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Title:

An Energy Management Simulation in Microgrids

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Abstract

The conventional power grids rely on the traditional energy production using fossil fuels. These energy sources are depleting, their costs are rising and the worldwide energy demand is growing. All these factors make the power grid not being able to satisfy this demand. This project addresses both economic and environmental issues. It aims at deploying solar energy and an energy storage system and integrating them into the grid. This requires the existence of an Energy management system. Two energy management methods: “heuristic” and “optimization” methods are considered in this work. Both of these methods aim to reduce the overall usage of the conventional energy source from the main grid by utilizing the maximum possible output of the two other sources (solar energy and storage system), thus reducing the overall cost. This study shows the difference in both grid usage and cost between the two used methods during a 24 hour simulation considering cloudy and clear day conditions while ensuring the user’s comfort.

Acknowledgement

First and foremost, we would like to thank almighty "allah" for his endless gifts and blessings, "Alhamdulillah".

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We are extremely thankful to our families whom did not hesitate a second in supporting us with everything possible, so we hope we make them proud of us with this humble work.

We would like to give a special thanks to all the teachers who taught us everything since elementary school until our superior studies.

Finally, our thanks go to everyone who contributed to make this thesis possible whether it was direct or indirect contribution.

Dedication

My thesis is dedicated to my family and many friends. I owe a particular debt of appreciation to my devoted parents, Kamal and Malika, whose words of encouragement and insistence on perseverance still sing in my ears. My sister Zeyneb and brother Islem whom have never left my side and are extremely dear to me. I also dedicate this work to my many friends “El-Kabir” who have supported me throughout the process.

Farouk

I dedicate my honest work to my family and many friends. A special feeling of gratitude to my loving parents Abdenour and Wahiba, whose words of encouragement and push for tenacity ring in my ears. A special thanks to my beloved sister Wassila for honest continuous support. I would like to dedicate all my friends inside and outside the institute.

Amine

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List of Abbreviations

- **MG:** Microgrid.
- **DG:** Distributed Generators.
- **DER:** Distributed Energy Resources.
- **RES:** Renewable Energy Resources.
- **CHP:** Combined Heat and Power.
- **PV:** Photovoltaic.
- **WTG:** Wind Turbine Generator.
- **ESS:** Energy Storage System.
- **PE:** Power Electronics.
- **AC:** Alternating Current.
- **DC:** Direct Current.
- **PCC:** Point of Common Coupling.
- **MPPT:** Maximum Power Point Tracking.
- **IGBT:** Insulated Gate Bipolar Transistor.
- **VR:** Voltage Regulation.
- **EMS:** Energy Management System.

General introduction

Due to rapid expansion in numerous sectors and modern technology, as well as the rise of globalization, demand for Conventional types of energy made by burning fossil fuels, particularly towards the end of the twentieth century, has significantly increased especially at the beginning of the twenty-first century. This source of energy is the primary source of energy today, accounting for more than 90% of total energy use. This huge share has harmed the environment since the demand for these sources has outpaced the rise in reserve rates, resulting in an inability to supply rising energy demands. Countries have little option but to explore for new energy sources that are both clean and affordable, particularly as worries about global warming and climate change continue to grow.

Energy may be derived from the wind, flowing water, or other natural processes that can generate energy. The globe has recognized the serious threat that other, more frequent forms of energy (particularly oil and natural gas) pose to the environment, making renewable energy the best alternative. But exploring them and using them efficiently does not come in an easy way, the whole infrastructure should be updated in order to harvest them.

Microgrid technology, which is regarded as the key to the efficient use of distributed energy resources, has overcome many challenges such as climate change, rising petroleum prices, and lower costs of renewable energy systems, making the integration of renewable energy systems to address electricity generation the best solution. As a result, this technology has gained broad adoption and marketing, allowing for the implementation of an energy management plan in the system. The Smart Grid idea has lately been applied to electricity networks with success.

As a result, Many country leaders have devised future plans for renewable energies, paving the path for green energy dynamics. For example, many African countries such as Algeria, aspire to be leaders in the generation of electricity from wind and solar energy due to better solar irradiance than most of the rest of the world, and huge mountain surface to harvest wind, which will serve as the engine for long-term economic growth and inspire a new growth model.

The purpose of this study is to illustrate the advantages of integrating an energy management system into a microgrid that includes a Solar Array and an energy storage system, in terms of minimizing the grid (conventional) usage and thus lowering energy cost. This project is about implementing a microgrid simulation with an Energy Management System with two different methods “Heuristic” and “Optimization”, and observe the differences between them in terms of Grid’s energy usage and the overall cost.

To finalize, the first chapter begins with an overview of microgrid systems in general, renewable energy sources, and energy management. Then, the second chapter discusses demand response in general, and how the microgrid would react to load fluctuations especially at peak demand using two different approaches that will be followed in implementing such a system. Following that, the Last chapter will show the simulation and results with a discussion on the difference between the followed approaches using Matlab/Simulink software.

Chapter 1: Microgrid System Overview

1. Introduction:

As the need for energy rises as a result of electrification, the government and other relevant institutions are concerned about meeting the rising demand. The traditional method of energy production (thermal/coal power plants) has contributed to considerable environmental damage in terms of global warming. NASA's global warming index for the past 100 years is shown in Figure 1.1 [1] . Engineers and scientists have been driven to explore for alternatives in the field of power systems due to the decrease of fossil fuels and their harmful influence on the environment. These issues have prompted scientists to research alternative energy sources such as solar energy, wind energy, Combined Heat and Power (CHP) systems, energy storage systems, and micro-turbines in comparison to traditional power generation sources.

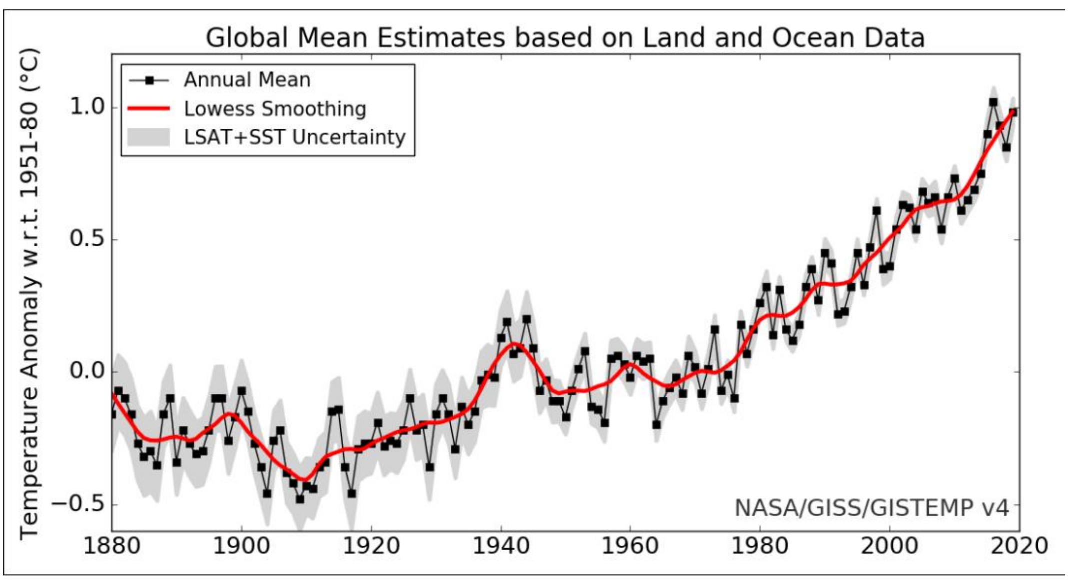


Fig 1.2: Index of global warming over the last 100 years [1]

Coupling of Renewable Energy Sources (RES) with the traditional grid provides a durable and reliable option as the generating, transmission, and distribution networks age.

In addition, the innovation pioneered the notion of on-site generation, which refers to generating sources that are close to the load in order to prevent transmission losses. The term for this form of onsite generation is Distributed Energy Resources (DER), which encompasses a wide range of power sources. As a result, the generation type is referred to as Distributed Generation (DG).

Despite the fact that renewable energy has environmental and operational advantages over fossil fuels, high installation and maintenance costs are a barrier to their widespread adoption around the world [2]. Governments have set targets for reducing greenhouse gas emissions, increasing the percentage of renewable energy sources, and improving energy efficiency in the future to attain the goal of a carbon-free environment [3]. Figure 1.2 depicts worldwide demand and the contribution of potential energy sources that might meet it until 2050. [4]. With the increasing contribution of renewable energy sources (RES) to the power industry, experts predict that by 2050, RES will account for roughly 80% of total power generation.

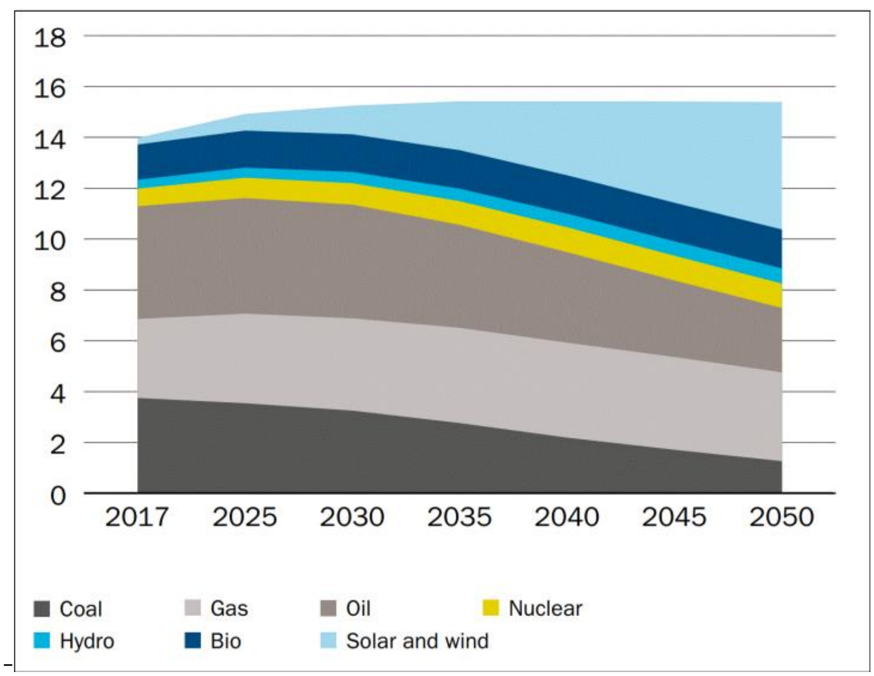


Fig 1.2 : Balance of energy globally in main energy from 2017 until 2050 [4]

2. Distributed generation:

Electricity is mostly produced at large generation facilities located far away from users under the centralized generation paradigm. The electricity is then transported through transmission and distribution grids to reach end users, or loads.

