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In **Telecommunication Engineering**

Title:

Microgrids Resiliency Using Multi-Agent System Communication Technology

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Registration Number:……../2024

Abstract

Nowadays, communication and data exchange are key factors for the resilience improvement of a microgrid (MG) against natural disasters and play a pivotal role in the energy management (EM) fields. Hence, the main objective of this project is to improve MG resilience and control its energy management system (EMS) using a multi-agent system (MAS) communication approach.

First, the proposed work optimizes the load power consumption inside one MG based on the available power resources; then, the strategy is expanded to optimize power usage to improve resilience when dealing with many MG systems.

The simulation of the multi-microgrid (MMG) system is done using both MATLAB Simulink and Cisco packet tracers. Various scenarios are simulated to evaluate the performance of the MAS in maintaining flexibility, stability, and resiliency. The Cisco packet tracer is used to model the communication network to ensure a robust and secure data exchange between agents. The results demonstrate that the integration of MAS communication technology significantly improves MGs' power management.

Keywords:

Multi-Agent System, Microgrid, Multi-microgrid, Energy Management System, resiliency, MATLAB, Cisco packet tracer

Acknowledgment

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Finally, I would like to record my sense of gratitude to all who, directly or indirectly, have lent their helping hand in this project.

Thank you all for being a part of this long journey.

Dedication

In the name of God, the most gracious, the most merciful, First and foremost.

I would like to dedicate this work to *'Lina'*, to myself, for being strong and patient enough to not give up facing obstacles and hard times.

To my beloved parents...
To my sweetest sisters...
To my source of inspiration, my husband...
To all *ATTOU's* and *HAMBLI's*.
Today, I am officially an engineer.

Contents

List of Figures

List of Tables

List of Abbreviations

AC	**A**lternative **C**urrent
ACL	**A**gent **C**ommunication **L**anguage
CGS	**C**onventional **G**eneration **S**ource
CS	**C**ontrol **S**ystem
DC	**D**irect **C**urrent
DER	**D**istributed **E**nergy **R**esource
DG	**D**istributed **G**eneration
DS	**D**istributed **S**ystem
DR	**D**emand **R**esponse
EM	**E**nergy **M**anagement
EMS	**E**nergy **M**anagement **S**ystem
ESS	**E**nergy **S**torage **S**ystem
ESU	**E**nergy **S**torage **U**nit
GS	**G**eneration **S**ource
HAN	**H**ome **A**rea **N**etwork
ICT	**I**nformation and **C**ommunications **T**echnologies
IP	**I**nternet **P**rotocol
IPv4	**I**nternet **P**rotocol **V**ersion **4**
LAN	**L**ocal **A**rea **N**etwork
LC	**L**ocal **C**ontroller
LV	**L**ow **V**oltage
MAC	**M**edia **A**ccess **C**ontrol
MAS	**M**ulti-**A**gent **S**ystem
MG	**M**icro**G**rid
MGCC	**M**icro**G**rid Central **C**ontroller
MMG	**M**ulti-**M**icro **G**rid
MPPT	**M**aximum **P**ower **P**oint **T**racking
MV	**M**edium **V**oltage
NAN	**N**eighborhood **A**rea **N**etwork
PC	**P**ower **C**onverter
PV	**P**hoto**V**oltaic
PCC	**P**oint of **C**ommon **C**oupling
RES	**R**enewable **E**nergy **S**ource
SG	**S**mart **G**rid
SOC	**S**tate **O**f **C**harge
TCP	**T**ransmission **C**ontrol **P**rotocol
WAN	**W**ide **A**rea **N**etwork
WLAN	**W**ireless **L**ocal **A**rea **N**etwork

General introduction

The global population's rapid growth is driving a concurrent surge in energy demand. This escalating energy consumption poses a significant challenge, raising concerns about environmental impact and the complexities of energy procurement.

The traditional centralized utility grid, known as the smart grid, is an interconnected network. It takes energy from large, far-away energy generation plants and transmits it over long distances to consumers. As technologies and policies continue to evolve, communities and businesses can choose to supply their own energy locally by building their own MG.

Nowadays, MGs are becoming a mainstay in the power and energy fields due to their numerous advantages. They demonstrably enhance the resilience, reliability, and recovery capabilities of regional electric grids, fostering improved operational stability. Additionally, MGs offer the potential to reduce energy costs for both consumers and businesses. Furthermore, they contribute to environmental sustainability by facilitating the integration of clean energy sources. Ultimately, MGs represent a promising paradigm shift, offering both environmental and economic value to society.

Our project proposed a resiliency improvement of MMG using MAS communication technology. This report explores smart grids, microgrids, communication networks, and the EMS. By investigating the interconnected chapters, readers will achieve By navigating through the interconnected chapters, readers will gain a holistic understanding of how these technologies are developing a more flexible, resilient, and sustainable energy future. This report is organized as follows:

The first chapter provides an overview of the theoretical foundations related to the project. It covers topics such as smart grids, microgrids, and multi-agent system technology. The chapter aims to establish a solid understanding of the fundamental concepts and principles that form the basis of the project.

The second chapter focuses on the multi-agent system and its use in both single microgrid and networked microgrid systems, highlighting the different algorithms and methods used to control each system.

The third chapter focuses on the modeling and simulation of the system using both MATLAB Simulink and Cisco packet tracer software. The simulation setup is configured to simulate the system's performance for both single microgrids and multi-microgrids.

The fourth chapter covers the results and discussion part of this project and the different scenarios we got to improve the systems' resilience.

Finally, this report ends with a general conclusion and sets the stage for future work.

Chapter 1

Theoretical background and Literature review

The requirement for energy is increasing rapidly in parallel with population growth all over the world. This energy incremental cause environmental concerns and the procurement of energy.

Smart grids (SGs) are network structures that provide power quality, sustainable, efficient EM, as well as smart production, transmission, and consumption. This preference accelerated the conversion from conventional to SGs. Also, MGs will increase the supply flexibility of the SG, which uses bi-directional information and communications technologies (ICT). In this way, it allows real-time data flow and dynamic pricing. The main aim of SG is to reduce carbon emissions through the effective use of energy. The energy storage unit (ESU) and distributed energy resources (DER) systems are involved in the MG structure. MGs also increase power flow and reduce power losses in transmission lines in SM structures.

SGs and MGs are new paradigms in electric power systems made to improve the efficiency, reliability, security, and environmental friendliness of the electricity generation process.

Through this chapter, we are going to introduce both SG and MG by highlighting their definitions, main concepts, characteristics, architectures, and applications, as well as the technologies used to control each of them..

1.1 Smart Grids

1.1.1 Definition and concepts

SG is an electricity network that uses several technologies to monitor and manage the transmission of power from generation sources (GSs) to all loads and users [1]. It is a bi-directional (two-way communication) supply and data transfer network from power generation units to end users. It aims to reduce investment, operation, and maintenance costs and improve energy efficiency using new technologies. Each technology is implemented in the electricity grid, from the GSs to consumers. It is more secure and sustainable for future energy implementation because of existing electricity system issues such as aging infrastructure and increasing demands. The basic concept of a SG is to monitor, control, and communicate capabilities to the worldwide delivery infrastructure to enhance system reliability, resiliency, flexibility, and stability.

1.1.2 Characteristics, architecture and application of smart grid

SG is characterized as follows [2]. It offers self-healing, environmental friendliness, and improved efficiency, reliability, and safety in power delivery and use, making them resistant to physical and cyberattacks.

SG infrastructure key elements, such as smart meters, circuit breakers, transformers, feeders, substations, control centers, and grid stations, are required in well-formed communication network architectures.

SG infrastructure is divided into three main communication network architectures, such as local area networks (LANs) home area networks (HANs), neighborhood area networks (NANs), and wide area networks (WANs).As well as the many advantages, smart grids are faced with many barriers, such as bi-directional communication systems, integration with the grid with renewable energy resources, ineffective utilization of distributed generation (DG), inadequate existing grid infrastructure and storage, etc. One of the methods to attain effective utilization of the DG is to handle electricity generation, energy storage, and loads as a localized group. MG is essential to the SG concept. It is a piece of the larger grid, which involves nearly all of the components of the utility grid, but these components are smaller. While MGs take place at a larger utility level, such as large transmission and distribution lines, MGs are smaller in scale and can operate independently from the larger utility grid. Figure 1.1 represents SG structure.

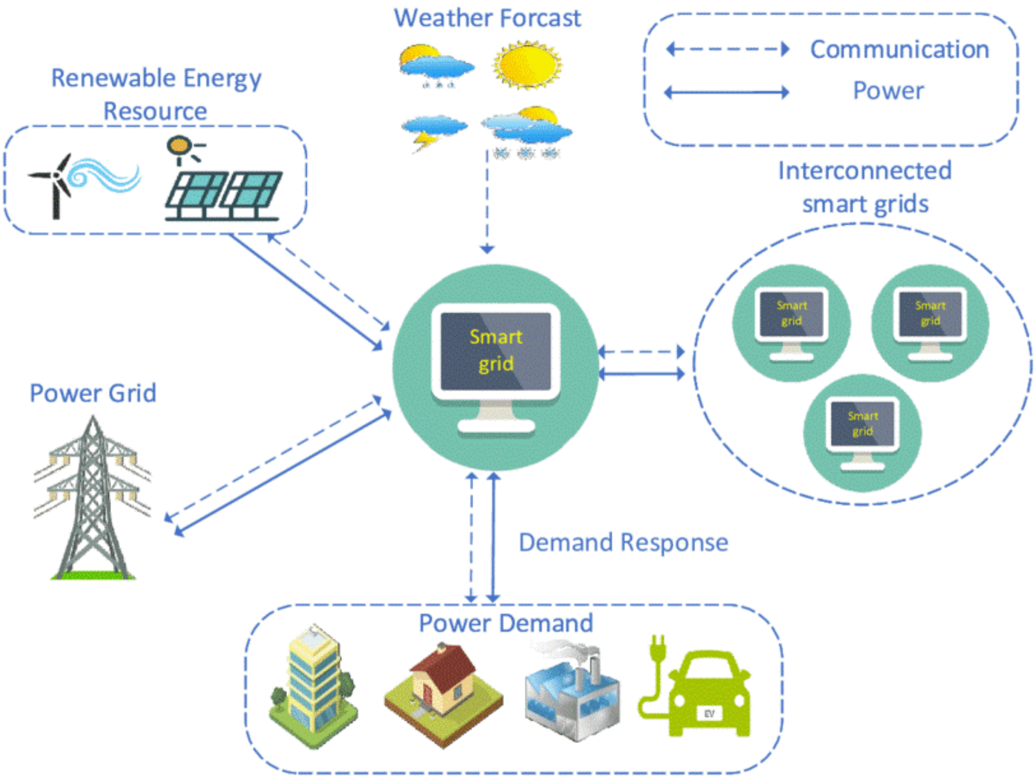


Figure 1.1: The structure of smart grid.
[3]

1.2 Microgrid

The traditional centralized utility grid, known as SG, is a big interconnected network. It takes energy from large, far-away energy generation plants and transmits it over long distances to consumers. As technologies and policies continue to evolve, communities and businesses can choose to supply their own energy locally by building their own MG.

1.2.1 Definition and concepts

MG is a relatively small-scale localized energy network, which includes loads, a network control system (CS), and a set of DER, such as generators and energy storage devices.

MG equipped with intelligent elements from smart grids has been adopted to enable the widespread use of DERs and demand response programs in distribution systems (DSs) [4].

MGs can operate in an interconnected mode linked to the main grid at the point of common coupling (PCC) or in islanded mode when it is disconnected from the main grid [5]. It integrates a variety of components, including loads (power consumers), power converters (PCs), and DERs such as renewable energy sources (RESs), conventional generation sources (CGSs), and energy storage systems (ESSs). In grid-connected mode, MG trades surplus energy with the main grid to increase its revenue, but it operates in an islanded model in case of disturbances or failure of the main grid to ensure system stability and provide supply to critical loads while ensuring system stability. MG ensures continuous supply to critical loads in islanded mode with the effective management of DERs, load shedding, and DS. The central controller and local controllers (LCs) are used for the supervisory operation of the MG system [6]. Hence, the effective management and coordination of DERs in MG results in improved system performance and sustainable development [7]. Figure 1.2 represents a general scheme of MG.

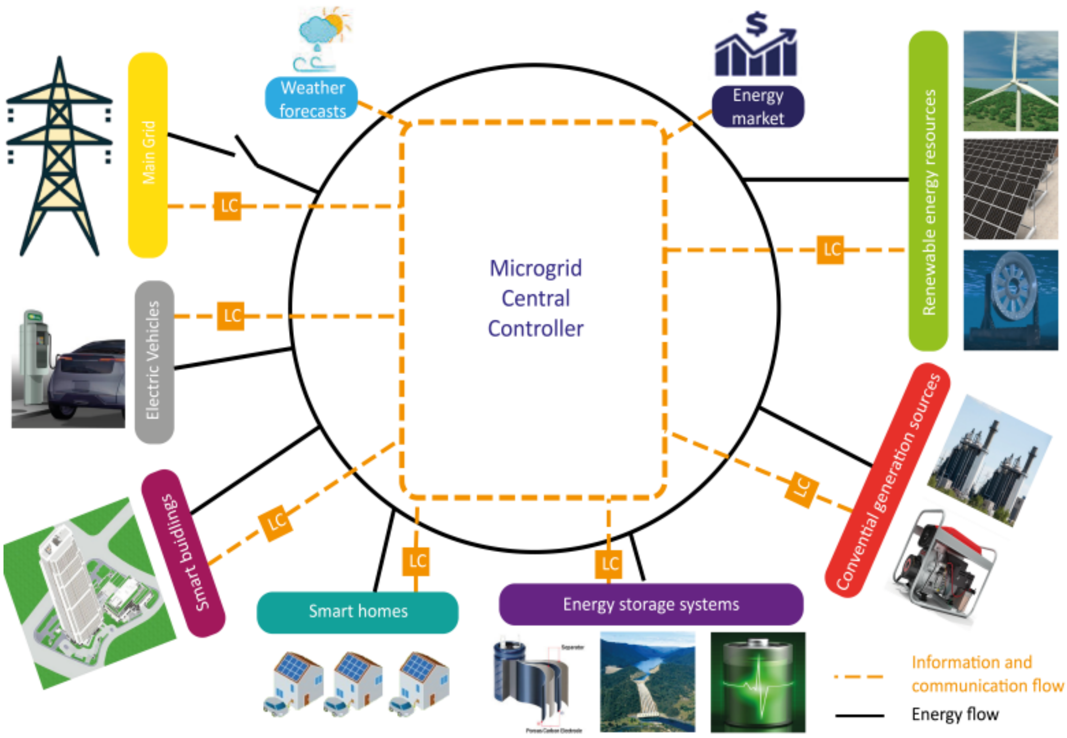


Figure 1.2: Microgrid General Scheme.
[8]

1.2.2 Advantages of Microgrid

Nowadays, MGs are becoming a mainstay in the power and energy fields due to their numerous advantages. The MG improves the electric reliability, resilience, recovery, the operation and stability of the regional electric grid. It can lower energy costs for both consumers and businesses. Also It provides the environment with clean energy and brings economic value to society. [9]

1.2.3 Microgrid Components

MG can operate autonomously in two different modes of operation, and it has three different architectures, which define the components used in each architecture and mode. MGs are composed of DERs, including DGs, which are detachable, RESs, and ESSs, which also have a flexible load. The major components of a MG in general can be listed as follows:

1.2.3.1 Generation

Mainly, the generation of power is defined by energy sources, which are categorized into two main types: dispatchable and non-dispatchable units.

Dispatchable units define the resources that can be controlled in a centralized form regarding electricity demand and need. These units are also known as non-RESs and can be committed and dispatched by MG operators depending on technical constraints like generation capacity, fuel availability, ramping, minimum on/off time, and emission limits [10]. The non-RES includes diesel generators, fuel cells, microturbines, etc.

The second type is non-dispatchable units, which are known as RESs. RES refers to energy sources that derive their power from natural sources, for instance, photovoltaic (PV) systems, wind turbines, hydroelectric generators, etc. These units cannot be controlled by MG operators due to the varied input sources of each source, such as solar irradiance, wind speed, and water flow. [11]

1.2.3.2 Storage

A storage system, or ESS, is a system where the MG stores excess energy to use it when the generated energy is low or the demand is high.

ESSs are coupled with RESs in order to compensate for the generated power intermittency and volatility and ensure the MG generation adequacy. They have the potential to improve power quality, stability, and reliability. Generally, electric ESSs are categorized into three kinds: electrochemical systems (batteries and flow batteries), potential energy storage (pumped-hydro and compressed-air storage), and kinetic ESSs (flywheels).[12]

1.2.3.3 Consumption

Generally, MG energy consumption includes electricity, heat, and cooling loads. Electrical consumption within a MG can be classified into dynamic or static loads.

Static loads, mostly used in hospitals, police stations, data centers, etc. They cannot be altered and must be adjusted to adapt to normal and emergency circumstances. Moreover, this category of load cannot be scheduled in the demand response (DR) program.

On the other hand, concerning dynamic loads, MG operators can reduce and adjust these types of loads based on demand, market price, and required control actions. These loads can be either shiftable or curtailable, depending on their supply priority. [13]

The MG components are summarized in the following classification, shown in figure 1.3.

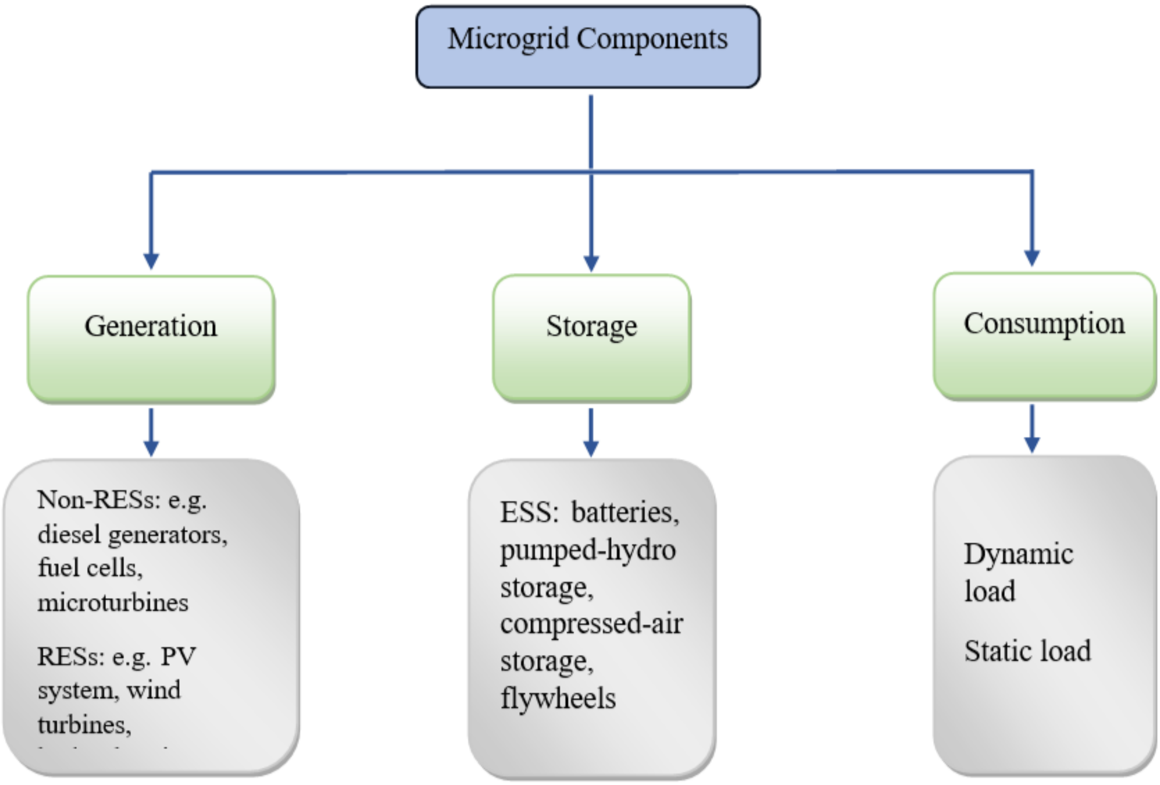


Figure 1.3: Classification of Microgrid Components

1.2.4 Microgrid Control

As mentioned in the above section, MG consists of three main parts: generation, storage, and consumption. In order to perform some tasks, such as determining the amount of power to be transferred or received, an effective EMS must be established between MG components. Thus, MG operators control the system and satisfy the energy demand from the load to achieve appropriate EM. [14]

EMSs are control software that distributes power output through DG units and finds the most economical way to feed the needed load. This is done by considering power reliability, safety, and quality. Generally, MG EMSs receive multiple inputs and then act on the available information to achieve the defined target set by the MG operators. provides an illustrative overview of a MG EMS. A summary of an MG EMS is shown in figure 1.4.

