidding mechanism is considered. All bids to sell electrical energy will be priced at the marginal cost of the energy.

In a double side bidding market, the demand elasticity is considered. Both the generation and demand side bidding have been included when determining the value of c_{MCP} . In addition, only linear variations in generation and demand with price are considered. In this bidding mechanism, the power generated by the i^{th} generation bidder is the same as (3.1) in the previous chapter. Likewise, consider the load demand required by the j^{th} demand bidder where the demand curve is expressed as:

$$p_{D,j} = \frac{c_{oD,j}}{m_{D,j}} - \frac{c_{D,j}}{m_{D,j}} \quad (4.1)$$

where $p_{D,j}$ is the active load demand required by the j^{th} demand bidder; $c_{oD,j}$ is the price intercept of the j^{th} demand curve; $c_{D,j}$ is the price offered by the j^{th} load to consume $p_{D,j}$; and $m_{D,j}$ is the bidding rate of the j^{th} demand bidder.

Likewise, the total demand curve for M demand bidders is given as:

$$\begin{aligned} p_{D,Total} &= p_{D,1} + p_{D,2} + \dots + p_{D,N} \\ &= \sum_{j=1}^M \frac{c_{oD,j}}{m_{D,j}} - \sum_{j=1}^M \frac{c_{D,j}}{m_{D,j}} \end{aligned} \quad (4.2)$$

At MCP, total generation must be equal to the total load demand which is given as:

$$c_{MCP} \sum_{i=1}^N \frac{1}{m_{G,i}} = \sum_{j=1}^M \frac{c_{oD,j}}{m_{D,j}} - c_{MCP} \sum_{j=1}^M \frac{1}{m_{D,j}}$$

Therefore, the value of c_{MCP} for a double side bidding market can be found by rearranging the terms and is expressed as:

$$c_{MCP} = \frac{\sum_{j=1}^M \frac{c_{oD,j}}{m_{D,j}}}{\sum_{i=1}^N \frac{1}{m_{G,i}} + \sum_{j=1}^M \frac{1}{m_{D,j}}} \quad (4.3)$$

where N is the number of generation bidders; and M is the number of loads participating in the competitive electricity market.

Similarly if the minimum and maximum generation and demand limits denoted by $p_{G,i,min}$, $p_{G,i,max}$, $p_{D,j,min}$ and $p_{D,j,max}$ are imposed, then the updated expression for c_{MCP} can be expressed as:

$$c_{MCP} = \frac{\sum_{j=1}^M \frac{c_{oD,j}}{m_{D,j}} [U(p_{D,j} - p_{D,j,min}) - U(p_{D,j} - p_{D,j,max})]}{\sum_{i=1}^N \frac{1}{m_{G,i}} [U(p_{G,i} - p_{G,i,min}) - U(p_{G,i} - p_{G,i,max})] + \sum_{j=1}^M \frac{1}{m_{D,j}} [U(p_{D,j} - p_{D,j,min}) - U(p_{D,j} - p_{D,j,max})]} \quad (4.4)$$

where

$$U(p_{D,j} - p_{D,j,min}) = \begin{cases} 1, & \text{when } p_{D,j} \geq p_{D,j,min} \\ 0, & \text{when } p_{D,j} < p_{D,j,min} \end{cases}$$

$$U(p_{D,j} - p_{D,j,max}) = \begin{cases} 1, & \text{when } p_{D,j} \geq p_{D,j,max} \\ 0, & \text{when } p_{D,j} < p_{D,j,max} \end{cases}$$

Based on the value of c_{MCP} calculated in (4.3) for a double side bidding market, the dispatch for the generators and loads can then be determined by substituting the value of c_{MCP} obtained from (4.3) into (3.1) and (4.1) respectively subject to the following constraints:

Firstly, the total microgrid generation and load must be balanced at all times with the utility grid either injecting or absorbing energy during unbalanced periods.

$$\sum_{i=1}^N p_{G,i} + p_{Grid} = \sum_{j=1}^M p_{D,j} \quad (4.5)$$

where p_{Grid} is the active power delivered from/into the utility grid to maintain power balance within the microgrid.

In addition, each generation unit has to abide by its generation limits as follows:

$$P_{G,i,\min} \leq P_{G,i} \leq P_{G,i,\max} \quad (4.6)$$

where $p_{G,i,\min}$ is the minimum power generated by the i^{th} generation; and $p_{G,i,\max}$ is the maximum power generated by the i^{th} generation.

Similarly, each load has its consumption limits as follows:

$$P_{D,j,\min} \leq P_{D,j} \leq P_{D,j,\max} \quad (4.7)$$

where $p_{D,j,\min}$ is the minimum power required by the j^{th} load which is also regarded as the base load; and $p_{D,j,\max}$ is the maximum power required by the j^{th} load based on the maximum capacity rating.

In addition, whenever the utility grid is required to maintain power balance in the microgrid due to either insufficient or excess generation, market participants will follow utility grid prices accordingly during the market clearing process.

4.2.2 Locational Marginal Pricing

The nodal pricing or LMP refers to the lagrangian multipliers which are derived from active power flow equations at each bus within a system [136]. LMP was selected as the pricing mechanism because it takes into account power losses among other factors which are typical in a medium-low voltage network. In general, LMP at any node in the system consists of three components which include the reference marginal cost, a marginal loss component and a congestion component which is expressed as:

$$\text{LMP} = \lambda_{ref} + \frac{\partial P_{loss}}{\partial P_i} \lambda_{ref} + \lambda_{congestion} \quad (4.8)$$

where λ_{ref} is the reference marginal cost which is obtained from (4.3) and is the same for all nodes in the system; $(\partial P_{loss}/\partial P_i)\lambda_{ref}$ is the marginal loss component which is further explained in the next section and $\lambda_{congestion}$ is the congestion component which generally consists of a shadow price and a generation shift factor.

Therefore, the LMP for each market participant will be location specific factoring into account the marginal loss component. In subsequent simulation studies, the congestion

component will not be considered as no congestion is assumed in the illustrated system, i.e. $\lambda_{congestion}$ equals zero.

However, if congestion is considered in simulation studies, Figure 4-1 and Figure 4-2 illustrates how the congestion in the power network can be analyzed using the PowerWorld simulator [137]. Figure 4-1 depicts the single-line diagram of a three-phase seven bus power system. It consists of three generating units, three loads and a slack generating unit (utility grid). During normal operation, the power generated by the generating units is transferred from the generation bus to the load bus via cables that have a certain specified power carrying capacity limit. The excess power generated by the generating units flows back to the slack bus (utility grid) and the direction of the green arrows indicate the power flow in the network. The pie chart on the cables in Figure 4-1 represents the percentage of the capacity currently used for transferring the generated power and it is observed that the cables are well within the capacity limit of the cables.

Figure 4-1: Example of cables without congestion

In the event that the cable power carrying capacity limit has been/nearly violated, additional power cannot be transferred via the cables without jeopardizing the life expectancy and safety of the cable should the load demand increase or the power generated by the generating units increase. An example of such a situation is shown in Figure 4-2. In this figure, cables that have nearly violated their capacity limits are identified by the orange pie chart (<100%) and cables which have exceeded their capacity are identified by the red pie chart (> 100%). In such situations, it is important to study where the congestion

takes place and then take the necessary action to penalize either the generating units or loads via the congestion component in LMP. However in the subsequent sections, the focus is to optimally match the supply and demand in a way that either maximize the DG surplus or the load surplus or a combination of both. Therefore, the congestion component in the LMP is assumed to be zero in the simulation studies.

Figure 4-2: Example of cables with congestion

4.2.3 Marginal Loss Factor

The loss sensitivity factor, $\partial P_{\text{loss}}/\partial P_i$ is part of the marginal loss component in (4.8) and is referred as the incremental loss in [138]. Loss sensitivity factors in a power system are derived directly from AC power flow. In a typical power flow problem, the error between the calculated and scheduled real and reactive power at bus i can be expressed in the following:

$$\Delta P_i = \sum_{k=1}^N \frac{\partial P_i}{\partial \theta_k} \Delta \theta_k + \sum_{k=1}^N \frac{\partial P_i}{\partial |E_k|} \Delta |E_k| \quad (4.9)$$

$$\Delta Q_i = \sum_{k=1}^N \frac{\partial Q_i}{\partial \theta_k} \Delta \theta_k + \sum_{k=1}^N \frac{\partial Q_i}{\partial |E_k|} \Delta |E_k| \quad (4.10)$$

where ΔP_i is a function of voltage magnitude E_k and phase angle θ_k at bus i ; ΔP_i and ΔQ_i represent the change in active and reactive power at bus i respectively.

Equations (4.9) and (4.10) can be arranged in the Jacobian matrix form as follows:

$$\begin{bmatrix} \Delta P_1 \\ \Delta Q_1 \\ \Delta P_2 \\ \Delta Q_2 \\ \vdots \end{bmatrix} = \underbrace{\begin{bmatrix} \frac{\partial P_1}{\partial \theta_1} & \frac{\partial P_1}{\partial |E_1|} & \dots \\ \frac{\partial Q_1}{\partial \theta_1} & \frac{\partial Q_1}{\partial |E_1|} & \dots \\ \vdots & \vdots & \ddots \end{bmatrix}}_{\text{Jacobian matrix}} \begin{bmatrix} \Delta \theta_1 \\ \Delta |E_1| \\ \Delta \theta_2 \\ \Delta |E_2| \\ \vdots \end{bmatrix} \quad (4.11)$$

The first step determines the ratio of change in power at the reference bus, ΔP_{ref} when a change in power at bus i , ΔP_i or ΔQ_i is made. The formulation begins with the above power flow problem where four new terms are subsequently introduced i.e. $\frac{\partial \theta_i}{\partial P_i}$, $\frac{\partial |E_i|}{\partial P_i}$, $\frac{\partial \theta_i}{\partial Q_i}$ and $\frac{\partial |E_i|}{\partial Q_i}$. These terms can be extracted from the inverse Jacobian matrix.

Therefore, the change in active power at the reference bus, ΔP_{ref} can be expressed as a change in active power at bus i , ΔP_i and a change in reactive power at bus i , ΔQ_i as shown below:

$$\begin{aligned} \Delta P_{ref} &= \sum_i \frac{\partial P_{ref}}{\partial \theta_i} \Delta \theta_i + \sum_i \frac{\partial P_{ref}}{\partial |E_i|} \Delta |E_i| \\ &= \sum_i \frac{\partial P_{ref}}{\partial \theta_i} \frac{\partial \theta_i}{\partial P_i} \Delta P_i + \sum_i \frac{\partial P_{ref}}{\partial |E_i|} \frac{\partial |E_i|}{\partial P_i} \Delta P_i \end{aligned} \quad (4.12)$$

$$\begin{aligned} \Delta P_{ref} &= \sum_i \frac{\partial P_{ref}}{\partial \theta_i} \Delta \theta_i + \sum_i \frac{\partial P_{ref}}{\partial |E_i|} \Delta |E_i| \\ &= \sum_i \frac{\partial P_{ref}}{\partial \theta_i} \frac{\partial \theta_i}{\partial Q_i} \Delta Q_i + \sum_i \frac{\partial P_{ref}}{\partial |E_i|} \frac{\partial |E_i|}{\partial Q_i} \Delta Q_i \end{aligned} \quad (4.13)$$

where ΔP_{ref} is a function of voltage magnitude E_i and phase angle θ_i at bus i ; ΔP_i and ΔQ_i represent the change in active and reactive power at bus i respectively. In addition,

whenever a change in ΔP_i or ΔQ_i is made, all phase angles and voltages in the network will change accordingly.

By writing out (4.12) and (4.13) for every bus i in the network and arranging them in the inverse Jacobian matrix form, the resulting equation for a network with N buses is expressed as follow:

$$\begin{aligned} & \begin{bmatrix} \frac{\partial P_{ref}}{\partial P_1} & \frac{\partial P_{ref}}{\partial Q_1} & \frac{\partial P_{ref}}{\partial P_2} & \frac{\partial P_{ref}}{\partial Q_2} & \dots & \frac{\partial P_{ref}}{\partial P_N} & \frac{\partial P_{ref}}{\partial Q_N} \end{bmatrix} \\ &= \begin{bmatrix} \frac{\partial P_{ref}}{\partial \theta_1} & \frac{\partial P_{ref}}{\partial |E_1|} & \frac{\partial P_{ref}}{\partial \theta_2} & \frac{\partial P_{ref}}{\partial |E_2|} & \dots & \frac{\partial P_{ref}}{\partial \theta_N} & \frac{\partial P_{ref}}{\partial |E_N|} \end{bmatrix} \begin{bmatrix} J^{-1} \end{bmatrix} \end{aligned} \quad (4.14)$$

By transposing the above, (4.15) is obtained as shown below:

$$\begin{bmatrix} \frac{\partial P_{ref}}{\partial P_1} \\ \frac{\partial P_{ref}}{\partial Q_1} \\ \vdots \\ \frac{\partial P_{ref}}{\partial P_N} \\ \frac{\partial P_{ref}}{\partial Q_N} \end{bmatrix} = \begin{bmatrix} J^{T^{-1}} \end{bmatrix} \begin{bmatrix} \frac{\partial P_{ref}}{\partial \theta_1} \\ \frac{\partial P_{ref}}{\partial |E_1|} \\ \vdots \\ \frac{\partial P_{ref}}{\partial \theta_N} \\ \frac{\partial P_{ref}}{\partial |E_N|} \end{bmatrix} \quad (4.15)$$

where $J^{T^{-1}}$ is the transpose of the inverse Jacobian matrix for the electrical network. The change in phase angles and voltage magnitudes in the electrical network can then be obtained by employing any non-linear programming techniques available. An Interior Point Method (IPM) [139] is used in this thesis for determining changes in phase angle and voltage magnitude parameters in the network. Details of IPM are described in Appendix B.

Next, consider the active power losses on a transmission line between bus i and bus j which is expressed as:

$$P_{loss_{ij}} = \left[|E_i|^2 + |E_j|^2 - 2|E_i||E_j|\cos(\theta_i - \theta_j) \right] \text{Re}(Y_{ij}) \quad (4.16)$$

where Y_{ij} is the admittance between bus i and bus j .

