DEVELOPMENT OF MULTI-AGENT SYSTEM BASED ENERGY MANAGEMENT SYSTEM FOR MICRO GRIDS

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Degree of Master of Science by Research

Department of Electrical Engineering

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DECLARATION

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ABSTRACT

In this thesis, our objective is to introduce multi agent concept for the energy management of micro grids. This objective is very significant as micro grids are emerging as a method to integrate the operation of distributed energy sources (DES) in modern power systems. They introduced advanced communication technologies, optimizing techniques, sensing and monitoring features for the power distribution network. However, optimal energy management is still a challenge for microgrids when controlling renewable DES's with intermittent generating patterns. In this research, a Multi Agent System (MAS) based architecture is used for the operation of energy management system (EMS) of a microgrid. The objective of this research is to implement an agent based control architecture for DES's, loads and energy storage systems (ESS) of a microgrid to achieve optimal energy management. This document discusses the modeling, simulation and hardware implementation of agent based energy management system. Initially, JADE (Java Agent Development Environment) is used to implement the agent based control architecture. A microgrid is modeled in Matlab/Simulink and interlinked with agents developed in JADE through a middle layer. The decision making authority is shifted to ground hierarchy, enabling local agents to take control over DES's to optimize the renewable power consumption. The outcome of this research shows that MAS based control architecture can be used to optimize the energy management in a microgrid. This thesis presents a complete literature review about the background of this research and similar projects, and the results obtained through the research in both simulation and hardware implementation in developing a multi agent based energy management system for a micro grid.

Keywords— Agents, Multi agent systems, Energy management, microgrid, JADE

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H.V.V. Priyadarshana.

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LIST OF ABBREVIATIONS

ABEMS	Agent Based Energy Management System
ACL	Agent Communication Language
ABM	Agent Based Modeling
ADK	Agent Development Toolkit
AMS	Agent Management System
CLP	Critical Load Power
CEMS	Centralized Energy Management Systems
DEMS	Distributed Energy Management Systems
DER	Distributed Energy Resource
DSM	Demand-side management
DF	Decision Function
EMR	Electro Mechanical Relay
EMS	Energy Management Systems
GHG	Green House Gas
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
JADE	Java Agent Development Environment
LCD	Liquid Crystal Display
MEMS	Multi-agent Energy Management Systems
MAS	Multi Agent System
NCLP	Non-Critical Load Power
NCRE	Non-Conventional Renewable Energy
PCC	Point of Common Coupling
RER	Renewable Energy Resource
SCADA	Supervisory Control and Data Acquisition
SSR	Solid State Relay
TSD	Two Stage Dispatch
TLP	Total Load Power
TFT	Thin Filmed Transistor
TRP	Total Renewable Power
WTP	Wind Turbine Power

1. INTRODUCTION

1.1. Overview

Today world is paying more attention to the environment with the rise of factors like climate change, greenhouse gases, global temperature rising etc. Electrical power generation has been a major industry which has been affecting the environment over decades with conventional power generation methods such as oil, gas, coal and many other methods [1]. As a result, the researches about renewable energy generation from green energy sources increased. The environment friendly renewable energy generators like solar Photovoltaic , wind power , hydro power , tidal wave power , geo thermal getting more and more popularity in the power industry over last decade. On the other hand, complexity of power system structure is increasing as the increment of demand and increment of applications of electrical energy[2].Power system restructuring by including distributed renewable sources, deregulation, integration with utility grid, maintaining the power quality with intermittent nature of renewable sources are the major problems found today [3].The word " micro grid " came to the industry as a solution provider for all such issues in controlling renewable energy sources in a reliable and optimized manner. The basic technology behind today's electrical power grid hasn't been updated since last century. The centralized power electrical grid structure is an inefficient system architecture from number of aspects. In a centralized power system structure, power plants do not have real-time updated data of termination points and power demand. The whole power transmission network structure is created to manage peak demand and it's not sustainable. It is very clear that conventional electrical power grids must be upgraded in number of aspects such as power monitoring, DSM (Demand-side Management), fewer downtimes, shorter downtimes, minimum power losses etc [4]. The electricity demand is strongly increasing and available centralized grid structure has no capacity to fulfill the complex power generation and demand [5]. When referring to latest surveys and statistical analysis on power, the estimated global share of electrical energy consumption from total energy consumption of the world is expected to increase from 20% to 23%–27% in next decade [6]. Considering these facts, there must be a significant change in the centralized grid to face this challenge. As a strong solution new concepts like micro grids, multi energy systems, smart grids are emerging with artificial intelligent technologies and advance communication protocols.

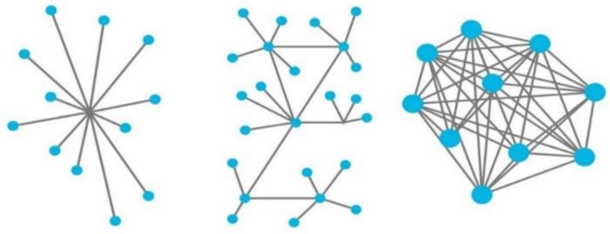


Figure 1.1: Centralized, Decentralized, Distributed Structures

“Three D’s /3D (Democratize, Decarbonize, and Decentralize)” is a very new concept for electrical network planning and designing. The basic objectives of this concept is to increase the power systems reliability, efficiency and sustainability, CO_2 emission controlling, generate electricity with low cost etc. Micro grids is the only power system solution which was supporting 3D concept as micro grids are capable of controlling renewable energy sources in an optimized manner [7].As a solution to the above mentioned challenges, modern power system is moving for more decentralized structure from its conventional centralized structure. The major advantage received from this movement is the ability to control DER (Distributed Energy Resources) in a reliable and efficient manner [8]. MAS (Multi Agent Systems) ,Blockchain Technology, IoT (Internet of Things), AI (Artificial Intelligence), are the latest concepts which are getting involved with micro grids giving them the ability to operate in more efficient and complex energy management algorithms and strategies in controlling DERs’.[9]

1.2. Research Background, Objectives and Scope

The renewable power generation is taking control over the world’s power generation rapidly. This revolution in the energy sector is driven by several reasons. Limited fossil fuel resources, emerging of green concepts, advanced renewable energy systems (RES), energy liberation are some of them [10].The sustainable development goal (SDG) of the world’s power sector is to increase the share of renewable energy from total power consumed [11]. Microgrids as the most successful structure to integrate the operation of renewable power sources, have to play a vital role. However, microgrids still need to come over a lot of challenges in maintaining power reliability and quality [12]. MAS, a collection of autonomous, intelligent computational entities or agents, can be successfully used to answer the power management problems of microgrids in various aspects [13]. MAS based architectures took attention of most of the recent researches related to micro grids because MAS based architectures improve operational efficiency, system reliability and flexibility [14]. Considering the research background and the current situation of micro grids and DES controlling, the motivation for the research can be identified as follows

- Complexity of energy management of microgrids with intermittent generating patterns of DER's.
- Introduce multi agent concept for micro grid and use qualities of MAS for EMS of the microgrids.

Throughout this thesis we discuss modeling, simulation and hardware implementation of agent based EMS. The major project objectives are as follows,

- Design and develop multi-agent controlled micro grid with multiple agents for distributed energy sources which interact each other and work as an integrated system.
- Propose control algorithms, communication protocols and data collection patterns
- Develop an energy management system based on MAS.

The main objective is to research on the applicability on MAS based architecture for energy management in microgrids and identify the positive and negative features. Initially, JADE simulation platform is used to implement the agents (software entities). The JADE simulation platform is implemented using java programming language. Multi agent systems implemented JADE simulation platform complies with foundation of intelligent and physical agent (FIPA) specifications, under IEEE standards. JADE platform enables multi agent system modeling with agent communication (peer to peer) and task execution. Distributed local controlling of DES and loads of a microgrid using agent based platform improves the efficiency of operations. The control architecture of a microgrid should be resilient, fast and maintain continuous operation in any condition. In a multi agent based architecture each agent has a local responsibility and local decision making authority. At the same time agents can work as an integrated system to achieve the global objectives. This quality gives the ability for multi agent systems to operate continuously even in malfunctions or losses in communication channels [15]. When considering the recent researches related to the topic, a MAS based cloud architecture is proposed in [16]. An agent based scheduling strategy is proposed in [17].MAS based dynamic control and management strategies for microgrids are proposed in [18] [19] [20].Through this research we are moving a few steps forward, by modeling, simulating and implementing a MAS concept based EMS for a microgrid physically on a testbed. Finally a micro grid with a MAS based operation can be simply explained as dividing following tasks done by a central controller in a SCADA system in to individual tasks of different agents.

- ✓ Utility Grid monitoring and controlling
- ✓ Load monitoring and controlling
- ✓ DES monitoring and controlling
- ✓ Battery bank monitoring and controlling
- ✓ Implement Coordination among all load and source controllers

1.3. Microgrids and smart grid concepts

To understand the concept behind micro grids and smart grids, the conventional grid and its operation should be explained. The word "Grid" refers to power electric grid or utility grid, a complex power network of high voltage transmission lines, electrical transformers, distribution lines, grid substations etc. The responsibility of the grid is to transmit power generated in power plants to the consumer units. Micro grid is a mini scale electrical grid which is organized in a limited are and capable of operating independently.

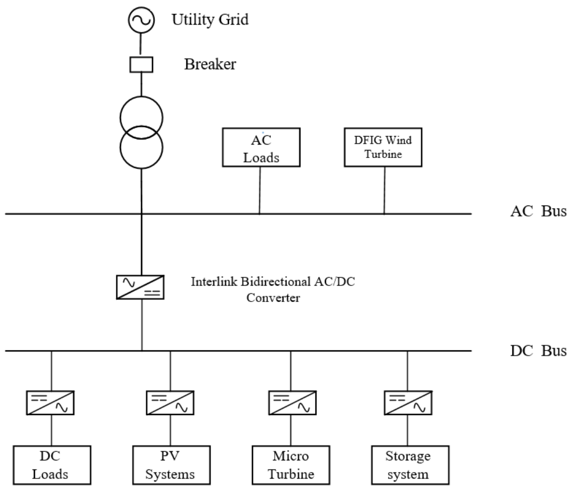


Figure 1.2: System Architecture of a micro grid

When defining a micro grid and its operation, we can find number of definitions in recent literatures [21] [22] [23] [24]. Considering general features of a micro grids, a definition for a micro grid can be bring out as an integrated team of distributed energy generators or resources and different types of electrical loads which are organized inside a predefined electrical border and capable of operating as an independent controllable unit with respect to the utility grid [21].

Micro grids are capable to operate with connected to the utility grid (grid connected mode) or without connected to the utility grid (islanded mode) [25]. When the micro grid is working without the grid, which is usually called isolated or islanded mode, maintaining the power quality is a complex and challengeable process. On the other hand grid-connected operation means the microgrid is operating with exchanging power with the utility grid. The most challengeable scenario for a micro grid is to maintain the power quality. Specially maintaining the proper frequency and voltage in the system [26]. Considerable amount of researchers are been conducted with the objective of finding an optimized controlling techniques for micro grids. Different control models, system architectures, operating algorithms are proposed for micro grid operation. A micro grid can be considered as a collection of lot of sub systems such as control system, energy management system, and energy storage system, power conditioning system, energy sources and loads. PCC is located at the connection point of the utility grid and micro grid [27].A micro grid and a smart grid has a very significant differences. Meaning of the word “smart” is the use of latest communication technologies or IoT. Number of features like advance sensor usage , high speed communication networks , automated controlling , server-client algorithms ,smart metering have been introduced to micro grids with the word “Smart” [28]. A micro grid which is using digital IoT technologies to control DER and loads can be identified as a smart grid [29].

1.4 Microgrid Communication protocols and System architectures

1.4.1 Communication protocols

The main objective of a microgrid is to maintain a reliable operation of DER's (Distributed energy resources) in an optimized manner. Advanced communication architectures and protocols are essential for micro grids to achieve such objectives [30].

When selection a communication architecture and protocols for a micro grid, basically following facts are considered.

- Control objectives of the micro grid
- Performance, traffic volume of data , characteristics
- Implementation and maintenance costs of the communication system

The communication networks used in modern micro grids or smart grids can be categorized in various aspects and various hierarchical segments of micro grid communication networks. W-A-N (Wide Area Network), H-A-N (Home Area Network), N-A-N (Neighborhood Area Network) can be observed as segments of smart grid communication network.

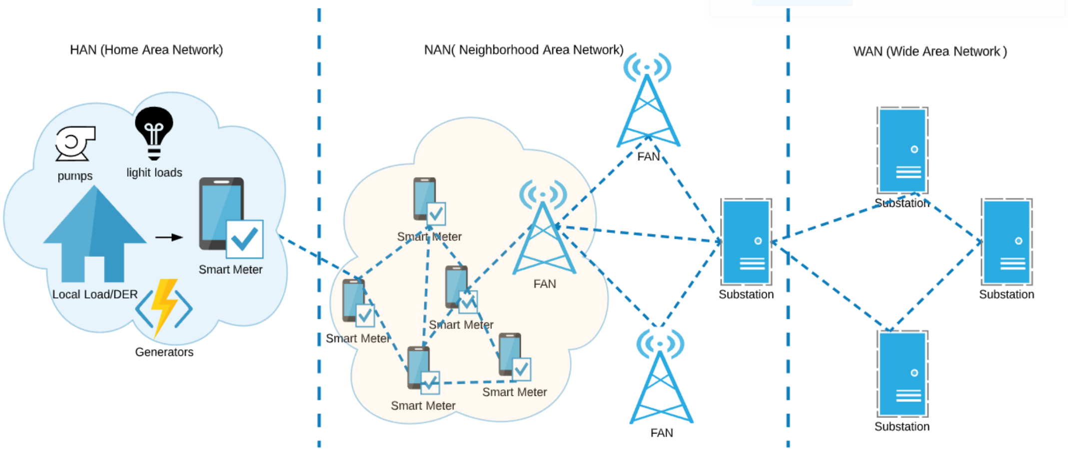


Figure 1.4: Communication Network arrangement in a smart grid

HAN performs in local level with the lower hierarchical loads and DER's. HAN contributes to local data collections through smart meters. HAN's responsibility is to sense and monitor the local environment of the smart grid. NAN handle bulk data volume's from smart meters and also can be partitioned to FAN (Field Area Networks).They can be considered as substations. WAN interconnects substations and manage the total data volume [31]. Smart micro grids commonly use wireless communication technologies as the developed reliability in considerable amount in last decade. And most commonly used conventional method, power line wired communication has lot of disadvantages such as electromagnetic interference, comparatively high cost in implementation and maintenance. These reasons led the path to use of wireless communication technologies in micro grids. [32] Wi-Fi, Bluetooth, ZigBee, cellular are some of the wireless technologies widely used.

1.4.1 Communication protocols

ZigBee: ZigBee based communication networks are based on IEEE 802.15.4 standards. ZigBee can be identified as a short range wireless communication technology and mostly used in ISM band (Industrial , medical , Scientific) applications. Transmission distance is less than 100m and has a data transmission rate of 250kbits/s.

Bluetooth :Bluetooth can be identified as a short distance wireless communication technology which is competing with IEEE 802.15.1 standards. Low power consumption and ability to transmit data rapidly are the major advantages of this technology. But the coverage distance is very low compared to ZigBee and Wi-Fi technologies.

Wi-Fi (Wireless Fidelity) :Wi-Fi wireless network technology is based on IEEE 802.11 standards. Wi-Fi networks are basically designed for LAN (Local Area Network) applications with maximum data volume is less than 150 Mbps. Wi-Fi network can cover a range of around 250 m. It’s a well enough network coverage area for a microgrid application. Generally a Wi-Fi network which is operating on 2.4 GHz frequency band can manage data rates of around 11 Mbps. There are lot of other versions based on IEEE 802.11a standards which can be considered as improved version of Wi-Fi. For example 5.8 GHz frequency band using OFDM (Orthogonal Frequency Division Multiplexing) technology. Wide range , network scalability and IP support are the advantages of Wi-Fi network. In this research we are using Wi-Fi as the communication technology to implement the communication network in between DER’s and loads in the micro grid.

1.5 Previous Researches

Multi agent systems have been a very popular research area among smart grid related researches during the recent few years. And lots of researcher's have used MAS concept for various applications in microgrids and distributed power source controlling. The following table contains the recent researches conducted in microgrid energy management based on multi agent concepts.

Table 1: Recent MAS based researches for microgrid management

Author	Research	Year	Reference	Application
T. Logenthiran	ERS (Energy Resource Schedule)	2011	[33]	MAS concept used to develop energy generation resource management system
Davarzani S	DRM (Demand response management)	2019	[34]	MAS based model for DRM of a microgrid.
Ju L	Micro grid coupling	2019	[35]	Microgrid group coupling control concept based on multi agent intelligent schedule.
OGC	EMS (Energy Management System)	2015	[36]	An MAS based model for energy management in a city area.
P. Mancarella	MES (Multi-energy Systems)	2013	[37]	Agent based control model for MES control.
Yang Han	(DCC) Distributed Coordinated Control	2017	[38]	Propose a DCC model for microgrids using MAS architecture
W. Radziszewska	EMS (Energy Management System)	2014	[39]	PBS (power balancing system) model smart trading and load scheduling
Sambeet Mishra	Microgrid expansion Process	2019	[40]	An agent base approach for microgrid expansion planning and P2P decision taking.
Akhtar Hussain	Microgrid protection	2016	[41]	A protection mechanism for microgrids based on agent concept.
Cui Wang	Microgrid stabilization	2018	[42]	Discuss the possibility of agent based concepts for stabilization of power systems

MAS is not a concept which is currently under academic research only , it's practically used in several industries. There are some real world graphical applications where MAS concept is applied for computer games. And MAS have been widely used in film industry, for networking applications (self-healing and high scalability networks) and mobile application, for dynamic and automatic supply and load balancing, defense systems , transportation, graphics, logistics, GIS etc.

1.6 Energy Management Systems (EMS)

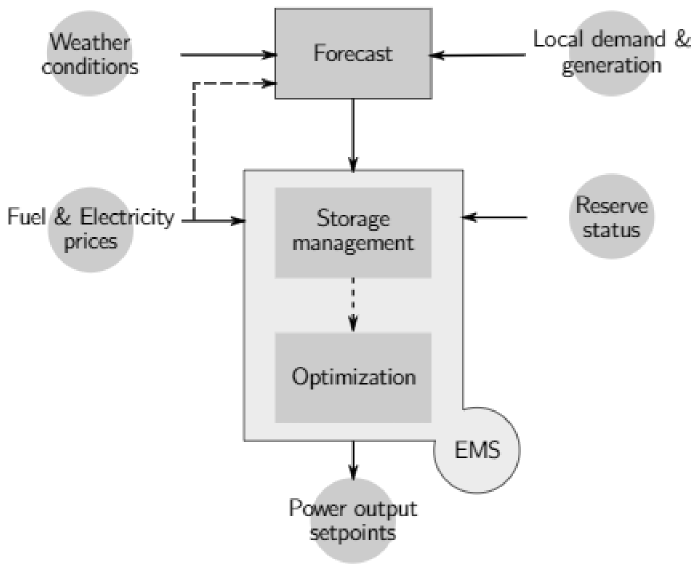


Figure 1.6: Basic EMS architecture of a micro grid

A micro grid with an energy management system (EMS) can successfully control the distributed power sources and loads to compensate supply and demand in an efficient manner. With the help of an energy management algorithm, and EMS can minimize the power losses, power imbalances, dependency on utility grid, and negative effects on environment. An EMS for a micro grid should have a forecasting process to estimate different parameters for optimization, be real time updated about demand and generation of energy, updated about fuel and grid electricity prices, and reserve status etc [43]. Power generation, power consumption and storing in a micro grid is very complex and dynamic parameters. Forecasting or predicting these parameters for the purpose of demand and supply balancing is a complex and difficult procedure with intermittent, dynamic and variable power generating patterns of renewable distributed energy sources. Previous studies have developed various forecasting models which generate predictions based on historical data, weather data, societal data etc [44][45]. EMS should be able to process the control algorithms, make decisions in controlling the loads and DER in micro grid. Various control algorithms have been proposed in previous studies for EMS in micro grids [46].The objective of this research is to develop an EMS based on MAS concepts for a micro grid with a decentralized approach.

1.7. Thesis outline

The structure of the thesis is as follows. Chapter 2, discuss about the agent concept and behavior of multi agent systems. And it also discuss about how multi agent system architecture can be used for energy management of a microgrid.

Chapter 3 presents the development of MAS based architecture with agent development toolkits. A literature review is presented on the currently available ADK's (Agent development toolkits).It describes about the JADE (Java Agent Development Toolkit) which is used to develop and simulate the MAS based EMS for a micro grid.