This process contributes to transmission and distribution network losses, which comes at a price. Decentralized systems, from the other hand, include distributed generation, which is more complex but has greater benefits once accomplished [3].

Various organizations have defined distributed generation in different ways. Small-scale, environmentally friendly technologies – such as micro-turbines, photovoltaics (PV), wind turbines, and batteries as energy storage systems (ESS) – are deployed at the distribution level to service users in defined premises, according to P. A. Daly [5]. Microturbines and internal combustion engines improve voltage stability and reduce reactive power losses in systems where RES integration plays a role in the production of active power [5]. Because the producing units are positioned close to the electrical load, one of the key advantages of having DERs is that transmission losses that occur while carrying power are reduced. A system with well-designed and run DGs can also help with energy efficiency, cost savings, and reliability [5].

3. Microgrid:

While placing DERs on-site can lessen the requirement for distribution grid upgrade, maintaining and operating a large number of DG units presents a number of additional issues for network management and operation. When connected to the AC grid, microgrids partially address this issue by coordinating DERs in a more decentralized fashion, decreasing the pressure on the main grid and allowing them to provide more flexibility [6]. While putting DERs on-site can reduce the need for a distribution grid upgrade, maintaining and operating a large number of DG units creates a slew of new network management and operation challenges. Microgrids, when connected to the AC grid, alleviate this issue in part by coordinating DERs in a more decentralized manner, reducing the load on the main grid and allowing them to give more flexibility [7]. Norway has had certain projects connected to the development of microgrids in various regions, as the progress of microgrids has shown substantial advantages. Hvaler Energy Park, which consists of 1200 square meters of PV and one wind turbine, was the first full-scale microgrid in 2017, according to a research by 'Smart Innovation Norway.' When the local power grid goes down, the microgrid can operate in island mode until the grid returns to normal, at which point it will switch back to grid-connected mode. From spring until fall, the facility should be able to run on its own for about six months [8].

4. Microgrid system overview:

Although Thomas Edison invented the first microgrid in 1882, the contemporary and optimal notion of microgrids emerged with the change to a liberalized approach with RES and DG inclusion into the distribution grid. The definition of a microgrid is currently ambiguous. Microgrids have been described by many organizations depending on their ideas and opinions.

The IEEE, the "Conseil International des Grandes Réseaux Electriques" (CIGRE), and the US Department of Energy (DOE) have all published definitions of microgrid.

- **US DoE:** A microgrid is a group of linked loads and dispersed energy sources that function as a single, controlled entity inside well-defined electrical boundaries. A microgrid may connect to and disengage from the grid, enabling it to operate in both grid and island mode [9].
- **IEEE:** A group of linked loads and DERs with well-defined electrical boundaries that function as a single controlled entity in reference to the grid and can connect and disengage from it to operate in grid connected and island modes [10].

- **CIGRE:** Microgrids are electricity DS (Distribution systems) that can manage and coordinate loads and DERs (such as distributed generators, storage devices, or controlled loads) while linked or unlinked to the main power grid. [11].

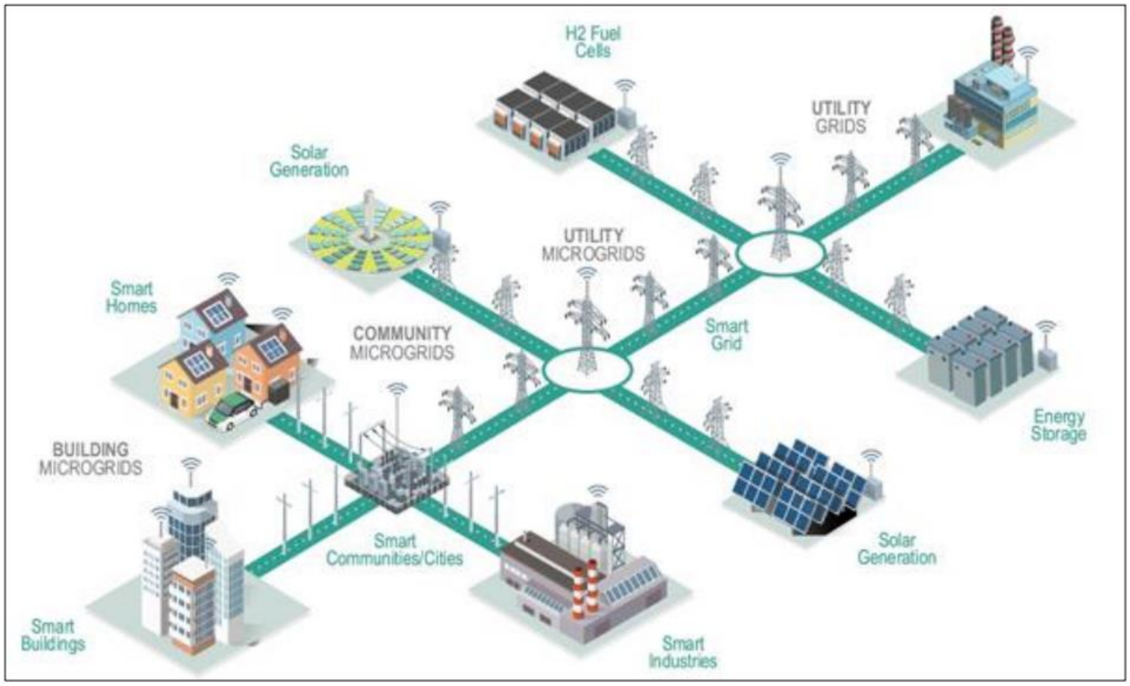


Fig 1.3: An example of a microgrid with energy generating and consumption sources (Source – SEIA and SEPA) [12].

Solar Energy Industry Association (SEIA) [12]; As seen in Figure 1.3, has constructed a simplified graphical representation of a generic microgrid. One of the key advantages of an MG from a grid perspective is that it is treated as a controlled entity within the power system, i.e. it may be considered a single aggregated load when in operation. This ensures that controllability is simple in accordance with grid codes. In the eyes of the customers, MG meets their needs for electrical and heat energy while also providing the convenience of having an uninterruptible power supply at all times [3,13].

A typical microgrid may be made up of several different types of equipment that are integrated to form a power system network that connects to the grid at the Point of Common Coupling (PCC). The equipment used to link the DERs and loads to the microgrid, such as power electronic converters, transformers, relays, and circuit breakers, is chosen according on whether the microgrid is operated in AC, DC, or AC/DC technology [10].

5. Microgrid's classifications:

Because a microgrid is made up of a variety of micro-generating sources, some, such as solar, provide DC power while the rest produce AC power without the need for a converter.

To link the RES and meet the load requirement, several configurations are based on technical topologies. Based on the nature of the voltage delivered to the load, microgrids can be categorized into primarily two sorts of topologies. As a result, the microgrid can be classified as an AC microgrid, a DC microgrid, or a hybrid AC-DC microgrid.

5.1. AC Microgrids:

Because a microgrid is made up of a variety of micro-generating sources, some, such as solar, provide DC power while the rest produce AC power without the use of a converter. To couple the RES and meet the load requirement, different configurations are based on the technical topologies. Based on the nature of the voltage that is provided to the load, microgrids can be classed into essentially two sorts of setups. As a result, the microgrid can be classified as AC, DC, or hybrid AC-DC [14].

The decentralized AC-coupled technique for the MG connection is another option. The architecture of the decentralized AC microgrid is such that all technologies individually link to the load directly. As a result, no matter where the energy sources are located, they can connect to the load. This arrangement has the disadvantage of making power control difficult to manage. Because of its controllability, the centralized system is preferred over the decentralized setup [15].

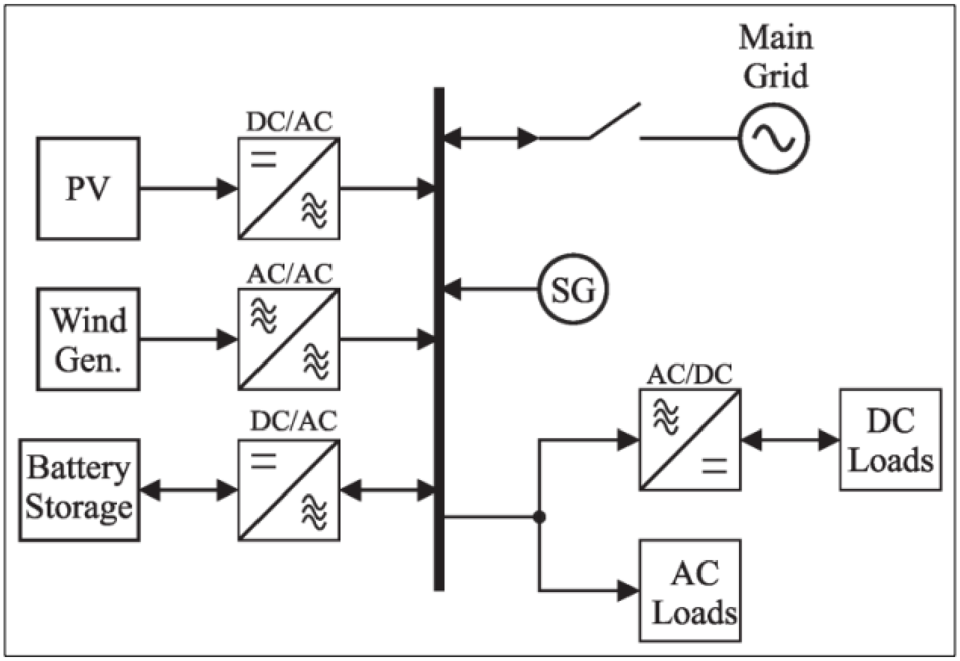


Fig 1.4 : AC Coupled Microgrid [15].