By taking the derivatives of (4.16) with respect to θ_i and θ_j , we have the following terms:

$$\frac{\partial P_{loss_{ij}}}{\partial \theta_i} = 2|E_i||E_j|\sin(\theta_i - \theta_j)\text{Re}(Y_{ij}) \quad (4.17)$$

$$\frac{\partial P_{loss_{ij}}}{\partial \theta_j} = -2|E_i||E_j|\sin(\theta_i - \theta_j)\text{Re}(Y_{ij}) \quad (4.18)$$

The loss sensitivity factor which is the ratio of change in real system losses with respect to a change in power at bus i , ΔP_i , can then be calculated by multiplying the change in phase angle and voltage parameter obtained in (4.15) with either (4.17) or (4.18) and is expressed as:

$$\frac{\Delta P_{loss}}{\Delta P_i} = \sum_{\text{All lines}} \frac{\partial P_{loss, line \ell}}{\partial \theta_j} \frac{\partial \theta_j}{\partial P_i} \quad (4.19)$$

Similarly, (4.19) can be extended to every bus in the network. Therefore in a network with N buses, the matrix equivalent expression is expressed as:

$$\begin{bmatrix} \frac{\partial P_{loss}}{\partial P_1} \\ \vdots \\ \frac{\partial P_{loss}}{\partial P_N} \end{bmatrix} = \begin{bmatrix} \frac{\partial \theta_1}{\partial P_1} & \dots & \frac{\partial \theta_N}{\partial P_1} \\ \vdots & \ddots & \vdots \\ \frac{\partial \theta_1}{\partial P_N} & \dots & \frac{\partial \theta_N}{\partial P_N} \end{bmatrix} \begin{bmatrix} \frac{\partial P_{loss}}{\partial \theta_1} \\ \vdots \\ \frac{\partial P_{loss}}{\partial \theta_N} \end{bmatrix} \quad (4.20)$$

where $(\partial \theta_i / \partial P_j)$ are the values obtained from (4.15) for every i and j and $(\partial P_{loss} / \partial \theta_j)$ are obtained from (4.18) by taking the derivatives of P_{loss} with respect to θ_j .

Alternatively, another approach to determine $(\partial \theta_i / \partial P_j)$ was also discussed in [138] which basically uses a linearized form to calculate all bus phase angles in a network. The active power flow at bus i in a given network is expressed as the sum of all nodes j connected directly to bus i . It is expressed as:

$$P_i = \sum_{\substack{\text{over all nodes } j \\ \text{connected directly} \\ \text{to } i}} P_{ij} = \sum_j \frac{1}{x_{ij}} (\theta_i - \theta_j) \quad (4.21)$$

where x_{ij} is the reactance between bus i and bus j ; θ_i and θ_j are the phase angles of bus i and bus j respectively. Therefore, the equivalent matrix representation of (4.21) for N buses in a network is given as follows:

$$\begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_N \end{bmatrix} = [B_x] \begin{bmatrix} \theta_1 \\ \theta_2 \\ \vdots \\ \theta_N \end{bmatrix} \quad (4.22)$$

where $B_{x_{ii}} = \sum_{\substack{\text{over all lines } j \\ \text{connected to } i}} \frac{1}{x_{ij}} \text{ for } i \neq \text{ref}$

$B_{x_{ii}} = 0 \text{ for } i = \text{ref}$

$B_{x_{ij}} = \frac{-1}{x_{ij}} \text{ for } i \neq \text{ref and } j \neq \text{ref}$

$B_{x_{ij}} = 0 \text{ for } i = \text{ref and } j = \text{ref}$

Rearranging (4.22) will give the following:

$$\begin{bmatrix} \theta_1 \\ \theta_2 \\ \vdots \\ \theta_N \end{bmatrix} = [\mathbf{X}] \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_N \end{bmatrix} \quad (4.23)$$

The relationship for the incremental change between the phase angles and active power flows at each bus can also be determined from (4.24) which is given as:

$$\begin{bmatrix} \Delta\theta_1 \\ \Delta\theta_2 \\ \vdots \\ \Delta\theta_N \end{bmatrix} = \begin{bmatrix} \frac{\partial\theta_1}{\partial P_1} & \cdots & \frac{\partial\theta_1}{\partial P_N} \\ \vdots & \ddots & \vdots \\ \frac{\partial\theta_N}{\partial P_1} & \cdots & \frac{\partial\theta_N}{\partial P_N} \end{bmatrix} \begin{bmatrix} \Delta P_1 \\ \Delta P_2 \\ \vdots \\ \Delta P_N \end{bmatrix} \quad (4.24)$$

The values of $(\partial\theta_i/\partial P_j)$ in (4.20) can be obtained by transposing $\mathbf{X}$. It is also claimed [138] that the loss sensitivity factors derived from this alternative approach produces nearly the same results as those solved using any non-linear programming methods. Compared to the non-linear approach, the minor difference in the computed values from the alternative approach is due to the linearization of the network power flow parameters. However, the tradeoff of using the alternative approach is a faster computation time. Therefore, the loss sensitivity factor at each bus in the network can be obtained and will be subsequently used by LMP to compute the nodal price at each node in the network.

4.2.4 Agent Optimization Objectives

The generation and load agents developed in this paper are given certain objectives to accomplish. There are basically three different objectives defined in this thesis where each objective specifies a different policy of market operation. The first objective that agents may be tasked to perform is to maximize DG surplus. Agents tasked with this objective aim at maximizing the profit of generation agents which participate in the trading process. Generation agents can either sell their energy to load agents or the utility grid depending on the MCP derived in (4.3) or the grid buyback price. Figure 4-3 illustrates the generation bidding curve for a DG where the corresponding parameters are previously defined.

Figure 4-3: Generation bidding curve

Based on Figure 4-3, the profit for each generation agent is expressed as:

$$\begin{aligned} \text{Profit}_{Gi} &= \text{Revenue} - \text{Generation cost} \\ &= [P_{Gi,exchange} * C_{BB,Grid} + P_{Gi,\mu grid} * LMP] - [0.5 * P_{Gi,sch} * \lambda_{ref}] \end{aligned} \quad (4.25)$$

where $C_{BB,Grid}$ is the grid buyback price for the power injected back into the utility grid; $P_{Gi,exchange}$ is the power flow exchange between the utility grid and the i^{th} DG; $P_{Gi,\mu grid}$ is the power sold to the microgrid load; and $P_{Gi,sch}$ is the total scheduled power sold to the microgrid load and the utility grid.

Similarly, the second objective is to maximize load surplus. Agents under this objective aim at maximizing savings for the load which also implies minimizing the load cost for each load agent. Load agents can either buy energy from the generation agent or directly from the utility grid depending on energy prices during trading. Figure 4-4 illustrates the

demand bidding curve for a load where the corresponding parameters are also previously defined.

Figure 4-4: Demand bidding curve

Based on Figure 4-4, the load saving for each load agent can be expressed as:

$$\begin{aligned} \text{Save}_{Dj} &= \text{Load cost} - \text{Amount payable} \\ &= 0.5 * P_{Dj,sch} (\lambda_{ref} + c_{oD,j}) - [P_{Dj,grid} * c_{RP,grid} + P_{Dj,\mu grid} * LMP] \end{aligned} \quad (4.26)$$

where $P_{Dj,sch}$ is the total scheduled power bought from generation agents and the utility grid by the j^{th} load agent; $c_{RP,grid}$ is the retail price offered by the utility grid; $P_{Dj,grid}$ is the amount of power bought from the utility grid; and $P_{Dj,\mu grid}$ is the amount of the power bought from generation agents.

Consequently, the third objective is to maximize both DG and load surplus simultaneously which is the combination of (4.25) and (4.26). In (4.25), the maximization of DG surplus focuses mainly on the generation agents such that it also maximizes load costs at the same time. Similarly, (4.26) focuses mainly on load agents such that it minimizes DG profits at the same time. Therefore, the third objective aims at maximizing both the generation and load agent surplus simultaneously.

4.3 Proposed Multi Agent Platform for Microgrids

The proposed MAS approach for simulating market environment as well as the simulated response of DERs is shown in Figure 4-5. The developed multi agent and coordination

system operates in compliance with IEEE FIPA specifications [118]. Market and control operations were implemented in JADE and the coordination layer between Simulink models and agents were implemented in MACSimJX which uses TCP/IP protocol and windows pipe for its communication channels.

JADE was used for multi agent implementation because it has an agent platform that complies with IEEE FIPA standards. It mainly consists of an AMS, a DF and a message transport system which is required under the FIPA specifications. In addition, JADE exhibits numerous inherent features found in distributed systems. Most of JADE's complexities are hidden from users enabling more focus on logical aspects of the system. Furthermore, JADE provides graphical interface for monitoring agents as well as an extensive library of classes with methods based on FIPA standards.

Figure 4-5: Schematic diagram of proposed multiagent system

Similarly, MACSimJX was used as the coordination layer because it specifically integrates Simulink with JADE and facilitates the development of software control structures with a range of features [127]. In addition, MACSimJX has a client-server architecture and has the capability of parallel processing information as well as handling multi threaded programs, a requirement for distributed systems.

4.3.1 Agents Developed in Proposed MAS Platform

Microgrid agents developed in the proposed MAS include generation (DG) agents, load (Demand) agents, market clearing engine (MCE) agent, coordination (CO) agent, utility

grid (UG) agent, and other ancillary agents. A brief description of the functionalities for the main agents are given below.

- *DG Agent*: This agent models combined heat and power (CHP) units, dispatchable units which may include MTs, fuel cells and energy storage systems and non-dispatchable units which may include PVs and WTs as an aggregated equivalent DG unit under the same owner to participate in microgrid market operations through negotiations with Demand Agents. It also regulates and controls output power and status of DG units. Information contained in this agent includes an agent identifier, minimum and maximum generation limits and dynamic data such as bidding rate, generation settings, revenue and DG surplus. This agent have the basic functionalities similar to the Generation Agent (GA) designed in Chapter 3 with the exception that the algorithm used during scheduling and trading differs because LMP and load participation in the market were considered in this Chapter.
- *Demand Agent*: This agent models an aggregated equivalent load unit under the same consumer to participate in market operations through negotiations with DG Agents. It is also capable of regulating and controlling the power demand and status of the respective load units based on energy prices. Information residing in this agent includes an agent identifier, minimum and maximum demand limits and dynamic data such as bidding rate, power demand settings, load costs and savings. This agent retains the basic functionalities similar to the Load Agent (LA) designed in Chapter 3 with the exception that the algorithm used for scheduling and trading differs because the market participation of the loads are considered in this Chapter.
- *MCE Agent*: This agent becomes active if the MCP computation of the microgrid is required for a specified period. It takes in bids from DG and Demand Agents and liaises with CO Agent during market operations. Furthermore, it contains aggregated information on microgrid generation and demand levels. This agent have similar functions compared to the Price Agent (PA) designed in Chapter 3 with the exception that it will consider the bidding rate of the loads when

computing the MCP.

- *CO Agent*: This agent is responsible for coordinating the entire microgrid market operation as well as monitoring the network for any technical violations. It coordinates with MACSimJX Agent to signal the beginning and end of market operations for that period.
- *UG Agent*: The utility grid agent basically behaves similar to an Independent System Operator (ISO) and is responsible for power balance in the microgrid. It also broadcasts retail price signals to DG and Demand Agents at regular intervals to facilitate decision making in the corresponding agents.
- *MACSimJX Agent*: This agent basically performs coordination between Simulink and JADE as well as manages an Agent Task Force (ATF) which consists of several ancillary agents to transmit simulink data to the CO, DG and Demand Agents. These ancillary agents are the counterparts of the CO, DG and Demand Agents that are represented in the ATF to transmit information to/from Simulink. In addition, an Agent Environment (AE) residing within this agent also acts as an interface for coordinating control signals between Simulink and JADE.

4.3.2 Agents Interaction and Coordination

A hierarchical control architecture [50, 51] is used for the simulation of microgrid operation. The entire microgrid market operation and simulation are achieved by distributing responsibilities to the various agents. Agents accomplish assigned tasks by proactively interacting among themselves as shown in Figure 4-6. Generally, a typical electricity market operation consists of a pre-gate and gate closure period. The gate closure period occurs, say about an hour before the actual energy delivery time while the pre-gate period occurs a few hours before the gate closure period. The pre-gate period is the time when DGs and loads enter into negotiations to sell or buy a given quantity of electricity at an agreed price. The gate closure period is the time when DGs and loads stop negotiating and power balancing is executed to ensure that DGs and loads whose generation or load demand are still not satisfied after negotiations have been balanced. Similarly, the proposed market operation in this simulation study also adopts the pre-gate and gate

closure periods. Referring to Figure 4-6, steps 1 to 7 are executed a few hours before gate closure which indicates the beginning of the pre-gate period. Steps 8 to 10 are only executed after gate closure, say about an hour before the actual energy delivery when the utility agent performs power balance on the microgrid. Therefore, they define the pre-gate and gate closure periods typical in electricity markets.

During initialization, AE will instruct ATF to inform CO Agent to begin market operation. MCE Agent then requests DG and Demand Agents to supply bidding data as well as grid pricing data. Once all bids have been received, MCE Agent then computes MCP and informs relevant agents about the results. Every DG and every Demand Agent then perform an internal scheduling and concurrently check for any technical violations with their ATF counterparts. The energy trading which solves a symmetrical assignment problem [74] between DG and Demand Agents will commence after all technical violations have been resolved. DG and Demand Agents will aim at achieving a certain objective based on one of the three agent objectives assigned as described in Section 4.2.4.

Figure 4-6: Interaction between agents for market operation and implementation

Under maximizing DG surplus objective, DG Agents will search through DF and negotiate with every Demand Agent and UG Agent to sell their energy at the highest offered price. Similarly for maximizing load surplus objective, Demand Agents will search through DF and negotiate with every DG Agent and UG Agent to buy energy at the lowest offered

price. For maximizing both the DG and load surplus objective, DG Agents, Demand Agents and UG Agent will negotiate among themselves to arrive at a common price that benefits both DG and Demand Agents. UG Agent then performs power balance for the microgrid whose generation or load is still not satisfied after negotiations by either buying back the excess power from DG Agents or selling power to Demand Agents. Market operation ends when DG and Demand Agents inform CO Agent about the trading results and the updated dispatch will be passed on to ATF and AE for implementation in Simulink.

In the event that there is no final agreement or communication loss with the utility grid agent, DG and load agents will have to accept whatever offer made earlier by the utility grid agent in order to finalize the trading results. In the unlikely scenario in which all possible communication links including manual communications via telephones are lost, the microgrid will have to perform an internal power balance based on whatever offers agreed earlier. This means that DGs and loads whose generation and load demand are still not satisfied after negotiations will have to adjust their active power setpoints and curtail load demand respectively until the microgrid supply and demand is balanced. In such situations, it is assumed that the load agents may have their own generation to meet their supply shortfall or they can afford to wait for cheaper electricity at a later time. In addition, the algorithm can be executed at sub-hourly intervals by programming the agent environment (AE) and agent task force (ATF) in Figure 4-6 to initiate the algorithm more frequently. This could help the system be more responsive to the uncertainty in non-dispatchable DG production and dynamic load changes.