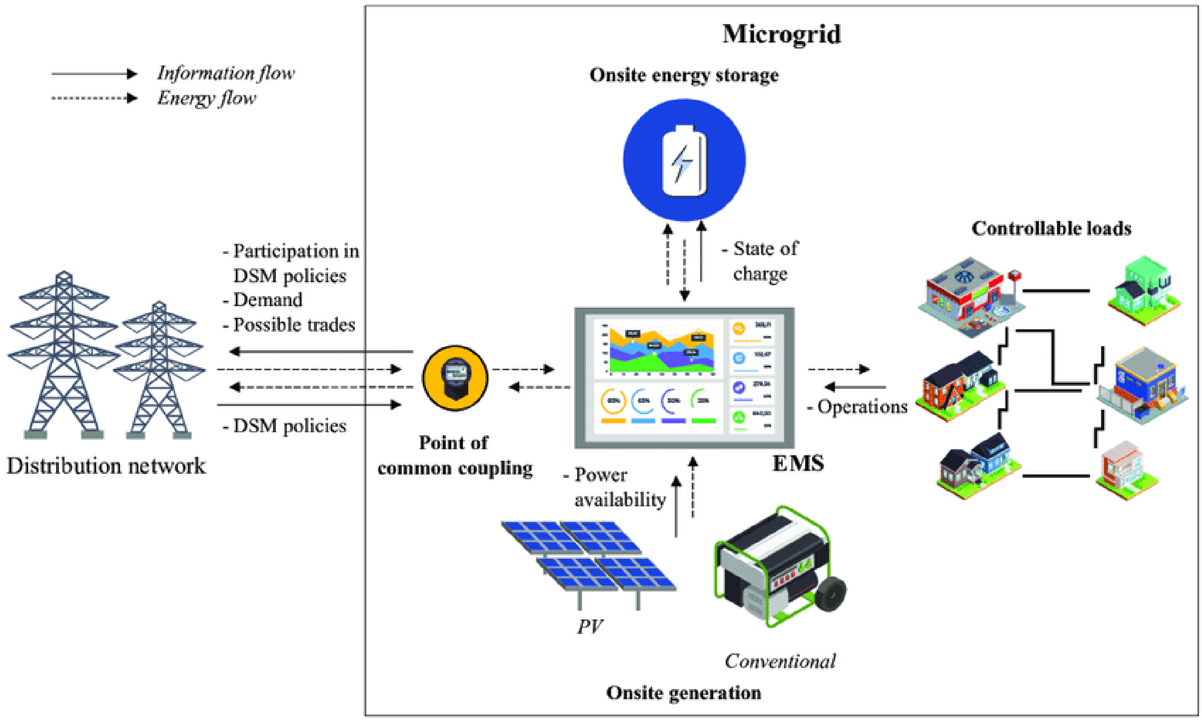


Figure 1.4: Energy Management System of a Microgrid.
[15]

EM is assisted due to EMSs. It enables the realization of scenarios such as the stored power in ESSs. The idea is when the power needed by the system is less than the power produced by RESs and comparing the required power from ESSs if the power demanded exceeds the power produced by renewable energy resources. Between the production, consumption, and storage systems and the control of battery charging and discharge, an effective EMS is needed. Thus, the system collaborates with the load's demand to achieve appropriate EM using different approaches applied to EMS [16], which are summarized in the following classification, presented in figure 1.5.

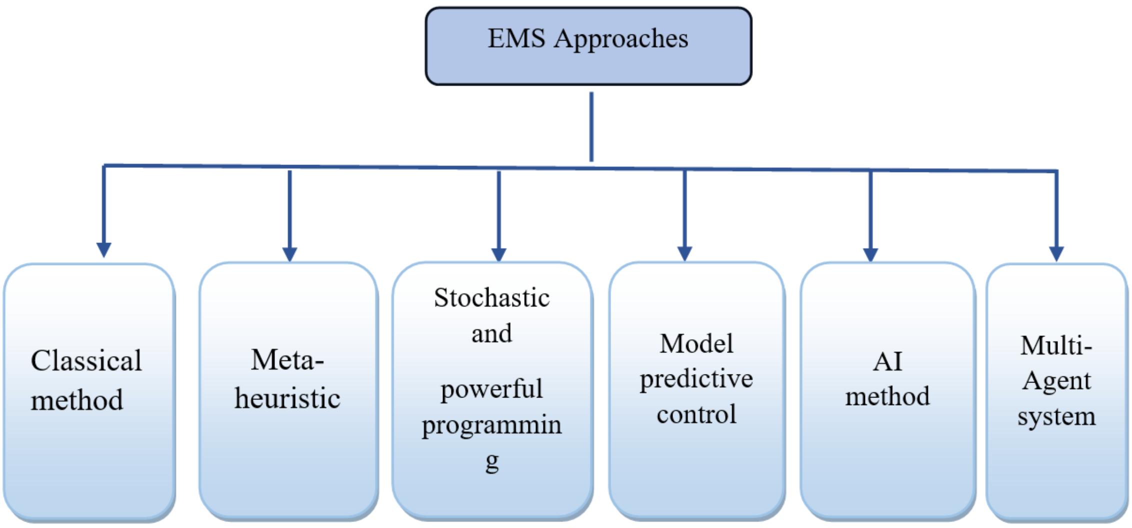


Figure 1.5: Applied approaches to energy management systems in a microgrid

1.2.5 Microgrid operation modes

Broadly speaking, the MG network can operate in two distinct modes: (a) isolated, remote and off-grid areas, particularly remote communities such as mountains, and military compounds; (b) grid-connected configurations, specifically critical infrastructure such as university campuses, commercial centers, and industries.

1.2.5.1 Grid-connected operation

In this mode, a MG is connected to a main grid or a network of MMGs. In such a case, MG trades energy with the main grid or other MGs to maximize its energy trading profit [17]. It buys energy when local generation is insufficient to satisfy the load demand and injects excess power into the main grid in cases where local generation exceeds load demand and ESSs are fully charged. As MG is connected to the main grid, the frequency at PCC voltage is set by the main grid, and MG cannot change it [18]. Furthermore, it can act as a grid-supporting unit by adapting its power to provide ancillary services to the main grid network, depending on its state, in order to avoid instability.

1.2.5.2 Islanded operation

In this mode, the MG is completely disconnected from the utility grid. It is isolated from the main grid and continues to operate as an islanded MG. Moreover, the local frequency and voltage are regulated by the distributed RESs and ESSs [19]. In this stage, ESSs are critical elements of the MGs that can maintain the energy balance, minimize power fluctuations, and improve reliability and system efficiency [20].

The ESSs absorb excess RES generation when the generation exceeds the demand. It can be used to supply power to the MG in periods where the demand exceeds the local generation. This minimizes any instances where RES power curtailment and/or load shedding should be carried out. In addition, ESSs can also be used to improve the voltage and frequency regulation of the islanded MG.

Both operation modes are represented in Figure 1.6.

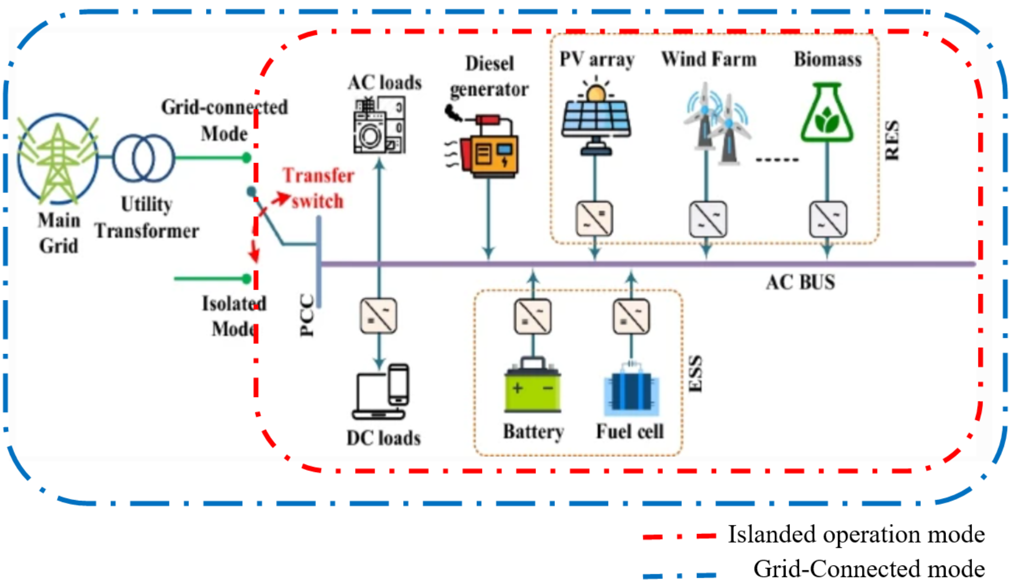


Figure 1.6: Island and grid-connected modes

1.2.6 Microgrid architecture

As previously mentioned, the MG network can either operate in grid-tied (grid-connected) or stand-alone (islanded) mode.

Based on the functionalities of the MG and the way the common bus is interconnected, the MGs can be classified into three different groups, depending on the way in which the AC and DC buses are connected, which are: alternative current (AC) MGs, direct current (DC) MGs, and hybrid MGs. The various architectures are further detailed in the following section.

1.2.6.1 AC microgrids

In this group, AC MGs have a common AC bus that is generally connected to mixed loads (DC and AC loads), DGs, and ESS.

AC MGs are more taken into account in research as they present several challenges in voltage amplitude and frequency controls, both active and reactive power flows, in addition to the connection to the utility grid [21]. An AC MG topology is shown in Figure 1.7.

The AC MGs are usually used, while the majority of the power sources in the MG generate AC voltages that can match the grid level through interfacing PCs. In such an AC-coupled local power system, the main power management requirement is to ensure that the power generated meets the load requirement. This issue becomes more important in the islanded operation mode, as the main control objective becomes the stabilization of AC bus voltage in terms of both frequency and amplitude. [21]

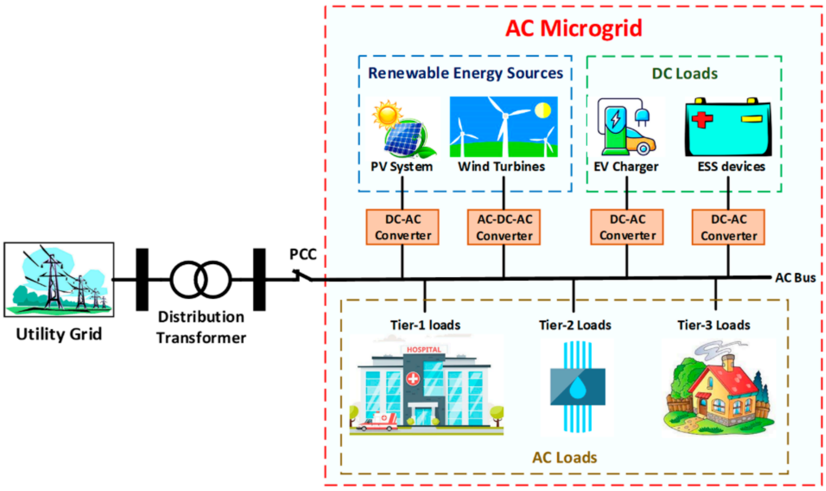


Figure 1.7: Topology of a AC Microgrid [22]

1.2.6.2 DC microgrids

In these MGs, a common DC bus is used to connect to the grid through an AC/DC converter. The operation principle of DC MG is similar to that of AC MG. Furthermore, comparing both AC MG and DC MG, it's better to use the DC MG since it is a good solution to reduce power conversion losses because it only needs one power conversion to connect the DC bus. Therefore, DC MG has higher system efficiency, a lower cost, and a smaller system [21]. Hence, a DC MGs system is considered in our project. A DC MG topology is shown in Figure 1.8.

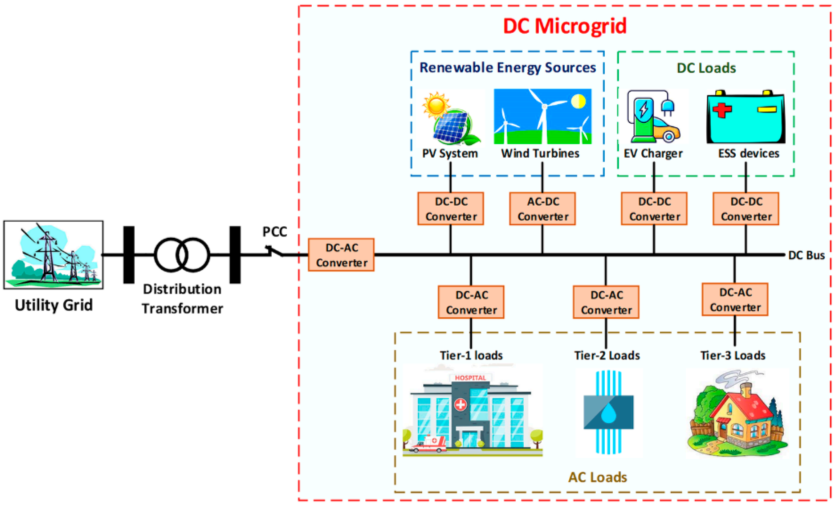


Figure 1.8: Topology of a DC Microgrid
[22]

1.2.6.3 Hybrid Microgrids

Hybrid MG systems are designed to acquire advantages from both AC and DC MG, as shown in figure 1.9. They are composed of two separate AC and DC parts[18]. It is a combination of AC and DC MGs in the same distribution grid, facilitating the direct integration of both AC and DC-based DG, ESS, and loads. This architecture has advantages of both AC and DC MG, such as the minimum number of interface elements, easier integration of DERs, reduced conversion stages, energy losses and total costs, and higher reliability. Moreover, when DG, loads, and ESS are directly connected either to the AC or DC networks, there is no need for synchronization of generation and ESS. [23][24]

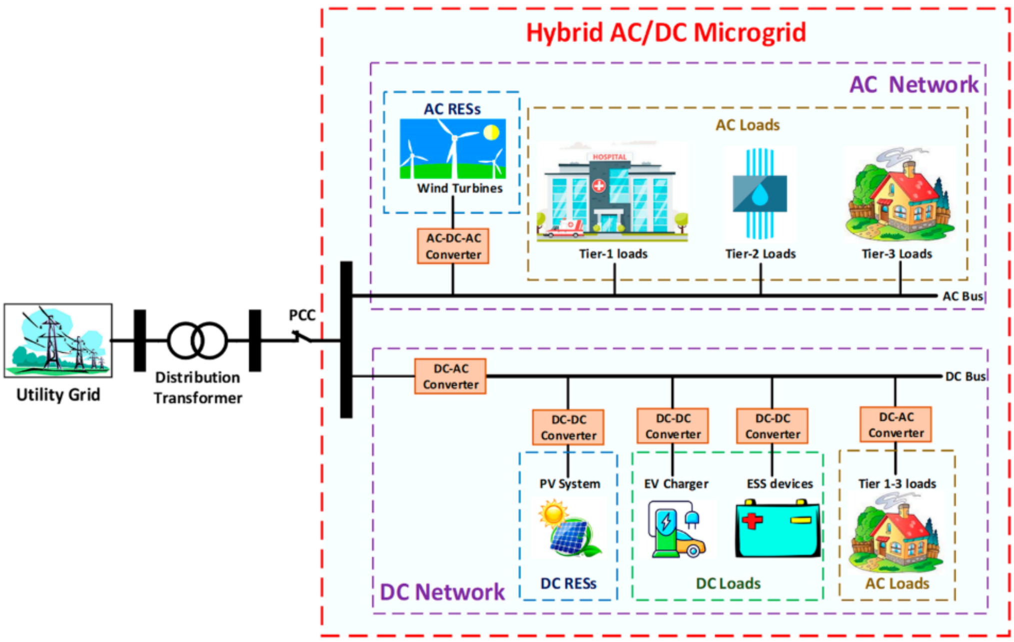


Figure 1.9: Topology of hybrid AC/DC Microgrid
[22]

1.3 Microgrid Resiliency

Before discussing MG resiliency, a definition of resilience must be agreed upon. The words resilience and resiliency are used interchangeably throughout the literature. Numerous organizations have different definitions of resilience, depending on their preferred application, but in its simplest form, resilience refers to the ability to function in the presence of a disturbance [25]. More precisely, resiliency includes the ability to prepare for and adapt to a sudden change, resist, and recover from attacks, accidents, or naturally occurring threats or incidents. [26]

MG can have a surplus or a need for power. In the grid-connected mode, the MG absorbs energy from its own generation components. Furthermore, if the system is in shortage or in need, power will be provided from the main grid, which provides its surplus power. In islanded mode, the MG operates as an independent power system. According to the different natural disasters that have risen, they may affect the MG system and its work routine. As a result, the resilience improvement of power grids against these natural disasters has become a major consideration for power and energy sector researchers and engineers in recent years. Therefore, the power industry has been focusing on developing methods to improve MG resilience. [27]

The resilience can be improved for a single MG to prevent it from damaging either one component or the whole system. Moreover, it can be improved for MMGs, which are networked MGs interconnected through transmission lines and maybe disconnected using circuit breakers or switchers depending on the demand of each MG.

There are some factors that affect the MG's resilience. It can be affected by any unit of the MG that has the potential to disturb its normal work. The list of factors that can affect resilience is presented in Table 1.1.

Table 1.1: Summary of Factors that Affect Microgrid Resilience.

No	Factor that Affects Resilience
1	Size of ESS
2	Layout of distribution cables (either above or below ground)
3	storage capacity
4	Distributed for centralized DERs
5	Size of DERs
6	Level of investment in system maintenance
7	System redundancy
8	Reliability and maintainability of all MG components
9	Rate and probability DER resupply

1.4 Multi-microgrid

As discussed in the above section, resilience can be improved for both MG and MMGs, which are networked MGs interconnected through cables or disconnected using switchers.

A single MG system can only produce and distribute power within a localized area, which is low-voltage (LV). Researchers seeking new techniques to improve the power system developed a new concept, the MMG. It is related to a higher-level structure, formed at the medium voltage (MV) level [28]. Figure 1.10 represents the MMGs system.

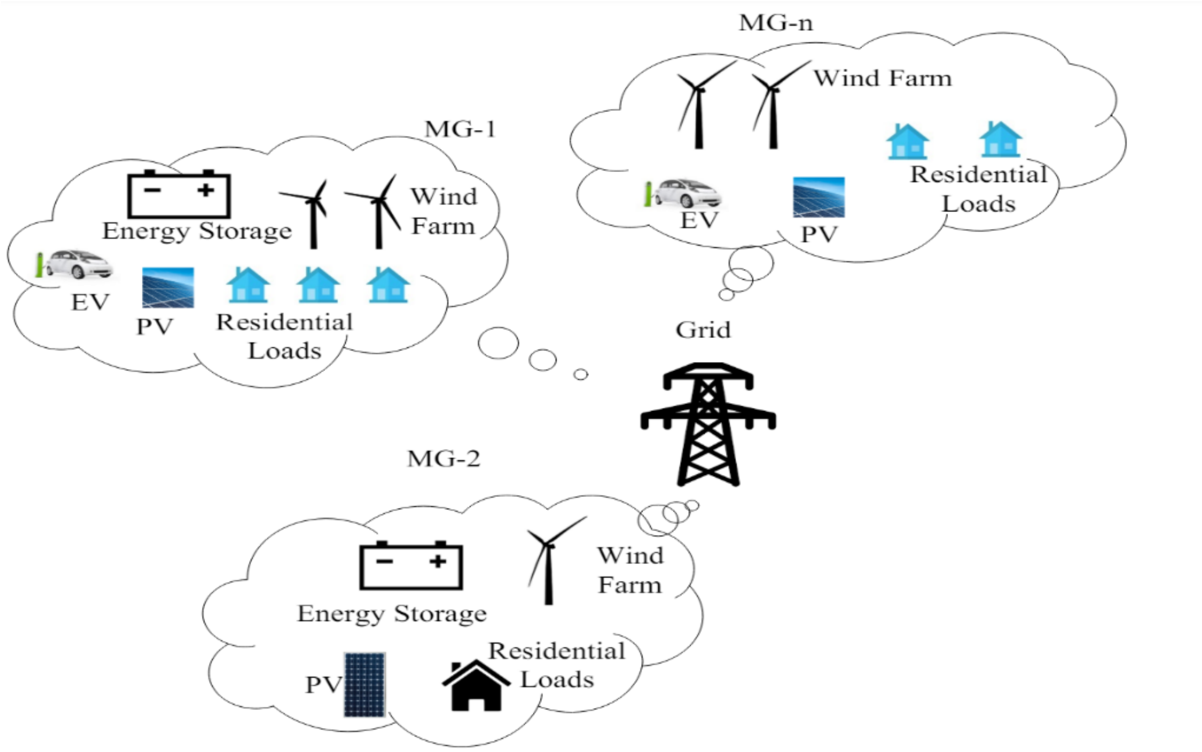


Figure 1.10: Typical networked microgrid (MMGs) system

The two-layer hierarchical model is shown in figure 1.11. The single MG central controllers (MGCC) are on the lower layer, implemented for the operation and management of the corresponding MGs. Both the communication network and tie line are on the upper layer, which are satisfying data communication and power exchange [29].