In chapter 4, explains the process of developing a multi agent system with JADE platform. Implementation of agents, implementation communication in-between agents, integrated operation of agents.

Chapter 5, presents the results obtained through the simulation after processing proposed algorithm in the developed multi agent system in JADE framework. Discusses the results for different case studies done with analyzing realistic data patterns.

Chapter 6, discusses the hardware implementation of micro grid testbed and implementation of a MAS for energy management for a micro grid with ESP-8266 microcontrollers

Chapter 7, Discuss the limitations of the research project in simulation step and in hardware implementation step

Chapter 8, summarizes the results, conclusions and achievements of the research and discusses the future improvements and recommendations.

2. Multi Agent Systems (MAS)

2.1 An Agent

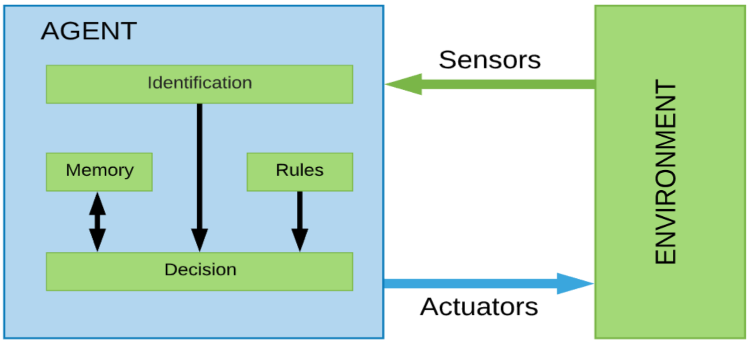


Figure 2.1: Operation of an agent

An agent is something more than a software.It's not only a set of predefiend instructions (set of rules) and a memory. An agent can be an intelligent entity with autonomous behaviours and selflearning features.The operation of an agent in a certain enviroment is explained in figure 1. Agents can identify the status of the enviroment and make changes within its authorized boundary. Agents have very significant qualities when considering the behaviour. They are as follows,

- ✓ Autonomous : Ability to operate and achieve objectives taking decisions itself without the interaction of external control commands or hunam guidance.
- ✓ Social : Ability to communicate inbetween agents using ACL(Agent Communication Languages) and ability to cooperate with other agent to achieve globle objectivs.
- ✓ Reactive : Ability to react the changes in the operating enviroment
- ✓ Proactive : Ability to take the starting action or initiate the action.

The objectives of these agents can be different depending on the application of MAS used and the agent's skills, resources used , services provided and attached physical entities can be varied. Controlling, optimizing ,reasoning and learning are some general qualities of an agents.

2.2 Multi Agent Systems (MAS) Architecture

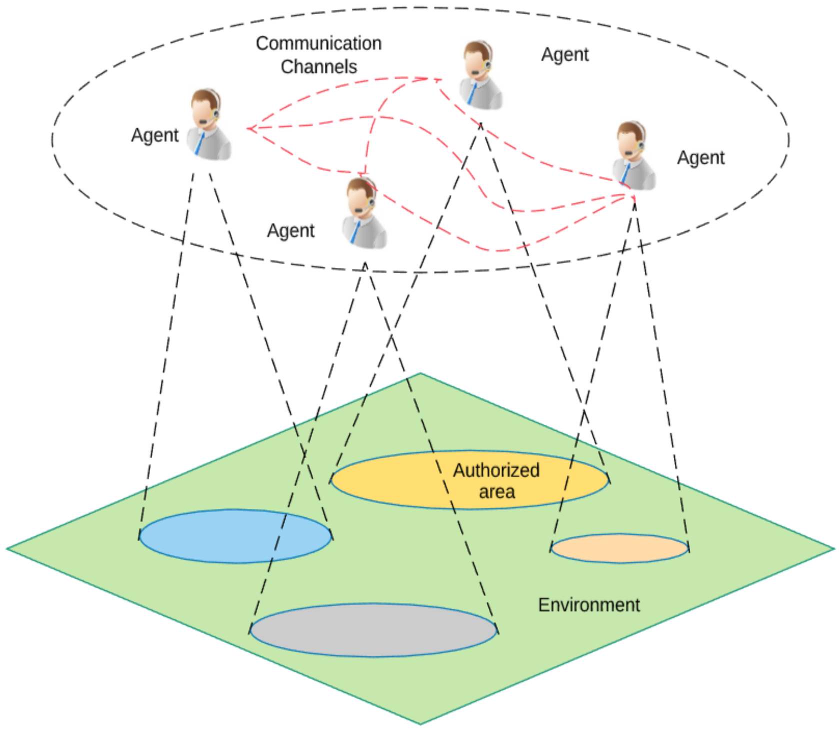


Figure 2.2 MAS system architecture

A definition for a MAS can be given as a set of Agents, which are intelligent and autonomous software entities. Each agent has local objectives and decision making authority in a pre-defined boundary. These software agents form a communication network in-between each other and able to work as an integrated team.

In an MAS based control system, each agent has a set of pre-defined goals, responsibilities and certain boundary in the environment under its authority. The cooperation in-between these agents depends on the communication network or effective information sharing [47].The major advantages of implementing agent based control architectures (ABCA) are system survivability, ability to maintain continuous operation, asynchronous operation, dynamic flexibility, decentralized operation, extendibility, ability to handle complex operations etc. Multi agent systems can be categorized based on hierarchy, decision making function, topology and communication. The following literatures have deeply discussed about the features of different multi agent systems.

2.3. Categorization of Multi-Agent Systems

2.3.1. Hierarchy

In a MAS, an agent is capable to command other agents in the MAS. That behavior can be considered as agent's leadership quality. Based on leadership quality we can categorize MAS in to two basic types. First type is leader follow MAS's where process of other agents are controlled by leader agent and the second type is leaderless MAS's where each and every agent has the equal decision making authority.

2.3.2 Linear / Non- Linear Decision Function

MAS's can be categorized based on variation of the output DF (Decision Function) in MAS with variation of input parameters for the MAS. If DF output is directly proportional to input parameter variations of the system environment, that MAS is categorized as linear MAS. Linear MAS's can be analyzed with a mathematical procedure. But in a non-linear MAS, the outputs of DF are not directly proportional to the inputs.

2.3.3 Communication

Bidirectional communication channels in a MAS allows agents to exchange information in-between them. This communication can be event triggered communication or time triggered communication. Agents in time triggered MAS's collect data using sensors, process data and work integrated with other agents in MAS continuously. Agents in event triggered MAS communicate with each other only when a variation in environment parameter sensed.

2.3.4 Topology

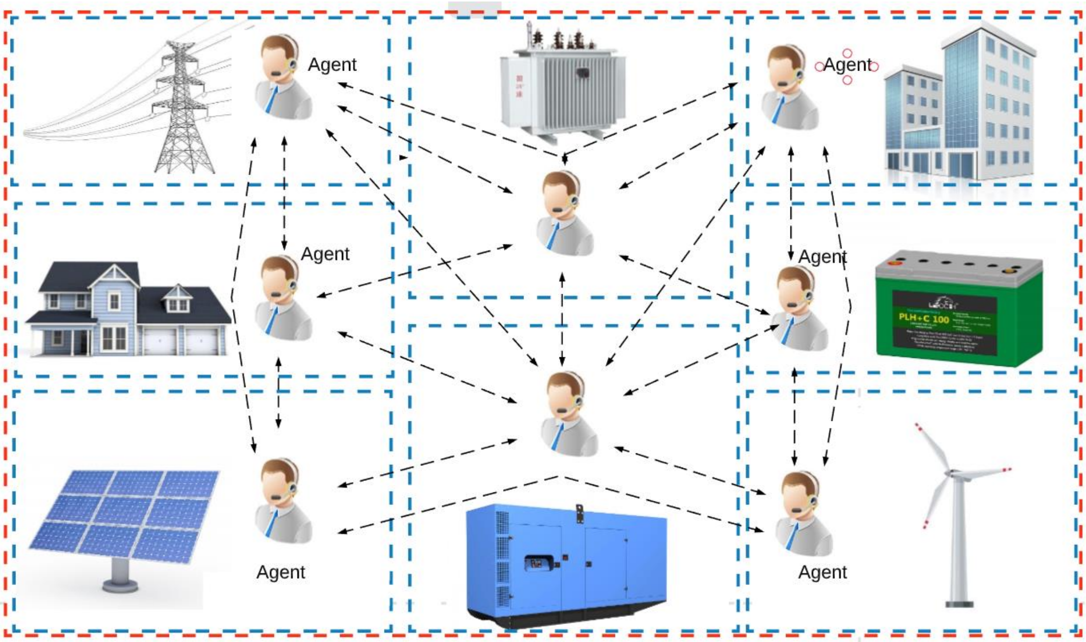
Topology based categorization can be done to MAS. Depending on the application agents position in environment and agents relationships can vary. MAS can be categorized to two basic forms as static topology and dynamic topology. Static topology we can see stable relationships of agents with other agents in MAS and the position in the environment is fixed. Dynamic topology, agent of MAS's position in the environment varies with time and the communication network patterns of agents also varies.

Table 2: Categorization of multi agent systems

Feature	Categorization	References
Topology	Static agent system	[48]
	Dynamic agent system	[49][50]
Hierarchy	Leader-follow method	[51][52]
	Leaderless method	[53][54]
Communication	Event triggered system	[55][56]
	Time triggered system	[57]
Decision function	Linear type Decision Function	[58][59]
	Non- Linear type Decision Function	[60][61]

2.4 Multi Agent based approach for micro grids

Microgrid is a group of distributed sources, energy storage units and loads. The most optimized way to manage microgrid is at lower hierarchical steps of a microgrid. (Ex: MPPT control for PV and Wind). Agent based architecture is decentralized and it makes the coordination of microgrid's lower hierarchical subsystems efficient. In an agent based approach for a microgrid, the power flowing through the microgrid system can be considered as the environment (Figure 2.2). Agents can be assigned to all the units in a microgrid (loads, sources, storage units). Also each agent is given the responsibility of each unit (controlling, monitoring, decision making etc.). Each agent has a local goal, manage the responsible unit to achieve the local objectives (lower hierarchical management). At the same time agents can work as an integrated group to achieve the global objectives of a microgrid. Multi agent systems will behave very positively in microgrid environments with the efficient and reliable bidirectional communication. That decentralized communication network will help to run better



control algorithms, networking techniques, fault detections compared to conventional method. Each and every agent is able to manage its own data base. They can collect each and every detail of the microgrid through other agents. This feature helps agents to take decisions independently without communicating with a central controller or a central agent.

Figure 2.4: MAS Architecture for microgrid management

In a general microgrids we can find sources like solar PV, wind and diesel generators. We can develop a mathematical model and understand the control objectives for the management of energy of a microgrid. And as the next step, an ABM can be designed to achieve the energy management goals of a microgrid. A mathematical model for power flow can be developed as follows [62],A mathematical formula for power generation of a PV array can be developed considering the intermittent generating nature of Solar PV systems[63].

Considering PV system,

$P_{pv}(t) = A_{pv} \times \eta_{pv} \times G(t)$

η_{pv} – PV module efficiency , A_{pv} – total surface area of PV modules , G(t) - solar irradiance

Considering wind turbine,

$P_{wt}(t) = 0$, when $v \leq v_{ci}$ or $v \geq v_{co}$

$P_{wt}(t) = a \times v3(t) - b \times P_{rate}$ when $v_{ci} < v < v_r$

$P_{wt}(t) = P_{rate}$ when $v_r < v < v_{co}$

v – wind speed , v_{ci} –cut-in speed, v_r - rated speed , v_{co} – cut-off speed, Prate – rated output power , a and b are parameters from power curve of wind turbine. [62]

Considering ESS,

$E_{ESS}(t)=E_{ESS}(t-1)+P_{charging} \times \Delta t \times \eta_{charge} - P_{discharging} \times \Delta t / \eta_{dishcharge}$

$P_{discharging}$ – discharging power , $P_{charging}$ – charging power , η_{charge} , $\eta_{dishcharge}$ are discharging and charging efficiencies of ESS , $E_{ESS}(t)$ and $E_{ESS}(t-1)$ are stored energy in battery at time (t-1) and t. To maintain the power balance of the system total power generation of the microgrid should be equal to total power generation.

$(\Sigma P_L(t)) - P_{PV}(t) - P_{WG}(t) - P_{ESS}(t) - P_{DG}(t) = 0$

The main objective of agents is to maintain the above power balance and there are some other significant objectives which we can achieve through a multi agent controlled microgrid. They are increasing the power availability, low economic factors (operation costs, fuel costs etc.), minimize load shedding, maximize the revenue, minimize the ESS capacity etc. The objective of this research is to study how MAS based energy management architecture will achieve these objectives. In the proposed MAS for a microgrid in this research there are there are seven agents. They are server agent (SA), photovoltaic agent (PVA), critical load agent (CLA), wind turbine agent (WTA), diesel generator agent (DGA) energy storage agent (ESA), non-critical load agent (NCLA). A brief idea of the operation of the major agents in the proposed MAS is given below.

2.4.1 Server Agent (SA) : Generally SA directly communicate with every other agent. This agent can be consider as the main decision taker of the system (not only). SA has the responsibility of generation planning and load shedding. At the same time this agent keeps connection with the manual operator and able to take decisions considering the priority hierarchy. SA negotiates with other agents to operate in the decided energy market based (economic) schedule and manages a database.

2.4.2 Photovoltaic Agent (PVA) : This agent is responsible for controlling and monitoring PV system. The local boundary including PV arrays, inverter units, circuit breaker with AC bus bar is under the authority of PV agent.). PVA manages a database and save all necessary data related to local boundary. PV agent is able to bi-directionally communicate with the SA in normal operation. And with decentralized MAS architecture, it can communicate with the SA through any other agent when a communication channel with SA is failed.

2.4.3 Wind Turbine Agent (WTA): This agent is responsible for controlling and monitoring wind turbine system. The local boundary including wind turbine, inverter units, circuit breaker with AC bus bar is under the authority of WT agent.). WTA manages a database and save all necessary data related to local boundary. The communication ability is equal to the PV agent.

2.4.4. Energy Storage Agent (ESA): ESA has the responsibility for monitoring and controlling the SOC level (state of charge) energy storage system (battery bank). ESA manages a database and save all necessary data related to local boundary. The local boundary including battery bank, inverter units, circuit breaker with AC bus bar is under the authority of ESS agent. This agent operates negotiating with the SA.

2.4.5 Critical & Non-Critical Load Agents (CLA and NCLA) : This agent is responsible for monitoring and controlling (only on & off control) the loads. The communication ability is equal to every other agent and manages a database.

3.0 Developing Multi Agent Systems

3.1 Agent Developing Toolkits (ADK)

An agent developing toolkit creates a runtime environment where agents can operate. This runtime environment must be active on a provided host and one or more agents can live in this environment at the same time. And generally these agent modeling toolkits are coming with a library of classes which can be used while programming agents and a set of graphical tools to monitor and analyze the operation of agents. There are number of agent modeling toolkits available such as JADE , Jack , ADK , Jason , MadKit etc. In this research we are using JADE as agent development platform. In this section, a justification for the selection of JADE is provided comparing with other toolkits. A qualitative analysis is done as following.

- ✓ Communication: The technology used for communication in-between agents
- ✓ Language : The programming language used for developing agents

- ✓ GUI (graphical user interface): Available/ Not Available
- ✓ Security : Security is concerned / Not
- ✓ Source availability: Open source / Not

Table 3: Qualitative analysis of Agent Developing Toolkits

ADK	COMMUNICATION	SECURITY	LANGUAGE	GUI	SOURCE
AgentBuilder	HTTP	Yes	Python	Yes	No
JADE	HTTP, TCP/IP	Yes	Java	Yes	Yes
CapNet	DCOM	No	C#	Yes	No
C-BDI	TCP/IP	Yes	C++	No	No
DECAF	KQML	No	Java	Yes	No
Jason	speech-act, KQML	No	Java	No	Yes
MadKit	Java Sockets	Yes	Java	No	Yes
Mage	RMI	No	Java	No	Yes
PMADE	Java Sockets	Yes	Java	No	Yes
Jack	TCP/IP	YES	Java	Yes	No

When referring to the details in above qualitative analysis, we decided to select JADE as out agent development platform in developing our system. We considered following facts for our decision.

- ✓ JADE is an open source framework
- ✓ JADE compliances with FIPA standards
- ✓ JADE platform has a internally build GUI
- ✓ JADE is the most widely used ADK in university research projects

3.2 ACL (Agent Communication Language)

An ACL gives agents the ability to share data withing the communiation network of a MAS. Number of methods used to share information between different applications previously such as RPC (Remote Procedure Call), RMI (Remote Method Invocation) etc. ACL's are currently stands a level above those technologies. ACL's can manage rules, propositions, and actions up to any complex level. When an agent use ACL to communicate with other agents, it uses a low level protocols such as HTTP, TCP/IP, IIOP etc. ACL's are operating based on speech act theory. Standard set of keywords are used to expresses speech act. They are called performatives (request, confirm, inform, ask etc.).

The message structure of JADE framework ACL is as follows,

Performative :FIPA message type, ex: INFORM , CONFIRM (Qualitative analysis done in Table 4)

Content :This is the main set of information in the message

Address : Sender (ID of the agent sends the message)

: Receiver (ID of the agent receives the message)

Language : Language used in content

ConversationID : A unique ID used interconnect messages in a conversation.

Ontology : Ontology used in content

Protocol : The protocol used for communication

ReplyBy : Time limit setting of a reply

InReplyTo : Sending agent uses to get support for distinguish answers

ReplyWith : A field to support distinguish answers

Example,

(INFORM

```
:sender
( agent-identifier :name SA@192.168.8.100:1099/JADE
 :addresses (sequence    http://LAPTOP-RDI66PFL:7778/acc ))
 :receiver  (set ( agent-identifier :name DGA@192.168.8.100:1099/JADE ) )
 :content  "Update" )
```

In a FIPA ACL message performative plays a significant role. Performative contains what message sending agent wants to be done for the content by the receiving agent. An example of an ACL message with INFORM performative is given above. Following table contains a qualitative analysis of different performatives of FIPA ACL language.

Table 4: Qualitative analysis of FIPA ACL Performatives

Performative	Error Handling	Action Performing	Negotiation	Passing Information	Request Information
AGREE		Yes			
CANCEL		Yes			Yes
CONFIRM				Yes	
NOT-UNDERSTOOD	Yes				
CFP			Yes		
ACCEPT-PROPORSAL			Yes		
FAILURE					
DISCONFIRM				Yes	
QUERY-IF					Yes
QUERY-REF					Yes
PROPOSE			Yes		
INFORM				Yes	
INFORM-IF				Yes	
INFORM-REF				Yes	
REQUEST		Yes			
REQUEST-WHEN		Yes			
REQUEST-WHENEVER		Yes			
REFUSE		Yes			Yes
SUBSCRIBE					
REJECT-PROPORSAL			Yes		
NOT-UNDERSTOOD	Yes				

3.3 Java Agent Development Framework (JADE)

JADE is an open source agent development platform which compliance with FIPA standards.[63] JADE can be basically described as a runtime environment for FIPA compliant agents and a java framework which can be used to develop different applications of multi agent systems. [64] JADE platform includes a library to develop agents which are able to works as integrated team. JADE runtime environment allows concurrent, parallel, multiple, agent activities. JADE has a set of Graphical tools which support logging, monitoring, debugging agent operations. JADE contain Yellow Pages which can be consider as a directory, where agents in the MAS can register their services/abilities and search for services provided by other agents.

