STUDY OF A MULTI-AGENT SYSTEM FOR A SINGLE-PHASE MICROGRID

DARITH LENG

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF ENGINEERING IN COMPUTING IN ENGINEERING SYSTEMS
INTERNATIONAL COLLEGE
KING MONGKUT'S INSTITUTE OF TECHNOLOGY LADKRABANG
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Thesis Title	Study of a Multi-agent System for a Single-phase Microgrid
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ABSTRACT

Microgrid is the new trend of power system which can produce energy with environment friendly. One main drawback of microgrid is the most of its sources are highly dependent to environment. Therefore, to improve the efficiency as well as reliability of microgrid, the effectiveness control that provide faster responds to system dynamic, is needed. In this thesis, a decentralized control system was proposed which consisted of three control levels. Primary control was droop control, which have been used to ensure power sharing for parallel generators. Secondary control was frequency restoration; it aimed to restore the frequency from deviation, which resulted from droop control method. Tertiary control was a supervisory control; the multi-agent system was utilized for this control purpose and it was also the main focus in this thesis. To evaluate the proposed control, software simulation and hardware (real system) experiment were developed. For software simulation experiment, the proposed multi agent based control architecture was developed using the JADE platform and it was used to control a microgrid simulated in MATLAB/SIMULINK. To enable data exchange between microgrid models in Matlab/Simulink with multi-agent system created under JADE Platform, the MACSimJX has been used. For real system experiment, the multi-agent system was created using Mobile-C platform and used Ch as the agents run-time. The experimental microgrid system was implemented by interconnecting of two parallel generators with the critical and non-critical loads. The DSPF28235 and Arduino were utilized as local controllers and data acquisition. The microgrid and the multi-agent system exchanged data between each other through RS-232 serial communication. The results shown the effective of developing a reliable control mechanism for power sharing, changing microgrid operation mode, load-shedding and control slack generator and based on decentralized control.

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Bangkok, June 2015

Darith Leng

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ACC	Agent Communication Channel
ACL	Agent Communication Language
AID	Agent Identifier
AMS	Agent Management System
AP	Agent Platform
CHP	Combined Heat and Power
DF	Directory Facilitator
DG	Distributed Generation/Distributed Generator
DER	Distributed Energy Resource
FIPA	Foundation for Intelligent Physical Agents
GUI	Graphical User Interface
IEEE	Institute of Electrical and Electronics Engineers
JADE	Java Agent Development Environment
MAS	Multi Agent System
MV	Medium Voltage
MTS	Message Transport Service
OS	Operating Systems
PCC	Point of Common Coupling
PV	Photovoltaic
RES	Renewable Energy Sources
SCADA	Supervisory Control and Data Acquisition
TCP/IP	Transmission Control Protocol / Internet Protocol

CHAPTER 1

INTRODUCTION

1.1 Introduction

From time to time, the energy demand keeps increasing and the fossil energy is slightly decreased. If we rely on nuclear power plant to handle the increasing of power demand, it seems not a sustainable solution, as it may result a massive disaster like it happened in japan in the last few years. After that disaster, nuclear power plant becomes a restriction to some counties around the world. One more problem that many people around the globe pay much attention right now is environment problem like global warming. In those, the energy production is a factor that has impact to the environment. Therefore, to increase the energy production with the environment friendly, using renewable energy is the best solution.

In power system nowadays, it faces some problems such as frequently of natural hazard or fault that cause of the aging of power system structure, energy efficient bottlenecks and the high standard power quality required by user. To solve these, building a new sustainable energy system is an evitable.

Building a new sustainable energy system using renewable energy as the main sources is one of effective ways. As the concept microgrid emerges. Microgrid is a new form of grid in term of power system. It is created by interconnecting of distributed generators, energy storage and a cluster of loads as shown in Figure 1.1 and it operates as a single controllable system that provides power to its local area.

To improve the system reliability and stability; microgrid must interoperate with other utility. It really needs the control techniques that can perform fast respond to dynamically change and work automatically when microgrid operates in islanded mode. Many researches have been conducted by using various control technique such as [1–3]. But, those controls techniques are still not good enough to realize microgrid control purpose as well as to provide some intelligent behaviors.

One of the most widely use for control microgrid for enhancing the stability, as far proper load sharing is conventional droop control. Droop control is a well-known technique because of its reliability, independence in the operation of every inverter unit and low cost makes it the best choice for microgrid. It might be a possibility that this technique will be considered as a standard scheme for load-sharing of parallel generator in the future for microgrids. In microgrid, this technique is implemented to achieve plug-and-play concept for islanded mode operation [4]. Beside droop control, In order to provide control capacity for better microgrid application, multi-agent system (MAS) is a technique coming forward in this aspect. MAS have been developed for a wide range of applications in power systems [5].

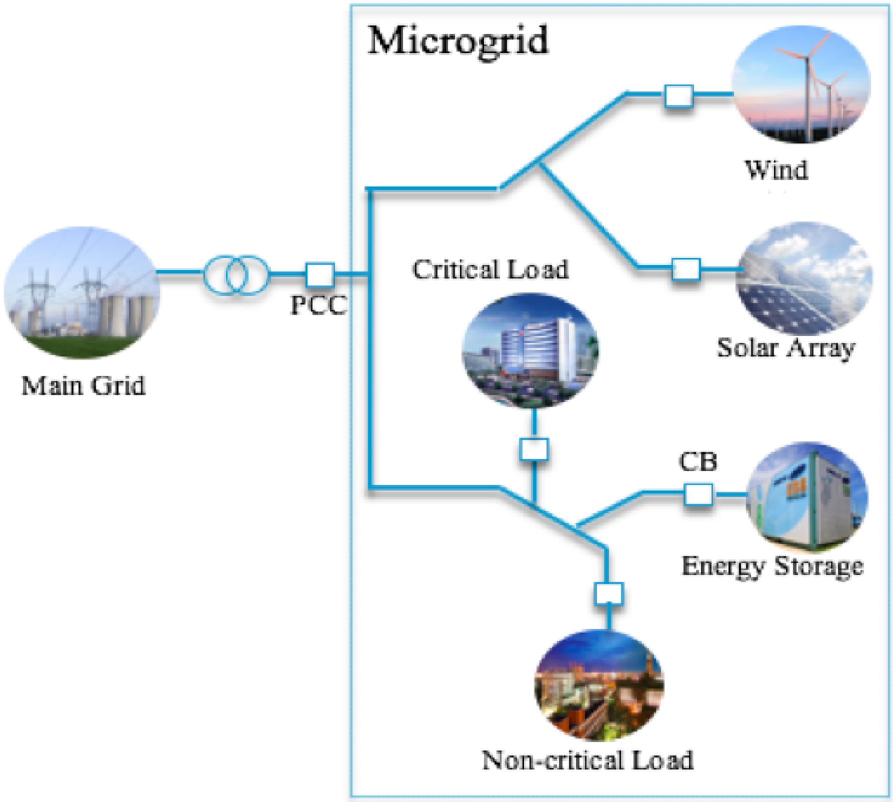


Figure 1.1: Microgrid architecture

1.2 Objective of the Research

Microgrid is the new type of power system, which operates at the distributed level. From microgrid, it can be developed to a smart system by introducing the communication and providing the intelligent performances. All the things above are the thesis motivated.

The objective of this research is to develop a decentralize control system to improve the efficiency operation of the microgrid as well as to drive up the system reliability and stability; at the same to provide smart control ability for better microgrid application. The decentralize control system consists of three control techniques. Primary control is droop control. It is the effective decentralize control for power sharing between parallel generators. With droop control, it may lead to frequency deviation so the secondary control is developed to handle this drawback, called frequency restoration. Tertiary control is a supervisory control; multi-agent is used for this control to provide microgrid intelligent performances.

The steps taken to realize the objectives of the thesis statement are listed below, and are further detailed in Section 1.3:

1. Development of Microgrid model using Matlab/Simulink with droop control and frequency restoration technique.
2. Design and develop multi-agent system architecture.
3. Integration of the multi agent system and the microgrid.
4. Validation of proposed method using software simulation and hardware experiment.

1.3 Methodology

The methodology consists of the following four steps:

Step 1: Development of Microgrid model using Matlab/Simulink with droop control technique.

Microgrid is formed by the combination of distribution generators, loads, energy storage and connected to the main grid in a controllable system. In this research, the microgrid simulation is composed of three generators. Two generator are independently controlled using droop control technique for stable load sharing during islanding mode of operation and another one is model as a PV generator. These generators are model based on power amplifier (programmable power supply) characteristics for the later experimental stage. There are fixed and variable loads connecting in the microgrid model. The variable load has the profile of general service type surveyed by the Metropolitan Electric Authority of Thailand (MEA).

Step 2: Design and develop multi-agent system architecture

The concept of using multi-agent system is to simplify a complex problem; a centralized system and a distributed system handled by a single entity into something much smaller, simpler problems that can be handled by several entities. Developing a multi agent system uses a selected toolkit consists of following steps. Initially, the abilities of each agent have to be specified, followed by identifying each of their roles and responsibilities, through building role models and defining social and domain responsibilities. Then the ontology of the system has to be created based on modeling their knowledge or facts. Further details on designing and developing the multi agent architecture is presented in Chapter 3.

Step 3: Integration of the multi agent system and the microgrid simulation

For software simulation experiment:

The multi-agent system developement aims to control physical entities or a simulation of the same. The multi-agent system and the simulation are inherently in two domains. The multi-agent system runs on a JAVA platform while the simulation is run on a simulating environment (MATLAB/SIMULINK). Therefore, in order to establish communication between the two domains, for sensing and control, MACSimJX middleware is used.

For hardware experiment:

The multi-agent system is developed by using Mobile-C and it execute under Ch environment. The two generators are controlled by droop and frequency restoration that those controls are implemented by using DSPF28335. The agents and microgrid exchange data or command through serial communication RS-232. Details regarding the creation of this interface are given in Chapter 5.

Step 4: Validation of results using software simulation experiment and hardware experiment

Difference scenarios are carried out to verify the implementation of decentralized control system within a simulated microgrid test-bed environment also real microgrid system, which developed in laboratory. They demonstrate the functionality of the system in islanding, protecting/securing supply to critical loads and managing load priorities during islanded mode operation. The case studies and their results are presented in detail in Chapter 4 and Chapter 5.

1.4 Thesis Organization

This thesis is organized into 6 chapters and separated in two experiments such as simulation and hardware experiment. For simulation experiment, the microgrid model is implemented using MATLAB/Simulink and the multi-agent system is developed under Jade based on Java.

For hardware experiment, the microgrid is developed with the interconnection of the generators with converter-based, active and reactive load and the multi-agent system is created by using Mobile-C based on C/C++.

Following the chapter on introduction, the rest of the thesis is outline as follows.

Chapter 2 provides a literature review of this research that it includes a review of microgrid, droop control and multi-agent system.

In chapter 3, the detail about decentralized control and a single-phase microgrid model in this study are presented. This chapter is divided into three main sections. Primary section, some basic knowledge as well as the theory are provided relate to droop control scheme such as droop characteristic, frequency droop control, angular droop control, voltage droop control and the implementation of droop control. Secondary section, the implementation of frequency restoration is provided. Tertiary section, the standard for agent, the multi-agent architecture and building toolkit for both of simulation and hardware experiment are presented.

Chapter 4 is about simulation experiment. In this chapter, the simulation setup and the main components using in this experiment is presented. It also includes with the results and discussion on three different scenarios.

The purpose of the simulation experiment setup is to evaluate the effectiveness of the proposed control technique for implementation in real application. In chapter 5, the hardware experiment setup is implemented which contains of generators and loads and it go along with the results and discussion.

The general conclusions and future works are given in Chapter 6. Appendix A provides the detail about the FIPA standard. Appendix B provides the MATLAB-MACSimJx configuration in order to interface between the multi-agent systems with microgrid simulation model. Appendix C describes the procedure how to execute multi-agent system in Jade.

CHAPTER 2

REVIEW OF RELATED LITERATURE

In order to control microgrid, its really important to exactly know about its behaviour. This section, the detail about microgrid is provided which include it operation and various control method done in microgrid control. Further, the control method which use in this thesis also provide in this part with the briefly talk and its application have been done by other researcher with the various purpose.

2.1 Microgrid

A Microgrid is a new form of electric grid in term of power system. It is formed by the interconnection of various small-distributed energy resources with the cluster of loads and energy storage. The most sources of the microgrid are based on renewable energy such as PV, wind power, micro turbine, natural gas, combine heat and power (CHP) and biogas. The energy storage can be battery, flywheel or super-capacitor. The microgrid has two different operation modes, grid-connected and islanded mode.

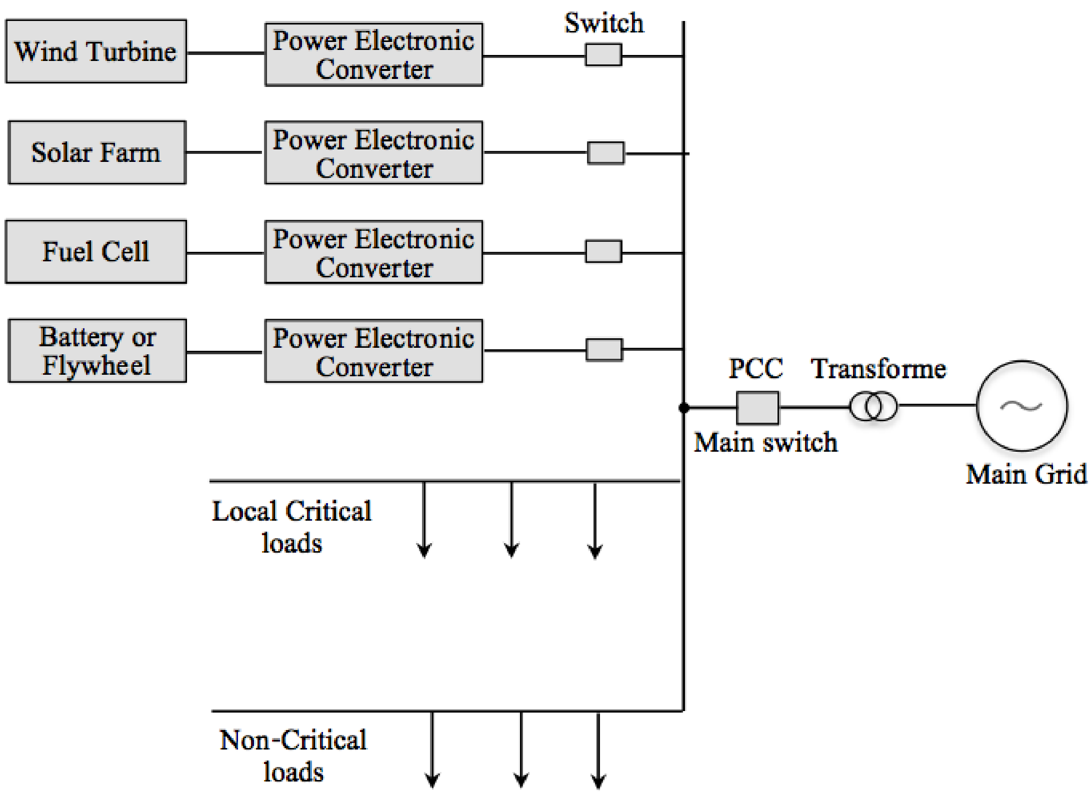


Figure 2.1: Basic structure of microgrid

Implementation of microgrid systems provide many advantages both from the user and from the electric utility provider:

From grid point of view, the main advantage of a microgrid is that it is treated as a controlled entity within the power system. In addition, microgrid can reduce the power flow on transmission and distribution lines, so as to reduce losses and reduce costs for additional power. Moreover microgrid can also reduce the load on the network by eliminating the impasse in meeting electricity needs and help repair network in case of errors [6]

From customers point of view, microgrids are beneficial for locally meeting their electrical/heat requirements. They can supply uninterruptible power, improve local reliability as well as network quality, reduce feeder losses and provide local voltage support and can reduce the cost to be incurred by the user.

From environmental point of view, microgrids reduce environmental pollution and global warming through utilization of low-carbon technology.

2.1.1 Operation and Control

Microgrid development has done by many countries such as India, Malaysia, and Haiti [7] . Since microgrid offers many advantages such as better power quality and more environmentally friendly. Moreover the economic potential that may still be used from this system is the opportunity to utilize the waste heat from the engine generator using a combined heat and power (CHP). However, to achieve a stable and secure operation, a number of technical, regulatory and economic issues have to be resolved before microgrids can become commonplace. Some problem areas that would require due attention are the intermittent and climate-dependent nature of generation of the DERs, low energy content of the fuels and lack of standards and regulations for operating the microgrids in synchronism with the power utility. The study of such issues would require extensive real-time and off line research, which can be taken up by the leading engineering and research institutes across the globe.

2.1.1.1 Islanded Mode

As mentioned in the above part, the microgrid can be operating in islanded mode and grid-connected mode. In the islanded mode, the microgrid is separated from the main grid by opening the main switch at point of common coupling (PCC). The microgrid switch to islanded mode when the up-steam system (main grid) faces some inconvenient condition like up-steam fault or maintenance purpose. In this operation mode, the total power demand is fully supplied by the DGs of microgrid; some low priority loads (non-critical load) need to be cut to secure the system from collapse as the power supply shortage. Moreover, the system voltage and frequency are not fixed which are dynamic based on the active and reactive power requirement. The all about problems can be solved by developing some control techniques, which conducted by other researcher to regulate voltage and frequency as well as perform load-shedding.

2.1.1.2 Grid Connected Mode

Another operation mode of microgrid is grid-connected. In grid-connected mode, the voltage and frequency of microgrid are followed to utility voltage and frequency. The power can flow from microgrid to main grid when the power demand is less than the total rated power of the DGs and flow from main grid to microgrid in case of over demand. For this operation mode, the function of the overall control is thus to issue the real and reactive power commands for the systems. The overall control can calculate the commands based on a variety of criteria, such as market signals and economy of the microgrid; optimal operation and well being of the microgrid; host grid conditions and requirements; and microgrid internal conditions and requirements. For example, during hours when the grid electricity is cheap, the overall control may decide to reduce the power outputs of the gas micro-turbines and charge the energy storage devices mainly through the grid power. At the same time, in response to a grid command, it may dispatch the DER systems in such a way that the microgrid draws reactive power from the host grid, in order to prevent an overvoltage on the grid side of the MPC. It has one thing to notify that in the system which consist motor load, a slight transient in voltage cause large power swing. So the voltage at PCC should not deviate from it normal value and the VSCs must quickly supply to power demand. To realize the better power tacking in grid-connected mode, the microgrid is commonly control by current-mode and voltage-mode control [8] as show in Figure 2.2 and Figure 2.3. For these control method, the DERs have been assumed to be dispatch, which is, its real and reactive power are commonly byproduct of an optimal operating condition.

2.1.1.3 Control Method

The basic structure of microgrid as shows in Figure 2.1 contains many power electronics equipment such as the microgrid separation device at PCC, power flow controllers, and solid state breakers and so on. While generation control in grid-connected inverters is straightforward, significant complexities appear in the microgrid mode of operation. A reliable and robust operation of a microgrid system strongly relies on an efficient control scheme of microgrid generators. For insuring the flexibility and reliability of microgrid it is necessary to control the various power

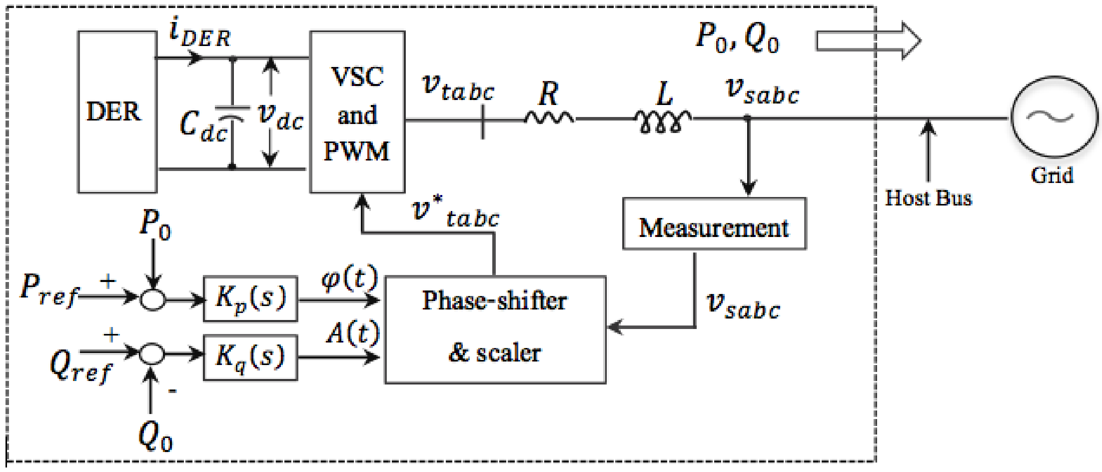


Figure 2.2: Schematic diagram of voltage mode control of real and reactive power

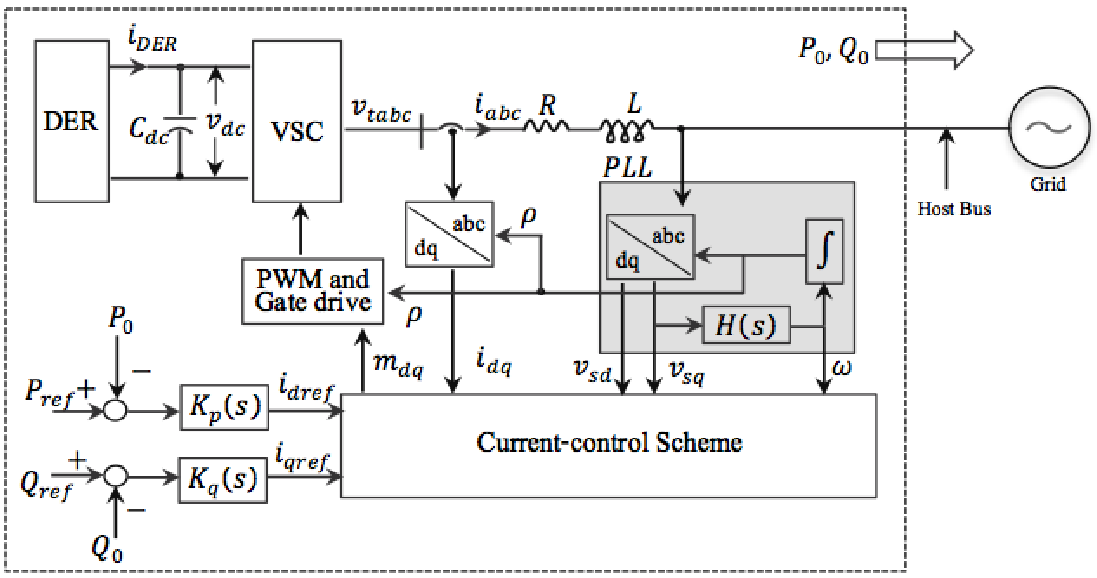


Figure 2.3: Schematic diagram of current mode control of real and reactive power

electronic equipment as well as microsources properly.

The control mechanisms aim to provide the microgrid with reliability, stability, power quality as well as facility to both of user and utility. The control can perform through regulation voltage and frequency, as well as reactive and active power output, to fit the setting or create some advance supplement devices. Many researches have been conducted by using various control methods to control the microgrid devices such as Microsource, loads and energy storage system.

The most sources of microgrid are based on renewable energy or converter interfaced which are strongly dependent on the weather condition, so it important to make the optimal operation planning for microgrid. The author S. Agko et al [9] proposed the PSO (Particle Swarm Optimization) method to make an optimal planning for islanded microgrid operation which takes into consideration of the uncertainties of renewable power generations and loads demand. With the inverter interfaced generator, we can get the desire output active power by control frequency or converter voltage angle and reactive power by control the converter voltage amplitude. The author [10] use voltage and frequency droop control method to realize microsources plug-and-play concept for sharing the power demand automatically by using only local information such as voltage and frequency, instead of communication between each microsource.

Normally, the microgrid can operate in grid-connected and islanded mode. There are some cases in which microgrid operates in islanded mode like up-steam fault and maintenance purpose; microgrid must resynchronize before it reconnects to the main grid. It seems not an easy task for microgrid-utility synchronizing since the microgrid consists of multiple DGs. It is needed to control multiple generators in a coordinate ways. To handle this, the author C. Changhee et al [11] proposed an active synchronizing control scheme that adopts the network based coordinated control of multiple DGs.

There are some factors can affect to the efficiency operation of microgrid such as microgrid structure, type of the microsource and its operation, the sensibility of the load on the power quality. So that, the difference control are used when microgrid operate in difference mode. To maintain the microgrid stability, reliability, security and economical for all operation, the coordinated control of micro-power and energy storage device is proposed [12].

In some industrial microgrids, the controllable and non-controllable DERs have to work together in close coordination. To effective share the power demand between controllable and non-controllable DERs, the author P.K. Vineet [13] have implemented a supervisor control system, object linking and embedded for process control (OPC), for the controllable DER fuelled by producer gas. From this control technique, the power output has been controlled using a control system in cascade configuration.

In the medium-voltage microgrid, the dynamic loads (e.g. line-start induction motor (IM) loads) could be high penetrating. It can be subjected to power oscillation and instability when the highly nonlinear IM dynamics is involved. Motivated by the aforementioned difficulties, the author A. Kahrobaeian et al [14] proposed a two-degree-of-freedom active damping controller to stabilize the newly introduced oscillation dynamic.

To improve the power quality from the wind turbine with an excellent tracking ability during wind change, the researcher [15] has been implemented a robust and much faster vector control algorithm based strategy for two-level IGBT full power converter with a hybrid DC-AC link topology to operate the wind generation either in Maximum Power Point Tracking (MPPT) mode, or non-MPPT mode.

For optimal operation of a group of Small Water Turbines integrated in a medium voltage AC grid, a variable speed solution has been proposed. The efficiency of hydro machines is increased as there is a large variation in water flow, so operation at variable speed is considered such that the connection to the 50 Hz power grid can be done using an AC/DC-DC/AC interface. The purpose of a reactive power and a harmonic voltage compensation and transfer of energy from generator to grid is achieved by the use of power electronic based interface [16].