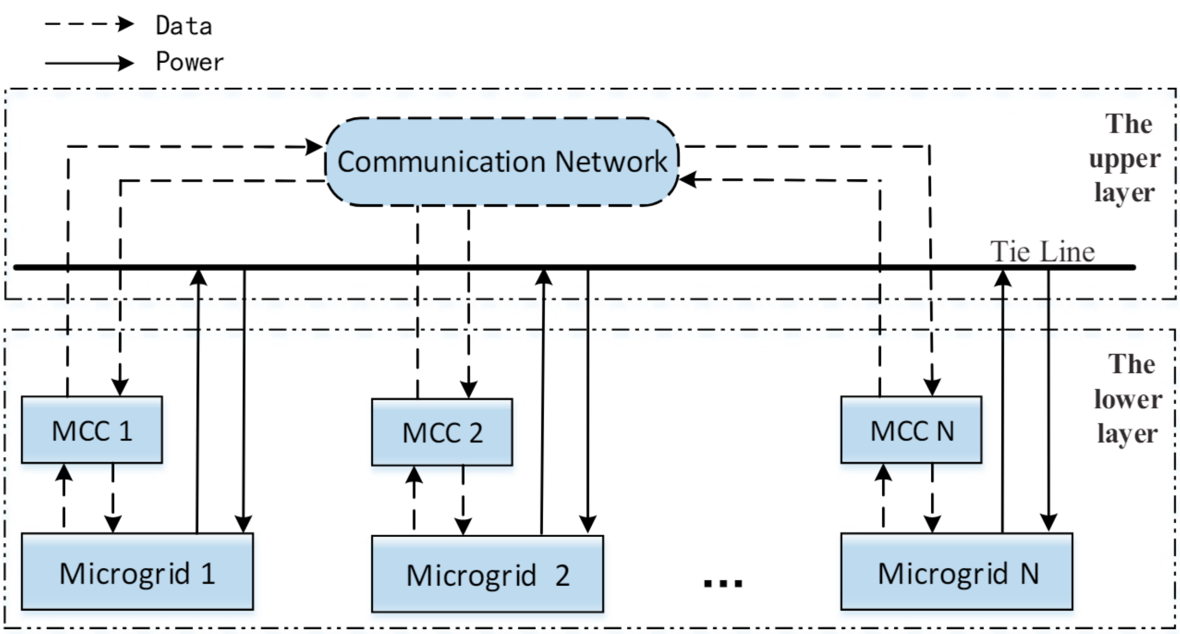


Figure 1.11: Two-layer hierarchical model of Mult-microgrid

The MMG system can operate in five modes, which are explained briefly as follows and represented in figure 1.12 [30]:

- Interconnected mode: the MMG system is connected to the distribution grid, which regulates the voltage and frequency of the MMG system.
- Islanded mode: Following islanding, the MMG system remains in this state until reconnected with the distribution grid.
- Synchronization: During this time, the islanded MMG system synchronizes its frequency, voltage, and phase sequence with that of the distribution grid in preparation for reconnection.
- System collapse: A complete blackout occurs across the MMG system due to a single or multiple contingencies, leading to the shutdown of all DG units.
- Black start: From a state of system collapse, the MMG system is slowly restored by initially reconnecting DG units, followed by the formation of small islands.

Regardless, MMG can operate in five modes, but mostly it operates in grid-connected mode when it is connected to the MV distribution grid and also in autonomous or islanded mode when it is disconnected from the MV distribution grid [31].

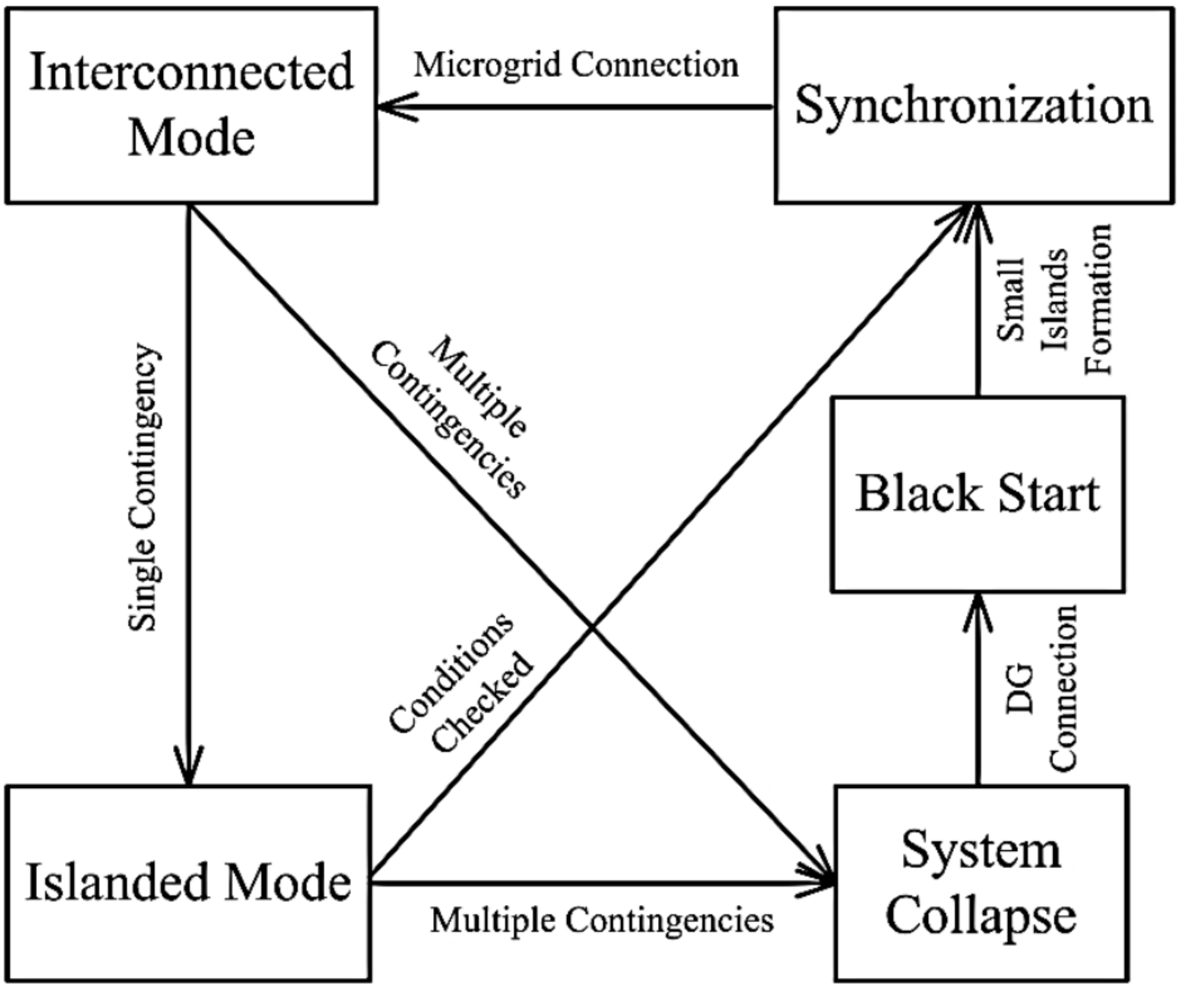


Figure 1.12: Operating modes of multi-microgrid

1.5 Multi-Agent System

Nowadays, simulation and computation tasks are becoming significantly more complex as their size continues to increase. Thus, it is a difficult challenge to handle using centralized methods. Researchers from different fields are applying the MASs. [32]

MASs is defined as a system that consists of two or more agents that cooperate with each other while achieving local goals, and these agents collaborate together using their skills and knowledge to solve problems that a single agent finds difficult or ineffective to solve on its own. The MAS is described in figure1.13.

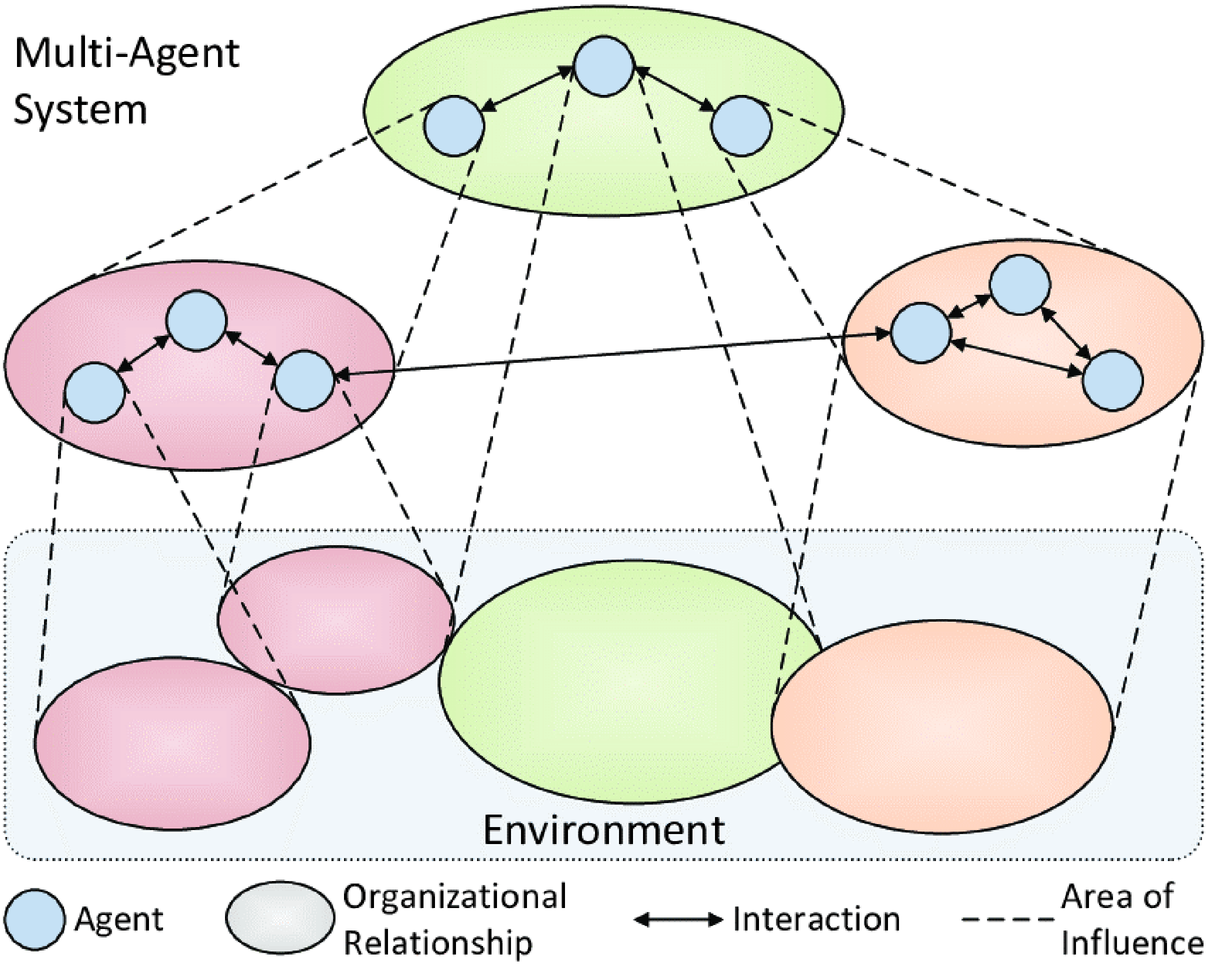


Figure 1.13: Multi-Agent System description
[33]

1.5.1 Agent

Each agent is defined as a sophisticated computer system installed in each area to autonomously solve a growing number of complex problems to meet its design objectives [34]. It works by sharing its knowledge with other agents or by taking initiative. Even a single agent can operate as a system. An agent is an entity positioned in any environment to sense and extract different parameters that are used to make a decision, based on the aim of the entity. It performs the necessary action on the environment based on this decision.[35]

The above definitions contain four important keywords, which are: agent, environment, parameters, and actions. First, An agent entity can be a hardware or software entity that possesses social coordination and communication abilities in order to achieve a larger overall goal by addressing individual tasks. The environment refers to the location of the agent. It can be a network or software, The agent uses the information sensed from the environment for decision-making [36]. However, the parameters are introduced as different types of extracted and sensed data from the environment by the agent, which can perform an action that results in some changes in the environment[35]. Figure 1.14 describes the structure of the agent in the environment.

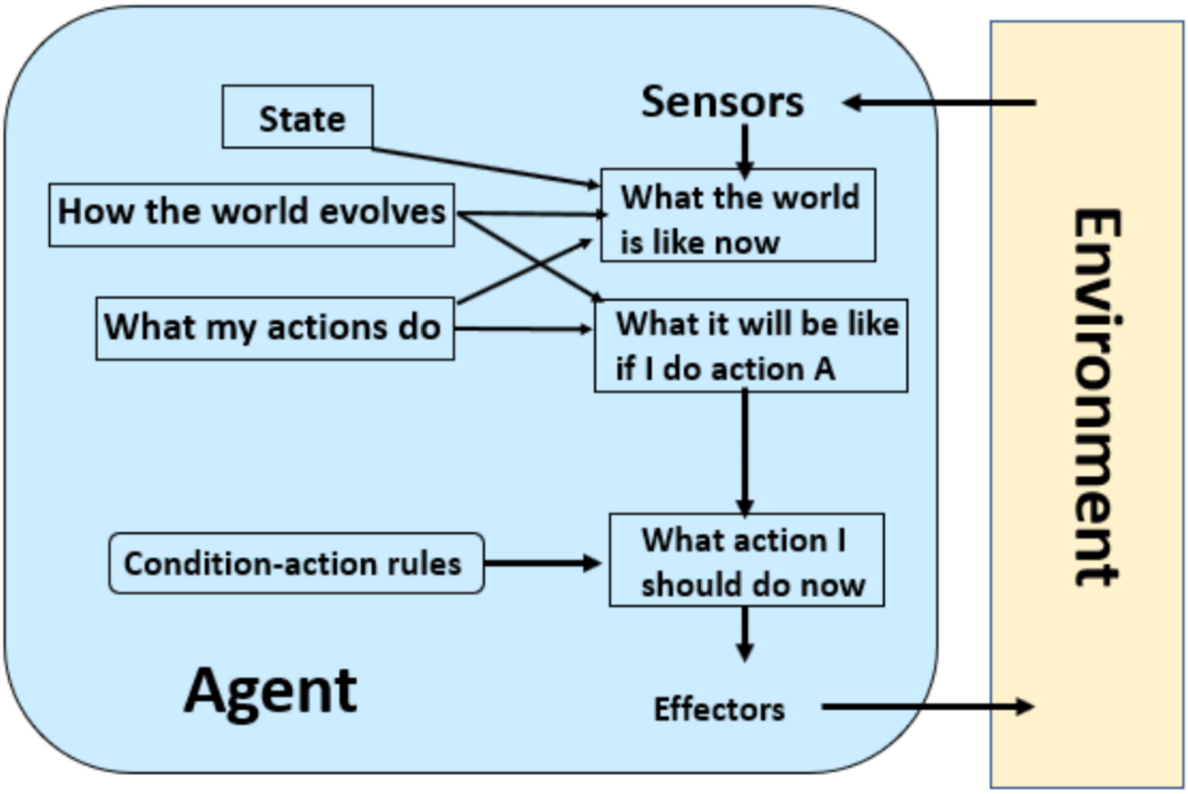


Figure 1.14: Agent and the environment
[37]

1.5.2 Multi-Agent System Applications

Depending on the salient features of MAS, including efficiency, low cost, Flexibility and reliability make it an effective solution to solve complex tasks. This technology has become indispensable in numerous disciplines, such as computer networks, power grids, robotics, city and environmental buildings, and modeling. [35]

A summary of these applications and their examples is outlined in figure 1.15.

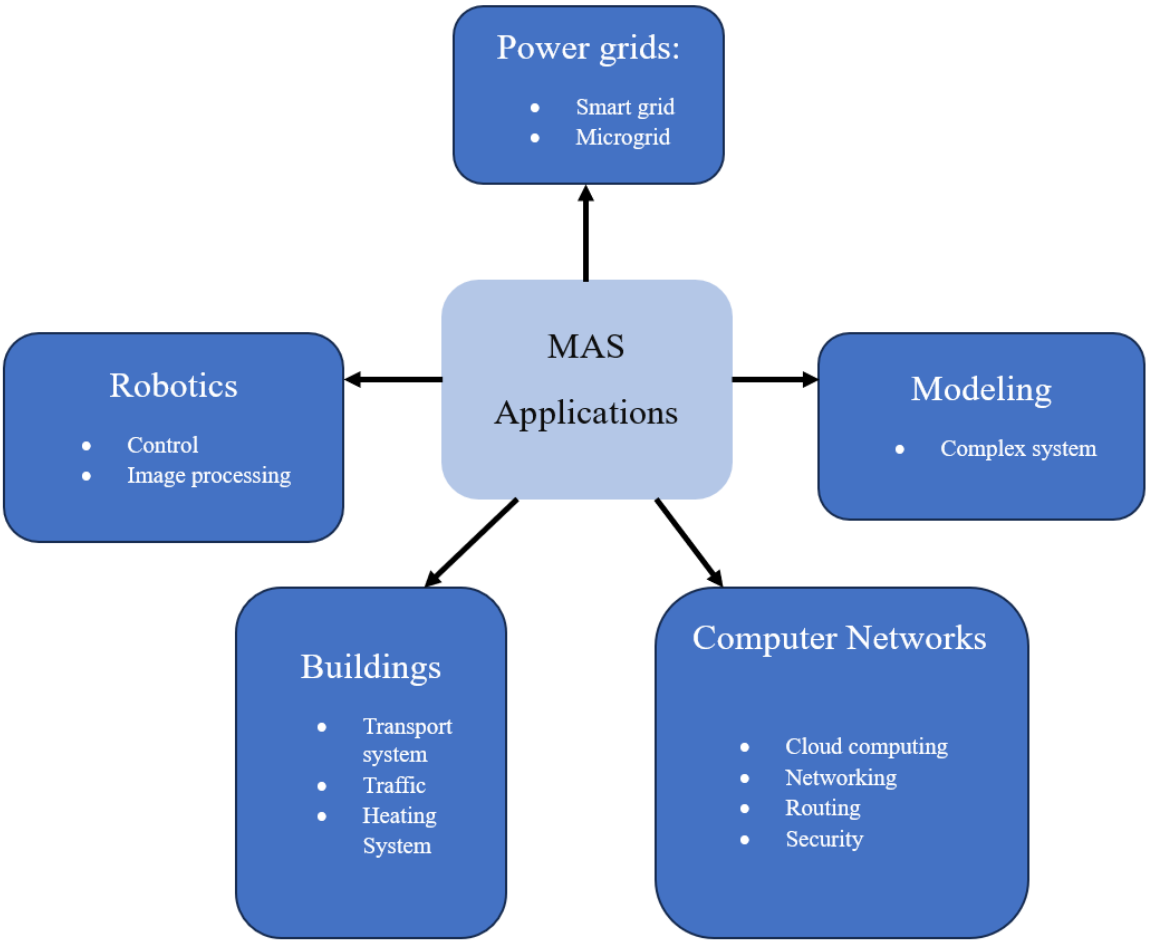


Figure 1.15: Multi-Agent System in Different Disciplines

1.5.3 Multi-Agent System Advantages

The construction of MAS integrates technologies from different areas of knowledge and fields because of their benefits, cited as follows:

- Scalability: Distributing the workload with MAS requires handling larger-scale problems by distributing the workload among multiple agents.

- Robustness: any failure in any agent doesn't stop the functionality of the system; it works with other agents, which take over the tasks of the failed agent.

- Flexibility: MAS can adapt to any required change in environments or requirements.

- Efficiency: Connecting more agents together requires a quick-find solution. [38]

1.6 Conclusion

The main objective of this chapter was to present an overall introduction to MGs and MMGs, followed by their classifications, operation modes, and the control approaches used in MGs. The MAS is one of these approaches, highlighted through this chapter by defining its components, its importance, and its application in numerous fields.

Chapter 2

Multi-Agent System in Networked Microgrids

The increase in demand for energy pushed researchers to seek out new technologies in order to enhance the power system. The reached technology is MG.

MGs are an advanced, complex technology that needs to be controlled. There are numerous approaches and methods to control these MGs. One of these approaches is MAS communication technology. Choosing the MAS technique for the MG control allows a single MG to operate autonomously and/or collaboratively with other interconnected MGs.[39]

This chapter represents the technology used to control the EMS of each of a single MG and MMG, highlighting the used algorithms and methods.

