REAL-TIME MANAGEMENT OF SMART GRID USING

MULTI-AGENT SYSTEM

A Thesis

Presented to

the Faculty of the Electrical and Computer Engineering

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in Partial Fulfillment

of the Requirements for the

Degree Master of Science

in Electrical Engineering

by

Tariq Khan

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An Abstract

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Abstract

In this thesis, we explore the following three areas: Design of a multi-agent system (MAS) and a microgrid, implementation of MAS in a microgrid, and real-time resource management in smart grid networks. This includes a detailed anatomy of the multi-agent system, a complete description of various components of the microgrid, a thorough analysis of the communication between these two independent systems and, finally two case studies to experience the usage in actual real-life conditions.

The microgrid has been simulated in a Matlab/Simulink environment with standard distribution elements. The microgrid consists of one Solar Farm as the Distributed Energy Resources (DER) with main grid feeding the residential areas during normal operation and DER during fault condition. JADE is chosen as the multi-agent system framework and the communication between the multi-agent system and the microgrid model in Simulink is established using MACSimJX, a third-party interface for protocol conversion.

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Chapter 1: Introduction

1.1 What is a Microgrid?

Microgrid, as the U.S. Department of Energy defines it, is a local energy grid with control capability, which means it can disconnect from the traditional grid and operate autonomously [1]. Homes, shops and other establishments are powered by the grid which is connected to central generation sources, which allow us to use appliances, heating/cooling systems and electronics. Due to the extensive interconnection of the grid to the residential areas, in case of any fault or repair, the whole area gets affected. A Microgrid can be powered by distributed generators, batteries, and/or renewable resources like solar panels, wind farms etc., which can be a distributed energy resource (DER) [1].

From the user end perspective, a Microgrid can enhance the quality of the power network, reduce the risk of outage and overall cost of the energy. From the utility perspective, the Microgrid can help reduction in the power flow in the transmission and distribution lines, reduce the losses in those lines, reduce the load on the network and helps network repair in case of any fault [2]. The Microgrid can operate both connected to the main grid and in islanding mode. This system can be useful in resolving the intermittency and uncertainty issues of the RES which creates a resilient load/generation network [3]. Implementation of Microgrid system will improve the environment by making us less dependent on fossil fuels which will cause the decline of carbon emissions and thus reducing the threat of climate change. Implementation of this system with RES as an alternative energy resource is clearly the future of power systems.

1.2 Architecture of the Microgrid

Microgrid system operate at distribution side of the grid connected at the point of common coupling (PCC) which is low voltage compared to the transmission lines. The network has several distributed energy resources (DER) such as Photovoltaic cells, Energy storage systems, Fuel cells etc., attached to it, as illustrated in Figure 1.1, which is controlled/managed by a central management system. The ability to operate connected to the grid (on grid) or disconnected to the grid (off grid/islanded) is the unique feature of the Microgrid [4].

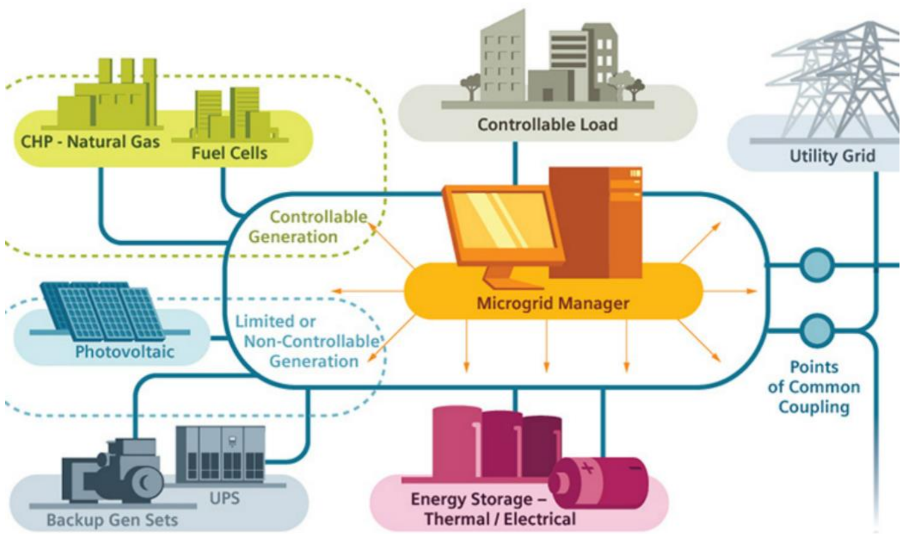

Figure 1.1 An illustration of an architecture of a typical Microgrid [5].

Technologies involved in the Microgrid includes battery, super capacitors and flywheels which are used in the system to stabilize it in case of load change, to share the load, help reducing the sudden load increases and noises and act as a backup energy resource [6].

1.3 What is a Smart Grid?

Before going to the Smart Grid, the traditional grid must be explained. "The grid," refers to the electric grid, a network of transmission lines, substations, transformers which deliver electricity from the generating stations to residential areas and other buildings. The current electric grid of the U.S. was built in the 1890s and today, it comprises of more than 9,200 electric generating units with more than 1 million megawatts of generating capacity connected to more than 300,000 miles of transmission lines. To keep up with the current technology, a new kind of electric grid is needed, which can exploit digital and computerized equipment and technology of this day and age—and one that can automate and manage the increasing complexity and needs of electricity in the 21st Century.

What makes a traditional grid "Smart" is the use of digital technology that allows for two-way communication between the utility and its customers, and the sensing for errors and faults along the transmission lines. The Smart Grid consists of control equipment, server-client mechanism and automation which will work with the electrical grid to respond dynamically to the change in electric demand [7]. As reported in [8], Smart Grid is about reworking the existing electricity infrastructure by encompassing technology, policy, and business models. It is not merely smart metering, but an automated way of managing the power from both the utility and consumer end. When these smart features are implemented in a grid with renewable energy sources, Distributed generation (DG), Energy storage devices etc., which can operate in grid-on mode as well as islanded mode, then the system is called a Microgrid with smart features or simply "Smart Grid". And thus in most cases the word Smart Grid and Microgrid can be used interchangeably. An illustration of Smart Grid is shown in Figure 1.2.

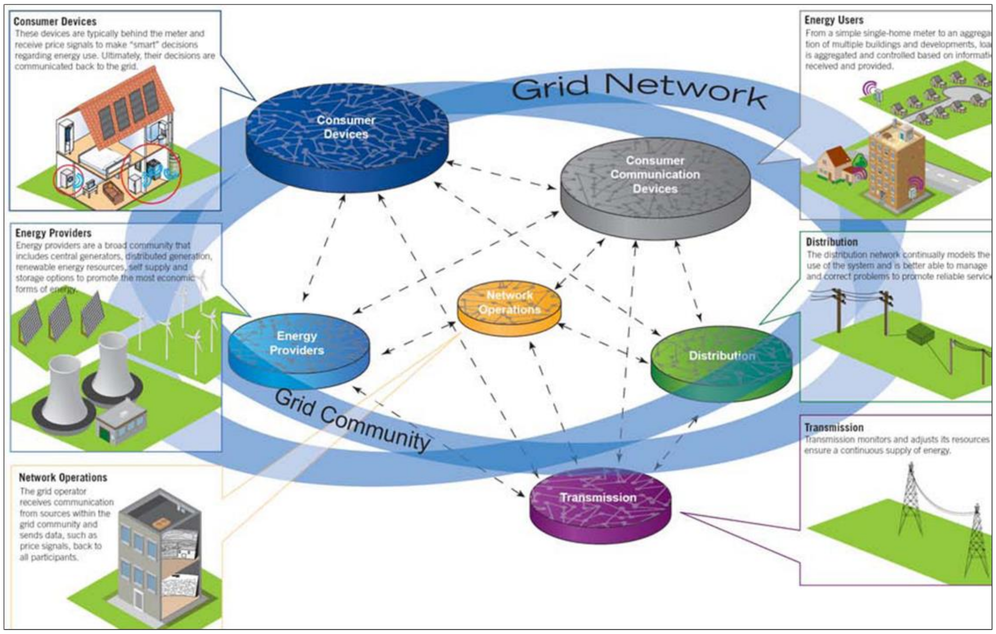

Figure 1.2 An illustration of a Smart Grid

The features/components of a Smart Grid on utility side are as follows:

- Sensors, Embedded processors
- Hardware integration
- SCADA and Energy Management software
- High-speed and High-bandwidth communication systems

The features/components of a Smart Grid on consumer side are as follows:

- Load management with utility
- Integration of energy resources, e.g., RES with the utility
- Management of critical and non-critical loads

1.4 Standards, Programs and Policies for Smart Grid

With the passage of Energy Independence and Security Act of 2007, the support for Smart Grid in the United States have become a federal policy. With this law in action, there has been a funding of $100 million per fiscal year of 2008-2012 to encourage utilities and consumers to build Smart Grid capabilities, assess the advantages of demand response and device the needed protocol standards [9].

Smart Grids got further backing with the American Recovery and Reinvestment Act of 2009. This legislation put aside $4.5 billion of funding for Smart Grid development, implementation, and training for the skilled workers [10].

The Federal Energy Regulatory Commission (FERC) issued a proposed policy statement and action plan on March 19, 2009 for standards governing the development of a Smart Grid, leading to a final rule issued July 16, 2009 [11]. This is to ensure industries to follow certain standards and guidelines moving forward with Smart Grid technologies. There are rules for electric vehicles which allow charging during off-peak time of the day. The commission is likely to install vehicle-to-grid technologies in near future.

The Department of Energy (DOE) issued a Notice of Intent and a draft Funding Opportunity Announcement (FOA) which will provide grant of $20 million for deployments of Smart Grid technology and grants up to $5 million for the deployment of grid monitoring devices though a program called Smart Grid Investment Grant (SGIG) [12]. There is also grants for the support of regional Smart Grids, energy storage and monitoring systems.

IEEE has established itself as one of the leading authority to standardize Smart Grid interoperability, given its substantial and immensely depth prowess of technology expertise and an active community. IEEE already has existing standards and developing projects in areas like information and controls systems, networking, security, stability, evaluation, interconnection of distributed resources including renewable energy sources to the grid, sensors, smart metering etc.

IEEE has more than 100 standards and standards in development relevant to Smart Grid, including the over 20 IEEE standards named in the NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 1.0. The NIST report depicts an efficient reference model for the Smart Grid, distinguishes about 80 existing standards that can be utilized to bolster Smart Grid advancement and recognizes immediate need for new or modified norms [13].

Members of American National Standards Institute (ANSI) have teamed up to jointly develop a standard under the national Smart Grid effort. The standard from the American Society for Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) and the National Electrical Manufacturers Association (NEMA) will provide a common basis for electrical energy consumers to describe, manage, and communicate about electrical energy consumptions and forecasts. ASHRAE/NEMA Standard 201P, Facility Smart Grid Information Model, will define an object-oriented information model which will enable home appliances and control systems in buildings and industrial facilities to manage electrical loads and generation sources intelligently with the electrical grid and to have a better communication with other utilities and electrical service providers [14].

1.5 Limitations and Issues with Smart Grid

Indeed, Smart Grid has greatly increased the overall grid performance, reliability, robustness and capability to communicate with the consumers. The exchange of information via a two-way communication system has improved the quality of supply and also encouraged the consumer to integrate their energy resourced to the grid. Increased amount of digital information being transferred along with actual power within the grid has increased the system complexity, the risk of security of the network, issues with the privacy of the customers, risk of communication failure or lack of communication between grid and consumers etc. These areas are some of the most important issues which can limit the implementation of Smart Grid in wider scale.

With the increased penetration of renewable energy resources into the grid, more complex technologies are needed to integrate it with the grid. And due to the unpredictable and fluctuating nature of these sources, even more complicated technologies are needed in order to integrate those sources feasibly. The equipment needed for it often contain power electronics circuit and are responsible for injecting harmonics into the grid. The protection grid is not reliable enough to isolate those harmonics from the grid and thus degrades the quality of power [15].

A fully integrated Smart Grid is a very complicated system with numerous voltage levels, voltage type conversion devices and because it's main purpose is to have a two-way communication, there can be tens of millions of nodes. Such a large-scale network can be very difficult to manage, troubleshoot in case of a failure or to predict a failure itself due to many dependent and independent factors involved [16].

Due to the two-way communication nature of the Smart Grid, consumers can now interact with the grid exchanging information, e.g., power consumptions, consumptions patterns, information about their energy resources etc. These data would help the grid to make smarter decisions and give it the ability to make intelligent predictions about load demand, type of failure, location of failure etc. But on the other hand, it can lead to some serious privacy issue on the consumer end [17]. Since the data is being transferred digitally, there is always a risk of potential hacking, cyber theft, management issues etc. These are some of the issues the utility has to tackle.

Traditionally, the transformer tap-changers (LTC), the line regulators, and the shunt capacitors are used at the substations and distribution feeders to provide the proper voltage regulation. With the introduction of many DER units connected among the loads on or low voltage feeders makes the controlling of these devices very complicated and inefficient [18]. Therefore, in case of any sort of failure in the system would lead to the either entire shutdown of the grid or would lead to poor transition from grid mode to islanded mode with lots of harmonics caused due to the power electronics or very high transient voltage due to switching. Moreover, it is almost impossible to control the entire system by a single central system, when there are numerous energy resources scattered miles away from the central grid [19]. If such a control system were to be implemented, it would increase the cost of infrastructure drastically and would add complexity to the centralized supervisory control. It not only poses a threat to the stability of the network but also creates management and communication problems within the network. This issue would be addressed in detail in next section and a solution would be proposed in the later chapters.

1.6 Contribution of this Thesis

Although there has been extensive research on various aspects of the Smart Grid since its inception, the study on the communication and efficient resource management aspect on smart gird networks is suntil limited. The focus of this thesis would be the communication and resource management aspect of the Smart Grid.

In summary, a solution to the above problem is addressed by designing, implementing a Multi-Agent System specifically for a Microgrid environment. It is expected this work would be give us the basis for the realization of a Multi-Agent System based Microgrid. Furthermore, the work also contributes to a more efficient design of the Multi-Agent System for a better communication and resource management by designing better algorithms for control, new ways of networking, techniques for fault detection and management of load in worst case scenarios.

The contribution of this thesis extends by providing case studies of real-life conditions which can help implement the system more feasibly. The case studies will describe not only the conditions we expect from a Smart Grid connected to various distributed energy resources but also the ways to sense those faults and make intelligent decisions based on the data acquired.

To conclude, the thesis provides a new way of interaction between various components of the Smart Grid in such a way that, the information about each and every part of the Smart Grid is available to every other components of the Smart Grid via the Multi-Agent System, and thus can take decision independently and intelligently without relying on the central management system.

1.7 Organization of this Thesis

The thesis has been organized into six chapters containing various sections, each addressing a specific portion of the entire research. The thesis starts with the introduction discussing the structure and the current status of the Microgrid in the united states.

Chapter 2 outlines the objective of this research in detail and also lays out the methodology used to achieve the objective. A small briefing of the case studies is also given in the same chapter.

Chapter 3 breaks down the Multi-Agent System, which is the core of this research. A brief comparison has been done with several other agent building kits available. Then justification of using JADE as the agent building kit has been made. Furthermore, the architecture and communication system within the JADE is explained.

Chapter 4 is dedicated to the simulation part of this thesis. It describes the Microgrid in Simulink environment and a walkthrough of all the elements of the Microgrid is given.

Chapter 5 describes the agent building process for the Microgrid and lays out the role of each agents used in the Microgrid. Then the structure and the communication system of the interface between Simulink and JADE has been discussed.

In Chapter 6, the results from the experiment conducted has been shown. A discussion is done based on the results. Then the thesis ends with a conclusion and the future work of this research has been proposed.