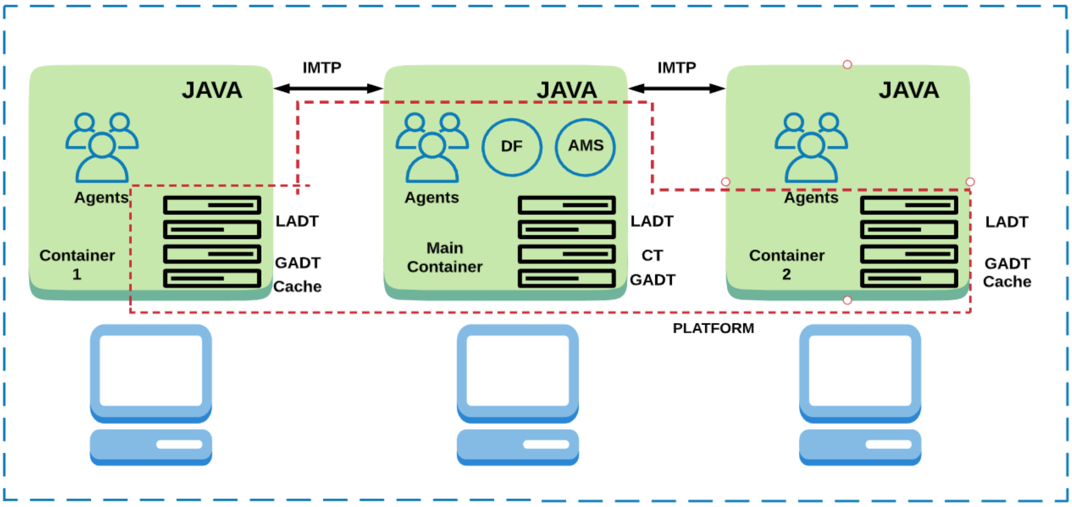


Figure 3.3: JADE system architecture

Figure 3.3 display a JADE system which has three containers including the main container. Every multi agent system developed in JADE need a main container as it is responsible for agents lifecycle management. Each container has number of agents. Main container provides each agent a unique ID or a unique name which is called Agent Identifier (AID). When agent system is operating , main container is managing two built-in agents which are called AMS (agent management system) and DF (directory facilitator). AMS agent is built-in main container and responsible for providing AID for other agents (ex:SA@192.168.8.100:1099/JADE). SA is the local name given for the agent. At the same time AMS is responsible for creating and removing agents from the system. DF agent has a significant role in a MAS. It provides a yellow page service and that service can be used by all other agents in the system.

Through this service any agent can register the services it provides to the system and any agent can find out the services provided by other agents. So agents can get the help of other agents to achieve the objectives.

3.4 Simulating Multi Agent Systems

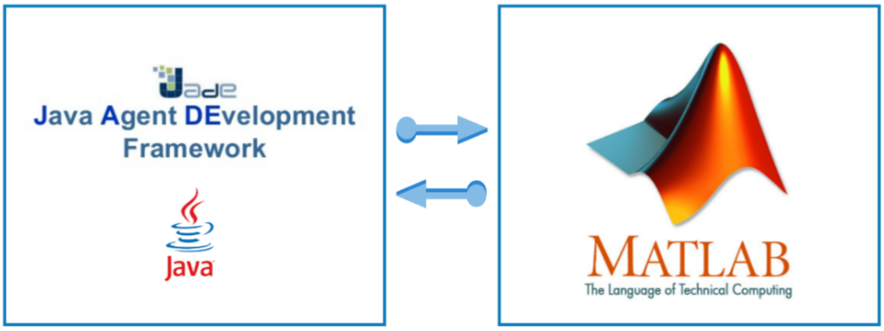


Figure 3.4: Integrating JADE framework and Matlab/Simulink

JADE and Matlab/Simulink are two completely different platforms. As Matlab does not support parallel operations, MAS can't be directly developed in Matlab for real time operations. As MAS operates in a decentralized manner parallel operation is essential [65]. An agent development platform must be used to develop a MAS. The selection of JADE (Java Agent Development Framework) was justified in the previous chapter. Microgrid control strategies for real time operation are reviewed in recent literatures [66][67]. The only option is develop the MAS in JADE and connect it with Matlab/Simulink. Here in this research MAS operation is fully implemented in JADE platform. Matlab/Simulink model sense the environment and simulate the actuator operations. In this research, a database is used as a middleware to connect Matlab and JADE as those two frameworks can't be connected directly. The developed program to communicate JADE agents with the excel database is provided in Appendix B.

Here in the simulation step of this project, the MAS for the EMS for the micro grid is developed in the JADE platform. Real time switching data generated from the MAS, according to the predefined algorithm and those data is written to a data base real time by the JADE platform. Then the Matlab model reads the switching data and displays the active power behavior of the system.

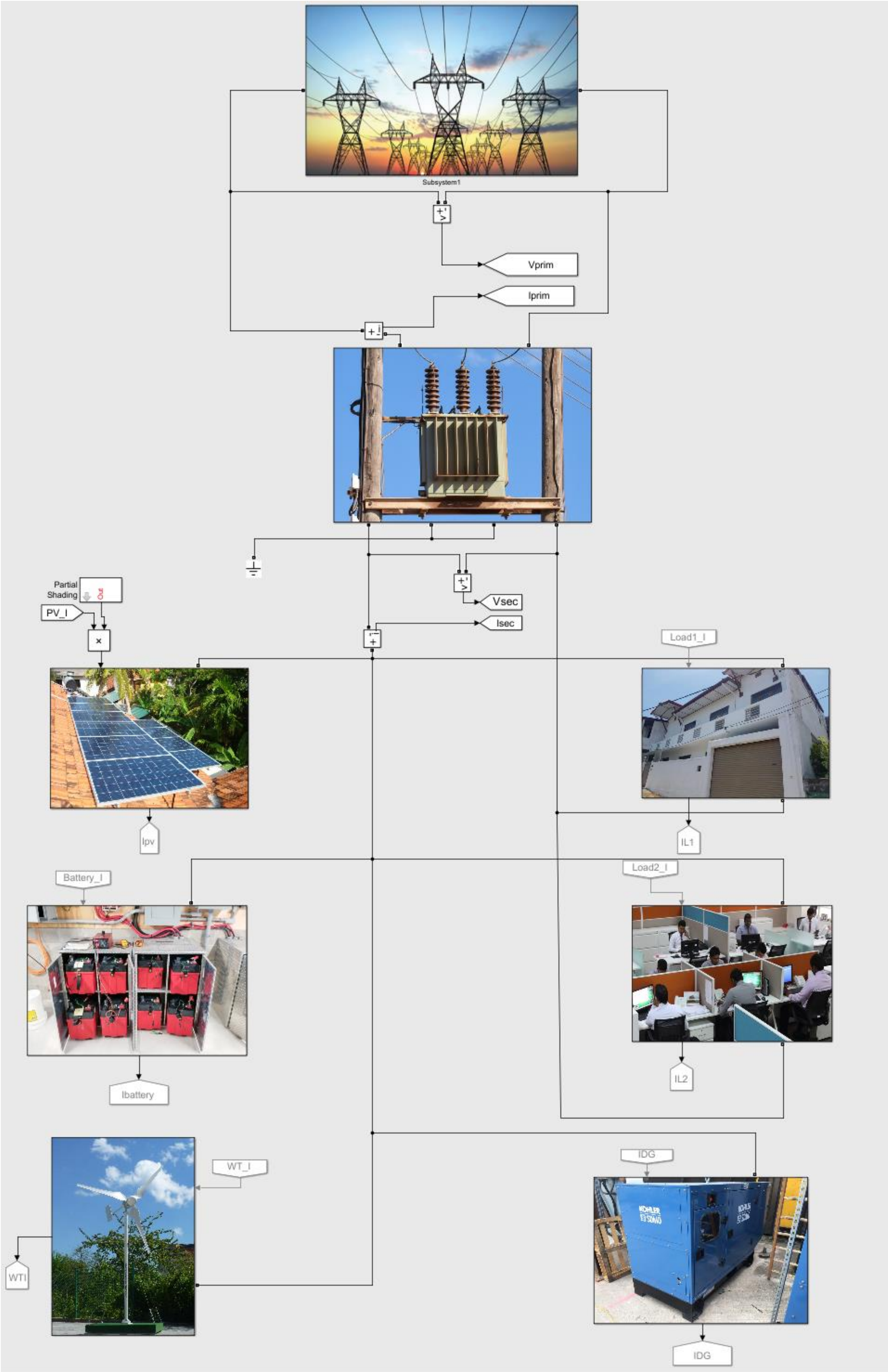


Figure 3.5 Developed Matlab model for the micro grid.

4.0 Developing MAS based EMS for a microgrid in JADE platform

4.1 Creating Agents in JADE framework

According to above literature review, multi agent systems are no more than a set of software entities which are able to share their intelligence to achieve given objectives. A multi agent system can be developed using any programming language. [68] JADE can be generally operated with windows CMD. But to program the agents with java programming language, a java IDE (Integrated Development Environment) must be used. Java IDE is a collection of software tools which are required for a developer when developing a MAS system for a particular application. Most commonly used java IDE's are Eclipse, NetBeans, and JDeveloper etc. In this research we are using Eclipse as Java IDE and java programing language to program the agents for the microgrid energy management system. JADE is available as a library (jade.jar) which can be added to java IDE. Referring to Figure 3, the micro grid energy management system we developed has seven major agents. They are Photovoltaic agent (PVA) , Wind turbine agent (WTA) , Diesel generator agent (DGA) , Energy storage agent (ESS) , Critical load agent (CL1) , Non critical load agent (NCL2) and Server agent (SA). As all seven agents in the MAS are intergrated inside the JADE platform, they all agree with FIPA (Foundation for Intelligent Physical Agents) specifications. Agents in Jade can be created by extending the Agent class found in jade.core package. The jade.core package contains all the basic classes which are responsible for generating and managing agents and containers, communication in-between agents etc. Creating a JADE agent is shown in the following example.

Ex:

```
package Distributed_units;
import jade.core.Agent;
public class PV_Agent extends Agent
{
  public void setup(){}
 }
```

All the seven agents for the distributed units are generated under the package called "Distributed_units". And agent classes belongs to a sub packages of "Distributed_units" package. To run the MAS developed on jade the library files jade.jar, jadeExamples.jar and commons-codec/commons-codec-1.3.jar were added to the CLASSPATH environment variable.

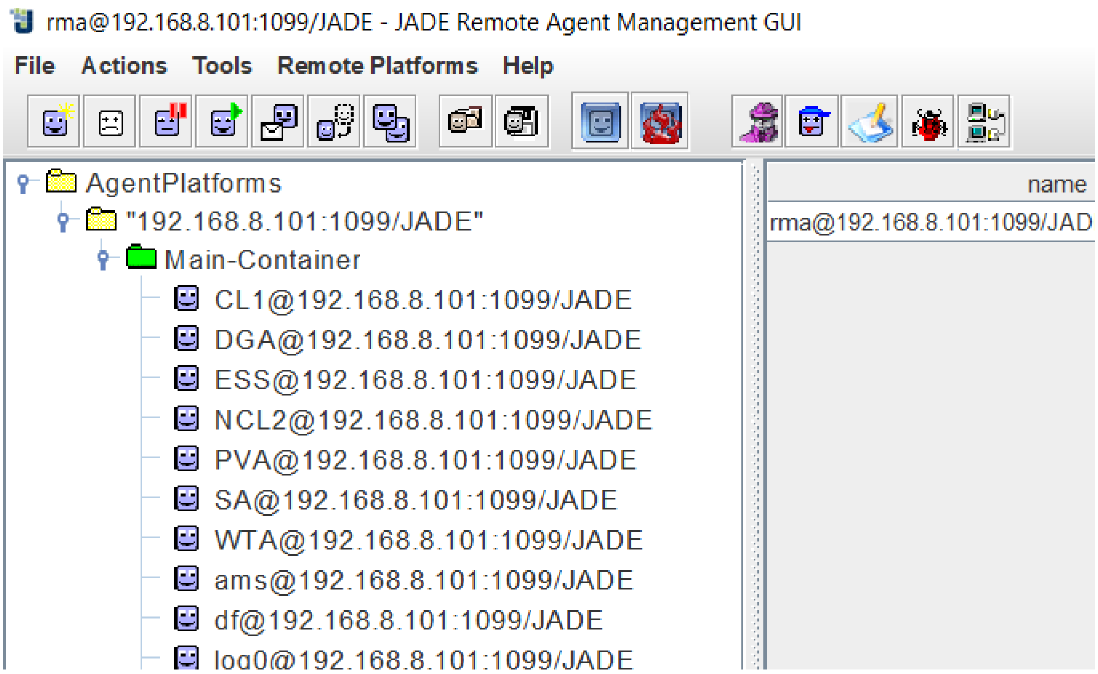


Figure 4.1: Creating agents in JADE for micro grid management application

4.2 Implementing Agent Communication

The most significant quality of MAS is the efficient communication ability of agents. The communication is accomplished by agents through sharing messages which contains information. A relevant agent communication language must be used to implement the communication between agents depending on the agent development framework selected. There are various axillary data on a message other than the content information like message type, sender data, receiver data etc. It is simple and often method is to keep the content as “String “with application dependent meaning. All the attributes of ACL language used are discussed in 4.2 section.

Ex:

```
ACLMessage msg = new ACLMessage(ACLMessage.INFORM)
msg.setContent( "" +power_requirement + "PV");
msg.addReceiver( new AID("SA", AID.ISLOCALNAME ) );
send(msg);
```

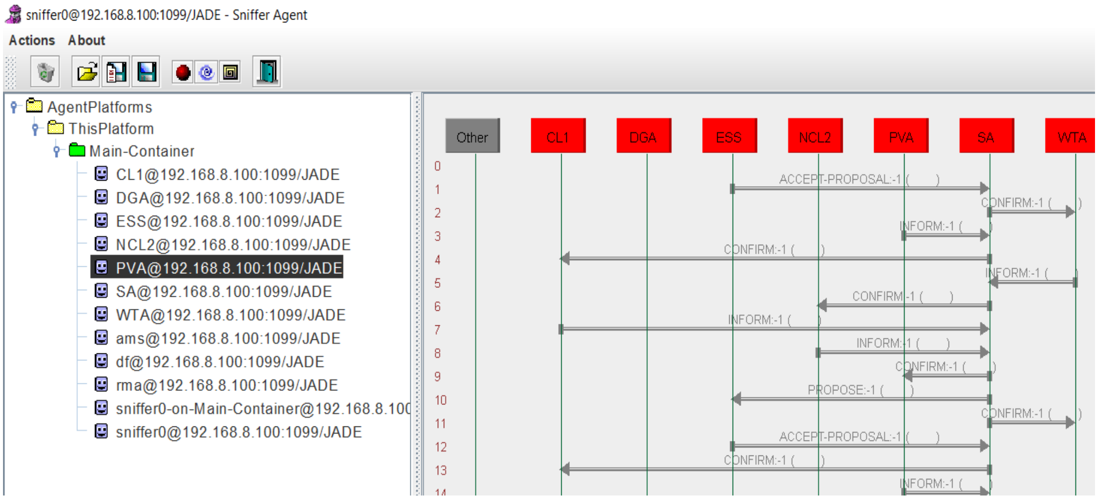


Figure 4.2: Communication of agents developed in JADE

In this research, all the agents in MAS developed for energy management in microgrid must communicate in between agents to achieve agent's local targets and system's overall objectives. SA (server agent) generally communicate with every other agent in the system with different performatives depending on the operational algorithm used. The control algorithm of proposed system will be discussed in the next section. To send information for an agent, sending agent should consider the Agent ID (AID) of the receiving agent. The messages sending are routed to the location of destination agent based on AID. The most commonly used performatives in this MAS are, INFORM: to send information, REQUEST: command to do some action, QUERY: asking a question, PROPOSE: start negotiation etc.

4.3 Operation of Agents in MAS energy management system for a micro grid

Agents in a MAS can operate according to a pre-programed algorithm. In this research a certain operating algorithm is applied for the seven agents in MAS to manage the power stability in the micro grid. Here we are considering a grid tied micro grid. Supply and demand side management in number of different situations are considered. In this simulation, 24 hours in day is sampled to 1440 samples representing 60 seconds/1 minute. The MAS developed in microgrid process a set of data in each 10 second continuously. In the simulated model, the two renewable source related agents, WTA and PVA reads the power generation from the middle layer database described in section 4.4. In a hardware implementation this part is done through sensors. As the next step WTA and PVA inform the power generation to the SA (Server Agent). At the same time CL1 and NCL2 agents sends their demands to SA. SA sends a confirmation message to each agent when it receive information from the relevant agent.SA calculates total renewable power generation and total load requirement. The operation of the MAS system starts depending on those two parameters according to the algorithm displayed in Figure 7.

Using this MAS based EMS model for a microgrid, four different scenarios are examined with different cases.

I. Renewable Power Generation > Total Demand
II. Renewable Power Generation < Total Demand and Grid Available, DG not economical
III. Renewable Power Generation < Total Demand and Grid Not Available , DG available
IV. Renewable Power Generation < Total Demand and Grid Not Available , DG not available

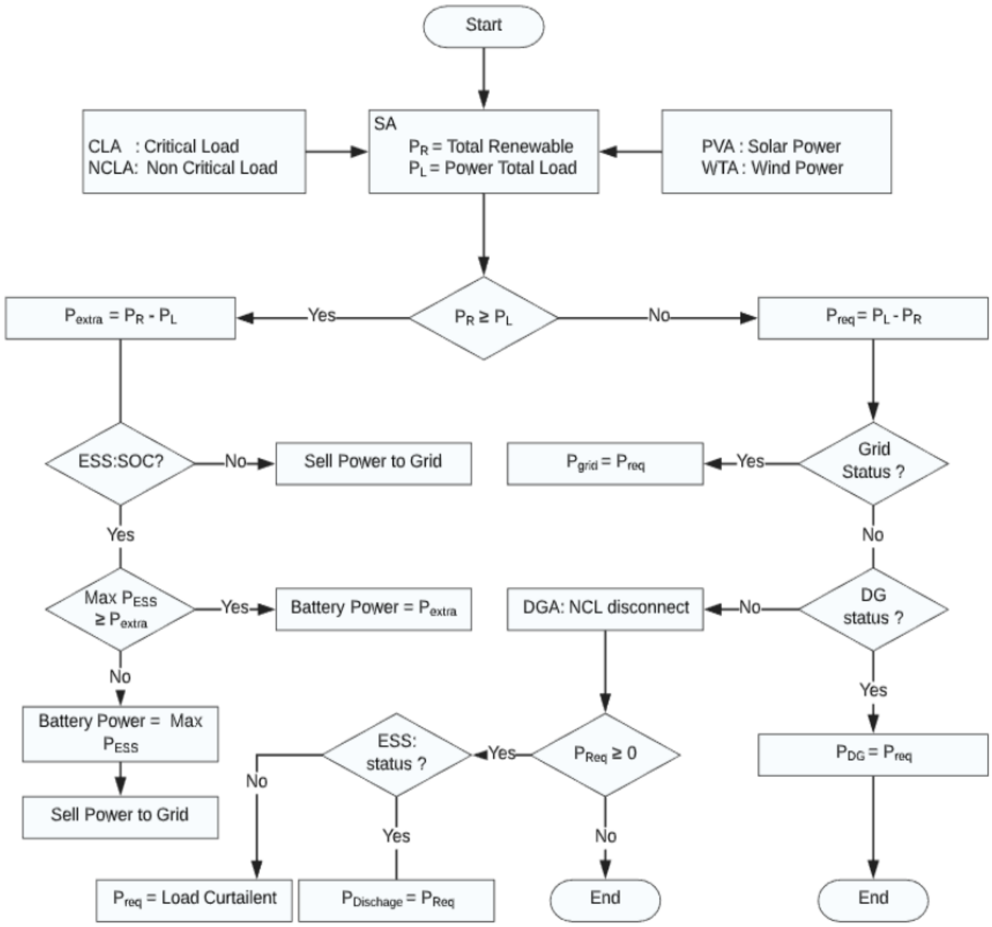


Figure 4.3.1: Operating Algorithm of MAS based EMS

A set of case studies were conducted for the developed multi agent based energy management system in JADE framework. A realistic data set was provided for the system and the performance of multi agent system is studied under different cases with the programed algorithm. A realistic data set of 1440 data points which represents one data set for each 10 seconds, throughout a full 24 hours day. (Appendix A)

The variation of the power generation of DES and power consumption of loads are as follows.