5.2. DC Microgrids:

According to current trends, the development of DC microgrid systems has piqued the interest of academics [16]. All energy sources are linked to the DC bus via converters in the DC combination. A DC-coupled microgrid can be seen schematically in Figure 1.5 [17].

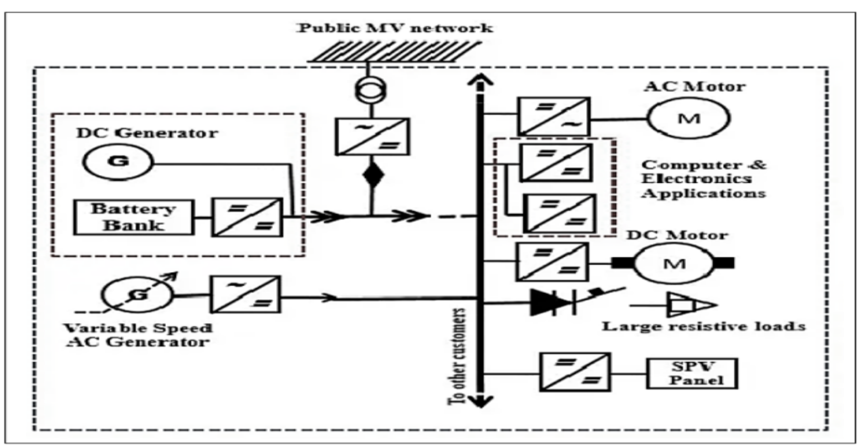


Fig 1.5 : DC Coupled Microgrid [17].

DC microgrids contain fewer converters in the microgrid than AC microgrids, which can result in considerable energy savings. Another benefit of the DC system is that it addresses some of the microgrid's control difficulties. One advantage is that the DGs don't need to be synchronized, and the controls are based directly on the DC bus voltage.

The majority of contemporary equipment and appliances run on DC power, which is another advantage of having a DC microgrid [17].

5.3. AC-DC Hybrid Microgrids:

The ideas of AC and DC coupled microgrids discussed in the preceding sections enable the use of bidirectional converters to establish an AC and DC coupled microgrid system. In an individual AD or DC microgrid, a mixed couple system can minimize the amount of DC-AC-DC and AC-DC-AC power conversions. Figure 1.6 depicts the design of a hybrid mixed pair AD-DC system [18].

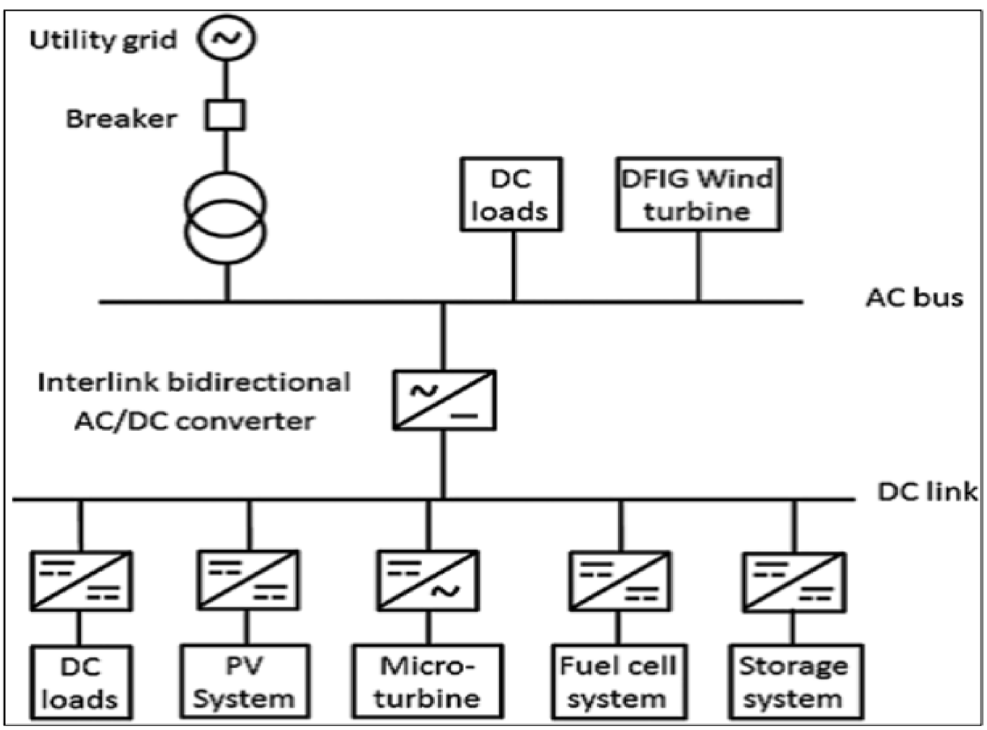


Fig 1.6 : AC-DC Hybrid microgrid [18].

The system efficiency is greatly dependent on the kind and quantity of linked producing units and loads, which is a significant drawback of employing such a structure. Hybrid microgrid systems are best suited for small, isolated sites that rely heavily on wind and solar power generation for power [17].

6. Microgrid's components:

This section looks at the many components and equipment that may be utilized to build a microgrid. Despite the fact that numerous little detailed components are just as important as large ones, only the most common technical pieces are covered in depth here. Microgrid operation, dependability, and efficiency are all influenced by renewable energy sources (PV/Wind) and their integration into the grid at the distribution level, necessitating a theoretical examination of functioning. Micro synchronous generators, power electronic converters, transformers, load, and, most critically, batteries will all be examined. Electrical loads, cables, and transformers are briefly described; however, PV, wind turbines, power electronics, synchronous generators, and batteries are thoroughly explored.

Transformer: At all stages of the AC power system, transformers are employed. The voltage can be stepped up or down by a transformer to get the appropriate output value. Overloading in the system may be avoided by properly sizing the transformer (rating and impedance).

Load: Loads can be either purely resistive and require no reactive power to work, or a reactive load (inductive or capacitive; generally inductive) and require reactive power to work.

Cables: In a microgrid or distribution grid, cables are one of the most important components. The voltage level, maximum power transfer to the load from the producing unit, and provision of short circuit current for a certain duration must all be considered while sizing the cables.

6.1. Synchronous Generators:

The synchronous generator is the heart of a power system since it is the primary generator for any system size. Steam turbo, hydro, gas turbo, and diesel generators are examples of synchronous generators that are frequently employed in a power system network. When the generator is linked to the grid in grid-connected operation, there are two basic modes of operation:

- PV Control: Constant active power and voltage at the terminals.
- PQ Control: Constant active and reactive power.

A generator's governor control determines the necessary torque for the generator to produce active and reactive electricity to the grid while maintaining grid frequency. In the PV mode of operation, the generator's exciter modulates current flow from the field windings to achieve VR (voltage regulation) via reactive power generation. [14]. Depending on the field excitation, synchronous generators can create both leading and lagging vars. When a synchronous generator is overexcited, it makes vars, and when it is under-excited, it absorbs vars [15].

6.2. PV Generators:

A photovoltaic array is a group of PV cells connected in series and parallel to produce the rated output voltage and current of a solar array. When the cells are linked in series, the output voltage equals the sum of the individual voltages of the cells. When the modules are linked in parallel, however, the output current equals the total of the cell's individual currents. Photovoltaics are DC voltage sources that provide DC power as an output, with current and voltage being interdependent. The interdependency of current VS voltage and voltage VS power is seen in Figure 1.7.

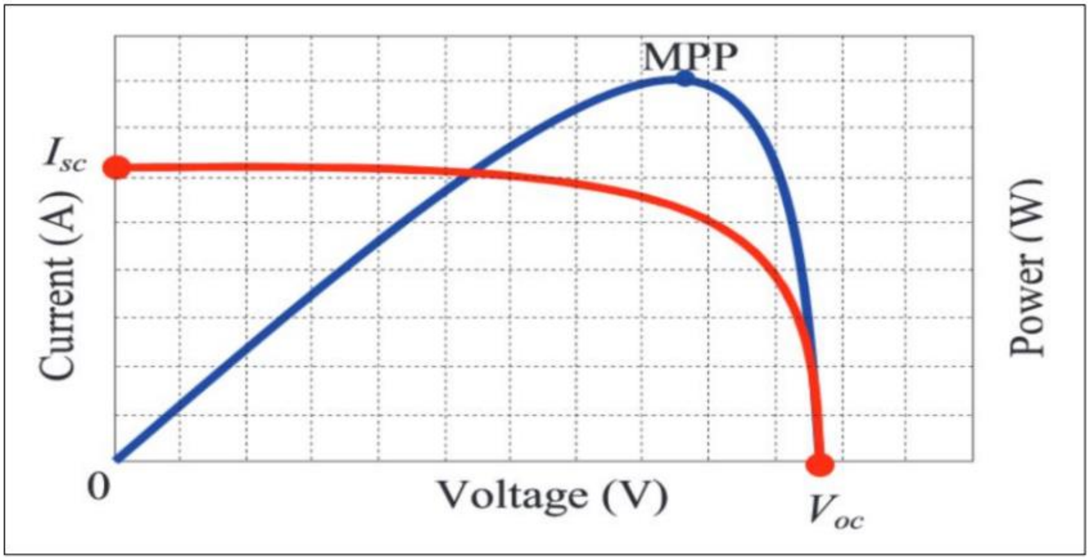


Fig 1.7: Current vs Voltage vs Power plot for a Photovoltaic cell [21].

6.2.1. Mathematical model of PV Cell:

Figure 1.8 depicts the two-diode circuit concept proposed by Z. Salam [21].