Since PV become widely use around the world, many researches have been conducted to bring down the cost of PV cell. PV is known as a main microsource of microgrid and PV inverter is a major device to bring PV to AC electrical grid. PV inverter consumes around 20 percents of the system cost with the guarantee from 5 to 10 years. To drive down the system cost, the reliability and efficiency of PV inverter is needed. The author Y. Xiaoming [17] proposed some major technique to increase efficiency and improve reliability of PV inverter.

The author K. Ashay et al [18] proposed a new smart energy system for hybrid grid based residential utility. This technique is suitable for department building, green data center, commercial and residential. The smart energy system consists of smart meter, smart energy management and central intelligent unit. With smart meter, it provides feasibility for monitoring the power consumption and electricity bill. The optimal decisions on energy flow direction can be release through smart energy management. The pricing, renewable energy output, load demand, storage, and forecasting, decisions are made and communicated by a central intelligent unit and thus providing a supporting power in cases of power cut, blackouts, grid failure, and peak demand, as well as results in minimum purchase from the utility.

The author T. Ise [19] has implemented a DC microgrid system, which is composed of several PV generation systems, a battery bank and loads. The converter in this system is controlled by two levels control such as MPPT and CV (constant voltage). The control levels are changed autonomously based on local information. However, there are several problems like voltage rise in dc link causing loss of maximum power control by sudden change of irradiance and load. The author proposed MAS (multi-agent system) as intelligent control to solve those problems as well as to handle bidirectional power and information flows.

A multi-agent based control framework with Particle swarm optimization (PSO) has been proposed for energy and comfort management in integrated smart building and micro-grid systems which is made up of a central coordinator-agent and multiple local controller-agents [20]. A.L Kulasekera et al [21] proposed a dual layer multi-agent systems for control microgrid aimed at intentional islanding. The primary layer includes a User agent, a Distributed Generator(DG) agent and a control agent. The secondary layer consist of a low voltage (LV) agent and Load agent. The MAS develop in JADE platform and used to control a microgrid simulated in MATLAB/SIMULINK.

2.2 Droop Control

The droop control is a technique commonly used for load-sharing of parallel generator and for regulating voltage amplitude and frequency. The main advantage of a droop-based approach is that it obviates the need for communication since the control action is performed merely based on local measurements. This feature gives droop control a significant flexibility in that as long as a balance between generation and demand can be maintained, there is no interdependency between the DER unit local controllers. The p vs. f droop loop allows parallel-connected generators to operate in a safe way sharing variations in the load demand in a pre-determined way without any dedicated communication means. Similarly, the q vs. v droop loop is used to minimize the circulation currents that would appear if the impedance between the generators and a common load were not the same.

There are a few drawbacks in this control technique due to its droop characteristics such as slow transient response, frequency and voltage deviation, imbalance harmonic current sharing and high dependency on converter output impedance.

To improve the performance of droop control scheme, many researchers have been conducted. In [22], a droop control technique is proposed in which high droop gains are used. High droop gains can give a better reactive power sharing among inverters in microgrid but simultaneously affect the stability of a system. A reactive power injection loop is used with the conventional droop control. This method does not require any communication link as it uses local measurements. There is another method in [23] which gives better functioning of power-frequency droop by using arctan function. This method not only increases system stability but also gives natural frequency bounding between the two-inverter systems. There are many adaptive techniques have been proposed by Joseph M. Guerrero, who is trying to build a foundation to use advanced control techniques to improve the performance of a conventional droop control. In paper [24], an adaptive control method is proposed in which estimated voltage magnitude and frequency and the angle of grid impedance is used. This enables an inverter to independently inject active and reactive power into the grid. When two inverters are connected in parallel then there is a flow of circulating current between them during their transient period. This circulating current emerges due to initial voltage differences between two inverters. A solution to this problem is proposed in [25] which is to improve the response speed of controller during the transient state. If the duration of transient period is longer, then circulating current can damage an inverter. A virtual impedance method is proposed in [26] to have better reactive power sharing between parallel-connected inverters regardless of the difference in line impedances and unequal sharing of non-linear load.

2.3 Multi-Agent System

Even a single agent can operate as a system, by reacting and interacting with its environment. Such an agent will require specific programming to provide itself with individual knowledge, actions and goals. Any other agents in the same environment will not have any effect on the operation of such an agent. As the aim of this thesis is to implement a multi agent system for distributed control (intelligence), the following available feature set is ideally suited for such applications. Features of a multi agent system [27]:

- Autonomy: Agents are capable of operating without human supervision.
- Social ability: Agents are able to communicate with each other as well as human operators using a common language.
- Reactivity: Agents are able to identify and react to changes in the environment.
- Reactivity: Agents are able to identify and react to changes in the environment.

2.3.1 The Multi-Agent System Versus SCADA

Most conventional power systems rely on Supervisory Control and Data Acquisition (SCADA) systems for control and communications. SCADA work like a centralize control system. It collects a large data from the system before it does some control tasks. Therefore, SCADA may provide slowly response when the system is so dynamic. In terms of a microgrid, the aim is to allow for flexible integration of a multitude of different distributed energy resources (DER) and/or non-conventional renewable energy sources (NCRES), which those sources are intermittent nature. So, SCADA is not a good application for microgrid control. Use of multi agent systems to provide distributed control capabilities to the microgrid applications offer various advantages over conventional SCADA systems. Multi agent system development platforms are available as Free and Open Source (FOSS) applications and most of them are based on Java, making them platform independent. They can also be combined with external programming to interface with different external hardware and software systems. These advantages make multi agent systems more suited for microgrid control. In addition, multi agent systems also have the following advantages in context of microgrid control:

- Multi agent systems are inherently flexible and extensible.
- Local loads and sources will have different specifications and systems. Therefore, an intelligent distributed control system is the best solution.
- The microgrid will have to take rapid autonomous decisions regarding seamless transition to islanded mode from grid-connected mode and protecting critical loads by load shedding.

Multi agent systems work like decentralize control system. It allows for a complex task to be broken down into several smaller tasks assigned to a team of agents. This allows for easier handling of a larger problem.

2.3.2 The Applications of the Multi-Agent System in Electrical Field

In the recent literature review demonstrated that the multi-agent system has been widely used cover the various categories such ass distributed microgrid control, electricity trading, optimization, power restoration, power monitoring and diagnostic and power system protection.

2.3.2.1 Distributed Control

The researches [28–43] focus on distributed control based multi-agent system. These researches, present the new trend of the MAS application in microgrid. The various architecture and framework are provided with the simulation to prove their effectiveness in the microgrid control.

The main feature and a basic hierarchical of MAS in [28] to demonstrate the ability of MAS to control small power in distributed microgrid. The multi-agent system technology is proposed in [29] to control the state (start/stop) of generator and loads in microgrid. In [30], the multi-agent system with the hierarchically equal control architecture without a central agent is given to resolve real and reactive power mismatch within microgrids. Though there is no central agent, a neighbour-to-neighbour three-step communication algorithm is used to determine the real and reactive power mismatches. In [31], a three tiered hierarchical coordinated control strategy which aims to utilize the MAS most efficiently for voltage stability and power balance in the microgrid has been proposed.

The MAS operation planning is accomplished by using artificial neural networks and fuzzy systems for generation planning and load forecasting. A multi-agent based control architecture that can ensure robust, stable, and optimal microgrid operation was proposed in [32] for a real-time power management and control system that attempts to optimize microgrid systems based on multiple objectives, such as power demands, fuel consumption, environmental emissions, costs, dispatchable loads, etc. Autonomous operation in island mode is proposed using a Multi-Agent Reinforcement Learning Algorithm that utilizes the concept of layered learning in [33]. The concept of layered learning is used to group various controls and actions of the agents depending on their effect on the environment and for the agents to ultimately coordinate in achieving their goals.

MAS controller for the MAS control architecture is given in [34]. An intelligent load controller is described in [35] based on the same system. Further, the ability of MASs to achieve efficient use of NCRES and green technologies is also described. A controller for bilateral switching between grid-connected operation and islanded operation is simulated in [36] for monitoring and control of a microgrid. Intelligent Distributed Autonomous Power Systems (IDAPS) of Virginia Tech [37] illustrates the capability of MASs to be considered as a software alternative to traditional hardware-based zonal protection that can be used for effective islanding. Their system demonstrates the MASs ability to disconnect and stabilize the microgrid while being able to allow for redefinition of zonal boundaries on the fly. A control algorithm comprising of an intelligent connection agent and grid synchronization system is used in [38] to ensure the appropriate microgrid disconnection from the main grid. This is used to improve the performance of microgrid and its interaction with the main network, or another microgrid, under grid voltage transients.

MAS based DG controllers have been presented in [39], [40], [41]. A multi-agent based DG microgrid control framework is presented in [39] for a DC distributed energy system that can be used in a microgrid as a modular power generation unit. Two-layered control architecture is presented in [40] to achieve local autonomy and global optimization respectively, operating in both grid-connected mode and islanded mode. A multi-agent models used in [41] take each element in the microgrid as a separate autonomous intelligent agent and are simulated using the Real Time Digital Simulator (RTDS) and the PowerWorld Simulator respectively.

A smart grid (SG) should ideally be built up of microgrids. Therefore a multi- microgrid system is essentially a SG system. Multi-microgrid systems inherit self-healing, intentional islanding, and the anticipation of the entire distribution network from SGs and the ability for dynamic behaviour from microgrids. MAS based control systems have been proposed for multi-microgrids in [42]. A hybrid MAS is presented in [43] where the controller is able to intelligently choose the operation model, self-control the optimal operation of microgrid, monitor real-time data and provide autonomous local protection.

2.3.2.2 Electricity Trading

MAS has been applied for electricity trading or market model analysis [44–49]. A power market model is introduced in [44] for the effective operation of the microgrid. MAS electricity-trading algorithm is proposed in [45] to maximize the revenue from the microgrid. A case study is used in [46] on price determination based on demand and supply side bidding strategies to propose a pricing mechanism for microgrid energy in the competitive electricity market. The same mechanism is developed in [47] by using a microgrid central controller to participate in the bidding process to settle the market-clearing price (MCP). This is done using a MAS which is able to incorporate the mechanisms of a prevailing electricity market for high integration of NCRES into microgrids. A retailing spot market of electric energy proposed in [48] is able to interoperate with other stakeholders in the utility grid using a cooperating MAS. The system described in [49] uses negotiation between two agents, representing an independent system operator and a transmission company, to determine whether a transmission circuit may be operate in excess of its rated load and, if so, how many compensation should be paid by the system operator to the transmission company.

2.3.2.3 Optimization

MAS based controllers has been used in [50–53] for optimizing microgrid operations. As loads and sources within a microgrid can be diverse and distributed, real-time reaction and DG source management is critical in preventing local power outages. It is also essential that this is done most efficiently and cost effectively as possible for the microgrid to be economically viable. The systems presented in [50] consider the characteristics of the source or load types and self-regulates with other agents in order to globally optimize in terms of cost and efficiency. The optimization MAS in [51] is able to determine the optimal operation of a solar-powered microgrid considering the load demand, environmental requirements and PV panel and battery capacities. A competitive pricing mechanism is also presented, using auction theory and two bidding techniques (i.e. single bidding and discriminatory bidding) in order to serve the consumers at a reduced price and to provide better revenues. In [52], power production is maximized with respect to production cost and DG unit constraints. Demand Side Management (DSM) is also utilized via a load control agent. The MAS is able to monitor energy resources and schedule generation (dispatch control) for optimized microgrid operation. An artificial immune system based algorithm is used by the MAS in [53] to optimize the production of the local DGs in order to optimize the microgrid operation.

2.3.2.4 Power Restoration

MAS has been used for power restoration of microgrids in [54–57]. The load restoration algorithm in [54] consists of agents that make synchronized load restoration decisions according to information learned from their direct neighbours. Though only the direct neighbours are contacted, global information is discovered based on the Average-Consensus theorem. Thereafter, the load restoration problem is modeled and solved using algorithms for the 0-1 Knapsack problems. Power restoration in the case of a large-scale blackout in a microgrid with DGs is discussed in [55], [56]. The models used the available capacity of DGs to reduce the blackout area. A MAS using the Agent-Environment-Rules (AER) ontology and the Constraint Satisfaction Problem (CSP) based model is used in [55]. An asynchronous backtracking algorithm is used to solve the AER model based on CSP. In [56], a multi-agent immune algorithm is used for rapid restoration of power. A method called a random tree method is used to code antibodies into the immune algorithm to prevent unfeasible solutions. High frequency mutation is carried out for the antigens to be dynamically changed in order to rapidly converge to the solution. A hierarchical control strategy for power restoration is given in [57] targeting swift power restoration to the most critical loads.

2.3.2.5 Monitoring and Diagnostic Functions

Multi-agent system approach is an excellent tool for collecting and manipulating distributed information and knowledge. Currently, power engineers use multi-agent system for the management and interpretation of data for a wide variety of monitoring and diagnostic functions such as condition monitoring and post-fault diagnosis. Condition monitoring [58], [59] of equipment and plant items offers a number of challenges such as gathering data from a variety of sensors and interpreting the data to extract meaningful information. This requires the use of multiple algorithmic and intelligent system-based approaches. Approaches combine the evidence and information from different interpretation algorithms to generate an overall diagnostic conclusion, deliver diagnostic information in the correct format to relevant engineers, and automatically alter power system and plant settings based on the condition of the plant. Multi-agent system allows the combination of data from all sources in a flexible manner by delegating the tasks of monitoring each source by an intelligent agent. Multi-agent system is one of the best suitable technologies for post-fault diagnosis [60] of power system faults. When operational engineers investigate the causes and impact of power system faults, they employ a number of data sources. These include data from SCADA, digital fault recorder data and travelling-wave fault locator data.

2.3.2.6 Power System Protection

Protection and fault management systems are important parts of the automation process in power systems. This should include the knowledge about failure modes and their causes and provide information about the presence of faults in the processes as soon as possible. This task involves timely detection of an abnormal event, diagnosing its causal origins and then taking appropriate supervisory control decisions and actions to bring the process back to a normal, safe, operating state or, at least, with minimal process operation degradation. The multi-agent system technology has been investigated for the protection of power system by several research groups [61] and [62]. It is a good option to create a distributed, modular and collaborative fault management system for the industrial processes [63]. Multi-agent system coordination for system protection is presented in [64] consists of relay agents, distributed generator agents and equipment agents. The agents communicate with each other within the same agent society or within different agent societies. For an example, a distributed generator agent communicates with relay agent to provide connection status. An innovative Fault Tolerant Networked Control System based on Multi-Agent Systems (FTNCS-MAS), is proposed in [65] with a framework involving simultaneously decentralized and centralized topology. Extensive research in protection and fault management has been done in the area of power system protection and shipboard power system protection [66].

CHAPTER 3

A SINGLE-PHASE MICROGRID AND THE DECENTRALIZED CONTROL

The microgrid concept involves of multi-operating of distributed energy resources, which the most of those sources are based on renewable or converter interface with the intermittent nature. From literature review in section 2.1.1.1, the voltage and frequency are dynamically based on the power demand change when microgrid in islanded mode. So the effectiveness control of the system that can provide faster response like decentralized control is highly appreciate.

In this research, a single-phase microgrid system is modelled as shown in Figure 3.1. This system consists of two parallel generator, a photovoltaic generator, loads and main grid.

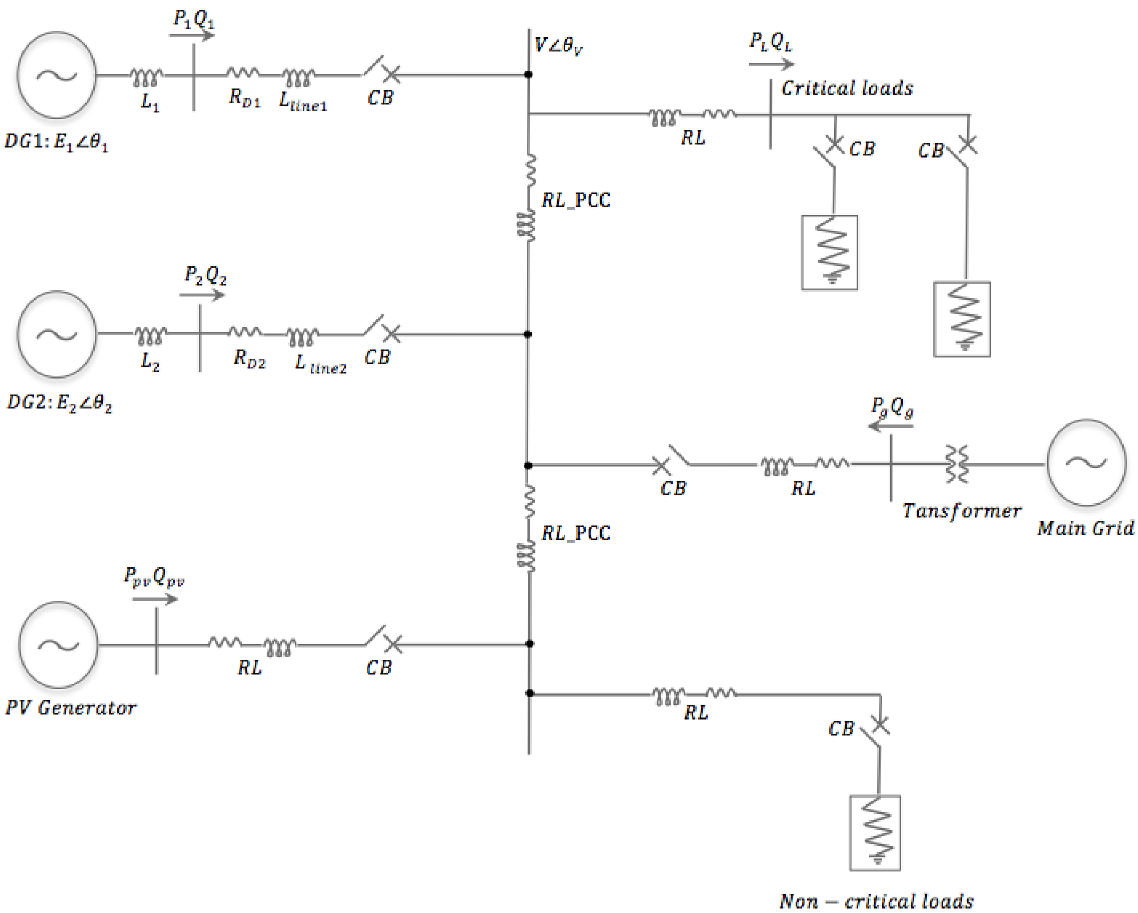


Figure 3.1: Single-phase microgrid system model

Where the converter output voltages are denoted by $E_1\angle\theta_1$ and $E_2\angle\theta_2$ and connected to the microgrid with output filter of inductance L_1 and L_2. P_1, P_2, P_{pv}, P_g and Q_1, Q_2, Q_{pv} and Q_g represent the real and reactive power supplied by the DG1,DG2, PV generator and main grid, while P_L and Q_L are respectively the real and reactive power demand of the load. The line resistances are denoted by R_{D1} and R_{D2} while L_{line1} and L_{line2} represent the line inductances.

The sizing of the microgrid components are designed based on the programmable voltage sources in the laboratory for the later experiment setup. For the simulation setup, both grid-connected mode and islanded mode are studied; while in the experimental setup only islanded mode will be implemented.

The decentralized control system for the microgrid is divided in three levels. Primary control which uses droop control technique for load sharing between the two generators. Secondary control is used to restore the operating frequency of the microgrid from deviation which results from droop control. Tertiary control or supervisory control aim to manage the overall operation of the microgrid, which the multi-agent system is adopted.

In the subsequence sections, the basic knowledge and the detail on designing of each control technique are given.

3.1 Primary Control: Droop Control

3.1.1 Droop Control Characteristic

The same principle is followed in this technique to control the flow of active and reactive power by controlling the frequency and amplitude of the output voltage. When the flow of active power increases due to the increase in load, frequency of an inverter drops, similarly when the flow of reactive power increases then voltage will drop. From Figure 3.2(a), the frequency droop characteristic can be interpreted as follows: when frequency falls from rated w_0 to w_1, the power output of the generating unit is allowed to increase the power dispatching value from P_0 to P_1. A falling frequency indicates an increase in loading and a requirement for more active power. In same way for voltage droop characteristic as shown in Figure 3.2(b) when the coupling point voltage of synchronous generator decreases from V_0 to V_1, generators are allowed to increase its reactive power from Q_0 to Q_1 level. A simplified of the Microsource shown in Figure 3.3(a), all vectors and their associated reference direction can be seen in it. Figure 3.3(b) is the vector diagram of the microsource.

The power inject from each DER can be described as follow:

$$S = P_s + Q_s \tag{3.1}$$

$$P_s = VIcos\varphi \tag{3.2}$$

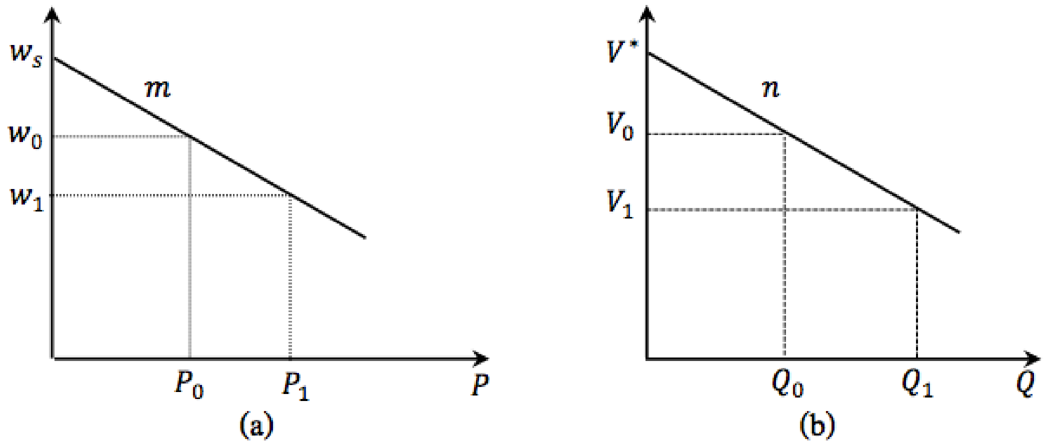


Figure 3.2: Frequency and voltage droop characteristic

$$Q_s = VIsin\varphi \tag{3.3}$$

Notice that $cos\varphi$ is the power factor, $\varphi = \angle\theta_V - \angle\theta_I$; $\delta = \angle\theta_E - \angle\theta_V$. By apply geometry knowledge to Figure 3.3(b), Eq. (3.4) and Eq. (3.5) can be got:

$$X_d I cos\varphi = Esin\delta \tag{3.4}$$

$$X_d I sin\varphi + V = Ecos\delta \tag{3.5}$$

Simplified Eq. (ref4) and Eq. (3.5), Eq. (3.6) and Eq. (3.7) can be got:

$$Icosn\varphi = \frac{1}{X_d} sin\delta \tag{3.6}$$

$$Isin\varphi = \frac{1}{X_d}(Ecos\delta - V) \tag{3.7}$$

With Eq. (3.6) and Eq. (3.7), Eq. (3.2) and Eq. (3.3) are rewritten as:

$$P_s = \frac{EVsin\delta}{X_d} \tag{3.8}$$

$$Q_s = \frac{EVcos\delta - V^2}{X_d} \tag{3.9}$$

Considering that the power angle δ is small (less than 0.1 rad), we can assume $sin\delta = \delta$ and $cos\delta = 1$, then the equation Eq. (3.8) and Eq. (3.9) can be simplified as:

$$P_s = \frac{EV}{X_d}(\theta_E - \theta_V) \tag{3.10}$$

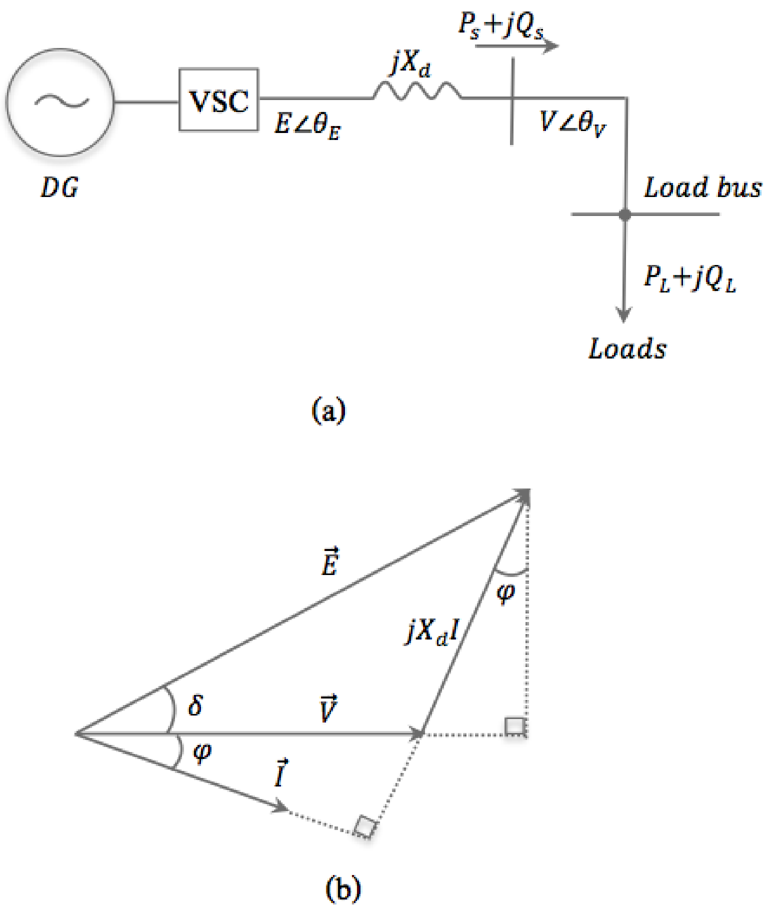


Figure 3.3: Phasor diagram of Microsource

$$Q_s = \frac{V}{X_d}(E - V) \tag{3.11}$$

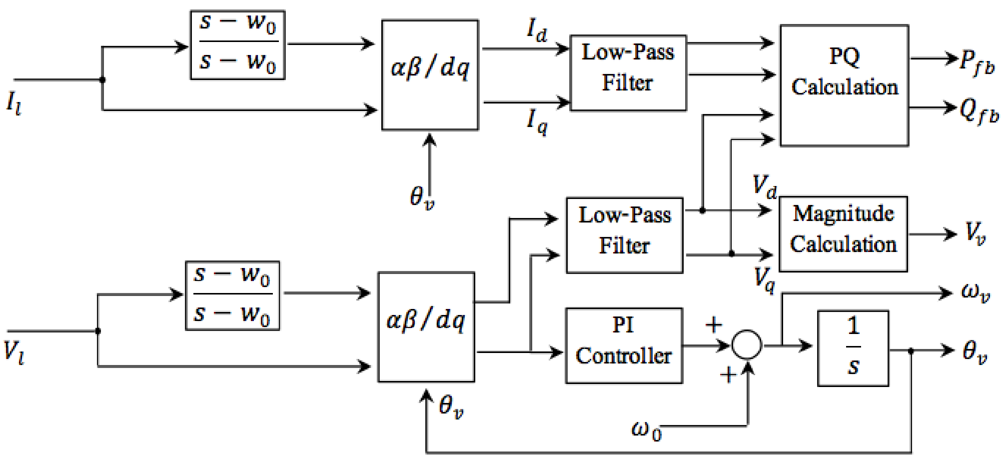


Figure 3.4: Parameter detection block for single-phase system

From equation Eq. (3.10) and Eq. (3.11), its clear that the active power from DER depend on converter output voltage phase angle θ_E and the reactive power rely on converter output voltage amplitude E. So the active power is controlled by control θ_E and the reactive power is controlled by control E.