Chapter 2: Objective and Methodology

2.1 Latest Research on Multi-Agent System in Microgrid

Several research has been done on the application of the Multi-Agent System in Microgrid for various specific reasons. In [20] the researchers have used Multi-Agent System to implement Mixed-integer linear programming (MILP) to optimize the power managed by the Energy Management System (EMS). In [21] voltage regulation across the Microgrid has been achieved by Multi-Agent System realized in Mobile-C architecture and Embedded Ch as the agents run time. In [22] a model for automatic control of the generation has been achieved by the implementation of MAS in Microgrid. Whereas in [23] market modelling, optimization and power restoration have been achieved by the use of distributed control framework for Microgrids. In [24] the researchers used Multi-Agent Systems to implement a control strategy to offer hybrid energy storage systems to the DC Microgrids with batteries and ultra-capacitors spatially distributed at different levels of the power distribution hierarchy. In [25] a process for coordinated switching control strategies is implemented to search for the optimal switching operation mode so that Microgrid can be switched during larger power balance. In [26] the research is much more focused on the economic side of the grid, which deals with the power management operations based on the fluctuations in the market price.

These research are very extensive and target specific aspect of the Microgrid. This thesis will address some of the issues not mentioned in the works above, e.g., sharing DER unit with multiple loads, real-time communication between agents etc.

2.2 Objective

The objective of this research is to design and develop a communication system within the Microgrid that can establish a robust two-way communication between the grid and the consumer with the capability of disconnecting the grid from the Microgrid during any kind of fault, feeding uninterruptible power to the critical loads using the DERs, and disconnecting non-critical loads (segregation and prioritization of the loads). Because all these features are highly critical to the stability and reliability of the system, all the communication must be performed almost in real-time if not exactly in real-time. Furthermore, the Multi-Agent System must be flexible enough to incorporate additional features with ease.

To accomplish the goal, the proposed solution is divided into sections for better understanding. The sections are as follows:

- Comparison between different MAS environment available
- The architecture of the proposed MAS
- Simulation of the Microgrid
- Development of the MAS
- Interfacing the Microgrid simulation with the MAS
- Fault detection and clearance
- Case studies
- Results and discussion
- Conclusion

2.3 Methodology

Since the development of agent-based systems, many agent building toolkits are available for the developers to build a Multi-Agent System. In this thesis various agent building toolkits are thoroughly compared based on criteria such as code language, cost for licensing, documentation for developers, agent mobility, inter-platform operability, response time, time delay between information exchange, FIPA compliance, and information security.

The architecture of the proposed Multi-Agent System is based on the need of the Microgrid. The whole point of the Multi-Agent System is to divide the task of the central controller into different agents. Thus in this thesis various agents would be developed through programming and will be assigned specific task through a unique code. Then there would be a common code which will be used to establish a communication system between the agents by which they can pass on information and thus take intelligent decisions without relying on a central management system.

A huge portion of the Microgrids is controlled by traditional SCADA systems with tasks such as generation, transmission, distribution and utilization. The SCADA functions can be classified form basic to highly advanced features. In this thesis the traditional SCADA system would be explained and compared to a relatively new Multi-Agent System in terms of features, convenience, intelligence, cost of implementation, operation and maintenance and thus make an argument to implement the Multi-Agent System into the grid or augment the traditional SCADA system with the Multi-Agent System.

After the choice of a proper agent-building toolkit is made, then the anatomy of the agent would be discussed which includes the structure of the code, the protocol for connection establishment, ontologies, protocol for information exchange, different blocks of code which the agents interact with before making any decision etc. This would give a basic to intermediate understanding of the working of the agent and the overall Multi-Agent System in the background of the simulation, which would be helpful for other to incorporate additional features, troubleshoot problems or scale the entire system.

One of the most important aspects of the Multi-Agent System in Microgrids is the ability to detect upstream faults as precisely and quickly as possible. This would ensure the stability of the entire grid and save the end user from any major voltage spikes. In this thesis, fault theory for a 3-phase network would be explained along with various fault detection and clearance techniques available in the literature which can be implemented.

The entire Microgrid would be simulated in MATLAB/Simulink environment with basic features as one can expect in a real-life scenario. The standards and ratings are according to the organizations like ANSI, IEC, NEC etc.,

The simulated Microgrid in Simulink and the Multi-Agent System have different protocols for communication. For this reason, a third party interface is needed so that those systems can establish a communication system. The interface is called MACSimJX and would be explained in detail in the later chapters.

After the implementation of the Multi-Agent System to the simulated Microgrid, the system would be tested in two real-life scenarios. Those case studies would strengthen the argument for the Multi-Agent System as a good alternative for SCADA systems.

2.4 Briefing of the Case Studies

The first case study is to show a seamless transition from grid-on to islanded mode. This means, the Microgrid must be able to transition from grid as primary energy source to DER as the primary source which causing any voltage/current drop or rise beyond the acceptable limits. A fault condition has been simulated which will trigger the control agents and through communication between agents, a decision to make or break the circuit breakers is taken. This case study will also show how the energy management works in a Multi-Agent System. This is demonstrated by feeding the critical loads in the user end without any interruption. The supply to the non-critical load is cut off at the same time. The assumption made in this case study is that the Solar farm can provide energy at any moment of time when the central grid fails.

In the second case study, since the DERs are very fluctuating and unpredictable, energy is stored from the DERs to an energy storage system, in this case a battery bank. The battery bank is charged by the DERs during the normal operation of the grid and the DERs don't provide any energy to the user end. During fault condition, the DERs are switched as the primary energy source and the battery is disconnected. In this thesis, the DER is a solar farm. A solar farm is active only during the peak hours of the daytime. Thus if a fault occurs during a daytime, the DER can act a primary source, but if the fault extends to later part of the day, the Multi-Agent System would decide to switch the primary source from DER to battery bank, if the central grid has not been restored yet. In this study, the peak hours on the solar farm would end during the middle of a fault and thus the battery bank will be switched to supply power. Various waveforms will be studied.

Chapter 3: Multi-Agent System

3.1 What is a Multi-Agent System?

Before coming to the definition of a Multi-Agent System, the definition of an "Agent" must be defined. According to The Robotics Institute of Carnegie Mellon University, "Agents are sophisticated computer programs that act autonomously on behalf of their users, across open and distributed environments, to solve a growing number of complex problems." [28]. But due to the widespread and distributed nature of scientific tasks, there is always a necessity of multiple agents to perform tasks efficiently. More than one agents can work together synergistically to complete the task.

Therefore, a Multi-Agent System is developed to implement the same autonomous nature of a single agent in a much wider scale. A Multi-Agent System (MAS) is a network of programmable agents, with a well-defined communication protocol, that interact to solve problems that are beyond the individual capacities or knowledge of each problem solver [28].

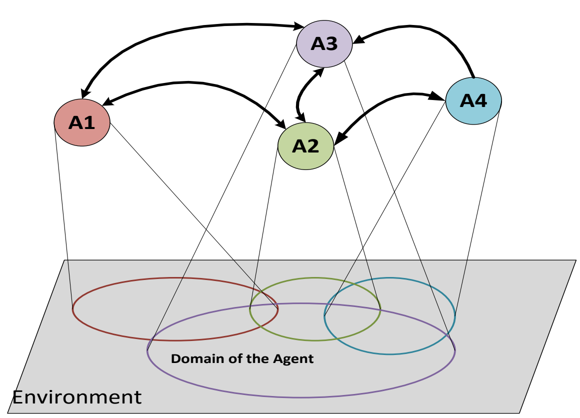

Figure 3.1 An illustration of behaviour of agents in a Multi-Agent System

The illustration in Figure 3.1 shows the behavior of the agents in the Multi-Agent System. There are four agents with their respective domains, i.e., a set of functions they are assigned to. The point to note is that the domain of each agent is not limited to its set of assigned task, it overlaps with other agents' domains too, i.e., each agent can have information about other agents and can share with agents who don't have that information.

Some of the characteristics of the agents in the Multi-Agent System are as follows:

- The agents are self-aware, partially independent and autonomous which can take decisions, without any user intervention, based on the information available.
- No agent has a full control (Global view) over the entire system, but has local views which it can share with other having different local views.
- There is no designated central controller for all the agents. The entire Multi-Agent System is completely decentralized [28] as we can see from Figure 3.1.

The MAS is being studied and being implemented for the analysis and development of complex problem-solving systems and control architectures [29]. The areas where Multi-Agent System has a potential to be useful are

- Cooperation and coordination,
- Distributed constraint optimization,
- Negotiation,
- Distributed problem solving,

to name a few.

3.2 Comparison of Agent-Building Toolkits

Agents are a series of codes with a specific purpose. The network of agent connected together forms a Multi-Agent System. There to design an agent and therefore a Multi-Agent System, an agent building environment is needed in which the agents will be based and thus will act as a framework for the Multi-Agent System.

There are various agent platforms available commercially. Some of the platforms that will be discussed are Grasshopper, ZEUS, Springs, JADE and Voyager. [30] Each agent platform is evaluated according to the following criteria:

- Compatibility with the standards like FIPA
- Inter-platform operability
- Agent Mobility, i.e., ability of system to migrate code and execution state
- Inter-platform communication security
- Usability and documentation for developers

Grasshopper is an open source, FIPA compatible agent platform with very good GUI used in many development projects, very good security features, average response time, logical grouping functionality. But the mobility of the agents is weak and has numerous communication protocols [30].

The main idea in ZEUS is an open source agent building toolkit focused on customization and collaboration, so that engineers with basic knowledge of the toolkit can develop agents with ease [31]. The main features are good documentation, user friendly GUI, FIPA compliant, support Java 2 platform, good security capabilities [30].

Springs is an Open source toolkit, developed by a group at University of Zaragoza in Spain. It focuses on scalability and reliability with high number of agents. Its main features include hierarchical structure, full location transparency, strong agent mobility, minimize problem arises due to quick movement of agents. But it is not FIPA compliant, does not have a secure communication system, the interface is not graphical with very little documentation [32].

JADE (Java Agent Development Framework) is an Open source, Java based agent-building toolkit. It if FIPA compliant with high performance for distributed agent system. The communication architecture is flexible in messaging system using the distributed object technology in JRE [31]. Additional features, called “Behaviours” can be added dynamically and can use ontologies to represent the information in agents. The platform struggles with mobility issues and support for proxies does not exist [32].

The Voyager was developed by Recursion software is computing middleware for the remote communication of protocols such as COBRA and RMI. It provides local transparency, use of proxies, simplified development of distributed systems. The disadvantages of Voyager are, it is not a free software, tracking system for agents is inefficient [32].

Based on the above comparison, JADE has been chosen as the agent-building toolkit for this thesis. Although a brief introduction of JADE was given in this section, a detailed analysis of JADE will be done in the next section in the context of using it for the development of Multi-Agent System for a Microgrid. The analysis will layout the main benefits and some possible limitations for using JADE for this purpose.

3.3 Using JADE as Agent Platform

JADE (Java Agent Development Environment) is a middleware that is used to develop Multi-Agent Systems. It includes the following features:

- It provides a runtime environment where the agents can reside and must be active before any function is executed.
- There are a number of inbuilt classes which the developers can use to create their own agents according to their needs.
- It has a well-built GUI for managing the agents and monitoring the activities of the running agents [33].

When JADE is initiated on a host device, it creates an instance of it. Each running instance of JADE is called a "Container." Whenever a JADE instance is initiated, it always has a default container in it called the "Main Container." A container is a place where all the agents reside. The main container can also hold agents. It depends on the developer to keep all the agents in Main Container or organize in different containers. There can be multiple Containers in one instance of JADE. A set of active containers is called a "Platform." An instance of JADE in a Platform, which can multiple host devices in a network, can only have one Main containers but can have several other containers. It is also possible to have multiple Main containers, but the Platforms has to be different, as the Main Container is registered with a unique host ID [33].

Figure 3.2 illustrates the concept of JADE Agents, Containers and Platforms work within a network and host devices.

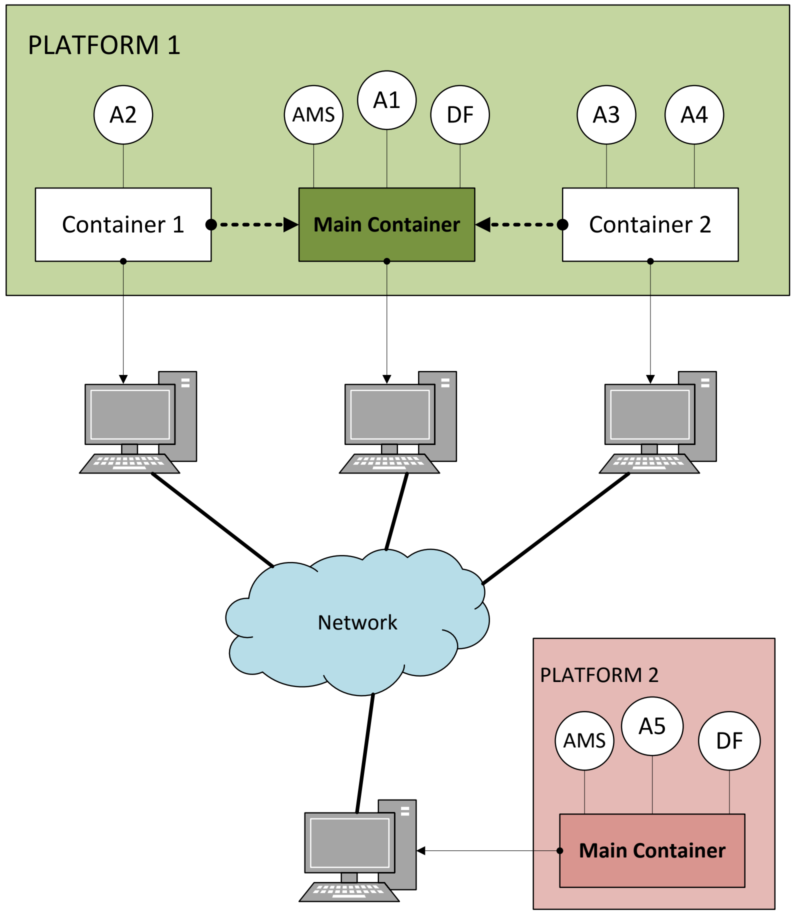

Figure 3.2 Concept of Containers and Platforms

In the Figure 3.2, there are three host devices, one of which contains the main container and the other two host the other two containers. Both Container 1 and Container 2 are registered to the main container. Altogether they form the Platform 1. On the other side, a separate host forms the Platform 2. Since it is a different platform, it can have its own main container. A1, A2, A3, A4, A5 are the agents contained within the containers. Each agent has a unique name and ID based on the host and port. All the hosts are connected to a single network and thus communicate regardless of their location.

When a JADE instance is created, a main container is launched by default. With the launch of the main container, two special agents are also created. They are called the Agent Management System (AMS) and Directory Facilitator (DF). Their roles are defined by the FIPA standards [34].

Agent Management System (AMS) is the supervisory body of the platform. It provides white pages' service of the platform, i.e., list of agents, container with their specific ID and other information. Every agent must register with the AMS in order to obtain a valid AID (Agent ID), which is critical to communicate with other agents. The AMS is also responsible for creating or killing the agents, creating or killing containers, or shutting down the platform [34].

Directory Facilitator (DF) is the special agent within the JADE framework that provided the yellow pages' services of the platform as seen in Figure 3.3.