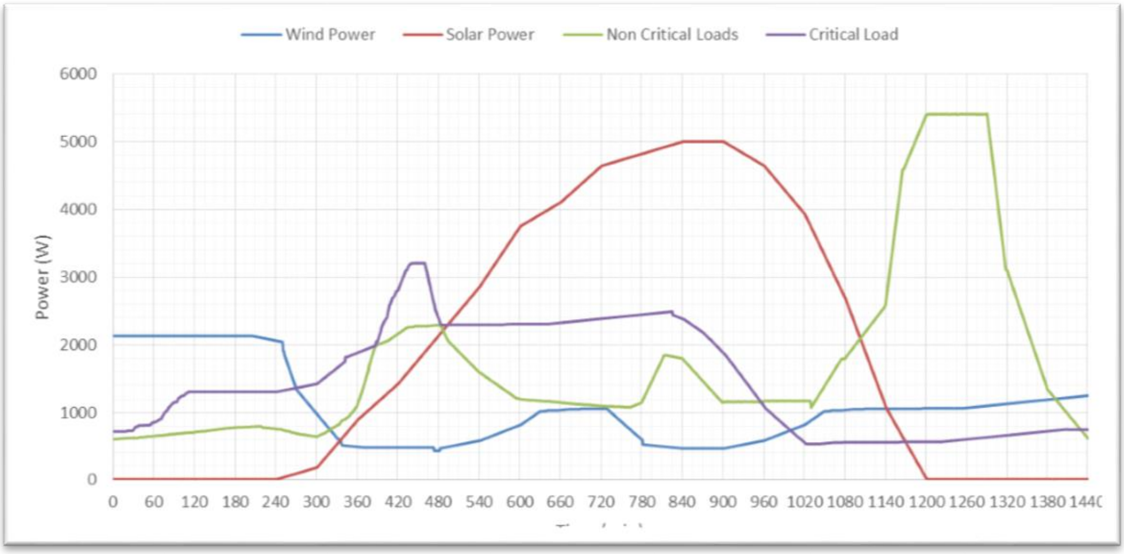


Figure 4.3.2. Power generation of DES and consumption of loads

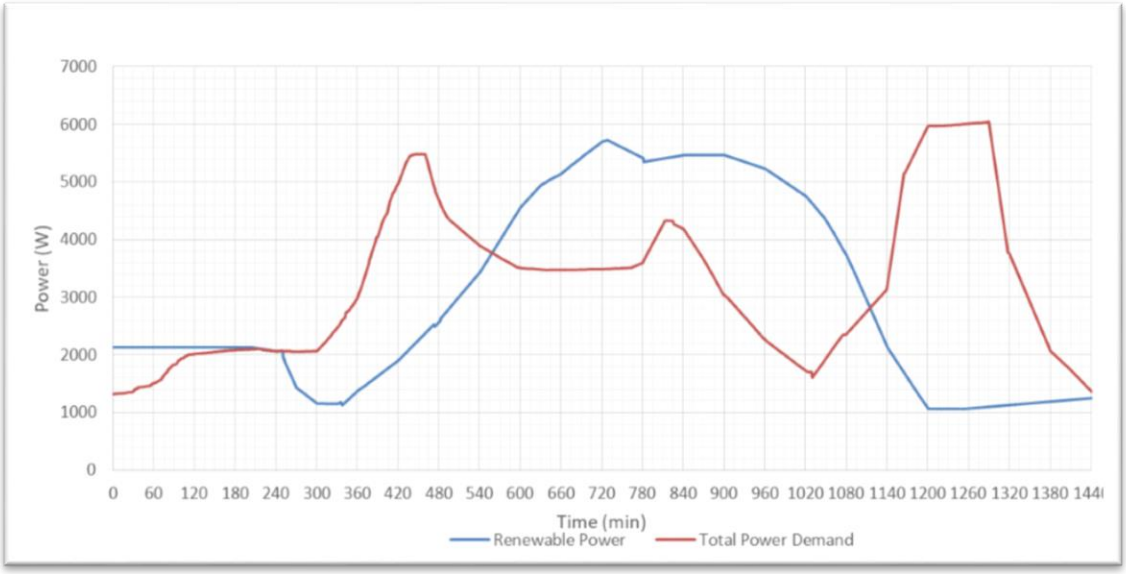


Figure 4.3.3 Total power demand and renewable power generation

To check all the situations using the multi agent system, both available periods and not available periods of diesel generation is considered.

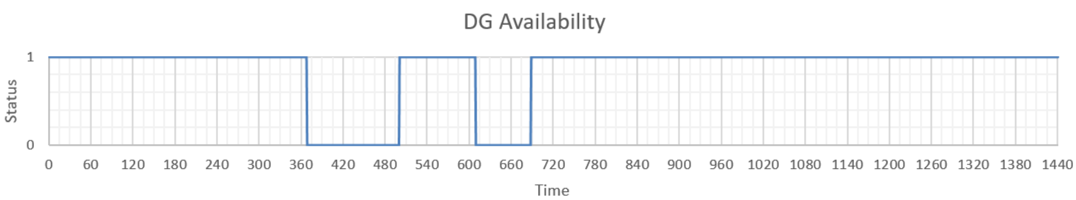


Figure 4.3.6 Availability of Diesel Generator within 24 hours

And Diesel generator is considered more economical during the peak hours as follows,

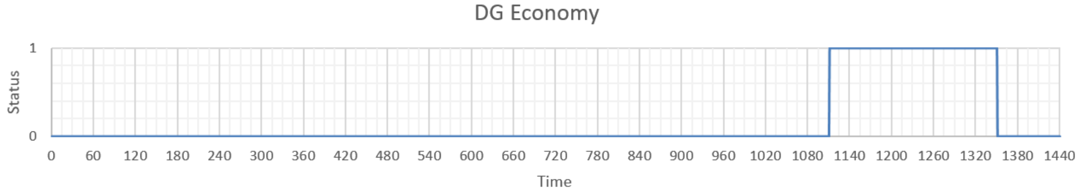


Figure 4.3.7 Economical period of Diesel Generator within 24 hours

To consider both islanded and grid connected mode of micro grid, grid available and not available periods are considered as follows,

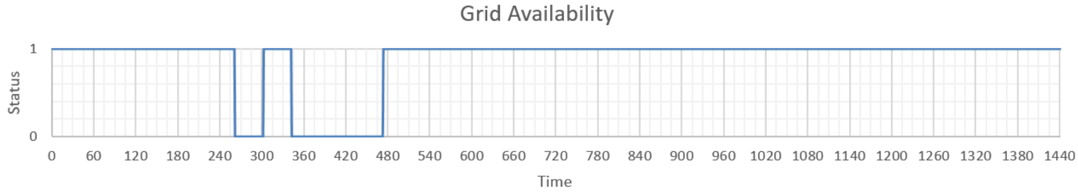


Figure 4.3.8 Availability of utility grid within 24 hours

4.3.1 Case Study 1

When total renewable power generation is larger than total power requirement from loads, system has to take decision for the extra amount of power generated. Here in the proposed system SA and ESS agents communicate with each other, negotiates and take decisions.

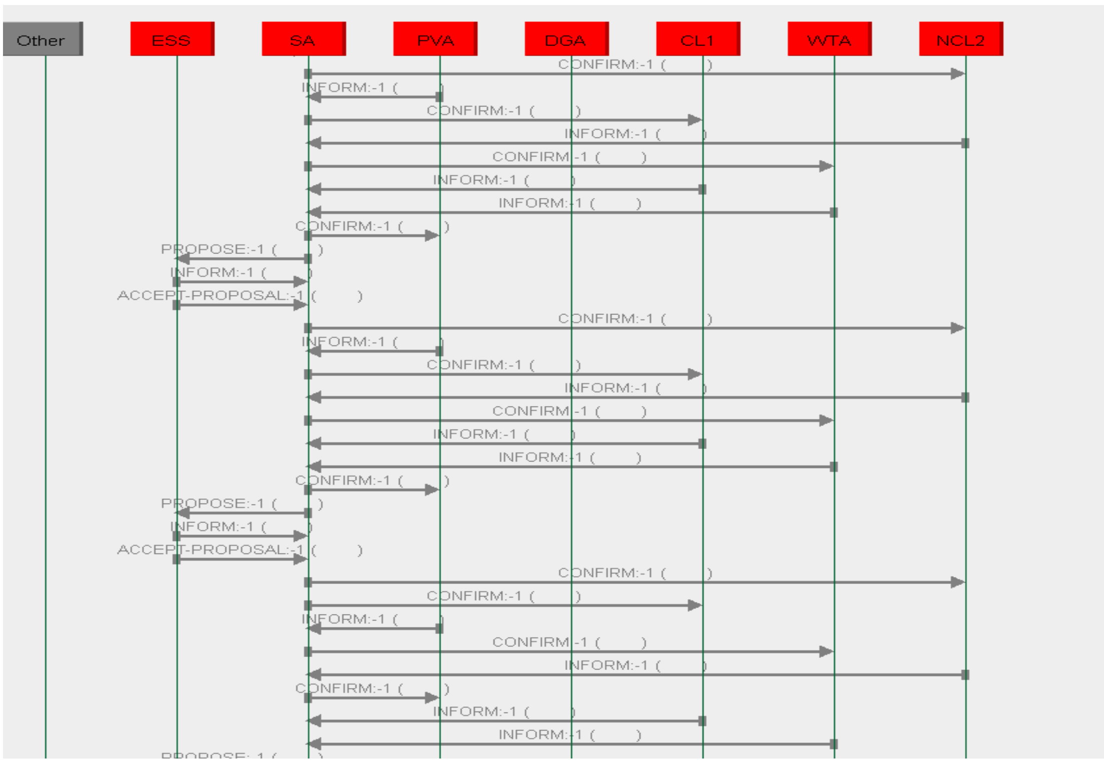


Figure 4.3.6. JADE sniffer agent output for case 1

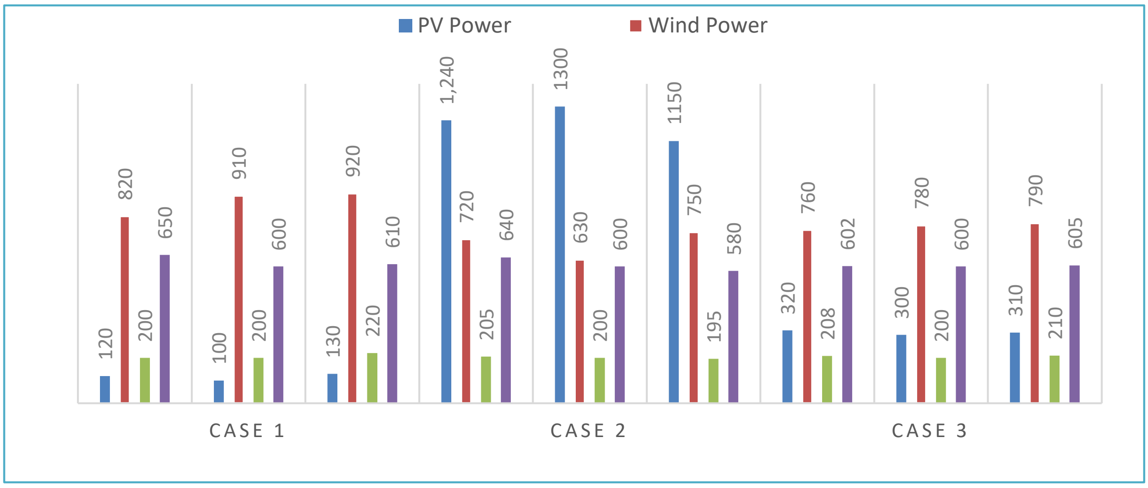


Figure 4.3.7. Power generation and consumption (W)

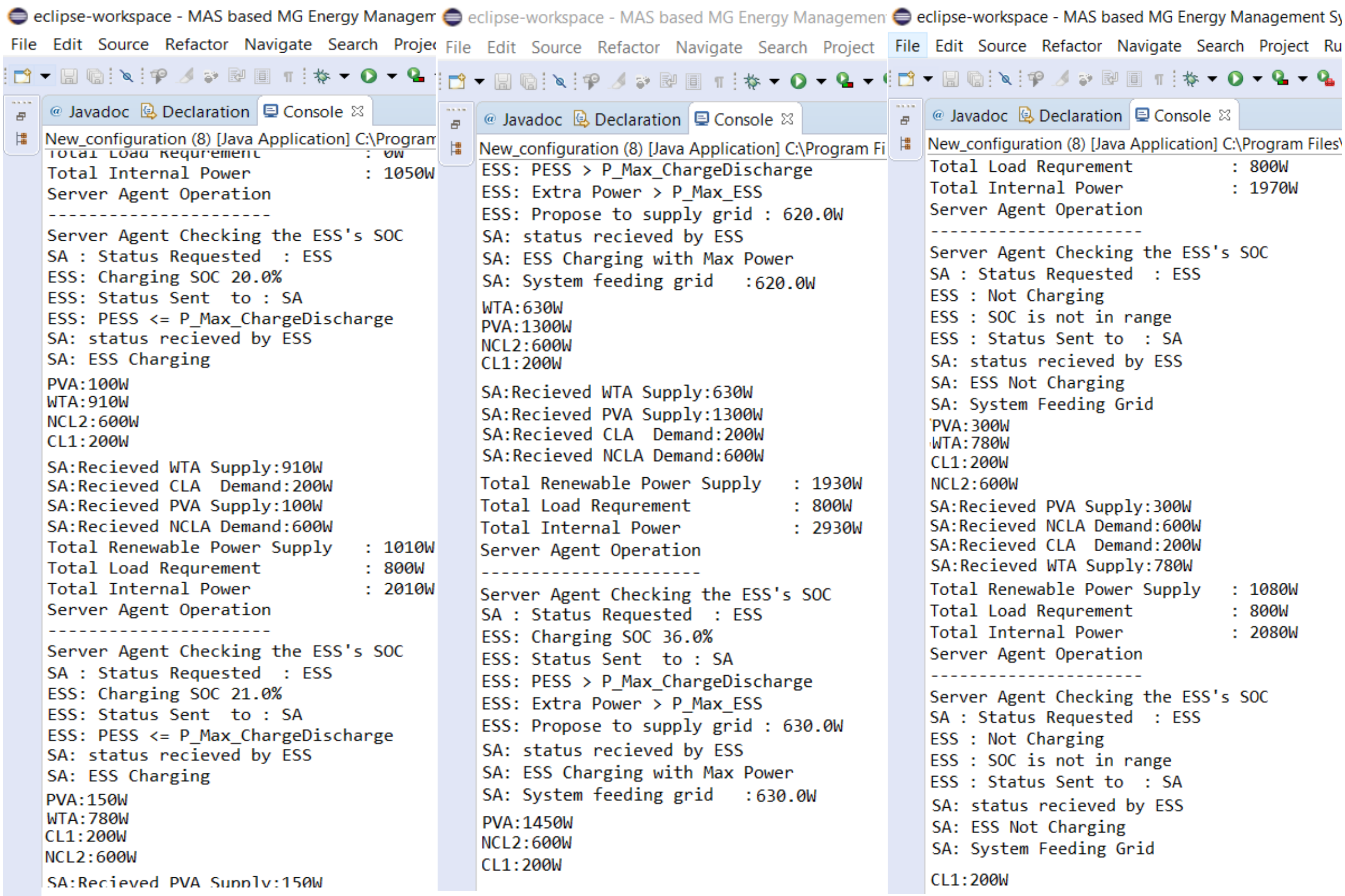


Figure 4.3.8 JADE console output for three cases

4.3.2 Case study 2

When renewable power generation is lesser than the total power demand, the MAS has to take decision to maintain the power balance. The options are taking power from grid, Diesel generator, non-critical load shedding and ESS. When taking decision comparing the grid and diesel generator, the financial factors must be considered. Here in this simulation, the system is considered as a customer category Industrial-2 (I2) in Ceylon Electricity Board (CEB) customer tariff. The rates for the power consumption is as follows [68].

Table 5: CEB Tariff Applicable for I2 Customers

Time Intervals	Energy Charge (LKR/kWh)	Fixed Charge (LKR/Month)	Maximum Demand Charge per month (LKR/kVA)
Peak (18.30-22.30)	20.50	3,000.00	1,100.00
Day (5.30-18.30)	11.00		
Off-peak (22.30-05.30)	6.85		

In this simulation, based on the tariff the diesel generator is assumed more economical in Peak hours than consuming for the grid. The MAS operation when total renewable power generation is less than the demand is as follows.

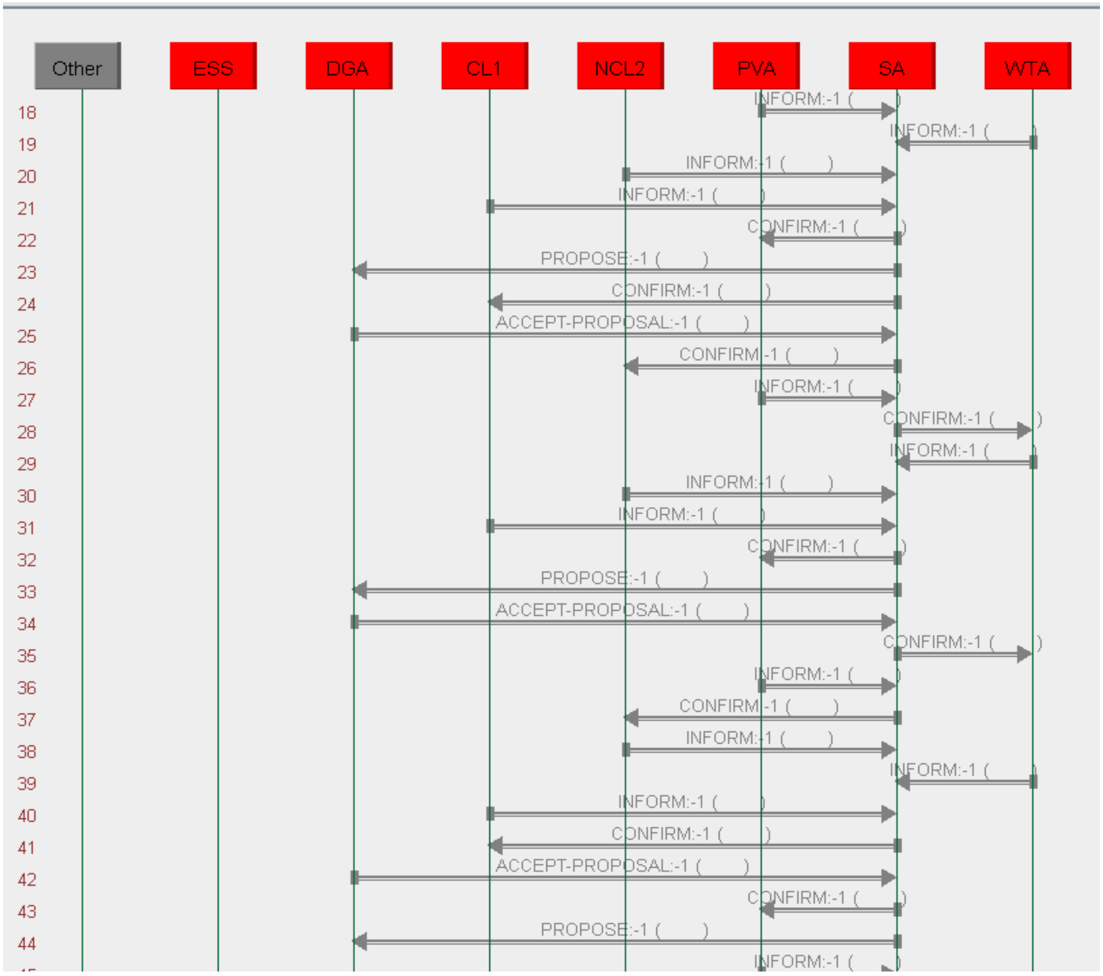


Figure 4.3.9. JADE sniffer agent output for case 2

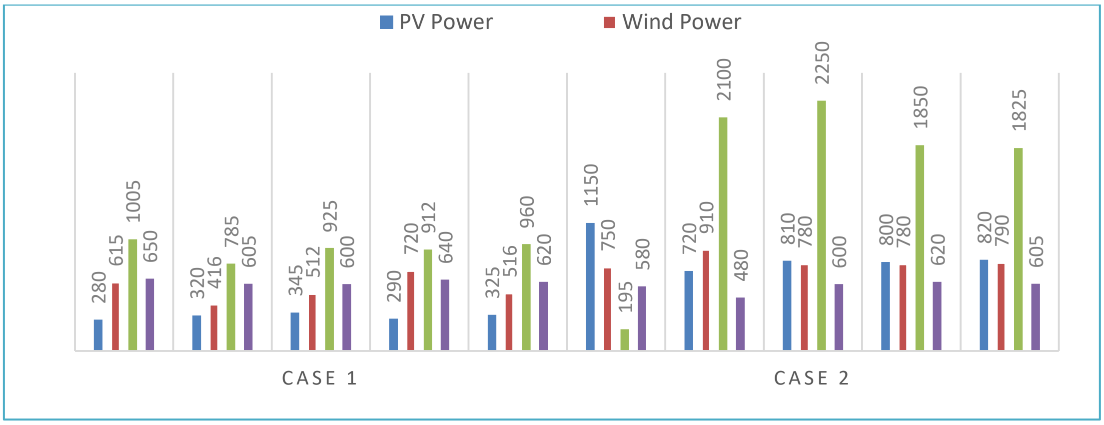


Figure 4.3.10. Power generation and consumption (W)