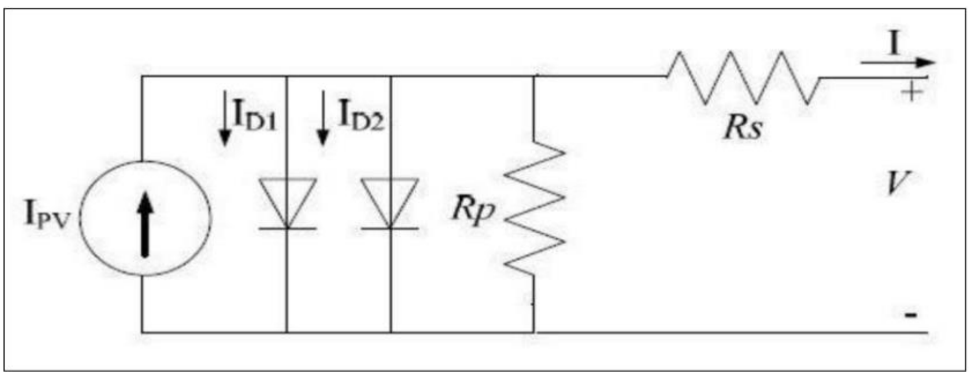


Fig 1.8 : Circuit model of a two diode Photovoltaic cell [21].

the output PV current is expressed by the following equation:

$$I = I_{PV} - I_{d1} - I_{d2} - \frac{(V+IR_s)}{R_s} \quad (1.1)$$

Where:

$$I_{d1} = I_{01}[\exp\left(\frac{V+IR_s}{a_1 V_{T1}}\right)] \quad (1.2)$$

$$I_{d2} = I_{02}[\exp\left(\frac{V+IR_S}{a_2V_{T2}}\right)] \tag{1.3}$$

Where:

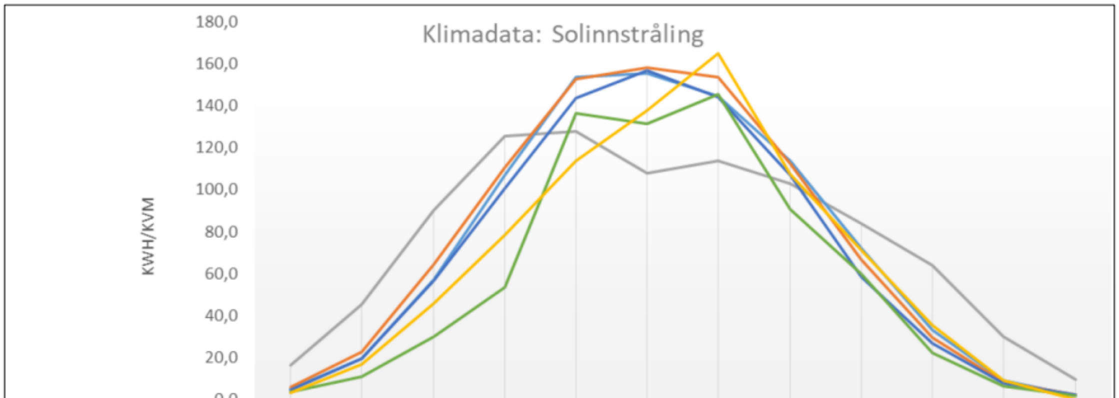
-I_{01} and I_{02} : the reverse saturation currents for diodes 1 and 2.

-V_{T1} and V_{T2} : the thermal voltages for diodes 1 and 2.

-a_1 and a_2 : the constant of ideality for both the diodes.

6.2.2. Maximum Power Point Tracking (MPPT):

The current going through the PV module determines the output voltage. The output voltage between the terminals falls as the current flow in the PV cell rises, as illustrated in Figure 1.7. When the voltage and current are combined in a specific way, the output power hits a maximum and then begins to drop as the voltage rises. Maximum Power Point is the name given to the point where the output power is at its highest (MPP). Charge controllers are used to get the most power out of the solar panels, and this approach is known as MPPT (Maximum Power Point Tracking). In a microgrid, the MPPT approach is used to run the PV array at MPP by sending a reference signal to the inverter (Active/reactive power regulated). As a result, the inverter output power is roughly equivalent to the PV array's maximum rated power [21].



	1	2	3	4	5	6	7	8	9	10	11	12
IDA ICE (Normal)	16,2	45,2	90,4	125,8	128,0	108,0	113,6	102,9	84,0	63,7	29,9	9,7
NASA (Normal)	5,0	19,3	57,0	106,8	153,8	155,7	144,5	113,8	72,0	32,9	9,0	1,9
Meteonorm (Normal)	5,7	22,8	64,4	110,6	152,9	158,2	153,7	112,2	66,6	29,6	8	2,5
PVGIS (Normal)	4,6	19,7	56,7	100,5	143,5	156,9	144,2	107,0	58,5	26,7	7,7	2,1
ASKO Midt (2017-2018)	3,7	11,0	29,8	53,6	136,4	131,6	145,5	90,6	59,9	22,2	6,2	1,7
Meteocontrol (2014)	3,1	17,0	45,9	78,6	113,7	137,8	165,1	107,3	71,1	35,2	9,1	0,0

Fig 1.9 : Solar irradiance through the years from different databases [22].

The output power of a PV system is strongly reliant on the angles between the modules and the sun, as well as the strength of the solar radiation; the higher the intensity of the radiation, the higher the output power [22].

6.3. Energy Storage System (ESS):

One of the major drawbacks of adopting renewable energy sources in a microgrid is that it suffers from intermittency due to its reliance on weather conditions. Stability concerns, frequency/voltage regulation, and unbalanced loads are all problems with RESs, resulting in poor power quality [23]. This is where energy storage (ESS) technology becomes vital and critical, since it compensates for the power outage in real time. To address with supply and demand imbalance difficulties in an MG, the ESS suppresses any power oscillations. Several types of ESS have recently been investigated. Lithium-ion batteries, supercapacitors, flywheel energy storage, and superconducting magnetic energy storage are among them. Table 1 below shows the general features of the ESS technologies available today.

Table 1.1: Different ESS techniques available for microgrid implementation [24].

Type	Efficiency (%)	Energy Density (Wh/kg)	Power Density (W/kg)	Response Time (ms)	Cycle Life (time)	Cost ($/kWh)
Battery	60 - 80	2 – 200	25 - 1000	30	200 - 2000	150 - 1300
SMES	95 - 98	30 – 100	1e4-1e5	5	1e6	High
Flywheel	95	5 – 50	1e3-5e3	5	> 20,000	380 - 2500
SuperCap	95	< 50	4000	5	> 50,000	250 - 350

Lithium-ion batteries are the most used today since they offer one of the finest energy-to-weight ratios and lose charge slowly when not in use. The charging and draining of the battery are represented by the equation below [24]:

$$C(t+1) = C(t) - \Delta t P_t^E \tag{1.4}$$

Where P_t^E is the power delivered by the battery bank at time t, and Δt represents the duration of a single interval. When the battery bank is depleted, the value of x is positive; when the battery bank is charged, the value of P_t^E is negative [29]. In a microgrid, the battery bank must also meet the following requirements.

Output power limits:

$$|P_t^E| \leq P_{max}^E \tag{1.5}$$

Stored energy limits:

$$C_{min} \leq C(t) \leq C_{max} \tag{1.6}$$

And starting limits:

$$C(0) = C_s \tag{1.7}$$

Where:

- P_{max}^{E}: Maximum charge/discharge rate.
- $C(t)$: Energy stored in the battery at instant t.
- C_s: Initial energy stored in the battery.
- C_{min}: Minimum battery energy stored inside it.
- C_{max}: Maximum battery energy stored inside it.

6.3.1. Battery sizing:

When choosing a battery energy storage system, it's important to consider how small the batteries in the system should be. A good battery bank with an adequate power and energy rating might help not only with peak shaving when demand is high, but also with storing energy from RESs and providing power during intermittency hours [24]. The equation below is used to calculate the minimal power delivered by the battery bank when the peak-shaving mechanism is established [24].

$$E_{dis}^{min} = \int_0^T \left(P_{load}^{i} - P_{grid}^{i,max}\right)\delta t, \qquad P_{load}^{i} \geq P_{grid}^{i} \tag{1.8}$$

Where,

T: End time set (hours/days/weeks).

δt: Time interval (hours).

P_{load}^{i}: System load power at instant i.

P_{grid}^{i}: Existing and renewable energy power at instant i.

$P_{grid}^{i,max}$: Maximum power supplied by both traditional and renewable generator units in the system.

When the power produced by the RESs in the system exceeds the demand, the batteries should switch into charging mode. The minimal energy required to charge the batteries is then calculated as follows:

$$E_{charge}^{min} = \int_0^T \left(P_{grid}^{i,min} - P_{load}^{i}\right)\delta t, \qquad P_{grid}^{i,min} \geq P_{load}^{i} \tag{1.9}$$

Where $P_{grid}^{i,min}$ is the minimum supplied power by the Renewable Energy Sources (RESs) in the system.

Finally, the equation below may be used to calculate the battery bank's minimum size [24]:

$$E_{ESS}^{min} = \max\left(\frac{E_{dis}^{min}}{\eta_d}, \eta_c . E_{charge}^{min}\right) \tag{1.10}$$

Where,

η_d : The rate of discharge for the battery bank.

η_c: Rate of charge for the battery bank.

$\frac{E_{dis}^{min}}{\eta_d}$: The minimal charge density for the battery bank.

$\eta_c . E_{charge}^{min}$: The charging energy of the battery bank.

6.4. Wind Turbine Generators (WTG):

Wind turbine generators are one of the most rapidly expanding sources of electrical energy. The availability of significant wind resources across the world, as well as a carbon-free power source and technological advancement, are all factors contributing to WTGs' rapid expansion. Increased integration of wind turbines into distribution networks can raise a number of issues and have a negative influence on the system's behavior [25]. The wind turbine's power production is determined by aerodynamic concepts such as wind speed, air density, turbine radius, and pitch angle [26]. The kinetic energy contained in the wind is described using the formula below [26]:

$$P_w = 0.5 * \rho * A * v^3 * C_p \tag{1.11}$$

Where:

ρ: The density of the air.