4.4 Simulation Studies and Results

4.4.1 7-Bus Microgrid System

Simulation studies were carried out on a three-phase, seven-bus, 400V grid-connected microgrid. The microgrid consisting of three equivalent DGs, three dynamic equivalent loads and a utility grid power source was modeled in Simulink. An equivalent single-line diagram is shown in Figure 4-7. Details on network parameters and the number of DGs and loads in each equivalent DG and load are given in Table 4-1 and Table 4-2. This setup considers a scenario with three DG owners and three load users that serve as a building

block for a larger dynamic power system.

In this setup, equivalent DGs and loads ranging from 0.75MW to 3.5MW were connected to the microgrid. Each equivalent DG consists of dispatchable and non-dispatchable units having various sizes. The minimum DG power represents the situation when cogeneration units are programmed to provide minimum heating requirements to the local community. It is the sum of all minimum power requirements of the cogeneration units and minimum power of any on-line units with similar physical constraints under the corresponding DG owner. Conversely, the maximum DG power is the sum of rated power of all units when all units under the respective DG owner participate in market operations. Local voltage regulating devices are placed at load buses to improve the load voltage profile when necessary. Network parameters were taken from a typical low voltage distribution network. The no-load price in Table 4-2 refers to the price intercept for the corresponding loads as described in (4.1). The utility grid acts as a power balancing source to maintain power balance in the microgrid during normal operations.

Figure 4-7: Single-line diagram of microgrid in Simulink

Table 4-1: 7-bus microgrid network parameters

Line number	From bus	To bus	Resistance (Ω/phase)	Reactance (Ω/phase)
1	1	2	1	1.571
2	1	4	2	1.885
3	1	6	3	2.2
4	2	3	0.205	1.477
5	4	5	0.205	1.477
6	6	7	0.205	1.477

Table 4-2: Details of distributed generators and loads

UNIT TYPE	SIMULINK MODEL	NUMBER OF UNITS	MIN. POWER (MW)	MAX. POWER (MW)	NO-LOAD PRICE (\$/MWh)
DG 1	Power Converter	400	1	2.75	-
DG 2	Synchronous Generator	700	2	3.25	-
DG 3	Synchronous Generator	550	1.5	3	-
Load 1	Dynamic Load	300	2	3.5	0.8
Load 2	Dynamic Load	250	1	3	0.7
Load 3	Dynamic Load	100	0.75	2.5	0.6

4.4.1.1 Power Converter Model

The Simulink model of the power converter used by DG 1 is shown in Figure 4-8. It is basically a three-phase switch-based inverter from the SimPowerSystems library where V_{DC} is the input DC voltage. S1, S2, S3, S4, S5 and S6 are switches which perform the inverter switching based on the pulse width modulation (PWM) signals generated from the inverter's controller. V_a , V_b and V_c are the three-phase output voltages of the inverter which is connected to the microgrid.

Figure 4-8: Three-phase power converter model

As mentioned previously, the PWM switch signals for the inverter is generated from the controller of the power converter and the block diagram of the controller is shown in Figure 4-9. In this figure, there are several functional blocks which include the real power controller, reactive power controller, space vector to ABC and the inner current and voltage control loops [140].

The real power controller block receives the reference frequency, W_{ref} and the active power output of converter, P_{abc} as inputs and converts these parameters into the power angle, δ and frequency signal, ω . The reactive power controller block receives the reactive

power output of the converter, Q_{abc} and converts it into a voltage signal, V . Both δ and V are then passed to the space vector to ABC block which then converts the inputs into the three-phase voltage references $V_{a,ref}$, $V_{b,ref}$ and $V_{c,ref}$. The inner current and voltage control loops block subsequently uses the three-phase voltage references as well as the output converter voltage, V_{abc} and output converter current, I_{abc} in order to produce the necessary updated signals for the inverter via the PWM block.

Figure 4-9: Block diagram of controller for three-phase power converter

The real power controller model is shown in Figure 4-10. It basically compares the active power output of the converter with the active power reference and the result is passed through a gain, $K_{P,i}$ which is subsequently compared with the frequency reference to output the frequency signal and power angle via an integrator.

Figure 4-10: Real power controller

The reactive power controller model is shown in Figure 4-11. Similar to the real power controller, it compares the output reactive power of the converter with the reference and is then passed through a proportional integral (PI) controller. The result is subsequently compared to the voltage reference to output the voltage signal.

Figure 4-11: Reactive power controller

The inner current and voltage control loops model is shown in Figure 4-12. The converter output voltage, $V_{conv,i}$ is compared with a voltage reference, $V_{ref,i}$ and the result is passed through a P+ resonant controller which has a transfer function of G_v . The equation describing the transfer function G_v is given below.

$$G_v = k_p + \frac{K_I s}{s^2 + \omega_0^2} \quad (4.27)$$

The output of the P+ resonant controller is essentially the current reference. It is then compared with the converter output current, $I_{conv,i}$ and is then passed through another gain, G_i . The equation describing the gain G_i is given below.

$$G_i = k_i \quad (4.28)$$

After which, the controller signal is converted into a PWM switch signal for the inverter.

Figure 4-12: Inner voltage and current control loops

Finally, the simulation parameters for DG 1 are shown in Table 4-3.

Table 4-3: Simulation parameters for DG 1

Simulation parameters		Values
DG 1	Switching frequency	10 kHz
	Filter inductance	4.7 mH
	Filter capacitance	5 μ F
	DC voltage	650 V
Controller Parameters	Frequency reference ω_{ref}	50 Hz
	Voltage reference V_{ref}	400 V
	Active power gain $K_{P,1}$	1/5000
	Voltage proportional gain k_p	0.1
	Voltage integral gain k_I	100
	Current gain k_I	0.1

4.4.1.2 Synchronous Generator Model

The Simulink model of the synchronous generator used by DG 2 and DG 3 is shown in Figure 4-13. This model takes in the mechanical power, P_m and field voltage, V_f as inputs and outputs a vector, m which comprise the output apparent power, active and reactive power, rotor mechanical angle, rotor speed and electromagnetic torque. The synchronous generator model output terminals A, B and C are connected to the microgrid to deliver the power generated by the synchronous generator.

Figure 4-13: Synchronous generator model in Simulink

The synchronous generator model also considers the dynamics of the stator, field and damper windings. The equivalent circuit is represented in the rotor reference frame i.e. dq frame as shown in Figure 4-14. The rotor parameters and electrical quantities are referred to the stator and are identified by primed variables.

Figure 4-14: Equivalent electrical model of synchronous generator

The subscripts used in the equivalent electrical model above are defined in the following:

- d, q – refers to the d and q axis
- R, s – refers to the rotor and stator
- l, m – refers to the leakage and magnetizing inductance
- f, k – refers to the field and damper winding

where

V_d and V_q refers to the d and q axis stator voltage; R_s is the stator resistance; L_l is the stator leakage inductance; ω_R is the rotor speed; ϕ_d and ϕ_q refers to the d and q axis flux; i_d and i_q refers to the d and q axis stator current; L_{md} and L_{mq} refers to the d and q axis magnetizing inductance viewed from stator; L'_{lkd} and L'_{lfd} refers to the d axis damper and field winding leakage inductance referred to stator; L'_{lkq1} and L'_{lkq2} refers to the q axis damper and round rotor winding leakage inductance referred to stator; R'_{kd} and R'_{fd} refers to the d axis damper and field winding resistance referred to stator; R'_{kq1} and R'_{kq2} refers to the q axis damper and round rotor winding resistance referred to stator; V'_{kd} and V'_{fd} refers to the d axis damper and field winding voltage referred to stator; V'_{kq1} and V'_{kq2} refers to the q axis damper and round rotor winding voltage referred to stator; i'_{kd} and i'_{fd} refers to the d axis damper and field winding current referred to stator; and i'_{kq1} and i'_{kq2} refers to the q axis damper and round rotor winding current referred to stator.

The set of equations describing the equivalent electrical model are as follows:

$$\begin{aligned}
 V_d &= R_s i_d + \frac{d}{dt} \varphi_d - \omega_R \varphi_q \\
 V_q &= R_s i_q + \frac{d}{dt} \varphi_q + \omega_R \varphi_d \\
 V'_{fd} &= R'_{fd} i'_{fd} + \frac{d}{dt} \varphi'_{fd} \\
 V'_{kd} &= R'_{kd} i'_{kd} + \frac{d}{dt} \varphi'_{kd} \\
 V'_{kq1} &= R'_{kq1} i'_{kq1} + \frac{d}{dt} \varphi'_{kq1} \\
 V'_{kq2} &= R'_{kq2} i'_{kq2} + \frac{d}{dt} \varphi'_{kq2}
 \end{aligned}
 \quad
 \begin{aligned}
 \varphi_d &= L_d i_d + L_{md} (i'_{fd} + i'_{kd}) \\
 \varphi_q &= L_q i_q + L_{mq} i'_{kq} \\
 \varphi'_{fd} &= L'_{fd} i'_{fd} + L_{md} (i_d + i'_{kd}) \\
 \varphi'_{kd} &= L'_{kd} i'_{kd} + L_{md} (i_d + i'_{fd}) \\
 \varphi'_{kq1} &= L'_{kq1} i'_{kq1} + L_{mq} i_q \\
 \varphi'_{kq2} &= L'_{kq2} i'_{kq2} + L_{mq} i_q
 \end{aligned}
 \tag{4.29}$$

From the above equations, it can be seen that the electrical part of the synchronous generator model is represented by a sixth-order state-space model. In addition, the mechanical system of the synchronous generator model is shown in Figure 4-15 and the equations are described in (4.30). Furthermore, the simulation parameters for DG 2 and DG 3 used in the simulation studies are shown in Table 4-4.

Figure 4-15: Mechanical system of synchronous generator model

$$\begin{aligned}
 \Delta\omega(t) &= \frac{1}{2H} \int_0^t (T_m - T_e) dt - K_d \Delta\omega(t) \\
 \omega(t) &= \Delta\omega(t) + \omega_0
 \end{aligned}
 \tag{4.30}$$

where

$\Delta\omega(t)$ is the speed deviation with respect to speed of operation; H is the inertia constant; T_m is the mechanical torque; T_e is the electromagnetic torque; K_d is the damping factor of

the damper windings; $\omega(t)$ is the mechanical speed of rotor and ω_0 is the speed of operation.

Table 4-4: Simulation parameters for DG 2 and DG 3

Simulation parameters		Values
DG 2	Initial field voltage V_f	9.94866 V
	Nominal frequency f_n	50 Hz
	Stator resistance R_s	$0.26 \times 10^{-6} \Omega$
	Stator leakage inductance L_l	0.114 mH
	Stator d-axis magnetizing inductance L_{md}	13.7 mH
	Stator q-axis magnetizing inductance L_{mq}	11 mH
	Field resistance R_f	0.13 Ω
	Field leakage inductance $L_{lfd'}$	2.1 mH
	Damper d-axis resistance $R_{kd'}$	$0.224 \times 10^{-7} \Omega$
	Damper d-axis leakage inductance $L_{lkd'}$	0.1 mH
	Damper q-axis resistance $R_{kq1'}$	0.02 Ω
	Damper q-axis leakage inductance $L_{lkq1'}$	1 mH
	Inertia	75 kgm^2
	Friction factor	0 Nms
	Pole pairs	4
DG 3	Initial field voltage V_f	10.0537 V
	Nominal frequency f_n	50 Hz
	Stator resistance R_s	$0.26 \times 10^{-6} \Omega$
	Stator leakage inductance L_l	0.114 mH
	Stator d-axis magnetizing inductance L_{md}	13.7 mH
	Stator q-axis magnetizing inductance L_{mq}	11 mH
	Field resistance R_f	0.13 Ω
	Field leakage inductance $L_{lfd'}$	2.1 mH
	Damper d-axis resistance $R_{kd'}$	$0.224 \times 10^{-7} \Omega$
	Damper d-axis leakage inductance $L_{lkd'}$	0.1 mH
	Damper q-axis resistance $R_{kq1'}$	0.02 Ω
	Damper q-axis leakage inductance $L_{lkq1'}$	1 mH
	Inertia	100 kgm^2
	Friction factor	0 Nms
	Pole pairs	4

4.4.1.3 Load Model

The Simulink model of the load used by Load 1, Load 2 and Load 3 is shown in Figure 4-16. The model basically represents a three-phase dynamic load whose active power and reactive power vary as a function of positive-sequence voltage. The inputs to this model are PQ (a vector containing the active power and reactive power setpoints) and the input

terminals A, B and C which are connected to the microgrid. The output of this model is a vector, m which contains the positive-sequence voltage, active power and reactive power measurements of the load model.

Figure 4-16: Three-phase dynamic load in Simulink

The load impedance is maintained constant if the load terminal voltage is lower than a minimum specified value, $V_{\min}$. When the load terminal voltage is greater than $V_{\min}$, the active power and reactive power of the load vary according to the following equations.

$$\begin{aligned} P(s) &= P_o \left(\frac{V}{V_o} \right)^{n_p} \frac{(1 + sT_{p1})}{(1 + sT_{p2})} \\ Q(s) &= Q_o \left(\frac{V}{V_o} \right)^{n_p} \frac{(1 + sT_{q1})}{(1 + sT_{q2})} \end{aligned} \quad (4.31)$$

where

V_o is the initial positive-sequence voltage; P_o and Q_o are the initial active and reactive power at initial voltage, V_o ; V is the positive-sequence voltage; n_p and n_q are exponents which control the nature of the load; T_{p1} and T_{p2} are time constants controlling the dynamics of the active power P , and T_{q1} and T_{q2} are time constants controlling the dynamics of the reactive power Q .

4.4.1.4 Simulation Results

Simulation studies for a typical day were carried out. The 24-hour bidding rates for DGs and loads are given in Table 4-5. The results of market clearing prices and grid prices [141] for a typical day are shown in Figure 4-17. High grid prices are observed between 0800h to 1600h which also coincide with the peak hours of a study day. Bidding patterns

of DGs and loads also follow grid pricing trend which result in MCP having a similar price trend during the same period.