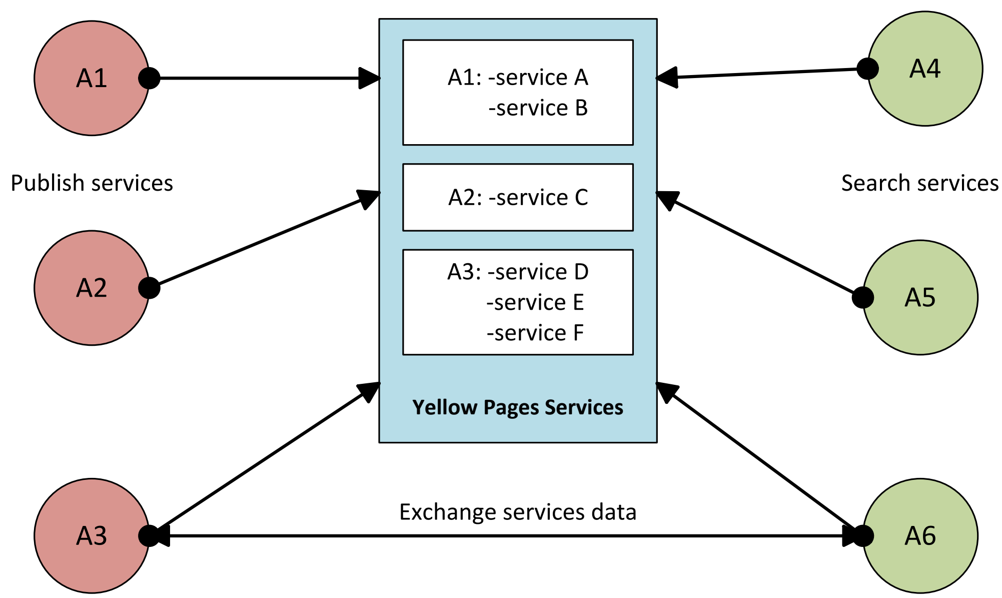

Figure 3.3 Directory Facilitator's Yellow Pages services

To be more clear, DF provides the listing of various services provided by other agents so that it can viewed by other agents looking for those services. DF accept the subscription of other agents whenever a match is made. To facilitate the services across various areas, JADE can initiate multiple DFs and thus can take off some of the load from one DF. The agents can publish their services through the procedures set by the standards of FIPA [34].

As shown in Figure 3.3, The Directory Facilitator act as a Yellow Pages service for the agent platform. A1, A2, A3 are the agents on the left publishing their services to the DF. With A1 providing service A and B, A2 providing service C, A3 providing service D, E and F. On the right, agents A4, A5 and A6 can be seen subscribing to DF to get information about certain services.

For example, A1 publishes service A into the DF. The DF keep the service name and the agent name in its database. If any agent, say A5, came looking for service A, the DF will direct A5 towards A1 and they can exchange their required information, as seen at the bottom between agent A3 and A6.

Remote Monitoring Agent (RMA) is a service agent provided by JADE which act as a graphical platform management console. It enables the developers to graphically monitor and manage agents and containers on a platform. At startup the RMA agent must register with the AMS so that its presence is notified to all the platform available and thus manage it graphically. Unlike AMS and DF, RMA is not a special agent defined by FIPA. It is developed by JADE to give the developers a graphical interface [34].

3.4 Communication within JADE

One of the most important service provided by JADE is the Message Transport Service (MTS). It manages all the message exchange within the platform as well as inter-platform information exchange. All the protocols for MTS are standardized by FIPA. JADE implements all the standard Message Transport Protocol (MTP) defined by FIPA for compatibility with other platforms. In JADE the MTP includes a transport protocol and an encoded message envelope [35].

The main container in any platform, by default, is initialized with a HTTP-based protocol. But the on other containers in the same platform no MTP is activated. Thus a server socket is created in the main container which can communicate with clients broadcasting in HTTP. Whenever a valid message is received by the main container, the MTP redirects it to the matching agents. While the main container communicates with the outside world via HTTP, the internal communication uses a different protocol called IMTP (Internal Message Transport Protocol) [35].

The IMTP is only used for communication between agents, in form of ACL messages, in different containers but in the same platform. Inter-platform communication between agents does not use IMTP. As it is used for internal communication, it is not FIPA compliant and thus can be tweaked for performance enhancement. IMTP is used not to exchange ACL messages but also commands like monitoring container status, management of distributed platform etc. [35]. To summarize, JADE uses HTTP for interoperability with other non-JADE platforms and uses IMTP for internal communication.

Chapter 4: Simulation of Microgrid

4.1 Simulation Circuit with Single-Phase Load

The Microgrid is simulated in MATLAB/Simulink environment using standards and ratings commonly used in U.S. There are two simulations of the Microgrid, one with grid and DER feeding three-phase loads which is seen in Universities, commercial buildings etc., and the other one being the Microgrid feeding single-phase loads as seen in residential areas of the country. This gives us a clear picture of the behavior of the Multi-Agent System in single-phase as well as three-phase systems.

As seen in Figure 4.1, the simulation circuit starts with a 66kV substation which is directly connected to the generation station. The substation act as the primary source of energy for the load. Then as Distribution Transformer steps the voltage from 66kV to 6.6kV for distribution. The distribution runs for 5 km (3.1 miles) then reaches the load area. The voltage from the distribution line is stepped down further from 6.6kV to 208V by a pole-mount transformer which is the standard three-phase voltage for commercial buildings, small industries etc. The transformer is connected to the main breaker which disconnects the entire load area from the grid in fault condition. This completes the grid area of the circuit.

The Microgrid is formed by the grid feeding the load and DER as backup. In this case, the DER is a solar farm. The solar farm is simulated in such a way that it provides constant voltage for certain time period and then voltage level drops down gradually for the rest of the time period. The power from solar farm is converted to three-phase power by a three-phase converter. The converter is then connected to the DER breaker, which gets connected during fault period and disconnects once fault is cleared.

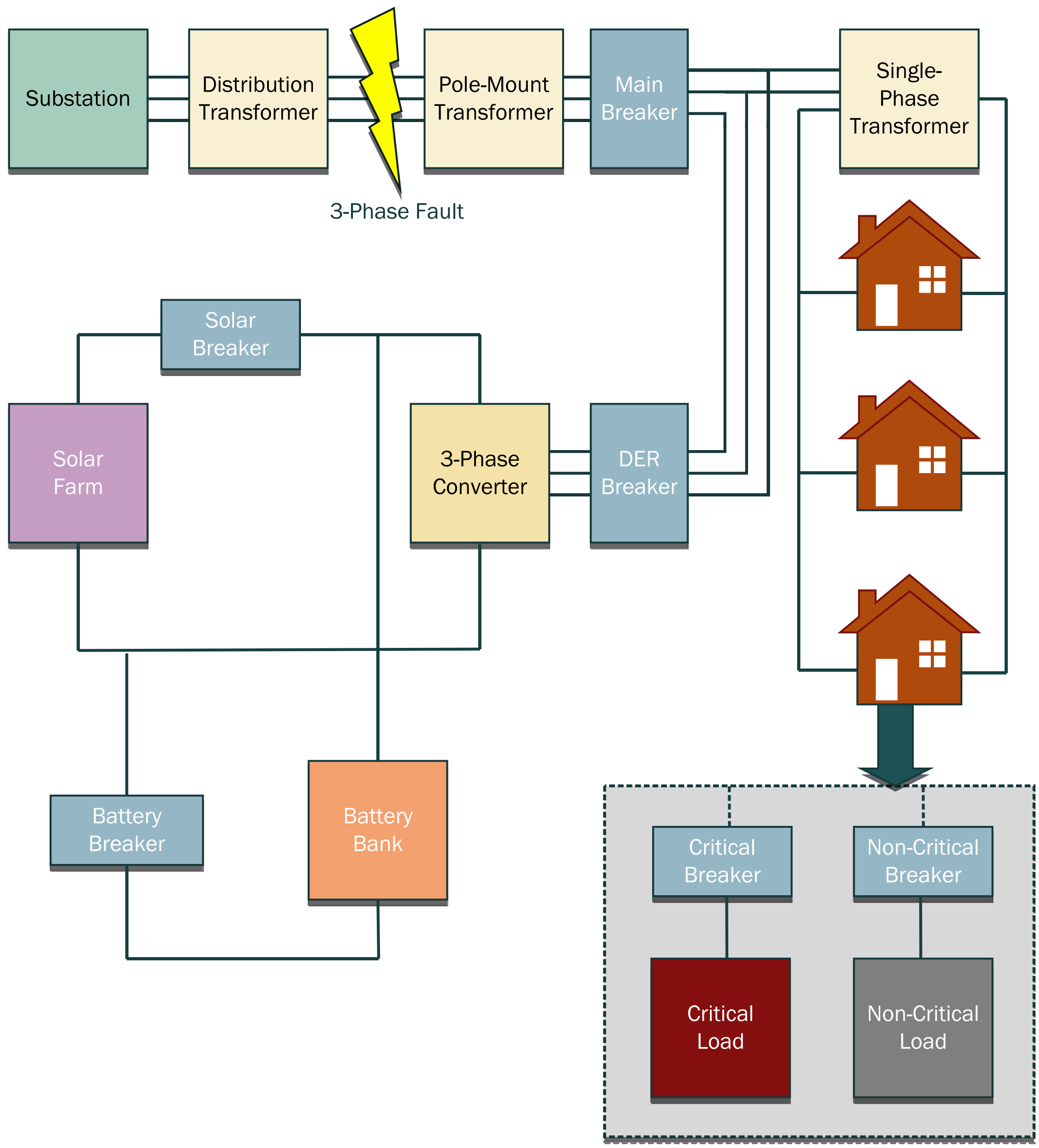

Figure 4.1 The block diagram of the simulation circuit feeding single-phase load

The solar farm is also connected to the battery bank which works as an energy storage system when DER can’t provide energy. The battery bank has its own breaker which connects during normal operation and disconnects when the solar farm is switched as primary source of energy. There is also a breaker which connects solar farm to the converter. Its role is to connect the solar farm to the converter when the solar farm is acting as the primary energy source and disconnects the solar farm once it is unable to provide energy and thus let the battery bank act as the primary energy source. The DER breaker is connected to the point of common coupling. This completes the DER area of the grid.

Now, two phases out of the three-phase power from the main breaker or DER breaker is given to the primary winding of a single-phase transformer. The single-phase transformer converts the voltage from 208V to 120V which is the common household voltage in the united states. The single-phase transformer, in this simulation, feeds three houses each with 20kW of load, which is the average household load in the united states.

The load in each houses are segregated into two different parts, i.e., Critical load and non-critical load, 10kW each. The critical load comprises on the load in the houses which has the utmost priority of power should any fault occurs. These types of load must be fed at all time either by the central grid or by the DER or by the battery bank. The non-critical load comprises of the load which are dispensable and have lower priority than the critical loads. These type of load will be shed in case of any fault and only be restored when the fault is cleared and the grid connected back to the system. The connection is hard wired during construction, but the user has full control over the division of the critical and non-critical appliance in the household.

4.2 Simulation Circuit with Three-Phase Load

The Figure 4.2 shows the second simulation circuit.

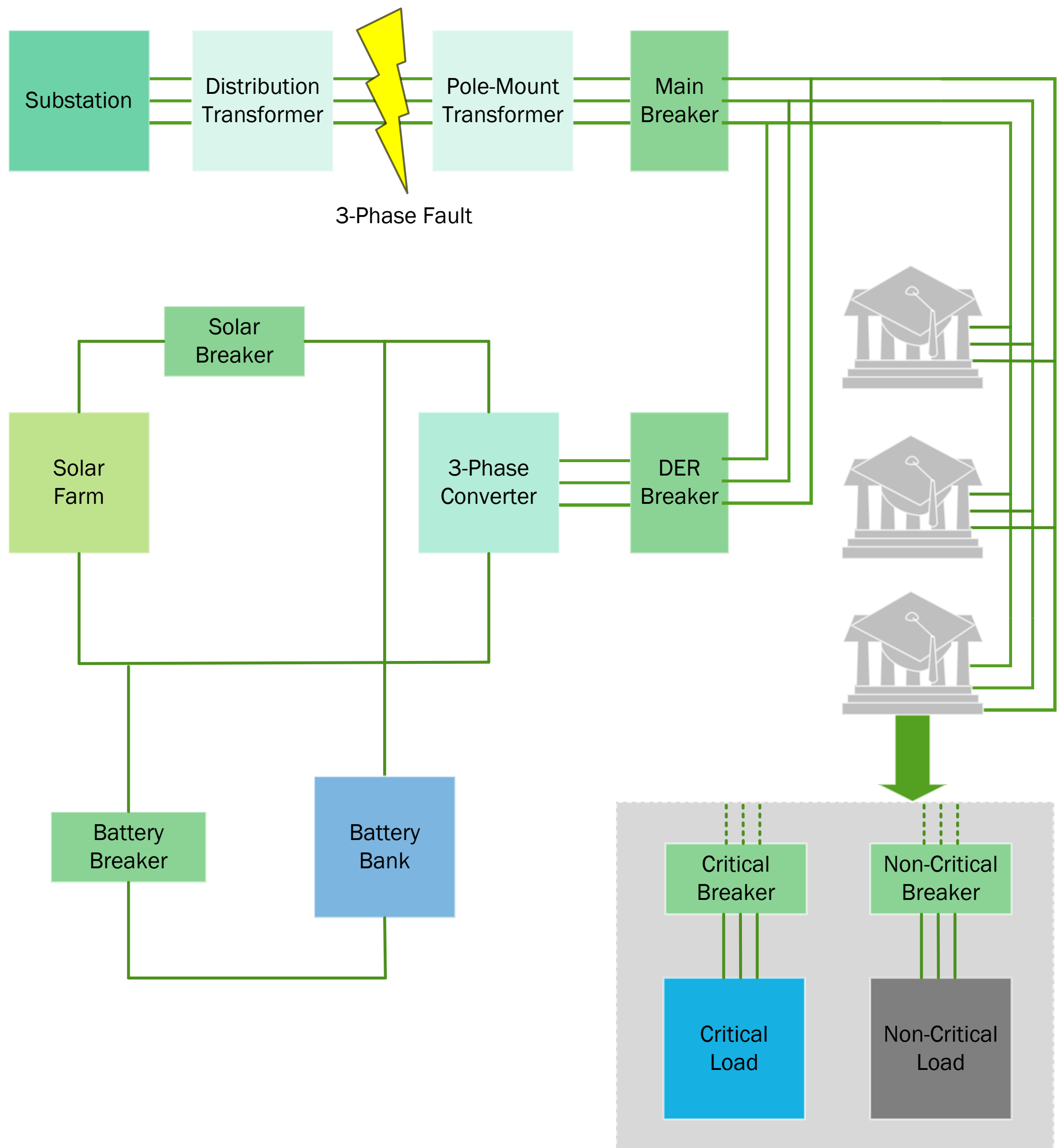

Figure 4.2 The block diagram of the simulation circuit feeding three-phase load

It is similar to the first one with few differences. First, there is no single-phase transformer, as the load are fed three-phase power at a voltage of 208V directly from the pole-mount transformer. Second, the loads are now commercial buildings and small industries requiring three-phase power. The loads in each building is divided into critical and non-critical load in the same way as the previous circuit.

The fault is simulated in both the circuit. The fault type is L-L-L-G fault which is a symmetrical three-phase fault. The fault occurs at the distribution side at the distribution line, as lasts for few seconds before it gets cleared. Although not very common, it makes the simulation circuit less complicated and makes it easier to demonstrate the features of the Multi-Agent System without any complication. The fault would be discussed in detail in the following chapters.

The two simulation circuit described above will serve a reasonable purpose of testing the Multi-Agent System in two very different environments. The simulation circuit in Figure 4.1 will demonstrate the usual household electrical system with single phase supply of 120V. Since is it a single-phase system, the phase difference is not an issue and therefore any kind of time delay because of the Multi-Agent System, if any, will be acceptable up to certain extent.

The simulation circuit in Figure 4.2 shows the second simulation circuit that will be used to demonstrate the effect of Multi-Agent System on three-phase system. Since phase difference is critical to three-phase system, this model will display the effect of time delay in the Multi-Agent System, if any, in the phase angle of the voltages and currents in the three-phase system.