2.1 Single microgrid

In this section, we will deal with a single MG in island mode. As mentioned previously, MG is composed of three main parts:1) Generation and production components, which are the different RESs and non-RESs; 2) Storage components, which include ESS with all its possible categories; and 3) Consumption, which includes both static and dynamic loads. MG can easily manage its EMS by using a specific method and algorithms. It closes or breaks the circuits breakers of each components (Agents) in the aim of protect the system itself.

2.1.1 Multi-agent system technology in an islanded microgrid

As each MG can operate independently as a power unit. Numerous assumptions were made to control MG one of them is by using MAS. The MAS is a very effective tool for MG real-time operation and control. In this case, it is islanded because the circuit breakers connecting to the main grid are off, so there is no exchange of power with the exterior systems. [40]

The MAS technique requires the development of a representative agent for each MG component and a supervisor agent, which represents and controls the MG in its internal environment and ensures the success of a bi-directional information exchange between each embedded agent associated with each MG component [41].

Actually, the agent can execute two function: Measurement recovery to measure the different parameters (current, voltage, irradiance, temperature,etc.) and Physical Action to be physically connected/disconnected between component, assuming that the communication is based on basic Ethernet communication,

As covered in the previous sections, the representation of the Agent associated to each element, controlled by the main agent inside a MG environment that ensure the communication and data exchange is shown in figure 2.1.

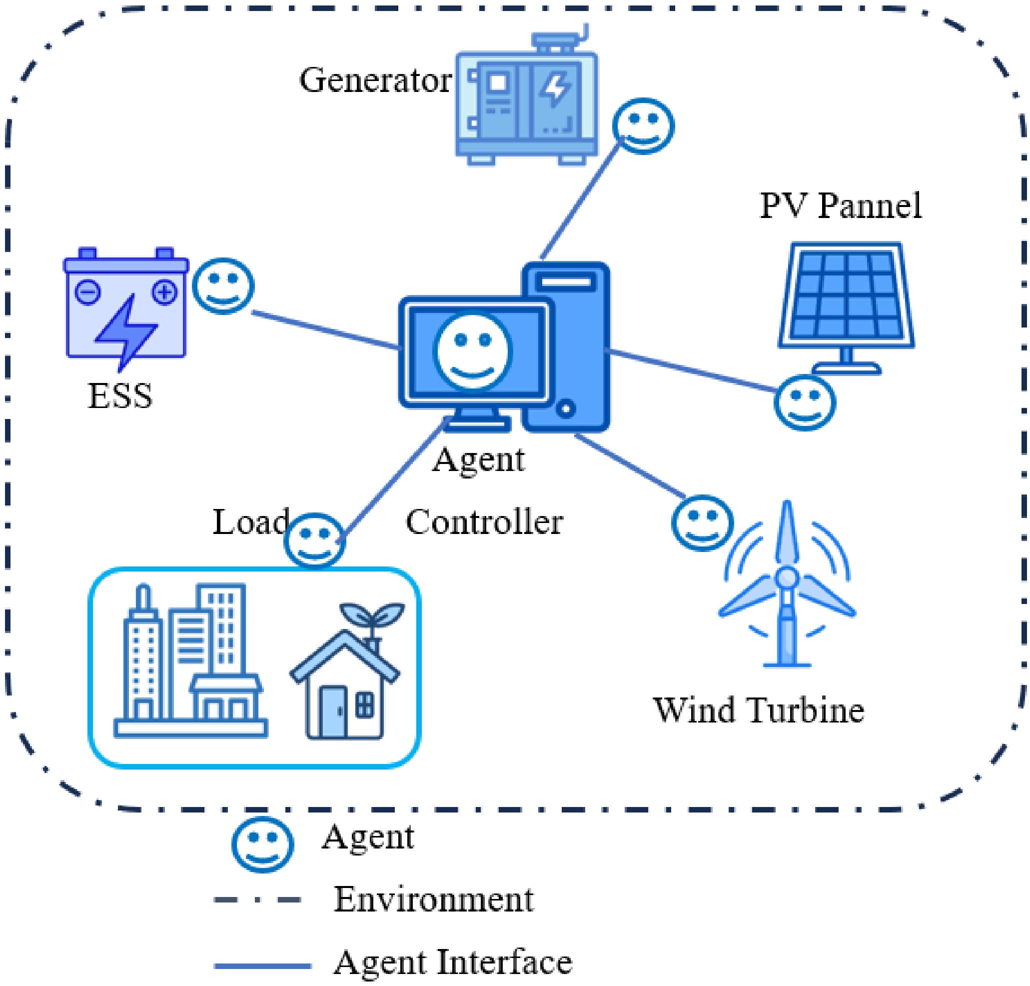


Figure 2.1: Application of Multi-agents in microgrid operation

2.1.2 Communication between agents inside a microgrid

Communication between agents is the fundamental function of MAS, enabling interactions to gain external information and distribute control commands.

MG Agents communicate with each other to achieve specific objectives and are intelligent enough to react to the dynamic environment. An agent sends or receives a message by using agent communication language (ACL). This characteristic matches the control system as it enables the operation of plug-and-play, active, and distributed approaches.[42]

In MG, the combination of ACL and Transmission Control Protocol/Internet Protocol (TCP/IP) over Ethernet provides a strong framework to communicate and control between various agents.

2.1.2.1 Agent Communication Language (ACL)

As mentioned previously, in MG, agents use specific communication languages and protocols in order to communicate efficiently. ACL is used for high-level communication between the associated agents of each MG component. This language constructs their message using performative such as request, inform, query, etc.

2.1.2.2 Communication protocols

The communication infrastructure is based on ACL messages and TCP/IP. The messages are transmitted via Ethernet cable.TCP/IP is a link that provides the network with fast information exchange.

In MG, it is essential for enabling reliable communication and data exchange between agents, and it also ensures secure communication through encryption. The Internet Protocol Version 4 (IPv4) addressing is commonly used to address a system within the TCP/IP.

IPv4 is a 32-bit address that allows the identification and location of devices within a network. It enables subnetting, which allows the network address to be divided into sub-networks.

The Ethernet is the most commonly used networking technology for LANs and provides the essential physical and data link layers for TCP/IP communication.

2.1.2.3 Communication flow

In an islanded MG, dealing with agents inside a MG means that all agents are under the same network (same LAN), and each component is connected to the same router.

This transaction is made as follows:

After connecting all the agents via Ethernet cable, each of these agents is assigned an IP. Then, the message indicating the demand (need or surplus) must be constructed using ACL. The transmission of the message must be done after it is encapsulated within an IP packet,so that this latter is also encapsulated forming an Ethernet frame, which includes the Media Access Control (MAC) Address of both the source and the destination. The frame is then transmitted over the physical channel i.e Ethernet cables.

After it is transmitted, at the destination level, the message must be de-ecapsulated by the receiving agent to extract the IP packet from the frame and decode the ACL message to retrieve its content. At this stage, the role of the controller agent starts. It sends a request performative message to the corresponding agents, and wait for the inform performative message which is the reply message corresponding to the sent request.

Finally, the controller agent analyzes the message once again and determines the solution to satisfy the MG requirements, then sends a signal to the breakers to control the power flow.

Figure 2.2 represents the encapsulation and the de-encapsulation process made at each layer of the TCP/IP protocol.

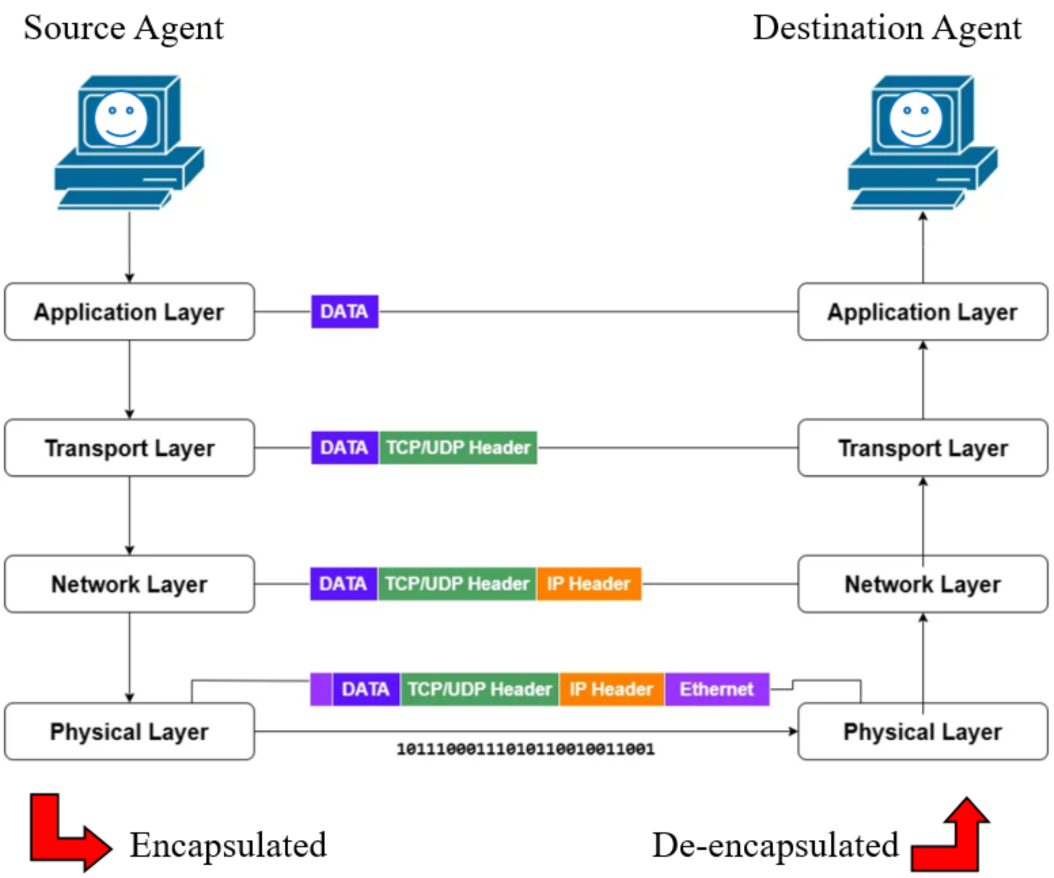


Figure 2.2: Encapsulation and De-encapsulation process in TCP/IP model

2.1.3 Control of agents within a Microgrid

MAS technology controls the MG using connectivity with the different MG agents, in which the supervisory agent sends a request and the corresponding agents receive and transmit the needed information and ensure a successful exchange of data by closing or breaking the circuit breakers associated with each MG component.

More precisely, depending on the rules and knowledge bases that compose the agent database [43]. This database manages to make a decision depending on the desired actions.

The power exchange occurs from one MG to another through the controller agents. After the communication is done, a signal flag sends 1's or 0's to make a decision to break or close the breakers to satisfy the demands of the system.

This point is summarized through figure 2.3.

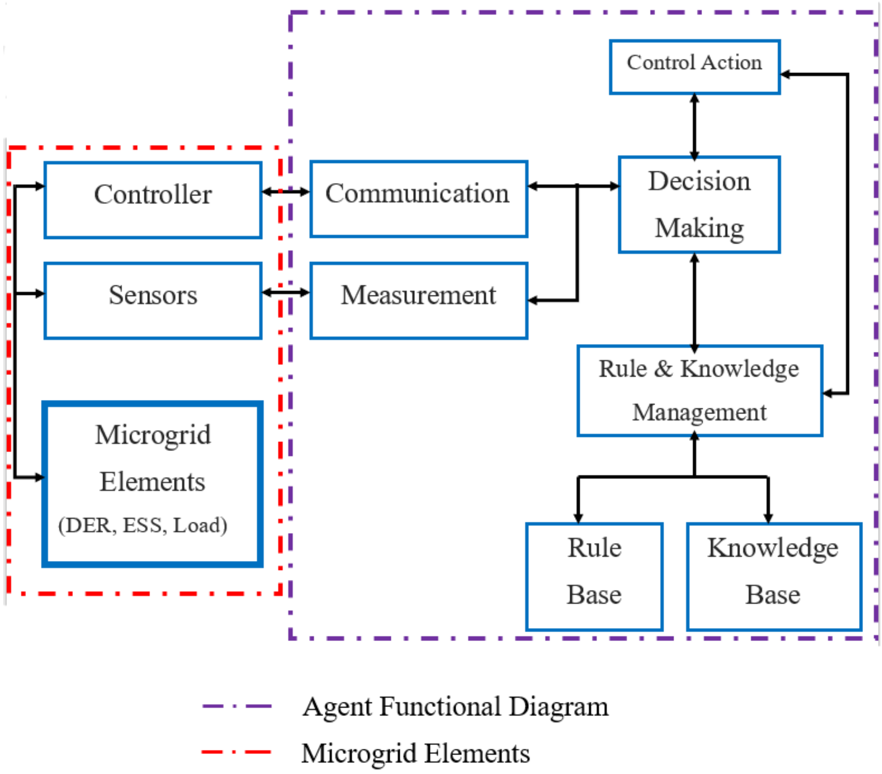


Figure 2.3: Functional diagram of agents

The designed single MG has four main agents which are: Load Agent, control Agent, DER Agent, and ESS Agent. Each of these agents has its specific functions, tasks and characters. Each agent task is represented in table 2.1.

Table 2.1: Microgrid Agents' tasks

Agent	Tasks
DER Agent	-Assembles the associated data with the energy source. - Ensures the availability of the power in real time.
Load Agent	- Obtains the load consumption. -Assembles the load information such as its voltage, current, and power. - Responsible to control and protect the load.
ESS Agent	- Obtains the recommendations from the control agent in order to store or to provide energy.
Control Agent	- Responsible to protect the MG operation modes, monitoring and controlling all agents within MG. -Supervises the state of MG, by controlling the PCC.

As previously mentioned the communication method between agents, the control algorithm and flowchart must be shown to clarify further how the MAS works.

In a MG, the storage unit (ESS), consumption unit (dynamic/static), and production unit (non-RES/RES) are controlled continuously based on the randomness of both the load consumption and the RES production. The MAS estimates all logical decisions and chooses the most suitable action for a suitable EM.

The system follows a procedure. Firstly, a communication occurs between the load and the DER agents through an ACL message. If the DER power is not sufficient to satisfy the load, it investigates the storage unit. The ESS supplies the full amount required until it gets drained, and at each instant, the ESS agent must check the state of charge (SOC) of the ESS.

Moreover, after taking from the ESS, the load is satisfied, and if there is still surplus energy, the ESS agent checks the SOC and stores the surplus power in the ESS till it is full once again.

Finally, if all the systems are satisfied, the control agent closes the PCC breaker to connect within the grid.(case studied in the coming sections).[42]

The SOC is explained in figure 2.4 and table 2.2.

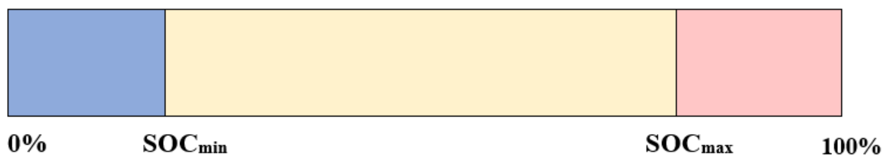


Figure 2.4: State of charge representation

Table 2.2: State of Charge ranges

0 - SOCmin	Undercharging mode
SOCmin - SOCmax	Range of SOC, the ESS may charge or discharge
SOCmax - 100	Overcharging mode

The flowchart represented in Figure 2.5 summarizes the previous procedure.

The red boxes imply the grid-connected mode. Whether a MG has a surplus or a need, an exterior exchange will occur within a MMGs.

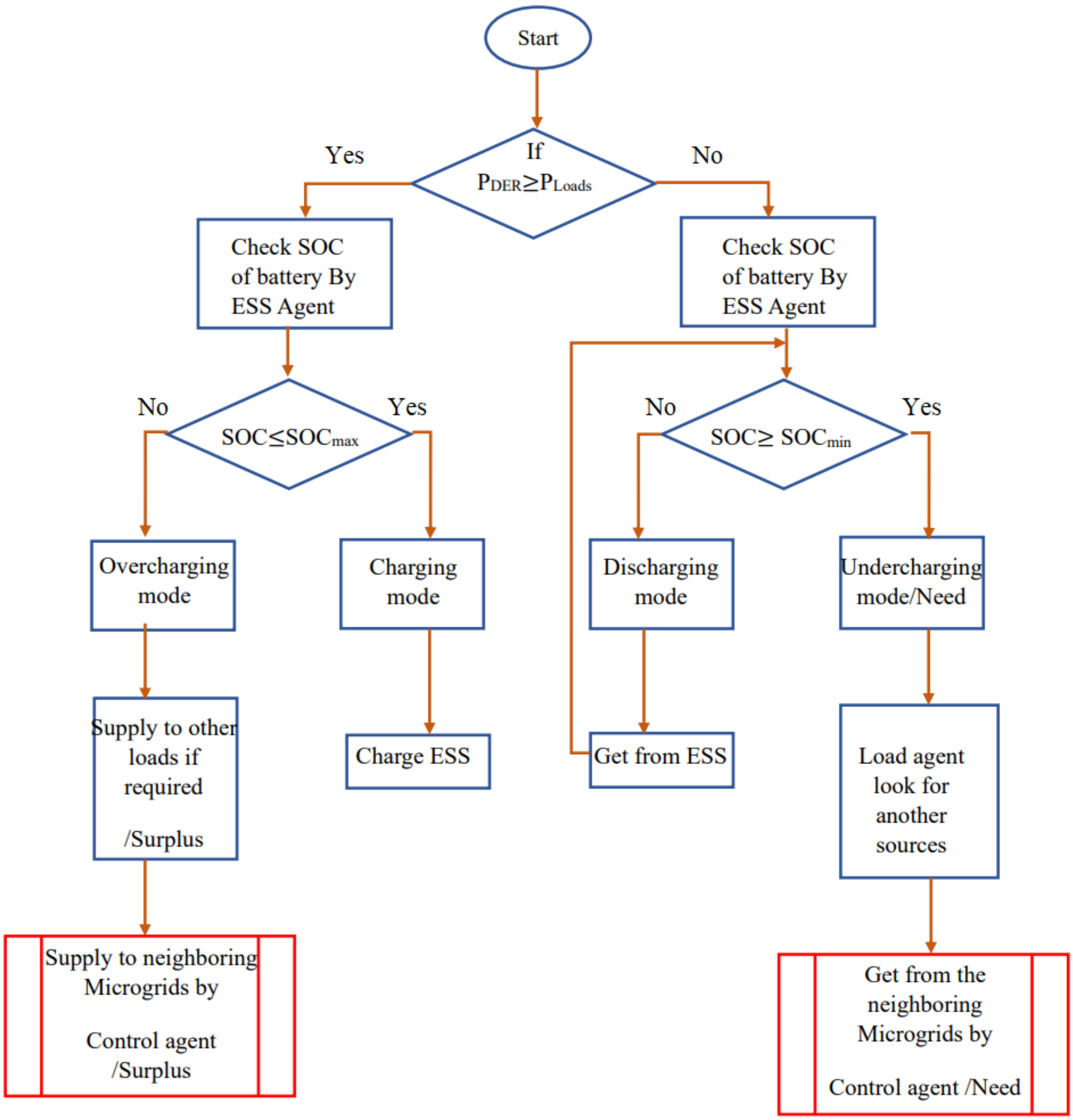


Figure 2.5: Flowchart of the control strategy in a Microgrid using agent

2.2 Multi-microgrid

As described previously, MG can generate and distribute power within a localized area, but MMG can exchange power within more than one MG to ensure a good distribution of power and satisfy each system.

In this section, we will deal with a MMG, which is a networked MGs interconnected with a two way lines: Communication and power, these MGs must be in grid-connected, so each MG is able to exchange its own data with others MGs within the network.

2.2.1 Multi-agent system technology in a networked microgrids

The above section was about implementing an associated agent for each MG in order to organize communication and power exchange between components. In some cases, a single MG cannot satisfy itself (as shown in figure 2.4 inside red boxes). The solution is to connect it with other MGs to ensure better satisfaction with energy production.

The MAS technique within the MMG requires to connect a global supervisor agent with the controller agent of each MG within the Networked MGs. This global agent controls all the MGs and ensure a two-way information exchange between each controller agent.[38]

Figure 2.6 represents the communication between controller agents and the global agent in a multi-microgrid operation.