A: The area which is normal relative to wind speed.

v: wind's velocity.

C_p: Energy conversion coefficient (amount of wind energy converted to mechanical one).

The output power of a wind turbine is shown in figure 1.10 as a function of wind speed below [26]:

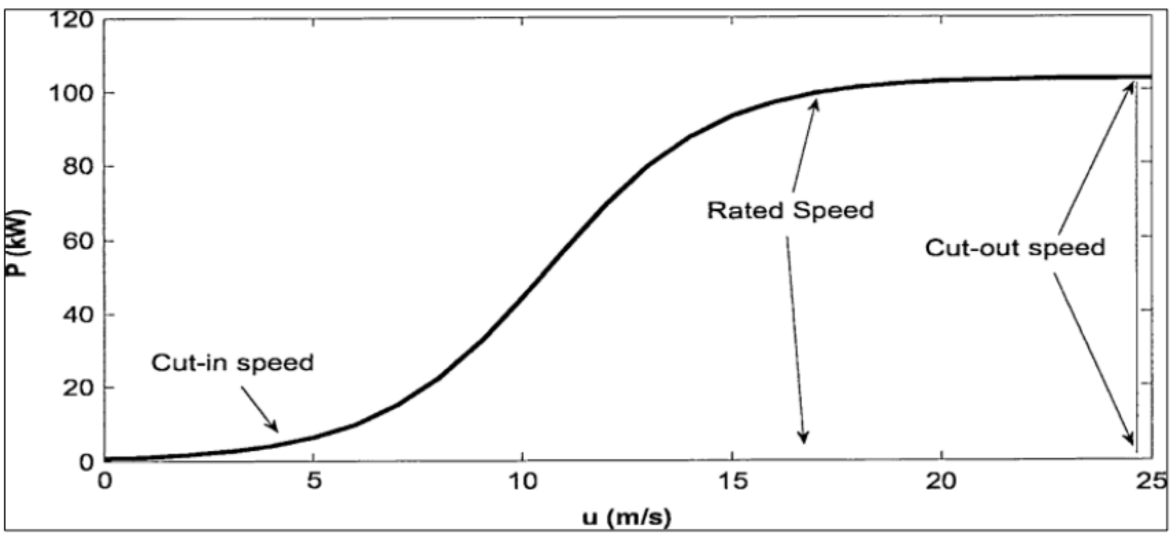


Fig 1.10 : Power Vs wind speed graph for a commonly used wind turbine [26].

6.5. Power Electronics Converters:

As demonstrated in Figure 1.11, power electronics (PE) allows AC power to be converted to DC power and vice versa [27]. A power converter with semiconductor switches and major electric elements such as transformers, capacitors, resistors, inductors, and diodes make up each power electronic interface. It also includes a control device that oversees the flow of electricity in the system as well as current and voltage conversions [27].

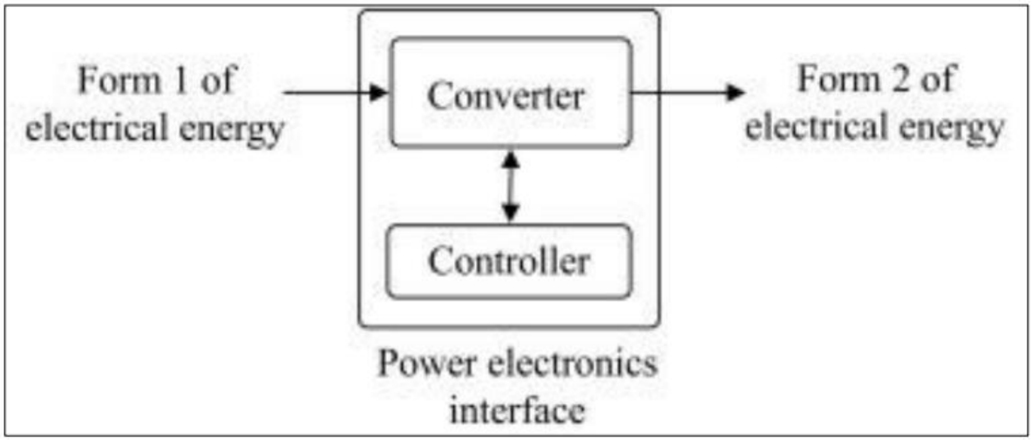


Fig 1.11 : Representation of a PE interface [27].

On either side of the converter, different frequencies, voltage levels, and voltage and current types may exist. The power converter should be able to allow bidirectional power flow in some instances (for example, battery charging and discharging). Nonetheless, most converter designs are unidirectional, i.e., they accept power from the producing sources and feed it to the loads via inverters. The input and output kinds of currents and voltages can be used to classify power electronic converters.

6.5.1. DC-DC Converters:

The input and output voltages and currents are the same for the DC-DC inverter; however, the converter creates regulated DC voltages and currents as the output. When the ESS is linked into the network, this sort of converter is used in DC microgrid applications or AC/hybrid microgrids [27].

6.5.2. AC-AC Converters:

The term ‘rectifier' refers to an AC-AC converter that converts AC to DC with a regulated output voltage. To provide a higher degree of controllability and allow bi-directional power flow, a controlled rectifier based on semiconductor switches can also be utilized [27]. Inverters is a word that is used to describe DC-AC converters. They are powered by DC and provide AC outputs with variable frequency, amplitude, and phase. Inverters are crucial in many industrial applications, particularly in motor operation, where controlling the torque and speed of induction motors is critical. Figure 1.12 depicts the architecture of an AC-DC converter for a three-phase system [28].

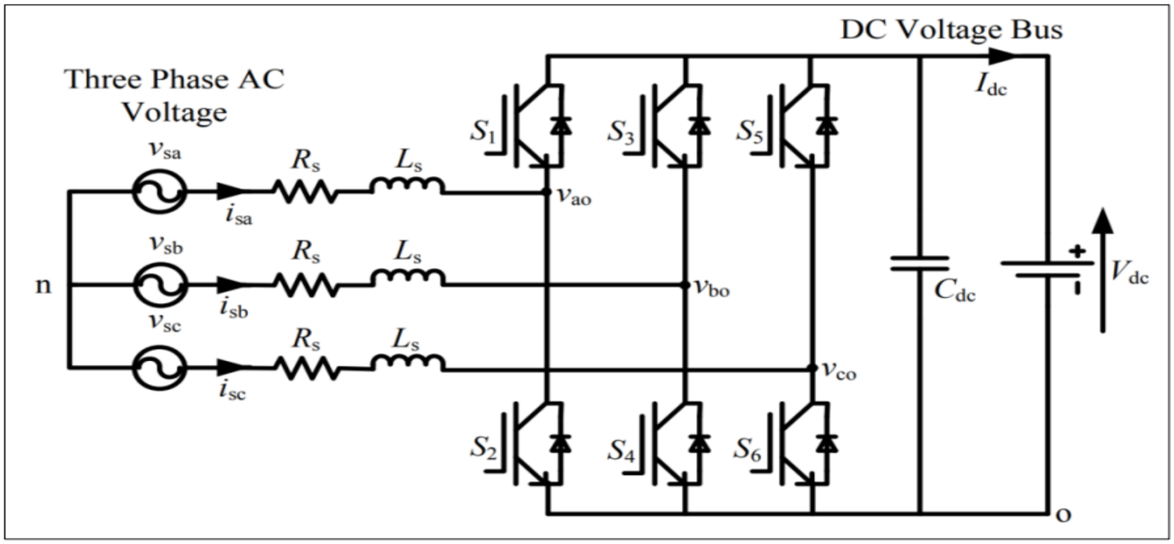


Fig 1.12 : Three phase, bidirectional AC to DC converter circuit model [28].

As illustrated in Figure 1.12, the AC-DC bidirectional converter is made up of six IGBT switches (S1–S6). The IGBTs are coupled to the 3-phase power source through a series filter inductance L_s and a resistance R_s. A DC capacitor C_{dc} is placed across the DC voltage bus to maintain the voltage V_{dc} constant. The bidirectional converter functions as a rectifier and an inverter at the same time [28].

6.6. Micro Turbines (MT):

A micro-turbine is a CHP device with four basic components: a turbine, alternator, compressor, and combustor [29]. A microturbine is the microgrid's backbone, especially in cold climates where power and heat are generated simultaneously. The benefits of using a micro-turbine in a system include high power density, minimal carbon emissions, low maintenance, high dependability, and great durability, as well as being substantially lower in weight than conventional turbines [30].

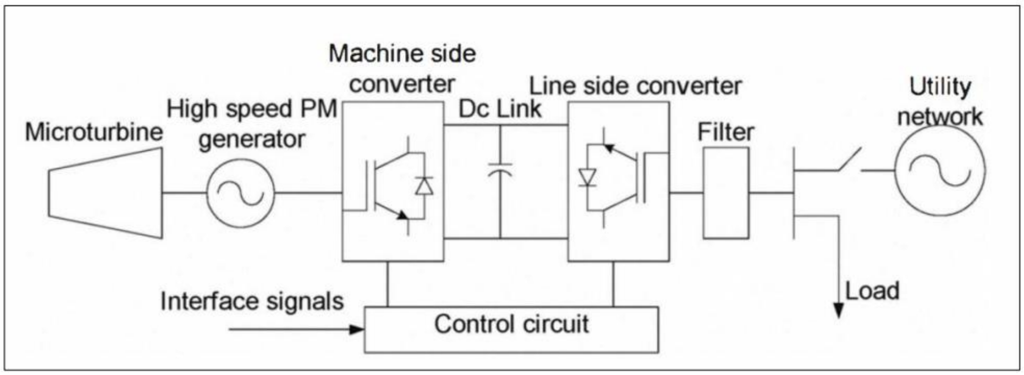


Fig 1.13 : Micro turbine generator schematic with back-to-back converters [31].