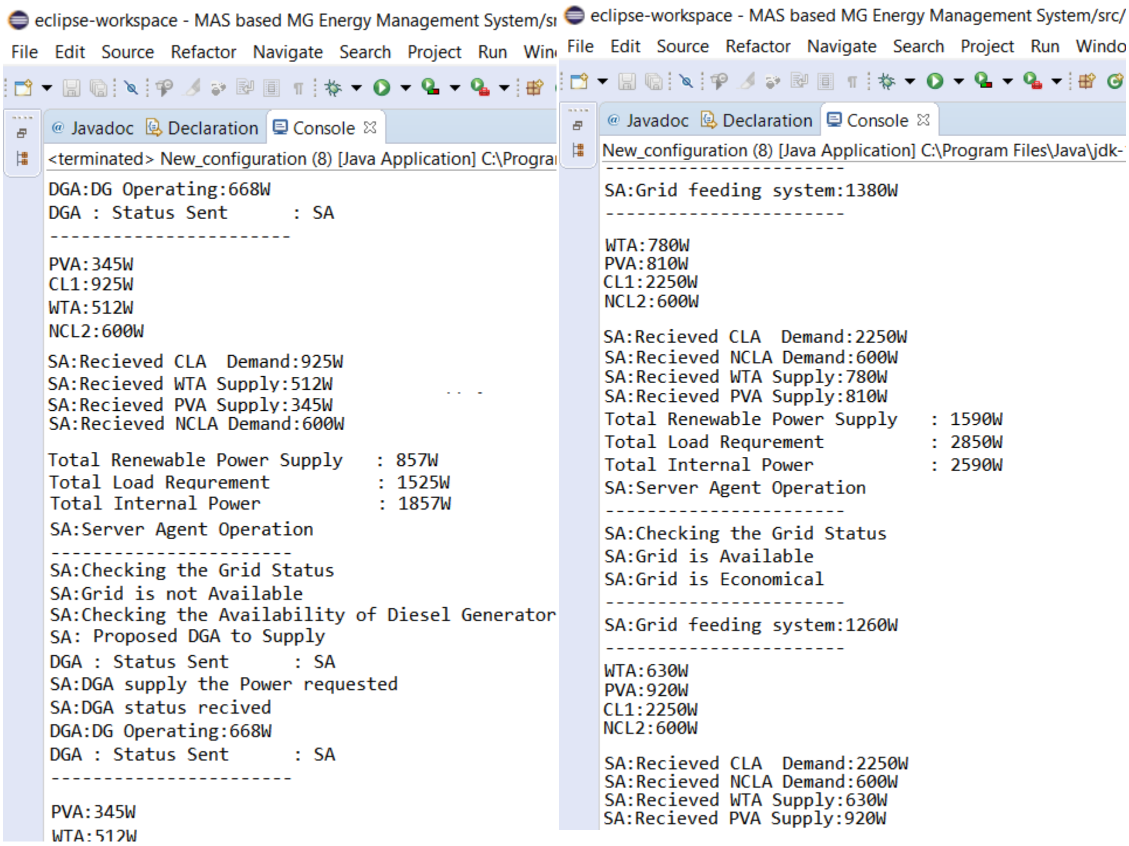


Figure 4.3.11. Results from JADE based EMS for Micro grid

4.3.3 Case study 3

When total renewable power generation of the system is less than the total load requirement and both grid and diesel generator is not available system is moving for non-critical load shedding. In this operation the decentralized actions of the MAS based EMS is clearly showed as the DGA is taking control over NCL2, instead of SA

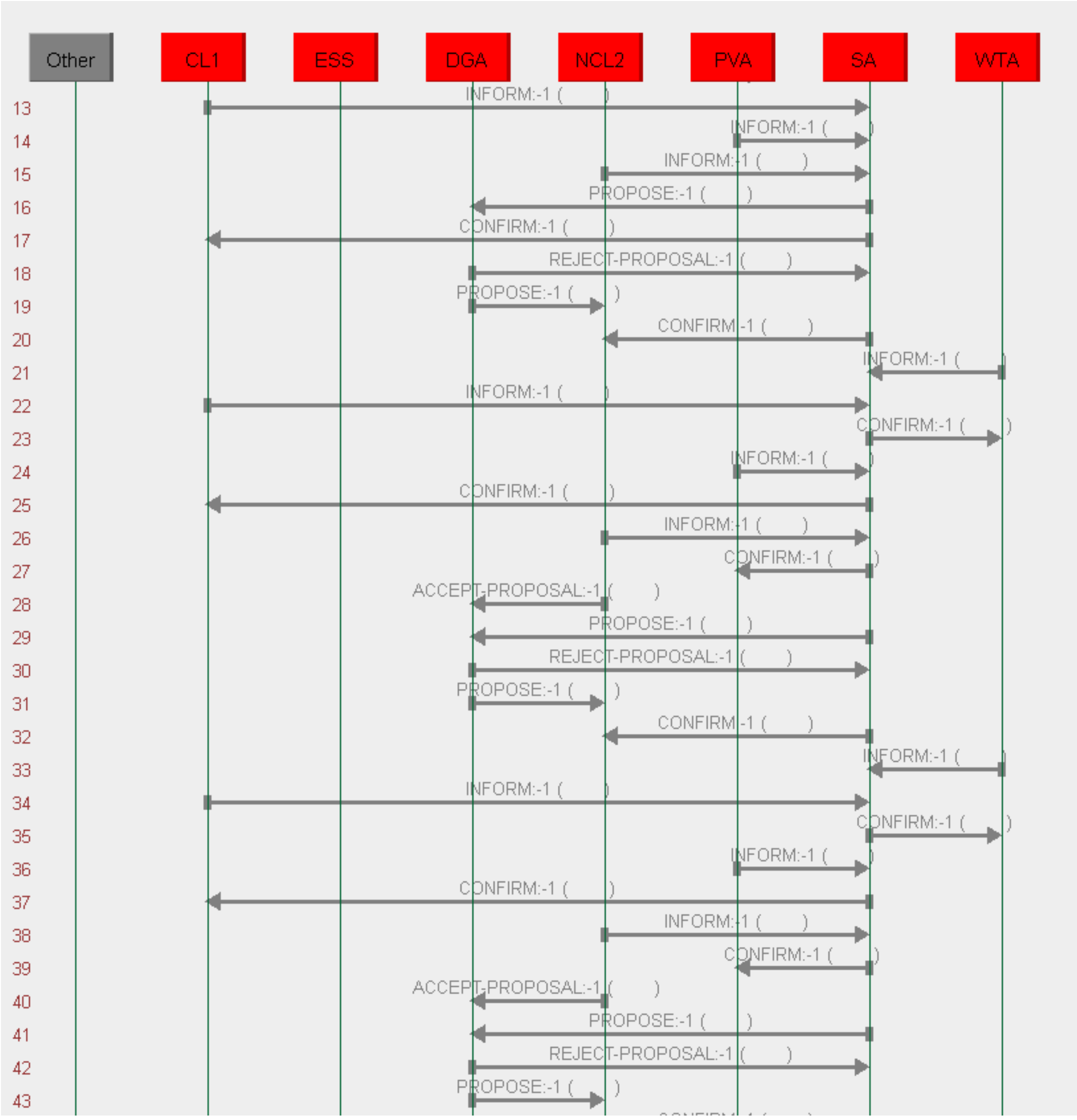


Figure 4.3.12. JADE sniffer agent output for case 3

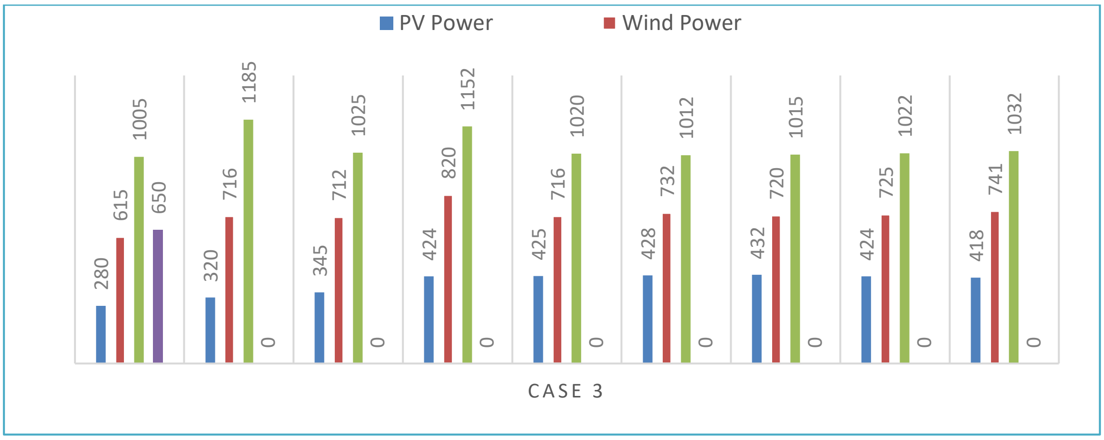


Figure 4.3.13. Power generation and consumption (W)

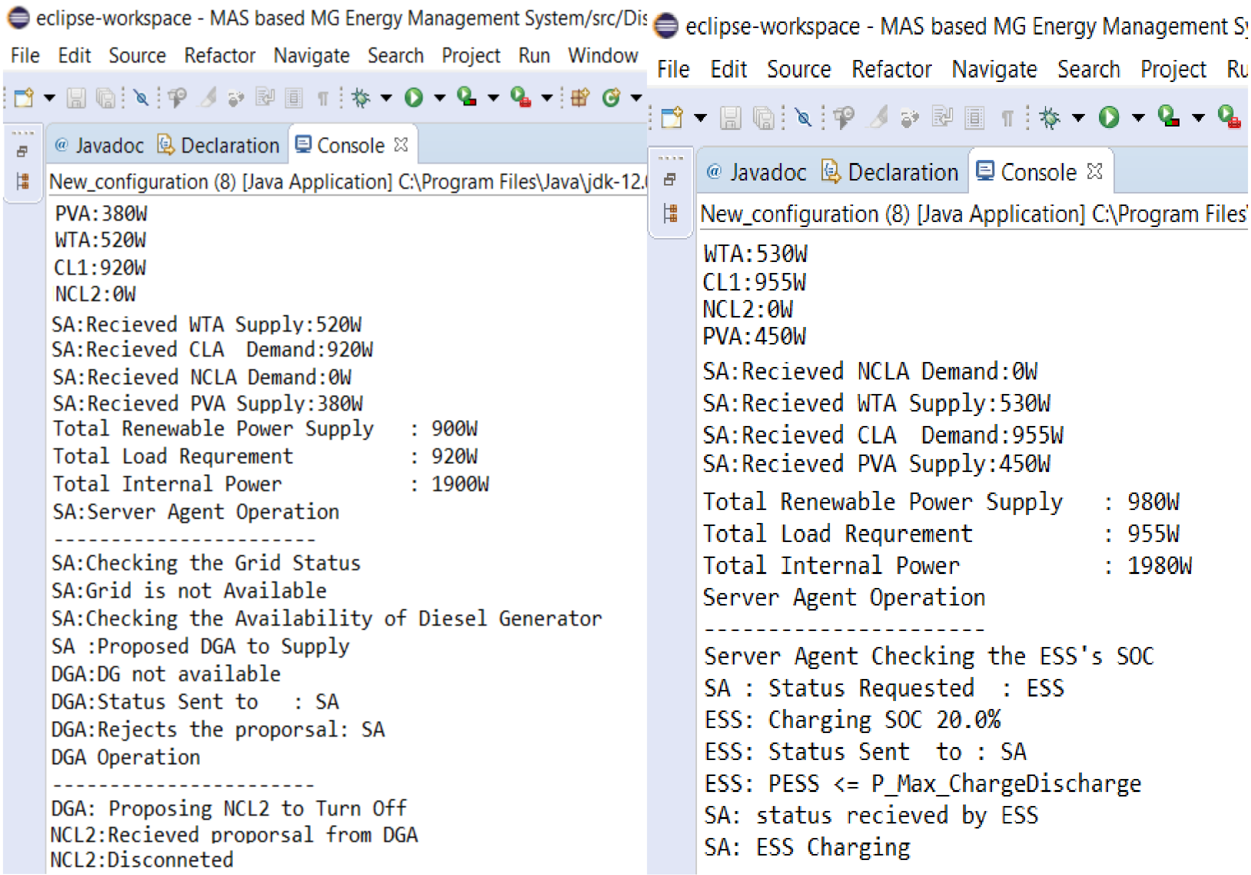


Figure 4.3.14 Results from JADE based EMS for Micro grid

4.4 Results generated by MAS developed in JADE framework

Multi Agent System developed in the JADE framework generated the switching signals for the operation of micro grid as follows. The following results were generated after the simulation for every data set continuously for 24 hours.

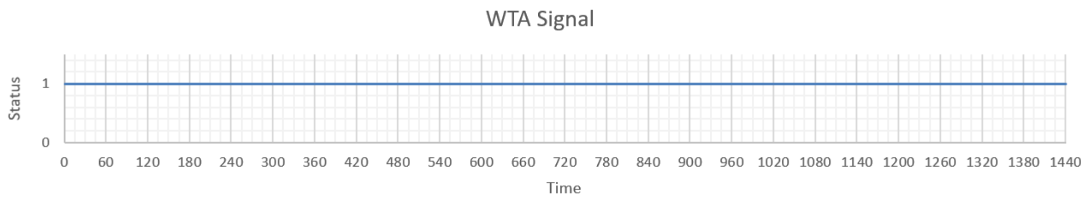


Figure 4.4.1: Switching Signal Generated by Wind Turbine Agent

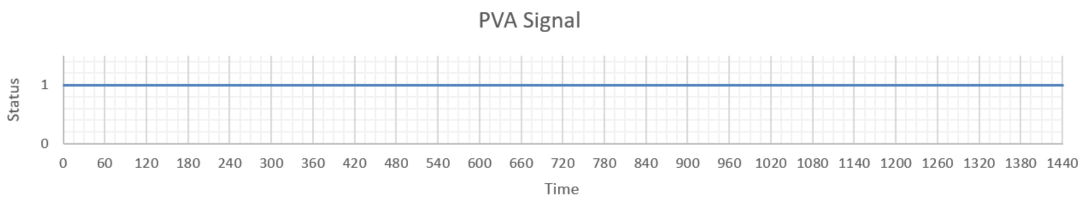


Figure 4.4.2: Switching Signal Generated by Solar PV Agent

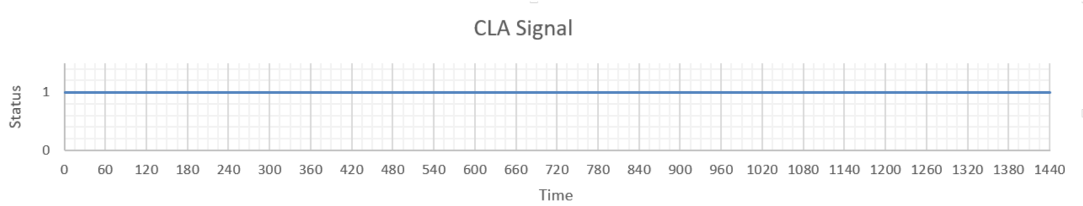


Figure 4.4.3: Switching Signal Generated by Critical Load Agent

According to the proposed operation algorithm for the multi agent based EMS in figure Figure 4.4.1, it always use solar power system and wind turbine without tripping except in an emergency situation. At the same time the algorithm supply the power demand by the critical load. So as a result of the operating algorithm output for the switching signals of PV , WT and CLA were resulted as above.

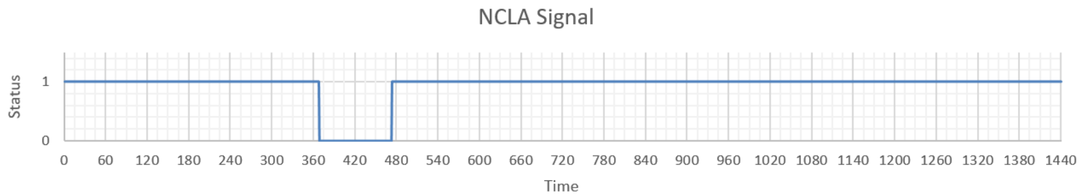


Figure 4.4.4: Switching Signal Generated by Non Critical Load Agent

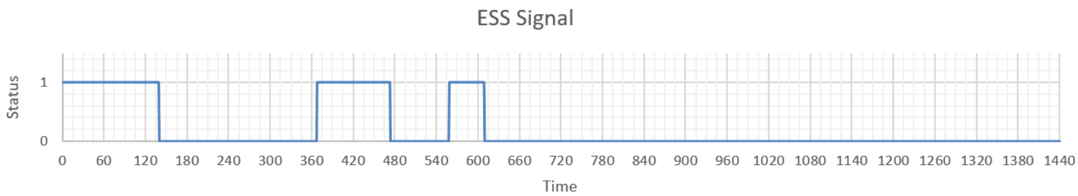


Figure 4.4.5: Switching Signal Generated by ESS Agent

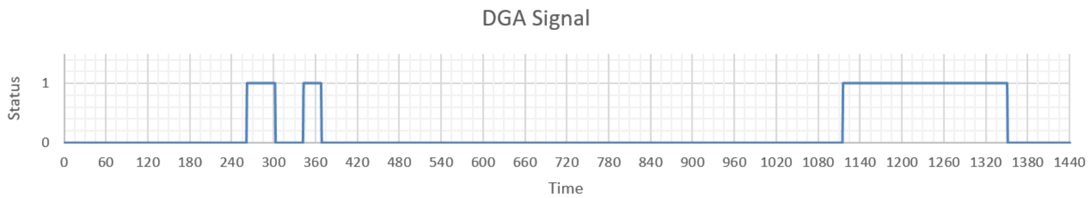


Figure 4.4.6: Switching Signal Generated by DGA Agent

And the micro grid import and export energy from the utility grid depending on the situation and status of sources according to the proposed algorithm.

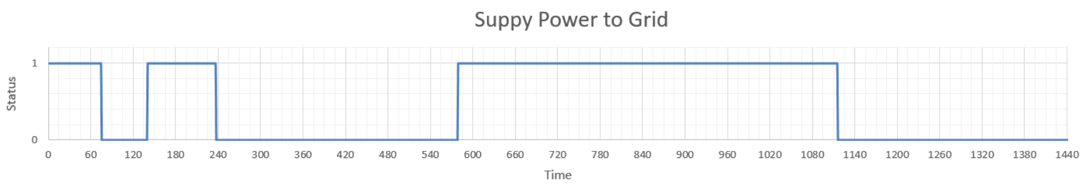


Figure 4.4.7 : Switching signal generated by server agent for power export

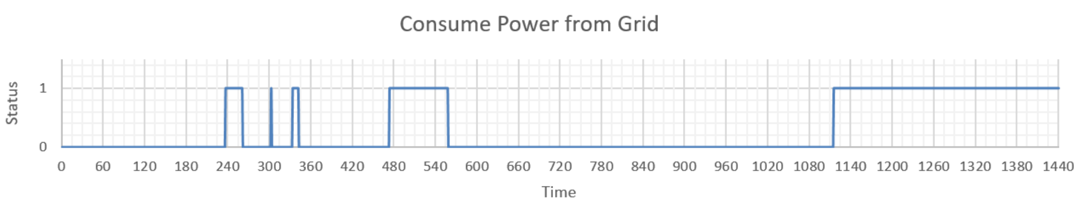


Figure 4.4.8 : Switching signal generated by server agent for power import

From the above results, we can observe that MAS based control architecture has sucessfully controled the DES's and Loads balancing the supply and demand. From these results we can identify two basic features. First one is , MAS improves the communication efficency of the control system because of the decentralized architecture

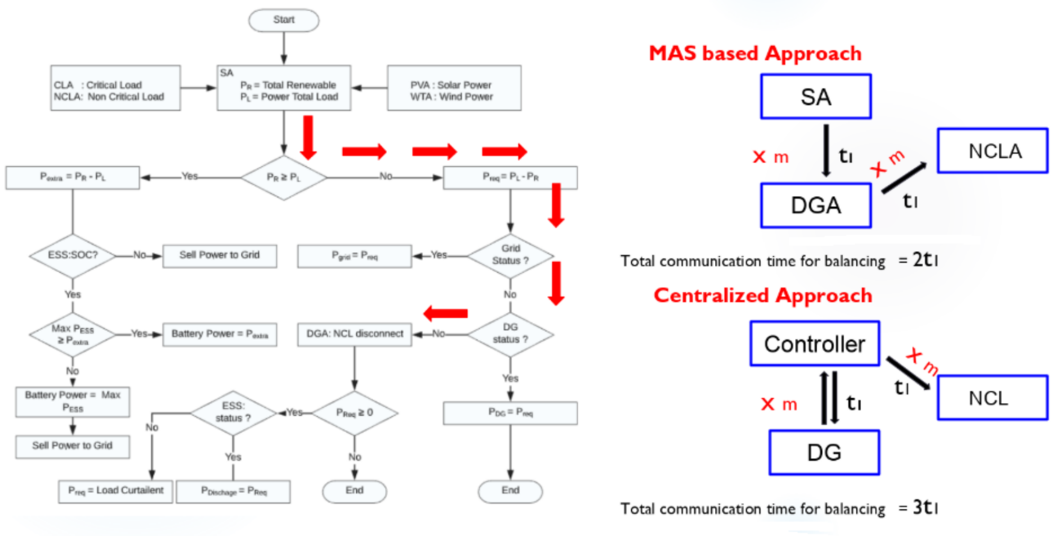


Figure 4.4.9: Operation of Decentralized communication architecture of MAS

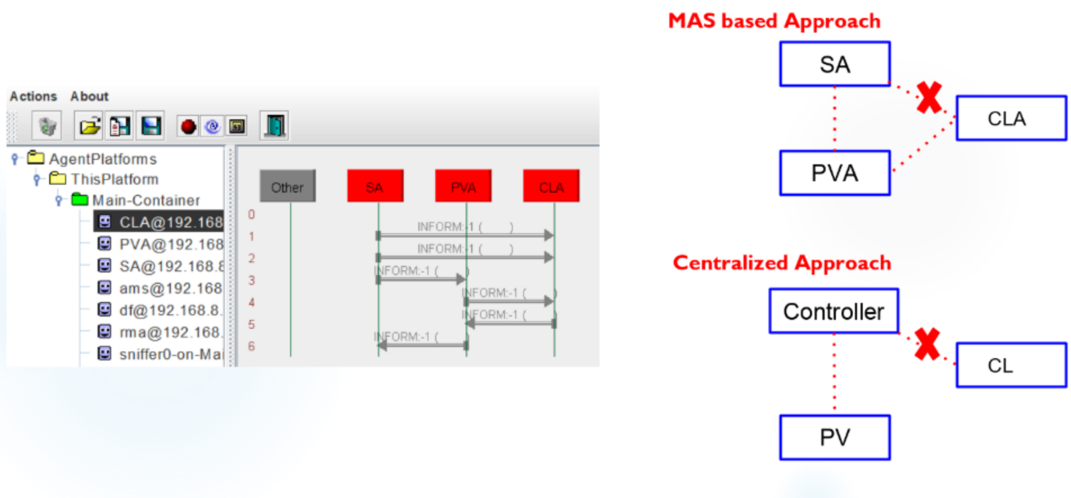


Figure 4.4.10: Relay type communication process of MAS in a fault situation

When there is a fault in a communication channel in-between two agents, communication can be reestablished through other agents and continue operation. It's and very significant feature of a MAS based control architecture.