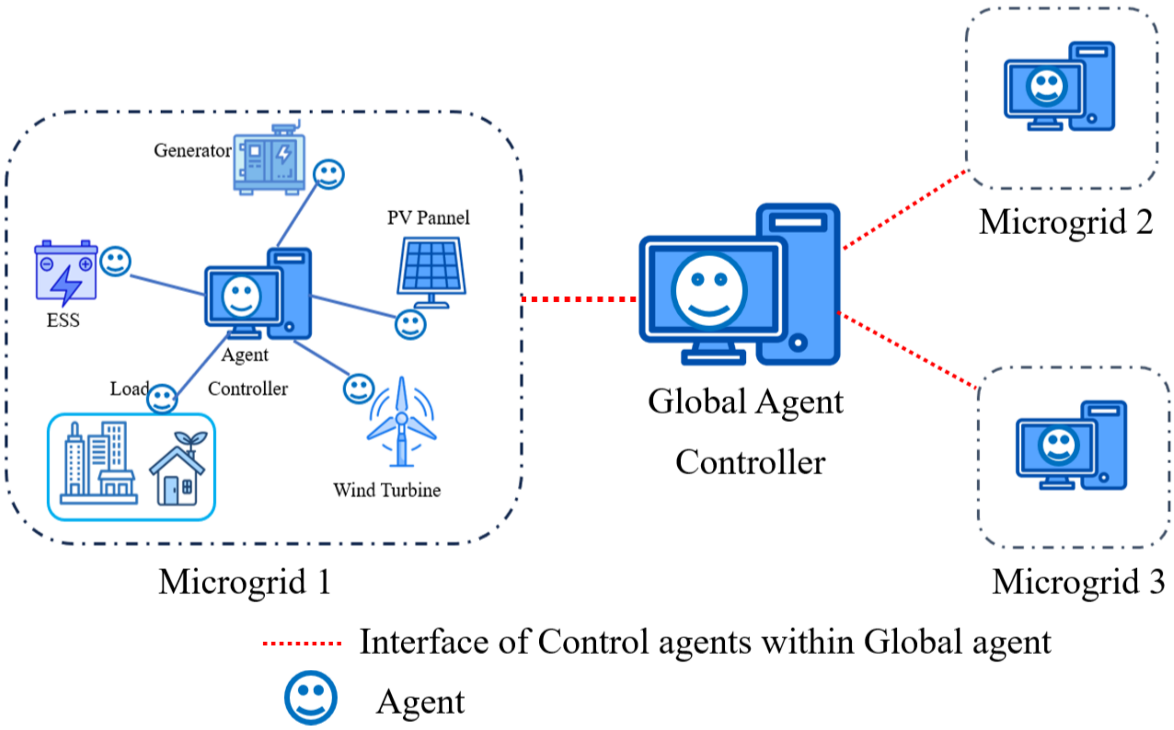


Figure 2.6: Control agents and global agent in multi-microgrid operation

2.2.2 Communication between microgrids

The MG network is a complex system where there are multiple MGs, and each of them is self-organized by maintaining the supply-demand balance within internal elements. Either in MMG or inside a single MG, agents communicate between them using ACL, and messages are transmitted over Ethernet cables using TCP/IP protocols. Each controller agent associated to each MG communicate with the other by an ACL message transaction via an Ethernet cable.

2.2.3 Communication flow within a Multi-microgrid

In a grid-connected MMG, it deals with the controller agent of each MG with the network.The data exchange is made as follows:

After connecting all the controller agents with the global controller agent via Ethernet cable, all of these agents are assigned an IP address.

After each MG analyzes its data (section 2.1), the controller agents make a decision if the preformative message is to request or to send the power. It can broadcast the need, the surplus, or both.

Assuming that the first MG is in need. The encapsulated ACL message leaves the first MG within an IP packet, then forms an Ethernet frame including the MAC addresses of each destination and source. This procedure is done from the controller agent to the global controller agent, then to all the surrounded controller agents of the other MGs; this is called the broadcast (one to all). The message starts its journey to investigate which MG provides the needed data to satisfy MG's needs.

Meanwhile, MGs with a surplus inform their controller agents about their states.This information is transmitted to the global controller agent, which analyzes the request message to find its destination.

Finally, the global controller agent analyzes the message and determines the destination to satisfy the MG needs by sending a signal to the breakers to control the power flow.

2.2.3.1 Control of agents in a Multi-microgrid system

MAS technology controls the MMG using connectivity with the different MMGs, in which the supervisory agents (controller) send their requests and the global controller agent collects these data, then monitors the system by ensuring the power connection between the requested MG and the corresponding MGs with a surplus.

The power exchange between MGs occurs as follows: The first case is when a failure happens in an area of a MG or the whole MG. The associated agents of the failed component, or the MG, identify the causes and send the ”0” flag to the breaker or switch agent to isolate that area and mitigate the impact of cascading failures; this helps to not affect other MGs since a failure at one MG can affect nearby MGs. When the fault is solved, the associated agent should reconnect the system within the network. [44]

In the second case, when MG component agents communicate between them and need power, they send the ”1” flag to the control agent in order to close the breakers and connect with the exterior environment by sending a request to the global agent in order to transmit it to the MGs with a surplus of power, so they will provide the needed amount to satisfy their needs.

These two cases are the most common and may affect the normal work of a MG or MMG.

The flowchart represented in figure 2.7 summarizes the previous procedure

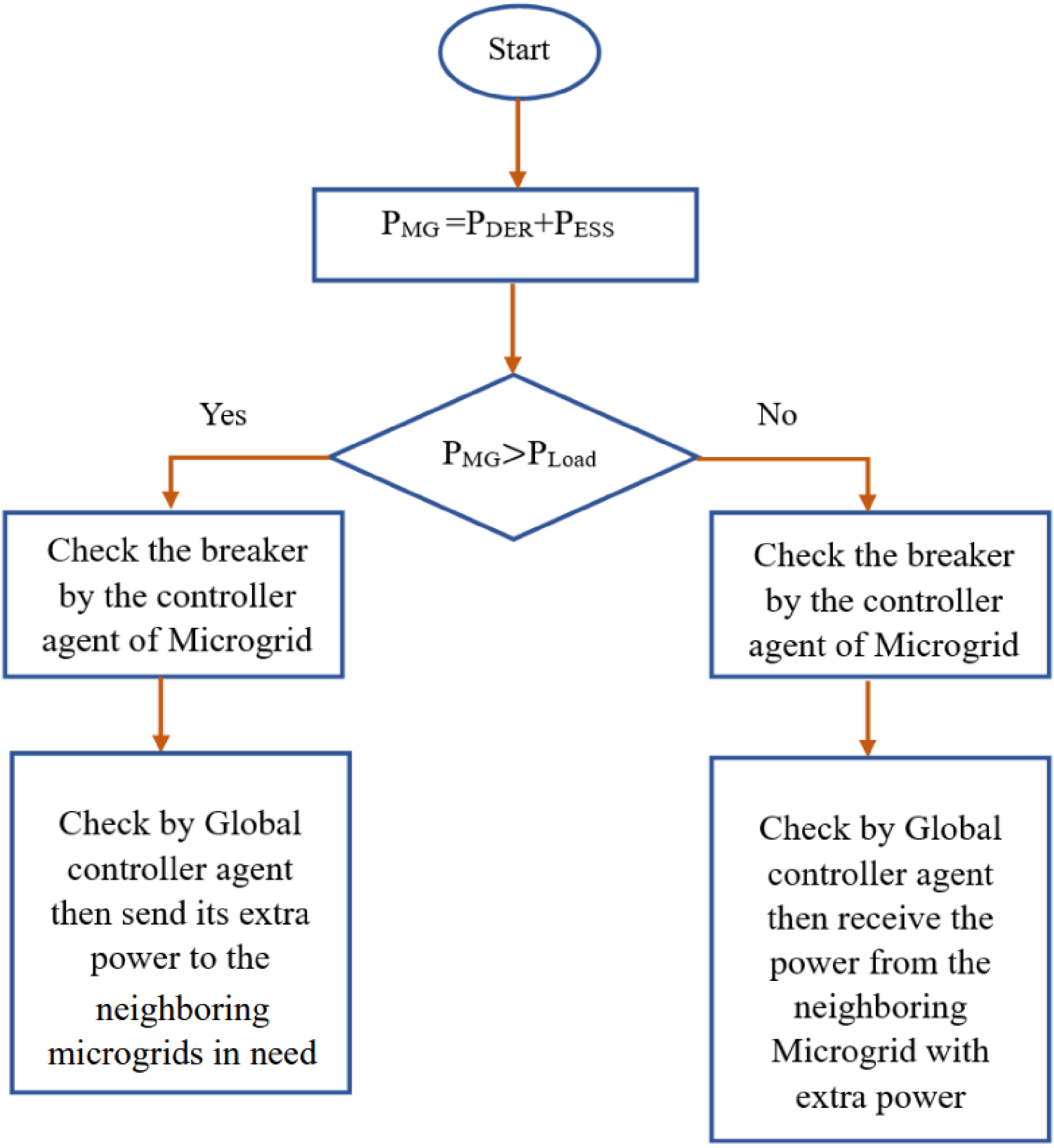


Figure 2.7: Flowchart of the control strategy in a Multi-microgrid using agent

2.3 The proposed approach

This section outlines the step-by-step approach used in order to apply the MAS communication technology. The proposed approach is to use the following flowchart inside one MG and between the n-MGs interconnected with each other.

2.3.1 Single Microgrid proposed approach

The proposed flowchart represented in figure 2.8 is used to calculate each MG's extra power. Thus, depending on the value of this extra power, it controls the state of each breaker assigned to each MG. There are two breakers, the first one (Breaker1) allows the send and the second one (Breaker2) allows the request for the power. (Set 1 to close, 0 to break).
Table 2.3 describes inputs and outputs of a single MG.

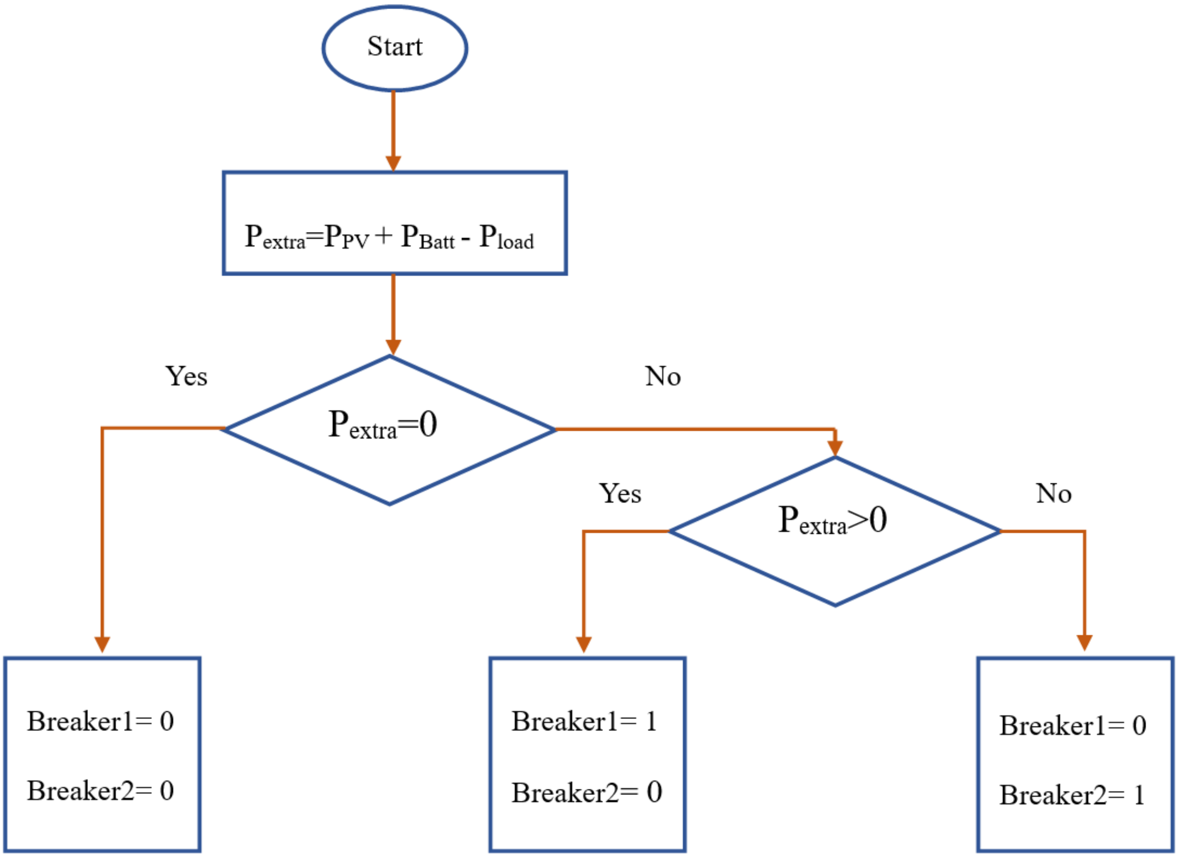


Figure 2.8: Flowchart of the proposed approach for single microgrid

Table 2.3: Inputs and outputs and their descriptions

Inputs/Outputs	**Description**
Ppv	It represents the instantaneous power delivered from the PV source.
Pextra	It represents the extra power delivered from the MG.
PLoad	It represents the power absorbed by the load.
Pbatt	It represents the power remaining inside the battery.
Breaker1	It represents the state of the breaker that delivers power (Surplus register).
Breaker2	It represents the state of the breaker that receives power (Resilience register).

2.3.2 Multi-microgrid proposed approach

The previous flowchart is used to compare the extra power of each MG and the power entered into each MG in order to control the state of each MG, whether it is in need or in surplus of power.

The flowchart represented in figure 2.9 summarizes the process of each MG in sending or receiving power. It represents the power exchange between two MGs to show the state of their breakers, and this will be applied to n-MGs.

Table 2.4 describes the breakers of each breaker system on each MG.

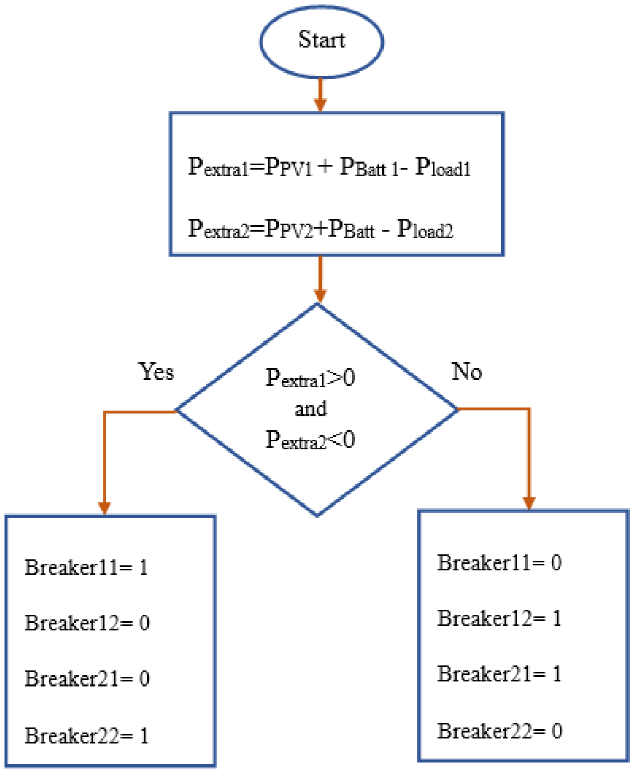


Figure 2.9: Flowchart of the proposed approach for Multi-microgrid

Table 2.4: Breakers of each microgrid and their descriptions

Breakers	**Description**
Breaker11	It represents the state of the MG1 breaker that delivers power (Surplus register).
Breaker12	It represents the state of the MG1 breaker that receives power (Resilience register).
Breaker21	It represents the state of the MG2 breaker that delivers power (Surplus register).
Breaker22	It represents the state of the MG2 breaker that receives power(Resilience register).

2.4 Conclusion

The MAS presents the smart interfaces of the MG system. The main objectives of this chapter were to present the MAS communication technology and its impact on controlling the MG and communication within a networked MG, highlighting the proposed approaches and algorithms.

Chapter 3

Implementation of the proposed approach

This chapter presents the designed models to simulate the MG and MMG systems using both Cisco Packet Tracer and MATLAB Simulink. The aim of this study is to improve the resilience of both MMG and MG. The simulation incorporates the main components of a MG, including generation units, i.e., RES non-RES, storage units, i.e., ESS, and consumption units, i.e., static and dynamic loads.

In order to satisfy the communication infrastructure and manage the power flow of MMG and MG, the following sections outline the process.

3.1 Sizing of the microgrid

In this chapter, we will deal with the islanded and grid-connected MG.For the islanded MG, the system is implemented by connecting the main components: the PV system, the ESS, and the load. However, in the grid-connected MG, the system is implemented by connecting several MGs, separated by circuit breakers.To size our system, we need to take into consideration the localization and the demand of the system. The sizing is done using PVSyst and the global solar atlas.

PVSyst is a software package used to study the size, simulation, and data analysis of PV systems. It allows users to model various aspects of a PV system and extract the solar irradiance, module characteristics, and electrical configuration. The Global Solar Atlas is an online platform created by the World Bank Group that provides access to solar resource data and tools for assessing solar energy potential worldwide.

To design a PV system, we first need to choose the location where we want to install it. In this study, we chose Boumerdes, Algeria. The sizing process involves the following steps:

3.1.1 Solar data analysis

Depending on the global solar atlas, we extract the weather and irradiation data for any location worldwide, as illustrated in figures 3.1 and 3.2, respectively. (Appendix A)

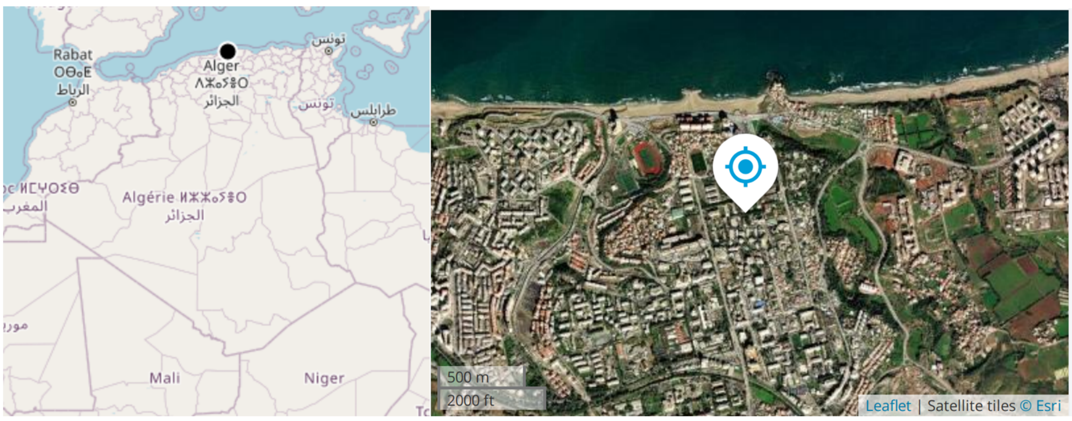


Figure 3.1: Geographical site, Boumerdes, Algeria.

Figure 3.2: Annual average irradiation, Boumerdes, Algeria.

3.1.2 Generation unit sizing

In our case, the generation unit is represented by the PV system, which contains the PV array and the maximum power point tracking (MPPT) controller. The use of PVSyst software was to select the type of PV array and calculate the number of PV arrays in series and parallel. (Appendix B)

3.1.3 Storage unit sizing

It is an indispensable system in a MG. In our case, we have three MGs, as mentioned previously. Each ESS is used to store excess energy produced by the PV system during daylight, and it discharges during the days of autonomy or during night use. (Appendix B)

3.1.4 Consumption Unit Sizing

Starting with analyzing the energy demands of the load and determining the peak power demand depending on the daily energy consumption. In our case, we used three different MGs. Each MG must have a different load in order to test and achieve the goal of resiliency improvement.

3.2 Used softwares Overview

3.2.1 Cisco Packet Tracer Overview

Cisco Packet Tracer is a powerful network simulation tool developed by Cisco Systems. It allows users to create different network topologies and simulate networks, including LAN, WAN, and wireless local area networks (WLANs). The software provides a graphical user interface to design and configure devices such as routers, switchers, clients, and servers. [45]

In this chapter, it is used to realize the communication infrastructure between agents. Each agent is represented by a device that has its own IP and MAC addresses.

3.2.2 MATLAB Simulink Overview

MATLAB Simulink is a simulation and model-based design software for dynamic and embedded systems developed by MathWorks. It is used to simulate systems before they are implemented in the real world.

In this chapter, it is used to build the MMG and MG environments in order to exchange power.

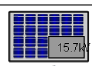
3.3 Single Microgrid

3.3.1 Communication within a microgrid

To design a MG network using the Cisco Packet Tracer, we represent each agent by a device, including its IP and MAC addresses.

The four devices within a MG represent the consumption (load) agent, the storage (ESS) agent, the generation (PV) agent, and the controller agent. These devices are represented in table 3.1.