Table 4-5: Bidding rates (m_G , m_D in \$/MWh/MW) over 24-hour period

Hour	DG 1	DG 2	DG 3	LOAD 1	LOAD 2	LOAD 3
1	0.3125	0.2734	0.2482	0.221	0.152	0.106
2	0.2864	0.2549	0.2019	0.265	0.196	0.157
3	0.2489	0.1986	0.1917	0.288	0.225	0.175
4	0.2168	0.1662	0.1529	0.325	0.269	0.229
5	0.2259	0.1827	0.1717	0.311	0.254	0.205
6	0.2341	0.1955	0.1875	0.292	0.249	0.194
7	0.2626	0.2185	0.2089	0.277	0.201	0.167
8	0.2978	0.2637	0.2314	0.247	0.173	0.141
9	0.1874	0.1596	0.1545	0.042	0.033	0.014
10	0.2136	0.1775	0.1924	0.118	0.081	0.055
11	0.2316	0.2072	0.1899	0.127	0.095	0.079
12	0.1956	0.1671	0.1717	0.092	0.077	0.047
13	0.1782	0.1419	0.1574	0.078	0.054	0.02
14	0.2121	0.1836	0.1985	0.115	0.085	0.056
15	0.2015	0.1735	0.1833	0.101	0.091	0.064
16	0.2584	0.2263	0.2044	0.172	0.151	0.123
17	0.2252	0.1989	0.1822	0.188	0.141	0.13
18	0.2445	0.2112	0.1984	0.166	0.141	0.112
19	0.1928	0.1731	0.1631	0.112	0.104	0.096
20	0.2147	0.1884	0.1726	0.141	0.122	0.132
21	0.2033	0.1798	0.1677	0.124	0.113	0.105
22	0.2626	0.2332	0.1988	0.277	0.175	0.146
23	0.2594	0.2461	0.2144	0.281	0.195	0.189
24	0.2911	0.2679	0.2338	0.255	0.188	0.138

Figure 4-18 shows the simulation results of DG scheduling and power supplied by the utility grid for the same study day. Between 0000h to 0800h and 2100h to 2400h, DG 2 was scheduled to generate 2MW. At 0800h and 1200h, DG 2 was scheduled at 3.25MW. Likewise, DG 1 and DG 3 were also scheduled accordingly. All DGs operate within the MW limits shown in Table 4-2. By observing the power generated from the utility grid at the various hourly intervals, the microgrid experiences different conditions during the study day. A slight variation in utility grid power is observed at each hour to maintain power balance in the microgrid except at 0800h when the microgrid has excess generation and exports 1MW back to the utility grid. At 0900h, the microgrid's generation and load demand are balanced resulting in no power exchange from the utility grid. At 2100h, the microgrid experiences a slight shortage in generation and imports about 0.07MW from the utility grid to maintain power balance. This shows that the power management by the agents is able to handle various microgrid conditions.

Figure 4-17: Grid and market clearing prices

Figure 4-18: Simulated DG scheduling

Figure 4-19 shows the outcome of load scheduling and system losses for the day. Between 0000h to 0800h and 2100h to 2400h, it is observed that Load 1 requires a constant 2MW which shows that the simulated load scheduling works as the minimum power for Load 1 has been reached. Similarly, Load 2 reaches maximum demand of 3MW at 0800h and 1200h while Load 3 reaches peak demand of 2.5MW at 1200h. The first system load peak occurs from 0800h to 1500h. Its peak behaviors coincide with peak DG generation and high grid retail price in Figure 4-18 and Figure 4-17 respectively. The second load peak occurs from 1800h to 2100h whose behaviors coincide with the second DG generation peak but at a lower grid retail price. The total system power losses remain around 0.1MW

throughout the day and account for approximately 3% of the total load demand. Details of hourly DG and load dispatch, marginal loss factors and LMPs for the 7-bus microgrid system can also be found in Appendix C.

Figure 4-19: Simulated load scheduling and system losses

From Figure 4-19, it is observed that there is a sudden drop in load demand at the beginning of 1500h since the market clearing engine is assumed to clear once for each hourly interval. In reality, the real-time load will change gradually over the entire hour and the load increment/decrement will not be so sudden and huge. The DGs respond to the sudden load drop by adjusting their active power reference settings accordingly. Based on Figure 4-19, DG 1 changes its production from 2.35MW to 1.62MW while DG 2 changes from 2.73MW to 2MW and DG 3 changes from 2.59MW to 2.05MW to accommodate the change in load at 1500h. DG 1 is modeled as an equivalent power electronics generator in this simulation. From Figure 4-20, DG 1 generates 2.35MW in the previous hour until at 1500h. Its generation decreases to 1.65MW within 0.5 seconds to meet the new operating condition. This shows the fast response of the DG for dynamic microgrid operation.

Figure 4-20: DG 1 active power response during 1500h

Figure 4-21: DG 2 active power response during 1500h

Figure 4-22: DG 3 active power response during 1500h

The waveforms in Figure 4-21 and Figure 4-22 show the active power response for DG 2 and DG 3 respectively. In this simulation study, DG 2 and DG 3 are modeled as an equivalent conventional synchronous generator. From Figure 4-21, DG 2 generates 2.733MW in the previous hour until 1500h. At 1500h, its generation gradually decreases to 2MW within 10 seconds to meet the new operating condition. Similarly in Figure 4-22,

DG 3 generates 2.59MW in the previous hour until 1500h. At 1500h, its generation decreases to 2.05MW within 12 seconds to meet the new operating condition. Based on the observations, it is clear that a conventional synchronous generator requires a longer time to reach its new steady state condition compared to that of the power electronics converter based DG 1. This is due to the different characteristics of the synchronous generator and the power converter based DG. The synchronous generator has a large rotating inertia constituting a slower response time while the power converter based DG consists of fast-acting power electronics which can respond to system changes at a much faster rate.

In Figure 4-23, it is observed that the per unit voltage at Load 1 terminal at 1500h rises momentarily by about 0.6% to 1.006 p.u. during the first 0.04 seconds before settling down at about 1 p.u. after 0.2 seconds. The voltage rise is attributed to the sudden drop in load demand while the system takes some time for the dynamics to settle down before it reaches a new steady-state operating condition. During transition, a brief period of excess generation causes the load terminal voltage to rise momentarily. The afterwards effect on voltage is regulated at 1 p.u. which is maintained by a 13.5 kvar local capacitor bank.

The waveforms shown in Figure 4-24 and Figure 4-25 represent the per unit voltage at the terminals of Load 2 and Load 3 respectively. In Figure 4-24, it is observed that per unit voltage at Load 2 terminal at 1500h initially rises to 1.003 p.u. and oscillates for 10 seconds before settling down at 1 p.u. Similarly in Figure 4-25, it is observed that the initial per unit voltage at Load 3 terminal at 1500h increases to 1.002 p.u. and then oscillates for about 12 seconds before settling down at 1 p.u. In both figures, the voltage transients seen at Load 2 and Load 3 terminals are basically due to the hourly change in operating conditions of the DGs and loads. The afterwards effect on voltage is also regulated at 1 p.u. by a 4.5 kvar local capacitor bank each at Load 2 and Load 3.

Figure 4-23: Load 1 per unit voltage profile during 1500h

Figure 4-24: Load 2 per unit voltage profile during 1500h

Figure 4-25: Load 3 per unit voltage profile during 1500h

Comparisons of the DGs profit under different agent objectives are given in Figure 4-26, Figure 4-27 and Figure 4-28. Figure 4-26 shows a snapshot of DG 1 profits for different agent objectives in the same study day. A base objective where agents trade directly with the utility grid and do not participate in the microgrid market operations is used for comparison. It is observed from Figure 4-17 that during periods where MCP is below the grid retail price, DG 1 agent reports similar profits when assigned under the agent maximization objectives. However, during periods where MCP is above the grid retail price, DG 1 agent reports varying profit levels when assigned different agent objectives. In addition, DG 1 agent reports negative profits during certain periods when assigned the load surplus maximization or base objective indicating that the generation cost is higher than the revenue. This shows that the grid price can affect DG profits. Similar observations are also seen in DG 2 and DG 3 and the same reasoning applies to these DGs.

Figure 4-26: DG 1 profits with different agent objectives over a study day

Figure 4-27: DG 2 profits with different agent objectives over a study day

Figure 4-28: DG 3 profits with different agent objectives over a study day

Similarly, the load savings for the loads under different agent objectives are shown in Figure 4-29, Figure 4-30 and Figure 4-31. Figure 4-29 shows a snapshot of Load 1 savings when subjected to different agent objectives for the same study day. Load 1 agent reports similar savings whenever MCP is below grid retail price and varying level of savings when MCP is higher than the grid retail price. Load 1 agent also reports negative savings between 0800h and 1400h when the agent was assigned the base objective. Referring to Figure 4-17, the negative savings are attributed to high grid retail prices during the same period which results in a higher amount payable by Load 1 as compared to the load cost. Similar observations are also seen in Load 2 and Load 3. However, it is interesting to note that Load 3 records a negative saving at 0800h for every agent objective. This means that the energy price during that period is high enough such that the amount payable by Load 3 is higher than its load cost. This explains the negative load saving for Load 3 during 0800h.

Figure 4-29: Load 1 savings with different agent objectives over a study day

Figure 4-30: Load 2 savings with different agent objectives over a study day

Figure 4-31: Load 3 savings with different agent objectives over a study day

Numerical results for DG revenues and profits as well as load costs and savings over a 24-hour period are given in Table 4-6 and Table 4-7. Table 4-6 shows the revenue and profit for each DG as well as the aggregated amount. In general, DG agents have a better profit when agents are assigned optimization objectives compared to the base objective. Although maximizing DG surplus yields the highest profit, load savings are minimized simultaneously. This shows that maximizing DG surplus favors the generation side and likewise maximizing load surplus favors the load side. However, DG agents assigned to maximizing the DG and load surplus objective yield optimal profits which maximize both the DG profits and load savings simultaneously. It is also observed that the profit of DG 2 is negative under the base objective. This indicates that DG 2 has accumulated a net negative profit of $-\$0.82$ over the 24-hour period which is due to a higher generation cost compared to the revenue collected.

Table 4-7 shows the load costs and savings for each load agent under different agent objectives. It is observed that load agents assigned to maximizing the DG and load surpluses yield optimal savings. In addition, load savings are significantly higher when load agents are assigned the optimization objectives compared to those of the base objective. Load 3 has negative savings under the base objective indicating that the amount payable by Load 3 is higher than the load cost. Since Load 1 reports the highest savings under the base objective, the total load savings for the microgrid remains positive despite negative savings from Load 3.

Table 4-6: Distributed generators revenue and profit over 24-hour period

UNIT TYPE	MAX. LOAD SURPLUS		MAX. DG SURPLUS		MAX DG AND LOAD SURPLUS		BASE OBJECTIVE	
	REVENUE (\$)	PROFIT (\$)	REVENUE (\$)	PROFIT (\$)	REVENUE (\$)	PROFIT (\$)	REVENUE (\$)	PROFIT (\$)
DG 1	16.45	7.24	18.74	9.53	17.60	8.39	9.69	0.48
DG 2	19.43	6.85	22.45	9.87	20.94	8.36	11.76	-0.82
DG 3	18.63	7.73	21.41	10.51	20.02	9.12	11.14	0.25
Total	54.51	21.82	62.60	29.91	58.56	25.87	32.59	-0.09

Table 4-7: Load energy costs and savings over 24-hour period

LOAD TYPE	MAX. LOAD SURPLUS		MAX. DG SURPLUS		MAX DG AND LOAD SURPLUS		BASE OBJECTIVE	
	COSTS (\$)	SAVINGS (\$)	COSTS (\$)	SAVINGS (\$)	COSTS (\$)	SAVINGS (\$)	COSTS (\$)	SAVINGS (\$)
Load 1	23.91	11.36	25.07	10.19	24.49	10.77	31.24	4.02
Load 2	20.83	7.67	21.81	6.69	21.32	7.18	27.32	1.18
Load 3	16.39	3.81	17.17	3.02	16.78	3.41	21.26	-1.07
Total	61.13	22.84	64.05	19.90	62.59	21.36	79.82	4.13

From the results in Table 4-6 and Table 4-7, it is evident that maximizing both DG and load surplus objective provides optimal benefits to both the DGs and the loads and is not biased to either side. Similar trends are also observed for each hour during the study day. During each hourly interval, DG and Demand Agents coordinate and trade according to assigned agent objectives. At the end of each trading session, the UG Agent maintains power balance by accepting all sale requests from DG agents which have excess generation and accepting all purchase requests from Demand Agents which have unsatisfied load. This shows the effectiveness of agents in handling various conditions.

4.4.2 Extended Analysis on IEEE 14-Bus Test System

The proposed approach is further tested on a modified IEEE 14-bus test system [139] which is shown in Figure 4-32. In this system, there is one utility grid generator, four DGs and eleven loads. The utility grid generator is located at bus 1 which is also the reference bus. The four DGs are located at buses 2, 3, 4 and 12. The eleven loads are located at buses 2, 3, 4, 5, 6, 9, 10, 11, 12, 13 and 14.

Figure 4-32: IEEE 14-bus power system

The utility grid generator is represented by a UG Agent. Each DG is represented by a DG agent and each load by a Demand Agent. Generator and load data is obtained from [139]. The line parameters are obtained from the IEEE 14-bus test system [142] which is shown in Table 4-8. More details of hourly load and generation data, hourly load and DG bidding rates, DG and load dispatch, marginal loss factors and LMPs for the IEEE 14-bus test system can be found in Appendix D.

Table 4-8: IEEE 14-bus power system line parameters

Line number	From bus	To bus	Resistance (p.u.)	Reactance (p.u.)
1	1	2	0.01938	0.05917
2	1	5	0.05403	0.22304
3	2	3	0.04699	0.19797
4	2	4	0.05811	0.17632
5	2	5	0.05695	0.17388
6	3	4	0.06701	0.17103
7	4	5	0.01335	0.04211
8	4	7	0	0.20912
9	4	9	0	0.55618
10	5	6	0	0.25202
11	6	11	0.09498	0.1989
12	6	12	0.12291	0.25581
13	6	13	0.06615	0.13027
14	7	8	0	0.17615
15	7	9	0	0.11001
16	9	10	0.03181	0.0845
17	9	14	0.12711	0.27038
18	10	11	0.08205	0.19207
19	12	13	0.22092	0.19988
20	13	14	0.17093	0.34802

There are four DG Agents and eleven Demand Agents in the 14-bus test system. The dispatched power, marginal loss factor values, LMP and MCP for DG at bus 3 and load at bus 9 over a 24-hour period are shown in Table 4-9. The results of the other buses can be found in Appendix D. It can be observed that the LMP values differ slightly from MCP due to the contribution of marginal loss factors. Positive marginal loss factor values indicate that the change in power injection at the corresponding bus results in an increase of system losses while negative values indicate a reduction of system losses due to a change in power injection at the bus. Based on the values obtained, DGs will fetch a higher price for positive marginal loss factor and will fetch a lower price for negative values. Conversely, loads will be penalized for positive marginal loss factors and rewarded for negative values according to (4.8) when the energy trading algorithm is executed.