Before the converter get the correct control signal, some parameters are needed to know in advance. Figure 3.4 shown the detection block which detecting voltage, frequency, active and reactive power for signal-phase system. The value of load bus voltage V_l and the microsoure output current I_l can be got by using voltage sensor and current sensor. The outputs from PLL block are the load bus voltage vector $\vec{V}'$s phase angle $\angle\theta_v$ and fundamental frequency w_v. The load bus voltage amplitude V_v is calculated by the rotating frame transformation block. The instantaneous power P_{fb} and Q_{fb} injected from the microsouce can express as:

$$P_{fb} = \frac{1}{2}(V_q I_q - V_d I_d) \tag{3.12}$$

$$Q_{fb} = \frac{1}{2}(V_q I_d - V_d I_q) \tag{3.13}$$

3.1.2 Power Sharing for Parallel Generator

Assume, we have a system contains of two DGs supply to the loads as depicted in Figure 3.1. The droop characteristic of these two generators is shown in Figure 3.5. From Figure 3.5;

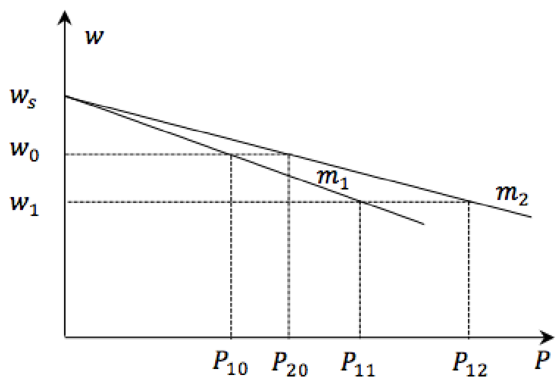


Figure 3.5: Parallel generator droop characteristic

When the power demand increase, the frequency drops can be express as:

$$\Delta w = w_s - w_0 \tag{3.14}$$

For generator#1:

$$m_1 = \frac{w_s - w_0}{P_{10}} \tag{3.15}$$

For generator#2:

$$m_2 = \frac{w_s - w_0}{P_{20}} \tag{3.16}$$

The relationship between Eq. (3.15) and Eq. (3.16), Eq. (3.17) can be got:

$$m_1 P_{10} = m_2 P_{20} \tag{3.17}$$

From Eq. (3.17), we conclude that the generators in the system can share the power between each other proportional to droop coefficient.

3.1.3 Frequency Control

For conventional droop control [1–3], frequency-active power and voltage-reactive power can express by the following equations:

$$\begin{aligned} w &= w_s - mP \\ V &= V^* - \frac{Q}{n} \end{aligned} \tag{3.18}$$

Which m and n are droop coefficients, w_s is the reference frequency, V^* is the reference voltage, V is the generator output voltage, w is the generator frequency, P and Q are the generators active and reactive power respectively.

3.1.4 Angle Control

It is possible for a VSC to instantaneously change its output voltage waveform and power sharing in a microgrid by controlling the output voltage angle of the DGs through droop. Let us consider same microgrid system as shown in Figure 3.1 is considered. First, the load sharing with angle droop is derived using the DC load flow method. It is possible to share power among the DGs proportional to their rating by dropping the output voltage angles.

The angle droop control strategy is applied to all the DGs in the system. It will be prove in section below.

3.1.4.1 Angle Droop Control and Power Sharing

From the Eq. (3.10) and Eq. (3.11), the power from the DER to the microgrid can be express as:

$$P_s = \tfrac{EV}{X_d}(\theta_E - \theta_V)$$
$$Q_s = \tfrac{V}{X_d}(E - V)$$

It is to be noted that the VSC does not have any direct control over the microgrid voltage at the bus $V\angle\theta_V$, see Figure 3.3 (a). Therefore from Eq. (3.10) and Eq. (3.11), it is obvious that if the power angle difference δ is small, real power can be controlled by controlling θ_E, while the reactive power can be controlled by controlling voltage magnitude $\vec{E}$. Thus the power requirement can be distributed among the DGs, similar to a conventional droop by dropping the voltage magnitude and angle as:

$$\begin{aligned} \theta_E &= \theta_{Erated} - K_m(P_s - P_{rated}) \\ E &= E_{rated} - K_n(Q_s - Q_{rated}) \end{aligned} \tag{3.19}$$

Where E_{rated} and θ_{Erated} are the rated voltage magnitude and angle respectively of the DG, when it is supplying the load to its rated power levels of P_{rated} and Q_{rated}. The coefficients K_m and K_n respectively indicate the voltage angle drop vis-$\grave{a}$-vis the real power output and the voltage magnitude drop vis-$\grave{a}$-vis the reactive power output. These values are chosen to meet the voltage regulation requirement in the microgrid.

To derive power sharing with angle droop, a simple system of Figure 3.1 with two machines and the loads is considered. Applying DC load flow with all the necessary assumptions we get,

$$\begin{aligned} \theta_{1E} - \theta_E &= (X_1 + X_{L1})P_1 \\ \theta_{2E} - \theta_E &= (X_2 + X_{L2})P_2 \end{aligned} \tag{3.20}$$

Where $X_1 = wL_1/E_1V$, $X_{L1} = wL_{Line1}/E_1V$, $X_2 = wL_2/E_2V$, $X_{L2} = wL_{Line2}/E_2V$. From Eq. (3.19, the angle droop equation of two DGs can give by:

$$\begin{aligned} \theta_{1E} &= \theta_{1Erated} - K_{m1}(P_1 - P_{1rated}) \\ \theta_{2E} &= \theta_{2Erated} - K_{m2}(P_2 - P_{2rated}) \end{aligned} \tag{3.21}$$

The offsets in the angle droop are such that when DG output power is zero, the DG source angle is zero. Therefore the rated droop angles are taken as $\theta_{1Erated} = -K_{m1}P_{1rated}$ and $\theta_{2Erated} = -K_{m2}P_{2rated}$. Then from Eq. (3.21) we get:

$$\theta_{1E} - \theta_{2E} = K_{m2}P_2 - K_{m1}P_1 \tag{3.22}$$

Similarly from Eq. (3.22):

$$\theta_{1E} - \theta_{2E} = (X_1 + X_{L1})P_1 - (X_2 + X_{L2})P_2 \tag{3.23}$$

Assuming the system to be lossless (as normally used in DC load flow, $P_2 = P_L - P_1$), we get,

$$(X_1 + X_{L1})P_1 - (X_2 + X_{L2})(P_L - P1) = K_{m2}(P_L - P_1) - K_{m1}P_1 \tag{3.24}$$

$$P_1 = \frac{X_2 + X_{L2} + K_{m2}}{X_2 + X_{L2} + K_{m2} + X_1 + X_{L1} + K_{m1}} P_L \tag{3.25}$$

Similarly P_2 can be calculated as:

$$P_2 = \frac{X_1 + X_{L1} + K_{m1}}{X_2 + X_{L2} + K_{m2} + X_1 + X_{L1} + K_{m1}} P_L \tag{3.26}$$

From Eq.(3.25) and Eq.(3.26), the ratio of the output power is calculated as:

$$\frac{P_1}{P_2} = \frac{X_2 + X_{L2} + K_{m2}}{X_1 + X_{L1} + K_{m1}} \tag{3.27}$$

It is to be noted that the value of X_1 and X_2 are very small compared to the value of K_{m1} and K_{m2}. Moreover if the microgrid line is considered to be mainly resistive with low line inductance and the DG output inductance is much larger, we can write:

$X_{L1} \ll X_1 \ll K_{m1}$ and $X_{L2} \ll X_2 \ll K_{m2}$

Therefore from Eq. (3.22), it is evident that the droop coefficients play the dominant role in the power sharing. Since the droop coefficients are taken as inversely proportional to the DG rating, from Eq. (3.26) we can write:

$$\frac{P_1}{P_2} \approx \frac{K_{m2}}{K_{m1}} \tag{3.28}$$

$$K_{m1}P_1 \approx K_{m2}P_2 \tag{3.29}$$

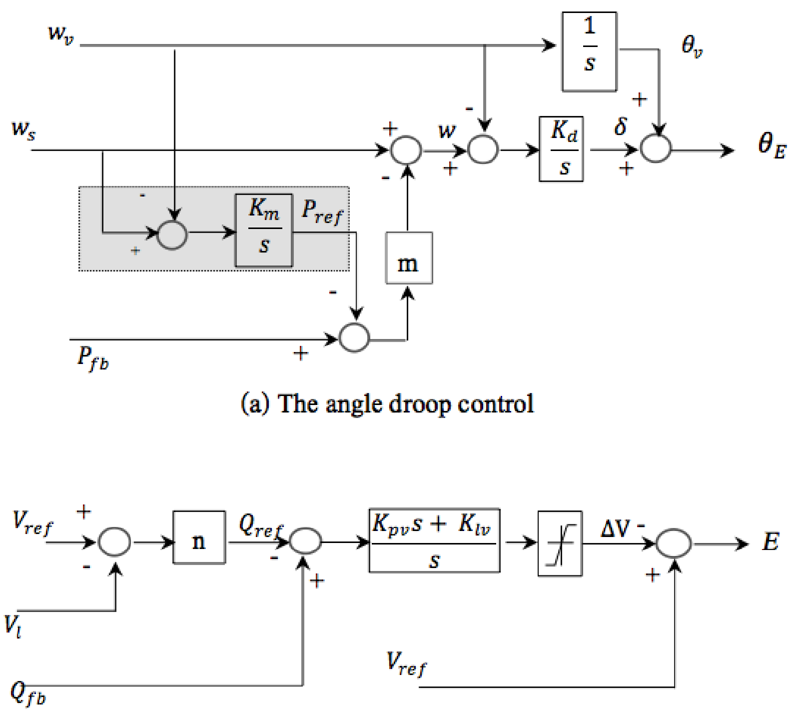
From Eq. (3.29), we could conclude that the generators in the system can share the power between each other though dropping the output voltage phase angles.

3.1.5 Implementation of Droop Control

In this section, the implementation of droop control, which use to control the generator in this research is presented. According to the author R. Majumder [67], the angular droop can provide high efficiency over frequency droop with the low frequency deviation.

For converter-based generators, the frequency droop control can be modified so that instead of frequency, the voltage phase angle is directly controlled [67], [68]. The block diagram of the modified droop control is shown in Figure 3.6. In Figure 3.6(a), the angular droop frequency w is derived from Eq. (3.18). The instantaneous power P_{fb} is determined based on Eq. (3.12) and the droop coefficient m is calculated based on Eq. (3.30).The frequency different between w and the microgrid frequency w_v is subjected in the integral controller to produce the require power angle and reference voltage angle θ_E of the generator. The integral gain K_d is used to control the dynamic response of the system [68].

$$m = \frac{w_{max} - w_{min}}{P_{max}}, \qquad w_{max} = w_s \tag{3.30}$$



(a) The angle droop control

(b) The voltage droop control

Figure 3.6: Droop control

Table 3.1: Droop control parameters

System Quantity	Values
S	2kVA
$P.F$	0.8
w_s	50
V^*	225.5
m	$2\pi(0.0009375)$
n	0.01296
K_d	0.2
K_m	200
K_{pv}	0.001
K_{lv}	0.1

$$n = \frac{V_{max} - V_{min}}{Q_{max}}\sqrt{2}, \quad V_{max} = V^* \tag{3.31}$$

For the voltage droop control in Figure 3.6, the reference reactive power Q_{ref} is calculated using the $V - Q$ droop characteristic of the generator, Eq. (3.18). The droop coeficient n is calcuted based on Eq. (3.31).The instantaneous power Q_{fb} is calculated by using Eq (3.13). The regulated component ΔV is generated from the error power ΔQ through the PI controller. The output voltage magnitude of the generator E is the summation of the microgrid reference voltage V^* and the output from PI controller.

The important parameters for droop control implementation using in this research is provided in Table 3.1.

3.2 Secondary Control: Frquency Restoration

The quickly change of load demand and power sharing with droop control may result in frequency deviation from the reference value w_s. To handle this problem, the frequency restoration is implemented as show in shaded area of Figure 3.6(a) and express in Eq (3.32), to restore the microgrid frequency. The controller gain K_m is proportional to the angle droop coefficient of each generator [69].

$$P_{ref} = \frac{K_m}{s}(\Delta w) \tag{3.32}$$

3.3 Tertiary Control: Microgrid Management Using Multi-Agent System

The increasing use of multi-agent system in automatic control, especially in power system has led to the availability of a large amount of agent development toolkit. Its really important to select a right platform for agent building which is compliant to well-known standard. The right selection will allow for easier inter-operability between different systems and universal applicability.

This research, conduct in two different experiments (simulation and real system experiment), so difference agent building toolkits are used for multi-agent system development to serve these experiments. Although two difference toolkits are utilized for development agent, these toolkits conform to a common standard of agent, which is Fundamental Intelligent Physical Agent (FIPA).

3.3.1 Standard for Agent Development

3.3.1.1 Foundation for Intelligent Physical Agents Standards

Foundation for Intelligent Physical Agents (FIPA) was originally proposed in 1996. It is an international organization that is dedicated to promoting the industry of the intelligent agents by openly developing specifications supporting inter-operability among agents and agent-based application [70]. FIPA has been widely recognize as the major standards in the area of agents-based computing. Many standard specifications has been developed, such as Agent Communication Language (ACL) and Interaction Protocols (IPs), etc. Figure 3.7 shows the overview of the FIPA standards and the detail on FIPA specification can be found in Appendix-A. In this part only one main FIPA standard specification; agent management system standard, is presented.

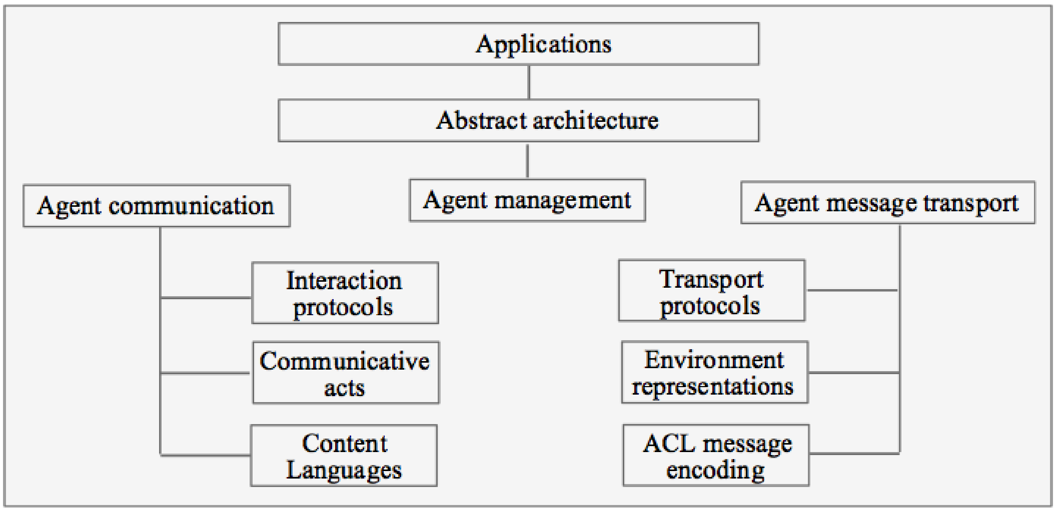


Figure 3.7: Overview of FIPA standard

3.3.1.2 FIPA Agent Management System Standard

The FIPA Agent Management System Standard Specification (SC00023K) denoted as agent management reference model of the runtime environment that FIPA agents inhabit. The logical reference is established for agent creation, registration, communication, location, migration and retirement. The referent model includes a set of logical-based entities, such as:

- an agent runtime environment for defining the notion of agent used in FIPA and lifecycle;
- an agent platform (AP) for deploying agent in a physical infrastructure;
- a Directory Facilitator (DF) which provides a yellow pages service for the agents registered on the platform;
- an Agent Management System (AMS) acting as a white pages service for supervisory control over access to the agent platform;
- a Message Transport Service (MTS) for communication between the agent registered on different platforms .

Figure 3.8 gives the FIPA agent management reference model constitution.

3.3.2 Implementation of Multi-Agent System Using JADE

In this section, the multi-agent system is developed for control microgrid model in Matlab/Simulink. A suitable, agent building toolkit platform should be selected based on its ability and standard compliant.

According to Wooldridge an agent may be defined by its characteristics as autonomous, reactive, pro activeness, with social ability. To implement a multi-agent controller, there are numbers of open-source agent platforms available such as JADE [71], ZEUS [72], SPRINGS [73] and Tracy [74]. In the context of the controlling microgrid, it is very important to select an agent platform that is based on a well-known standard, that is the IEEE standard on Foundation for Intelligent Physical Agents (FIPA). Based on the agent toolkits listed above, agent platforms that are FIPA-compliance are Zeus and JADE. For the simulation experiment, the microgrid is modeled and simulated using MATLAB/Simulink, and each agent has to exchange data with MATLAB/Simulink. In recently, a middleware called MACSimJX has been developed in the special purpose to allow multi-agent system implemented in JADE platform to exchange data with MATLAB/Simulink. This helps simplify the adaptation of MAS for electrical engineer as well

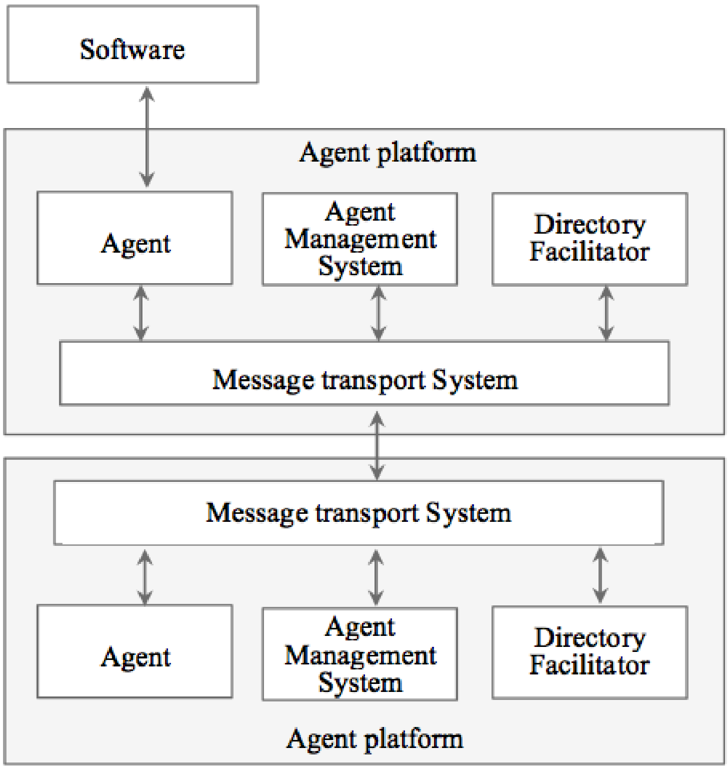


Figure 3.8: FIPA agent management reference model

as my research. Therefore, JADE has been used as MAS development platform and MACSimJx used as the middleware.

3.3.2.1 Multi-Agent System Architecture

In this section, we design multi-agent system capable control distributed of a microgrid. The MAS is developed in JADE (Java Agent Development) platform and it is used to control a micro-grid simulated in MATLAB/Simulink. There are several different multi-agent architectures have been presented in [75]. Based on the proposed control architecture, it is necessary to define the functions and roles of each agent accordingly. A function of an agent is defined by a set of behaviors. An agent can execute several behaviors in parallel or concurrently. Within this research, multi-agent system consists of three agents such as Control agent, DER agent and Load agent. Each agent serves at different responsibility as show in Figure 3.9:

- **Control agent:** The main function of the control agent is to control switch at common coupling point (the point of connecting between micro-grid and main system) and perform load-shedding. The complete task of control agent is provided in Figure 3.10.

- **DER agent:** This agent is responsible for storing information regarding the DG unit. The

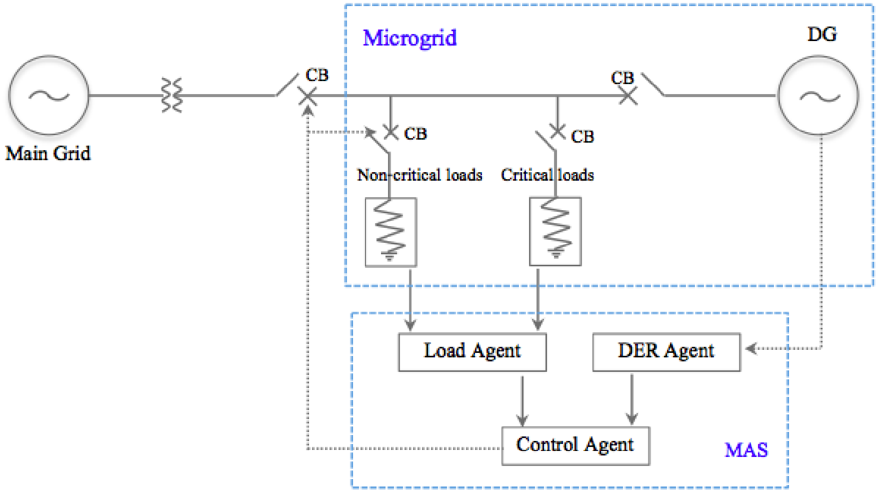


Figure 3.9: Multi-agent architecture

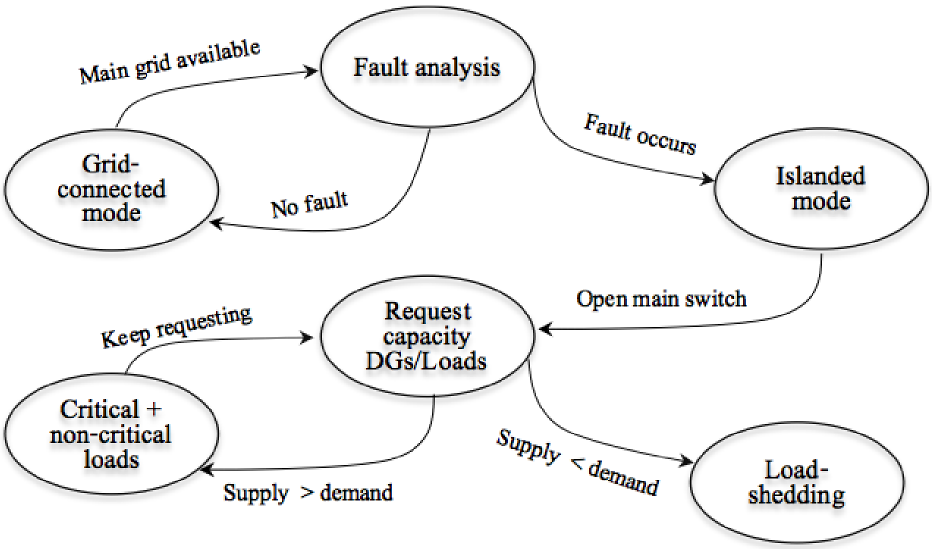


Figure 3.10: State diagram of Control agents tasks

information stored regarding the DG includes connection status and power rating.

- **Load agent:** It use to monitor and control load and varying power consumption.

3.3.2.2 JADE

JADE was originally developed under TILab, formerly CSELT, in Italy (Bellifemine et al. 2005) to address the lack of support available for building agent systems. As its name suggests, this framework offers an environment in which to create agents written in Java. It provides a run-time environment, which the agents require in order to operate, an extensive library of classes with methods built around the FIPA specification of agent characteristics, and graphical interfaces for monitoring active agents. As show in Figure 3.11, Jade is composed from four main components such as:

- **Agent management system:** The AMS ensures that each agent has a unique name and can be used for creating and removing agents from the platform.
- **Directory facilitator:** It implements like the yellow page service. From DF, an agent can register their service or get from other agent in the system.
- **Agent communication channel:** It works as gate or routes for agent to exchange information by using an agent communication language (ACL).
- **Message transport:** It uses to transfer data from agent to agent.

Each instance of a runtime environment is called a container; several of these make up a platform. The first container to be created needs to be designated as the main container; subsequent containers then register with this as they join the platform. Containers can be spread across several networked computers. The main container hosts an agent management service (AMS) and a Directory Facilitator (DF).