Table 3.1: Agents configuration in Cisco Packet tracer

Agent Component	Type	Configuration
Load Agent	Thing	 Load
ESS Agent	Battery	 ESS
PV Agent	Solar panel	 PV System
Controller Agent	PC	 Controller Agent

We connect the above devices under a switch, as shown in figure 3.3.

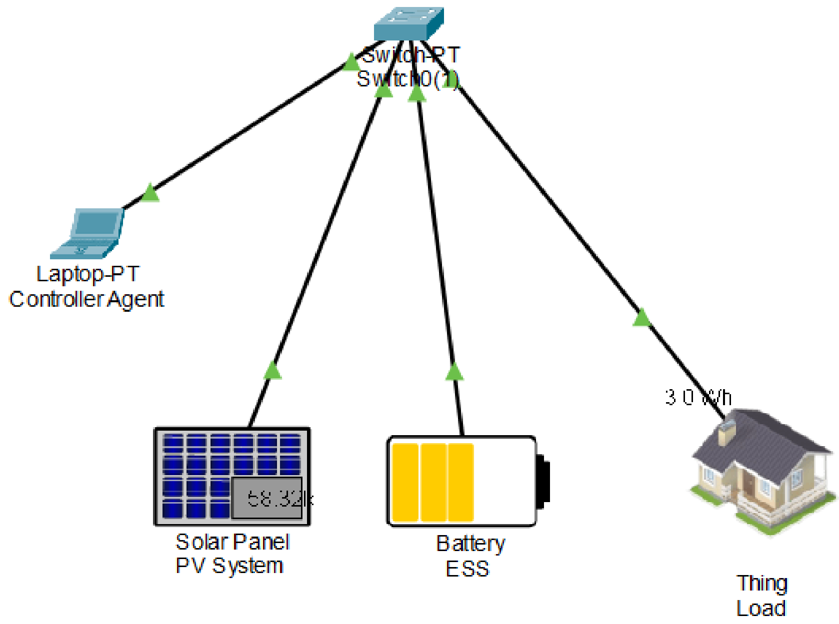


Figure 3.3: Configuration for a single Microgrid agents

To configure these devices, The following procedures should be done:

3.3.1.1 Devices IP Configuration

The following configuration is shown for one device, and it will be done for each of the remaining three devices.
As a first step, we determine the network IP and host addresses. Since we have four devices, the network address is chosen to be 192.168.0.0/29. Figure 3.4 specifies the chosen device.

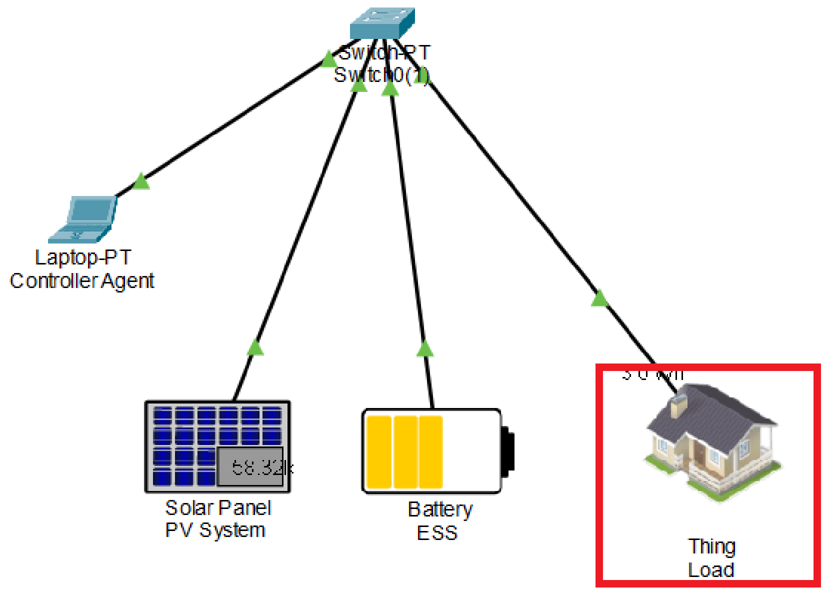


Figure 3.4: The chosen device

We enter the IP address in the ”IPv4 Address” and the subnet mask as it is described shown in figure 3.5.

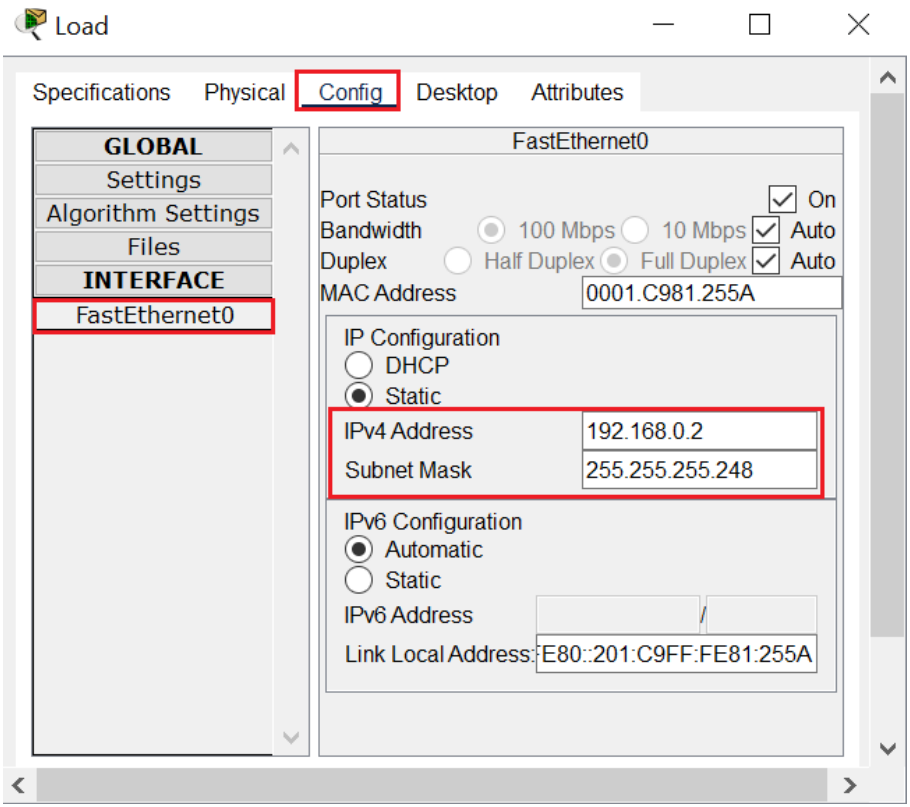


Figure 3.5: Entering the IP Address and the Subnet Mask

We repeat the same steps with all other devices, and fill the corresponding addresses as described in table 3.2.

Table 3.2: IP addresses, interface of each agents in a single microgrid

Device	Interface	IP Address	Subnet Mask	Default Gateway
Load Agent	FastEthernet0	192.168.0.2	255.255.255.248	192.168.0.1
PV Agent	FastEthernet0	192.168.0.3	255.255.255.248	192.168.0.1
ESS Agent	FastEthernet0	192.168.0.4	255.255.255.248	192.168.0.1
Controller Agent	FastEthernet0	192.168.0.5	255.255.255.248	192.168.0.1

- We have to make sure that the four devices are connected to the same switch (switch1 IP Address) as shown in figure 3.6.

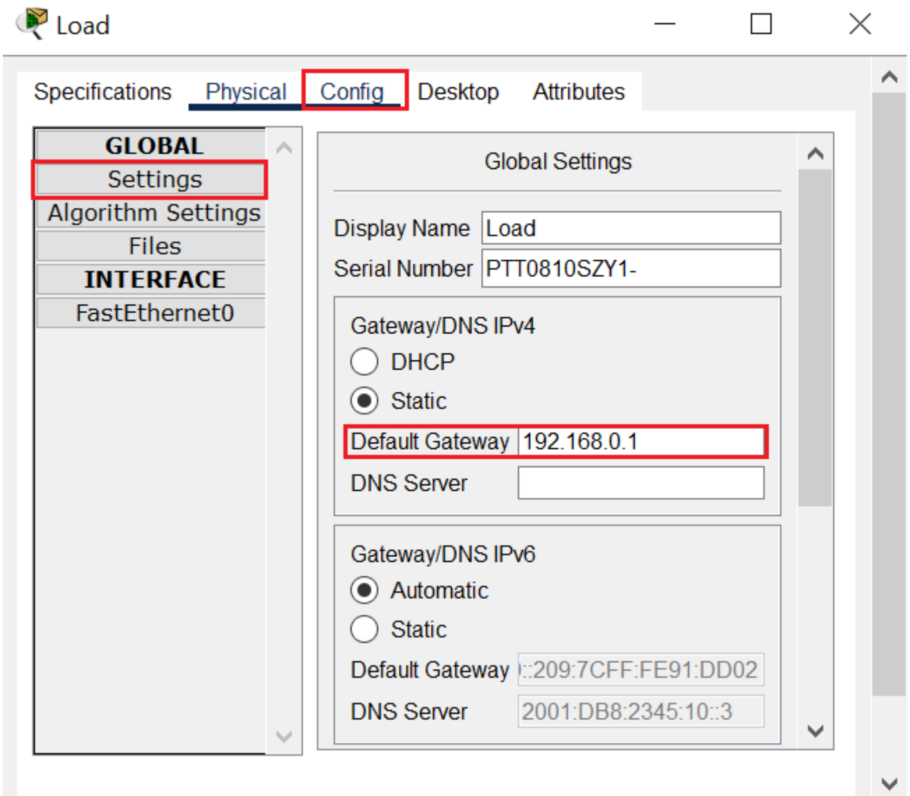


Figure 3.6: Default Gateway interface

When finishing these steps, single MG agents are able to communicate and exchange data with each other.

3.3.2 Power control within a microgrid

Using MATLAB Simulink, we implement a MG by connecting the corresponding components found in the library.

3.3.2.1 Generation unit

The generation unit as detailed previously, is represented by the PV array and its MPPT charge controller.

The PV array is a set of solar panels connected together in order to convert the sunlight to an electrical power. It performance change depending on its configuration, temperature and irradiance. The PV array Simulink model is represented in figure 3.7.

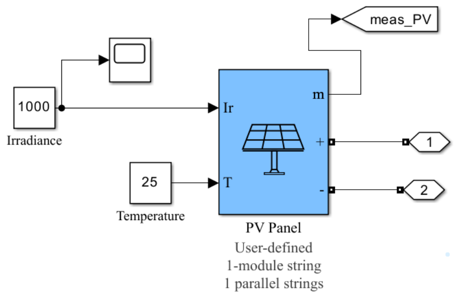


Figure 3.7: PV array block

The charge controller must be designed in order to optimize the power transfer between the solar system and the load. This process is done by twisting and adjusting the duty cycle of the boost converter controlled by the MPPT algorithm. figure 3.8 illustrates the MPPT charge controller within a PV system.

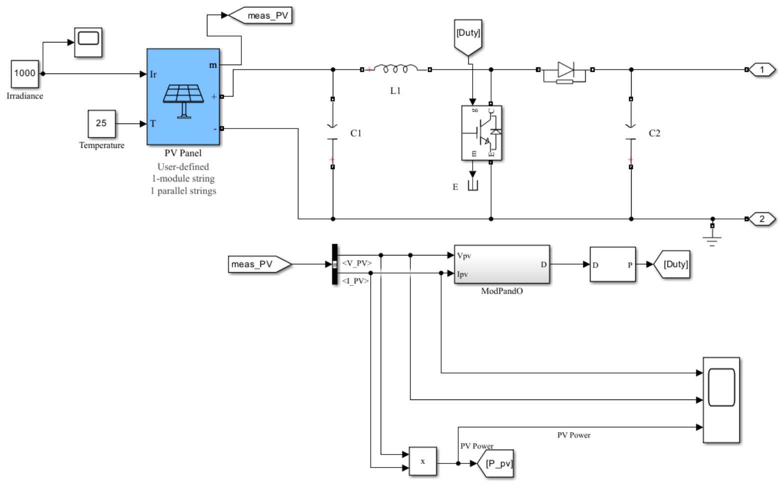


Figure 3.8: MPPT charge controller Simulink model

3.3.2.2 Storage unit

This unit is important for balancing MG power. It ensures a continuous power supply during the system outages. It is represented by the battery and its bi-directional Buck-Boost Converter. The ESS unit is shown in figure 3.9.

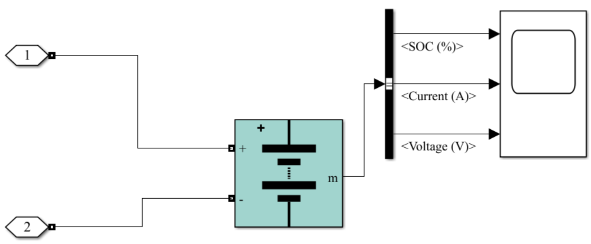


Figure 3.9: Battery Simulink model and its parameters

In a MG system, the DC bus connected to the battery is controlled by the bi-directional DC/DC converter in order to manage and to enable the power flow in both directions while the charging and the discharging of the battery. The storage unit is illustrated in figure 3.10.

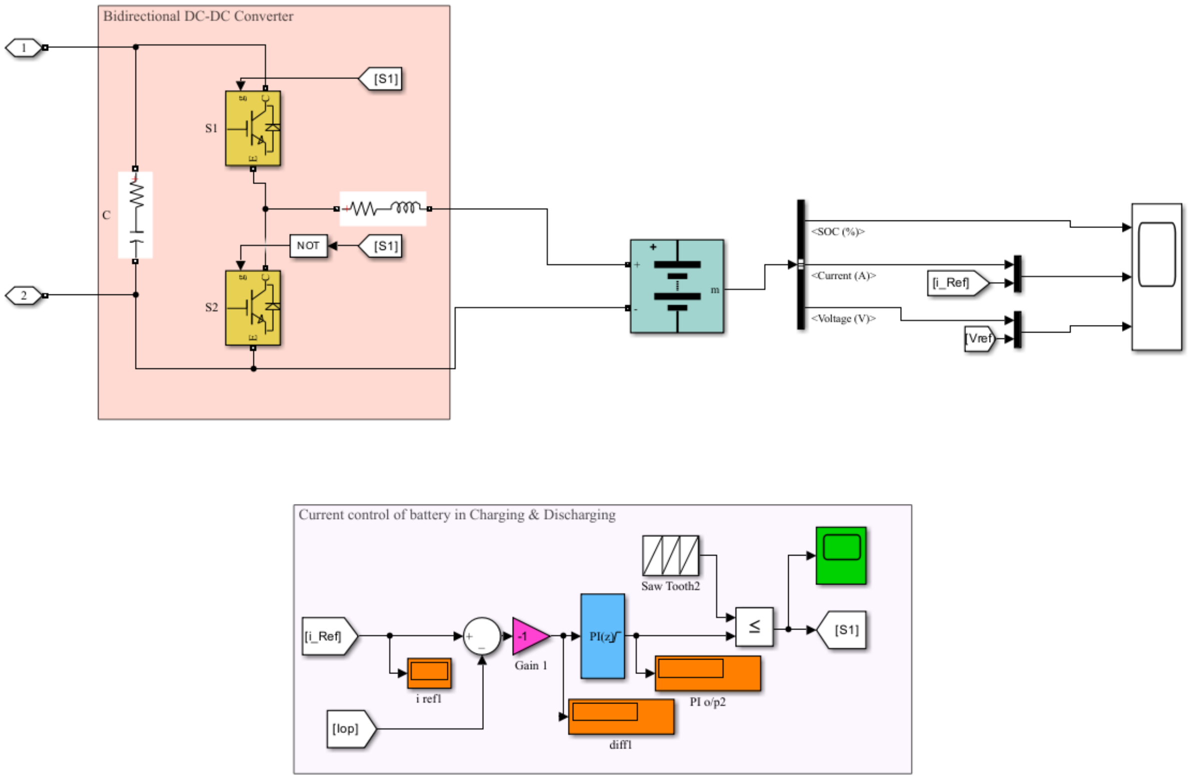


Figure 3.10: Simulink model of the storage unit

3.3.2.5 Matlab/Simulink architecture of the overall single microgrid

Figure 3.11 illustrates the overall Simulink block representing the single MG simulation.

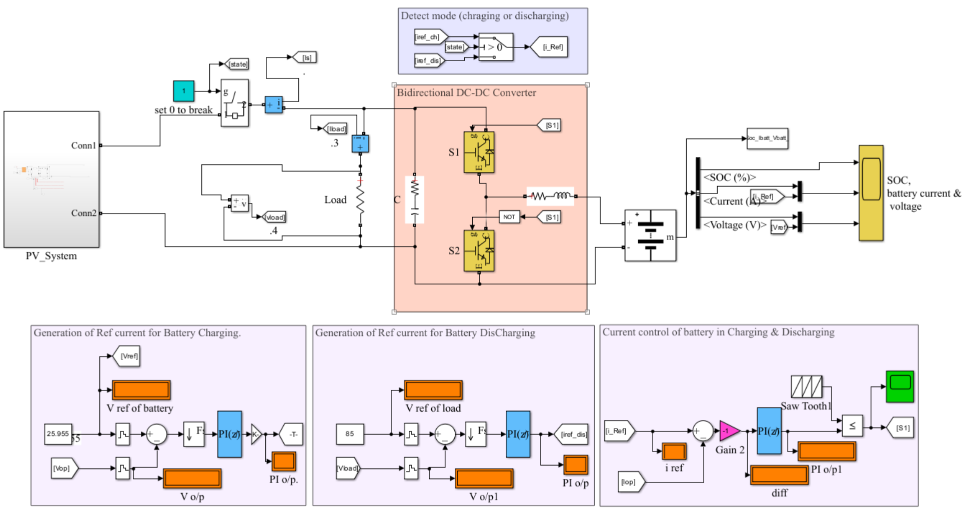


Figure 3.11: Simulink model of the overall microgrid system.

3.4 Multi-microgrid

3.4.1 Communication between MMG

After designing a single MG agent network, the network is duplicated into three MG networks, and each MG agents is then grouped into a cluster. Then, each of these clusters is connected to a multilayer switch under a router.

The multilayer switch is a network Layer 3 device. It combines the functions of a switch and a router, improving network performance, security, and potentially lowering costs while enabling faster traffic forwarding through hardware-based routing.

The overall network is shown in figure 3.12.

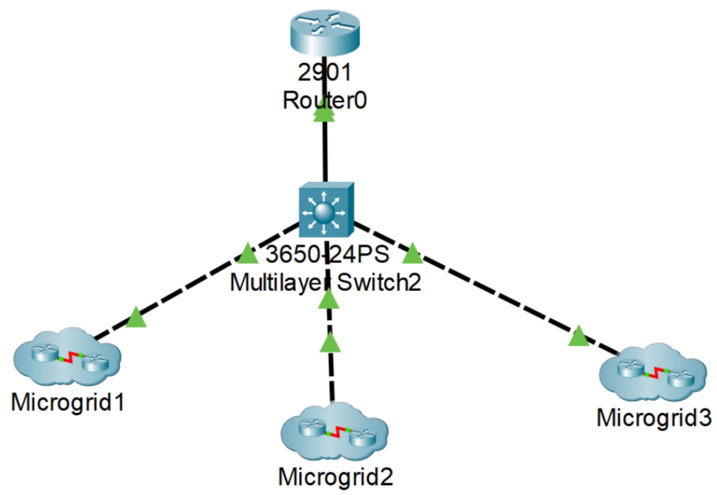


Figure 3.12: Configuration of Multi-microgrid

Each MG must be assigned a different subnet address; because each MG is connected to a different switch. The configuration of each MG as shown in table 3.3.

Table 3.3: IP addresses of agents in a multi-microgrid

MG	Device	Intf.	IP Address	Subnet Mack	Default Gateway
MG1	Load Agent1	Fa0	192.168.0.2	255.255.255.248	192.168.0.1
	PV Agent1	Fa0	192.168.0.3	255.255.255.248	192.168.0.1
	ESS Agent1	Fa0	192.168.0.4	255.255.255.248	192.168.0.1
	Controller Agent1	Fa0	192.168.0.5	255.255.255.248	192.168.0.1
MG2	Load Agent2	Fa0	192.168.0.10	255.255.255.248	192.168.0.9
	PV Agent2	Fa0	192.168.0.11	255.255.255.248	192.168.0.9
	ESS Agent2	Fa0	192.168.0.12	255.255.255.248	192.168.0.9
	Controller Agent2	Fa0	192.168.0.13	255.255.255.248	192.168.0.9
MG3	Load Agent3	Fa0	192.168.0.18	255.255.255.248	192.168.0.17
	PV Agent3	Fa0	192.168.0.19	255.255.255.248	192.168.0.17
	ESS Agent3	Fa0	192.168.0.20	255.255.255.248	192.168.0.17
	Controller Agent3	Fa0	192.168.0.21	255.255.255.248	192.168.0.17

As mentioned previously, MG agents are controlled by the controller agent, which transfers the data to other controller agents in the case of grid-connected MG. In this case, we have to allow only the controller agent PC to communicate with other MGs using the Cisco access control lists. The access control list is a rule-based mechanism used to filter network traffic on Cisco routers and switches. It is considered a security tool by allowing or denying traffic based on predefined criteria.