Chapter 5: Development of Multi-Agent System

In the previous Chapter 3, the Multi-Agent System was explained in detail including its architecture, exclusive features and the advantages of implementing it in a Microgrid. In Chapter 4, the simulation circuits were discussed in which the Multi-Agent System are to be implemented. In this chapter, the features of the Multi-Agent System, that will be implemented in the Microgrid, will be discussed.

5.1 Role of the Multi-Agent System in the Microgrid

Now that the simulation circuit has been designed, the Multi-Agent System need to be implemented. To do this, all the tasks to be done by the Multi-Agent System must be laid out. The whole purpose of Multi-Agent System is to divide a single complex task into various parts among various agents. Thus eliminating the need for a central controller. The role of the Multi-Agent System is defined by dividing the Microgrid into the following individual task:

- Grid monitor/control
- Load monitor/control
- DER monitor/control
- Battery bank monitor/control
- Solar Farm monitor/control
- Service publisher
- Coordination among all controllers

5.2 Agents in the Multi-Agent System

The role of the Multi-Agent System was described in the section above. To achieve this those roles must be realized within the Multi-Agent System. Therefore, each task will be assigned to a separate agent and thus creating a distributed control system. The description of each agent are as follows:

- Grid Agent:

  It is the agent which resides on the distribution side of the Microgrid and fulfills the role of grid monitor and control. Its job is to constantly monitor the grid voltage, current and frequency. It also has the ability to dispatch more power during the peak hours by switching reserve generators, if the grid has any. If any unusual activity is sensed, it has the ability to switch the main breaker disconnecting the grid from the load.

- Load Agent:

  This agent resides on the consumer end of the Microgrid and fulfills the role of load monitor and control. The job of Load agent is to constantly monitor voltage and current in each houses/buildings. The second task is to monitor the load change on the consumer end, so that grid agent can prepare for it. The third task of the load agent is to switch the critical and non-critical loads during the failure of the grid. The data acquired by the load agent can be displayed to the consumer for convenience. By doing this, the consumer will be aware of the power consumed, the power quality supplied and the source of the power, e.g., during fault if DER is supplying the power, the consumer will be aware of it.

- DER Agent:

  This agent is present at the DER side of the Microgrid and fulfills the task of DER monitor and control. The role of this agent is to monitor the status of the main breaker. For this reason, it has to be in constant interaction with the grid agent. By monitoring the main breaker status, it can ensure the power supply is being provided by the grid. In case of a fault, the main breaker will close, which will be sensed by the DER agent and it will switch the DER breaker connecting the DER as the primary energy source.

- Battery Agent:

  This agent resides on the DER side of the Microgrid and in the energy storage system to be specific. It fulfills the battery monitor and control task of the Multi-Agent System. As the DER are very unpredictable, during normal operation of the grid the energy from it is stored in a Battery Bank as a backup. The role of the battery bank agent is to monitor the voltage, current level of the bank alongside the state of charge. During the normal operation of the grid, the battery agent will switch the battery breaker connecting it to the solar farm, so that it can charge. During fault condition, it will switch the breaker open, so that the solar farm can act as the primary energy source. It will also close the breaker when the solar farm is unable to provide sufficient power. In this case the battery will act the sole primary source of energy. Since it can monitor the state of charge, the duration for which the bank is capable of providing the power can be obtained. This feature is useful for the utility and consumer to get prepare for a shutdown when the battery bank runs out of charge.

- Solar Agent:

  This agent is also present at the DER side of the Microgrid and fulfills the control and monitoring of the Solar farm. The DER in this simulation circuit is a solar farm which has peak hours and inoperable hours. The solar farm can provide the energy during Peak hours only. Thus the task of the solar agent is to monitor the voltage and current level coming out of the solar farm. The second task is to monitor the inoperable hours and share with other agents. Using this feature the solar agent opens the solar breaker disconnecting the solar farm and let the Battery bank take over during inoperable hours seamlessly.

- Directory facilitator (DF):

  This agent is a special agent built inside the JADE framework which fulfills the role of services publishing in the Multi-Agent System. In the Microgrid, all agents must share the data acquired (services) with other agents. This task is handled by the DF agent. DF agent has been discussed in detail in third section of Chapter 3.

- Agent Coordinator:

  This agent is present in the framework of the Multi-Agent System and is accessible to every other agent in the Microgrid. It fulfills the task of coordination amongst the agents in the Multi-Agent System. It ensures the data arriving from the sensors are passed to the relevant agent. Once the data is processed by the target agent, the agent coordinator will send back the data to the source agent. The agent coordinator works with DF agent to do this task.

5.3 Interfacing the Multi-Agent System with the Simulation Circuit

The development of the Multi-Agent System in JADE and the simulation of the Microgrid in Simulink was discussed in detail in previous chapters. Since JADE and Simulink are completely two different software based on different programming language and have a different protocol for communication, a third party software is required to be the communication interface for these software.

Since JADE interacts with other platform via HTTP, a client socket can be opened in MATLAB and can be used as a S-function in Simulink without using a third party software. But S-functions are not capable of handling multiple threads of execution causing huge time delay and instability [35, 36]. Thus the use of an interface is inevitable.

To overcome the above described issue, a program called MACSim [35] will be used. It uses the S-function ability of MATLAB as a gateway to pass data from Simulink with parallel processing without causing instability. MACSim stands for Multi-Agent Control for Simulink. It has a client-server architecture where client is in S-function of Simulink and the server is in different program. The communication is done using "Pipes" in Windows. An illustration of the architecture is shown in Figure 5.1. The MACSim only works with code written in C++, but includes a wrapper which gives the ability to interact with program in other languages such as Java. Thus a program called MACSimJX exploits this functionality to enable interaction between JADE and Simulink. By using MACSimJX, all the functionalities of MACSim is achieved and programming agents in Java language also became possible [37].

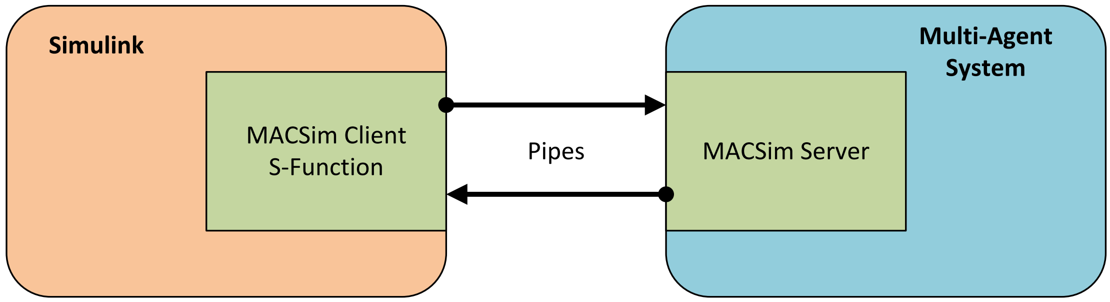

Figure 5.1 MACSim Structure

The structure of MACSim have been discussed in the section above. Using it as a reference the structure of MACSimJX and hence the structure of the entire system will be discussed. Figure 5.2 shows the structure and interaction of the entire Multi-Agent System. The figure shows various communication channels and show the direction of information exchange within the system.

The Microgrid model resides in the Simulink which also contains the S-function which contains the client code of MACSimJX. Then the Agent Server is created in the MACSimJX which interacts with Simulink's S-function Client. This completes the interaction between Simulink and MACSimJX.

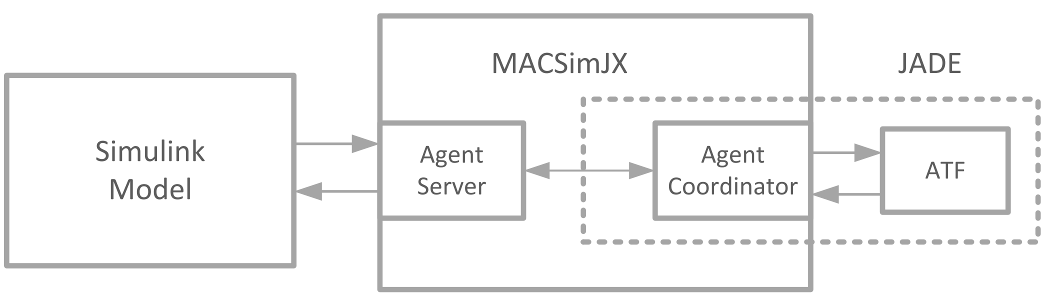

Figure 5.2 Structure of the entire Multi-Agent System

In JADE, MACSimJX creates an agent called the Agent Coordinator, which was discussed in the previous section of this chapter. The Agent coordinator handles the transport of the data from agent server of MACSimJX to the agents present in JADE platform. The agent coordinator act as an interface between MACSimJX and JADE.

All the agents described in the previous section are created in JADE and reside on a JADE Platform. In order to communicate with MACSimJX an Agent Task Force (ATF) is created in JADE where all the agents are contained. Each ATF has its own sub-package and can be customized according to the developers need. The ATF allows three standard messages to be passed within the agents, which are as follows [37]:

- UpdateData:

It provides any new data passed by Simulink during each sample step.

- DataAmended:

It is the acknowledgement from the agent in the ATF of the processed data to the Agent coordinator.

- ShuttingDown:

It is the instruction received from an agent to terminate the current process. In other words, the instruction is received by an agent to another agent to shut down.

This concludes the interfacing of the simulation circuit in Simulink with the Multi-Agent System in JADE. This chapter showed the development of the Multi-Agent System in JADE, roles of each agent in the system and the communication network of the entire system.

Chapter 6: Demonstration of the Experiment

6.1 Case Studies

- Case Study #1:

  This case study is to show a seamless transition from grid-on to islanded mode. This means, the Microgrid must be able to transition from grid as primary energy source to DER as the primary source which causing any voltage/current drop or rise beyond the acceptable limits and vice-versa.

  The simulation is run for a duration of 0.6s. The Microgrid starts in grid-connected mode from time t=0s until t=0.1s. At time t=0.1s, a three-phase L-L-L-G fault occurs at the distribution line. It lasts for 0.2s and gets cleared out at time t=0.3s.

  The expectation from this case study is that the voltage/current at the consumer end must be seamless from t=0s through t=0.6s. This case study will also show how the energy management works in a Multi-Agent System. This is demonstrated by feeding the critical loads in the user end without any interruption. The supply to the non-critical load is cut off at the same time. Therefore, the voltage and current for non-critical loads from t=0s through t=0.6s is expected to be zero. The assumption made in this case study is that the fault lasts during the peak period of the Solar farm, i.e., The solar farm can provide energy at any moment of time when the central grid fails. The results would be discussed later in this chapter.

- Case Study #2:

  In this case study, the Microgrid would be tested in much more realistic scenario, where the energy from DER is variable. Since the DERs are very fluctuating and unpredictable, energy is stored from the DERs to an energy storage system, in this case a battery bank.

  The simulation and the fault duration would be the same as the first case study. The difference would be the voltage output of the solar farm. The voltage profile is set such that the peak point of the solar farm would end at time t=0.2s and thus it would be unable to provide energy during rest of the fault condition.

  Thus after t=0.2s the solar breaker is expected to open disconnecting the solar farm from the three-phase converter and the battery breaker is expected to close connecting it to the three-phase converter. Thus the battery bank will act the primary energy source from t=0.2s though t=0.3s.

The results for both of the case studies will be discussed in the next section. The discussion will include waveforms of voltages, currents and frequency for all relevant areas and for both three-phase and single-phase loads.

The action of the Multi-Agent System will also be displayed by the message exchange between the agents. It is acquired by the Sniffer agent present in the JADE framework and shows the source/target agent along with the direction and type of message transferred. The control action of the agents would be represented by the control signals triggered at certain time intervals and it will be discussed in context of the waveforms.

6.2 Results and Discussion

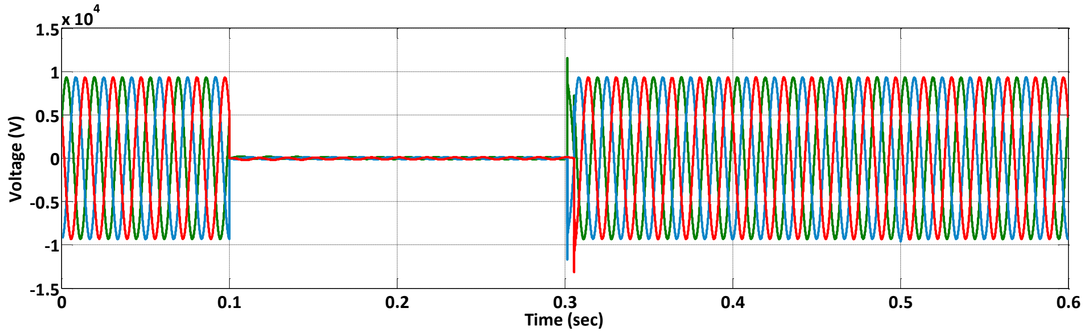

Figure 6.1 Grid Voltage

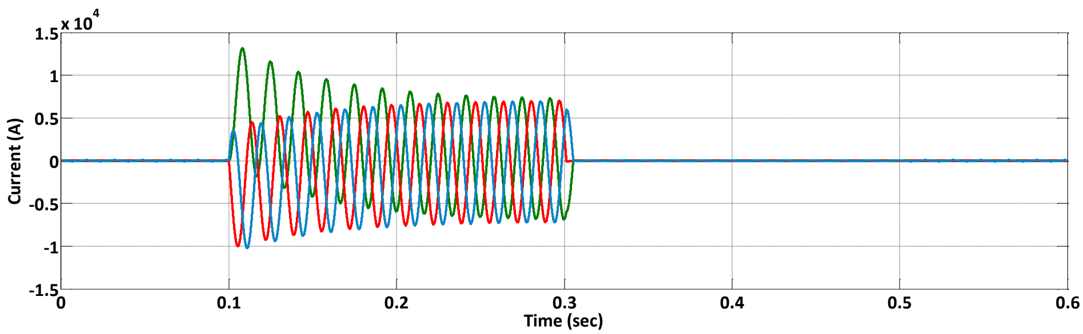

Figure 6.2 Grid Current

The Figure 6.1 shows the voltage across the grid throughout the simulation and Figure 6.2 shows the grid current. The voltage and current are measured at the distribution line of the grid, therefore the voltage under the normal condition would be 6.6kV. As seen from the figures, the voltage and current start normally from t=0s through t=0.1s. At t=0.1s fault occurs, and as expected the voltage drops to zero and the current rises to extreme values in the order of magnitude of 10^4A. Since in both of the case studies the configuration of the grid remains same, the waveform of voltage and current in the grid for both the case studies would be similar. A closer look at the waveform of the grid current before the fault is shown in the below.