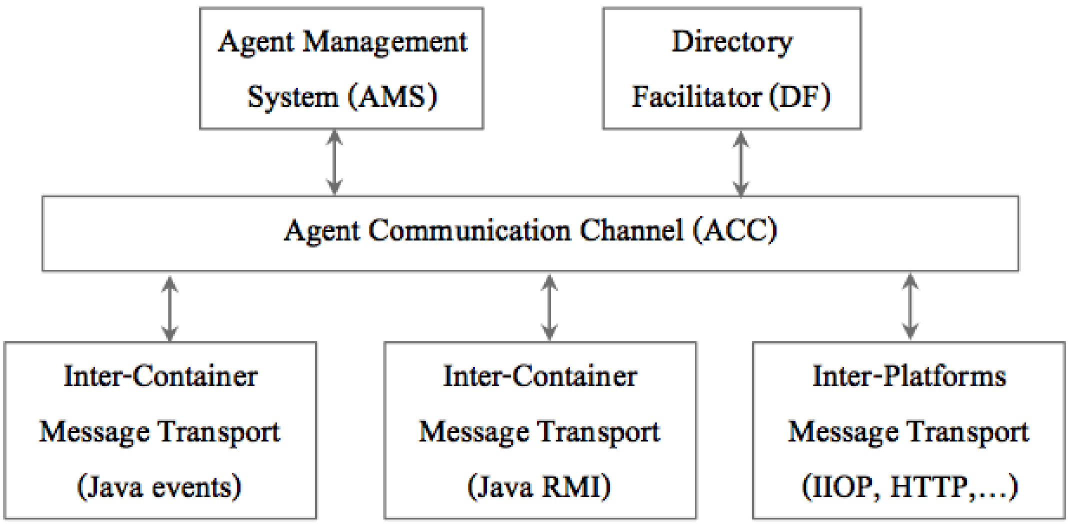


Figure 3.11: Jade architecture

Agents operate from within the containers. The structure of an agent consists of a setup() method, one or more behaviour methods, and a takeDown() method. The setup() method is executed the first time an agent is created and runs only once. It sets all the initial conditions needed to get the agent up and running, including the behaviours it requires.

The behaviour methods can run concurrently and are responsible for carrying out the main tasks of an agent. This includes communicating with other agents. An agent can be put to sleep if it has no behaviours operating and awaken after a specified period, or on receiving a message, to carry out an action. This can be very useful because the agent consumes no processing power when it is in sleep mode.

Agents communicate using the agent communication language (ACL) specified by FIPA (Bel- lifemine et al. 2003), which divides a message into sections that include information about the sender, the recipient and the message type, which could be a query or request. The behaviours can be designed to respond differently to various types of message.

3.3.2.3 MACSimJX Middleware

This section, presents the detailed implementation of the communication middleware used in the controlling microgrid simulation model. The communication middleware allows the MAS to send/receive data to/from the microgrid model in the simulink. The MAS needs to know the status of the agents to take the necessary control actions that are applied to the electric model. MACSimJX, or the Multi-Agent Control for Simulink program is an interface that enables models of systems created in Simulink to exchange data with a multi-agent system created using JADE, described in [76]. It was purposely developed as a medium through which a program for implementing agent designs developed in C/C++ or Java might pass data to and from Simulink. MACSimJX has a client-server architecture, where the client part is embedded in Simulink through an S-function, and the server code is then incorporated in the separate program. The communication between the client and server is then performed through the use of named pipes in Windows as show in Figure 3.12.

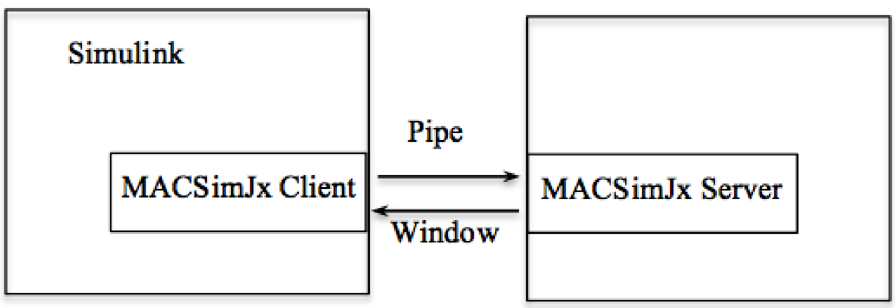


Figure 3.12: Structure of MACSimJx

3.3.2.4 Jade-Simulink Data Exchange with MACSimJX Interfacing

MACSimJX provides the means, utilizing JADE, to receive data from Simulink via the MACSim interface and to pass this on to relevant agents for processing. Once the agents have finished working on the data, the data must be returned to Simulink along the same channels. The agents are designed to accomplish some goal, such as optimization of incoming data.

For this purpose it seemed logical to divide the agent model into two parts, the Agent Environment (AE) and the Agent Task Force (ATF). The environment is a transformation of the MACSim server, previously mentioned, to provide a transparent connection between Simulink and the JADE agents. It contains the groundwork required for any generic agent model spread across Simulink and a JADE program, including responsibility for passing any data between the two programs.

The other part, the ATF, contains the agents responsible for interacting with the Simulink data. Some simple protocols need to be followed by the agents of the ATF to ensure the appropriate exchange of data with the AE. For all other purposes, these agents may be developed as normal, with the behaviours and goals one may wish to see implemented in a real-life system. The arrows in Figure 3.13 outline the communication paths for the three sections of the complete model.

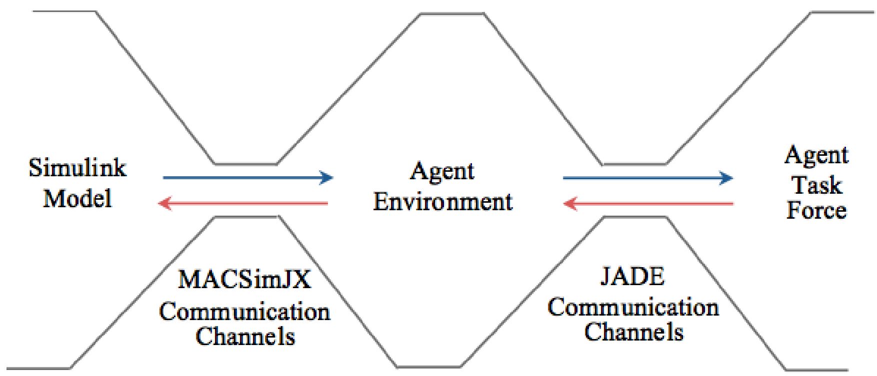


Figure 3.13: Outline of the complete interface

3.3.3 Implementation of Multi-Agent System Using Mobile-C

In this section, the multi-agent system is developed for hardware experiment purpose. With hardware involved, the agent building toolkit must be superior, which can applicable with both high-level and low-level functionalities. In term of memory access, C/C++ is a proper for a mobile agent code language because it provides powerful functions. Mobile-C is an agent building platform. it is not only compliant to FIPA standard but also base on C/C++ standard language. Below, Mobile-C platform and other relevant software are presented.

3.3.3.1 Multi-Agent System Architecture

The concept of using multi-agent system is to simplify a complex problem; a centralized system and a distributed system handled by a single entity into something much more smaller, simpler problems that can be handled by several entities.

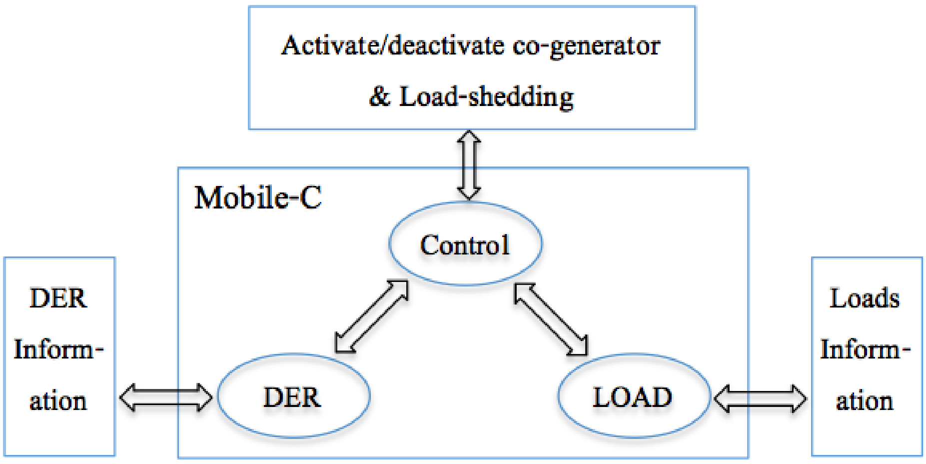


Figure 3.14: Multi-agent architecture

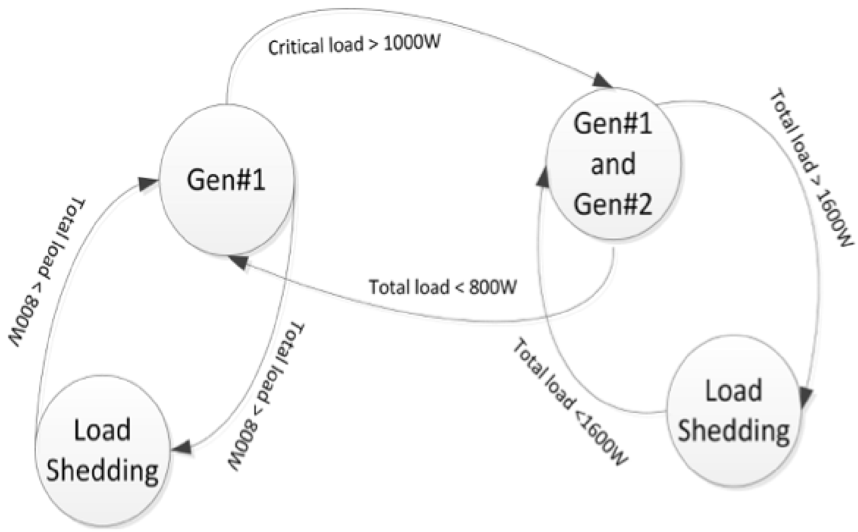


Figure 3.15: State diagram of control agent

The MAS architecture is shown in Figure 3.14. Three agents have been implemented for this experiment, such as:

- **Control:** It gathers all data got from Der and Load agent. After perform some analysis, it sends command to control non-critical load and generator#2.
- **Der:** It collects information like generator capacity and power availability.
- **Load:** It uses to get information from load like power demand and load connectivity.

  From the Control agent, it migrates an agent in XML format to Der and Load agency throw network connection to get some raw data from microgrid like power demand and power available then it performs some control tasks as shown in the state diagram above (Figure 3.15).

3.3.3.2 Mobile-C

Mobile-C [77] is a mobile agent building toolkit, which develop based on C/C++ language and compliant to IEEE FIPA (Foundation for Intelligent Physical Agents). Mobile-C has been developed for deploying in real time application like embedded system and network intelligent mechatronic.

The architecture of Mobile-C is shown in Figure 3.16. Unlike Jade, Mobile-C composes of two elements such as Agency and Agent. Agency resides in each node of a network and work as container or environment for mobile agents executes. The interaction from one agency to other agency in order to exchange information is possible by migrating agent in XML format. The core elements of agency are listed below:

- Agent Communication Channel (ACC): It works as gate or routes for agent to exchange information by using an agent communication language (ACL).
- Agent Management system (AMS): It works like the system supervisor. It controls all agent functions and life cycle of agents as well. All agent need to register with AMS in order to get an AID.
- Agent Security Manager (ASM): The ASM is responsible for maintaining security policies for platform and infrastructure.
- Directory Facilitator: It implements like the yellow page service. From DF, an agent can register their service or get from other agent in the system.
- Agent Execution Engine (AEE): It works like container or environment where the agent executes or invokes with Ch runtime.

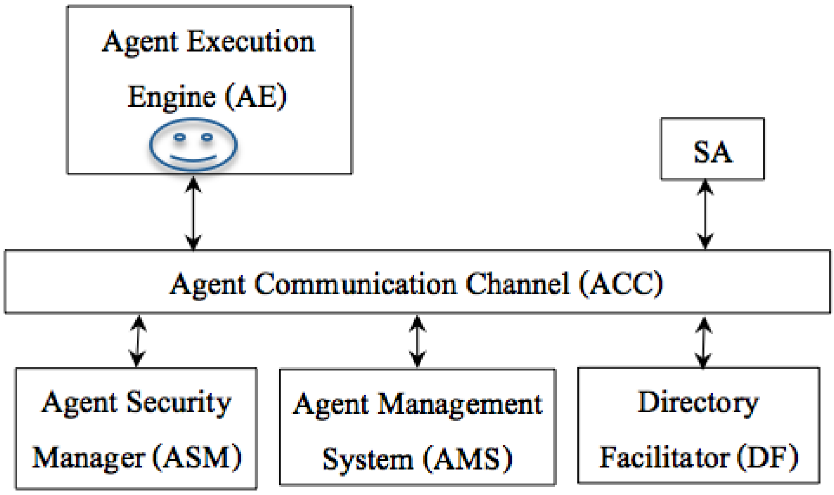


Figure 3.16: The system architecture of agency in Mobile-C

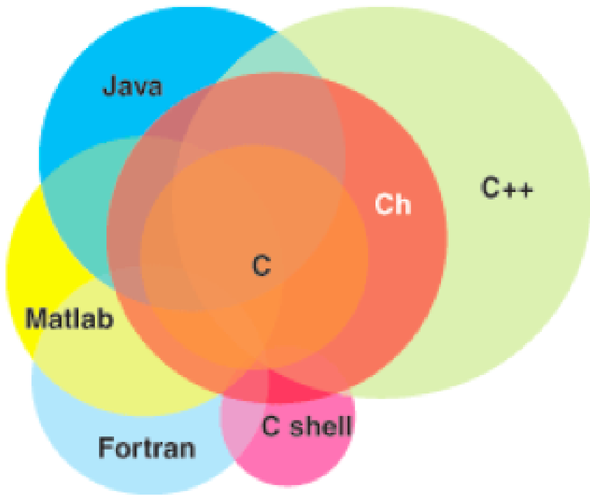


Figure 3.17: Ch versus other programming

3.3.3.3 Ch

Ch is a kind of C compiler and known as a superset of C. It not only contains all features of C standard in ISO 1990 but also adds new features in C99 and classes in C++. It performs as a C/C++ scripting engine when it embeds in other applications. Ch can work perfectly in cross-platform scripting and embedded scripting application which use by Mobile-C. Different from many other software packages, Ch works as a bridge the gap between low-level language and very high-level language. Ch is created by borrowing some feature from other major computer programming language. The relation between Ch and other programming language is illustrated in Figure 3.17.

CHAPTER 4

SIMULATION SETUP AND RESULTS

After complete description of all theory use in this project as well as toolkit for development agent, this chapter will presents the experiment setup for simulation model and go along with result and discussion.

4.1 Simulation Setup

In this section, we briefly talk on procedure and important equipment used in this experiment. The microgrid simulation model and single-line of simulation experiment setup are shown in Figure 4.1 and Figure 4.2, respectively. The system consists of two generators which control by droop control and frequency restoration technique, PV generator, loads, main grid, MAS running inside Jade and MACSimJx interfacing. The bundle of data from simulation such as power demand, power available and abnormal condition of the system; are pass through MACSimJx to DER and Load agent. Data from DER and Load agent share to control agent. After, the control agent gets the necessary information and performs some analysis then it send data or command back to the microgrid simulation through MACSimJx for control main switch at PCC and perform load-shedding. The important parameters of the microgrid are shown in Table 4.1.

Table 4.1: Microgrid parameters in software simulation

Microsource 1 and 2 (Gen 1, Gen 2)	
Model	Kikusui PCR2000M
Power Rating	220V, 50Hz, 2kVA
P-Angle Droop Coefficient (m)	2(0.0009375)
Q-V Droop Coefficient (n)	0.01296
Digital Controller	Sampling Rate: 12.78kHz
Xd	4mH
Simulating Solar Inverter	
Model	Kikusui PCR2000M
Power Rating	220V, 50Hz, 2kVA
Digital Controller	Sampling Rate: 12.78kHz
LOAD	
LOAD 1	General Service Load Profile from MEA Study
LOAD 2	19.36+j14.52
Non-critical load	3kw

4.1.1 Generator

In order to evaluate the proposed control, a simulation test bed is developed in MATLAB/Simulink as a simplified distribution circuit. Figure 4.2 illustrates a single-phase microgrid

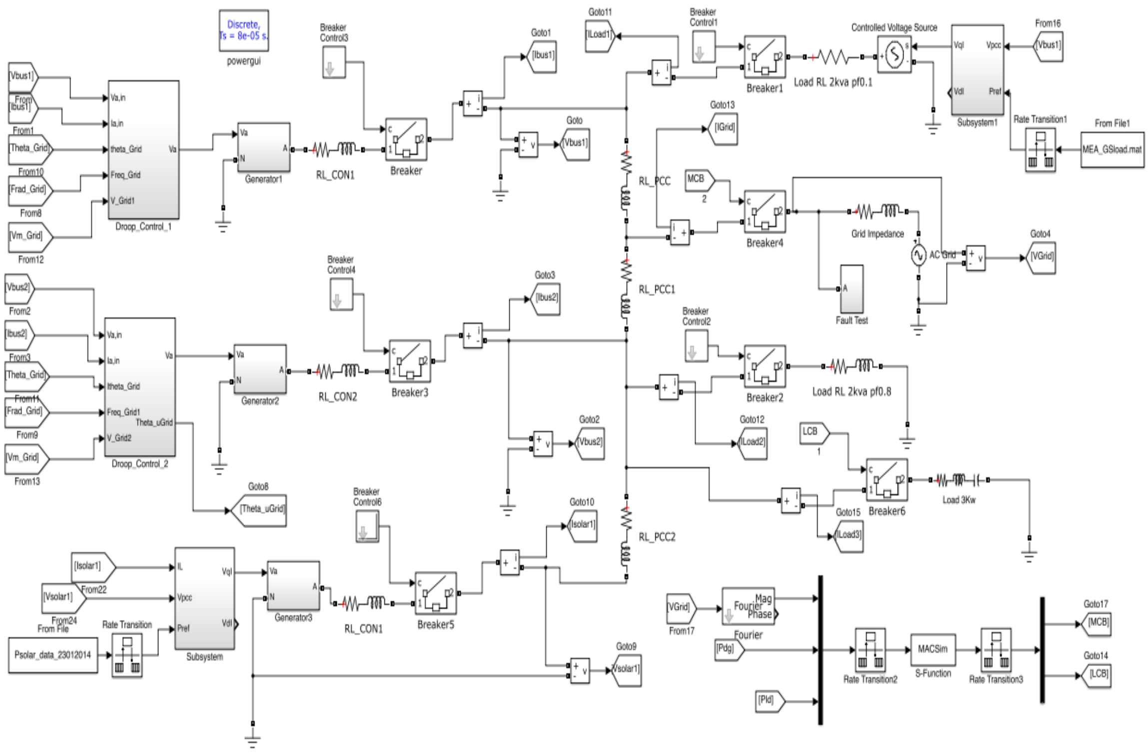


Figure 4.1: Microgrid simulation model

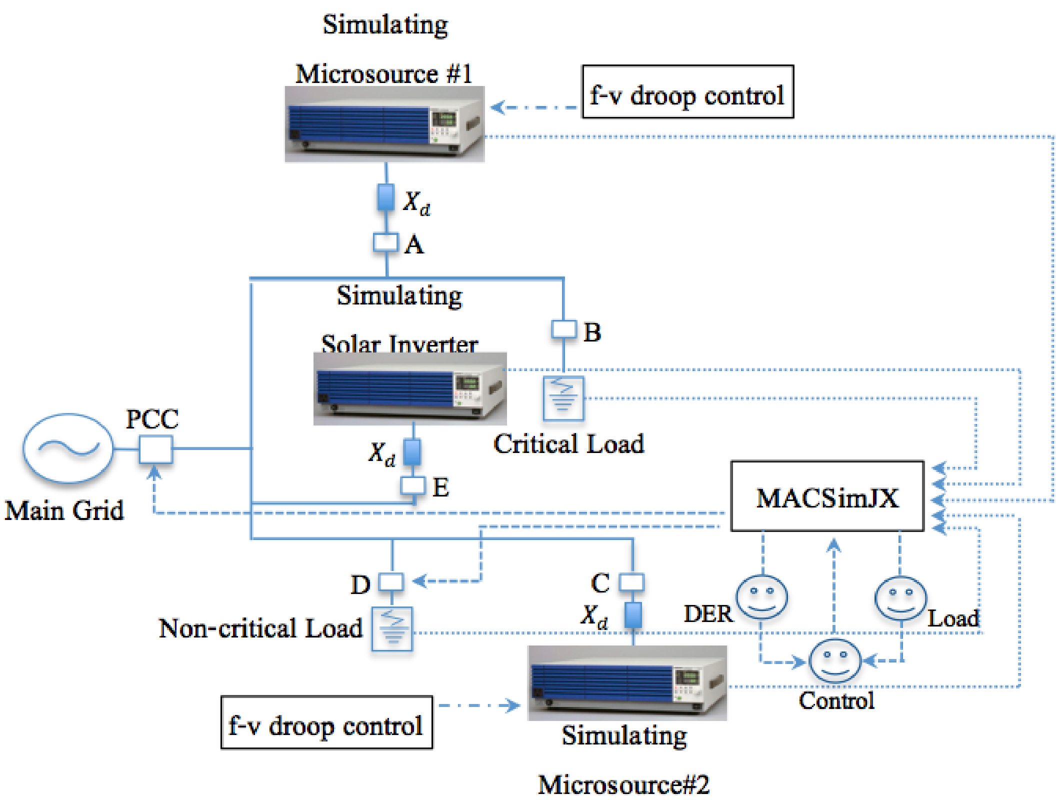


Figure 4.2: Single-line of microgrid simulation test bed

model that comprises of two distributed generators are independently controlled using droop control technique for stable load sharing during islanding mode of operation. These generators are model based on power amplifier (programmable power supply) characteristics for the later experimental stage. Another generator is model as a PV generator, which uses the power generating profile obtained from the 3kW PV generator installed in the laboratory from 7 am to 6 pm of February 14, 2014. The PV generating power was sampled every 5 minute and scaled to 1 second in this simulation.

4.1.2 Load

There are the fixed and the variable loads connecting in the microgrid, these loads divide in two groups: Critical (Load1 and Load2) and Non-critical load. The variable load has the profile of general service type surveyed by the Metropolitan Electric Authority of Thailand (MEA).

4.2 Simulation Results

MAS prototype was implemented and integrated with microgrid simulation model. The goal of the MAS is to isolate microgrid during fault condition or power failure and to serve loads with highest priority (critical loads) with the available power of microgrid sources. If the power demand becomes greater than both DGs and grid or greater than DGs in case of islanded mode, non-critical load should be disconnected. In order to test the operation of the MAS and to evaluate its performance, a microgrid test bed was simulated and multi-agent performs their task. In Figure 4.3, the agents live in Jades container and ready to start. Once the simulation starts, the multi agent can communicate and share information between each other as show in Figure 4.4; and Jade environment exchange data with Simulink through MACSimJX (agent coordinator).

Then three scenarios and results are discussed below.

4.2.1 Grid Connected Mode

First of simulation start, the microgrid is in islanding mode and take care only critical load. At the time of 50sec, the control agent gets the present of main grid then it sends closing signal to main circuit breaker at PCC to switch microgrid to grid-connected mode (Figure 4.5 Middle graph). During the grid-connected mode, the microgrids voltage and frequency are controlled such that they follow the grid's voltage and frequency which are roughly at $220\sqrt{2}$ V (Upper graph) and 50 Hz (Lower graph), respectively. The DGs and main grid can secure the entire loads in the system.

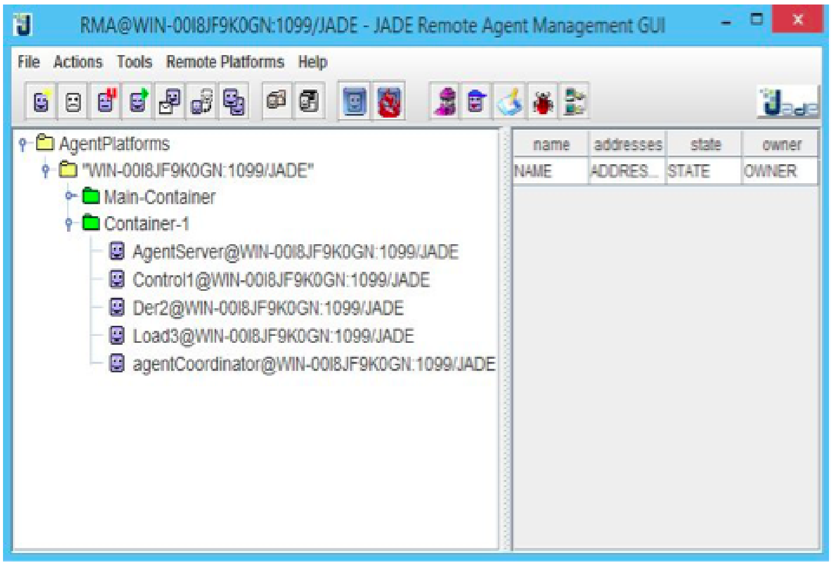


Figure 4.3: JADE Remote Agent Management GUI

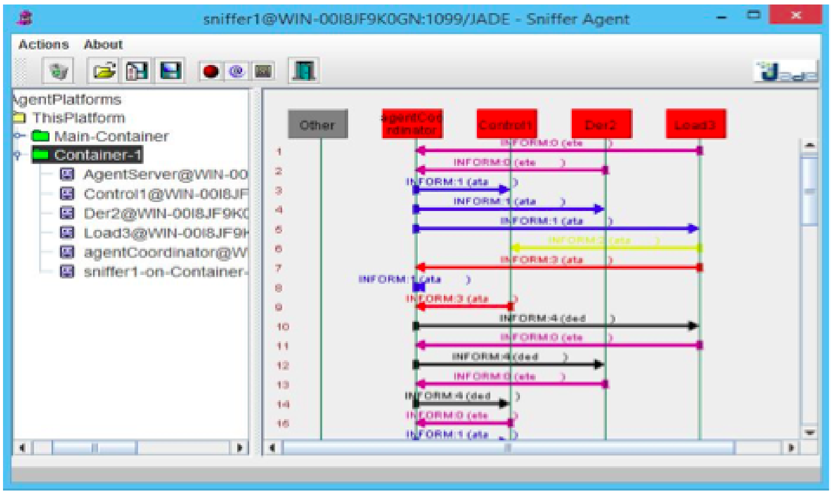


Figure 4.4: Sniffer agent

4.2.2 Transition Period

While the fault occur at t = 100sec, the control agent sense this fault and it commands to open the main circuit breaker A, at PCC as show in Figure 4.7 (Upper graph) to isolate microgrid from the main grid (Figure 4.6, Upper graph). After, the control agent sends signal to switch microgrid to islanded mode, it performs one more task by requesting and comparing the power production and consumption from DER and Load agent. Once the power demand is greater than power supply, the control agent will performs load-shedding by sending open signal (Figure 4.7 , Lower graph) to disconnecting non-critical loads (Figure 4.6, Lower graph) from the system in order to stabilize or prevent the microgrid from collapse.