To create the access control list, we first have to identify the IP address of each device to communication via the router. In this case, we have the three controller agents IP addresses as described in table 3.4. We permit only the controller agents IP addresses and deny all others. Figure 3.13 represents the configuration command to create the access control list .

Table 3.4: Allowed devices to communicate

Permitted Device	**IP Address**
Controller Agent1	192.168.0.5
Controller Agent2	192.168.0.13
Controller Agent3	192.168.0.21

```
Switch>enable
Switch#configure t
Enter configuration commands, one per line.  End with CNTL/Z.
Switch(config)#access-list 101 permit ip host 192.168.0.5 any
Switch(config)#access-list 101 permit ip host 192.168.0.13 any
Switch(config)#access-list 101 permit ip host 192.168.0.21 any
Switch(config)#do show access
Extended IP access list 101
    10 permit ip host 192.168.0.5 any
    20 permit ip host 192.168.0.13 any
    30 permit ip host 192.168.0.21 any
```

Figure 3.13: Multilayer switch configuration to permit the controller agents

After creating the access control list, we have to configure the three interfaces that are connecting each MG cluster with the multilayer switch. The multilayer switch interfaces are represented in table 3.5. Figure 3.14 represents the configuration command of each interface.

Table 3.5: Multilayer switch interfaces with other devices

Device	**Interface**	**IP Address**
MG1	G1/0/1	192.168.0.1
MG2	G1/0/2	192.168.0.9
MG3	G1/0/5	192.168.0.17
Router	G1/0/3	18.3.0.0

```
Switch(config)#interface g1/0/1
Switch(config-if)#no sw
Switch(config-if)#ip access
Switch(config-if)#ip access-group 101 in
Switch(config-if)#ex
Switch(config)#interface g1/0/2
Switch(config-if)#no sw
Switch(config-if)#ip access
Switch(config-if)#ip access-group 101 in
Switch(config-if)#ex
Switch(config)#interface g1/0/5
Switch(config-if)#no sw
Switch(config-if)#ip access
Switch(config-if)#ip access-group 101 in
```

Figure 3.14: Interfaces configuration

3.4.2 Power control between MMG

After sizing and simulating a single MG system, the system is duplicated into three MG systems and its parameters were modified in order to have different scenarios (need, surplus, and islanded MGs). Each MG is represented inside a subsystem as shown in figure 3.15.

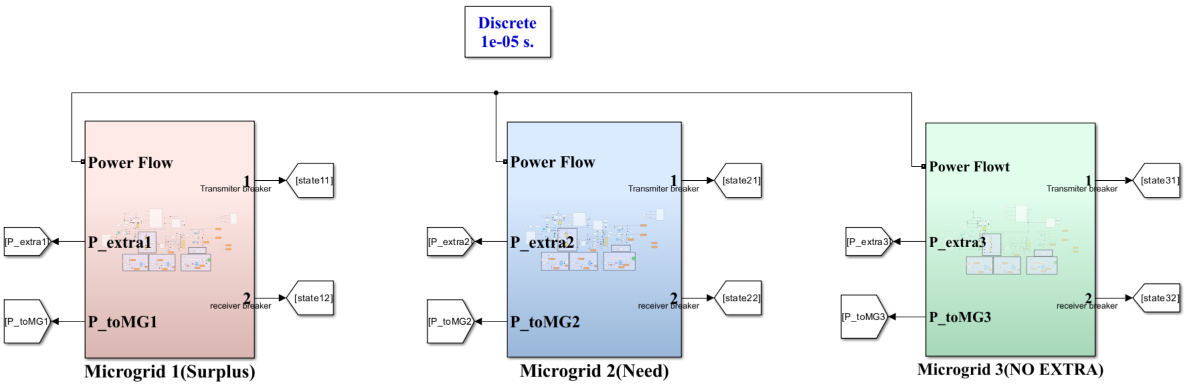


Figure 3.15: Simulink model of the overall multi-microgrid system.

Each MG is connected to a breaker system that allows the exchange of power. The breaker system location within a MG is shown in figure 3.16.

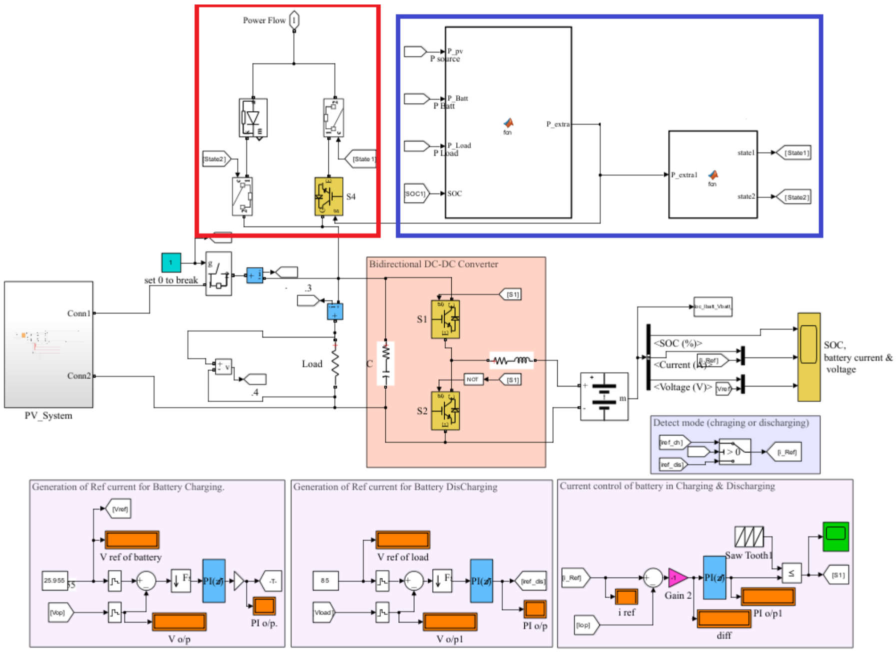


Figure 3.16: Power control of a microgrid within a multi-microgrid system

The red box in figure 3.16 represents the proposed breaker system, which allows the system to be grid-connected and exchange power. It consists of two breakers to avoid collisions of power flow within the power flow output. Each of these breakers is connected to a signal that controls its state (break or close). Figure 3.17 represents the detailed breaker system.

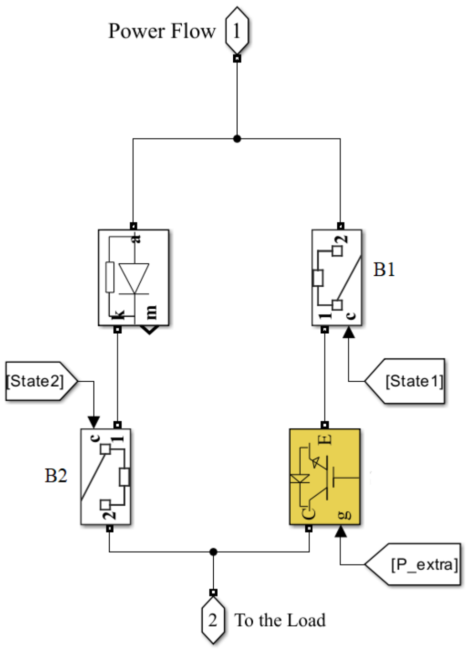


Figure 3.17: The proposed breaker system

Table 3.6 describes the state of each breaker in the MG breaker system.

Table 3.6: States of the breakers and their description

Breakers	State	Description
Breaker1	0	Breaker is opened, No power will be transmitted to the neighboring MG.
	1	Breaker is closed, Power will be transmitted to the neighboring MG.
Breaker2	0	Breaker is opened, No power will be received by the MG.
	1	Breaker is closed, Power will be received by the MG.

The blue box in figure 3.16 represents the proposed approach that controls the state of each breaker. This approach depends on a MATLAB file, which contains an algorithm that sends a binary signal depending on the calculated extra power to close or break the breakers.

Table 3.7 describes the inputs and the outputs of each MG.

Table 3.7: States of the breakers and their description

Microgrid	In/Out	Description
MG1	State11	Breaker1's state that transmits the power.
	State12	Breaker1's state that receives the power.
	Pextra1	The extra power transmitted out the MG1.
	PtoMG1	The power received by the MG1.
MG2	State21	Breaker2's state that transmits the power.
	State22	Breaker2's state that receives the power.
	Pextra2	The extra power transmitted out the MG2
	PtoMG2	The power received by the MG2.
MG3	State31	Breaker3's state that transmits the power.
	State32	Breaker3's state that receives the power.
	Pextra3	The extra power transmitted out the MG3.
	PtoMG3	The power received by the MG3.

3.5 Conclusion

Through this chapter a detailed MATLAB/Simulink model and Cisco Packet Tracer network of the overall system have been demonstrated and evaluated for both single MG and MMG. The communication part is done using the Packet tracer design by sending packet between controller agents, while the power exchange part is done through simulink by controlling the breaker state in the aim of resiliency improvement.

Chapter 4

Result and Discussion

The MG and MMG are simulated using MATLAB/Simulink and a Cisco packet tracer to observe the output under different operating modes and each MG's states. In this chapter, multiple scenarios are simulated by adjusting the irradiance and load demand in order to identify the efficiency of the proposed approach in each scenario, expose potential weaknesses, and assess the effectiveness of the control strategies.

4.1 Single microgrid simulation results

In order to study the behavior of a single MG system, some parameters are fixed, such as irradiance and the temperature at 25 °C.

Simulation results of a single MG are shown as follows. Figure 4.1 represents the power calculation of the system units (production, Storage and consumption)

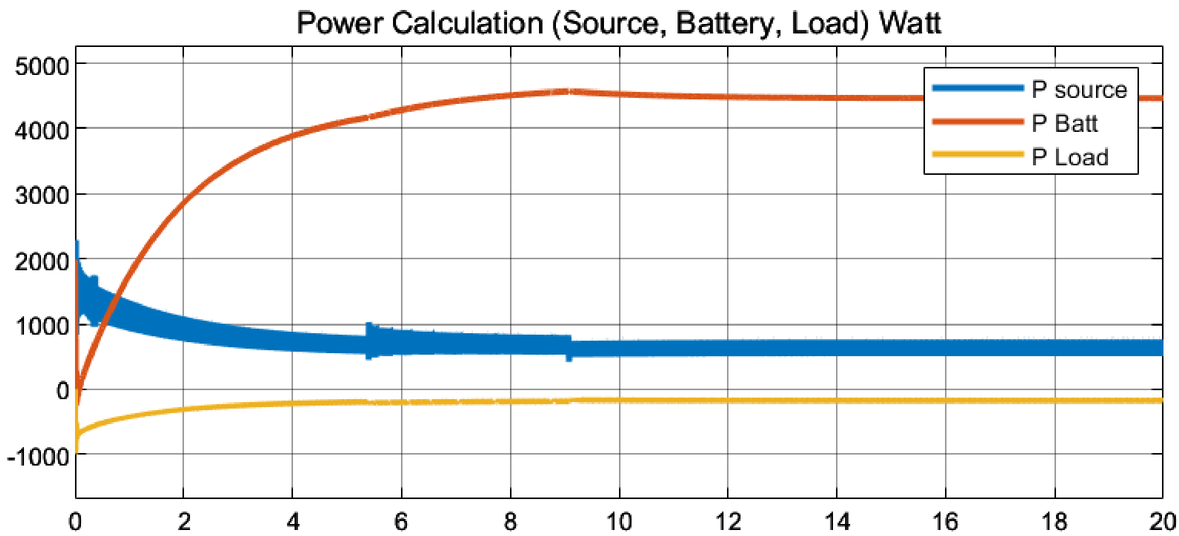


Figure 4.1: Power results of the source, battery and the load.

The figure above represents the three graphs in the same scope in order to easily compare the performance and extract the scenario. According to the depicted data, the source power decreases, which means the power is either stored or used. As a result, we notice that both battery and load power graphs increase. At the end, all the graphs are constant, which means the system is satisfied.

Since the MG is in island mode, the power gotten from the PV system is either used by the load or stored in the ESS system (battery). When the power within the MG satisfies the system and the ESS is fully charged, the surplus power must be delivered to satisfy the neighboring systems, and then the MG will be in a grid-connected mode.

4.2 Multi-microgrid simulation results

In order to study the performance of a MMG system, we connected the three MGs via a power line cable and separated each one by a breaker system. We have adjusted two scenarios in order to improve the resiliency of the system.

4.2.1 Scenario 1

In this case, the three MGs are sized to apply the three possibilities: surplus, need, and islanded MG.

The sizing is done to make the first MG in a surplus state, the second one in a need state, and the last one satisfying itself in an island mode. And this is to test the reliability and flexibility of the MMG system.

First, we depicted the breakers state of each MG.As mentioned in the previous chapter, each MG has two breakers, one to allow the power in and the other to allow the power out. Figures 4.2, 4.3, and 4.4 represent the states of each breaker system for MG1, MG2, and MG3, respectively. Where the red line represents the breaker that allows the delivery of power, and the blue line represents the breaker that extract power.

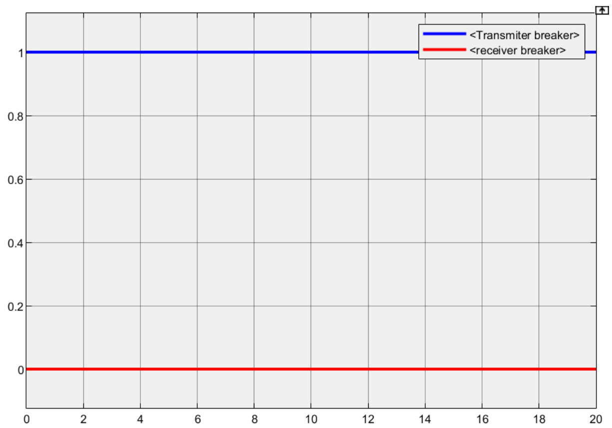


Figure 4.2: Breaker system in microgrid 1, Scenario 1

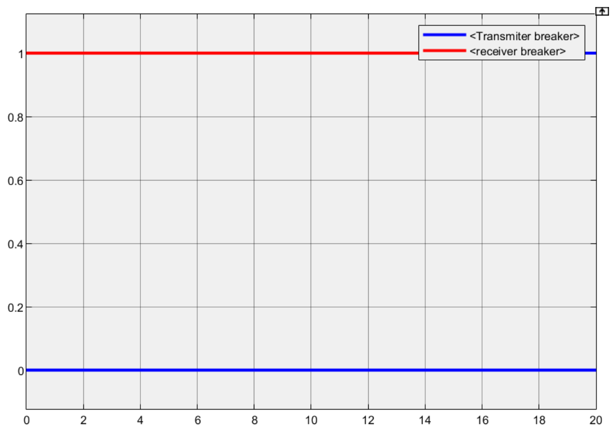


Figure 4.3: Breaker system in microgrid 2, Scenario 1

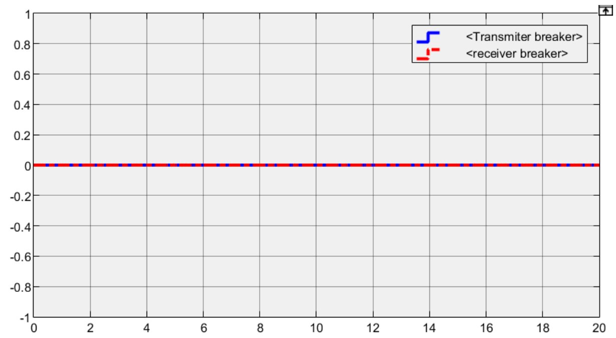


Figure 4.4: Breaker system in microgrid 3, Scenario 1

Figure 4.2 shows that the first breaker is closed to share the surplus power, and no power is received because the system is satisfied.

Figure 4.3 shows that the first breaker is opened because there is no surplus power to share with neighboring MGs, and the second breaker is closed, so the system is receiving power because it is in need.

Figure 4.4 shows that both breakers are opened, so the MG is in island mode; it can satisfy its load, but it has no extra power to share it with the neighboring MGs.

To better observe the power exchange, we depicted figures 4.5, 4.6, and 4.7.

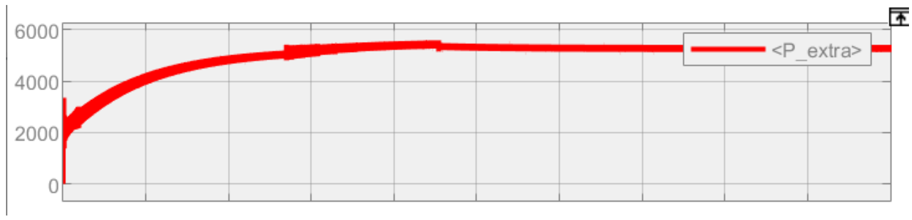


Figure 4.5: Power transmitted out of the microgrid 1.

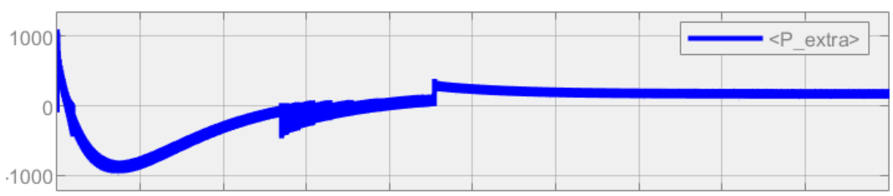


Figure 4.6: Power used in the microgrid 2.

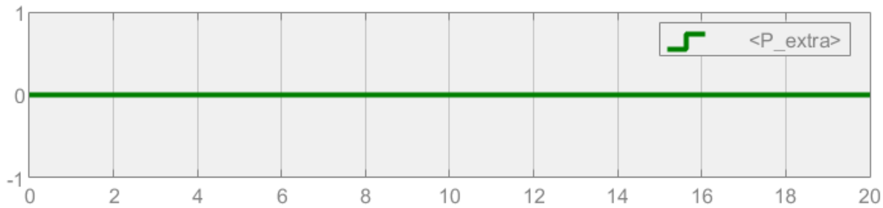


Figure 4.7: No power exchange in microgrid 3.

Since the source is always generating power, it is expected that the power will increase over time in the surplus state, as shown in figure 4.5.

Figure 4.6 shows the power used in MG2. It starts by using its generation and storage units, and when they are empty or helpless for the system, it receives power from MG1, and it increases until it is fully satisfied. After moment of satisfaction, we notice that at t=9s, the red graph decreases while the blue graph increases, it means that the first MG gives the second when it needed once again.

To summarize the above results, figure 4.8 is shown.

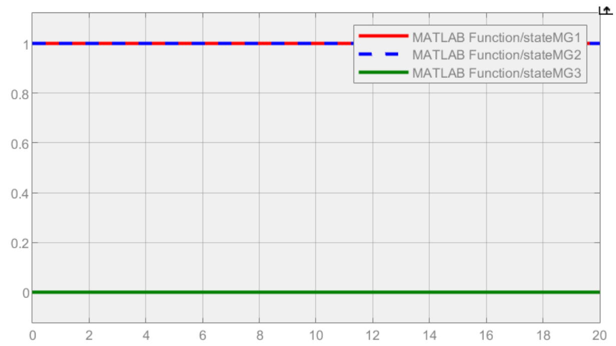


Figure 4.8: States of each microgrid

The red and blue lines at 1 define that both MG1 and MG2 are exchanging power between each other, so they are in grid-connected mode. where the green line at 0 shows that MG3 is in islanded mode. MG1 improves MG2's resilience.

Figure 4.9 represents the scenario of power exchange.

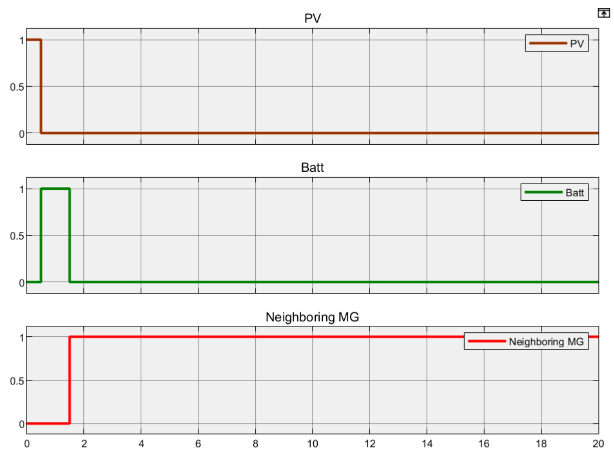


Figure 4.9: one microgrid control signal scenario

4.2.2 Scenario 2

In this case, the three MGs are sized to apply only two possibilities: surplus and need. So the three MGs are in grid-connected mode. The sizing is done to make two MG1 and MG3 in surplus states, and the MG2 is in need.