5.0 Hardware Implementation of Multi Agent System.

5.0 **Introduction**

In previous chapters we discussed about an agent in various aspects. When planning for a hardware implementation of an agent we can consider it as a software entity in a certain environment which receives inputs through sensors. At the same time agents can send outputs and execute it through actuators to achieve objectives. Sensor inputs are the measurements of different parameters which are need to be considered to perform controlling actions. When designing agents, they should be designed to take every relevant measurement depending on the local objective of the specific agent. Next step is to process the objective function through the multiple operation of the agents with the help of wireless communication network. Here we are implementing a multi agent system based test bed with microcontrollers, TCP/IP wireless communication network, sensors and actuators. In this section the development of hardware implementation is discussed with methodology.

5.1. **Hardware Implementation**

After implementing an agent, there are certain requirements. Firstly it should be able to process an algorithm or a program. Second, it should be able to take input parameters from sensors (both analogue and digital depending on the application). Third, it should be able to send output signals to actuators. Fourth, it should be able to communicate and transfer data with other control agents. When considering all the above requirements, the best option is to use a suitable microcontroller.

5.1.0 **Selecting a Micro-controller**

Selection of the micro controller depends on the design requirements of the application. Here a MAS is developed for a microgrid applications. Number of factors have to be considered when selecting a micro controller for an agent such as communication range, security , power consumption , frequency , data rate, price etc. Following table compares the above parameters of different micro controllers.

Table 6: Comparison of micro controllers

Parameter	Bluetooth	RF	Node MCU	ZigBee
Node	8	65	32	65000
Frequency	2.4GHz	3kHz-300GHz	2.4&5 GHz	2.4GHz
Range	10m	35m	100m	10m-100m
Security	Very Low	Low	Average	Low
Power Consumption	Low	Very Low	High	Very Low
Unit Price	900 LKR	700 LKR	850 LKR	6950 LKR
Typical Applications	Keyboard,mouse GPS,headset, webcam,printer	Mobile phone services , Radio & TV transmission	Security cameras, WLAN	Remote monitoring, BMS, smart grids

In the proposed MAS for the micro grid application, the Communication network plays the major role in a multi agent system. Wi-Fi , Bluetooth, ZigBee and RF are the communication technologies compare above. A micro grid can be defined as a set of distributed loads and generation units. When developing the communication network for such system, the communication range of the module is very significant. Two best options are ZigBee and Node MCU. ZigBee module, supports large amount of nodes but it is comparatively expensive with other technologies. Bluetooth technology can be reject directly as it support only small communication range and security is very low. RF modules and Bluetooth module need a separate micro controller for operation. Both Node MCU and ZigBee modules come as a combination of a micro controller, transmitter and a receiver [69]. Considering below facts Node MCU module (ESP 8266) has been selected as the micro controller to develop agents in the proposed multi agent system.

- ✓ Node MCU supports 100m distance communication range
- ✓ Node MCU has a data rate between 11-54 Mb/s
- ✓ Security level is high
- ✓ Reasonable unit cost
- ✓ Node MCU is a combination of micro controller , Wi-Fi transmitter and a receiver.

5.1.1 ESP-12E 8266 Node MCU module

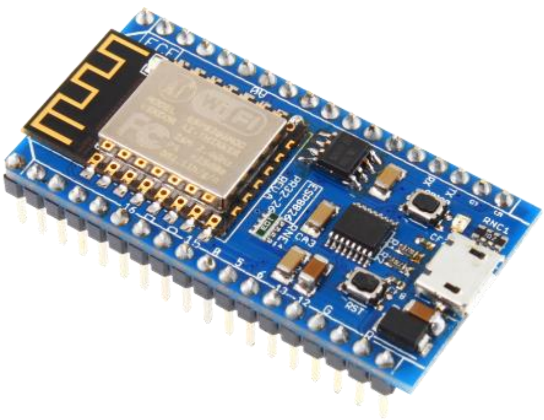


Figure 5.1.0 ESP-12E 8266 Module

The Node MCU or ESP8266 modules is capable of using Arduino IDE and it can be programed using Arduino Wire Language for various IoT applications. ESP8266 can be programed with a micro USB input and first press RST button and GPIO0 at the same time, then leave the RST button and after that release the GPIO0 button secondly. Those are the steps to activate the programming mode of Node MCU module.

Node MCU can monitor and control FET, sensors, solenoids ,control relays, motors PWM controllers, valves etc. Node MCU can be controlled from anywhere in the planet through a dedicated server. The micro controller development board has an ESP-12E module with an ESP8266 chip (Tensilica Xtensa| 32-bit |LX106 RISC microprocessor). It   supports RTOS and operates at 80 MHz -160MHz adjustable clock speed.

Specifications of the ESP-8266 Micro controller

- ✓ Low power consumption 32bit MCU
- ✓ Built in 10bit ADC
- ✓ Built in TCP/IP protocol stack
- ✓ Op.Temp range : -40 ° C to +125 ° C
- ✓ Operating Frequency range : 2.3GHz - 2.6GHZ
- ✓ Operating voltage range : 3.0V to 3.6V
- ✓ Operating current range : 80mA (Average)
- ✓ Network protocols used : IPv4, UDP /TCP/ FTP/ HTTP
- ✓ Integrated power management ,regulators and PLL units
- ✓ Support WPA/WPA2 Security (Wi-Fi 2.4 GHz)
- ✓ Standby power consumption of < 1.0mW

Pin output diagram of the Node MCU (ESP-8266) Module

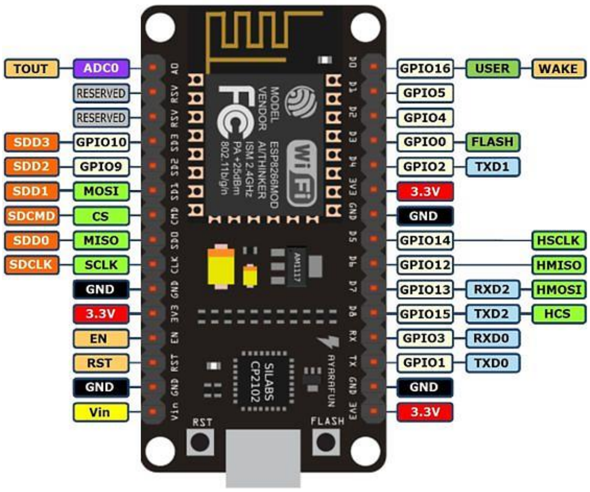


Figure 5.1.1 Pin diagram of ESP-8266 Module

Generally an ESP-8266 module has a single analog input and several digital input and output pins (I/0 and GPIO). There are 17 GPIO pins and 11 of them can be used for digital inputs and outputs as 6 GPIO pins (GPIO 6 – GPIO 11) are connected to the flash memory.

Table 7:Overview of I/O pins of ESP8266 module

GPIO	State	Function	Restrictions
0	3.3V	select Boot mode	No Hi-Z
1	-	TX0	No use for Serial transmission
2	3.3V (boot only)	Boot mode select TX1	Never connect to ground during boot time.
3	-	RX0	No use for Serial transmission
4	-	SDA (I^2C)	-
5	-	SCL (I^2C)	-
6 - 11	x	Flash connection	No use
12	-	MISO (SPI)	-
13	-	MOSI (SPI)	-
14	-	SCK (SPI)	-
15	0V	SS (SPI)	No use with Pull-up resistor
16	-	Start up from sleep	No pull-up resistor, but pull-down

5.1.2 Hardware Implementation of an Agent.

In the proposed test bed for the multi agent system, there are two agents for energy sources and three agents for loads. Two source agents are to control two solar power systems and the objective of both source agents are same. When designing the source agent following points were considered.

- ✓ Power supply for the agent
- ✓ Voltage and current measurements
- ✓ Plug and play compatibility
- ✓ Display unit to display operating status

Circuit arrangement of a source agent can be shown as follows.

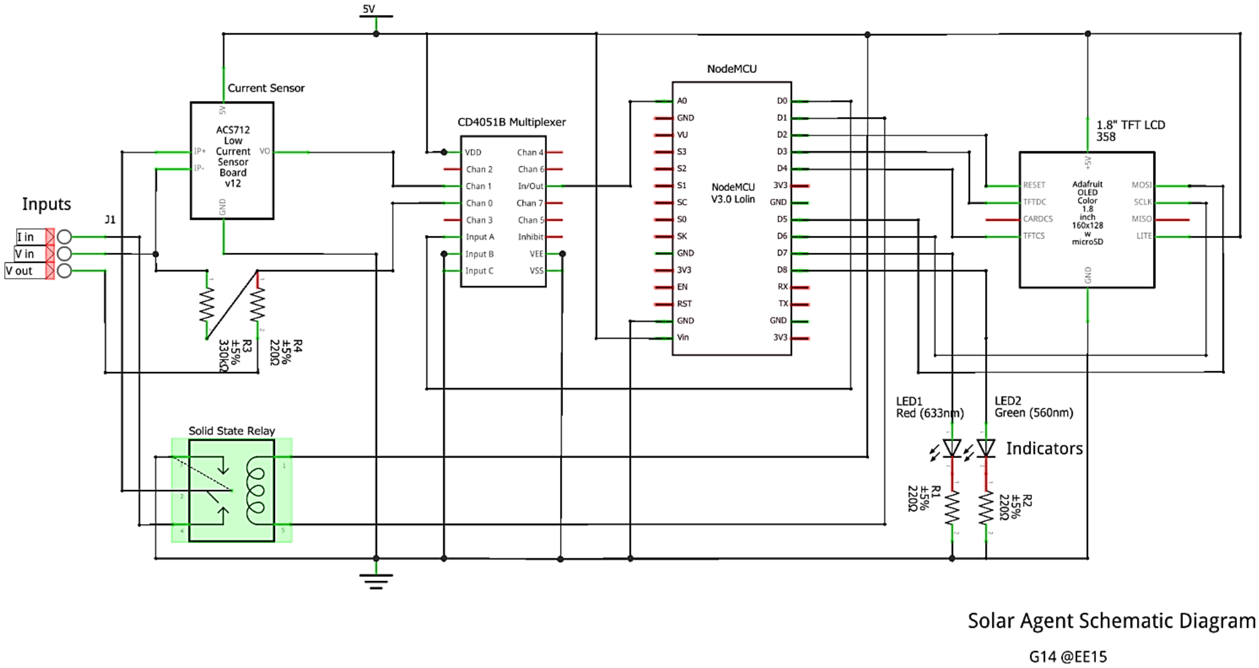


Figure 5.1.2 Circuit arrangement of a source agent

An agent is developed using an ESP8266 module, CD4051B Multiplexer, power supply circuit, solid state relay module, TFT LED display module and LED indicator lights.

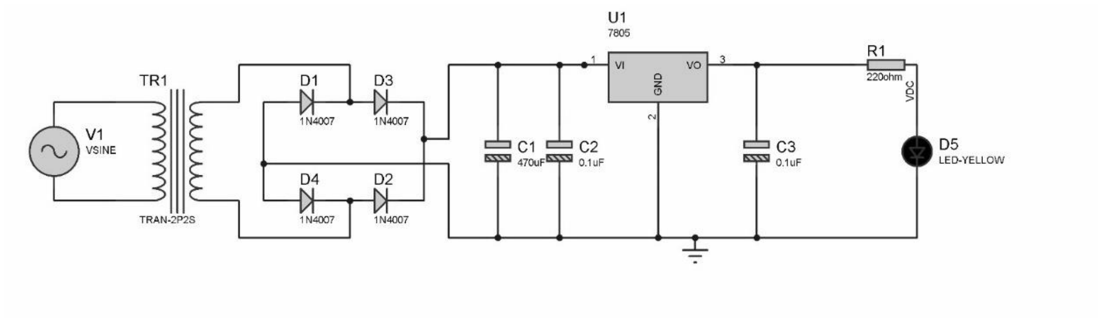
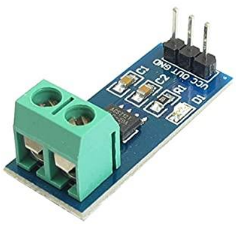


Figure 5.1.3 Circuit arrangement of power supply circuit

Node MCU module operates in low voltage. 230V AC is converted to 5V DC using a power supply circuit supply. Power supply circuit is a combination of a transformer unit to step down the voltage and a diode bridge to convert AC to DC and capacitors to make the DC supply smooth. Each and every agent in the implemented multi agent system is powered with a similar power supply unit. As mentioned previously an agent located in a certain environment understands the conditions of the environment through the measurements taken by the sensors. Here in this multi agent system which is developed for energy management purpose we use current sensors and voltage sensors to take measurements.



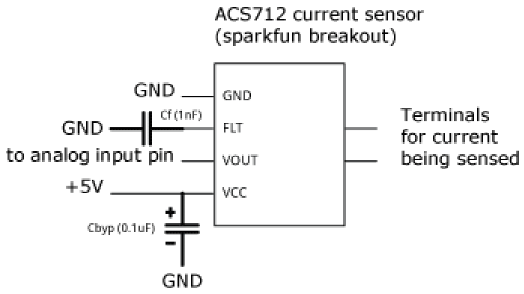
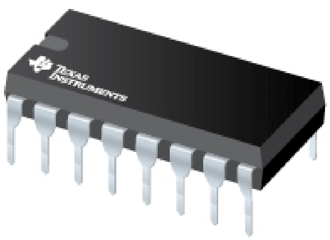


Figure 5.1.4 ACS 712 current sensor

ACS712 is a reliable current sensor which is compatible with any arduino based micro controllers. From ACS712 sensor series, Allegro ACS712ELC chip is commonly used. This current sensor come up with different current ratings as 30A, 20A and 5A in which the sensor operation is identical. For this project we used current sensor with 20A rating which has the following specifications.

Table 8: Specifications of ACS712 Current sensor

Chip	ACS712ELC-10A
Measurement Range	-20 to +20 Amps
Supply Voltage (VCC)	5Vdc Nominal
Scale Factor	100 mV per Amp
Voltage at 0A	VCC/2 (nominally 2.5Vdc)



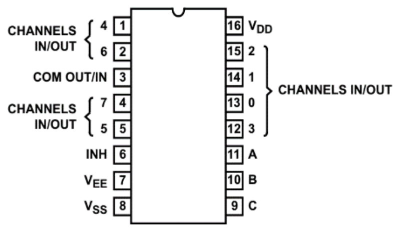


Figure 5.1.5 CD4051B Multiplexer

The CD4051B multiplexer is an 8-Channel multiplexer which has an inhibit input and three binary control inputs. The three binary input signals select one of eight channels to be status on, connect one of the inputs to the output. The DC input voltage range is -.5V to +.5V and current range is $\pm$ 10mA.

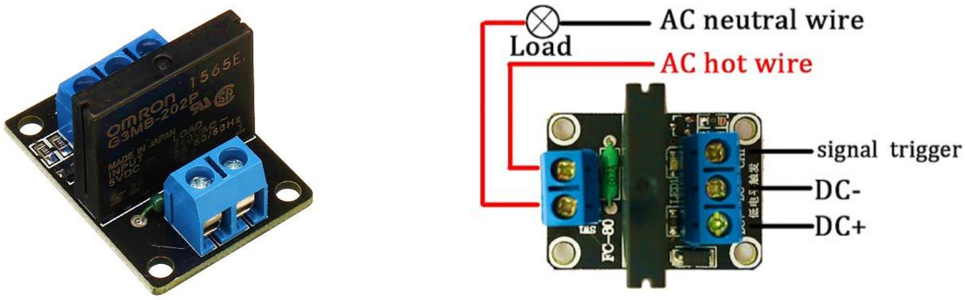


Figure 5.1.6 Single channel 5V Solid State Relay Module

In developing the agent, the switching operation is accomplished with the help of a 5V SSR relay. SSR relays are electronic and have faster response time compared to EMRs. The life span of SSRs is longer than EMRs under high speed switching and multiple operations. A SSR can control even high voltage AC power flow with a low voltage DC signal. It can be achieved by organizing SSR as an IR LED which is using Infrared light for the contact. It has number of advantages compared to EMRs such as their possibility of lower voltage and lower current switching, higher life span, faster switching etc.

Figure 5.1.7 TFT LCD module

A TFT LCD is a very commonly used display that uses TFT technology. Each and every source agent has a display unit to display the status and measurements. It has the following specifications.

- ✓ Input Voltage : 5V/3.3V
- ✓ Size : 1.8 inch
- ✓ Size : 54mm (length)*34mm (width)
- ✓ Dot Matrix : 128*160

In the hardware development for the MAS there are two agents dedicated to control loads. Those are referred as load agents in previous chapters. One load agent is dedicated for controlling critical loads in the system and other load agent is dedicated for controlling the non-critical loads of the system. Each load agent take voltage and current measurements through sensors and agents are designed in a plug and play format which can be easily installed and configured to the system. Each agent, both load agents and source agents come up with a display unit which displays the relevant data at the operating point and at the same time they are transmitted to the server agent

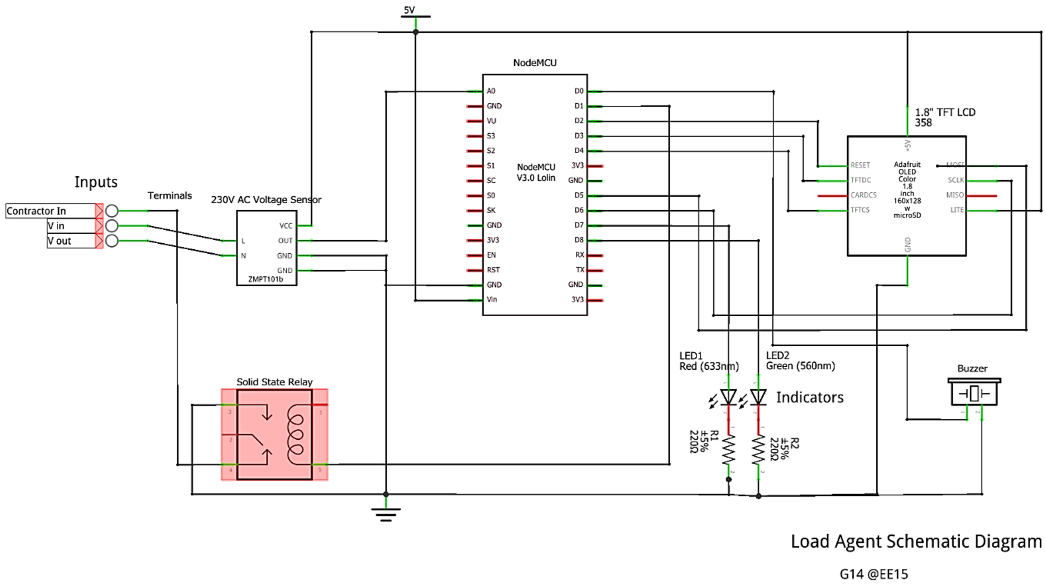


Figure 5.1.8 Voltage sensor connection to an agent

To take the voltage necessary measurements for the agents, we used ZMPT101B voltage sensor which can be used for general AC voltage measurements with ESP 8266 module. The accuracy of this sensor can be considered positive and it's with a good consistency and with a measurement range up to 250V. ZMPT101B configuration is not complex and it comes with a trim potentiometer (multi turn) to configure the ADC output signal.