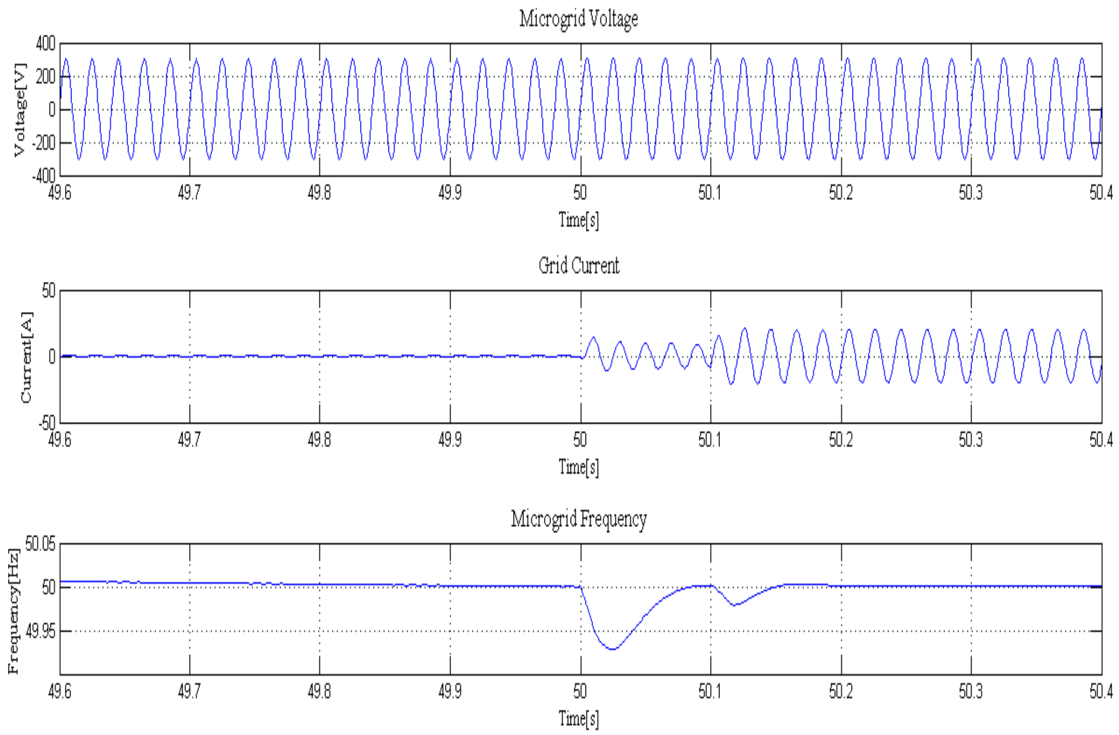


Figure 4.5: (Upper graph) Micrograph Voltage, (Middle graph) Grids Current, (Lower graph) Microgrids Frequency

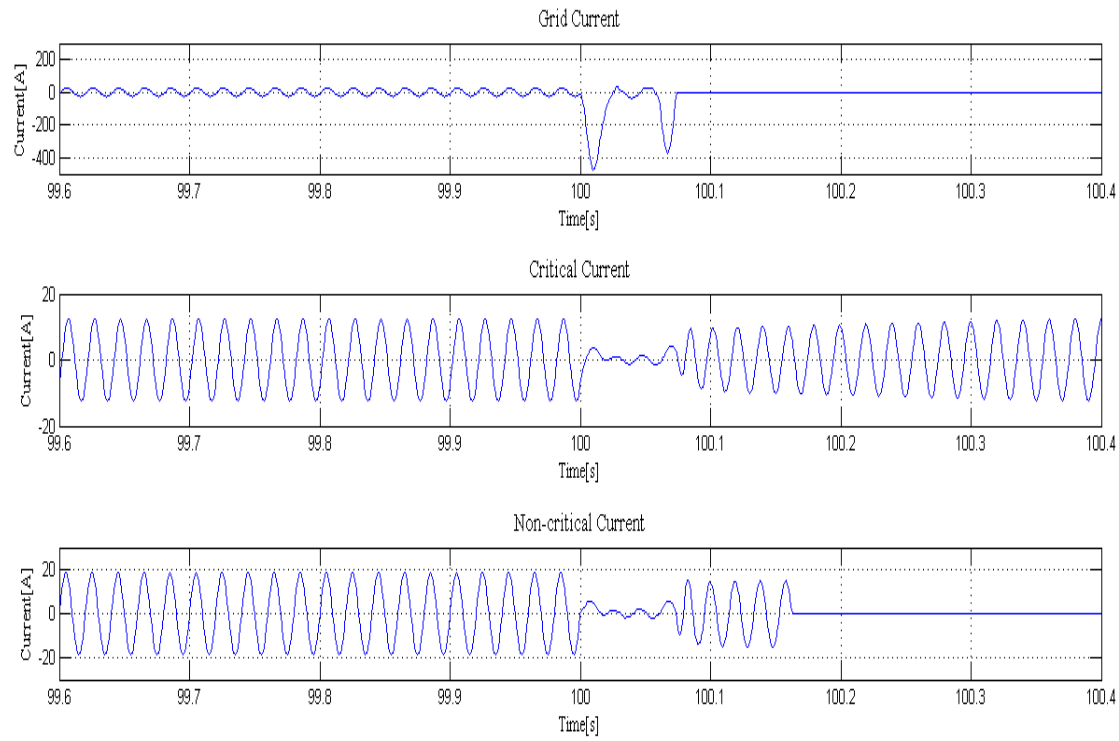


Figure 4.6: (Upper graph) Microgrids Voltage, (Middle graph) Grids Current, (Lower graph) Microgrids Frequency

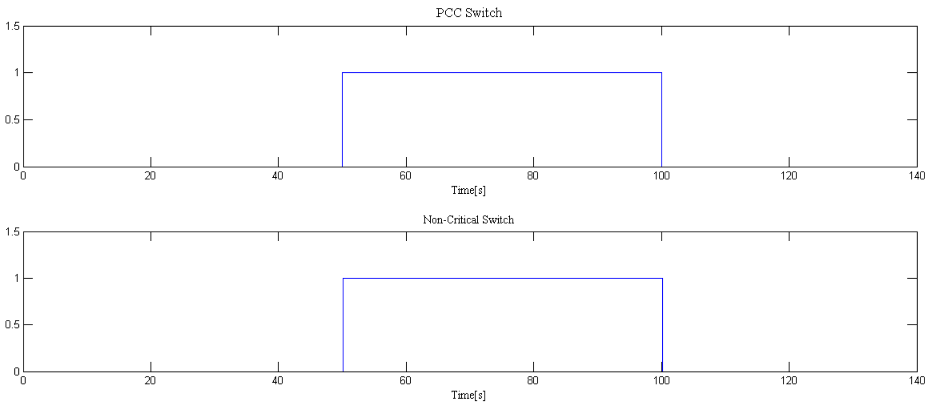


Figure 4.7: Signal (0; 1) generate by agent

4.2.3 Islanded Mode

After the fault has occurred at 100sec, the main grid is disconnected at 100sec (Figure 4.6, Upper graph) and the non-critical load has been cut from the system (Figure 4.6, Lower graph), as microgrid sources can not secure. The critical loads are fully supplied from DER sources (Figure 4.6, Middle graph). When the microgrid is operated in the island mode, and consists of critical loads the voltage is maintain at $220\sqrt{2}$ V and the frequency is always controlled at $50Hz$ as show in Figure 4.8.

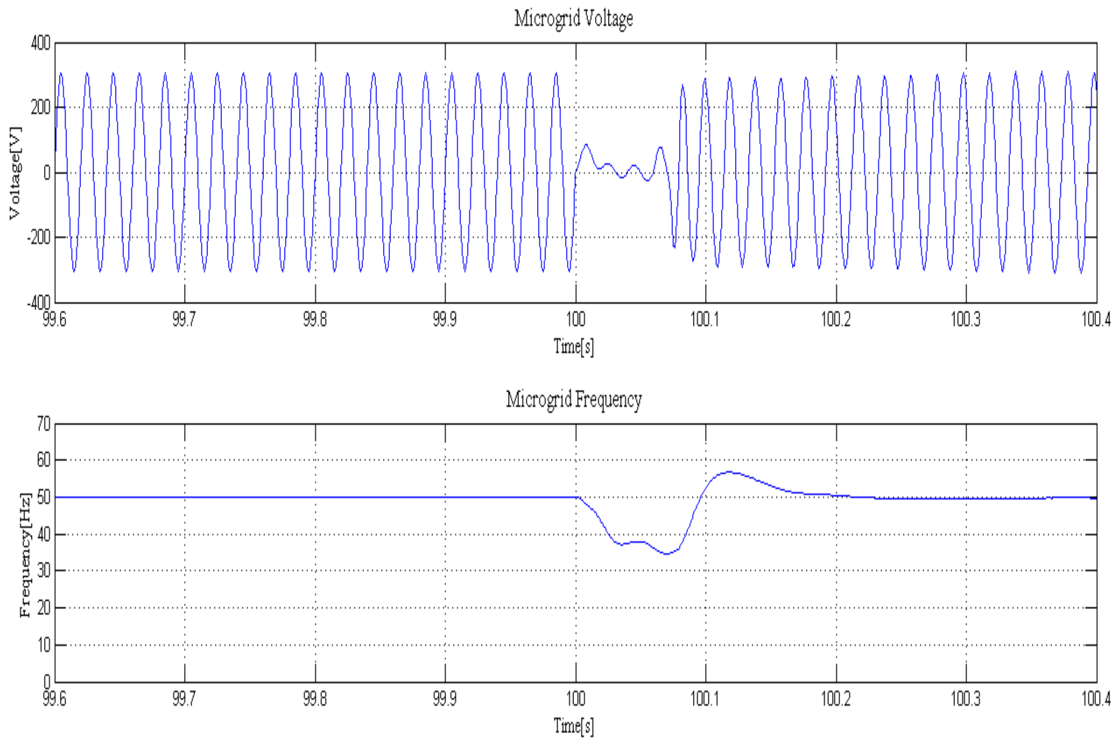


Figure 4.8: Voltage and Frequency of Microgrid

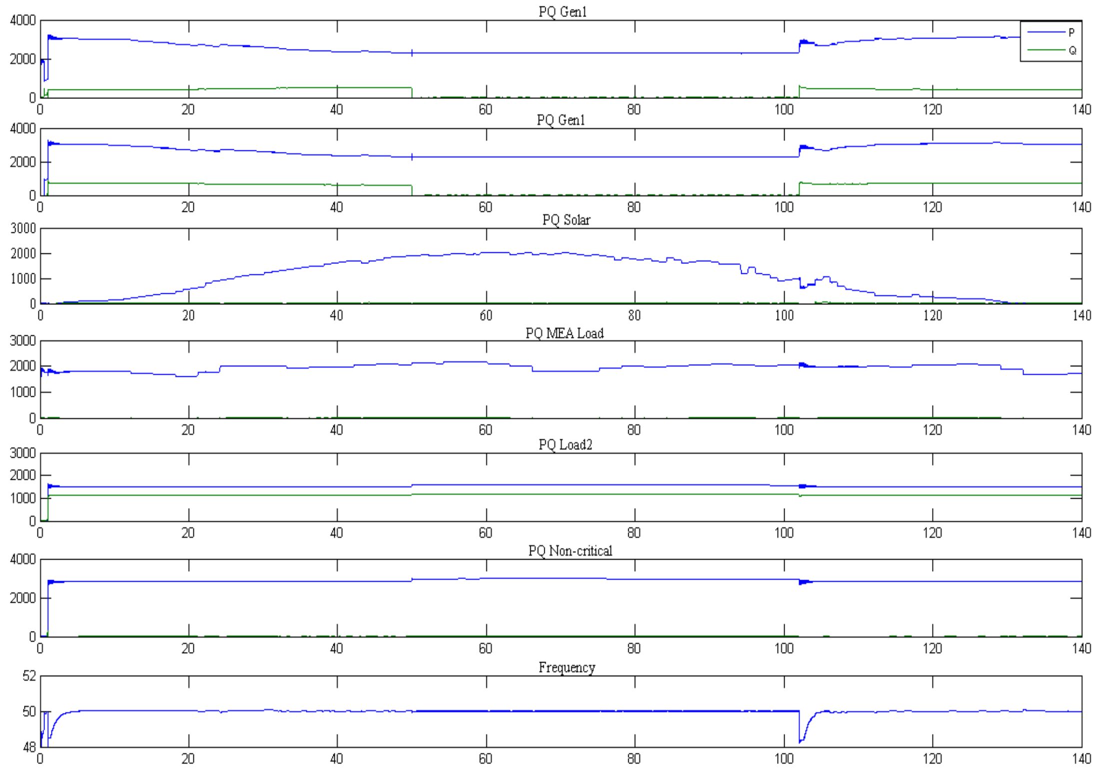


Figure 4.9: Power sharing of Gen1and Gen2

Figure 4.9 proves the effectiveness of droop control and frequency restoration. The simulation is divided in three steps:

- From 0 to 50s: Islanded mode
- From 50s to 102s: Grid-connected mode
- From 102s to 140s: Islanded mode

The generators is controlled by V-F control when microgrid operates in islanded mode and P-Q control when microgrid operates in grid-connected mode. As generator#1 and generator#2 are cooperated control by droop control with frequency restoration so these two generators can share the load between each other approximately by 50% (first two graphs) and the frequency is always restore to normal value (lower graph).

CHAPTER 5

EXPERIMENTAL SETUP AND RESULTS

This chapter, the hardware experimental setup is implemented and gone along with result and discussion. This experiment is conducted in islanded mode only. The scenarios may quite different from the simulation experiment but it serves the same purpose to validate the effectiveness of proposed control technique.

5.1 Experimental Setup

This section describes procedure and important equipment used in the experiments. The microgrid test bed and the single-line diagram of the microgrid in this experiment are shown in Figure 5.1 and Figure 5.2, respectively. The system consists of two generators controlled by DSP, a set of loads controlled by Arduino and relay board, MAS running on PC and the RS-232 is used for low level communication. The important parameters of the microgrid are demonstrated in Table 5.1.

Table 5.1: Microgrid parameters in hardward experiment

Microsource 1 and 2 (Gen 1, Gen 2)	
Model	Kikusui PCR2000M
Power Rating	220V, 50Hz, 2kVA
P-Angle Droop Coefficient (m)	2(0.0009375)
Q-V Droop Coefficient (n)	0.01296
Digital Controller (DSPF28335)	Sampling Rate: 12.78kHz
Xd	4mH
LOAD	
Critical load	100W, 200W, 300W, 400W
Non-critical Load	220V, 50Hz, 2kVA
Digital Controller (Arduino)	14GPIO, 6ADC, 16MHz
AGENT	
Mobile-C	V2.15
Ch	Professional v7.0
Embedded Ch	Professional v7.0
OS	Linux, Ubuntu 12.04, 32Bit

5.1.1 Generator

In this system the generators are classified as main generator (Generator#1) and co-generator (Generator#2). Generator#1 and generator#2 are controlled by droop control method for load-sharing and maintain system reliability and frequency restoration for restoring frequency from deviation. To avoid any equipment damage from malfunction or unexpected condition may

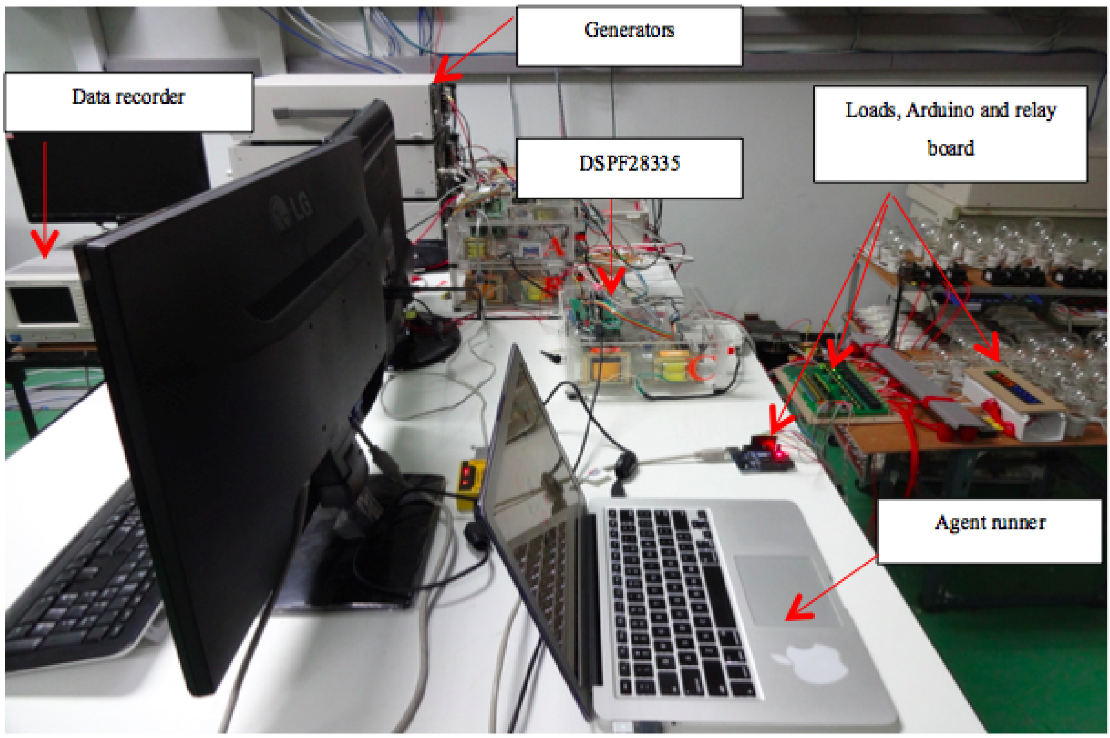


Figure 5.1: Microgrid test bed

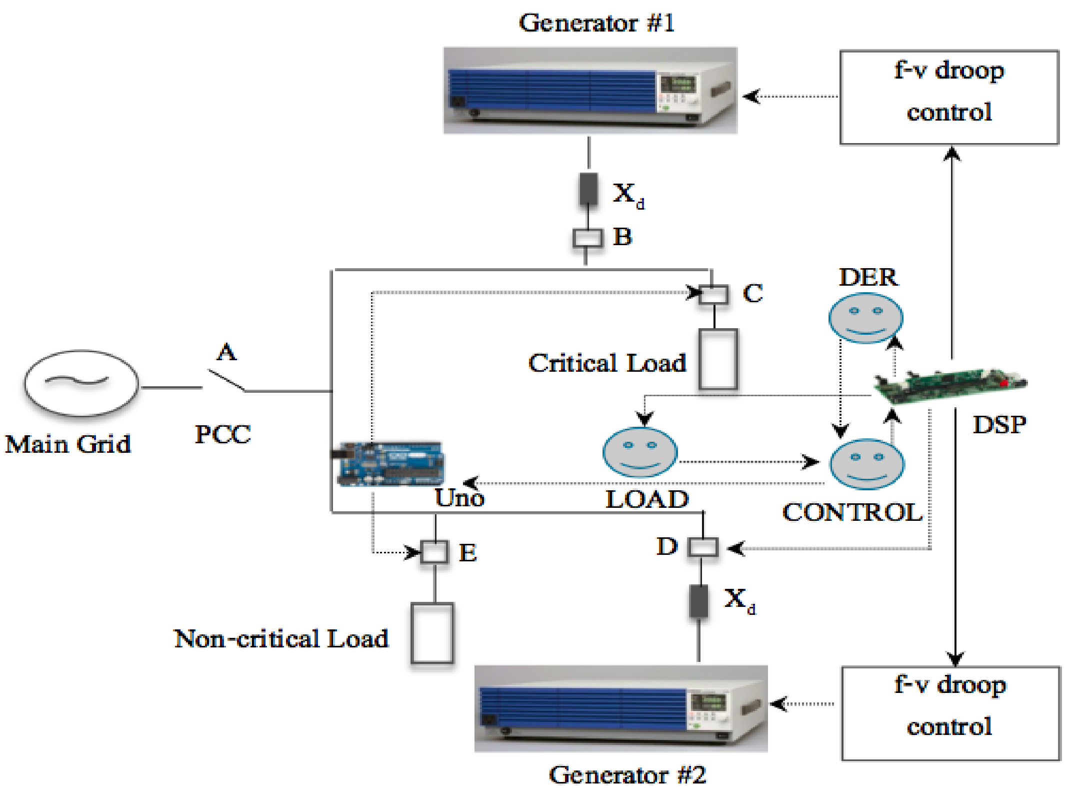


Figure 5.2: Single-line diagram of experimental test bed

happen during experiment, each of the generators have been set to 1000W for maximum capacity.

5.1.2 Load

While microgrid is in islanding mode, the microgrid sources may not be able to supply the entire loads in the system. To maintain the operation, some loads have to be disconnected. The loads set in this experiment is classified into critical group and non-critical group. Non-critical loads are divided into various groups based on power demand ranging from 100W to 400W. When non-critical loads asks to connect to the system, the agent will check for power availability and allow only the non-critical loads which has demand lower than power available.

5.2 Experimental Results

The objective of the experiment is to demonstrate the ability of the proposed MAS to do some tasks while the microgrid is operating in islanding mode such as performing load-shedding by disconnect non-critical load when the demand greater than generators capacity and connecting or disconnecting the co-generator(Generator#2) upon the operating conditions. All data records in this test perform through Yokogawa power meter model WT1600. In order to evaluate the agent's performance, the experiment was conducted for 5 minutes long and multi-agent performs their tasks.

Then two scenarios and results are discussed below.

5.2.1 Connecting or Disconnecting Co-generator

The experiment starts with Generator#1 supply some critical and non-critical loads. At t = 65s the critical loads reachs the Generator#1 capacity, and the agent activates Generator#2 as shown in Figure 5.3: E1 to supply all loads in the system. At the same time of the connecting of Generator#2, the system frequency is restored to 50 Hz as the result of the frequency restoration control, Figure 5.3: E4 (red line). As the loads demand decrease below Generator#1 capacity at the time of 240s, the agent switch off the Generator#2 (depicted in Figure 5.3 E1).

5.2.2 Load-Shedding

The experiment start with only Generator#1 is operated and the maximum power is set to 1000W. Some of critical and non-critical loads are connected to the system for 600W total. At 90sec, 400W critical loads are added to the system and the demand reaches generator capacity. The agent senses this change, then it sends command to disconnect non-critical loads as shown in Figure 5.4: E3 (green line).

At 180s, the critical loads demand is increased to surpass the Generator#1 maximum power,

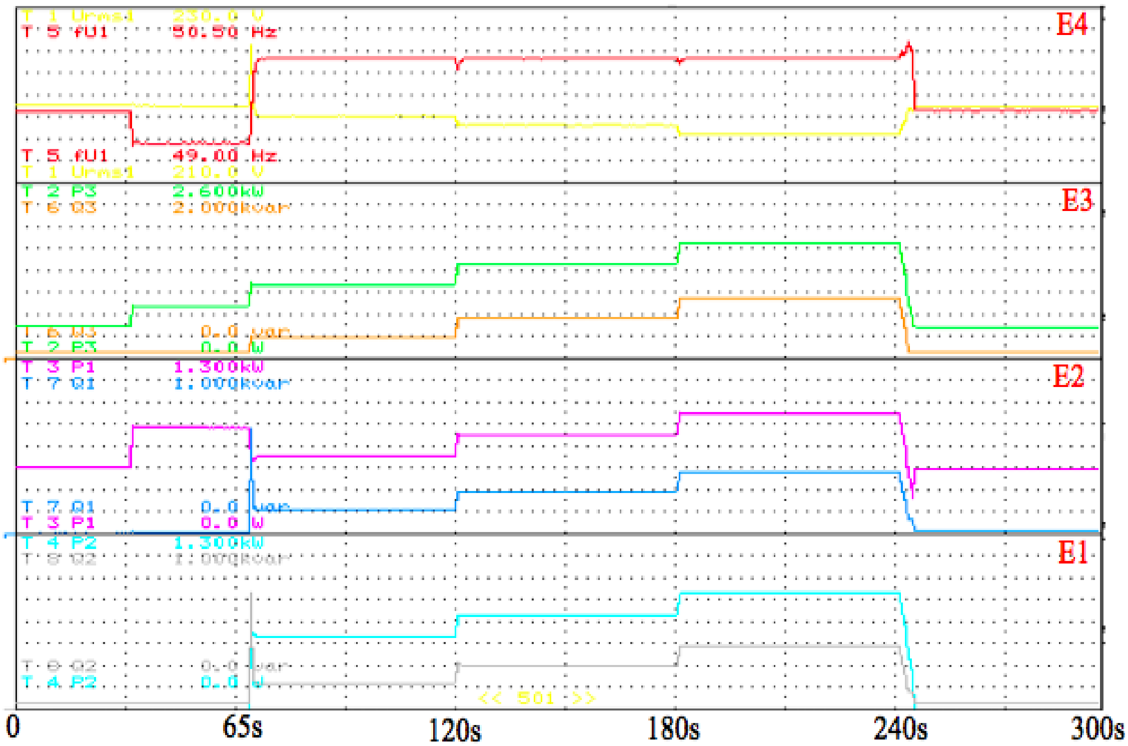


Figure 5.3: Experiment result for Load-shedding: E1: Power of Generator#2; E2: Power of Generator#1; E3: Ping line present to critical load power and green line for non-critical load power; E4: Bus voltage and frequency

then the agent activates the Generator#2. The two generators have maximum combined for 2000W. If the critical demand is less than these capacities, the non-critical loads can be connected back to the system as can be seen in Figure 5.4: E3 (green line). At 270s, critical loads demand decreased below Generator#1 capacity, then Generator#2 was deactivated by agent and some non-critical loads can be supported by Generator#1. In this experiment, frequency restoration is performed only when the two generators are connected.

Figure 5.5 demonstrates the effectiveness of droop control and frequency restoration. These two generators can equally share the load all over the range of operation. The system voltage and frequency are maintained within the allowable range roughly at 220 V (Figure 5.5: E4, lower line) and 50 Hz (Figure 5.5:E4, upper line), respectively for all dynamic condition.