Table 4-9: Results of DG and Load for 14-Bus system over 24-hour period

HOUR	DG AT BUS 3			LOAD AT BUS 9			MCP (\$/MWH)
	POWER (MW)	MARGINAL LOSS FACTOR	LMP (\$/MWH)	POWER (MW)	MARGINAL LOSS FACTOR	LMP (\$/MWH)	
1	0.468	0.0249	0.45	0.295	-0.0091	0.44	0.44
2	0.415	0.0293	0.44	0.285	-0.0011	0.43	0.43
3	0.377	0.0239	0.43	0.272	-0.0038	0.42	0.42
4	0.320	0.0275	0.41	0.258	-0.0128	0.39	0.40
5	0.488	0.0248	0.44	0.272	-0.0136	0.42	0.43
6	0.431	0.0324	0.50	0.286	-0.0002	0.48	0.48
7	0.667	0.0207	0.60	0.340	-0.0114	0.58	0.59
8	0.365	0.0362	0.62	0.381	0.0040	0.60	0.60
9	0.524	0.0361	0.65	0.408	0.0063	0.63	0.63
10	0.778	0.0383	0.67	0.476	0.0010	0.65	0.65
11	0.958	0.0435	0.69	0.517	0.0084	0.67	0.66
12	1.079	0.0447	0.71	0.544	0.0143	0.69	0.68
13	0.895	0.0411	0.67	0.530	0.0114	0.65	0.64
14	0.956	0.0362	0.65	0.530	0.0052	0.63	0.63
15	0.889	0.0352	0.63	0.517	0.0084	0.62	0.61
16	0.778	0.0395	0.61	0.476	-0.0004	0.59	0.59
17	0.889	0.0324	0.67	0.517	-0.0020	0.65	0.65
18	0.817	0.0437	0.71	0.585	0.0047	0.68	0.68
19	0.556	0.0508	0.67	0.558	0.0102	0.65	0.64
20	0.444	0.0535	0.65	0.544	0.0109	0.63	0.62
21	0.333	0.0529	0.63	0.490	0.0096	0.61	0.60
22	0.222	0.0394	0.58	0.422	0.0004	0.56	0.56
23	0.419	0.0257	0.51	0.34	-0.0086	0.50	0.50
24	1.108	-0.0126	0.46	0.30	-0.0229	0.46	0.47

Market results for DG and Demand Agents for the 14-bus test system over a 24-hour period is shown in Table 4-10. Results of the maximization of DG and load surplus objective were compared with those of the base objective. There are no market results for the DG connected at bus 4 because it is the most expensive unit and did not participate in the market operation during the 24-hour period. From Table 4-10, it is observed that DGs yield higher profits and loads have higher savings when compared to those of the base objective. They follow the same trend as those of the 7-bus microgrid system.

Table 4-10: Market results for 14-bus system over 24-hour period

DG LOCATION	MAX DG AND LOAD SURPLUS		BASE OBJECTIVE	
	REVENUE (\$)	PROFIT (\$)	REVENUE (\$)	PROFIT (\$)
Bus 2	7.79	5.56	4.77	2.54
Bus 3	6.33	5.08	3.44	2.20
Bus 12	2.79	2.09	1.33	0.63
LOAD LOCATION	COSTS (\$)	SAVINGS (\$)	COSTS (\$)	SAVINGS (\$)
Bus 2	4.30	0.73	4.40	0.64
Bus 3	18.20	5.44	18.29	5.34
Bus 4	9.55	3.07	9.61	3.01
Bus 5	2.81	0.09	2.83	0.08
Bus 6	3.60	0.03	3.69	-0.05
Bus 9	5.91	0.84	6.01	0.74
Bus 10	3.06	0.11	3.13	0.04
Bus 11	2.15	0.07	2.17	0.06
Bus 12	2.58	0.06	2.62	0.03
Bus 13	1.94	0.12	1.98	0.08
Bus 14	5.49	0.90	5.51	0.87

4.5 Summary

This chapter presents a MAS approach for distributed management of microgrids. The proposed MAS was developed using IEEE FIPA standards, and market operations were coordinated with implementation of the microgrid. Simulation studies and results demonstrate the effectiveness of the proposed distributed market operation and control technique displaying much potential for the autonomous operation of microgrids. It is found that maximizing the benefit for both energy buyers and sellers promotes unbiased transactions among them. The proposed market structure can be extended to manage a larger network comprising numerous participants.

Furthermore, the proposed approach can be implemented in actual microgrids with minimal additional software cost by replacing the Simulink models with the actual microgrid and the communication network interface between MACSimJX and actual microgrids can be achieved through TCP/IP and the necessary SCADA I/O devices. Simulation studies have shown that the proposed distributed system is capable of handling the economical and technical requirements of microgrids.

In terms of hardware implementation costs, it should be noted that there are some differences between distributed and centralized operation. This comparison can be viewed in terms of the interfacing and communication infrastructure costs. For the proposed MAS approach, the associated hardware implementation costs which include the purchase of modbus to TCP/IP converters/switches, the setup of the Internet and its associated subscription costs are estimated to cost about US\$5,000 based on the 7-bus microgrid system. For centralized operation, the associated hardware implementation costs which include the leasing of dedicated communication links as well as the installation of communication wires for direct communication between these communication devices and SCADA are estimated to cost about US\$10,000 based on the 7-bus microgrid system. Note that the cost of leasing dedicated communication links would be much higher than the Internet subscription cost. Some price difference is expected between the different service plans offered by different telcos. Therefore in comparison, an estimated saving of about US\$5,000 can be achieved by adopting the distributed MAS approach based on the 7-bus microgrid system. Furthermore, this saving is scalable and more substantial in larger power systems which may comprise thousands of DGs and load agents.

CHAPTER 5 CONCLUSION AND FUTURE WORKS

5.1 Conclusion

In this section, the significance, objectives and outcomes of this research are summarized. This research discusses a distributed agent-based approach for the management of microgrids and how this could contribute to the growing needs of modern restructured power industry. It also explores the research of agent-based techniques in microgrids and how the proposed approach can be extended to various aspects of power system operations and the practical implications of adopting such an approach.

By utilizing agents to optimize the use of distributed power generation and load consumption, the microgrid may be able to make a significant contribution by attempting to reduce the energy prices and maximizing the welfare of every market participant. The key objective is to maximize the benefits of energy sellers and energy buyers in an unbiased manner. The distributed nature of agents provide great potential in the management of numerous DGs and loads and allowing them to be adequately represented and integrated into microgrids with minimal impact on the cost of communication infrastructure. In this way, it is expected that the distributed approach can overcome the limitations of centralized approach and can better handle microgrid operations when more DGs are expected to integrate with the existing networks in future.

To understand the characteristics and behavioral properties of agent-based systems, the concept of multi agent systems as well as the overall agent design and implementation are introduced in Chapter 2. The IEEE FIPA specifications are used to standardize the design and development of agents. JADE and MACSimJX have been identified as the most suitable agent implementation software due to its compliance with FIPA standards as well as their inherent advantage of shortening agent development time. The main objective is to lay a Java-based agent framework for microgrid-based power market which would allow an efficient distributed management of microgrids by maximizing the revenue of DGs while minimizing the load costs. More specifically, the proposed market clearing algorithm

which considers incremental losses as part of its process and defines various agent objectives is addressed in Chapter 4.

In Chapter 3, the design and development of customized agents for decentralized microgrid operation was presented. Agent simulation was performed on JADE to test the functionalities of the customized agents. These agents are programmed to consider the market clearing price, agent's objective and electrical distance between each other as part of the criteria to perform supply-demand matching and trading negotiations. Simulation results have shown that MAS can effectively manage DGs as well as consider energy prices for trading of energy within a microgrid.

In Chapter 4, a proposed microgrid market clearing technique and scheduling of DGs and loads were presented. Two types of market bidding methods were discussed and a double-side bidding which considers the submitted bids of DGs and loads was used in this thesis. Subsequently, the MCP was determined from the intersection of the aggregated supply curve and the aggregated demand curve. Next, the scheduling of each DG and load was determined based on the MCP with respect to their respective individual supply/demand curve. In addition, the LMP of each DG and load agent was considered. The loss sensitivity factor, which is part of the marginal loss component in LMP was computed by solving the inverse Jacobian matrix of the network using an IPM to obtain the phase angle and voltage magnitudes and these values were subsequently used in the loss sensitivity factor matrix. Furthermore, three different agent objectives were defined which basically instruct agents to either maximize DG surplus or maximize load surplus or a combination of both. The objectives of defining agent objectives is to analyze the effects of various agent strategies on the proposed microgrid market clearing technique and to determine an optimal strategy which benefits every market participant in the microgrid.

The proposed market structure was tested on a 7-bus microgrid power system in Chapter 4. In market operations, DGs and price-sensitive loads participate in a microgrid energy market implemented in JADE. Each DG and each price-sensitive load is represented by the corresponding agents which perform various functions such as scheduling, coordination and market clearing subject to system, DG and load constraints. Each agent is assigned to

one of the three agent objectives which maximizes either DG or load surpluses or both. In the simulated operation of a microgrid, hourly power reference signals and load control signals from JADE are passed on to DG and load models developed in MATLAB/Simulink using MACSimJX. Simulated operation and dynamics of DGs and loads are studied by performing simulations under different agent objectives. Simulation results show that maximizing both the DG and load surplus objective provides optimal benefits to both DGs and loads and is not biased to either side. Similar trends were also observed for each hour during the study day. In addition, no voltage instability was observed during the simulation. This shows that agents are able to handle the market requirements as well as satisfy the power requirements of the microgrid under various microgrid conditions.

To enhance the presentation of MCPs and marginal loss factor values, an extended microgrid analysis on MCPs and marginal loss factor values to verify the effectiveness of the proposed technique using a modified IEEE 14-bus test system is discussed in Chapter 4. Simulation results show that the agents developed in this thesis are performing as intended and are able to handle the market and power requirements of the microgrid. As expected, the LMP values differ slightly from MCP due to the contribution from marginal loss factors. Similarly, the maximization of DG and load surplus yields optimal benefits for both the DGs and the loads compared to the other agent objectives. They follow the same trend as those of the 7-bus microgrid power system. Therefore, it is found that maximizing the benefit for both the energy buyers and energy sellers promotes unbiased transactions between them. Simulation results of the IEEE 14-bus test system shows that the proposed market structure can also be extended to manage a larger power network comprising numerous participants.

5.2 Contribution of Thesis

Although many microgrid research activities involving MAS have been reported, no proper MAS platform was implemented via integration of microgrid market operations and DERs. The work reported in the literature specifically focuses on either intelligent market

auction algorithms or agent based DER implementations while coordinated actions between market operations and DER implementations in microgrids are seldom addressed. A Java-based multi agent framework is proposed in this thesis to integrate microgrid market operations and implementation of DERs using Simulink, Java agent development framework (JADE) [117] and multi agent control simulation Jade extension (MACSimJX) [127]. In addition, the design and development of customizable agents for microgrid applications are also investigated. The agents are successfully deployed into a simulated microgrid environment where various studies have been conducted to study the behavior, coordination and interaction of agents under different conditions.

The key intention in this thesis is to coordinate agent-based market activities with DER implementations through agent communications which are separately addressed in the literature. The work reported in the literature also assumes that the results from market auction can be readily implemented in real-time microgrids. This thesis illustrates the agents' capability of coordinating distributed market operations and implementation of the microgrid in a simulated real-time environment. Both the t-domain dynamics of MW generation and bus voltages as well as market clearing price for each hourly interval can be simulated. Furthermore, the developed multi agent system acts in accordance to the Foundation for Intelligent Physical Agents (FIPA) [118] specifications which provide the basic necessary standards for agent development and implementation.

Agents developed under this proposed framework are tasked to accomplish certain objectives in order to maximize the economical benefits of the microgrid. The proposed multi agent based system models a market scenario where each energy seller or each energy buyer is represented by an agent that aims to maximize the benefits according to the defined agent objectives while ensuring the smooth operation and proper execution of microgrid operations under the simulated real-time environment. Three different agent objectives are defined which maximize benefits of energy sellers and/or buyers through an energy trading algorithm which considers LMP as part of the trading process. In addition, each agent objective and the impact of microgrid loss factors are analyzed. Two functions for microgrid operations were also demonstrated which basically include price-driven

generation and demand scheduling and locational marginal pricing (LMP) [136, 143, 144] for various participants in a distributed microgrid energy market.

5.3 Recommendation for Future Works

The following recommendations discuss future research and development works which may provide additional insights into the application of MAS in the operation of microgrids.

- In this thesis, the discussion and analysis of simulation results serve as a preliminary step towards the design and hardware implementation of distributed agent-based management for the efficient operation of microgrids. The proposed MAS-based concept for distributed management of microgrids requires further verification through the study and analysis of an actual experimental setup. A 125kW microgrid has been constructed at NTU under the A*STAR Intelligent Energy Distribution System (IEDS) project initiatives and we plan to implement the proposed MAS-based approach in the NTU microgrid.
- There are also plans to study the application of MAS for the optimized operation of interconnected electrical power supply networks as well as the chemical process operations which load the networks under the Cambridge-NTU CREATE Interdisciplinary Research Group (IRG) project which has begun in January 2014. The main objective of this project is to reduce net energy consumption and/or carbon and pollutant emissions for an integrated system of chemical plant loads and the electrical supply network. Furthermore, it attempts to address issues arising from evolving electrical systems having active load management, DG penetrations at distribution level and demand response under unexpected peak demand conditions. In addition, detailed studies will also be conducted on a Jurong Island sub-network located in Singapore to address the growing demand and additional power flows arising from centrally operated co-generation facilities.
- Another future work is to extend the proposed MAS-based approach to ancillary services [100, 145, 146] for microgrids. More specifically, the market structure proposed in this thesis may be considered for frequency regulation in microgrids

[147, 148]. The objective of introducing frequency regulation markets in microgrids is to further reduce the dependency on utility grid for power balancing. Unlike traditional generators, the set points of power converter based DGs may be pulsed faster than one second. This may be beneficial in stabilizing the frequency in the microgrid. In addition, DGs may be able to further utilize any remaining available capacity to competitively bid in frequency regulation markets after the energy market has cleared. This can further maximize DG revenue and also help improve the overall power quality of the microgrid. In this way, microgrids can be more self-reliant and provide more economical benefits for the microgrid participants.