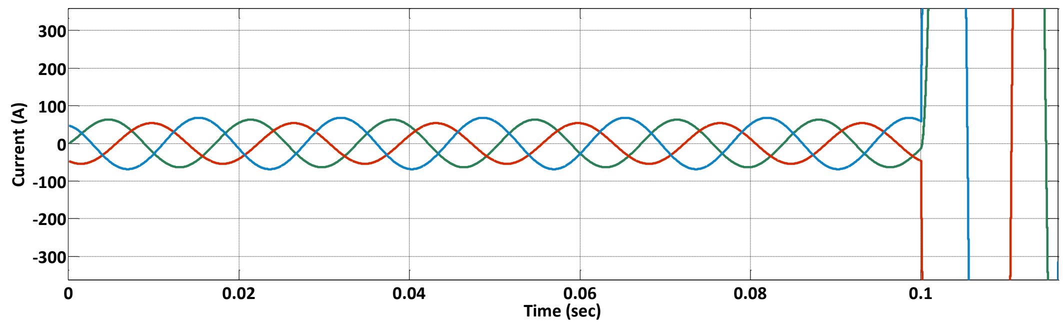

Figure 6.3 Grid Current Before the Fault

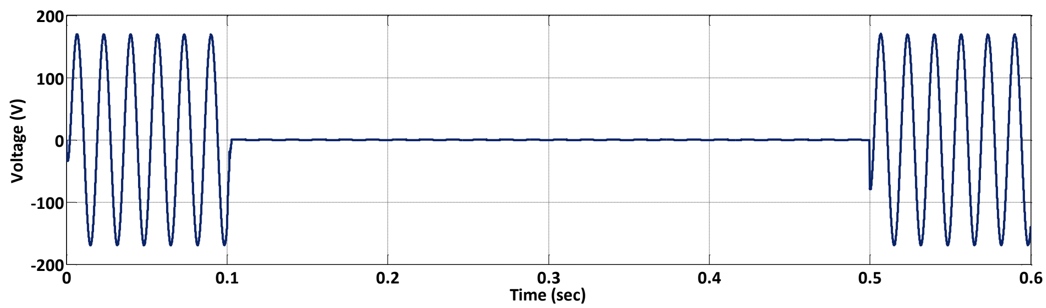

Figure 6.4 Voltage across Non-Critical Load in a House (Case Study #1)

The Figure 6.4 shows the voltage across a non-critical load in a house and marks the start of Case Study #1. This waveform is obtained by running the simulation circuit with single-phase load along with the Multi-Agent System. The current waveform of the same load is shown in Figure 6.5. As seen in both the figures, the load is receiving power, with voltage being 120V and current being 83.33A, from the starting of the simulation until t=0.1s. At this point fault occurs in the grid. The fault is sensed by the grid

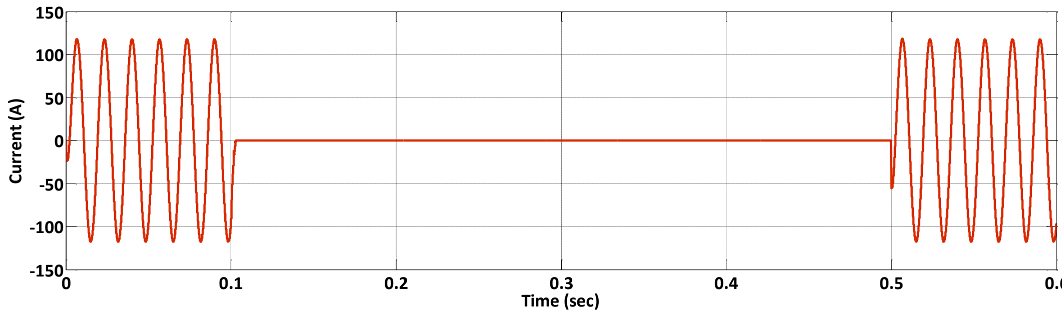

Figure 6.5 Current in a Non-Critical Load in a House (Case Study #1)

agent and opens the main breaker disconnecting the grid from the houses. The fault detection methods in literature are numerous such as using artificial neural network [38], using variable structure system [39] or using probabilistic approach [40]. In this thesis, a very simplistic approach for fault detection is used. The RMS value of the grid voltage is monitored through the grid agent and any change in recorded. If the voltage value exceeds 10% of the normal value, the grid agent declares it as a fault condition. Although it is not the optimal method for fault detection, a more sophisticated method may be applied as a future research.

Coming back to the event after the switching of the main breaker, the non-critical loads which are dispensable are not supposed to receive power during fault condition. Therefore, upon receiving the status of main breaker from the grid agent, the load agent switches the breaker of the non-critical loads disconnecting from the grid/other energy source. This is apparent form the zero value of both current from t=0.1s until t=0.3s.

A point to be noted is that even though the fault is cleared at t=0.3s, the figures above show the non-critical load not receiving power until t=0.5s. The reason is that since switching the main breaker back to grid-connected mode will cause a transient state which can distort the current and voltage waveforms. There a time period of 0.2s is given after the main breaker is closed for the grid to actually feed the loads. During this time period, the transient period is expected to reach the acceptable level and hence safe for the loads. From t=0.5s onwards the non-critical loads receive power from the grid as usual.

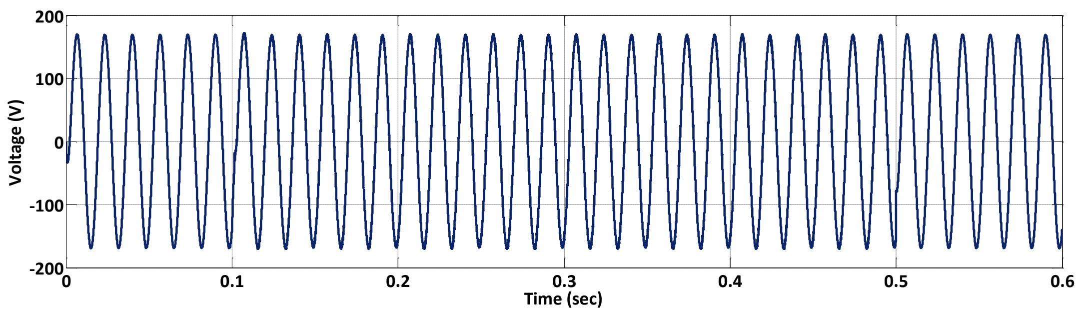

Figure 6.6 Voltage across Critical-Load in a House (Case Study #1)

The Figure 6.6 shows the voltage of 120V across the critical loads in the same house. As expected the load is receiving power throughout the simulation period. At t=0.1s due to fault condition, the grid agent opens the main breaker. Since the DER breaker monitors the status of the main breaker and switches accordingly, it closes the normally open DER breaker connecting the solar farm to the load. In Case Study #1, the solar farm is capable of supplying energy anytime, it provides the power throughout the fault period. After t=0.5s the load receives power back from the grid and thus DER breaker is opened by the DER agent. The waveform during the transition period is shown in the Figure 6.7 and Figure 6.8.

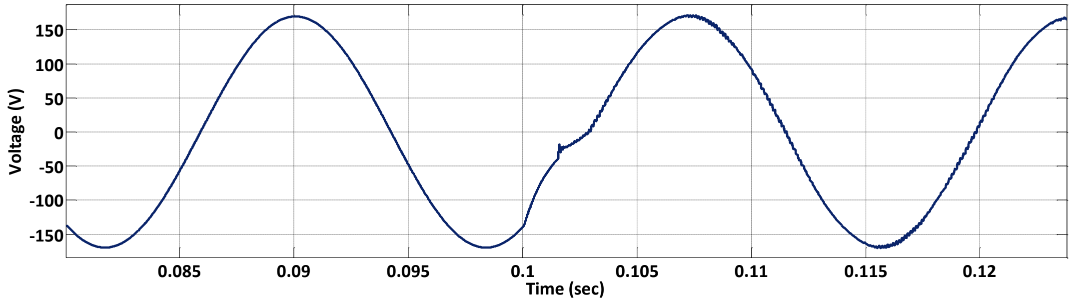

Figure 6.7 Voltage across Critical Load at the beginning of the fault (Case Study #1)

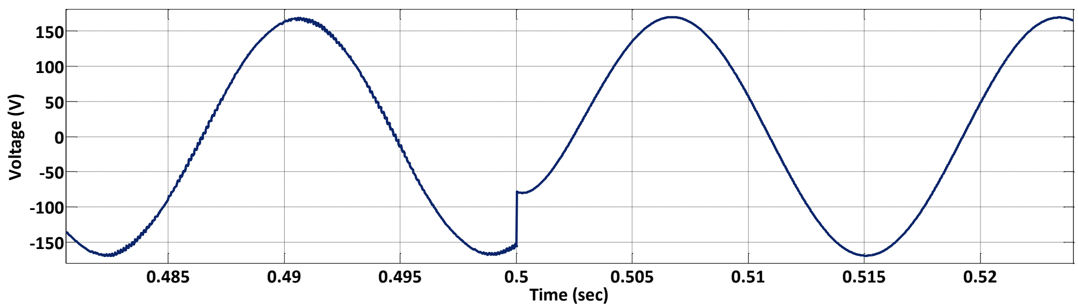

Figure 6.8 Voltage across Critical Load during Grid reconnection (Case Study #1)

In the first figure the transition from grid connected mode to islanded mode is shown. The difference in the waveform can be noticed. The waveform of the solar farm voltage has some harmonics in it, although not very apparent. The second figure shows the transition from islanded mode to grid connected mode.

As seen in the figures above, the transition from voltage from the grid to the voltage from the Solar farm is seamless with voltage fluctuations under the acceptable range of 10%. There are no voltage spikes often caused due to the switching of the breakers. The current waveforms for the same critical load can be seen in Figure 6.9, Figure 6.10 and Figure 6.11.

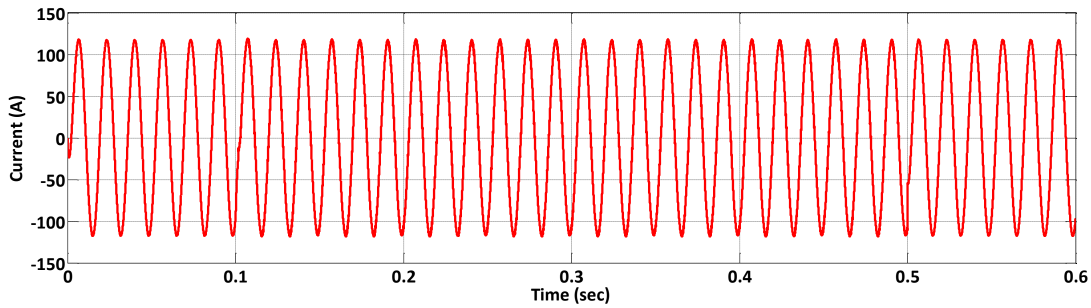

Figure 6.9 Current in the Critical-Load in a House (Case Study #1)

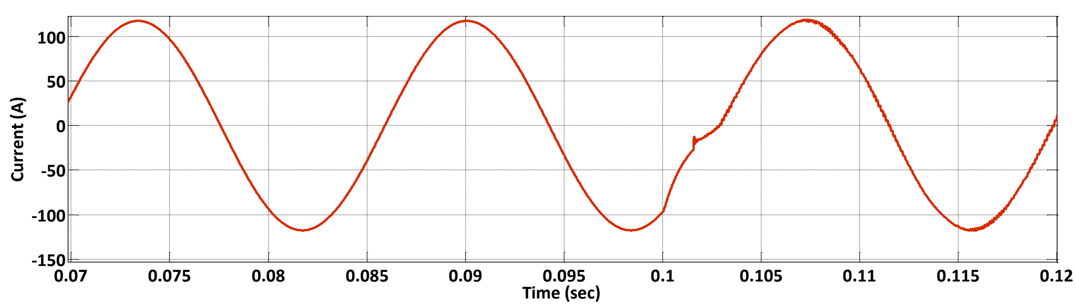

Figure 6.10 Current in the Critical Load at the beginning of the fault (Case Study #1)

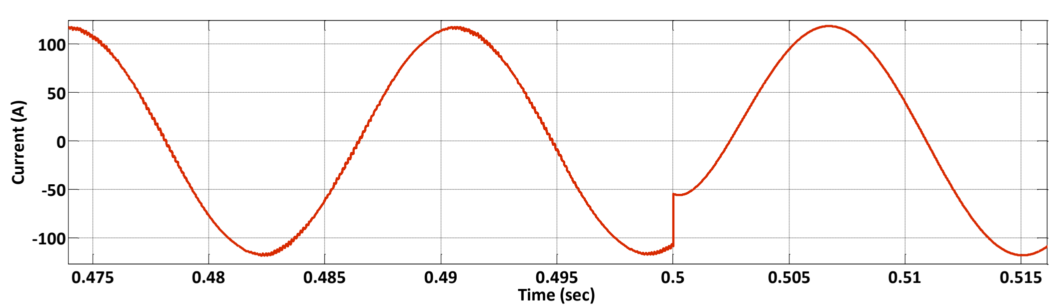

Figure 6.11 Current in the Critical Load during grid reconnection (Case Study #1)

As seen from the figures above, the waveform for the voltage and current are similar during the transition period.

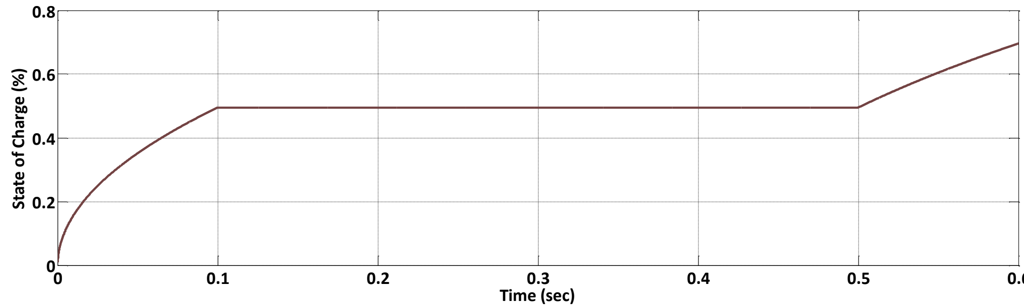

Figure 6.12 The State of charge of Battery (Case Study #1)

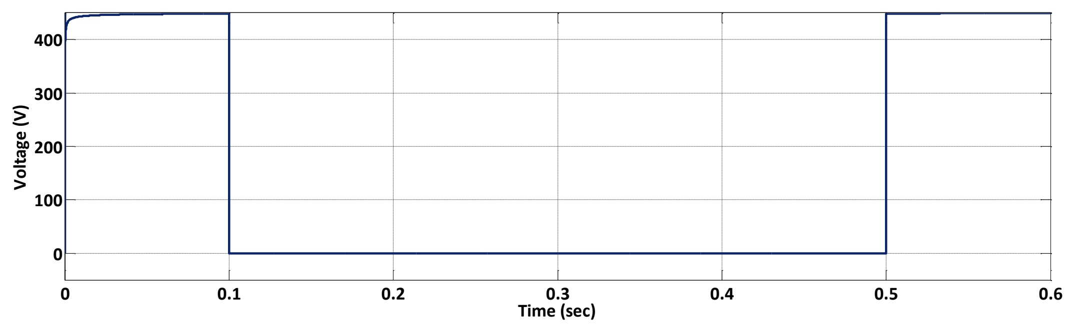

Figure 6.13 Voltage across the Battery (Case Study #1)

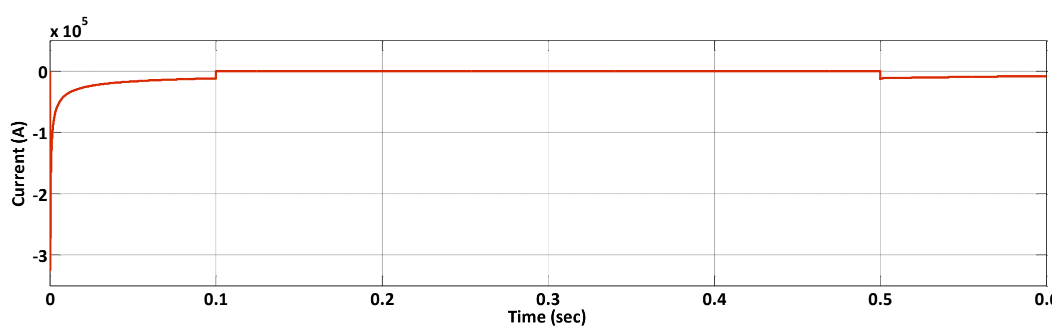

Figure 6.14 Current in the Battery (Case Study #1)

The Battery agent opens the battery breaker during fault condition and the battery stops charging and voltage drops to zero as seen in Figure 6.12, Figure 6.13 and Figure 6.14.