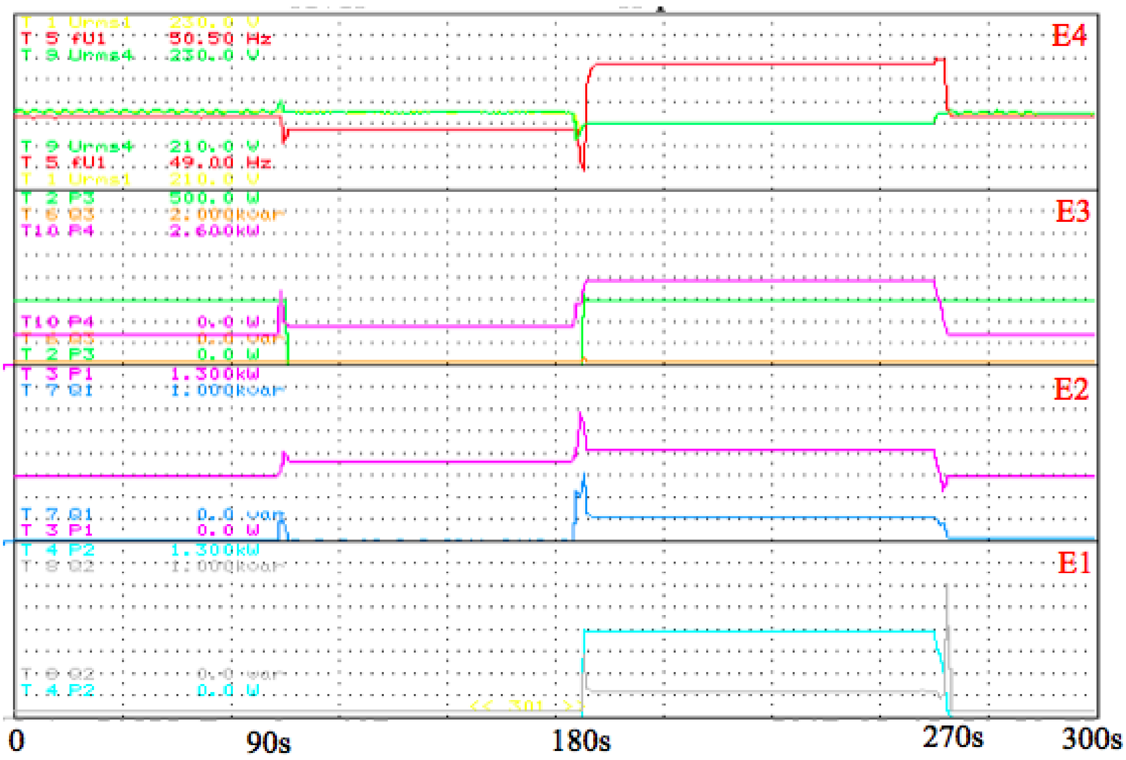


Figure 5.4: Experiment result for Load-shedding: E1: Power of Generator#2; E2: Power of Generator#1; E3: Ping line present to critical load power and green line for non-critical load power; E4: Bus voltage and frequency

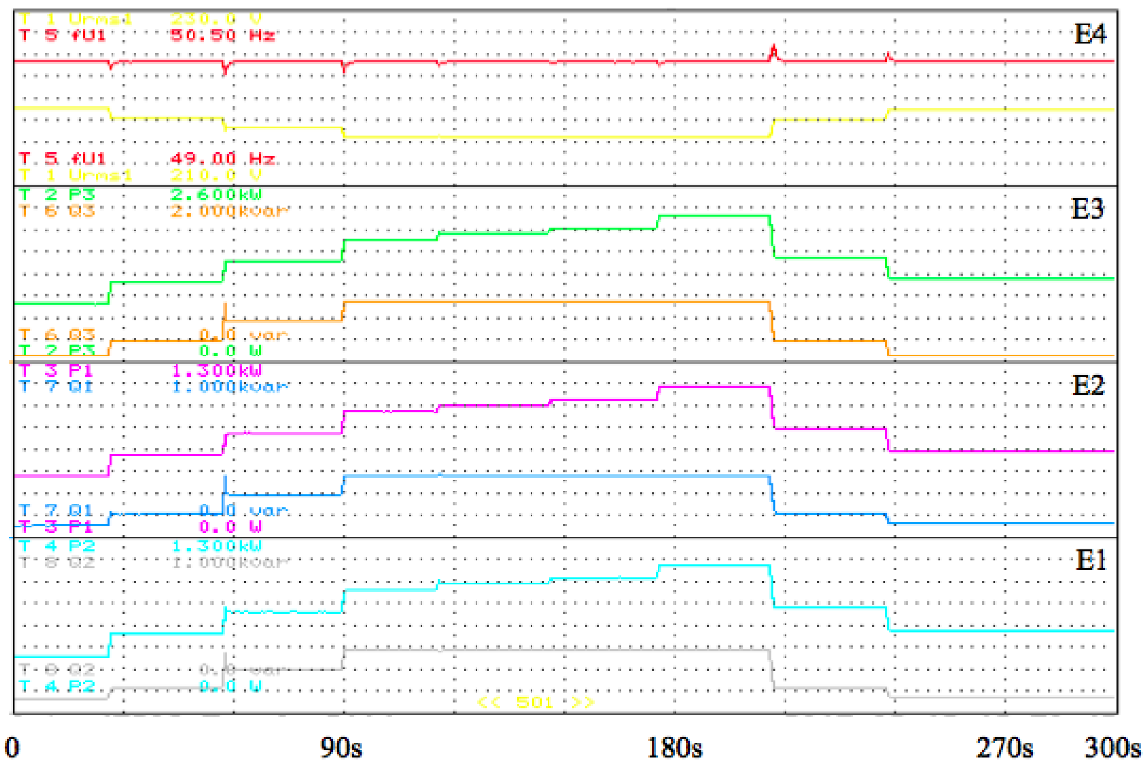


Figure 5.5: Experiment result of Droop control: E1: Power of generator2; E2: Power of Generator#1;E3: Power demand of loads E4: Bus voltage and frequency

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

In this research, a decentralize control system is proposed to control a single-phase microgrid. The decentralize control system composes of three controls method. The primary control is the droop control, secondary control is frequency restoration and tertiary control is supervisory control which uses multi-agent system. To evaluate the proposed technique, two separate experiments were developed.

First experiment was tested with software simulation. The microgrid simulation model was implemented. It composed of two DGs controlled by droop control and frequency restoration technique, PV generator, loads and main grid. The multi-agent system based control architecture was developed using the JADE platform and used to control a microgrid simulated in MATLAB/SIMULINK. The microgrid simulation test-bed and multi-agent were capable of sharing data between each other through a middleware called, MACSimJX.

The other experiment was tested with hardware implementation. The microgrid was implemented in laboratory which consisted of two DGs controlled by DSPF28335 and Loads (resistive and reactive) controlled by Arduino. The multi-agent system was developed using the Mobile-C platform and used to control a real microgrid test-bed. The microgrid and the multi-agent system exchanged data between each other through RS-232 serial communication.

The results of the experiments proved the capability of the proposed decentralize control system to effectively control both of generators and loads in microgrid by performing some tasks such as power sharing between each generators, restoring frequency from deviation, load-shedding and changing the microgrid state from connected to islanded mode when upstream fault occurs.

6.2 Future Work

Since the source of microgrid (solar energy, wind etc.) are highly depend with the weather condition, which is really dynamic. The power production may meet at the daytime with the low power consumption or high power consumption with low power production. To handle this problem as well as improve the microgrid reliability and economic operation, the further research is needed. The factors need to be developed for future research is described below:

* The energy storage system will be developed with the aim of improving stability and quality service.

* In real system, the microgrid operation mode will be extended for grid-connected mode.

* To provide faster respond to the dynamic environment, the multi-agent will develop to execute inside embedded computer on board (Gallileo).

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APPENDICES

APPENDIX A AGENT STANDARD: FIPA

A.1 Foundation for Intelligent Physical Agents Standards

Foundation for intelligent Physical Agents (FIPA) is an international organization that is dedicated to promoting the industry of the intelligent agents by openly developing specifications supporting inter-operability among agents and agent-based application.

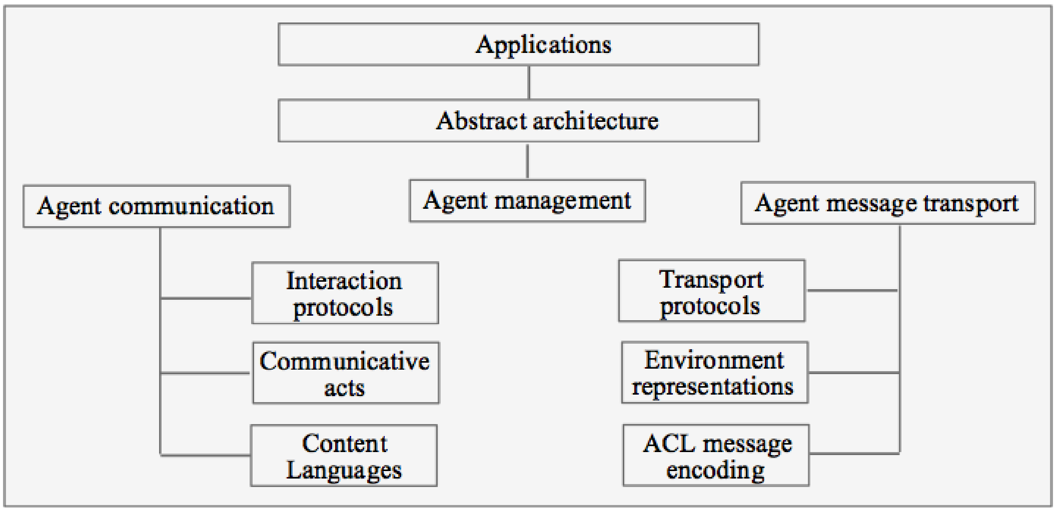

Figure A.1: Overview of FIPA standard

FIPA standards was originally proposed in 1996 to form the specification of software standards for heterogeneous and interaction agents and agent-based system [70]. In the past a few year, FIPA has been widely recognize as the major standards in the area of agents-based computing. Many standard specifications has been developed, such as Agent Communication Language (ACL) and Interaction Protocols (IPs), etc. On 8 June 2005, FIPA was officially accepted by the IEEE Computer Society. Figure A.1 shows the overview of the FIPA standards.

A.1.1 FIPA Abstract Architecture

The FIPA Abstract Architecture specification (SC00001L) acts as an overall description of the FIPA standards for developing multi-agent system. The main purpose of the FIPA Abstract Architecture is to provide interoperating ability to the agents, which reside in separate computing environment. It includes the management of the multiple message transport and encoding schemes and locating agents and server via directory services. Figure A.2 demonstrates the FIPA Abstract Architecture mapped to different concrete realizations from registering service to exchanging message. In addition, it also supports mechanisms to create the multiple concrete realizations for interoperation. The most important architectures include:

- a model of services and discovery of services available to agents and other services;
- message transport interoperability;

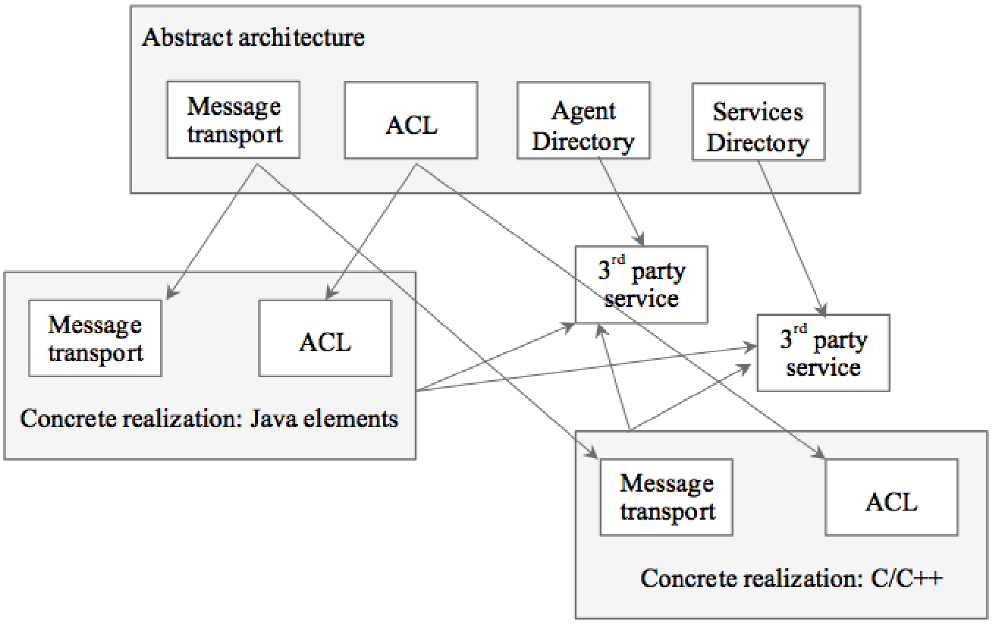

Figure A.2: FIPA abstract architecture mapped to different concrete realizations

- supporting various forum of ACL representation and content languages;
- supporting the representations of multiple directory services.

A.1.2 FIPA Agent Management System Standards

The FIPA Agent Management System Standard Specification (SC00023K) denoted as agent management reference model of the runtime environment that FIAP agents inhabit. The logical reference is established for agent creation, registration, communication, location, migration and retirement. The referent model includes a set of logical-based entities, such as:

- an agent runtime environment for defining the notion of agent used in FIPA and lifecycle;
- an agent platform (AP) for deploying agent in a physical infrastructure;
- a Directory Facilitator (DF) which provides a yellow pages service for the agents registered on the platform;

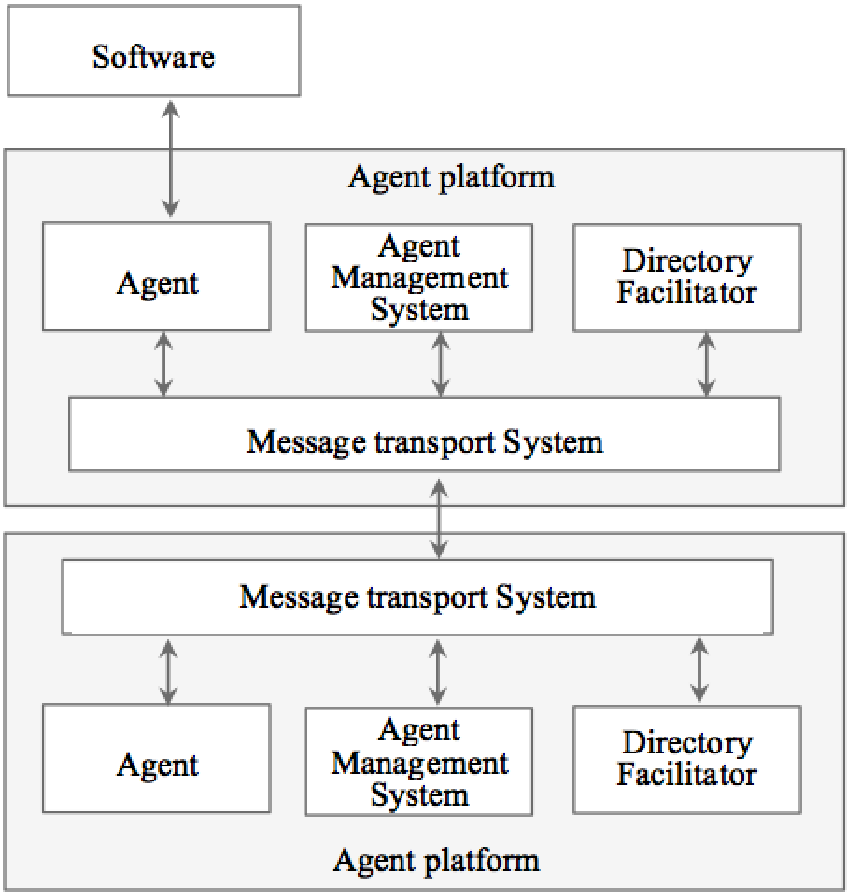

Figure A.3: FIPA agent management reference model

- an Agent Management System (AMS) acting as a white pages service for supervisory control over access to the agent platform;
- a Message Transport Service (MTS) for communication between the agent registered on different platforms .

Figure A.3 gives the FIPA agent management reference model constitution.

A.1.3 FIPA Agent Message Transport Service

The FIPA Agent Message Transport Service specification (SC00067F), as a part of the FIPA Agent Management specification, supports the message transportation between the interoperating agents. Two major specifications are involved, i.e. a reference model for an agent Message Transport Service (MTS) and the definitions for the expression of message transport information to an agent MTS.

A three-layered reference model is provided by MTS, i.e. the message Transport protocol (MTP) for physical message transport between two Agent Communication Channels (ACC), the

MTS which provide the FIPA ACL message transportation between agents on the platform, and the ACL representation from both MTS and MTP. Figure A.4 shows the FIPA message transport reference model. Additionally, other distinct components are involved in an agent MTS:

- two transport protocols, for transporting message between agents using the Internet Inter-Orb Protocol (IIOP) and Hypertext Transfer Protocol (HTTP), specified by FIPA Message Transport Protocol for IIOP (SC00075G), specified by FIPA Message Transport Protocol for HTTP(SC00084F);
- two message transport envelop specifications, i.e. FIPA Agent Message Transport Envelope Representation in Extensible Markup Language (XML) specification (SC00085J) and FIPA Agent Message Transport Envelope Representation in Bit-efficient Encoding Specification (SC00088D) which provide syntactic representations of a message envelop in XML form and bit-efficient form;

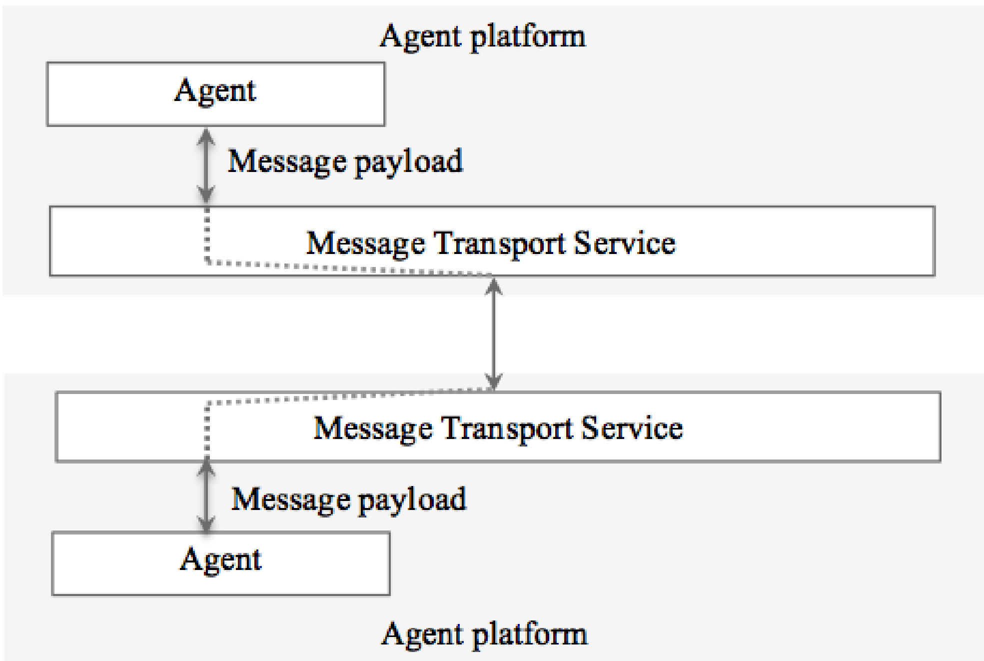

Figure A.4: FIPA message transport reference model

- three message representation specifications, i.e. FIPA ACL Message Representation in Bit-efficient Encoding Specification (SC00069G), String Specification (SC00070I) and XML Specification (SC00071E) for representing ACL syntax in a bit-efficient form, string form and XML form.

A.1.4 FIPA Agent Communication Standards

Agent communication is a major element of the FIPA standardize, which is used by agent to communicate between each other. It composts of four components such as Agent Communication Language (ACL) message, Communicative Act (CA) library, Content Language (CL) and Interactive Protocols (IPs) of message exchange.

- A FIPA ACL message contains a set of one or more message parameters. Those parameters can be performativity, sender, receiver, content, etc. The message is encoded in any form like XML, Bit-Efficient and String (EBNE notation).
- A number of different interaction message exchange protocols are dealt by FIPA Interaction Protocols (IPs) specifications, such as request and query interaction protocols, brokering and recruiting interaction protocols, subscribe and propose interacting protocols, etc.
- The communication which defines in form of function or act, called the communicative act (CA). The communicative act can be a statement like Accept Proposal, Agree, Cancel, Inform, etc. Those functions are detailed in the FIPA CA library (FIPA37).
- A set of language used in FIPA Message are denote by FIPA Content Language (CLs). For example:
  - a concrete syntax for the FIPA Semantic Language (FIPA SL) is defined by FIPA SL Content Language specification (SC00008I) for use in conjunction with the FIPA ACL;
  - FIPA Constraint Choice Language (CCL) Content Language specification (XC00009B) allows agent communication to involve exchanges about multiple interrelated choice;
  - FIPA Knowledge Interchange Format (KIF) Content Language specification (XC00010C) expresses the objects and proposition as terms and sentences;
  - FIPA resource Description Framework (RDF) Content Language specification (XC00011B) construct components of FIPA SL in the resource description framework representation.

APPENDIX B MACSIMJX CONFIGURATION

MacsimJx is a middleware, which create in the special purpose to allow agent develop in Jade exchange data with simulation model in Matlab/Simulink. MACSimJx use Borland C++ compiler as it compiler. But, this compiler is compatible with the matlabs version lower than 2007a only. The Matlab version later than 2007a, Borland not support any more as Matlab legacy. In order to interface Jade with Matlab/Simulink through MACSimJx, some configurations are needed. The way to configure this issue is described below.

Go to command prompt then type "%appdata% " as show in Figure B.1.

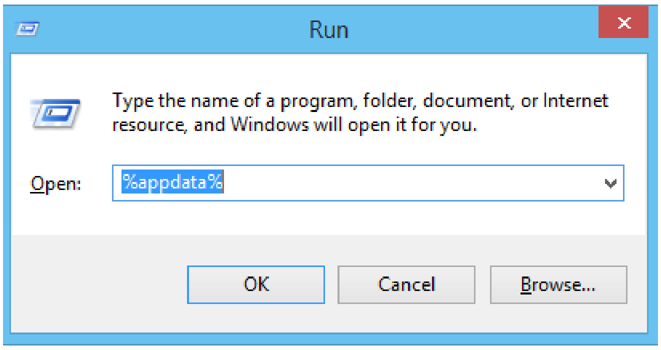

Figure B.1: Window command prompt

Copy a file name "mexopts " from Macsimjx/MyTools/Legacy, then paste it to MathWorks/MATLAB/R2011a. After that double click on "mexopts " file, see Figure B.2 for detail. Next, go to Macsimjx/MyTools/Legacy copy a file name "link-borland-mex " then paste it

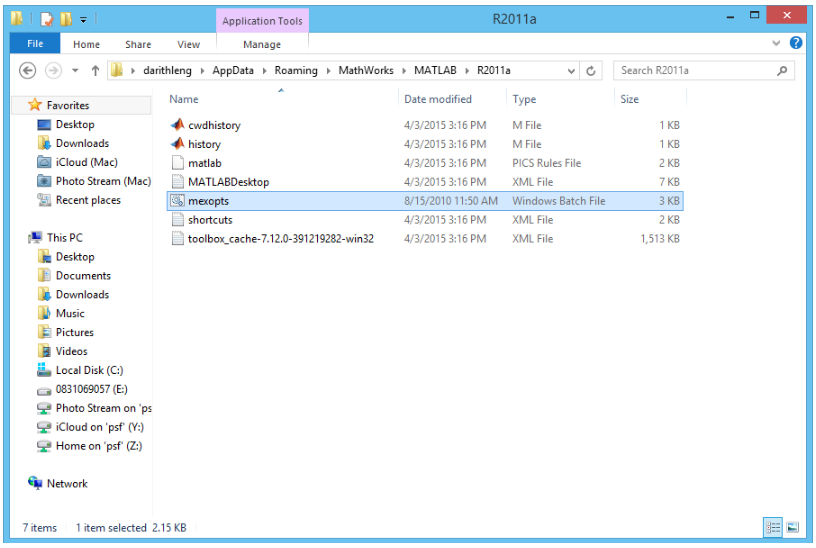

Figure B.2: Setup mexopt

in C:/Program File/MATLAB/R2011a/bin/win32.

Navigate to Macsimjx/MyTools/Legacy copy a folder name “borland ” after that paste it to C:/Program Files/MATLAB/R2011a/extern/lib/win32. Finally, Opening Matlab type “mex-setup ” in Matlab command window then select the compiler as shown in Figure B.3 (Microsoft Visual C++ 2010).

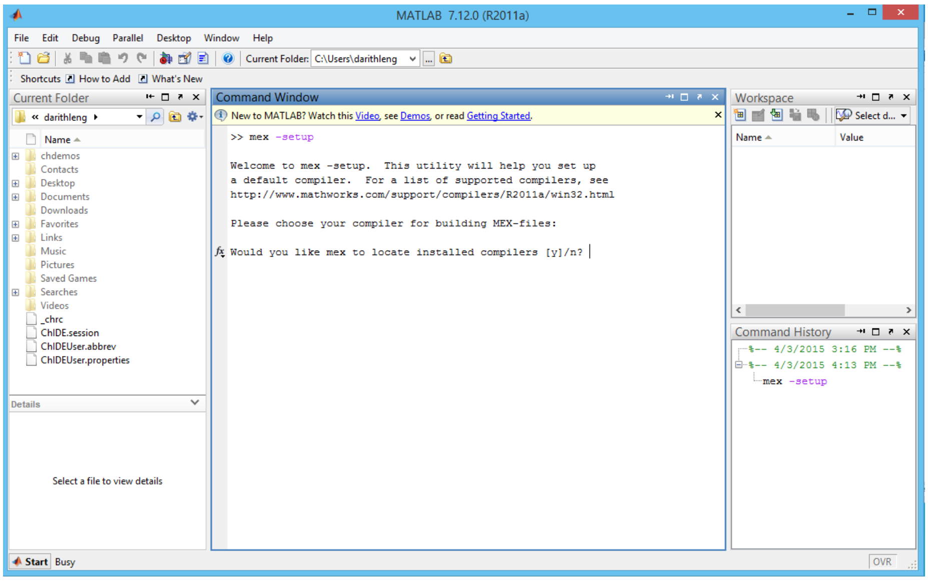

Figure B.3: Selection compiler

APPENDIX C MULTI-AGENT SYSTEM LAUNCHING

The multi-agent system attempts to control physical entities or a simulation of the same. This puts the multi-agent system and the simulation into two different domains. In order for the multi-agent system to work on the simulated environment establishing communication between the two domains is required. The multi-agent system runs on a JAVA platform while the simulation is run on a simulating environment (i.e. MATLAB/SIMULINK). Therefore, in order to establish communication between two domains, for sensing and control MACSimJx is used. To start the experiment, the procedure below is followed:

1. Open the microgrid simulation model in Matlab/Simulink, and then change the current folder to "C:/macsimjx/MyTools/MACSim/client/bin" , see Figure C.1.