The design of a typical microturbine-connected system with back-to-back voltage source inverters is shown in Figure 1.13. This design allows electricity to flow in both directions in a grid-connected MG system, from the converter to the grid and vice versa [31].

6.7. Energy Management System in a microgrid:

The Energy Management System of an MG is one of the most important factors in its growth. It is in charge of making the best judgments possible in terms of energy production, consumption, and exchange. Due to the necessity of bi-directional energy and data transfer inside the system, EMS in MGs confronts significant obstacles. To meet environmental, technological, and economic restrictions, the Energy Management System regulates energy inside the MG as well as transactions with the upper network (grid) [39].

7. Conclusion:

To recap, the modern world as we know it is converging into renewable resources step by step due to the absolute need to become completely independent of the traditional ways of generation, so that we reduce as much as possible the pollution resulted from it. Smart/micro grid is a must in order to implement the renewable sources with the grid, and to do so, a control and monitoring system is an obligation, which we call nowadays an Energy management system. The question to ask is how can we implement it ? and what are the different approaches that can be used to realize it. That's what we are going to discuss in the next chapter.

Chapter 2:

Energy Management System and Microgrid modeling.

1. Introduction:

As previously seen in section 1.7, The Energy Management System of a MG is one of the most important factors in its growth. It is responsible for making the best energy production, consumption, and transaction choices. Due to the necessity of bi-directional energy and data transfer inside the system, EMS in MGs confronts significant obstacles. To meet environmental, technological, and economic restrictions, the Energy Management System regulates energy inside the MG as well as transactions with the upper network (grid) [39]. This is just a definition, but what does an EMS really do ?

2. Energy Management System in a Microgrid:

2.1. The roles and objectives of EMS:

EMS is in charge of gathering data, managing DERs and ESS devices, assessing and choosing the best feasible MG operation plan, and predicting RES generation and load consumptions. The following are some of the EMS's most important roles in a microgrid:[39]

- Calculate how much energy the producing units generate and how much energy the linked loads use.
- Keep supply and demand for energy in balance.
- Ensure a proper implementation of a connection between the MG and the upper utility grid.
- Ascertain that the available resources are used to their full potential.
- Minimize the cost of the overall operation.
- Ensure that in the event of an emergency, the MG should be separated from the utility.
- Provide a suitable control mechanism to reconnect the MG to the higher network, After island mode operation.

When the microgrid is connected to the grid, the goal is to optimize the power flow and maximize the benefit, however when the microgrid is isolated, the focus is on the MG's reliability. EMS plays an important role in power balancing and may be used for both long and short-term activities. The MG wishes to achieve the following objectives in order to achieve power balance:[39]

- Regulated voltage at all buses.
- Regulated frequency of the whole system.
- Load control capability.
- Ensure compatibility between supply and demand.
- Microgrid's dynamic responsiveness must be satisfactory (voltage and frequency recovery after transients).
- Providing maximum power quality at the demand side.
- Ensuring resynchronization after faults or disturbances in order to reconnect to the main utility grid.

The long-term application EMS aims to achieve the following objectives[39]:

- Scheduling of DGs and ESS units to regulate power exchange with the network, maximize RES output, reduce losses and production costs.
- Improve the utilization of DR programs to recover interrupted loads.
- Taking into consideration the impact of overusing DERs on the environment and also considering their constraints.

2.2. Residential Demand Response:

DR is a method that allows consumers to engage in the energy market in order to increase the efficiency of the power system and incorporate renewable production [32]. The majority of current disaster recovery plans in the United States are for business and industrial clients and have been well researched. For residential consumers, just a few DR programs are in operation [33].

Residential DR, on the other hand, is becoming more appealing since smart grid technologies such as smart metering, smart appliances, and home area network technologies have advanced dramatically in recent years [34].

In order to increase the overall power system efficiency and reliability, residential DR necessitates the coordination of a large number of homes. Pricing signals are often used to achieve this coordination, given that buyers are price sensitive. In the literature, extensive algorithms [33,34]

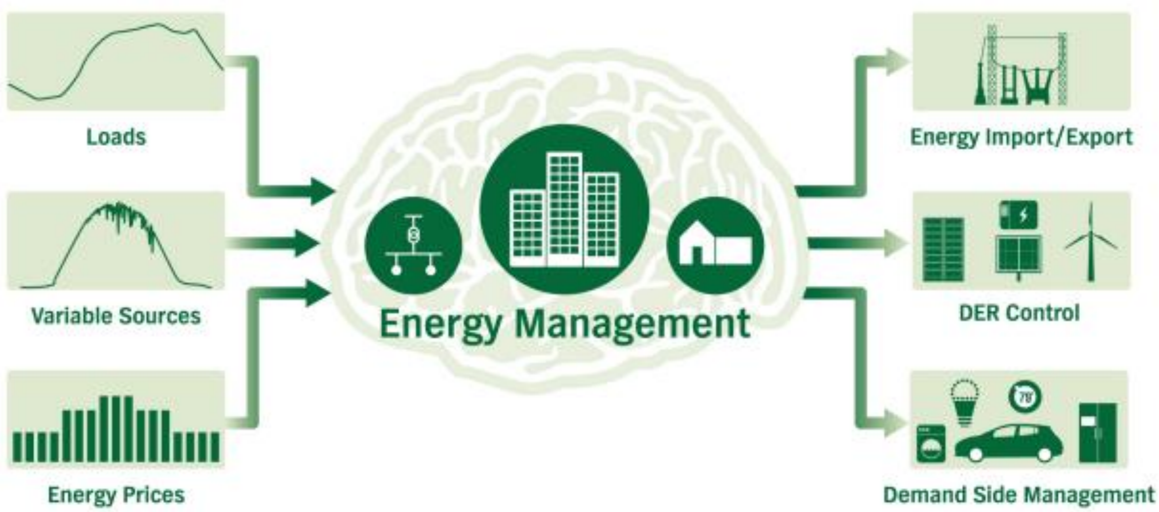


Fig 2.1 : An Energy Management Strategy [34]

have been presented to calculate pricing and consumer reactions to prices. The majority of these research treat supply-demand matching in DR as an abstract concept in which aggregate demand equals supply. Households, on the other hand, are not isolated from one another; they are linked by a power distribution network, which includes power flow limits (such as Kirchhoff's laws) and system operational constraints (e.g. voltage tolerances). As a consequence, past research' approaches may result in energy consumption/shedding choices that violate such limitations and are therefore unworkable. There are only a few studies that look at DR in DC distribution networks

[35]. They cannot, however, be used in the most common alternating current (AC) distribution networks.

2.3. Distributed Energy Management:

A microgrid's proper operation necessitates an energy management strategy EMS (EMS stands for energy management system or energy management strategy in this dissertation, depending on the context) that regulates power flows in the microgrid by adjusting power imported/exported from/to the main grid, dispatchable DERs, and controllable loads based on current and forecasted market, generation, and load information in order to meet certain operational objectives (such as minimizing costs) [36].

Microgrid energy management is often modeled as a nonlinear optimization problem. Mixed integer programming [37], sequential quadratic programming [38], particle swarm optimization [39], neural networks [40], and other centralized approaches have been developed in the literature to tackle it. The centralized techniques [37,40] need a large amount of computing power at the MGCC, which is neither efficient nor scalable. Furthermore, a centralized EMS necessitates the MGCC gathering DER (e.g., production costs, restrictions, etc.) and load (e.g., consumer preferences, constraints, etc.) information as inputs for optimization. Distinct DERs, on the other hand, may belong to different companies and keep their information secret [41]. Customers may also be hesitant to provide their information owing to concerns for their privacy [42].

In the literature, many distributed methods for microgrid operation have been presented. [41] proposes a distributed method for solving the traditional symmetrical assignment issue. [43] formulates energy management as a resource allocation issue, and proposes distributed methods for distributed allocation. [44] presents a convex issue formulation, and dual decomposition is utilized to construct a distributed EMS for microgrid supply-demand balancing. In [42], the privacy requirements are merged with the linear programming model and distributed algorithms are built to provide a privacy-preserving energy scheduling system in microgrids. The additive-increase/multiplicative-decrease technique is used to improve distributed DER operations in [45].

The difficulty with prior distributed techniques [41–45] is that they treat supply-demand matching as an abstract concept in which aggregate demand equals supply. They presume that all generators and loads are linked to a single bus, ignoring the underlying power distribution network and power flow (e.g., Kirchhoff's law) as well as system operating limits (e.g., voltage tolerances). As a result, the schedules generated by such algorithms may break certain requirements, making them impractical in reality. It's worth mentioning that distribution networks have been included in a few of recent DR investigations [46]. However, the concept of combining distribution networks with distributed energy management in microgrids, which considers both supply and demand side control, has yet to be explored.

2.4. Real-Time Energy Management:

Previous research [38,47,48] have often approached energy management in microgrids as an offline optimization issue for day-ahead scheduling. Because of the intermittency and variability of renewables, the spatial and temporal uncertainty in controllable loads (e.g., EVs), and the randomness in real-time pricing, most of these offline approaches assume perfect forecasting of renewables, demands, and the market, which is difficult to achieve in practice. To address this issue, researchers have attempted to simulate several scenarios to represent the uncertainty in day-

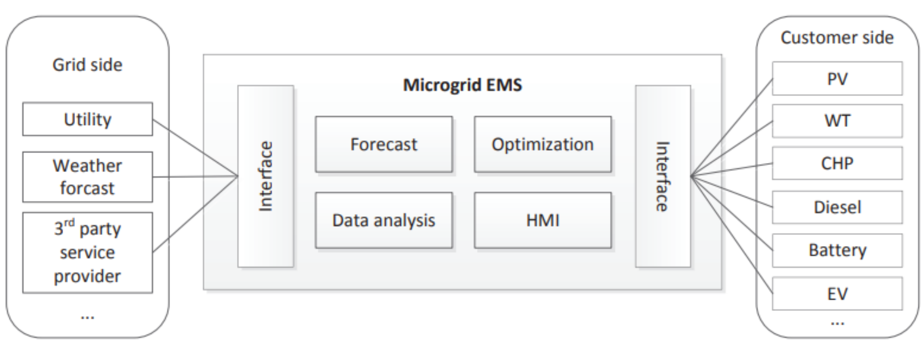


Fig 2.2 : An Energy Management System [47]

ahead scheduling [44, 49–50]. These methods often use stochastic programming to turn energy management into a deterministic issue based on scenarios provided by Monte Carlo simulations. Because the number of these cases might be huge, using these approaches can be computationally costly. Despite the fact that these techniques take into account uncertainties, they still need precise forecasting and do not generally adjust to real-time changes in the environment. Other research [39, 40] looks at the energy management issue at each time point separately and focuses on how to solve the optimization problem effectively in real time.