- The proposed MAS concept in this thesis considers the operation of a single microgrid. However, there are also other operational issues which need to be addressed when considering the coordination of multiple microgrids [97, 149]. Similar market mechanisms proposed in this thesis may be applied for multiple microgrids but further studies are required to verify their effectiveness. By considering the coordination of multiple microgrids, the research and development of larger power systems such as smart grids will be reinforced.
- In the simulation studies, the congestion component of the LMP was not considered as no congestion is assumed in the illustrated system. However in practical systems, the line capacity is considered to ensure that the power lines are not overload. Therefore, sensitivity analysis using simulation software such as the PowerWorld simulator could be done to include the congestion component in LMP and to analyze its effects on the agent behaviors in the proposed market structure.

APPENDIX A BASIC MICROGRID SYSTEM

Graphical User Interface (GUI)

The GAtemplate GUI window displays the following parameters and values:

Power Available for Sale (kW):	
Slope of incremental costs bid (\$/kWh/kW):	
Relative electrical position from PCC (km):	
Objective (0 - Max Microgrid Benefit, 1 - Max Profit):	
Seller Identifier:	GAtemplate@192.168.1.5:1099/JADE
Overall generation (kW):	50.0
Remaining available power (kW):	50.0
Incremental costs Slope:	0.1
Market Clearing Price (\$/kWh):	3.5
Grid Selling Price (\$/kWh):	3.5
Grid Buying Price (\$/kWh):	2.975
Microgrid operating mode:	GRID-CONNECTED
Distance from PCC (km):	3.0
This agent's objective:	Maximize microgrid benefit

Buttons at the bottom: Enter Data, Update Objective, Refresh, Cancel.

Figure A-1: Generation Agent GUI

The Loadtemplate GUI window displays the following parameters and values:

Enter load demand for purchase (kW):		Enter demand
Enter relative PCC position (km):		Enter Position
Negotiation status:	IDLE - No market participation.	
Market Clearing Price (\$/kWh):	3.5	
Agent Total Load (kW):	30.0	
Load satisfied (kW):	0.0	
Grid Selling Price (\$/kWh):	3.5	
Microgrid operating mode:	GRID-CONNECTED	
Distance from PCC (km):	5.0	

Buttons at the bottom: Refresh, Cancel.

Figure A-2: Load Agent GUI

SELLER IDENTIFIER	STATUS	BUYER IDENTIFIER	STATUS
GAtemplate@192.168.1.5:1099/JADE	Total: 50.0kW. Available: 50.0kW. Bid slope: 0.1. MCP: 3.5\$/kWh	Loadtemplate@192.168.1.5:1099/JADE	Load Demand: 30.0kW. Purchased: 0.0kW
GAtemplate3@192.168.1.5:1099/JADE	Total: 30.0kW. Available: 30.0kW. Bid slope: 0.3. MCP: 3.5\$/kWh	Loadtemplate2@192.168.1.5:1099/JADE	Load Demand: 60.0kW. Purchased: 0.0kW
GAtemplate2@192.168.1.5:1099/JADE	Total: 40.0kW. Available: 40.0kW. Bid slope: 0.2. MCP: 3.5\$/kWh		

Buttons at the bottom: Update, Refresh, Cancel.

Figure A-3: Monitor Agent GUI

Figure A-4: Grid Agent GUI

Figure A-5: Price Agent GUI

Figure A-6: Aggregate Agent GUI

Figure A-7: Control Agent GUI

Table A-1: GA and LA 24-hour dispatch

Time (hours)	P _{GA1} (kW)	P _{GA2} (kW)	P _{GA3} (kW)	P _{LA1} (kW)	P _{LA2} (kW)
0	5	15	20	50	65
1	10	25	40	32	56
2	8	12	30	25	40
3	15	28	31	33	52
4	11	22	25	30	49
5	2	10	12	22	31
6	7	14	18	15	26
7	5	11	14	12	30
8	12	24	27	29	39
9	18	30	33	42	30
10	20	32	44	45	44
11	15	18	50	41	32
12	9	14	55	34	30
13	13	19	52	37	41
14	17	30	59	28	60
15	11	33	50	20	54
16	18	22	53	21	48
17	10	39	58	26	70
18	18	34	37	39	50
19	11	32	47	48	42
20	8	22	54	43	41
21	5	26	56	49	38
22	10	32	34	36	40
23	7	34	39	24	56
24	12	19	25	21	35

Table A-2: MCP (\$) under different agent objectives

Time (hours)	MCP (No agent objective)	MCP (Maximization of load benefits objective)	MCP (Maximization of GA profits objective)
0	4.163	4	4
1	4.350	4	4
2	4.235	4	4
3	3.890	3.890	3.890
4	2.522	2.522	3.4
5	3.577	3.577	3.577
6	3.781	3.781	3.781
7	3.193	3.193	3.4
8	3.235	3.235	3.4
9	2.970	2.970	3.4
10	2.855	2.855	3.4
11	2.462	2.462	3.4
12	2.801	2.801	3.4
13	2.977	2.977	3.4
14	3.301	3.301	3.4
15	3.605	3.605	3.605
16	3.562	3.562	3.562
17	3.835	3.835	3.835
18	3.445	3.445	3.445
19	3.114	3.114	3.4
20	2.924	2.924	3.4
21	2.755	2.755	3.4
22	2.965	2.965	3.4
23	3.566	3.566	3.566
24	3.665	3.665	3.665

Table A-3: 24-hour GA revenue and LA energy costs (\$)

Time (hours)	GA1		GA2		GA3		LA1		LA2	
	Maximization of load benefits revenue	Maximization of GA profits revenue	Maximization of load benefits revenue	Maximization of GA profits revenue	Maximization of load benefits revenue	Maximization of GA profits revenue	Maximization of load benefits energy costs	Maximization of GA profits energy costs	Maximization of load benefits energy costs	Maximization of GA profits energy costs
0	20	20	60	60	80	80	200	200	260	260
1	40	40	100	100	160	160	128	128	224	224
2	32	32	48	48	120	120	100	100	160	160
3	58.354	58.354	108.928	108.928	120.599	120.599	128.928	128.928	202.953	202.953
4	27.737	37.4	55.475	74.8	63.04	85	87.475	103.5	142.777	177.7
5	7.154	7.154	35.769	35.769	42.923	42.923	83.769	83.769	118.077	118.077
6	26.47	26.47	52.94	52.94	68.066	68.066	56.94	56.94	98.536	98.536
7	15.963	17	35.118	37.4	44.695	47.6	39.118	40.8	104.658	109.2
8	38.822	40.8	77.645	81.6	87.35	91.8	97.645	98.6	126.172	135.6
9	53.468	61.12	89.113	102	101.891	112.2	124.759	142.8	89.113	102
10	57.106	68	95.182	108.8	125.632	149.6	128.486	153	125.632	149.6
11	36.931	51	44.317	61.2	132.482	170	100.944	139.4	78.785	108.8
12	25.207	30.6	39.212	47.6	162.434	187	95.228	115.6	84.025	102
13	38.695	44.2	56.554	64.6	157.32	176.8	110.131	125.8	122.037	139.4
14	56.121	57.8	99.235	102	196.354	200.6	92.435	95.2	198.075	204
15	39.657	39.657	116.304	116.304	178.823	178.823	72.104	72.1038	194.680	194.68026
16	64.115	64.115	78.201	78.201	185.059	185.059	74.801	74.80137	170.975	170.97456
17	38.352	38.352	144.786	144.786	222.443	222.443	99.716	99.71572	268.465	268.4654
18	62.001	62.001	117.113	117.113	127.447	127.447	134.336	134.3355	172.225	172.225
19	34.252	37.4	99.642	108.8	146.349	159.8	149.462	163.2	130.780	142.8
20	23.392	27.2	64.328	74.8	157.896	183.6	125.732	146.2	119.884	139.4
21	13.773	17	71.620	88.4	154.258	190.4	134.975	166.6	104.675	129.2
22	29.652	34	94.886	108.8	100.817	115.6	106.747	122.4	118.608	136
23	24.959	24.959	121.230	121.230	139.058	139.058	85.574	85.5744	199.674	199.6736
24	43.979	43.979	69.633	69.633	91.623	91.623	76.963	76.9629	128.272	128.2715
Total	908.161	980.562	1975.231	2113.705	3166.557	3406.040	2634.269	2854.230	3743.076	3973.556

APPENDIX B INTERIOR POINT METHOD

A nonlinear problem can be compactly described [150] which is given as:

$$\begin{aligned} & \text{Min} && f(x) \\ & \text{subject to} && g(x) = 0 \\ & && h_{\min} \leq h(x) \leq h_{\max} \end{aligned} \quad (\text{A.1})$$

where $f(x)$ is the objective function to be minimized; $g(x)$ is a vector of equality constraints; $h(x)$ consists of a vector of inequality constraints containing reactive power constraints; and $h_{\min}$ and $h_{\max}$ are the corresponding lower and upper limits for $h(x)$.

To convert the inequality constraints into equality ones, slack variables are introduced as:

$$\begin{aligned} h(x) - s_L - h_{\min} &= 0 & s_L &\geq 0 \\ h(x) + s_U - h_{\max} &= 0 & s_U &\geq 0 \end{aligned} \quad (\text{A.2})$$

where s_L and s_U are the respective lower and upper slack variables.

Using the logarithmic barrier function, the Lagrangian function can be established as shown:

$$\begin{aligned} L(s, s_L, s_U, \lambda, \pi_L, \pi_U, \mu) &= f(x) - \lambda^T g(x) - \pi_L^T (h(x) - s_L - h_{\min}) \\ &\quad - \pi_U^T (h(x) - s_U - h_{\max}) - \mu (\Pi_i \ln s_{Li} + \Pi_i \ln s_{Ui}) \end{aligned} \quad (\text{A.3})$$

where the following parameters are defined as:

- λ : Vector of Lagrangian multipliers for $g(x) = 0$;
- π_L : Vector of Lagrangian multipliers for $h(x) - s_L - h_{\min} = 0$;
- π_U : Vector of Lagrangian multipliers for $h(x) - s_U - h_{\max} = 0$; and
- μ : Barrier parameter.

Next, the Karush Kuhn Tucker (KKT) first-order necessary optimality condition of the Lagrangian function in (A.3) is derived as:

$$\begin{aligned}
L_x &\equiv \nabla_x f(x) - \nabla_x g(x)\lambda - \nabla_x h(x)(\pi_L + \pi_U) = 0 \\
L_\lambda &\equiv g(x) = 0 \\
L_{\pi_L} &\equiv h(x) - s_L - h_{\min} = 0 \\
L_{\pi_U} &\equiv h(x) + s_U - h_{\max} = 0 \\
L_{s_L} &\equiv \pi_L - S_L^{-1}\mu e = 0 \\
L_{s_U} &\equiv \pi_U - S_U^{-1}\mu e = 0
\end{aligned} \tag{A.4}$$

where S_L and S_U are diagonal matrices containing the elements s_L and s_U as the diagonal elements respectively; and e is a vector where all the elements are 1. Furthermore, the last two equations in (A.4) are converted into the following equations for ease of differentiating the KKT first-order condition.

$$\begin{aligned}
\tilde{L}_{s_L} &\equiv S_L \Pi_L e - \mu e = 0 \\
\tilde{L}_{s_U} &\equiv S_U \Pi_U e + \mu e = 0
\end{aligned} \tag{A.5}$$

where Π_L and Π_U are diagonal matrices with the diagonal elements of π_L and π_U respectively. With an initial guess, the correction equations of the first-order condition using Newton's method are shown as:

$$\begin{aligned}
H\Delta x + \nabla_x g(x)\Delta\lambda + \nabla_x h(x)(\Delta\pi_L + \Delta\pi_U) &= L_x^0 \\
H &\equiv \nabla_x^2 g(x)\lambda + \nabla_x^2 h(x)(\pi_L + \pi_U) - \nabla_x^2 f(x) \\
\nabla_x g(x)^T \Delta x &= -L_\lambda^0 \\
\nabla_x h(x)^T \Delta x - \Delta s_L &= -L_{\pi_L}^0 \\
\nabla_x h(x)^T \Delta x + \Delta s_U &= -L_{\pi_U}^0 \\
S_L \Delta\pi_L + \Pi_L \Delta s_L &= -\tilde{L}_{\pi_L}^0 \\
S_U \Delta\pi_U + \Pi_U \Delta s_U &= -\tilde{L}_{\pi_U}^0
\end{aligned} \tag{A.6}$$

where the right-hand side notations are the residuals of the KKT first-order condition derived in (A.4) and (A.5).

In order to reduce the size of the above set of correction equations, the following linear system which can be derived from (A.6) is shown as:

$$\begin{aligned}
 & \begin{bmatrix} \widetilde{H} & \nabla_x g(x) \\ \nabla_x g(x)^T & 0 \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta \lambda \end{bmatrix} = \begin{bmatrix} R_x \\ R_\lambda \end{bmatrix} \\
 & \widetilde{H} \equiv H + \nabla_x h(x) \left(S_U^{-1} \Pi_U - S_L^{-1} \Pi_L \right) \nabla_x h(x)^T \\
 & R_x \equiv L_x^0 + \nabla_x h(x) \left(S_L^{-1} \Pi_L L_{\pi_L}^0 - S_U^{-1} \Pi_U L_{\pi_U}^0 + S_L^{-1} \widetilde{L}_{s_L}^0 - S_U^{-1} \widetilde{L}_{s_U}^0 \right) \\
 & R_\lambda \equiv -L_\lambda^0
 \end{aligned} \tag{A.7}$$

The following steps outline the procedures that are widely used in IPM:

- 1) Initialize the primal and dual variables.
- 2) Calculate the complementary gap: $G_c = \pi_L^T s_L + \pi_U^T s_U$. If the gap and residuals is smaller than the given tolerance, output the optimal solution and stop the process.
- 3) Calculate the barrier parameter with $\mu = \sigma \frac{G_c}{2r}$ where r is the number of constraints and σ ($\sigma \in (0, 1]$) is the centering parameter.
- 4) Solve the correction vectors Δx and $\Delta \lambda$ in (A.7). After which, the parameters $\Delta s_L, \Delta s_U, \Delta \pi_L$ and $\Delta \pi_U$ can be obtained from (A.6).
- 5) Update the primal and dual variables and return to step 2.