First, we depicted the breakers' state of each MG. Figures 4.10, 4.11, and 4.12 represent the states of each breaker system for MG1, MG2, and MG3, respectively. Where the red line represents the breaker that allows the power to enter, and the blue line represents the breaker that extracts power.

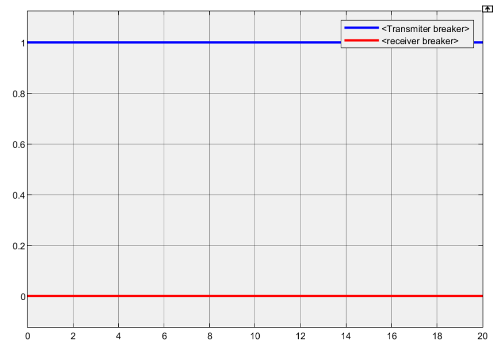


Figure 4.10: Breaker system in microgrid 1, Scenario 2

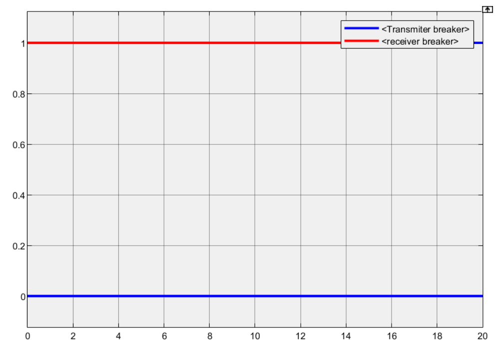


Figure 4.11: Breaker system in microgrid 2, Scenario 2

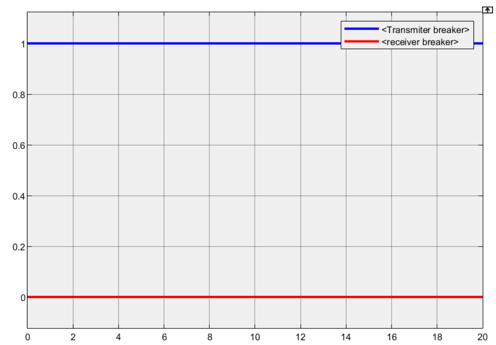


Figure 4.12: Breaker system in microgrid 3, Scenario 2

Figures 4.10 and 4.12 show that the first breaker of both MG1 and MG3 is closed to share their surplus power, and no power is received because both systems are satisfied.

Figure 4.11 shows that only the second breaker is closed, so the MG2 system is ready to receive power.

To better understand the power exchange, we depicted figures 4.13, 4.14, and 4.15. Since

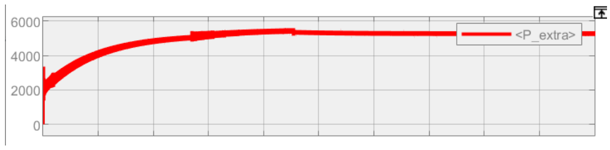


Figure 4.13: Power transmitted out of the microgrid 1.

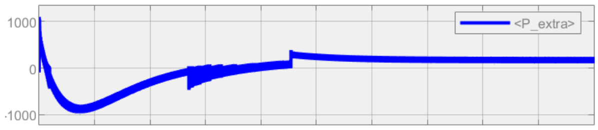


Figure 4.14: Power used in the microgrid 2.

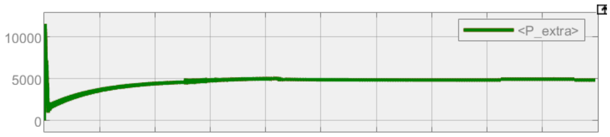


Figure 4.15: Power transmitted out of the microgrid 3.

both MG1 and MG3 sources are generating power, the power is increasing over time in the surplus state, as shown in figures 4.13 and 4.15.

Figure 4.14 shows the power used in MG2. It starts by using its generation and storage units, and when they are empty or helpless for the system, it receives power from MG1 and MG3, and it increases until it is fully satisfied. To summarize the above results, figure 4.16 is shown.

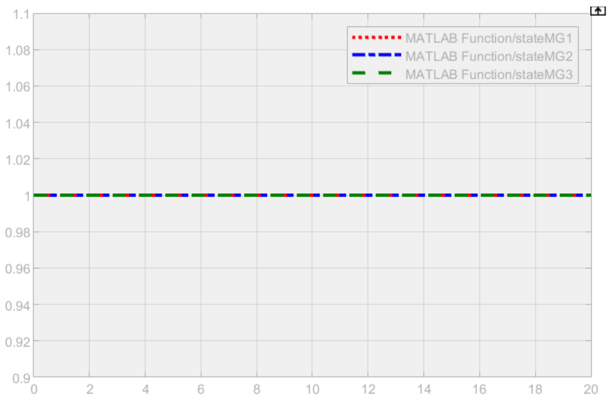


Figure 4.16: States of each microgrid.

All three lines are at 1; they define that all MGs are exchanging power between each other. In other words, both M1 and MG3 are improving MG2's resilience.

Table 4.1 summarizes the process done on this section.

Table 4.1: Surplus and Resilience register in each scenario

Microgrid	MG1		MG2		MG3	
	Surplus	Resilience	Surplus	Resilience	Surplus	Resilience
Scenario 1	1	0	0	1	0	0
Scenario 2	1	0	0	1	1	0

4.3 Conclusion

This chapter analyzes the project's results through the lens of MG resilience. We achieved this by designing scenarios to test the MG's response to various conditions. The chapter explores the states of the breaker system, the MG's operational states, and the specific scenarios that ensure successful power exchange within the MG.

General conclusion

This work focused on the MMGs resiliency improvement based on the simulation of a MG and MMG, assigning the implementation of the proposed approach with an effective EMS and a breaker system to satisfy the demands of the loads for different scenarios.

The objectives of this work were achieved as approved through the different chapters of this report, which covered a range of aspects:

For the modeling and simulation part, MATLAB/Simulink was used to evaluate the system's performance under various conditions. Also, a Cisco packet tracer was used to create the communication topologyto communicate connecting the MGs; it first analyzes the state of each MG before an exchange of power occurs. The breaker control system, including algorithms and flowcharts, was developed to ensure efficient EM and a more flexible and resilient system. The resilience can be improved for a single MG to prevent it from damaging either one component or the whole system. Also, it can be improved for MMGs, which are networked MGs interconnected through transmission lines and maybe disconnected using circuit breakers or switchers depending on the demand of each MG. The simulation results demonstrated that each MG interface can communicate with others by sending packets. In the power exchange part, the system improves resilience by managing power flow to protect the system or satisfy all the networked MGs.

Looking ahead, future work and perspectives should focus on improving the MGs resilience and flexibility. The future of MG resilience is brimming with innovation. Advanced control systems with MAS technology, improved cybersecurity, and novel energy storage solutions like next-generation batteries and compressed air will enhance MG response and backup capabilities. Additionally, seamless integration with distributed energy resources and standardized components will foster wider adoption and interconnection, while the rise of community-owned MGs empowers localities to achieve energy independence and bolster resilience against outages.

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Appendices

Appendix A

GLOBAL SOLAR ATLAS
BY WORLD BANK GROUP

Boumerdès

36.761441°, 003.475113°
Avenue de l'Indépendance, Boumerdès, Boumerdes, Algeria
Time zone: UTC+01, Africa/Algiers [CET]

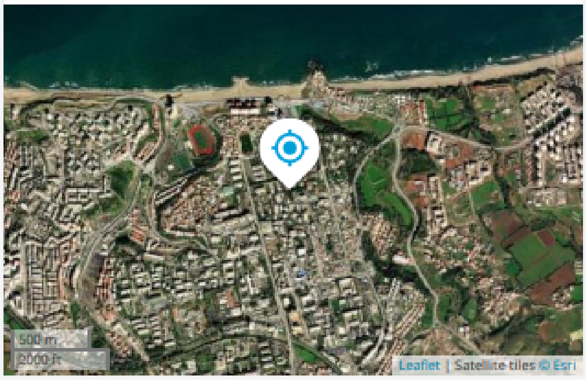
Report generated: 23 May 2024

SITE INFO

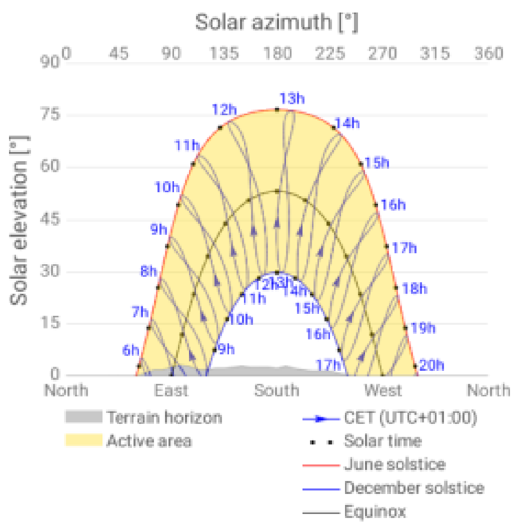
Map data

		Per year	
Direct normal irradiation	DNI	1676.0	kWh/m²
Global horizontal irradiation	GHI	1726.6	kWh/m²
Diffuse horizontal irradiation	DIF	694.1	kWh/m²
Global tilted irradiation at optimum angle	GTI opta	1959.8	kWh/m²
Optimum tilt of PV modules	OPTA	32 / 180	°
Air temperature	TEMP	19.0	°C
Terrain elevation	ELE	36	m

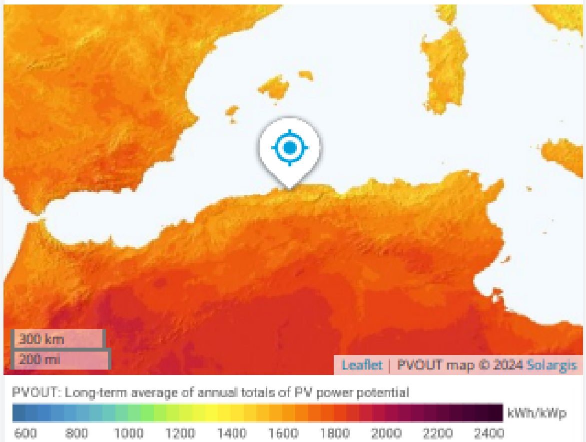
Map



Horizon and sunpath



PVOUT map



GLOBAL SOLAR ATLAS
BY WORLD BANK GROUP

PV ELECTRICITY AND SOLAR RADIATION

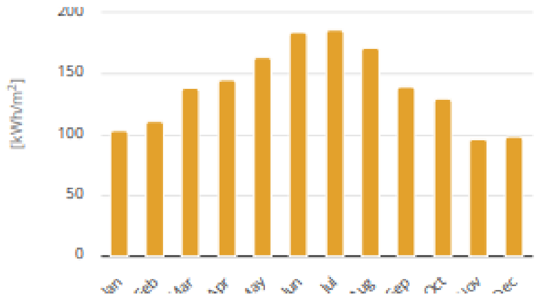
Annual averages

Direct normal irradiation

1668.1
kWh/m² per year

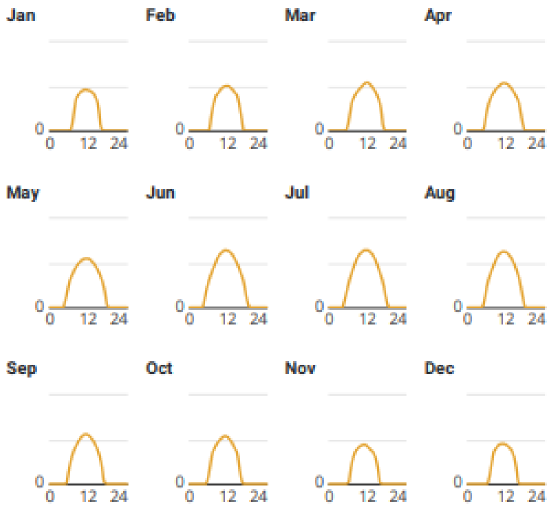
Monthly averages

Direct normal irradiation



Average hourly profiles

Direct normal irradiation [Wh/m²]



UTC+01

Average hourly profiles

Direct normal irradiation [Wh/m²]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5						5						
5 - 6				21	109	150	103	36	2			
6 - 7		2	86	219	275	293	259	235	173	103	16	
7 - 8	82	205	303	348	372	399	382	364	329	323	220	115
8 - 9	334	369	396	423	445	490	488	461	420	418	350	336
9 - 10	410	428	448	473	496	570	570	546	485	475	404	408
10 - 11	446	475	491	509	529	616	616	604	535	516	434	446
11 - 12	462	501	530	537	548	642	642	626	560	542	444	453
12 - 13	453	505	544	532	547	636	642	620	550	523	420	440
13 - 14	438	476	510	505	521	608	615	584	512	478	383	411
14 - 15	394	434	459	456	476	550	561	527	454	410	335	354
15 - 16	288	377	392	395	413	478	475	441	369	320	208	216
16 - 17	34	188	272	309	330	383	368	331	237	77	7	6
17 - 18			29	106	198	263	240	151	22			
18 - 19					14	65	51	2				
19 - 20												
20 - 21												
21 - 22												
22 - 23												
23 - 24												
Sum	3,341	3,960	4,461	4,834	5,274	6,149	6,015	5,529	4,646	4,186	3,220	3,185

Appendix B

Project: microgrid

Variant: New simulation variant

PVsyst V7.2.11
VC0, Simulation date:
23/05/24 22:08
with v7.2.11

Project summary

Geographical Site
Boumerdas
Algeria

Situation

Latitude	36.77 °N
Longitude	3.48 °E
Altitude	9 m
Time zone	UTC+1

Project settings

Albedo	0.20

Meteo data
Boumerdas
Meteonorm 8.0 (1996-2010), Sat=100% - Synthetic

System summary

Stand alone system

Stand alone system with batteries

PV Field Orientation
Seasonal tilt adjustment

azimuth	0 °
Summer Tilt	20 °
winter	50 °

Oct.-Nov.-Dec.-Jan.-Feb.-Mar.-

User's needs
Daily household consumers
Monthly Specifications

Average	0.2 kWh/Day

System information

PV Array

Nb. of modules	1 unit
Pnom total	145 Wp

Battery pack

Technology	Lithium-ion, LFP
Nb. of units	2 units
Voltage	26 V
Capacity	360 Ah

Results summary

Available Energy	225.0 kWh/year	Specific production	1552 kWh/kWp/year	Perf. Ratio PR	14.12 %
Used Energy	39.9 kWh/year			Solar Fraction SF	64.95 %

PVsyst V7.2.11
VC0, Simulation date:
23/05/24 22:08
with v7.2.11

Project: microgrid

Variant: New simulation variant

General parameters

Stand alone system — **Stand alone system with batteries**

PV Field Orientation

Orientation		**Sheds configuration**	**Models used**	
Seasonal tilt adjustment		No 3D scene defined	Transposition	Perez
azimuth	0 °		Diffuse	Perez, Meteonorm
Summer Tilt	20 °		Circumsolar	separate
winter	50 °			
Oct.-Nov.-Dec.-Jan.-Feb.-Mar.-				

User's needs
Daily household consumers
Monthly Specifications
Average 0.2 kWh/Day

PV Array Characteristics

PV module		**Battery**	
Manufacturer	Generic	Manufacturer	Generic
Model	ZT 145P	Model	Battery module Li-Ion, 26V 180 Ah
(Original PVsyst database)		Technology	Lithium-ion, LFP
Unit Nom. Power	145 Wp	Nb. of units	2 in parallel
Number of PV modules	1 unit	Discharging min. SOC	10.0 %
Nominal (STC)	145 Wp	Stored energy	8.1 kWh
Modules	1 String x 1 In series	**Battery Pack Characteristics**	
At operating cond. (50°C)		Voltage	26 V
Pmpp	132 Wp	Nominal Capacity	360 Ah (C10)
U mpp	18 V	Temperature	Fixed 20 °C
I mpp	7.2 A		

Controller		**Battery Management control**	
Universal controller		Threshold commands as	SOC calculation
Technology	MPPT converter	Charging	SOC = 0.96 / 0.80
Temp coeff.	-5.0 mV/°C/Elem.	Discharging	SOC = 0.10 / 0.35
Converter			
Maxi and EURO efficiencies	97.0 / 95.0 %		

Total PV power

Nominal (STC)	0 kWp
Total	1 modules
Module area	1.2 m²
Cell area	1.0 m²

Array losses

Thermal Loss factor		**DC wiring losses**		**Serie Diode Loss**	
Module temperature according to irradiance		Global array res.	42 mΩ	Voltage drop	0.7 V
Uc (const)	20.0 W/m²K	Loss Fraction	1.5 % at STC	Loss Fraction	3.4 % at STC
Uv (wind)	0.0 W/m²K/m/s				

Module Quality Loss		**Module mismatch losses**		**Strings Mismatch loss**	
Loss Fraction	2.5 %	Loss Fraction	2.0 % at MPP	Loss Fraction	0.1 %

IAM loss factor
ASHRAE Param: IAM = 1 - bo(1/cosi -1)
bo Param. 0.05

PVsyst V7.2.11
VC0, Simulation date:
23/05/24 22:08
with v7.2.11

Project: microgrid

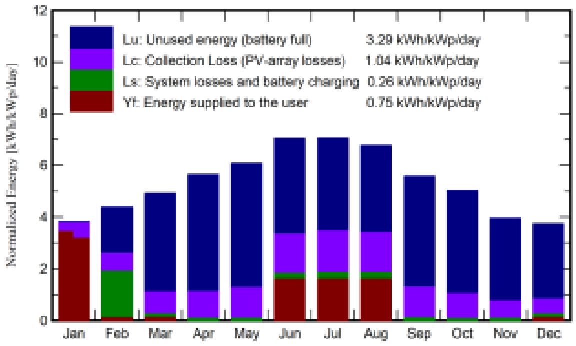
Variant: New simulation variant

Main results

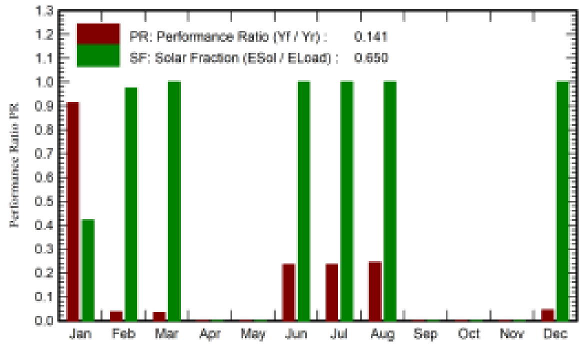
System Production

Available Energy	225.0 kWh/year	Specific production	1552 kWh/kWp/year
Used Energy	39.9 kWh/year	Performance Ratio PR	14.12 %
Excess (unused)	174.1 kWh/year	Solar Fraction SF	64.95 %
Loss of Load		**Battery aging (State of Wear)**	
Time Fraction	5.1 %	Cycles SOW	99.6 %
Missing Energy	21.5 kWh/year	Static SOW	80.0 %
		Battery lifetime	5.0 years

Normalized productions (per installed kWp)



Performance Ratio PR



Balances and main results

	GlobHor	GlobEff	E_Avail	EUnused	E_Miss	E_User	E_Load	SolFrac
	kWh/m²	kWh/m²	kWh	kWh	kWh	kWh	kWh	ratio
January	71.4	116.8	13.91	0.00	21.51	15.69	37.20	0.422
February	84.5	120.5	14.64	7.06	0.02	0.66	0.67	0.975
March	127.0	149.1	18.16	16.89	0.00	0.74	0.74	1.000
April	158.2	164.8	19.99	19.48	0.00	0.00	0.00	1.000
May	187.4	183.3	21.90	21.39	0.00	0.00	0.00	1.000
June	214.9	205.9	23.73	15.92	0.00	7.20	7.20	1.000
July	219.6	213.4	24.08	15.87	0.00	7.44	7.44	1.000
August	199.3	205.0	23.09	14.87	0.00	7.44	7.44	1.000
September	148.1	163.0	19.04	18.42	0.00	0.00	0.00	1.000
October	115.3	152.9	18.21	17.70	0.00	0.00	0.00	1.000
November	73.6	116.8	14.20	13.70	0.00	0.00	0.00	1.000
December	65.4	113.9	14.09	12.82	0.00	0.74	0.74	1.000
Year	1664.6	1905.4	225.05	174.13	21.53	39.91	61.44	0.650

Legends

GlobHor	Global horizontal irradiation	E_User	Energy supplied to the user
GlobEff	Effective Global, corr. for IAM and shadings	E_Load	Energy need of the user (Load)
E_Avail	Available Solar Energy	SolFrac	Solar fraction (EUsed / ELoad)
EUnused	Unused energy (battery full)		
E_Miss	Missing energy		