There have recently been efforts to construct online algorithms for real-time energy management in microgrids to maximize long-term cost, taking into account the uncertainties of renewables, demand, and the market [51,52]. These methods do not need any previous statistical understanding of the underlying stochastic processes and may adapt to changing conditions. These current online techniques, on the other hand, focus on the aggregate supply-demand balance while ignoring the underlying power distribution network, related power flow (e.g., Kirchhoff's laws), and system operating limitations (e.g., voltage tolerances). As a consequence, such techniques may lead to control choices that are inconsistent with real-world restrictions.

2.5. Energy management state of the art study:

A microgrid's functioning is monitored, controlled, and optimized by an EMS to meet specified operational goals (e.g., minimize costs). Implementing any energy management algorithms is critical. The operation and administration of a microgrid is more sophisticated than that of a traditional distribution system, which is implemented by an EMS, due to the combination of distributed generation (DG), distributed storage (DS), and adjustable loads. Due to these constraints, a microgrid EMS may vary greatly from EMS employed in traditional power systems [53].

Su and Wang [53] studied the significance of EMS in microgrid operations and identified four fundamental capabilities that a microgrid EMS must enable, as indicated in Fig. 1.4: forecast, optimization, data analysis, and human-machine interface (HMI). Many EMS frameworks [54–55] have been examined in the literature due to the relevance of EMS in power systems. While these prior research focused on distinct aspects of EMS, they all face engineering obstacles that must be considered when creating a microgrid EMS that can be implemented.

First and foremost, the microgrid management is complicated by the intermittency and variability of DERs (e.g., PVs and WTs) as well as spatiotemporal uncertainty in controlled demands, which the EMS must be able to handle. A microgrid thus initiates a slew of new applications (such as demand response, coordinated EV charging, vehicle-to-grid (V2G), and cutting-edge control algorithms [57, 46, 56]. The EMS must be able to communicate with them in a smooth manner. Furthermore, since many of the EMS's controlled devices are on the customer's side, they need a certain amount of autonomy and local intelligence, which the EMS must be able to offer. A microgrid, last but not least, controls a variety of energy components. However, the majority of them still employ proprietary protocols and are unable to communicate with one another [54]. The EMS must deal with the diversity and establish interoperability. Only by solving the technical hurdles and meeting the aforementioned functional criteria can a microgrid EMS be built to conduct effective management and control. Unfortunately, only a few prior EMS research have achieved both.

3. Microgrid model:

3.1. Modeling of Load profile:

The model will be using a variable load with an initial load power of 350 kW and fluctuating following the next graph (during 24 hours represented in minutes in the x-axis):

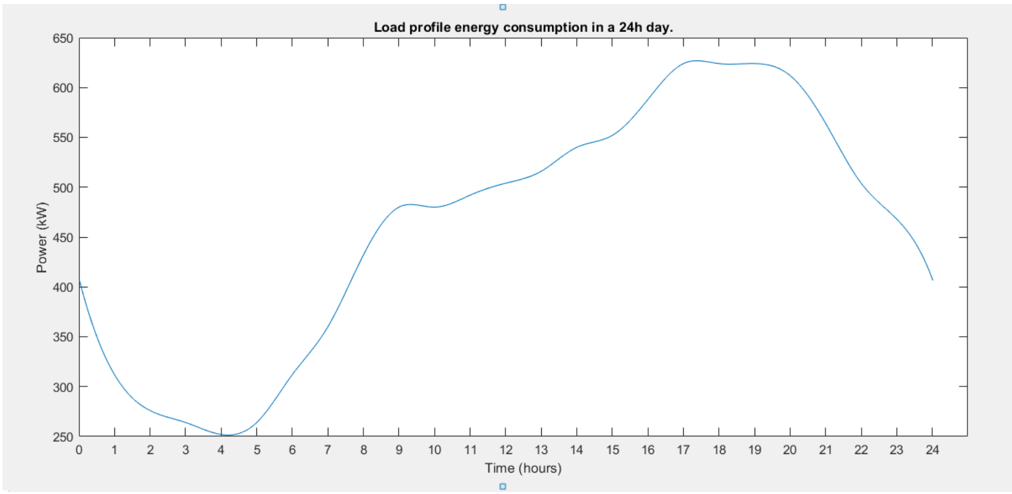


Fig 2.3: Load Power consumption during the day

As it is clearly observed, it changes throughout the day from positive to negative (depending on load demand) and it is easily seen that it is at its peak during the night when everyone is at home using electricity.

3.2. Modeling of Photovoltaic generator (Solar array):

Solar power is the energy produced by photovoltaic (PV) panels from sunshine. Solar panels turn sunlight into DC power. The quantity of direct and defused energy on the earth's surface is determined by the size of the PV panels and sun irradiation in solar power production. The sun irradiation is measured in W/m^2 and varies by location. PV panels should be operated in maximum power point tracking (MPPT) mode to ensure effective energy transmission. PV panels' output power is determined by their size and efficiency, and may be computed as a function of solar irradiation under the assumption of MPPT functioning as follows:

$$P_s = \eta_s \times A \times SI[1 + \gamma(T_0 - 25)] \tag{2.1}$$

where η_s denotes total efficiency, A denotes PV panel area, and SI denotes solar irradiation. The outside temperature is T_0, and the temperature coefficient of the maximum output power is

T, which is commonly expressed as a negative percentage per Celsius or Kelvin. The total output power of a number of solar generators may be calculated as follows:

$$P_{pv} = N_s \times P_s \tag{2.2}$$

Where N_s is the number of solar generators.

For the solar array output power, it differs during the day (peak at noon) and also changes depending on the weather (cloudy or clear), the output power of the solar array with an initial power of 500 kW during both clear and cloudy days is demonstrated in the two following graphs:

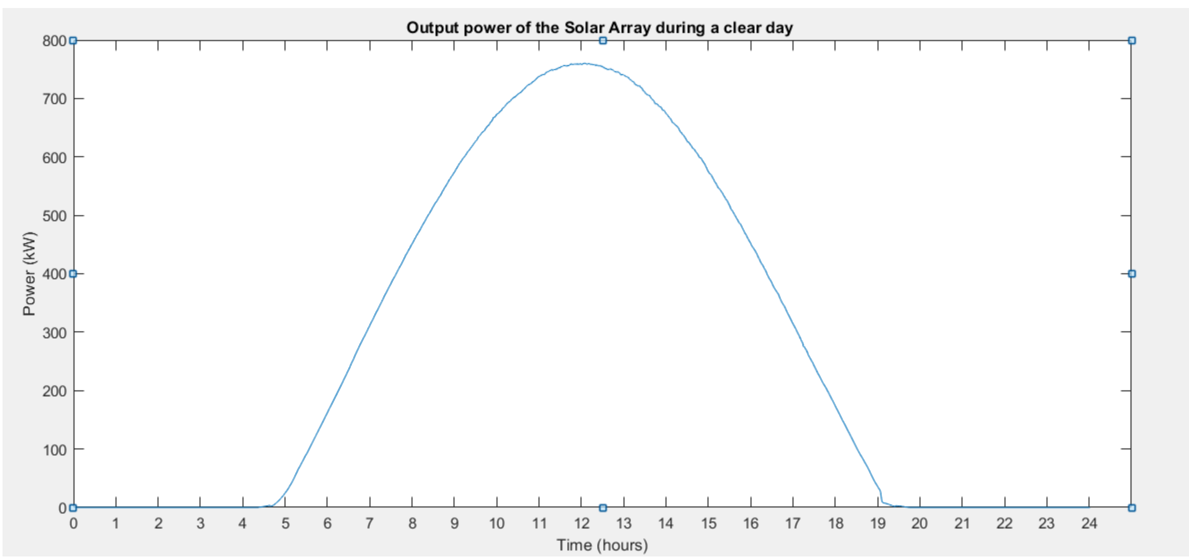


Fig 2.4 : Output power of the PV system during a clear day [58].

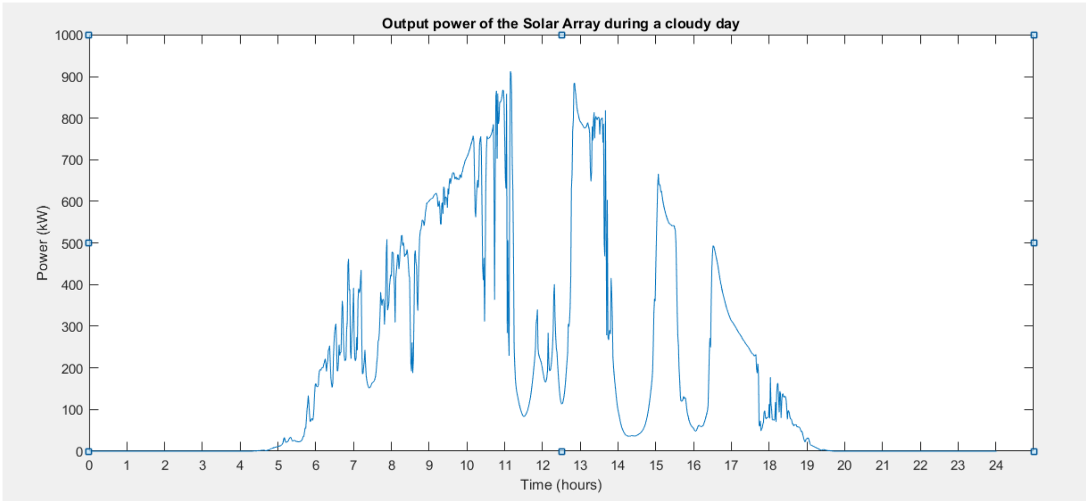


Fig 2.5 : Output power of the PV system during a cloudy day [58].