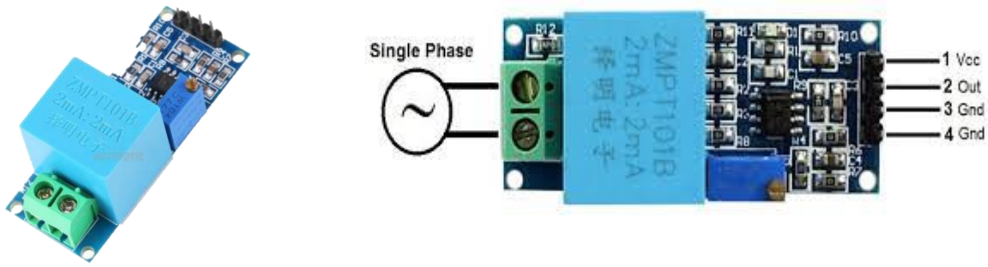


Figure 5.1.9 ZMPT101B Voltage

The ZMPT101B sensor used has following specifications

- ✓ Rated input current 2mA
- ✓ Measuring range 250V AC
- ✓ Dimensions 19.4 mm * 49.5 mm
- ✓ Op. temperature range - 40'C to + 70' C
- ✓ Output Signal Analog 0-5V

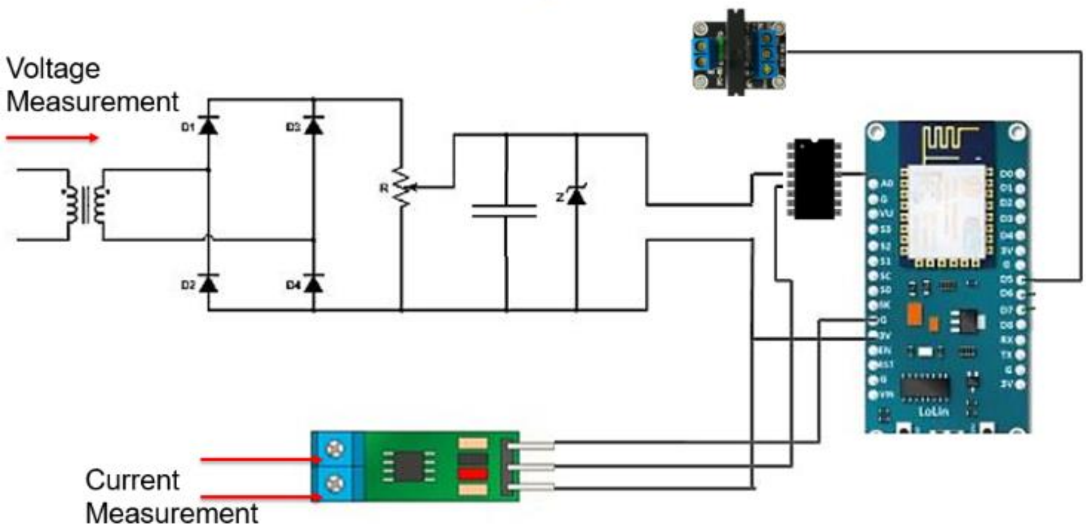


Figure 5.1.10 Circuit arrangement of Hardware implementation of an agent

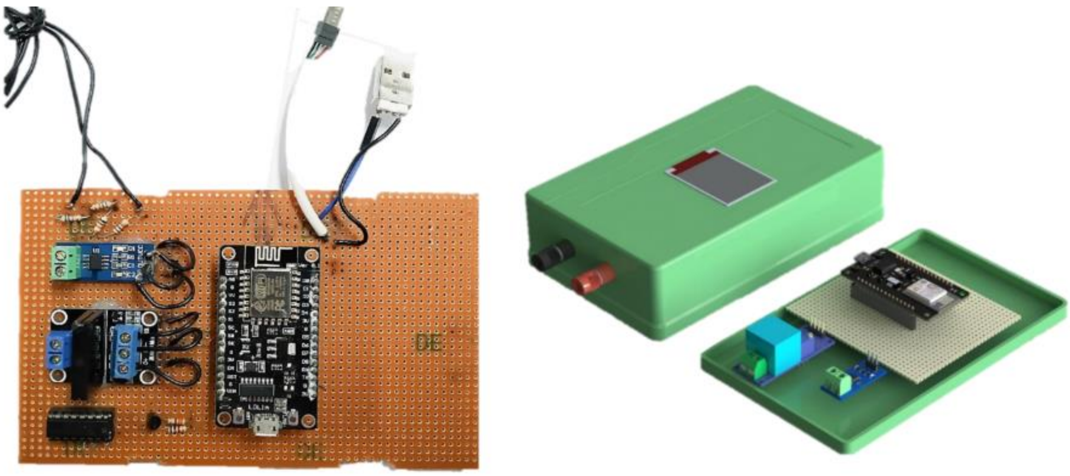
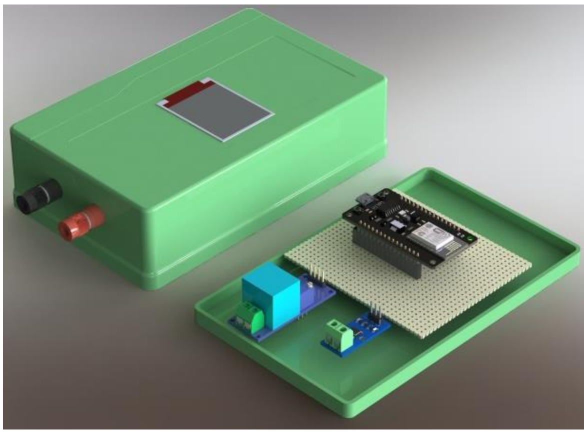


Figure 5.1.11 Implemented Circuit arrangement of an agent



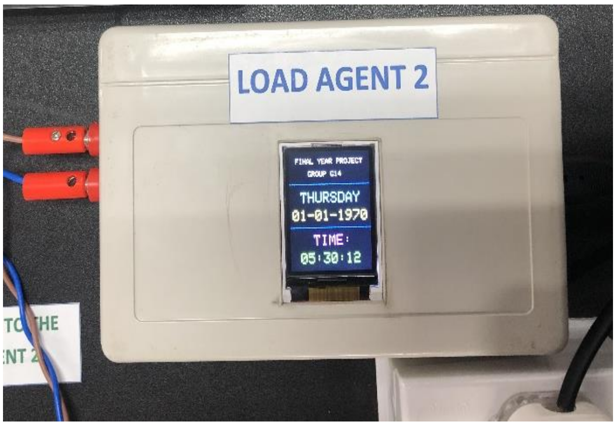


Figure 5.1.12 Completed Agent with display unit

5.1.3 Implementing Agent Communication

Communication is the main requirement in a multi agent system. We used ESP 8266 modules to implement the agents for this micro grid EMS. ESP 8266 module comes up with a wife transmitter and a wife receiver. In the multi agent system, each agents takes current and voltage sensor measurements through sensors for decision making according to the programed algorithm. Agents will send voltage and current sensor values will be received by the server agent. Communication process is done through Wi-Fi network and it's a real-time operation. Google Firebase, which is an online database used by developers to develop iOS, android apps are used to maintain the database in the server agent. There are various features in firebase like cloud messaging, analytics, authentication, real time database, test lab etc.

5.1.4 Firebase database for the multi agent system

The data transmitted to the server agent will be recorded in the firebase database. And when the server request the instantaneous data on the instantaneous power generation and instantaneous load demand, online database provide data. The current and voltage sensors connected to the agent provide output signals as analogue signals. As the first step, these analogue signals will be converted to digital signals by the ESP 8266 module. The values of these two digital signals will be sent to the online data base located at server agent real time through the Wi-Fi network. As the initial step of the control algorithm, the total load demand and total renewable power generation will be calculated by the server agent and the operation process will continue depending on the values.

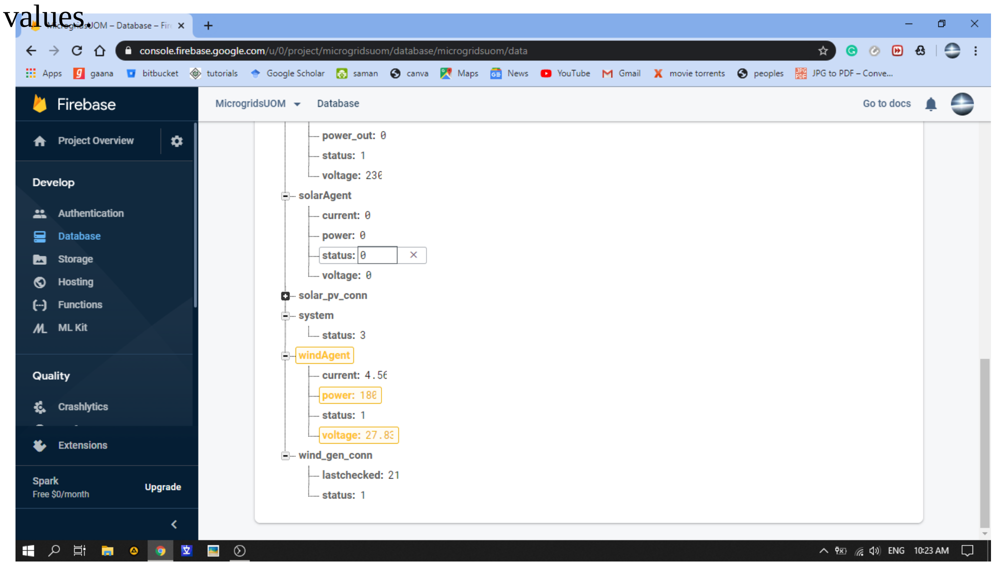


Figure- 5.14 - Developed online database with firebase

Throughout the operation server will update each agent on the required status (ON / OFF). Depending on that input signal the agent sends the control signal to the SSR to control the relevant DES or the load.

5.1.5 Programing the agents for the proposed algorithm

ESP 8266 module comes up with a programmable micro controller. It can be programed using arduino development toolkit. The same programs used in JADE platform for the operation of each agent can be used to program each agent after converting it from Java programming language to C++.

5.1.5.1 Server Agent Programming

Server agent is responsible for all the decision making in dispatching DES to the micro grid system based on the pre-defined algorithm. At the same time Server agent keeps the online database updated. This data base contains all the data such as Bus bar voltage measurements. Calculated instantaneous power values of each source and load, solar agent voltage measurement, PVA current measurement, Critical load voltage measurement, CLA current measurement, NCLA voltage measurement, Non-Critical load current measurement etc. Also server agent will keep records of the on-off (1 or

0) status of the each and every agent real time. This can be achieved by the bidirectional communication in between agents.

5.1.5.2 Solar Agent programing

In the developed test bed SA, is taking the DC measurements. DC side voltage is measured using a voltage divider circuit. The measured voltage sensor sends signal to the micro controller of NODE MCU. The DC current is measured by current sensor (ACS712) and sends to micro controller. These two analog signals are taken as inputs to the micro controller after sending through a multiplexer circuit. For the algorithm the micro controller must receive two analog signals at the same time as two parallel inputs. The analog signal is then converted to digital and then transmitting the data to the server agent database. The same procedure is followed for programming process of both source agents. Micro controller is programed according to the proposed algorithm and source agent is programed to achieve global objectives interacting with other agents and to achieve local objectives within its boundary.

5.1.5.3 Load Agent programing

There are two load agents, CLA and NCLA. NCLA is responsible for non-critical loads of the system. CLA is responsible for the critical loads in the micro grid. CLA take ac side measurements to determine the critical load demand. The current drawn by the critical load is measured using ACS712 current sensor. The analog output signal will be sent to the ESP 8266 module as an input signal. This will be converted to a digital signal and real time data will be sent to the SA. The SA is programmed to keep critical load agent active in all cases. And NCLA is programmed to maintain the power demand and supply even dedicating the operation.

5.1.6 Implementing the test bed

The developed MAS based EMS for a micro grid (Test Bed) is a MAS of five agents, two source agents, two load agents and the server agent. The circuit arrangement of the test bed is as follows

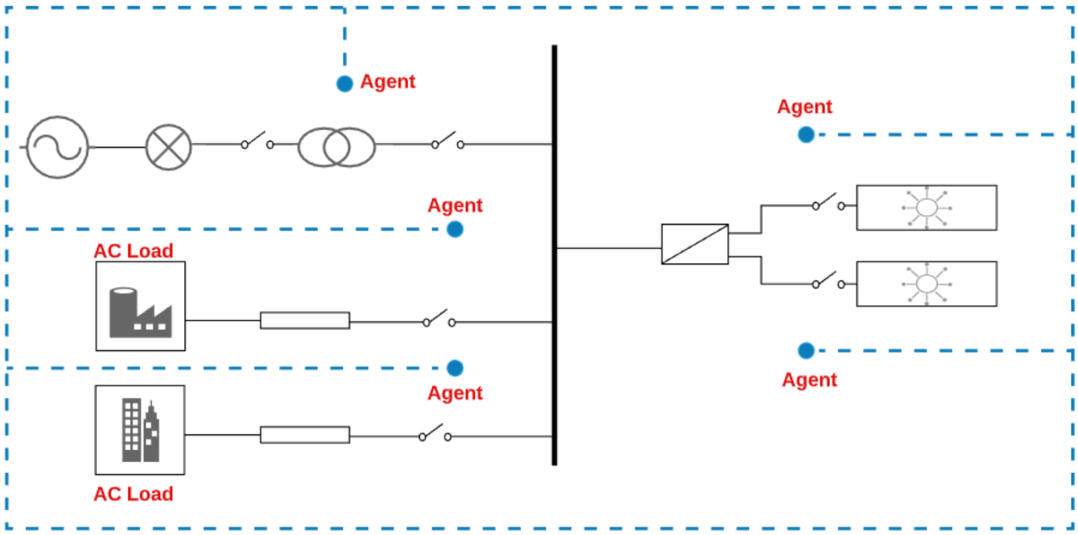
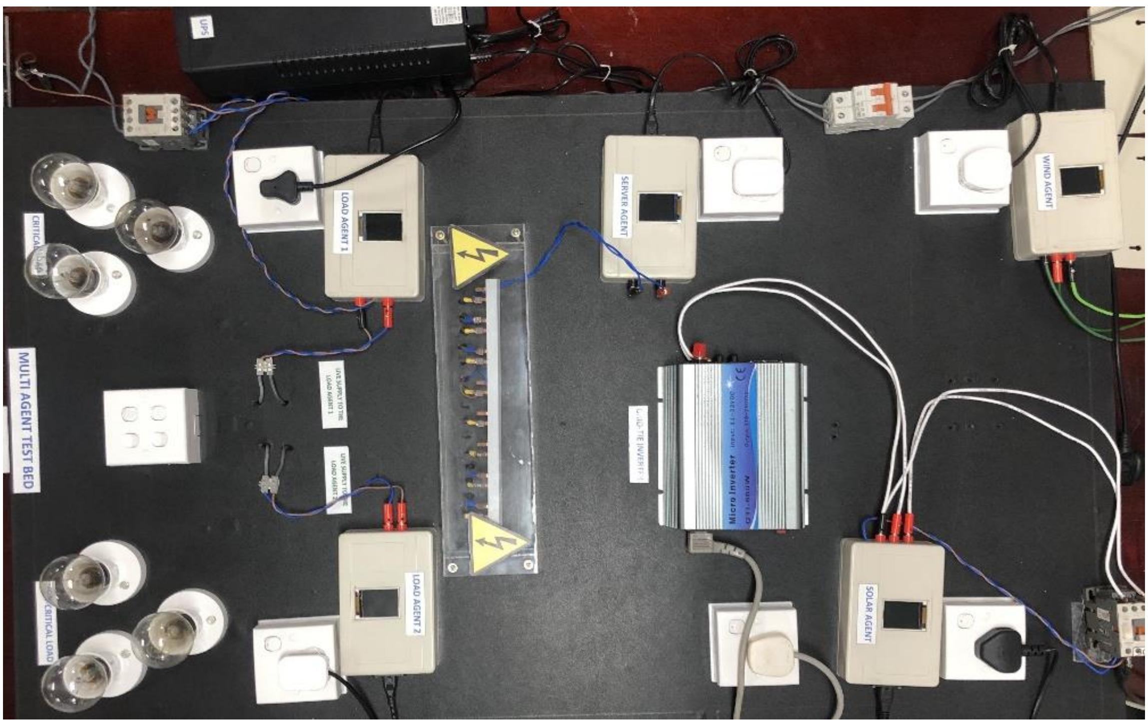


Figure 5.1.6 .0 - Single Line diagram of the test bed

Test bed is implemented as a single phase micro grid system and two solar photovoltaic systems are used as energy sources. Two loads are connected to the test bed and one load is considered as the non-critical load and other load as the critical load.



Here in the developed test bed the DC sources, solar panels are connected to AC bus bar through an inverter (grid tied). When the system is operating in islanded conditions, the EMS keep supplying the critical load demand with the battery backup and charge controller unit.

Figure 5.1.6 .2 – 500W grid tied inverter

Figure 5.1.6 .1 - Implemented MAS based microgrid EMS

Grid tie inverter is used to convert direct current generated in solar sources in to alternating current. Operation of grid tie inverters are active only when utility grid is in active status. The ac power output from the grid tied inverter unit is synchronized and same phase with the utility grid. The grid tie inverter unit we used for the test bed has the following specifications.

- ✓ Power :500 W
- ✓ Solar PV power : 500 – 600 W
- ✓ DC input range : 22-60 V DC
- ✓ MPPT voltage : 24-48 V
- ✓ DC Max current: 45 A
- ✓ AC Max Output : 500W
- ✓ AC output Voltage: 230V

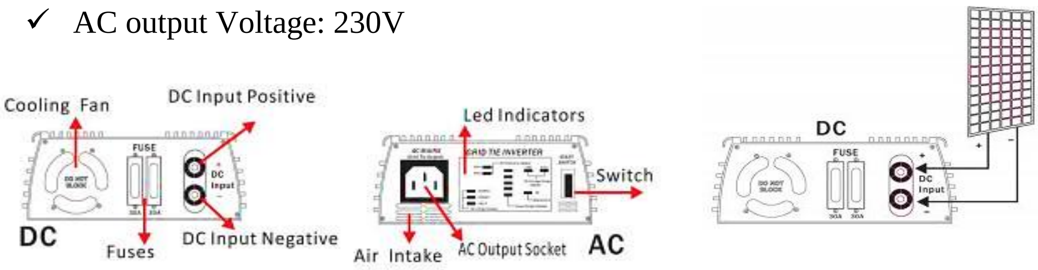


Figure 5.1.6 .3 – Pinout diagram of the inverter

In the test bed, the grid tied inverter is used with two 300W/ polycrystalline solar panels. As the second source is a standalone inverter is used with a charge controller DC powered with batteries

Figure 5.1.6 .4 – Standalone inverter and charge controller

A standalone power inverter convert's direct current (DC) stored in batteries usually (24V) and connected in parallel, into 230 V AC. First the standalone inverter is connected to a battery pack and after that AC devices can be plugged directly into the inverter or can take an AC output from the inverter. When the inverter take power from the battery pack connected, it starting to drain. The draining batteries must be recharged. For that solar panels, generator or a wind turbine can be used. In between the recharging source and the battery a charge controller is connected, which is the most significant component in the PV standalone inverter systems with battery bank storage. The objectives of using a charge controller is to charge the batteries avoiding overcharge, prevent reverse flow of current , and will keep the batteries safe and increase the life span. The test bed developed tested with a simple algorithm and the operation of the agents were tested. The relay operation of agents are as follows.