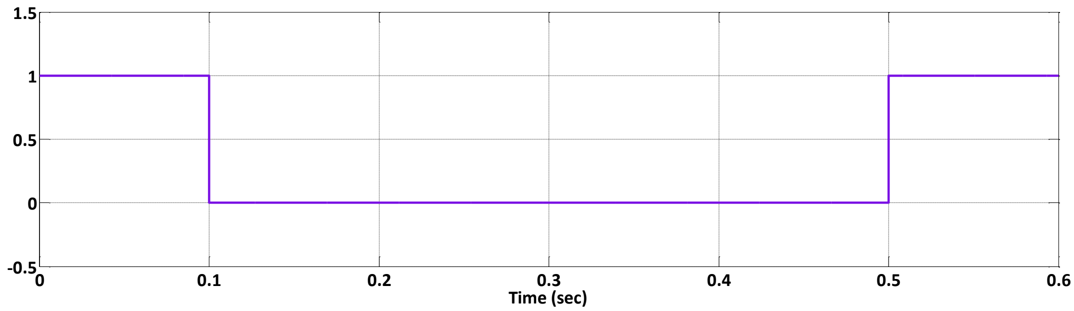

Figure 6.15 Control Signal for Grid, Non-Critical Load & Battery Breaker (Case Study #1)

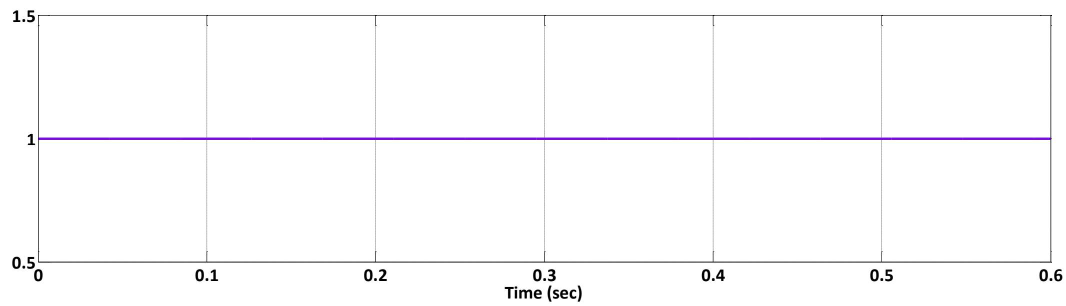

Figure 6.16 Control Signal for Critical Load and Solar Breaker (Case Study #1)

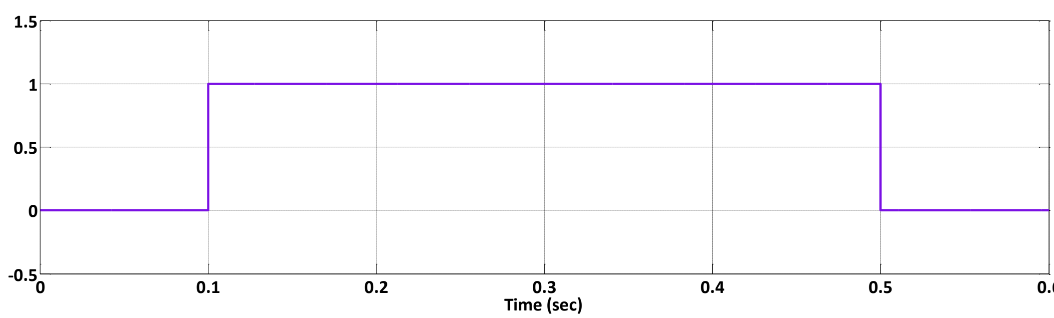

Figure 6.17 Control Signal for DER Breaker (Case Study #1)

Figure 6.15, Figure 6.16 and Figure 6.17 show the control signals sent by the agents to their respective breakers during normal operation and during fault condition.

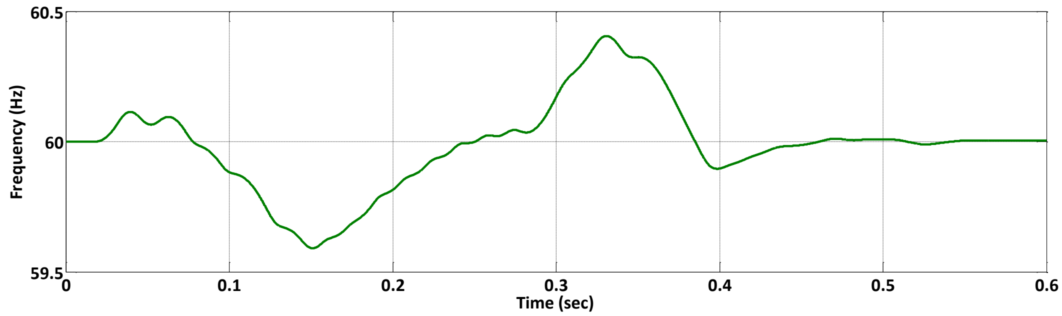

Figure 6.18 Grid Voltage Frequency (Case Study #1)

The Figure 6.18 shows the grid frequency during the simulation time period. The frequency fluctuates during the fault condition form t=0.1s to t=0.3s. After that it settles down to 60Hz. This ends the first case study.

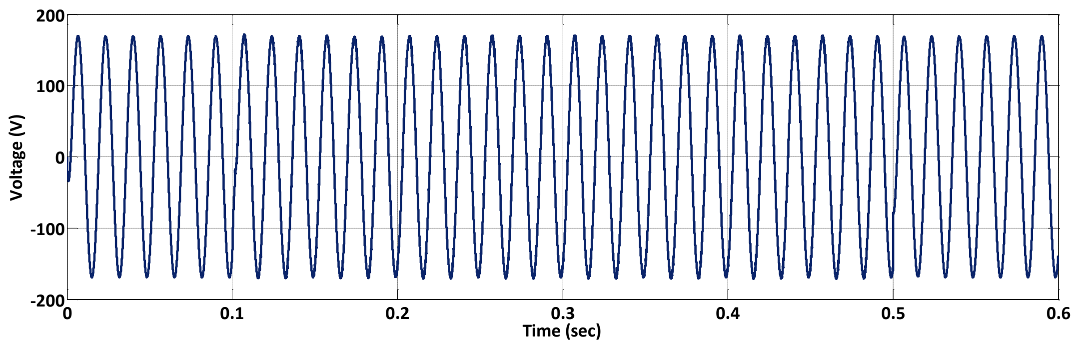

Figure 6.19 Voltage across Critical-load (Case Study #2)

In the Figure 6.19, the voltage waveform of the critical load is shown in the context of Case Study #2. In this case study, the power generation by the solar farm is not constant. The scenario is set such that the peak period of the solar farm ends at t=0.2s as shown in the Figure 6.20. Therefore, at t=0.1s the DER breaker closes and solar

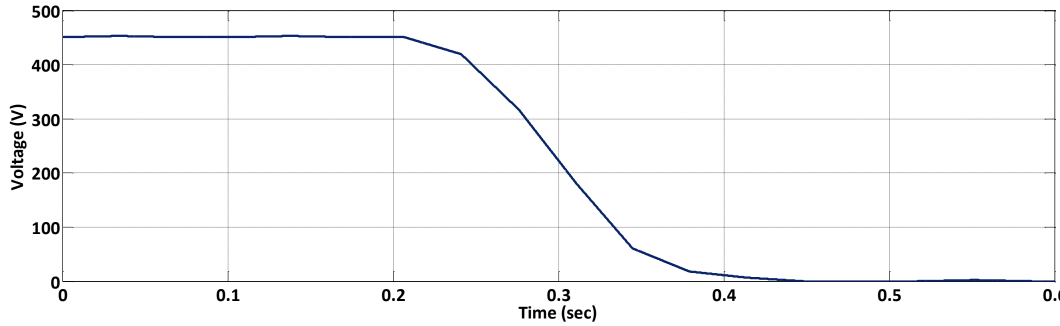

Figure 6.20 The Voltage across the Solar Farm (Case Study #2)

farm would provide the energy to the loads. At t=0.205s the solar farm would be out of the peak period as seen in Figure 6.20 and thus the solar agent would sense it and switch the solar breaker disconnecting it from the three-phase converter. The opening of the solar breaker will trigger the battery agent and thus battery breaker would be closed, connecting it to the three-phase converter. Now the battery bank is the primary energy source from t=0.205s to t=0.5s. The battery bank has an initial charge of 50% and rated as 125 Ah, i.e., it can provide constant energy to all the critical loads for 30 minutes or the entire residential area for 15 minutes.

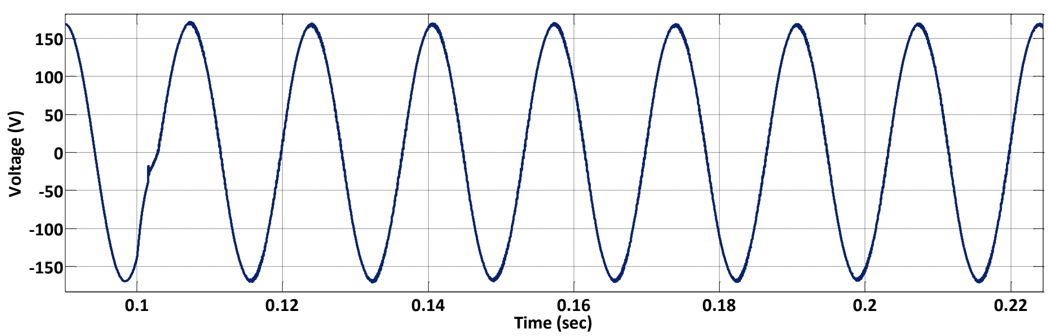

Figure 6.21 Voltage across the critical load during transition period (Case Study #2)

As seen from the Figure 6.21, the transition from grid connected to islanded mode is seamless and similar to the waveform in Case Study #1. The transition from Solar farm to battery bank is indistinguishable. The voltage fluctuations are in the acceptable range of ±10% and there are no significant voltage spikes due to switching. The current waveforms for the same load are shown in Figure 6.22 and Figure 6.23.

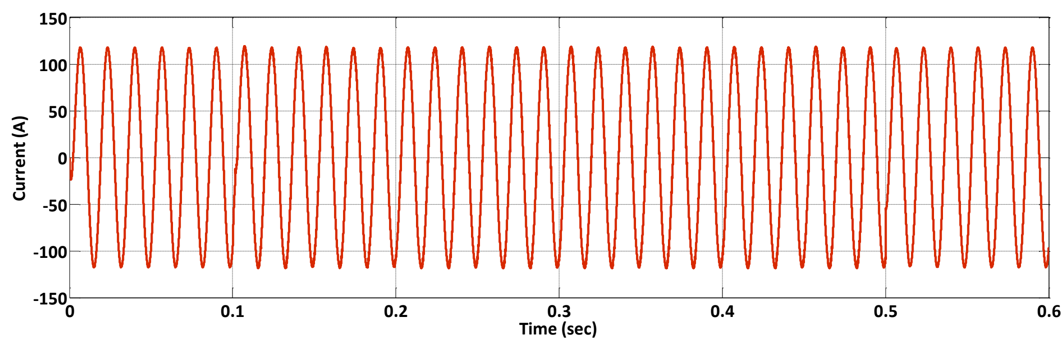

Figure 6.22 Current in the critical load (Case Study #2)

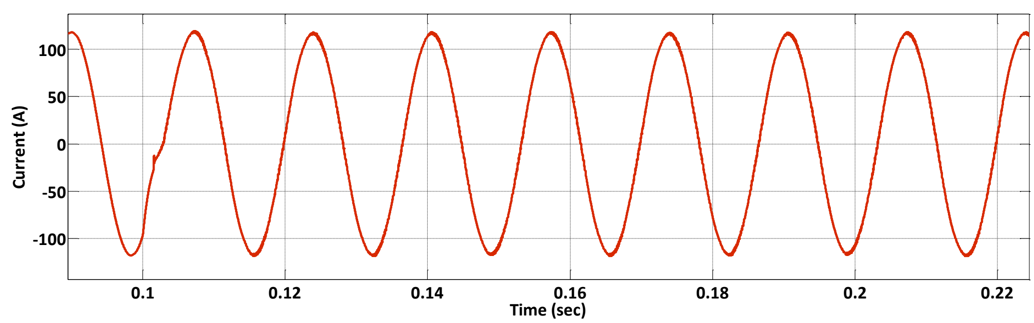

Figure 6.23 Current in the critical load during transition period. (Case Study #2)

As expected the current waveforms for the critical load are similar to the voltage waveforms. The current value is 83.33A throughout without any major fluctuations.

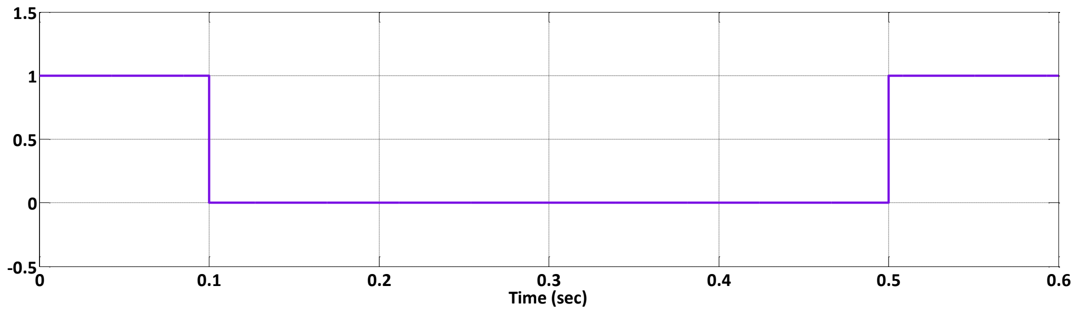

Figure 6.24 Control Signal for Grid and Non-Critical Load Breakers (Case Study #2)

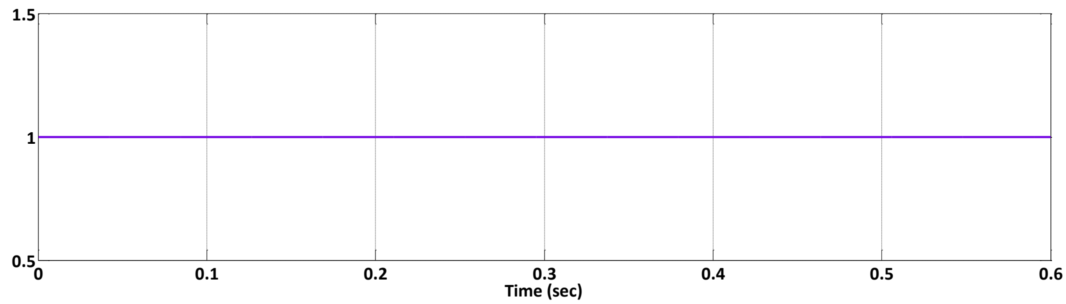

Figure 6.25 Control Signal for Critical Load Breaker (Case Study #2)

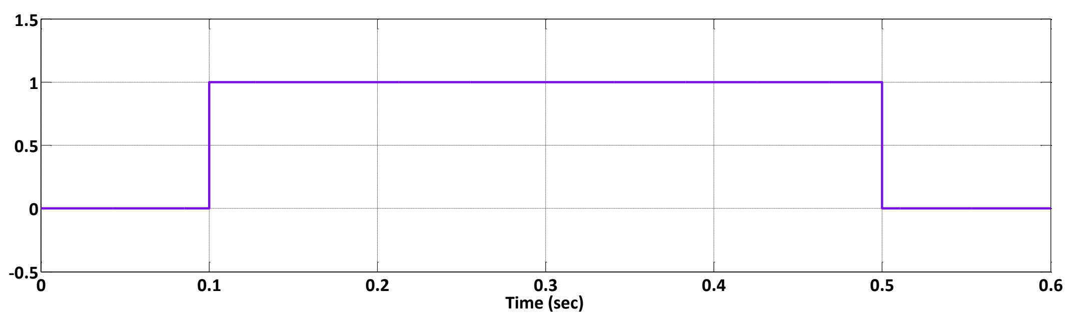

Figure 6.26 Control Signal for DER Breaker (Case Study #2)

Figure 6.24, Figure 6.25 and Figure 6.26 show similar control signals sent by the agents.