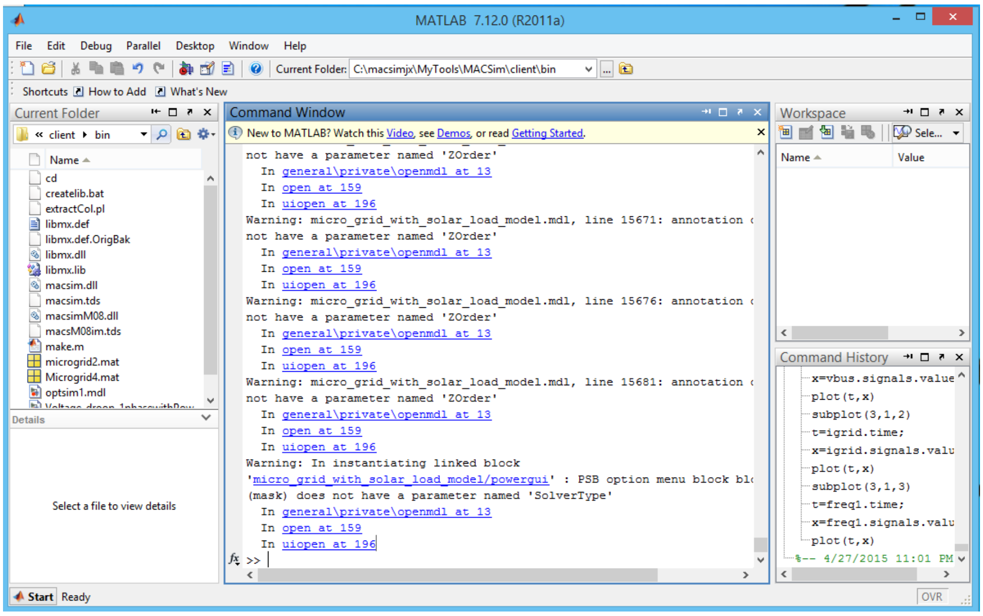

Figure C.1: Setup MACSimjx directory

2. Running JADE

   Tip for JADE: In System properties, create a system variable called CLASSPATH with properties "C:/JADE/lib/iiop.jar; C:/JADE/lib/http.jar; C:/JADE/lib/jadeTools.jar; C:/JADE/lib/jade .jar;" Set a main Jade environment container running: At command prompt enter "java jade.Boot -gui" .This command will open Jade GUI as shown in Figure C.2.

3. Running the MACSimJx Type: "cd C:/macsimjx" Type: "java -jar macsimjx.jar"

   This opens a MACSimJx GUI as seen in Figure C.3 that allows you to choose the group

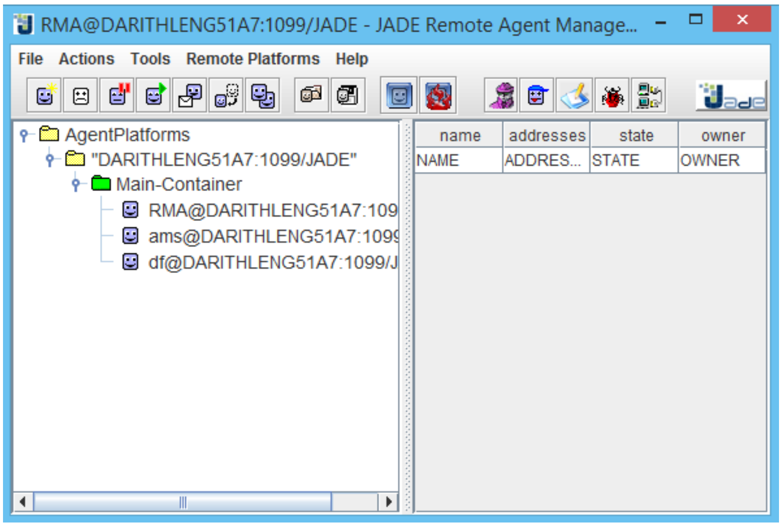

Figure C.2: Jade execution

of agents you wish to use (designated as the agent task force). The Gui also provides the means of incorporating your own agent task force and choose the ATF you wish to use.

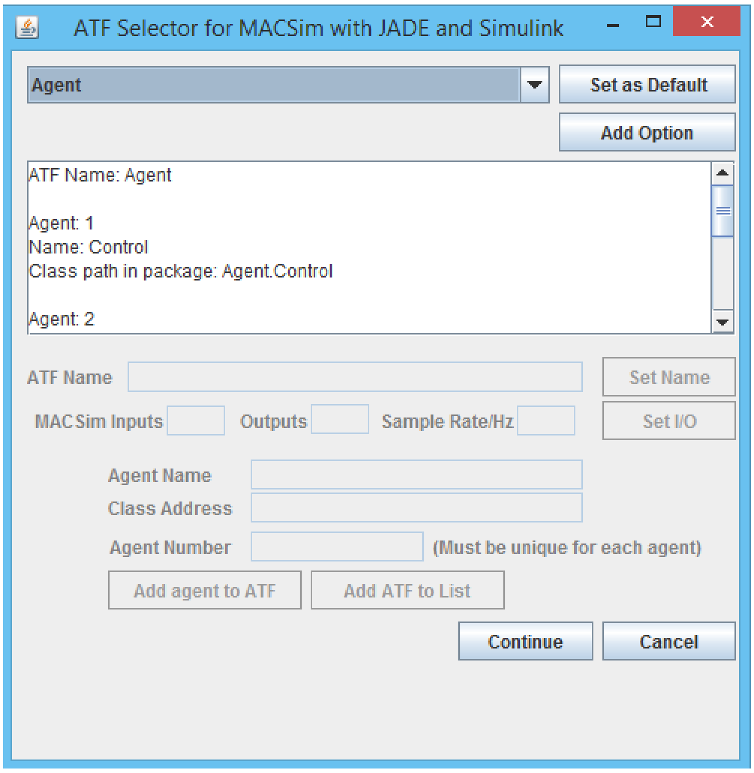

Figure C.3: Agent task force selection

LIST OF PUBLICATIONS

Some parts of this work are published in the following articles.

Reginal Conference Proceedings

1. Darith Leng and Sompob Polmai "Control of a Micro-Grid Based on Distributed Cooperative Control of Multi-Agent System" 2nd AUN/SEED-Net Reginal Conference on Energy Engineering(RCEneE 2014). Bangkok, THAILAND, Nov 13- 14, 2014.

International Conference

1. Darith Leng and Sompob Polmai "Experiment on Distributed Cooperative Control with Multi-Agent System for a Single-Phase Microgrid" 12th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON). Hau Hin, Thailand, June 24-27 2015.

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Bangkok, Thailand

13.-14.11.2014

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Control of a Micro-Grid Based on Distributed Cooperative Control of Multi-Agent System

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***Abstract*— This paper focuses on proposing a multi agent system to control distributed in a microgrid aimed at intentional islanding and Load-Shedding. The multi agent system consists of three main agents such as Control, DER (Distribution Energy Resource) and Load agent. Each agent serves the different responsibility that will discuss in this paper. The proposed multi agent based control architecture is developed using the JADE platform and it is used to control a microgrid simulated in MATLAB/SIMULINK. To enable Microgrid model in Matlab/Simulink to exchange data with Multi-agent created under JADE Platform, the MACSimJX has been used. In order to validate the effectiveness of the proposed method, investigations are carried out for islanding scenarios simulated on the test network. The results of this study show the capability of developing a reliable control mechanism for islanding operation of microgrids based on the proposed concept.**

***Index Terms*— Distributed energy resources (DER), Jade, Load-shedding, Macsimjx, Microgrid, Multi-agent system,**

I. Introduction

Nowadays, the increase in the demand of electricity and the increase in frequency of natural hazards or fault are the mains problem in power system. As reported in [1], It show that world energy consumption will grow by 56 percent between 2010 and 2040. Total world energy use rises from 524 quadrillion British thermal units (Btu) in 2010 to 630 quadrillion Btu in 2020 and to 820 quadrillion Btu in 2040. With this matter, it makes the security and resiliency of electric power supply to serve critical facilities are of high importance in today's world. Instead of building large electric power grids and high capacity transmission lines, an intelligent microgrid can be considered as a promising power supply alternative.

A Microgrid is a new type of power system, which is formed by the interconnection of various small-distributed energy resources (DERs). It can operate both in grid-connected mode, and island mode if disconnected from the grid [2]. However, there are multiple distributed energy resources (DERs) with significantly different power capacities and generation characteristics in a microgrid so they need a suitable control system; diverse control strategies exist in grid-connected mode, island mode. Therefore, how to control DERs in a microgrid efficiently and feasibly must be of prime consideration in microgrid design and operation.

In order to provide these local distributed control capabilities, development of distributed control systems are essential. Multi Agent Systems (MAS) is a technology coming forward in this aspect. MAS have been developed for a wide range of applications in power systems [3]. The use of MAS in microgrid applications has been evolving over the last decade with considerable amount of work being carried out regarding distributed control applications for microgrids [4]. Multi agent systems are complex systems composed of several autonomous agents with only local knowledge and limited abilities but are able to interact in order to achieve a global objective. These agents are able to act as autonomous social entities, which react to changes in their environment and take intuitive actions in order to realize their individual goals. The aim of a multi agent based control system is to apply this individual goal seeking in a manner such that the overall target required by the user is achieved efficiently and effectively as possible.

Since Microgrid become a potential part in Power system, many researches has been conducted in order to switch microgrid in islanding mode and perform load shedding such as [5]-[8]. Those researches based on TCP/IP to allow exchanging data between multi-agent system and microgrid simulation model.

In this research, the agents are incorporated in microgrid through a middleware called, MACSimJX. It means that the simulated microgrid and the agents exchange information and command through MACSimJX.

This paper is organized as follows: in the section II, An overview of microgrid systems is presented, A brief discussion about Multi-agent System architecture is presented in section III. The Integration of Multi-agent and Microgrid simulation model presented in Section IV. Section V describes the simulation carried out and their results, Finally the conclusions are given in section VI.

II. Overview of Microgrid

Microgrids are small-scale power system designed to supply electrical to loads for a small community, such as a housing estate or a suburban locality, or an academic or public community such as a university or school, a commercial area, an industrial site, a trading estate or a municipal region. Micro-grids can be created by embedding small-scale conventional generation units or Non-Conventional Renewable Energy Sources (NCRES) to existing electrical infrastructure. These NCRES can be mini-hydro, solar photo-voltaic (PV), wind, geo-thermal, small internal combustion (IC) engines, biomass or waste-to-energy systems [9]. These microgrids can be operated either in island mode, where the local loads are fully supplied by the local generation, or in grid connected mode, where the microgrid is either exporting or importing power from the main grid. The microgrid architecture provide in Fig.1.

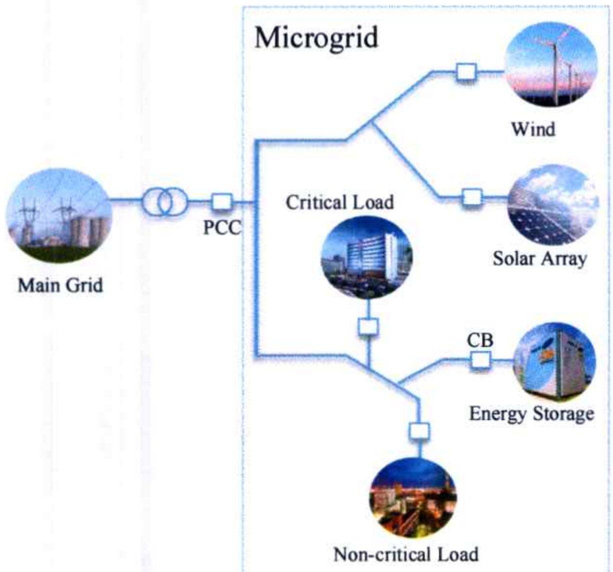

Fig. 1. Microgrid architecture

III. MULTIAGENT ARCHITECTURE

In this section, we design multi-agent system capable control distributed of a microgrid. The MAS is developed in JADE (Java Agent Development) platform [10] and it is used to control a micro-grid simulated in MATLAB/Simulink. There are several different multi-agent architectures have been presented in [11]-[13]. Based on the proposed control architecture, it is necessary to define the functions and roles of each agent accordingly. A function of an agent is defined by a set of behaviors. An agent can execute several behaviors in parallel or concurrently. Within this paper, multi-agent system consists of three agents such as Control agent, DER agent and Load agent. Each agent serves at different responsibility as show in Fig.2:

Control agent: use to control switch at common coupling point (the point of connecting between micro-grid and main system) in case of upstream fault or in order to run micro-grid in island mode and control switch of energy storage (charge when the price of electricity is low or over production from micro-grid) and perform load-shedding.

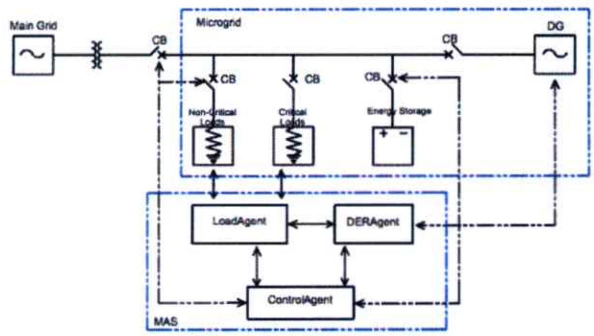

Fig. 2. Multi-agent system architecture

DER agent: will collect the information related to the DG such as availability, connection status, power rating, and energy source availability.

Load agent: use to monitor and control load and varying power consumption by load.

IV. INTEGRATION OF MULTIAGENT WITH MICROGRID SIMULATION MODEL

In this section, we will briefly discussion on available multi-agent system building framework and select a proper one for developing multi-agent in this research, microgrid simulation test bed and middleware, MACSimJx.

A. Multi-agent System

According to Wooldridge an agent may be defined by its characteristics as autonomous, reactive, pro activeness, with social ability [14]. To implement a multi-agent controller, there are numbers of open-source agent platforms available such as JADE [15], ZEUS [16], Voyager [17], SPRINGS [18] and Tracy [19]. In the context of the controlling microgrid, it is very important to select an agent platform that is based on a well-known standard, that is the IEEE standard on Foundation for Intelligent Physical Agents (FIPA) [20]. Based on the agent toolkits listed above, agent platforms that are FIPA-compliance are Zeus and JADE. In this research, the microgrid is modeled and simulated using MATLAB/Simulink, and each agent has to exchange data with MATLAB/Simulink. Recently, a middleware called MACSimJX has been developed to enable multi-agent on JADE platform to exchange data with MATLAB/Simulink. This helps simplify the adaptation of MAS for electrical engineer.

B. Microgrid Simulation Description

In order to implement the proposed Multi-agent system, a simulation test bed is developed in MATLAB/Simulink as a simplified distribution circuit. Fig. 3 illustrates a single-phase microgrid model that comprises of two distributed generators are independently controlled using droop control technique [21] for stable load sharing during islanding mode of operation. These generators are model based on power amplifier (programmable power supply) characteristics for the later experimental stage. Another generator is model as a PV generator, which uses the power generating profile obtained from the 3kW PV generator installed in the laboratory from 7 am to 6 pm of February 14, 2014. The PV generating power was sampled every 5 minute and is scaled to 1 second in this simulation. There are the fixed and the variable loads connecting in the microgrid, these loads divide in two groups: Critical (Load1 & Load2) and Non-critical load. The variable load has the profile of general service type surveyed by the Metropolitan Electric Authority of Thailand (MEA). The test bed was simulated for 140 sec to match with PV generator profile. The important parameters of the microgrid are presented in Table1.

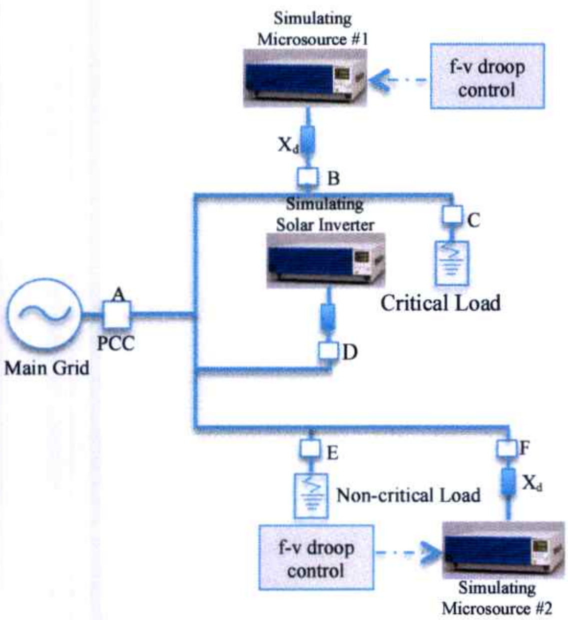

Fig. 3. Single-phase microgrid model

TABLE I. PARAMETERS OF SIMULATION MODEL

Microsource 1 and 2 (Gen 1, Gen 2)	
Model	Kikusui PCR2000M
Power Rating	220V, 50Hz, 2kVA
P-Angle Droop Coefficient (m)	$2\pi(0.000185)$
Q-V Droop Coefficient (n)	1/0.002592725
Digital Controller	Sampling Rate: 12.78kHz
X_d	4mH
Simulating Solar Inverter	
Model	Kikusui PCR2000M
Power Rating	220V, 50Hz, 2kVA
Digital Controller	Sampling Rate: 12.78kHz
LOAD	
LOAD 1	General Service Load Profile from MEA Study
LOAD 2	19.36+j14.52 Ω
Non-critical load	3kw

C. MACSimJX Middleware

This section, presents the detailed implementation of the communication middleware used in the controlling Microgrid Simulation Model. The communication middleware allows the MAS to send/receive data to/from the Microgrid model in the Simulink. The MAS needs to know the status of the agents to take the necessary control actions that are applied to the electric model. MACSimJX, or the Multi Agent Control for Simulink program is an interface that enables models of systems created in Simulink to exchange data with a multi-agent system created using JADE, described in [22]. It was purposely developed as a medium through which a program for implementing agent designs developed in C/C++ or Java might pass data to and from Simulink. MACSimJX has a client-server architecture, where the client part is embedded in Simulink through an S-function, and the server code is then incorporated in the separate program. The communication between the client and server is then performed through the use of named pipes in Windows as show in Fig. 4.

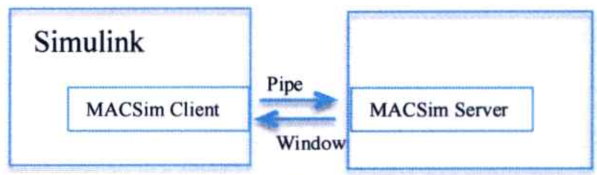

Fig. 4. Structure of Macsim

V. RESULT AND DISCUSSION

A MAS prototype was implemented and integrated with Electric simulation model. The goal of the MAS is to isolate Microgrid during fault condition or power failure and to serve loads with highest priority (critical loads) with the available power of DER sources. If load power becomes greater than both DER and GRID power or greater than DER in case of Islanded mode, then non-critical load should be disconnected. In order to test the operation of the MAS and to evaluate its performance, a microgrid test bed was simulated and multi-agent performs their task. In Fig.5, the agents are live in Jade's container and ready to start. Once the simulation starts, the multi agent can communicate and share information between each other as show in Fig.6; and Jade environment exchange data with Simulink through MACSimJX(agent coordinator).

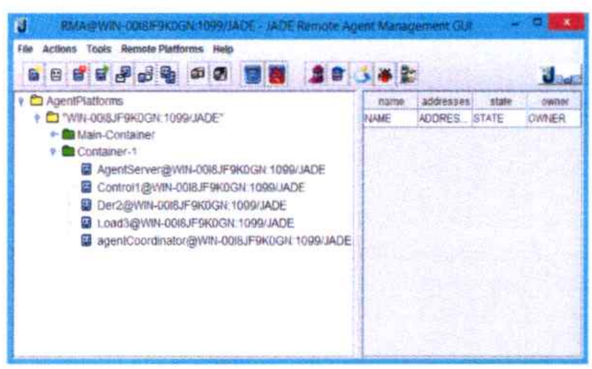

Fig. 5. JADE Remote Agent Management GUI

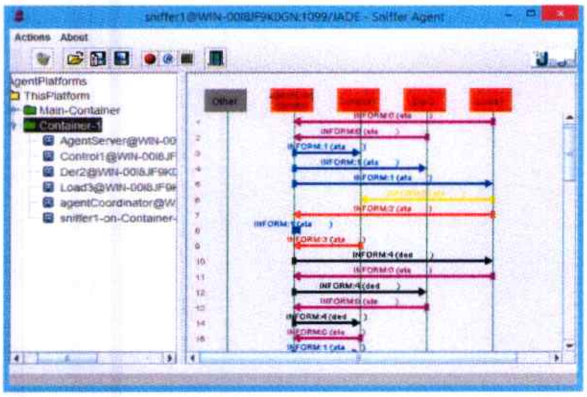

Fig. 6. Sniffer Agent

Then three scenarios and result are discussed below.

A. Grid Connected Mode

First of Simulink start, the microgrid is in islanding mode and take care only critical load. At the time of 50sec, control agent gets the present of main grid then sent closing signal to main circuit breaker at PCC to switch micro grid to Grid connected mode (Fig.7 Middle graph). During the grid-connected mode, the micro grid's voltage and frequency are controlled such that they follow the grid's voltage and frequency, which are roughly at $220\times\sqrt{2}$ V (Upper graph) and 50 Hz (Lower graph), respectively. The DER source and main grid can secure the entire loads in the system.

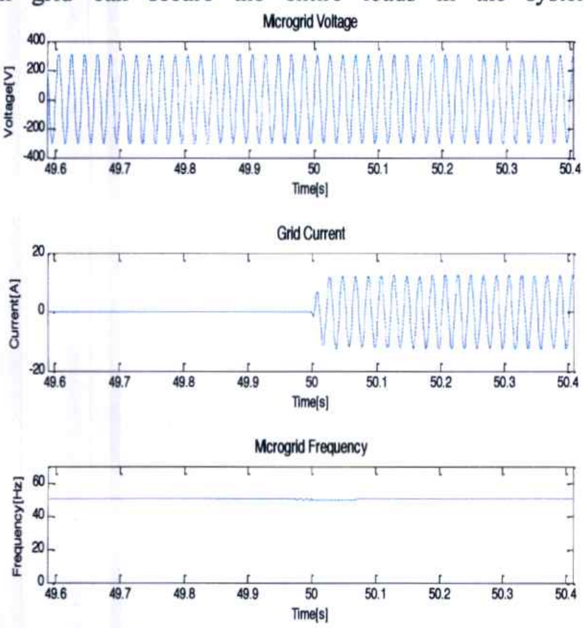

Fig. 7. (Upper graph) Microgrid's Voltage, (Middle graph) Grid's Current, (Lower graph) Microgrid's Frequency.

B. Transition Period

While the fault occur at t = 100sec, the control agent sense this fault and send signal to open the main circuit breaker A, at PCC as show in Fig.9 (Upper graph) to isolate microgrid from the main grid (Fig.8, Upper graph). After control agent give signal to switch microgrid in islanded mode, it perform one more task by request the power production and consumption from DER and Load agent. Once the power consumption from loads is greater than power production, control agent performs load-shedding by sending open signal (Fig.9, Lower graph) to disconnecting non-critical loads (Fig.8, Lower graph) from system in order to stabilize microgrid during the outage.

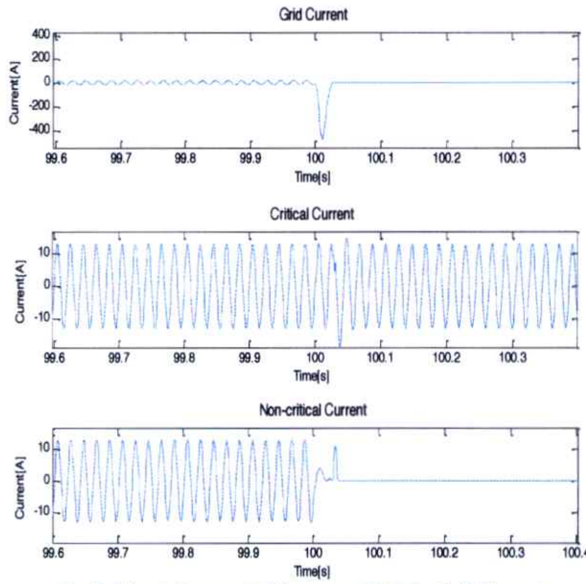

Fig. 8. Simulation result: (Upper graph) Main Grid Current, (Middle graph) Critical Load Current, (Lower graph) Non-critical Current.

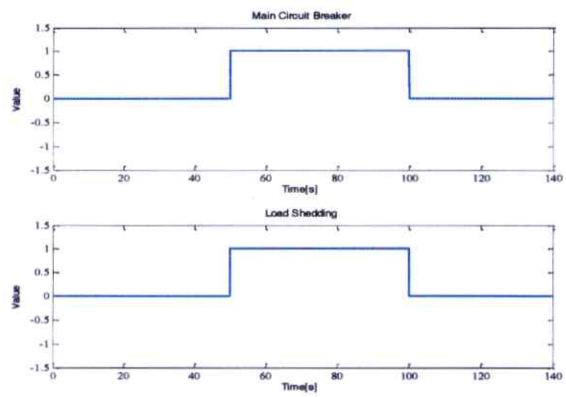

Fig. 9. Signal (0; 1) generate by agent.