Figure 5.1.6 .5 – Switching Operation of a source agent

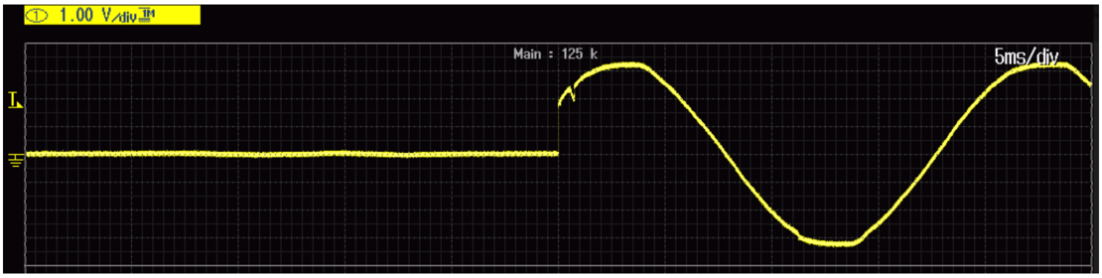


Figure 5.1.6 .5 – Switching Operation of a Load agent

6.0 Results and analysis

In the simulation of MAS based EMS for a micro grid, a multi agent system with multiple agents for all DES (WTA, PVA, and DGA) and loads (CLA, NCLA) (is simulated with realistic data set provided as inputs to the system. According to the algorithm, each agent generates switching signals and based on those switching signals the DES and loads are controlled to keep the micro grid power stability. The following results were obtained as the output of simulating the JADE developed MAS for 24 hours realistic DES and loads power data inputs.

After simulating the MAS developed in JADE for the proposed algorithm above results were given. Solar the two distributed renewable energy sources used, solar photovoltaic system and the wind power system were given realistic data inputs continuously. And for the two LA's, critical and non-critical loads, two realistic power data patterns was tested and both grid connected mode and islanded mode were considered based on grid availability. So the proposed control algorithm was tested for following four scenarios and sub scenarios under each topic.

I. Renewable Power Generation > Total Demand
II. Renewable Power Generation < Total Demand and Grid Available, DG not economical
III. Renewable Power Generation < Total Demand and Grid Not Available , DG available
IV. Renewable Power Generation < Total Demand and Grid Not Available , DG not available

After simulating for all the cases following outputs were given by the MAS based EMS developed in the JADE platform.

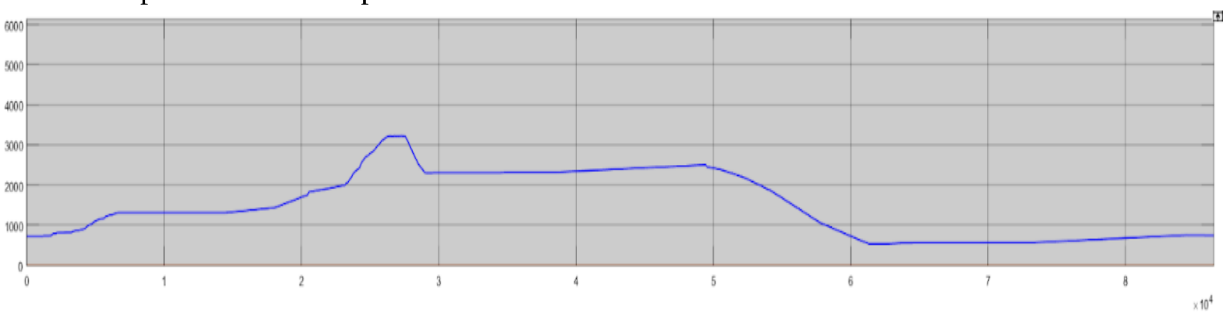


Figure 6.0- Critical load consumption

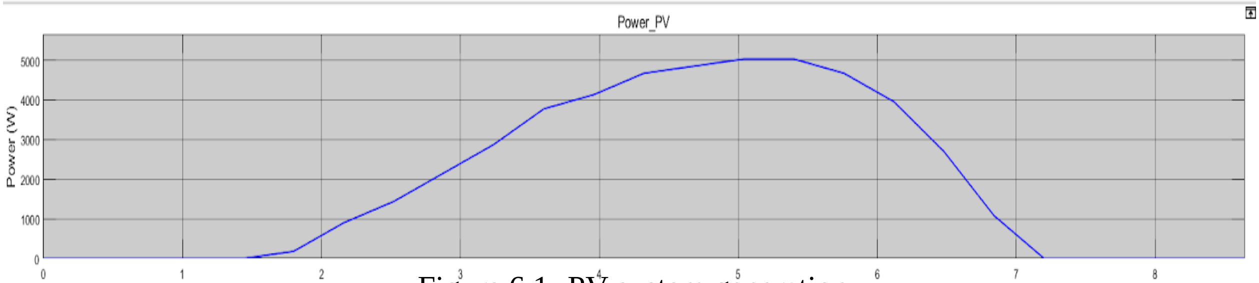


Figure 6.1- PV system generation

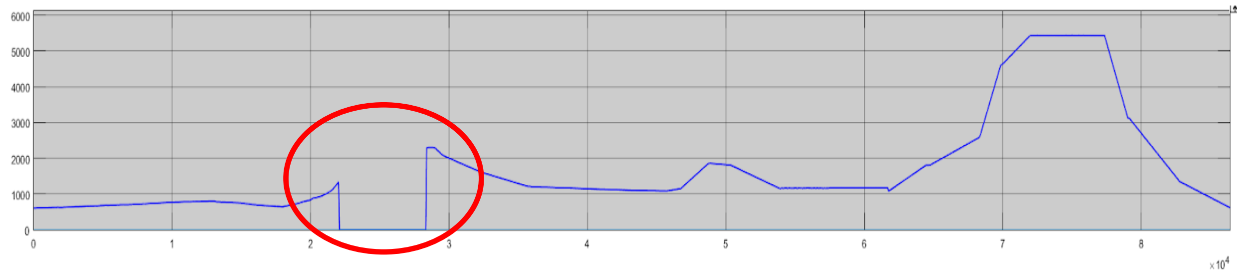


Figure 6.2- Non-critical load consumption

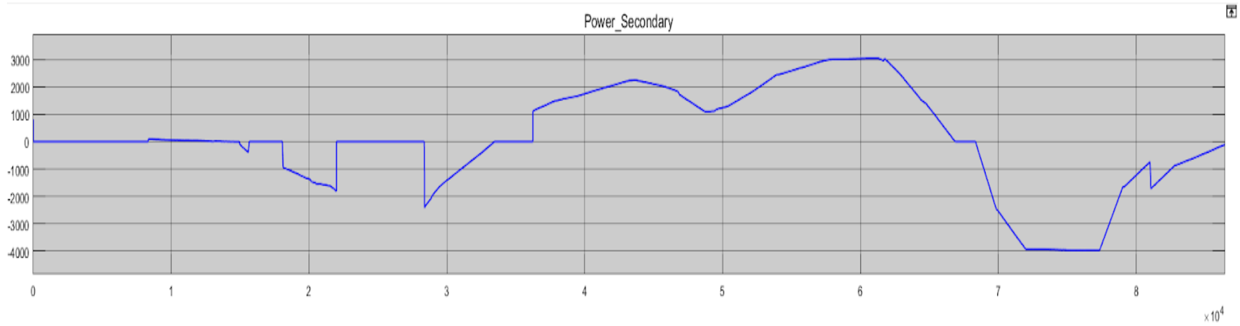


Figure 6.3- Power import/export from the utility grid

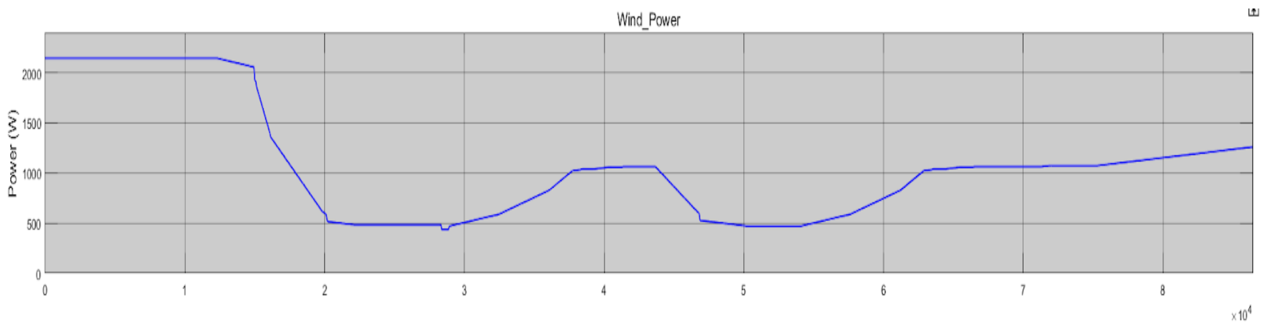


Figure 6.4- wind power Generation

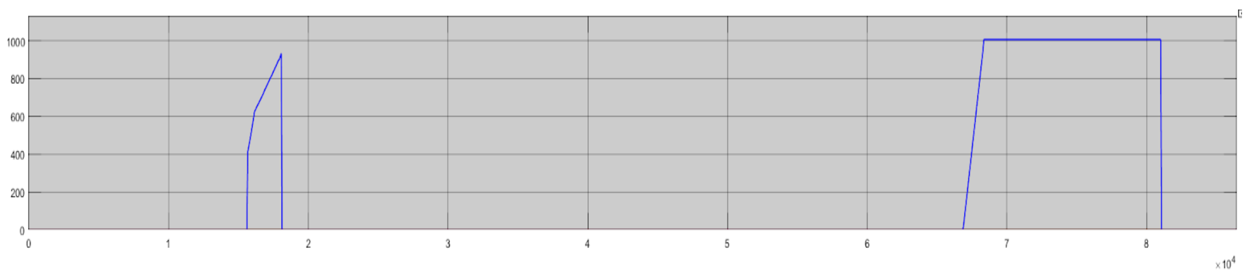


Figure 6.5- Diesel Generator

When looking at the results, Active power generation data and power consumption data of each DES and load, it's clear that MAS based EMS was able to maintain the active power balanced. That's means the balance between power supply and demand real time. We can analyze the results with the control algorithm. Major objective of the control algorithm was to fully utilize the power generated by renewable DES, solar PV system and wind power system. As Figure 6.1 and Figure 6.4 displays, MAS haven't tripped the two renewable sources throughout the time. In figure 6.2, the non-critical load was tripped for a particular time period to keep power supplied to critical load without interruption according to the algorithm. According to Figure 6.3 there are time periods with micro grid export extra generation to the utility grid and some time periods where micro grid request power from diesel generation when grid is not available. From the simulation results, we can come to a conclusion that with real time bidirectional communication ability, decision making ability and integrated agent operation can be used to manage all the control aspects of a micro grid.

7.0 Limitations of the study

When we conducting this research under the topic "Development of multi agent based energy management system for micro grid", we found various limitations in analytically deriving the results and in hardware implementation. Research limitations can be basically discussed under following topics.

7.1 Modeling and simulating limitations

ADK is an essential requirement to develop a MAS according to the FIPA standards. Most of the ADK's are not open source and very difficult to find resources to study the toolkit. JADE was the possible option. It is an open source platform and there were sources to study the platform but with number of limitations when developing a MAS for an electrical / power application.

- ✓ JADE platform is not developed as a fully user friendly platform
- ✓ GUI is not developed up to full extent and not able to conduct a quantitative analysis.
- ✓ Not able to customize the agents in MAS based on the agent environment
- ✓ Complex to connect with MathLab developed model to conduct a transient analysis.

7.2 Data and statistical limitations

There are various types of DES to be considered, various architectures to be considered and various environments to be considered when proposing a concept for micro grid energy management. The model developed for the proposed concept should be tested for real data patterns to validate the achievements of the concept over existing control methods. Receiving real data and statics of these micro grid applications is challengeable.

7.3 Hardware implementation limitations

Agents were developed with the ESP 8266 module. In simulation step, Agents MAS model develop can handle any number of environment parameters as system inputs and make reactions. But ESP 8266 module can only handle one analogue signal in the implementation we completed. And as the available DES were limited, we were not able to run the proposed algorithm in the developed test bed.

8.0 Conclusion

Through this thesis, a simulation and a hardware development of a MAS architecture based EMS for a micro grid has been discussed. We considered a full micro grid for the simulation in the JADE platform and almost all the scenarios were considered with realistic power data patterns. We were able to develop the MAS in JADE platform for a micro grid with multiple DES and loads to meet the following objectives.

- ✓ Multi agent concept was successfully introduced for the energy management operation of a micro grid with JADE simulation platform.
- ✓ Agent communication and integrated operation qualities of agents were used for the simulation process in JADE platform.
- ✓ Agents were programed according to an energy management control algorithm and given the responsibilities for each agents.
- ✓ MAS developed in simulation platform was tested with realistic data and checked for number of cases and results were presented and discussed.

From the simulation results, we can come to a conclusion that with real time bidirectional communication ability, decision making ability and integrated agent operation can increase the reliability, flexibility and efficiency of a micro grid energy management in various aspects.
As the second step a hardware implementation was done for a MAS based EMS for a microgrid. A simplified version of a micro grid with five agents and two power sources were implemented and we were able to achieve following objectives.

- ✓ Plug and play type dedicated agents were developed and all the technical details are discussed in the thesis.
- ✓ Implemented the bidirectional agent communication
- ✓ Agents were successfully tested for integrated operation communicating in-between agents.
- ✓ Switching operations of relays were tested with agent control signals.
- ✓ A monitoring platform was developed with enabled manual controlling.

The major objective of the research was to design and develop a MAS based EMS for micro grid. We were able to implement agents, implement bidirectional real time communication system, implement the integrated operation and control the distributed loads and sources balancing the active power of the micro grid. We were able to feed the critical load with uninterruptible supply continuously according to the algorithm proposed, which was tested for realistic power data.

Finally with the results we obtained through the simulation process and hardware implementation we can make the following conclusions

- ✓ Proposed MAS based decentralized architecture have higher communication efficiency compared to centralized micro grid control architectures.

- ✓ Proposed MAS based concepts can be used to control the operation of micro grids with multiple renewable DER and loads and manage intermittent generating patterns with real time power controlling.
- ✓ Agents were developed as plug and play modules, which reduces the complexity in installing and expanding process when adding new units.

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APPENDIX A - Realistic data set of power sources and load's used for the simulation of Multi Agent Based EMS in JADE framework.

Case 1

Time(min)	WTP(W)	SP(W)	TRP(W)	NCLP(W)	CLP(W)	TLP(W)
562	664	3170	3834	1446	2298	3744
563	668	3185	3853	1439	2298	3737
564	672	3199	3871	1432	2298	3730
565	676	3214	3890	1425	2298	3723
566	680	3229	3909	1418	2298	3716
567	684	3244	3928	1411	2298	3709
568	688	3259	3947	1404	2298	3702
569	692	3274	3966	1397	2298	3695
570	695	3289	3984	1390	2298	3688
571	699	3304	4003	1383	2298	3681
572	703	3319	4022	1376	2298	3674
573	707	3333	4040	1369	2298	3667
574	711	3348	4059	1362	2298	3660
575	715	3363	4078	1355	2299	3654
576	719	3378	4097	1348	2300	3648
577	723	3393	4116	1341	2301	3642
578	727	3408	4135	1334	2302	3636
579	731	3423	4154	1327	2303	3630
580	735	3438	4173	1320	2304	3624
581	739	3452	4191	1313	2305	3618
582	743	3467	4210	1306	2306	3612
583	747	3482	4229	1299	2307	3606
584	751	3497	4248	1292	2307	3599
585	755	3512	4267	1285	2308	3593
586	759	3527	4286	1278	2307	3585
587	763	3542	4305	1271	2307	3578

Case 2

Time	WTP	SP	TRP	NCLP	CLP	TLP
290	1110	146	1256	658	1404	-806
291	1098	149	1247	656	1406	-815
292	1086	152	1238	655	1408	-825
293	1074	155	1229	654	1410	-835
294	1062	158	1220	652	1412	-844
295	1050	161	1211	651	1414	-854
296	1038	164	1202	650	1416	-864
297	1026	167	1193	648	1418	-873
298	1014	170	1184	648	1420	-884
299	1002	173	1175	645	1422	-892
300	990	176	1166	640	1424	-898
301	978	179	1157	645	1426	-914
302	966	191	1157	650	1434	-927
303	954	202	1156	655	1442	-941
304	942	214	1156	660	1450	-954
305	930	226	1156	665	1458	-967
306	918	238	1156	670	1466	-980
307	906	250	1156	675	1474	-993
308	894	262	1156	680	1482	-1006
309	882	274	1156	680	1490	-1014
310	870	286	1156	685	1498	-1027
311	858	298	1156	690	1506	-1040
312	846	310	1156	695	1514	-1053
313	834	321	1155	700	1521	-1066
314	822	333	1155	708	1529	-1082
315	810	345	1155	716	1537	-1098
316	798	357	1155	720	1545	-1110
317	786	369	1155	725	1553	-1123
318	774	381	1155	730	1561	-1136
319	762	393	1155	735	1569	-1149

Case 3

Time	WTP	SP	TRP	NCLP	CLP	TLP
377	481	1036	1517	1633	1948	3581
378	481	1045	1526	1699	1952	3651
379	481	1054	1535	1722	1956	3678
380	481	1063	1544	1758	1960	3718
381	481	1071	1552	1792	1964	3756
382	481	1080	1561	1832	1968	3800
383	481	1089	1570	1855	1972	3827
384	481	1098	1579	1894	1976	3870
385	481	1107	1588	1922	1980	3902
386	481	1116	1597	1955	1984	3939
387	481	1125	1606	1985	1984	3969
388	481	1134	1615	1992	2033	4025
389	481	1143	1624	1996	2055	4051
390	481	1152	1633	2000	2044	4044
391	481	1161	1642	2004	2079	4083
392	481	1170	1651	2008	2103	4111
393	481	1179	1660	2012	2144	4156
394	481	1188	1669	2016	2166	4182
395	481	1196	1677	2020	2198	4218
396	481	1205	1686	2024	2245	4269
397	481	1214	1695	2028	2276	4304
398	481	1223	1704	2032	2298	4330
399	481	1232	1713	2036	2322	4358
400	481	1241	1722	2040	2344	4384
401	481	1250	1731	2044	2355	4399
402	481	1259	1740	2048	2377	4425
403	481	1268	1749	2052	2388	4440
404	481	1277	1758	2056	2399	4455
405	481	1286	1767	2059	2439	4498

APPENDIX B

```
Public void setup()  try {

 workbook = Workbook.getWorkbook(new File("D:/Load2data.xls"));

         } catch (BiffException | IOException e) {
                 System.out.println("Error occoured");
                 e.printStackTrace();
         }
        sheet  = workbook.getSheet(0);
         try {
              data = dd.readData("D:/Load2data.xls", 0);
         } catch (BiffException | IOException e) {
              System.out.println("The error1 occoured ");
              e.printStackTrace();
         }
         int rows = sheet.getRows();
         int columns = sheet.getColumns();

         for(int i=0; i < rows;i++) {
              for(int j=0;j < columns;j++) {
                power_requirement = Integer.parseInt(data[i][j]+ "");

                ACLMessage msg = new ACLMessage(ACLMessage.INFORM);
                msg.setContent( "" +power_requirement + "CLA");
                msg.addReceiver( new AID("SA", AID.ISLOCALNAME ) );
                System.out.println( "CL1:"+ power_requirement+"W"  );
                            send(msg);

                            try {
                                Thread.sleep(10000);
                            } catch (InterruptedException e) {
                                e.printStackTrace();
                            } } } }

                 public class ReadWriteExcel {
                     public String[][] readData(String path, int sheetNo)
throws BiffException, IOException
                     {
                Workbook workbook = Workbook.getWorkbook(new File(path));
                Sheet sheet  = workbook.getSheet(sheetNo);
                Cell cell;
                int rows = sheet.getRows();
                int columns = sheet.getColumns();
                String[][] data = new String [rows][columns];
                for(int i=0; i < rows;i++)
                     {
                                 for(int j=0;j < columns;j++)
                                 {
                                           cell = sheet.getCell(j, i);
                                           data[i][j] =
cell.getContents();

                     }}
                     return data;
                     } } }
```