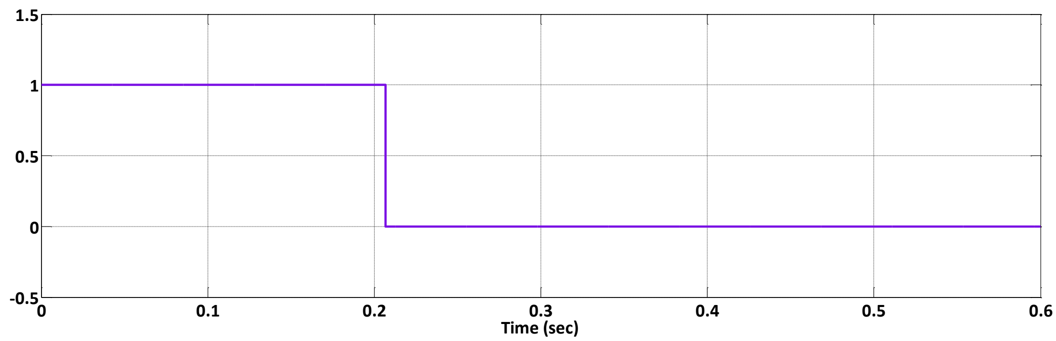

Figure 6.27 Control Signal for Solar Breaker (Case Study #2)

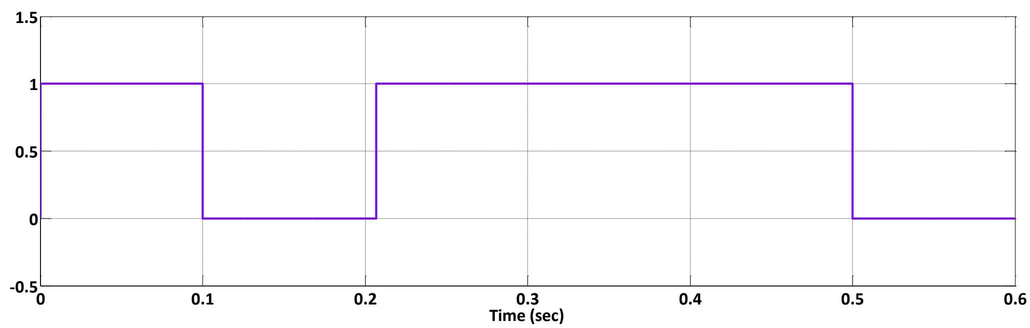

Figure 6.28 Control signal for Battery Breaker (Case Study #2)

The above figures show the control signals sent by the agents to their respective breakers. Figure 6.27, the solar breaker is closed feeding the load and charging the battery, then opens at t=0.205s when it gets out of the peak period.

In Figure 6.28, the battery breaker is closed getting charged by the solar farm until t=0.1s. After that it opens, letting the solar farm feed the critical load until t=0.205s. At this point the battery bank takes over as the primary source as the solar farm is unable to provide energy. The battery breaker opens again after the grid is reconnected. The waveforms of the battery bank are shown in Figure 6.29, Figure 6.30 and Figure 6.31.

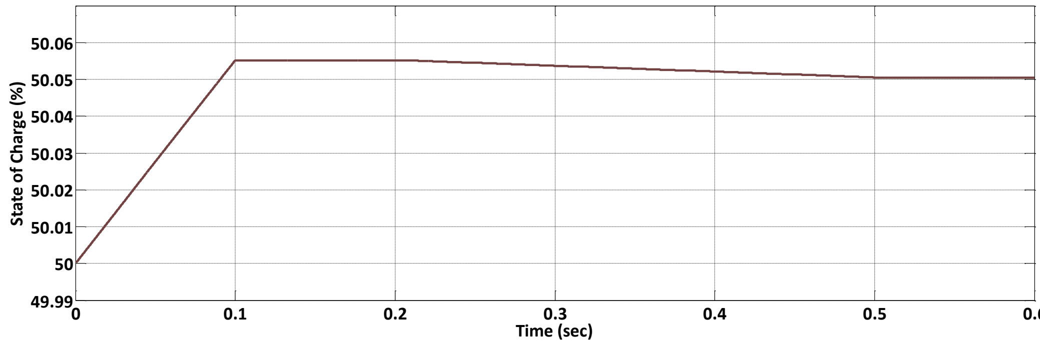

Figure 6.29 The state of charge of the battery bank (Case Study #2)

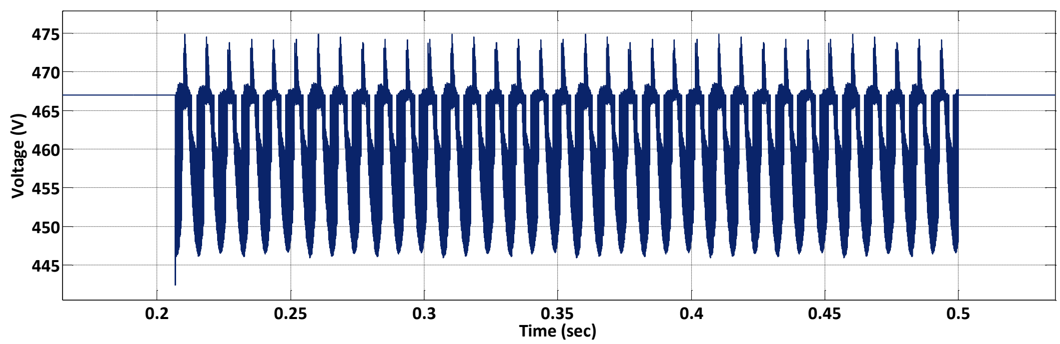

Figure 6.30 The voltage across the battery bank (Case Study #2)

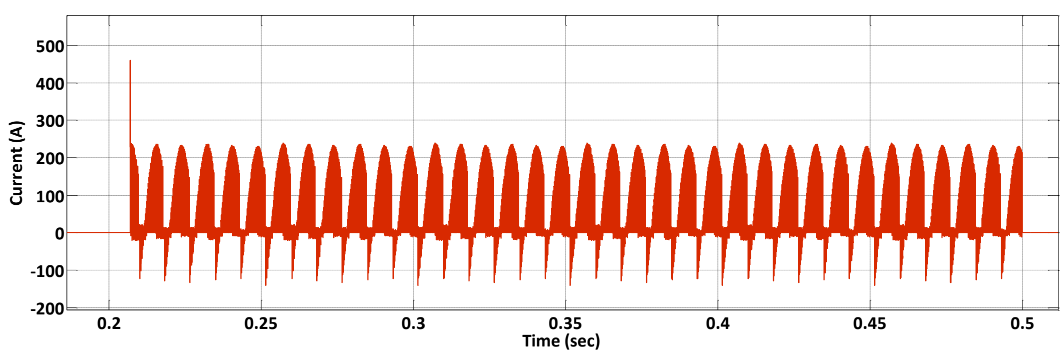

Figure 6.31 The current from the battery bank (Case Study #2)

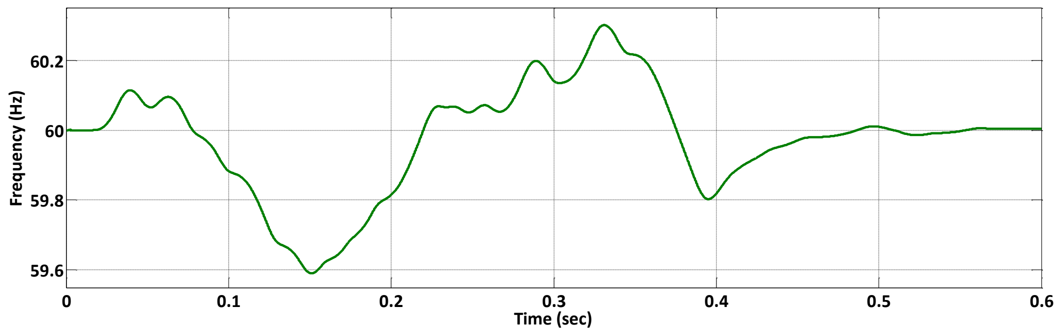

Figure 6.32 The grid voltage frequency (Case Study #2)

The Figure 6.32 above shows the grid frequency during the simulation time period in Case Study #2. The frequency fluctuates during the fault condition form t=0.1s to t=0.3s. After that it settles down to 60Hz. The waveforms for the current and voltage for critical and non-critical loads in three-phase load are shown below. The conditions are exactly the same as in the Case Study #2 and waveforms are also similar to single-phase system.

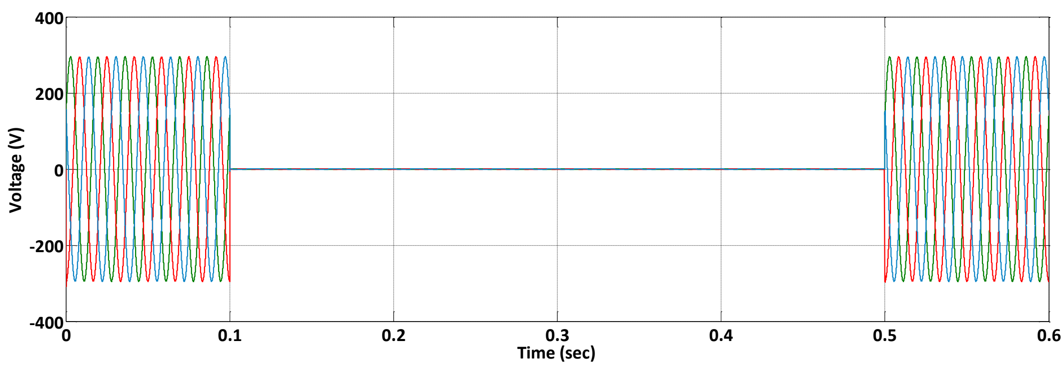

Figure 6.33 Voltage across non-critical three-phase load

As seen in the Figure 6.33, the voltage waveform for the non-critical load under the Case Study #2 is similar to that of single-phase system.

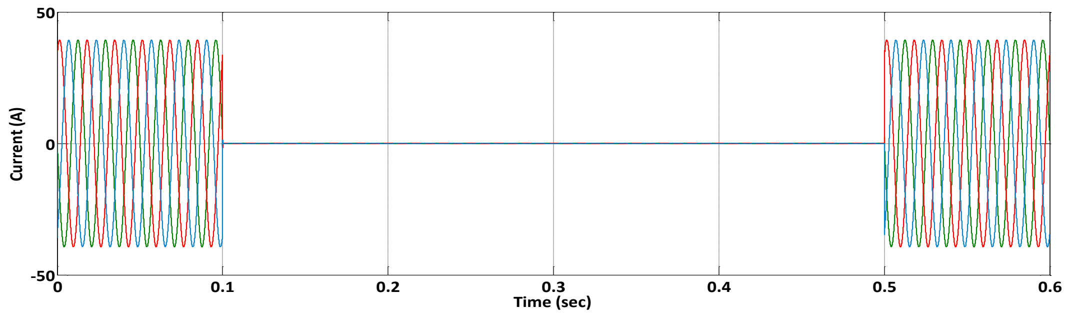

Figure 6.34 Current in the non-critical three-phase load

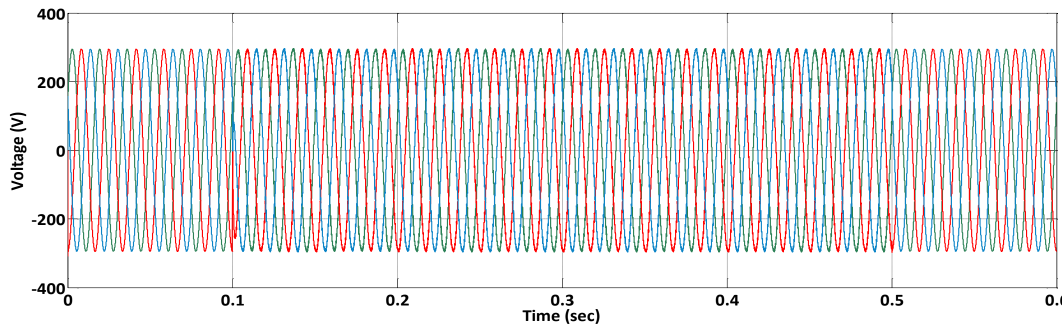

Figure 6.35 Voltage across the critical three-phase load

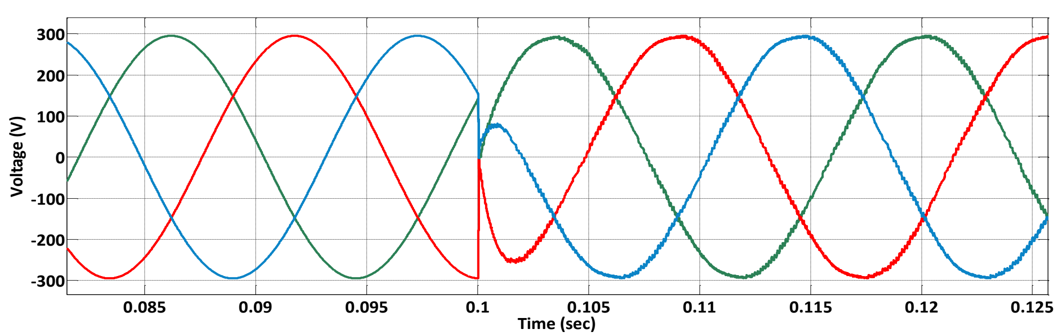

Figure 6.36 Voltage across the critical three-phase load during beginning of the fault

Figure 6.34, Figure 6.35, Figure 6.36 show the current in three-phase critical load and voltage across three-phase critical load in Case Study #2.

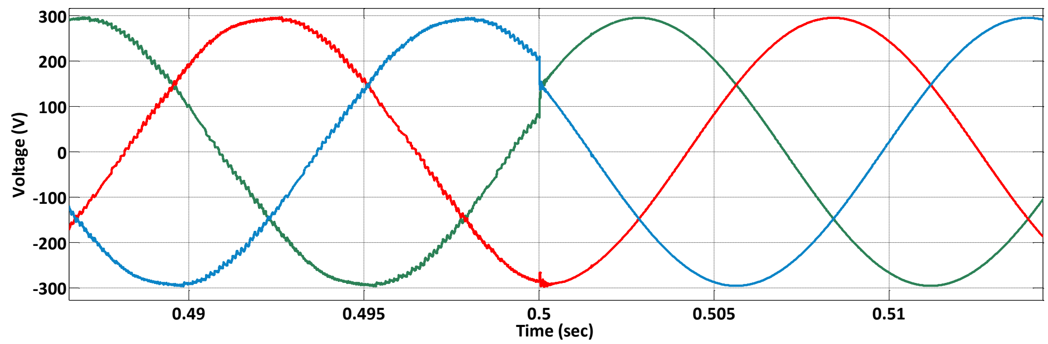

Figure 6.37 Voltage across the critical three-phase load during grid reconnection

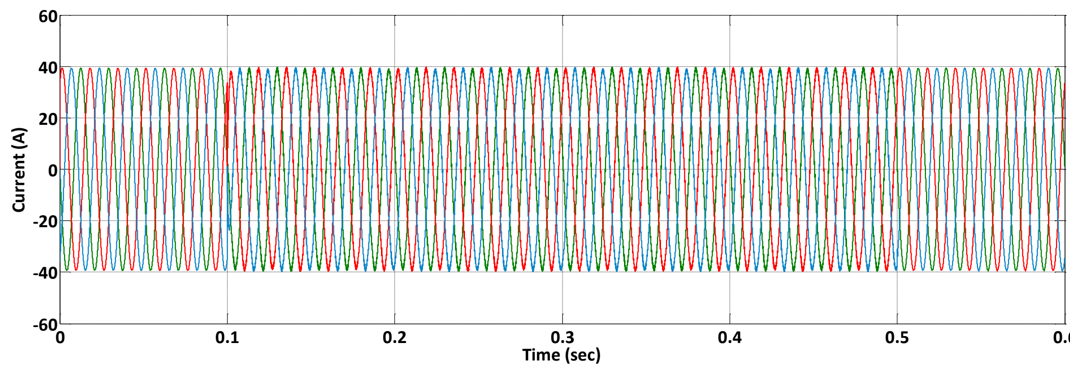

Figure 6.38 Current in the critical three-phase load

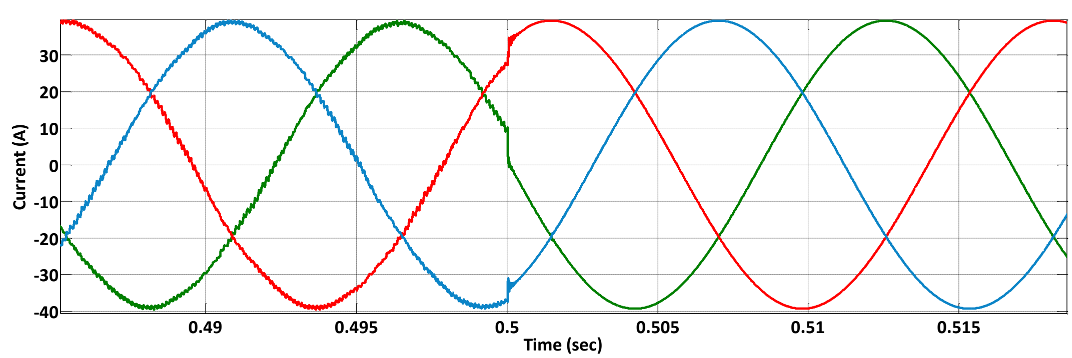

Figure 6.39 Current in the critical three-phase load during grid reconnection

Figure 6.37, Figure 6.38, Figure 6.39 show the voltage and current waveform for three-phase load in Case Study #2.