C. Islanded Mode

After the fault has occurred at 100sec, the main grid is disconnected at 100sec (Fig.8, Upper graph) and the non-critical load has been cut from system (Fig.8, Lower graph), as microgrid can't secure. The critical loads are fully supplied from DER source (Fig.8, Middle graph). When the Microgrid is operated in the island mode, and consists of critical loads the voltage is maintain at $220\times\sqrt{2}$ V and the frequency is always controlled at 50Hz as show in Fig.10.

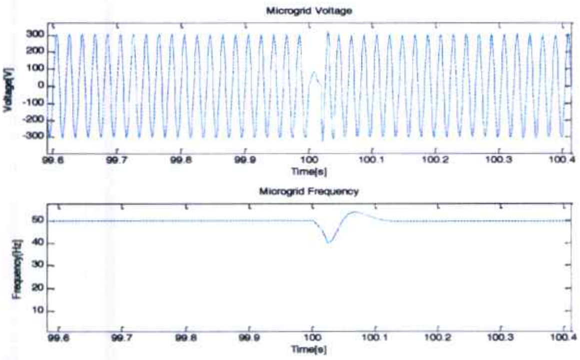

Fig. 10. Voltage and Frequency of Microgrid.

VI. CONCLUSION

In this paper, we presented a multi-agent system for controlling microgrid based on distribution in order to switch microgrid to islanding mode in case off Main grid failure and perform load-shedding. The multi agent system based control architecture is developed using the JADE platform and it is used to control a microgrid simulated in MATLAB/SIMULINK. The microgrid simulation test bed and multi-agent are capable of sharing data with each other through a middleware called, MACSimJX. The multi-agent system were designed and implemented; the microgrid simulation test bed created and ready to getting start. Once simulation started, the agents perform their task then three scenarios have discussed such as grid-connected mode, transition period and islanded mode. The results of experiments show the capability of the multi-agent system to effectively island in case of up-steam fault and secure the supply for its critical loads.

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Experiment on Distributed Cooperative Control with Multi-Agent System for a Single-Phase Microgrid

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Abstract— **In a microgrid, electric generation is based on combination of small generators and renewable resources such as solar and wind. The operating conditions of the microgrid are dynamically altered by both the load and the intermittent nature of the renewable resources. To maintain the voltage and frequency stability of such microgrid, this paper presents distributed cooperative control of a microgrid using multi-agent system. The multi-agent system is implemented by using Mobile-C based on Client-Server architecture, and Ch and Embedded Ch as the agents run time. Serial communication is implemented for data exchange between agents and microgrid elements. To validate the effectiveness of the proposed control system, two scenarios have been experimented. The experimental results demonstrate the generator connecting/disconnecting and load shedding ability of the microgrid.**

Keywords— Ch; Droop Control; Embedded Ch; Microgrid; Mobile-C; Multi-agent

I. INTRODUCTION

From time to time, energy demand keeps increasing and fossil energy has limited. If we rely on nuclear energy, it seems not a sustainable solution, as it becomes restriction to some countries. Otherwise from the users side, the high standards power quality is highly appreciated. All about problems, it leads to common goal for all countries to use renewable energy and create a new sustainable energy system. New form of electrical system by combining new energy and renewable energy is one of effective ways. As the concept microgrid emerges. Microgrid is created when a cluster of loads, interconnected distributed generators and energy storage units are combined as show in Fig.1.

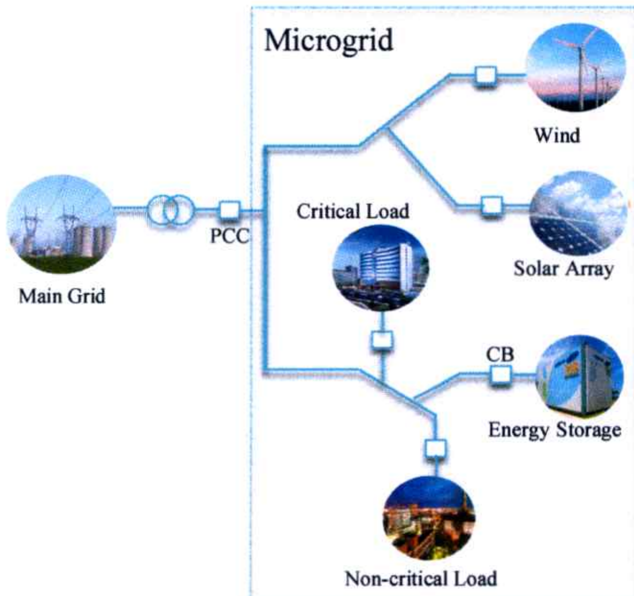

Fig. 1. Microgrid architecture

To improve the system reliability and stability; microgrid must interoperate with other utility. It really needs the control techniques that can perform fast respond to dynamically change and work automatically when microgrid operates in islanded mode.

Droop control is a technique for load-sharing of parallel generators used in microgrid. It provides autonomous and local control for parallel generators under islanding mode of operation. For power converters-based generators that convert dc power from renewable resources to ac power, both magnitude and phase angle can be precisely controlled. However, the lack of physical moment of inertia can result in undesired frequency oscillation during sudden load change. The virtual generator that mimics the power-frequency relationship of synchronous machine is proposed in [1], [2] to help smoothing the frequency oscillation. In [3] and [4] the frequency droop control has been modified so that instead of frequency, the voltage phase angle is directly controlled.

To maintain the stability of the microgrid, the generation and consumption are closely monitored by a management system. The generators have to be operated below their reserved capacities for stability margin or above their minimum generations for economy reason. The loads are divided into groups such as essential and non-essential groups, so that the nonessential loads can be cut off during emergency or high demand conditions.

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Energy storage, if presents in the microgrid, could improve the stability and power quality of the microgrid by release the shortage energy to the load or absorb the excessive energy from the generators.

Microgrid management system can be centralized or distributive. The distribute control is preferable due to the distributive nature of microgrid, the scalability, the redundancy and cost effectiveness.

In order to provide smart control ability for better microgrid application, the multi-agent systems (MAS) is an advance technique in this aspect. MAS have been developed for a wide range of applications as well as for energy management system in microgrid [5]-[9]. Among these, only few of them are realized experimentally [8], [9]. In the embedded system, the multi-agent building toolkit which supports high-level and low-level functionalities, is highly appreciated. Mobile-C platform is selected for MAS development. It is written in C with a small footprint and it uses embeddable C/C++ interpreter Ch [10] to support the execution of mobile agent C/C++ source code. Mobile-C is FIPA [11] compliant which is important for communication with other FIPA compliant agent.

In this paper, the authors implement microgrid local control by using V-F droop control for generators to achieve load sharing and stability during rapid change of load demand. At the management level, the MAS is developed based on Mobile-C and executed under Ch environment.

The remainder of the article is structured as follows. Section II presents the agent building toolkit. Section III describes about experiment carried out and the methodology uses in this research. Section IV, the result of experiment is discussed. Finally the conclusion is given in section V.

II. AGENT BUILDING TOOLKIT

This section will provide some background relates to necessary software for creating agent and the interaction between these software. The agent's building platform are listed below:

A. Mobile-C

Mobile-C [12] is a mobile agent building toolkit, which develop based on C/C++ language and it is compliant to IEEE FIPA (Foundation for Intelligent Physical Agents). Mobile-C has been developed for deploying in real time application like embedded system and network intelligent mechatronic.

The architecture of Mobile-C is shown in Fig. 2. Unlike Jade[13], Mobile-C composes of two elements such as Agency and Agent. Agency resides in each node of a network and work as container or environment for mobile agents executed. The interaction from one agency to other agency in order to exchange information is possible by migrate agent in XML format.

The core elements of agency are listed below:

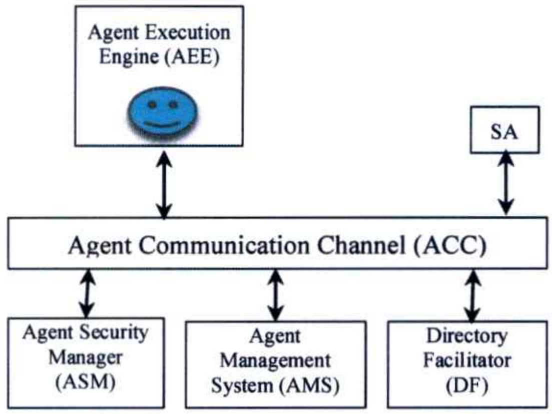


Fig. 2. The system architecture of agencies in Mobile-C

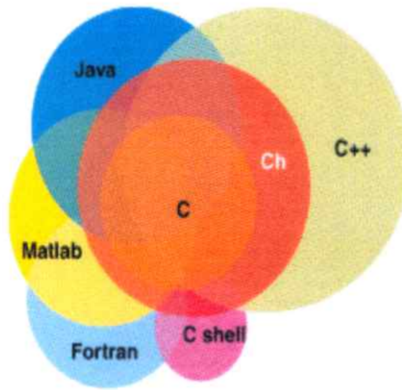


Fig.3. Interaction between Ch and other programing

- Agent Communication Channel (ACC): It works as gate or routes for agent to exchange information by using an agent communication language (ACL).
- Agent Management system (AMS): It works like the system supervisor. It controls all agent functions and life cycle of agents as well. All agent need to register with AMS in order to get an AID.
- Agent Security Manager (ASM): The ASM is responsible for maintaining security policies for platform and infrastructure.
- Directory Facilitator: It implements like the yellow page service. From DF, an agent can register their service or get from other agent in the system.
- Agent Execution Engine (AEE): It works like container or environment where the agent executes or invokes with Ch runtime.

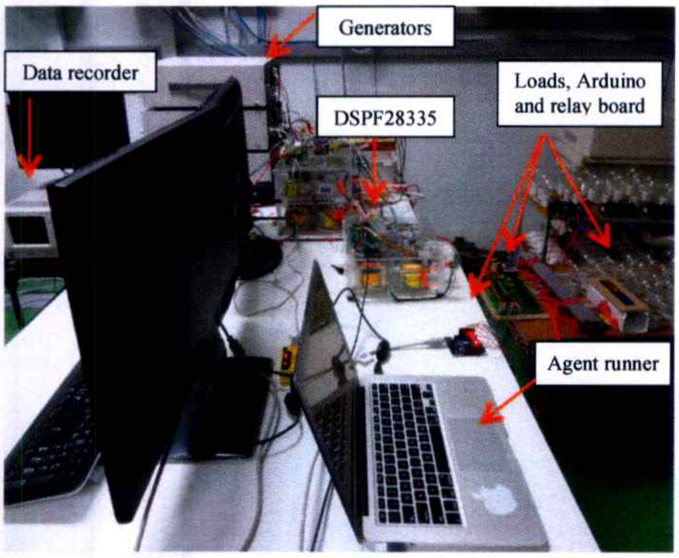
B. *CH*

Ch is a kind of C compiler and known as a superset of C. It not only contains all features of C standard in ISO 1990 but also adds new features in C99 and classes in C++. It performs as a C/C++ scripting engine when embed in other applications. Ch can work perfectly in cross-platform scripting and embedded scripting application, which use by Mobile-C.

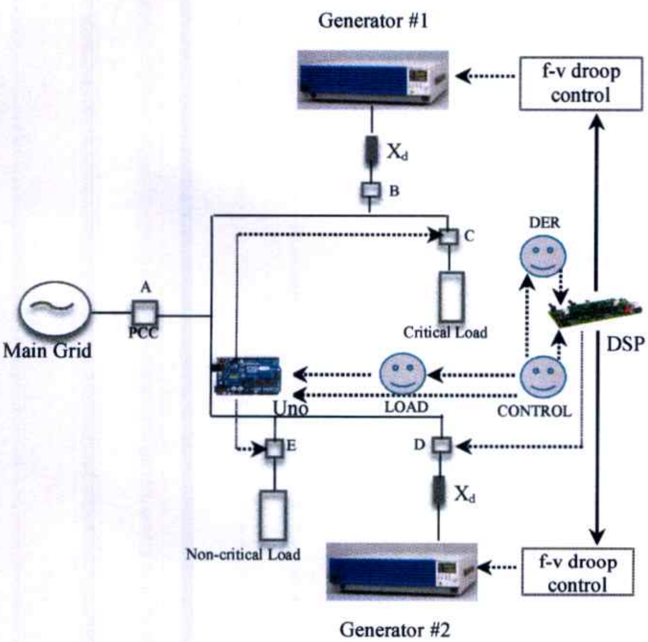
Different from many other software packages, Ch works as a bridge the gap between low-level language and very high-level language. Ch is created by borrowing some features from other major computer programming language. The relation between Ch and other programming language is illustrated in Fig. 3.

III. EXPERIMENTAL SYSTEM SETUP

This section describes procedure and important equipment used in the experiments. The microgrid test bed and the single-line diagram of the microgrid in this experiment are shown in Fig. 4 (a) and Fig. 4(b), respectively.



(a) Microgrid test bed



(b) Single line of experimental test bed

Fig. 4. The experimental setup

TABLE. I Microgrid experimental parameters

Microsource 1 and 2 (Gen 1, Gen 2)	
Model	Kikusui PCR2000M
Power Rating	220V, 50Hz, 2kVA
P-Angle Droop Coefficient (m)	2π(0.000185)
Q-V Droop Coefficient (n)	1/0.002592725
Digital Controller (DSPF28335)	Sampling Rate: 12.78kHz
X_d	4mH
LOAD	
Critical Load	1300VA, 600W
Non-critical load	100W, 200W, 300W, 400W
Digital Controller (Arduino)	14GPIO, 6ADC, 16MHz
AGENT	
Mobile-C	V2.15
Ch	Professional v7.0
Embedded Ch	Professional v7.0
OS	Linux, Ubuntu 12.04, 32Bit

The system consists of two generators controlled by DSP, a set of loads controlled by Arduino and relay board, MAS running on PC and the RS-232 is used for low level communication. The important parameters of the microgrid are demonstrated in Table I.

A. Generator Droop Control

The generators in this system is classified as main generator (Generator #1), co-generator (Generator #2). Generator #1 and Generator #2 are controlled by a DSP using droop control method for load-sharing and maintain system reliability. For conventional droop control [3-4], frequency-active power and voltage-reactive power can express by the following equations:

$$w = w_s - cP \quad (1)$$
$$v = v^* - Q/d \quad (2)$$

Which c and d are droop coefficients, w_s is the reference frequency, v^* is the reference voltage, v is the generator output voltage, w is the generator frequency, P and Q are the generator's active and reactive power respectively.

Fig. 5 shows general frequency-active power (f-P) and voltage-reactive power (v-Q) characteristic for each generator in droop control.

For converter-based generators, the frequency droop control can be modified so the voltage phase angle is directly controlled [3], [4] instead of frequency. The block diagram of the modified droop control is shown in Fig. 6. Fig. 6 (a) the angular droop frequency droop control w is derived from (1). The frequency different between w and the microgrid frequency w_v is subject in the integral controller to produce the require power angle and reference voltage angle $\emptyset^*$ of the generator. The integral gain K_w is used to control the dynamic response of the system [4]. The quickly change of load demand and power sharing with droop control may result in frequency deviation from the reference value w_s. To handle

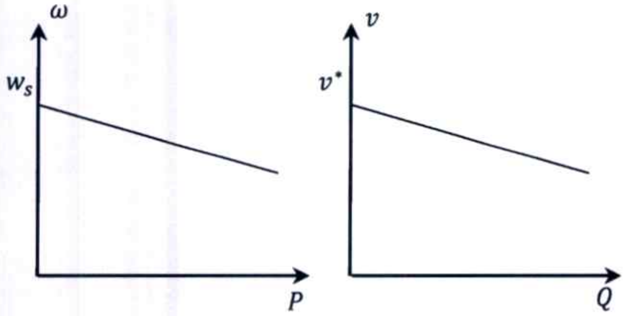
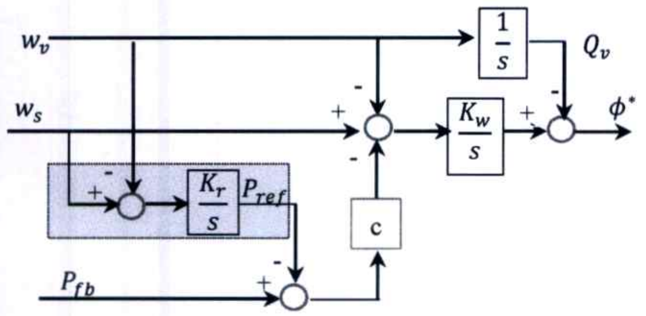
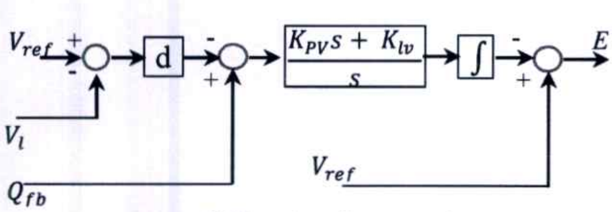


Fig. 5. Droop control generator characteristic



(a) The angle droop control



(b) The voltage droop control

Fig.6. Droop control

this problem, the frequency restoration is implemented as show in shaded area of Fig. 6 (a) to restore the microgrid frequency. The controller gain *Kr* is proportional to the angle droop coefficient of each generator [14].

For the voltage droop control in Fig. 6 (b), the reference reactive power is calculated using the V-Q droop characteristic of the generator by (2). The output voltage magnitude of the generator *E is* the summation of the microgrid reference voltage $V^*$and the voltage output from PI controller.

B. Load

While microgrid is in islanding mode, the microgrid source may not able to supply to entire loads in the system. To maintain the operation, some loads have to be disconnected. The loads set in this experiment is classified into critical group and non-critical group. Non-critical loads are divided into various groups based on power demand ranging from 100W to 400W. When non-critical loads asks to connect to the system, the agent will check for power availability and allow only the non-critical loads which has demand lower than power available.

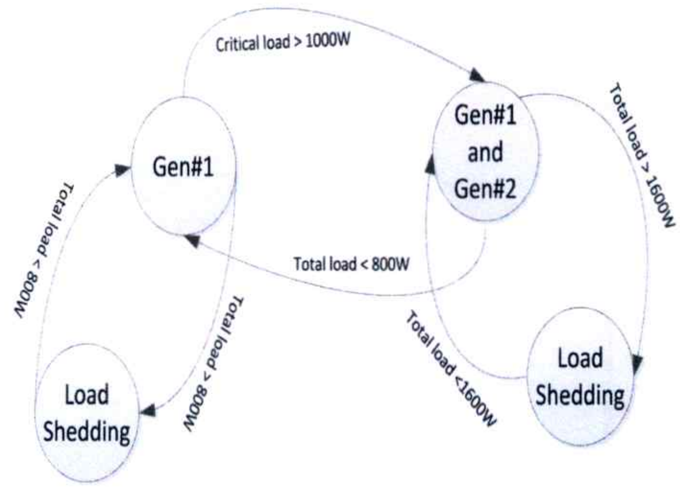


Fig. 7. State diagram of the control task

C. Multi-agent

The concept of using multi-agent system is to simplify a complex problem; a centralized system and a distributed system handled by a single entity into something much more smaller, simpler problems that can be handled by several entities. In this experiment, three agents have been implemented such as:

- Control: It gathers all data got from Der and Load agent. After perform some analysis, it sends command to control non-critical load and generator#2.
- Der: It collects information like generator capacity and power available.
- Load: It uses to get information from load like power demand and load connectivity.

From the Control agent, it migrates an agent in XML format to Der and Load agency through network connection to get some raw data from microgrid like load demand and power available then perform some control tasks as show in flowchart above (Fig.7).

IV. Testing and Result

The objective of the experiment is to demonstrate the ability of the proposed MAS to do some tasks while the microgrid is operating in islanding mode such as performing load-shedding by disconnect non-critical load when the demand greater than generator's capacity and connecting or disconnecting the co-generator upon the operating conditions.

To avoid any equipment damage from malfunction or unexpected condition happen during experiment, each of the generators have been set to 1000W for maximum capacity. All data records in this test perform through Yokogawa power meter model WT1600. The experiment was conducted for 5 minutes long and multi-agent performs their tasks, then two scenarios and result are discussed below.

A. Load-Shedding

The experiment start with only Generator #1 is activated and the maximum power is set to 1000W. Some of critical and non-critical loads are connected to the system for 600W total. At 90sec, 400W critical loads are added to the system and the demand reaches generator capacity. The agent senses this change, then sends command to disconnect non-critical loads as show in Fig.8: E3 (green line).

At 180s, the critical loads demand is increased to larger than the Generator #1 maximum power, the agent then activate the Generator #2. The two generators have maximum combined for 2000W. If the critical demand is less than these capacities, the non-critical loads can be connected back to the system as can be seen in Fig.8: E3 (green line). At 270s, critical loads demand decreased below Generator #1 capacity then Generator #2 was deactivated by agent and some non-critical loads can be supported by Generator #1. In this experiment, frequency restoration is performed only when the two generators are connected.

B. Connecting or Disconnecting Co-generator

The experiment starts with Generator #1 supplying some critical and non-critical loads. At t = 65s the critical loads reach the Generator #1 capacity, and the agent activates Generator #2 as show in Fig.9: E1 to supply all loads in the system. At the same time of the connecting of Generator #2, the system frequency is restored to 50 Hz as the result of the frequency restoration control, Fig.9: E4 (red line). As the loads demand decrease below Generator #1 capacity at the time of 240s, the agent switch off the Generator #2 (depicted in Fig.9 E1).

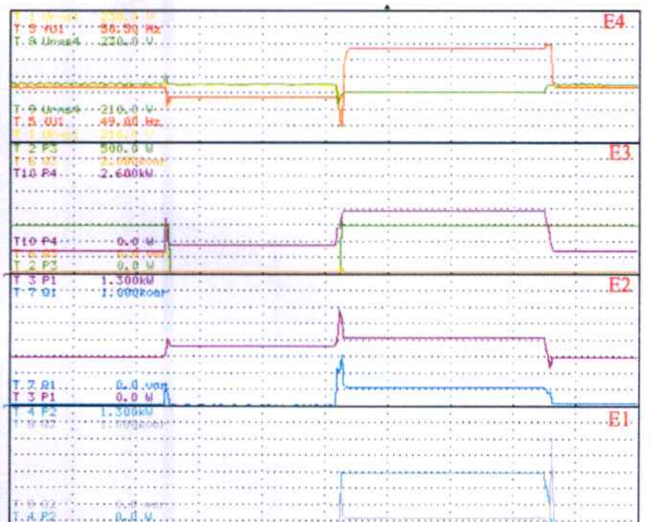


Fig. 8. Experiment result for load-shedding: E1: Power of generator #2; E2: Power of generator #1; E3: Ping line present to critical load power and green line for noncritical load power
E4: Bus voltage and frequency

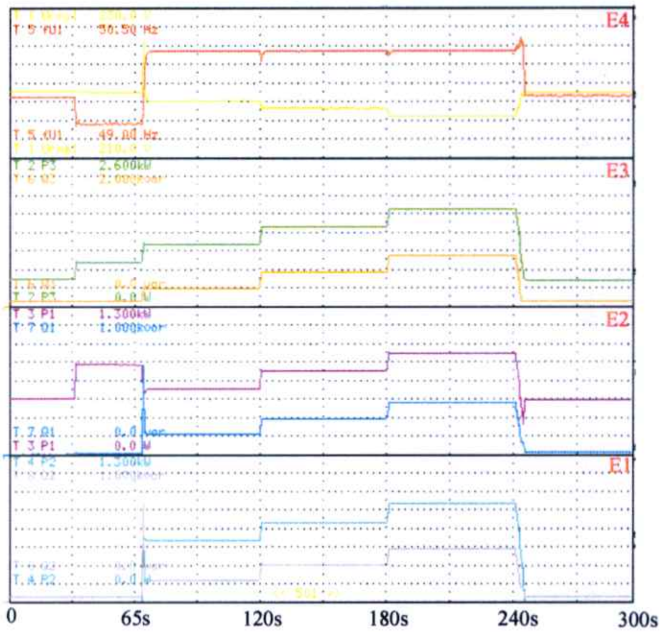


Fig. 9. Experiment result for activating generator #2: E1: Power of generator #2; E2: Power of generator #1; E3: Ping line present to critical load power and green line non-critical load power
E4: Bus voltage and frequency

Fig.10 demonstrates the effectiveness of droop control and frequency restoration. These two generators can equally share the load all over the range of operation. The system voltage and frequency are maintained within the allowable range roughly at 220 V (Fig.10: E4, lower line) and 50 Hz (Fig.10:E4, upper line), respectively for all dynamic condition.

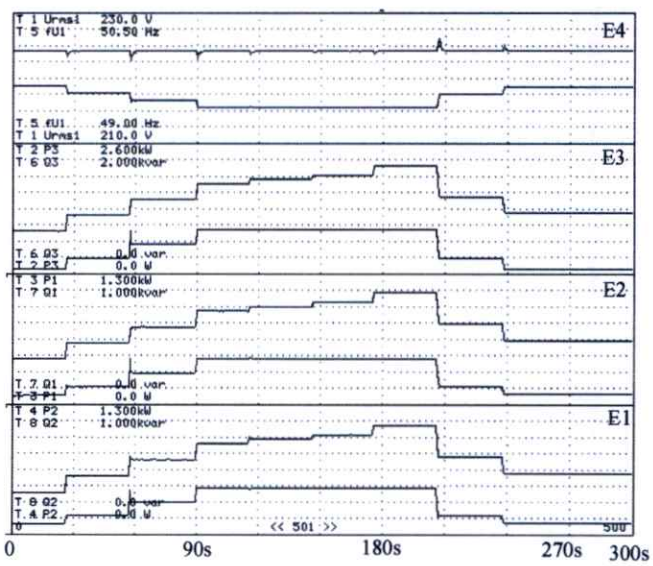


Fig. 10. Experiment result of droop control: E1: Power of generator #2; E2: Power of generator #1; E3: Power demand of loads
E4: Bus voltage and frequency

V. Conclusion

In this paper, Mobile-C-based MAS was developed for an experimental microgrid. The MAS running on a PC communicates with local controllers via RS-232. The modified droop control and frequency restoration has been adopted for local control of each generator. Two experimental scenarios have been carried out for load-shedding and co-generator activation. The results of experiments verify the effectiveness of the proposed MAS for distributed cooperative control of the microgrid.

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