APPENDIX C 7-BUS MICROGRID SYSTEM

Table C-1: 7-Bus microgrid system DG and Load Dispatch

Hour	BUS 1 Grid (MW)	BUS 2 Load 1 (MW)	BUS 3 DG 1 (MW)	BUS 4 Load 2 (MW)	BUS 5 DG 2 (MW)	BUS 6 Load 3 (MW)	BUS 7 DG 3 (MW)
1	-0.004287	2	1.414	1.6982	2	1.4918	1.7803
2	-0.116670	2	1.3166	1.6476	2	1.4200	1.8676
3	0.063333	2	1.3417	1.6269	2	1.5203	1.7421
4	0.004864	2	1.251	1.5940	2	1.4357	1.7738
5	0.011980	2	1.3166	1.5849	2	1.4760	1.7323
6	-0.037393	2	1.3517	1.5404	2	1.4616	1.6877
7	0.051861	2	1.3675	1.6960	2	1.4425	1.7191
8	-0.051936	2	1.3649	1.6968	2	1.3727	1.7565
9	-0.981862	3.5	2.75	3	3.25	1.5181	3
10	0	2.6864	2.2612	2.6790	2.7211	2.1273	2.5104
11	0	2.6171	2.0191	2.44597	2.2569	1.6755	2.4625
12	0	3.344	2.5171	2.6967	2.9465	2.2904	2.8675
13	-0.042711	3.4572	2.75	3	3.25	2.5	3
14	0	2.7472	2.2822	2.5403	2.6366	2.0700	2.4387
15	0	3.2259	2.3533	2.4815	2.7330	1.9659	2.5869
16	-0.145249	2.2109	1.6243	1.8561	2	1.4651	2.0535
17	-0.016023	2.1563	1.7522	2.1659	2	1.5799	2.1658
18	-0.003617	2.2793	1.7244	1.9742	2	1.5925	2.1252
19	0	3.2416	2.2663	2.5294	2.5242	1.6985	2.6790
20	0	2.7437	1.9242	2.3513	2.1929	1.4156	2.3936
21	0	2.9986	2.1061	2.4056	2.3814	1.6365	2.5532
22	0.076496	2	1.4293	1.8552	2	1.5387	1.8881
23	-0.088804	2	1.395	1.7340	2	1.2600	1.6878
24	-0.065780	2	1.3785	1.58897	2	1.4400	1.7163

Table C-2: 7-Bus microgrid system marginal loss factors and locational marginal prices

Hour	BUS 1		BUS 2		BUS 3		BUS 4		BUS 5		BUS 6		BUS 7	
	Marginal loss factor	LMP \$/MWh	Marginal loss factor	LMP \$/MWh	Marginal loss factor	LMP \$/MWh	Marginal loss factor	LMP \$/MWh	Marginal loss factor	LMP \$/MWh	Marginal loss factor	LMP \$/MWh	Marginal loss factor	LMP \$/MWh
1	0	0.442	0.0097	0.447	0.004	0.444	-0.0116	0.437	-0.0198	0.434	-0.0155	0.436	-0.0229	0.432
2	0	0.378	0.0109	0.382	0.0056	0.38	-0.013	0.373	-0.0213	0.37	-0.0231	0.369	-0.031	0.366
3	0	0.334	0.0107	0.338	0.0053	0.336	-0.0136	0.33	-0.0219	0.327	-0.0128	0.33	-0.02	0.328
4	0	0.272	0.0122	0.275	0.0072	0.274	-0.0149	0.268	-0.0233	0.265	-0.0177	0.267	-0.0251	0.265
5	0	0.298	0.0109	0.301	0.0056	0.3	-0.0152	0.293	-0.0235	0.291	-0.0141	0.294	-0.0213	0.292
6	0	0.317	0.0104	0.32	0.005	0.319	-0.0163	0.312	-0.0246	0.309	-0.013	0.313	-0.02	0.311
7	0	0.36	0.0102	0.363	0.0046	0.361	-0.0116	0.355	-0.0198	0.352	-0.0155	0.354	-0.0226	0.351
8	0	0.407	0.0102	0.411	0.0047	0.409	-0.0116	0.402	-0.0198	0.399	-0.0204	0.399	-0.0278	0.396
9	0	0.579	0.0114	0.586	0.0003	0.579	-0.0116	0.573	-0.025	0.565	-0.0703	0.539	-0.0832	0.531
10	0	0.483	0.0061	0.486	-0.0031	0.482	-0.0044	0.481	-0.0156	0.476	-0.0212	0.473	-0.0316	0.468
11	0	0.468	0.0091	0.472	0.001	0.469	0.003	0.47	-0.0062	0.465	-0.0387	0.45	-0.0491	0.445
12	0	0.493	0.0127	0.499	0.0025	0.494	-0.011	0.487	-0.0232	0.481	-0.0304	0.478	-0.0425	0.472
13	0	0.531	0.0107	0.537	-0.0005	0.531	-0.0116	0.525	-0.025	0.518	-0.0272	0.516	-0.0396	0.51
14	0	0.485	0.0069	0.488	-0.0024	0.483	-0.0063	0.482	-0.0172	0.476	-0.0206	0.475	-0.0307	0.47
15	0	0.475	0.0139	0.481	0.0044	0.477	-0.0108	0.47	-0.0221	0.464	-0.0318	0.46	-0.0427	0.454
16	0	0.42	0.0091	0.424	0.0026	0.421	-0.0066	0.417	-0.0149	0.414	-0.0294	0.408	-0.038	0.404
17	0	0.395	0.0061	0.398	-0.001	0.395	0.0028	0.396	-0.0054	0.393	-0.0299	0.383	-0.039	0.38
18	0	0.422	0.0086	0.426	0.0017	0.423	-0.0033	0.421	-0.0115	0.417	-0.0277	0.41	-0.0367	0.407
19	0	0.437	0.0155	0.444	0.0064	0.44	-0.0028	0.436	-0.013	0.432	-0.048	0.416	-0.0593	0.412
20	0	0.414	0.0129	0.419	0.0053	0.416	0.0022	0.415	-0.0067	0.411	-0.0472	0.394	-0.0574	0.39
21	0	0.429	0.0142	0.435	0.0057	0.431	-0.0019	0.428	-0.0117	0.424	-0.0447	0.41	-0.0555	0.405
22	0	0.376	0.0089	0.379	0.0031	0.377	-0.0066	0.373	-0.0149	0.37	-0.0187	0.369	-0.0267	0.366
23	0	0.362	0.0097	0.366	0.004	0.364	-0.0105	0.359	-0.0188	0.356	-0.022	0.354	-0.0291	0.352
24	0	0.402	0.0099	0.406	0.0044	0.404	-0.0149	0.396	-0.0233	0.392	-0.0155	0.396	-0.0226	0.393

APPENDIX D IEEE 14-BUS SYSTEM

Table D-1: IEEE 14-Bus System 24-hour DG generation limits

Hour	Bus 2		Bus 3		Bus 12	
	DG		DG		DG	
	$P_{\min}$	$P_{\max}$	$P_{\min}$	$P_{\max}$	$P_{\min}$	$P_{\max}$
1	-	-	0	0.468	-	-
2	-	-	0	0.415	-	-
3	-	-	0	0.377	-	-
4	-	-	0	0.32	-	-
5	-	-	0	0.488	-	-
6	-	-	0	0.431	0	0.2
7	-	-	0	0.667	0	0.4
8	0	0.337	0	0.365	0	0.6
9	0	0.338	0	0.524	0	0.65
10	0	0.621	0	0.778	0	0.7
11	0	0.722	0	0.958	0	0.75
12	0	0.722	0	1.079	0	0.9
13	0	0.714	0	0.895	0	1
14	0	0.715	0	0.956	0	0.95
15	0	1.033	0	0.889	0	0.6
16	0	1.26	0	0.778	0	0.2
17	0	1.617	0	0.889	-	-
18	0	2.127	0	0.817	-	-
19	0	2.101	0	0.556	-	-
20	0	2.028	0	0.444	-	-
21	0	1.619	0	0.333	-	-
22	0	0.864	0	0.222	-	-
23	0	0.178	0	0.419	-	-
24	-	-	0	1.108	-	-

Table D-2: IEEE 14-Bus System 24-hour load demand limits

Hour	Bus 2		Bus 3		Bus 4		Bus 5		Bus 6		Bus 9		Bus 10		Bus 11		Bus 12		Bus 13		Bus 14	
	Load		Load		Load		Load		Load		Load		Load		Load		Load		Load		Load	
	P _{min}	P _{max}	P _{min}	P _{max}	P _{min}	P _{max}	P _{min}	P _{max}	P _{min}	P _{max}	P _{min}	P _{max}	P _{min}	P _{max}	P _{min}	P _{max}	P _{min}	P _{max}	P _{min}	P _{max}	P _{min}	P _{max}
1	0	0.217	0	0.942	0	0.478	0	0.176	0	0.212	0	0.295	0	0.19	0	0.135	0	0.161	0	0.135	0	0.2
2	0	0.21	0	0.912	0	0.462	0	0.1735	0	0.209	0	0.285	0	0.186	0	0.135	0	0.16	0	0.13	0	0.23
3	0	0.2	0	0.868	0	0.44	0	0.17	0	0.204	0	0.272	0	0.182	0	0.135	0	0.17	0	0.135	0	0.28
4	0	0.19	0	0.825	0	0.418	0	0.1665	0	0.199	0	0.258	0	0.178	0	0.14	0	0.161	0	0.131	0	0.32
5	0	0.2	0	0.868	0	0.44	0	0.17	0	0.204	0	0.272	0	0.182	0	0.15	0	0.16	0	0.15	0	0.35
6	0	0.21	0	0.912	0	0.462	0	0.1735	0	0.209	0	0.286	0	0.186	0	0.135	0	0.161	0	0.145	0	0.4
7	0	0.25	0	1.085	0	0.55	0	0.1875	0	0.23	0	0.34	0	0.203	0	0.15	0	0.19	0	0.166	0	0.425
8	0	0.28	0	1.215	0	0.616	0	0.198	0	0.246	0	0.381	0	0.215	0	0.15	0	0.195	0	0.155	0	0.45
9	0	0.3	0	1.302	0	0.66	0.205	1	0.256	1	0	0.408	0.223	1	0.16	1	0.2	1	0.136	1	0	0.45
10	0	0.35	0	1.519	0	0.77	0.2225	1	0.282	1	0	0.476	0.243	1	0.16	1	0.205	1	0.16	1	0	0.475
11	0	0.38	0	1.649	0	0.836	0.233	1	0.298	1	0	0.517	0.256	1	0.165	1	0.215	1	0.15	1	0	0.48
12	0	0.4	0	1.736	0	0.88	0.24	1	0.308	1	0	0.544	0.264	1	0.18	1	0.23	1	0.155	1	0	0.5
13	0	0.39	0	1.692	0	0.858	0.2365	1	0.303	1	0	0.53	0.26	1	0.175	1	0.22	1	0.165	1	0	0.52
14	0	0.39	0	1.692	0	0.858	0.2365	1	0.303	1	0	0.53	0.26	1	0.17	1	0.21	1	0.16	1	0	0.55
15	0	0.38	0	1.649	0	0.836	0.233	1	0.298	1	0	0.517	0.256	1	0.17	1	0.2	1	0.15	1	0	0.58
16	0	0.35	0	1.519	0	0.77	0	0.2225	0	0.282	0	0.476	0	0.276	0	0.16	0	0.19	0	0.155	0	0.6
17	0	0.38	0	1.649	0	0.836	0.233	1	0.298	1	0	0.517	0.268	1	0.178	1	0.195	1	0.145	1	0	0.56
18	0	0.43	0	1.866	0	0.946	0.2505	1	0.323	1	0	0.585	0.263	1	0.183	1	0.2	1	0.15	1	0	0.485
19	0	0.41	0	1.779	0	0.902	0.2435	1	0.313	1	0	0.558	0.26	1	0.18	1	0.205	1	0.155	1	0	0.4
20	0	0.4	0	1.736	0	0.88	0.24	1	0.308	1	0	0.544	0.247	1	0.175	1	0.2	1	0.145	1	0	0.352
21	0	0.36	0	1.562	0	0.792	0.226	1	0.287	1	0	0.49	0.225	1	0.16	1	0.19	1	0.14	1	0	0.3
22	0	0.31	0	1.085	0	0.682	0	0.2085	0	0.261	0	0.422	0	0.22	0	0.15	0	0.18	0	0.136	0	0.245
23	0	0.25	0	0.955	0	0.55	0	0.1875	0	0.23	0	0.34	0	0.215	0	0.155	0	0.17	0	0.135	0	0.24
24	0	0.22	0	0.95	0	0.484	0	0.177	0	0.215	0	0.3	0	0.193	0	0.138	0	0.161	0	0.13	0	0.23

TABLE D-3: IEEE 14-BUS SYSTEM BIDDING RATES (m_G , m_D in \$/MWh/MW) OVER 24-HOUR PERIOD

Hour	Bus 2		Bus 3		Bus 4	Bus 5	Bus 6	Bus 9	Bus 10	Bus 11	Bus 12		Bus 13	Bus 14
	DG	Load	DG	Load	Load	Load	Load	Load	Load	Load	DG	Load	Load	Load
1	-	0.84	0.1	0.37	0.37	0.65	0.65	0.84	0.65	0.65	-	0.65	0.65	0.84
2	-	0.8	0.09	0.33	0.33	0.66	0.66	0.8	0.66	0.66	-	0.66	0.66	0.8
3	-	0.72	0.08	0.36	0.36	0.55	0.55	0.72	0.55	0.55	-	0.55	0.55	0.72
4	-	0.75	0.07	0.31	0.31	0.66	0.66	0.75	0.66	0.66	-	0.66	0.66	0.75
5	-	0.65	0.09	0.41	0.41	0.57	0.57	0.65	0.57	0.57	-	0.57	0.57	0.65
6	-	0.52	0.1	0.34	0.34	0.13	0.13	0.52	0.13	0.13	0.12	0.13	0.13	0.52
7	-	0.08	0.11	0.09	0.09	0.04	0.04	0.08	0.04	0.04	0.1	0.04	0.04	0.08
8	0.22	0.2	0.2	0.11	0.11	0.01	0.01	0.2	0.01	0.01	0.23	0.01	0.01	0.2
9	0.2	0.07	0.25	0.05	0.05	0.1	0.1	0.07	0.1	0.1	0.21	0.1	0.1	0.07
10	0.25	0.02	0.29	0.09	0.09	0.1	0.1	0.02	0.1	0.1	0.28	0.1	0.1	0.02
11	0.3	0.07	0.5	0.04	0.04	0.09	0.09	0.07	0.09	0.09	0.4	0.09	0.09	0.07
12	0.35	0.02	0.45	0.03	0.03	0.08	0.08	0.02	0.08	0.08	0.5	0.08	0.08	0.02
13	0.26	0.05	0.19	0.03	0.03	0.05	0.05	0.05	0.05	0.05	0.2	0.05	0.05	0.05
14	0.21	0.08	0.18	0.03	0.03	0.06	0.06	0.08	0.06	0.06	0.19	0.06	0.06	0.08
15	0.2	0.1	0.17	0.04	0.04	0.03	0.03	0.1	0.03	0.03	0.18	0.03	0.03	0.1
16	0.26	0.14	0.23	0.12	0.12	0.01	0.01	0.14	0.01	0.01	0.2	0.01	0.01	0.14
17	0.19	0.07	0.22	0.04	0.04	0.09	0.09	0.07	0.09	0.09	-	0.09	0.09	0.07
18	0.24	0.03	0.2	0.03	0.03	0.14	0.14	0.03	0.14	0.14	-	0.14	0.14	0.03
19	0.19	0.09	0.17	0.04	0.04	0.1	0.1	0.09	0.1	0.1	-	0.1	0.1	0.09
20	0.1	0.08	0.15	0.04	0.04	0.05	0.05	0.08	0.05	0.05	-	0.05	0.05	0.08
21	0.09	0.113	0.1	0.04	0.04	0.105	0.105	0.113	0.105	0.105	-	0.105	0.105	0.113
22	0.06	0.16	0.08	0.04	0.04	0.146	0.146	0.16	0.146	0.146	-	0.146	0.146	0.16
23	0.05	0.195	0.06	0.05	0.05	0.189	0.189	0.195	0.189	0.189	-	0.189	0.189	0.195
24	-	0.4	0.07	0.25	0.25	0.35	0.35	0.4	0.35	0.35	-	0.35	0.35	0.4