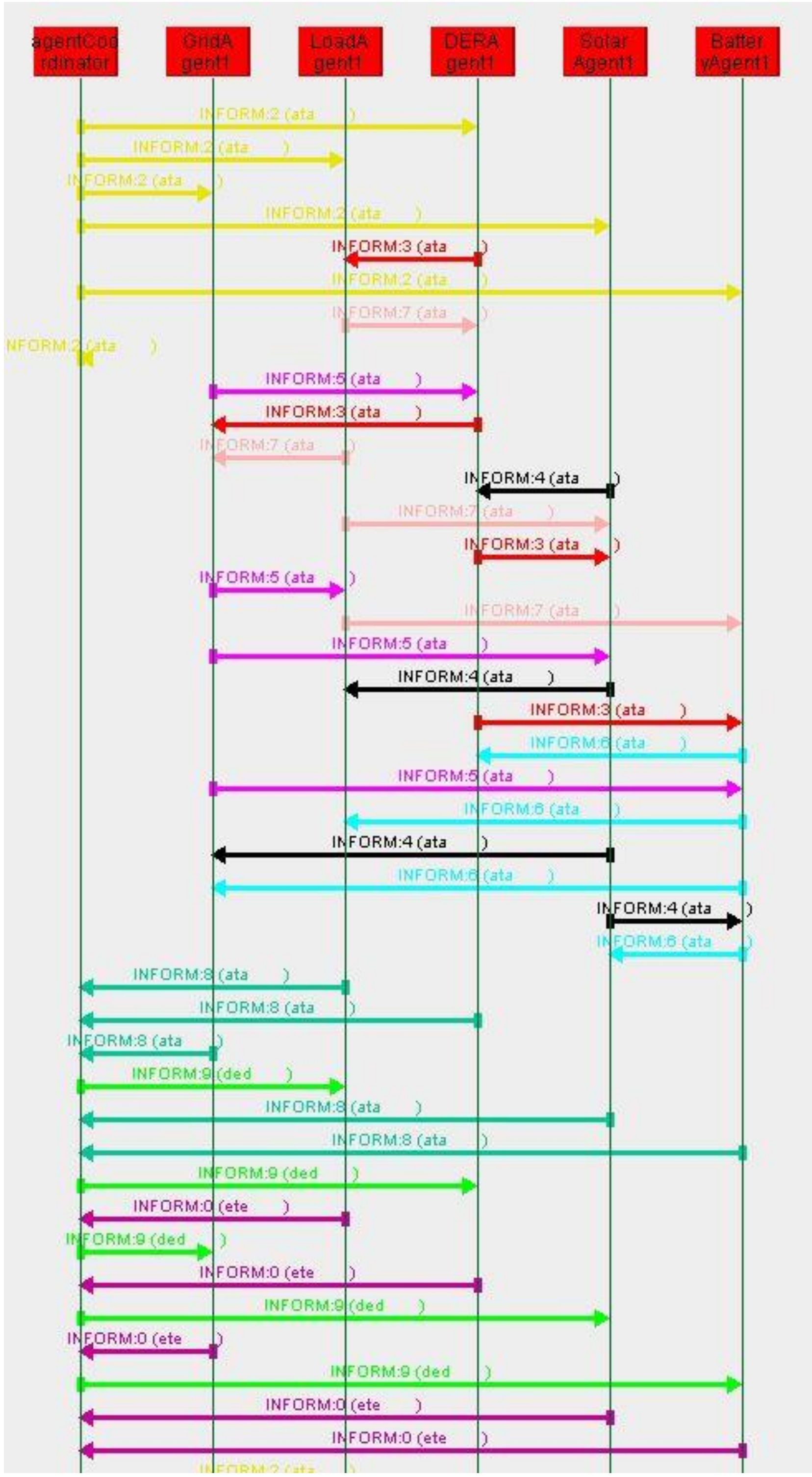

Figure 6.40 Exchange of messages between agents

Figure 6.41 The JADE GUI showing all the active agents in the container

The communication log of the agents is shown in Figure 6.40. As seen in the figure the agents communicate through the command INFORM. In the beginning, the agent coordinator sends a roll call message to all the agents, so that it can know how many agents are present in the container. The number beside the INFORM command is the message number, e.g., INFORM: 5 means, the fifth message of the session is being passed around. The fifth messages will be passed to all the agents (except agent coordinator). Once the fifth message has been passed to all agents, the sixth message will be initiated.

In the Figure 6.41, all the active agents are shown in the JADE interface. All the agents are present in the Container-1. The container also includes the AgentServer and the Agent coordinator, discussed in the previous chapter. As long as the agents are shown in the container, they can communicate with each other through messages. After the message has been passed out to all agents, the agents pass the received data to the agent coordinator. Then the agent coordinator passes the data to the Simulink via AgentServer.

6.3 Conclusion

In this thesis, the implementation of the Multi-Agent System has been studied. Various aspects of the Microgrid were covered from its architecture to its limitations. Then the Multi-Agent System was introduced and JADE was chosen to be the agent platform. Then the communication system and architecture of JADE were explored. The simulation circuit used in this thesis were explained in detail. Then the agents to be implemented were developed by describing their role in the Microgrid. Then the agents forming the Multi-Agent System were interfaced with the simulation and the experiments were conducted. The experiments comprised of two case studies based on real-life conditions. After the experiments, the results were shown and discussed thoroughly coming to the conclusion that the real-time communication feature of JADE as a Multi-Agent System can prove highly beneficial in improving the reliability, robustness and quality of the Microgrid. The expected results show the continuity of power flow during the time of fault, its gradual recovery and seamless transition from grid connected to island mode. The distributed control mechanism renders the need of centralized control system such as SCADA, inefficient.

The future of this study is to make the Microgrid more self-sufficient, showing smooth transition from grid connected to islanded mode, ability to compensate reactive power and effective voltage regulation. The charge stored in the batteries can be sent back to the grid and thus establishing a smart exchange of power between the household and the utility grid. This exchange can be monitored by the smart meter which will also interact with the agents making an intelligent and economically synergistic Smart Grid.

Bibliography

[1] Allison Lantero, “How Microgrids Work,” *http://www.energy.gov/articles/how-Microgrids-work,* July 2016.

[2] A. Yahaya and M. AlMuhaini, “Reliability assessment of load points including solar and wind DGs,” *Smart Electric Distribution Systems and Technologies (EDST), International Symposium,* pp. 200-205, 2015.

[3] B. Lasseter, “Microgrids [distributed power generation],” *Power Engineering Society Winter Meeting IEEE,* Vol. 1, pp.146-149, 2001.

[4] Wilsun Xu, Konrad Mauch, and Sylvain Martel, “An Assessment of Distributed Generation Islanding Detection Methods and Issues for Canada,” *CETC-Varennes,* 2004.

[5] Matt Ferguson, “Financing Tribal Energy Infrastructure & Energy Optimization Infrastructure (EOI),” *National Tribal Energy Summit: A Path to Economic Sovereignty,* Sept. 2015.

[6] Rudy Setiabudy, B.S. Hartono and Yan Budiyanto, “Review of Microgrid technology,” *QiR (Quality in Research), International Conference,* 2013.

[7] “What is the Smart Grid?,” *The Department of Energy's Office of Electricity Delivery and Energy Reliability (OE)*, July 2016.

[8] T. Samad and S. Kiliccote, “Smart Grid technologies and applications for the industrial sector,” Computers & Chemical Engineering, Vol. 47, No. 2012, pp. 76-84, Dec. 2012.

[9] Rep. Nick J. Rahall II, "H.R.6 - Energy Independence and Security Act of 2007," *110th Congress*, 2007-2008.

[10] Rep. David R. Obey, "H.R.1 - The American Recovery and Reinvestment Act of 2009," *111th Congress*, 2009-2010.

[11] Sen. Abraham A. Ribicoff, "S.826 - An Act to establish a Department of Energy in the executive branch by the reorganization of energy functions within the Federal Government in order to secure effective management to assure a coordinated national energy policy, and for other purposes.," *95th Congress*, 1977-1978.

[12] Rep. Nick J. Rahall II, "Smart Grid Investment Grant Program, H.R.6 - Energy Independence and Security Act of 2007, Section 1306," *110th Congress*, 2007-2008.

[13] "Standards," *http://smartgrid.ieee.org/resources/standards*, July 2016.

[14] ASHRAE, "Facility Smart Grid Information Model," *Advisory Public Review*, July 2012.

[15] Indian Smart Grid Forum and Indian Smart Grid Task Force, "The Smart Grid vision and roadmap for India," *Ministry of Power, Government of India*, Aug. 12, 2013.

[16] U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability, "Current cyber security issues," Study of security attributes of Smart Grid systems, April 2009.

[17] F.B. Beidou, W.G. Morsi, C.P. Diduch and L. Chang, "Smart Grid: Challenges, research directions and possible solutions," *Power Electronics for Distributed Generation Systems (PEDG), 2010 2nd IEEE International Symposium*, June 16-18, 2010.

[18] R.A. Walling, R. Saint, R.C. Dugan, J. Burke and L.A. Kojovic, "Summary of distributed resources impact on power delivery systems," *IEEE Trans. Power Del*., 23(3), pp. 1636-1644, 2008.

[19] J. Zhang, Ai Qian, Jiang Chuanwen, Wang Xingang, Zheng Zhanghua, Gu Chenghong, "The application of multi agent system in Microgrid coordination control," *Sustainable Power Generation and Supply, 2009. SUPERGEN '09. International Conference*, pp. April 1-6, 2009.

[20] J. S. Ren, K. T. Tan, B. Sivaneasan, P. L. So and E. Gunawan, "Energy management of a multi-agent based multi-Microgrid system," *IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, 2014.

[21] Darith Leng, "Experiment on distributed cooperative control with Multi-Agent System for a single-phase Microgrid," *Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), 12th International Conference*, 2015.

[22] Mao Meiqin, Dong Wei and Liuchen Chang, "Multi-agent based simulation for Microgrid energy management," *Power Electronics and ECCE Asia (ICPE & ECCE), IEEE 8th International Conference*, 2011.

[23] R. A. R. C. Gopura, K. T. M. U. Hemapala, N. Perera and A. L. Kulasekera, "A review on Multi-Agent Systems in Microgrid applications," *Innovative Smart Grid Technologies - India (ISGT India), IEEE PES*, Dec. 1-3, 2011.

[24] Branislav Hredzak, Vassilios G. Agelidis and Thomas Morstyn, "Cooperative Multi-Agent Control of Heterogeneous Storage Devices Distributed in a DC Microgrid," *IEEE Transactions on Power Systems,* Vol. 31, Issue 4, Sept. 10, 2015.

[25] Mengfei Lv, Tianyu Zhao, Yeping Ji and Heng Li, "Decentralized coordinated control of Microgrid based on Multi-Agent System," *IET Generation, Transmission & Distribution,* Vol. 9, Issue 16, March 12, 2015.

[26] Bharat Menon, Dipti Srinivasan, Sanjib Kumar Panda, Akshay Kumar Rathore and Rahul Mehta, "Market based multi-agent control of Microgrid," *Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP), IEEE Ninth International Conference*, April 21-24, 2014.

[27] Advanced Agent-Robotics Technology Lab, "Multi-Agent Systems," *The Robotics Institute, Carnegie Mellon University*, July 2016.

[28] Panait Liviu and Luke Sean, "Cooperative Multi-Agent Learning: The State of the Art," Autonomous Agents and Multi-Agent Systems, 11 (3): Pages 387–434, 2005.

[29] School of Computer Science, "The Multi-Agent Systems Lab," *University of Massachusetts Amherst*, Oct 16, 2009.

[30] Ms. Meena Agrawal and Dr. Arvind Mittal, "Multi-Agents Implementation Frameworks - An Overview," *International Journal on Recent and Innovation Trends in Computing and Communication*, Vol. 3 Issue 2, February 2015.

[31] Camacho David, Alex Ricardo, Castro César and Molina José M, "Performance evaluation of ZEUS, Jade, and SkeletonAgent frameworks," *Systems, Man and Cybernetics, 2002 IEEE International Conference*, 2002.

[32] R. Trillo, S. Ilarri and E. Mena, "Comparison and Performance Evaluation of Mobile Agent Platforms," *Autonomic and Autonomous Systems, ICAS07. Third International Conference*, June 19-25, 2007.

[33] Giovanni Caire, "JADE Overview," JADE Tutorial: JADE Programming for Beginners, June 30, 2009.

[34] Fabio Bellifemine, Giovanni Caire, Dominic Greenwood, "Developing Multi-Agent Systems with JADE," *Wiley Series in Agent Technology*, 2007.

[35] P. Mendham and T. Clarke, "Macsim: A Simulink Enabled Environment for Multi-Agent System Simulation," *Proceedings of the 16th IFAC World Congress, Prague, Czech Republic*, 2005.

[36] J. M. Solanki and N. N. Schulz, "Using intelligent Multi-Agent Systems for shipboard power systems reconfiguration," *Proceedings of the 13th International Conference on Intelligent Systems Application to Power Systems*, Nov. 2005.

[37] Charles R. Robinson, Peter Mendham, and Tim Clarke, ‘MACSimJX: A Tool for Enabling Agent Modelling with Simulink Using JADE,” *Journal of Physical Agents,* Vol. 4, No. 3, Sept. 2010.

[38] Majid Jamil, Sanjeev Kumar Sharma and Rajveer Singh, “Fault detection and classification in electrical power transmission system using artificial neural network,” *Springerplus,* PMC4496419, 4: 334, 2015.

[39] S. Saha, M. Aldeen and C.P. Tan, “Fault detection in transmission networks of power systems,” *International Journal of Electrical Power & Energy Systems,* Vol. 33, Issue 4, Pages 887–900, May 2011.

[40] W. Rebizant and J. Szafran, “Power system fault detection and classification using probabilistic approach,” *European Transactions on Electrical Power,* Vol. 9, Issue 3, Pages 183–191, May/June 1999.