TABLE D-4: IEEE 14-BUS SYSTEM 24-HOUR DG AND LOAD DISPATCH

Hour	Bus 1	Bus 2		Bus 3		Bus 4	Bus 5	Bus 6	Bus 9	Bus 10	Bus 11	Bus 12		Bus 13	Bus 14
	Grid (MW)	DG (MW)	Load (MW)	DG (MW)	Load (MW)	Load (MW)	Load (MW)	Load (MW)	Load (MW)	Load (MW)	Load (MW)	DG (MW)	Load (MW)	Load (MW)	Load (MW)
1	2.8018	0	0.217	0.46795	0.942	0.478	0.176	0.212	0.295	0.19	0.135	0	0.161	0.135	0.2
2	2.8038	0	0.21	0.41502	0.912	0.462	0.1735	0.209	0.285	0.186	0.135	0	0.16	0.13	0.23
3	2.80346	0	0.2	0.37697	0.868	0.44	0.17	0.204	0.272	0.182	0.135	0	0.17	0.135	0.28
4	2.7875	0	0.19	0.32017	0.825	0.418	0.1665	0.199	0.258	0.178	0.14	0	0.161	0.131	0.32
5	2.78731	0	0.2	0.48778	0.868	0.44	0.17	0.204	0.272	0.182	0.15	0	0.16	0.15	0.35
6	2.78412	0	0.21	0.43122	0.912	0.462	0.1735	0.209	0.286	0.186	0.135	0.2	0.161	0.145	0.4
7	2.86955	0	0.25	0.66684	1.085	0.55	0.1875	0.23	0.34	0.203	0.15	0.4	0.19	0.166	0.425
8	2.97	0.337471	0.28	0.36517	1.215	0.616	0.198	0.246	0.381	0.215	0.15	0.6	0.195	0.155	0.45
9	2.97	0.337758	0.3	0.52384	1.302	0.66	0.205	0.256	0.408	0.223	0.16	0.65	0.2	0.136	0.45
10	2.97	0.62134	0.35	0.77802	1.519	0.77	0.2225	0.282	0.476	0.243	0.16	0.7	0.205	0.16	0.475
11	2.97	0.72215	0.38	0.95846	1.649	0.836	0.233	0.298	0.517	0.256	0.165	0.75	0.215	0.15	0.48
12	2.97	0.722149	0.4	1.07936	1.736	0.88	0.24	0.308	0.544	0.264	0.18	0.9	0.23	0.155	0.5
13	2.97	0.714428	0.39	0.89532	1.692	0.858	0.2365	0.303	0.53	0.26	0.175	1	0.22	0.165	0.52
14	2.97	0.714512	0.39	0.95575	1.692	0.858	0.2365	0.303	0.53	0.26	0.17	0.95	0.21	0.16	0.55
15	2.97	1.03301	0.38	0.88903	1.649	0.836	0.233	0.298	0.517	0.256	0.17	0.6	0.2	0.15	0.58
16	2.97	1.2598	0.35	0.77796	1.519	0.77	0.2225	0.282	0.476	0.276	0.16	0.2	0.19	0.155	0.6
17	2.97	1.61662	0.38	0.889	1.649	0.836	0.233	0.298	0.517	0.268	0.178	0	0.195	0.145	0.56
18	2.97	2.12717	0.43	0.81693	1.866	0.946	0.2505	0.323	0.585	0.263	0.183	0	0.2	0.15	0.485
19	2.97	2.10102	0.41	0.55612	1.779	0.902	0.2435	0.313	0.558	0.26	0.18	0	0.205	0.155	0.4
20	2.97	2.02797	0.4	0.44406	1.736	0.88	0.24	0.308	0.544	0.247	0.175	0	0.2	0.145	0.352
21	2.97	1.61924	0.36	0.33304	1.562	0.792	0.226	0.287	0.49	0.225	0.16	0	0.19	0.14	0.3
22	2.97	0.863756	0.31	0.22204	1.085	0.682	0.2085	0.261	0.422	0.22	0.15	0	0.18	0.136	0.245
23	2.97	0.177973	0.25	0.41910	0.955	0.55	0.1875	0.23	0.34	0.215	0.155	0	0.17	0.135	0.24
24	2.2275	0	0.22	1.10791	0.95	0.484	0.177	0.215	0.3	0.193	0.138	0	0.161	0.13	0.23

TABLE D-5: IEEE 14-BUS SYSTEM 24-HOUR MARGINAL LOSS FACTORS

Hour	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6	Bus 7	Bus 8	Bus 9	Bus 10	Bus 11	Bus 12	Bus 13	Bus 14
1	0	0.0123	0.025	0.0111	0.0155	-0.0113	-0.0248	-0.0248	-0.0091	-0.0023	-0.0004	0.0247	0.0025	0.0079
2	0	0.0146	0.0294	0.0172	0.0192	-0.0041	-0.0149	-0.0149	-0.0011	0.0046	0.0058	0.0025	0.0058	0.0157
3	0	0.0135	0.0239	0.0166	0.0202	-0.0033	-0.0181	-0.0181	-0.0039	0.0028	0.0055	0.0344	0.0113	0.0198
4	0	0.0114	0.0275	0.0067	0.0126	-0.0154	-0.0289	-0.0289	-0.0128	-0.0067	-0.0048	0.0149	-0.0009	0.0122
5	0	0.0114	0.0249	0.0076	0.0133	-0.015	-0.0302	-0.0302	-0.0137	-0.007	-0.0044	0.0165	0.0008	0.0144
6	0	0.0148	0.0325	0.0159	0.0174	-0.0095	-0.0151	-0.0151	-0.0002	0.0047	0.0033	-0.0182	0.0007	0.0251
7	0	0.0106	0.0207	0.007	0.012	-0.0215	-0.0297	-0.0297	-0.0115	-0.0055	-0.0064	0.0072	-0.0068	0.0173
8	0	0.0138	0.0362	0.0187	0.019	-0.0149	-0.0138	-0.0138	0.004	0.009	0.0044	-0.0134	-0.0042	0.0288
9	0	0.0142	0.0362	0.0202	0.0205	-0.0129	-0.011	-0.011	0.0064	0.0115	0.007	-0.0062	-0.0028	0.0307
10	0	0.0114	0.0383	0.0158	0.0171	-0.0209	-0.0185	-0.0185	0.0011	0.0065	0.0007	-0.0176	-0.0098	0.0263
11	0	0.0128	0.0436	0.0203	0.018	-0.0197	-0.0104	-0.0104	0.0084	0.0128	0.0042	-0.0687	-0.015	0.0284
12	0	0.014	0.0448	0.0238	0.0199	-0.0181	-0.0042	-0.0042	0.0143	0.0185	0.0087	-0.0794	-0.0149	0.0331
13	0	0.0132	0.0412	0.0226	0.0206	-0.02	-0.0086	-0.0086	0.0114	0.016	0.0068	-0.038	-0.0121	0.034
14	0	0.0103	0.0362	0.0163	0.0158	-0.0262	-0.0154	-0.0154	0.0052	0.0099	0.0006	-0.0455	-0.0176	0.0301
15	0	0.0101	0.0353	0.0262	0.0256	-0.0081	-0.0099	-0.0099	0.0084	0.0148	0.0112	0.0087	0.0058	0.0435
16	0	0.0072	0.0396	0.0198	0.0219	-0.0121	-0.0192	-0.0192	-0.0004	0.0071	0.0046	0.0032	0.0053	0.0397
17	0	0.0039	0.0324	0.0235	0.0256	-0.0049	-0.0204	-0.0204	-0.002	0.0068	0.0085	0.0355	0.0154	0.0404
18	0	0.0033	0.0437	0.0283	0.029	-0.0014	-0.0132	-0.0132	0.0048	0.0129	0.0136	0.0342	0.0179	0.0403
19	0	0.0054	0.0509	0.0317	0.031	0.0026	-0.0065	-0.0065	0.0102	0.018	0.0181	0.0282	0.0197	0.0387
20	0	0.0065	0.0535	0.0319	0.031	0.003	-0.0055	-0.0055	0.011	0.0183	0.0182	0.0271	0.0188	0.0356
21	0	0.0093	0.053	0.0298	0.0293	0.0025	-0.0061	-0.0061	0.0096	0.0163	0.0165	0.0236	0.0167	0.0307
22	0	0.0107	0.0394	0.0211	0.0232	-0.0041	-0.0156	-0.0156	0.0004	0.0075	0.0083	0.0263	0.0099	0.019
23	0	0.0119	0.0257	0.0133	0.0178	-0.0097	-0.025	-0.025	-0.0087	-0.0011	0.0015	0.0299	0.0047	0.0115
24	0	0.0018	-0.0126	-0.0008	0.0074	-0.0176	-0.0382	-0.0382	-0.0229	-0.0152	-0.0105	0.0445	-0.0018	-0.0002

TABLE D-6: IEEE 14-BUS SYSTEM 24-HOUR LOCATIONAL MARGINAL PRICES IN \$/MWH

Hour	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6	Bus 7	Bus 8	Bus 9	Bus 10	Bus 11	Bus 12	Bus 13	Bus 14
1	0.44	0.446	0.451	0.445	0.447	0.436	0.43	0.43	0.436	0.439	0.44	0.451	0.442	0.444
2	0.43	0.437	0.443	0.438	0.439	0.429	0.424	0.424	0.43	0.432	0.433	0.432	0.433	0.437
3	0.42	0.426	0.431	0.427	0.429	0.419	0.413	0.413	0.419	0.422	0.423	0.435	0.425	0.429
4	0.4	0.405	0.411	0.403	0.406	0.394	0.389	0.389	0.395	0.398	0.399	0.406	0.4	0.405
5	0.43	0.435	0.441	0.434	0.436	0.424	0.418	0.418	0.425	0.427	0.429	0.438	0.431	0.437
6	0.48	0.488	0.496	0.488	0.489	0.476	0.473	0.473	0.48	0.483	0.482	0.472	0.481	0.493
7	0.59	0.597	0.603	0.595	0.598	0.578	0.573	0.573	0.584	0.587	0.587	0.595	0.586	0.601
8	0.6	0.609	0.622	0.612	0.612	0.592	0.592	0.592	0.603	0.606	0.603	0.592	0.598	0.618
9	0.63	0.639	0.653	0.643	0.643	0.622	0.624	0.624	0.635	0.638	0.635	0.627	0.629	0.65
10	0.65	0.658	0.675	0.661	0.662	0.637	0.638	0.638	0.651	0.655	0.651	0.639	0.644	0.668
11	0.66	0.669	0.689	0.674	0.672	0.647	0.654	0.654	0.666	0.669	0.663	0.615	0.651	0.679
12	0.68	0.69	0.711	0.697	0.694	0.668	0.678	0.678	0.69	0.693	0.686	0.627	0.67	0.703
13	0.64	0.649	0.667	0.655	0.654	0.628	0.635	0.635	0.648	0.651	0.645	0.616	0.633	0.662
14	0.63	0.637	0.653	0.641	0.64	0.614	0.621	0.621	0.634	0.637	0.631	0.602	0.619	0.649
15	0.61	0.617	0.632	0.626	0.626	0.606	0.604	0.604	0.616	0.62	0.617	0.616	0.614	0.637
16	0.59	0.595	0.614	0.602	0.603	0.583	0.579	0.579	0.59	0.595	0.593	0.592	0.594	0.614
17	0.65	0.653	0.672	0.666	0.667	0.647	0.637	0.637	0.649	0.655	0.656	0.674	0.661	0.677
18	0.68	0.683	0.71	0.7	0.7	0.68	0.672	0.672	0.684	0.689	0.69	0.704	0.693	0.708
19	0.64	0.644	0.673	0.661	0.66	0.642	0.636	0.636	0.647	0.652	0.652	0.659	0.653	0.665
20	0.62	0.625	0.654	0.64	0.64	0.622	0.617	0.617	0.627	0.632	0.632	0.637	0.632	0.643
21	0.6	0.606	0.632	0.618	0.618	0.602	0.597	0.597	0.606	0.61	0.61	0.615	0.611	0.619
22	0.56	0.566	0.583	0.572	0.573	0.558	0.552	0.552	0.561	0.565	0.565	0.575	0.566	0.571
23	0.5	0.506	0.513	0.507	0.509	0.496	0.488	0.488	0.496	0.5	0.501	0.515	0.503	0.506
24	0.47	0.471	0.465	0.47	0.474	0.462	0.453	0.453	0.46	0.463	0.466	0.491	0.47	0.47

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The author has the following publications.

Journal Publications

- [1] **Y. S. Foo. Eddy**, H. B. Gooi and S. X. Chen, "Multi Agent System for Distributed Management of Microgrids," IEEE Transactions on Power Systems, vol.30, no.1, pp.24,34, Jan. 2015.
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