As a remark, there is a difference between the cloudy and clear day due to solar irradiance fluctuations.

3.3. Modeling of converters:

The converters in a multi-source production system have a variety of functions, including the ability to synchronize with the grid, current control, MPPT control, and detection of islanding situations. Converters, such as DC/DC and DC/AC conversions, are used in the multi-source system. There are two techniques to modeling this conversion [102]: the European approach (eur) and the American approach (cec).

$$\eta_{eur} = 0.03\eta_{5\%} + 0.06\eta_{10\%} + 0.13\eta_{20\%} + 0.10\eta_{30\%} + 0.48\eta_{50\%} + 0.20\eta_{100\%} \quad (2.3)$$

$$\eta_{cec} = 0.04\eta_{10\%} + 0.05\eta_{20\%} + 0.12\eta_{30\%} + 0.21\eta_{50\%} + 0.53\eta_{75\%} + 0.05\eta_{100\%} \quad (2.4)$$

Where $\eta_{5,10,20,\dots\%}$ is the efficiency of the converter at a particular output power P_{conv}, expressed as a percentage of the nominal power P_n, as follows:

$$\eta_{\%} = 100\frac{P_{conv}}{P_n} \tag{2.5}$$

3.4. Modeling of Energy Storage System:

An appropriate model for the energy storage system must be designed to maximize the operational planning of a microgrid (ESS). As mentioned in Section 1.6.3, there are several types of energy storage, each with its own set of properties, such as reaction times, storage capacities, and peak current capabilities, that are used for different purposes and on different timescales. Electrochemical batteries were chosen for this research because of their widespread use in storing electrical energy for extended periods of time.

The energy stored in the ESS is utilized as the state variable by the management system in microgrids. The ESS system consists of a multiplicity of similar batteries linked in series to boost the voltage level and in parallel to increase the current level. Several parameters, including as capacity and charge/discharge rate, are required in battery modeling to explain its behavior, deep discharges are avoided to extend the life of the storage system, hence batteries are defined by their minimum and maximum capacities, respectively E^{min} and E^{max}, with:

$$E^{min} \leq E(t) \leq E^{max} \tag{2.6}$$

$$E(t+1) = E(t) - \Delta_t P_c(t)\eta_c, \qquad \text{charging}$$

$$E(t+1) = E(t) - \frac{\Delta_t P_d(t)}{\eta_d}, \qquad \text{discharging} \tag{2.7}$$

where $P_c(t)$ and $P_d(t)$ are the battery's charging and discharging powers at time t, respectively; $E(t)$ and Δ_t are the battery's stored energy at time t and the time interval, respectively; and η_c and η_d are the charging and discharging efficiency, respectively. The following are the battery's charge and discharge power limitations:

$$-P_c(t)\eta_c \leq P_c^{max}(t) \qquad \text{charging,} \quad P_c(t) < 0$$

$$\frac{P_d(t)}{\eta_d} \leq P_d^{max}(t) \qquad \text{discharging,} \quad P_d(t) > 0 \tag{2.8}$$

Where $E^{min}(t)$ and $E^{max}(t)$ are the battery's minimum and maximum energy levels, and P_d^{max} and P_c^{min} are the battery's maximum discharge/charge rates that must be observed during each operation.

Because battery control is an important consideration when operating a microgrid, the energy storage system can only be used in one of the following modes at a time:

1. **Charge modes:** With an energy amount that is not more than the charging rate, the battery may be charged from the grid and/or renewable energy sources.
2. **Discharge modes:** When prices are high, the battery provides energy to loads in a quantity that is within the battery discharge rate.
3. **Inactive modes:** In this mode, there is no battery energy activity since the grid utility and microgrid directly provide power to loads at certain hours to reflect economic considerations.

By applying the formula of battery sizing mentioned in section 1.6.3.2, we determined the battery size that will be used in the model which is 2500 kWh (Energy storage rated capacity), with an overall efficiency of 96%, thus the battery energy in joules is:

$$E_{batt} = 3.6 \times 10^6 \times E_{batt} \ (Joule)$$

$$E_{batt} = 3.6 \times 10^6 \times 2500$$

$$E_{batt} = 9 \ \times 10^9 \ (joule)$$

Since deep charging and discharging are avoided in order to extend the life of storage system, thus the minimum and maximum battery energies are defined, in this model minimum energy is set to be 20% of the total battery energy:

$$E^{min} = 0.2 \times E_{batt}$$

$$E^{min} = 0.2 \times 9 \ \times 10^9$$

$$E^{min} = 1.8 \times 10^9 \; (joule)$$

While its maximum is set to 80% of the total battery energy:

$$E^{max} = 0.8 \times E_{batt}$$

$$E^{max} = 0.8 \times 9 \times 10^9$$

$$E^{max} = 7.2 \times 10^9 \; (joule)$$

The following flowchart expresses how the coordination control inside the microgrid model is done:

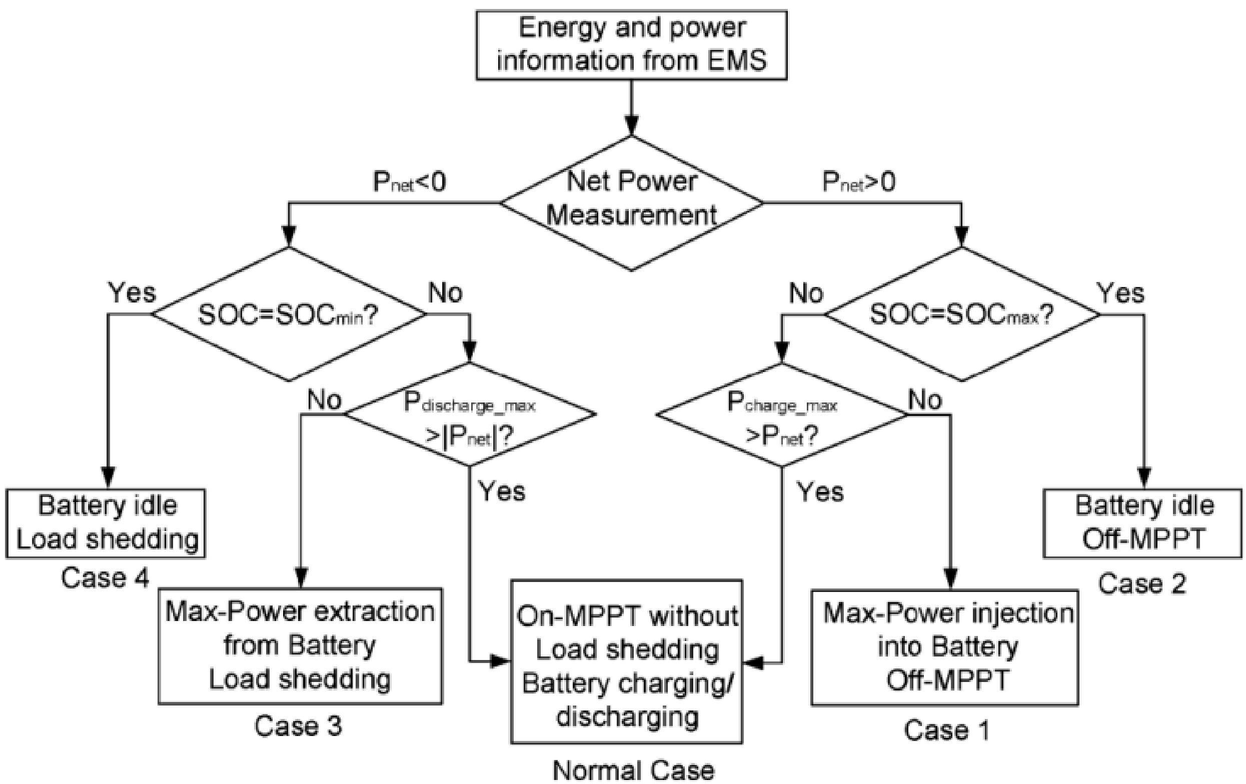


Fig 2.6 : Coordination control flowchart of ESS

Where SOC stands for State Of Charge of the battery bank which varies from 20% up to 80%.

Whereas P_{net} is the difference between load demand and supply power:

$$P_{net} = P_{pv} - P_L \tag{2.10}$$

- P_{pv}: Output power from the solar array.
- P_L: Combined load power (both variable and static).

3.5. Charging and discharging conditions with relation to varying grid prices:

The management is created as a uni-objective optimization problem in this study, with the main goal of optimizing the economic element and disregarding the environmental aspect. As a result, picking the least priced power at any given time and allocating it to the load is the top priority. Ascertaining that the consumer's energy balancing requirements are met while receiving the lowest feasible daily energy bill.

the following cases describe the relation between battery's current energy $E(t)$ with its minimum and maximum allowed energy and the cost of energy at that specific time

- **In case of** $(E(t) = E^{max})$, the storage system will be regarded the primary source, with the two other sources (photovoltaic and grid) serving as backup. The storage system's energy supply will be based on the amount of energy demanded and the unit energy price per hour. It's worth noting that the discharge rate is constrained by a maximum amount that must not be exceeded in accordance with the previous limits.
- **In case of** $(E(t) = E^{min})$, the storage system will need a particular quantity of energy from the cheapest sources in the microgrid at a given moment for the charging process. The microgrid will treat the storage system as a load in this circumstance. If all of the separate generators' unit energy costs are significantly high, and the load is fulfilled, the storage system's charging procedure will be postponed until the energy prices are suitably low.

- **In case of** $(E^{min} \leq E(t) \leq E^{max})$, Two scenarios may arise depending on the storage system's energy unit price:
  1. If the storage system's energy is the most costly, and the energy demands of microgrid customers can be met primarily by other sources, the storage system will continue to be charged, but its energy will not be used to serve the load. However, if the energy provided by the different generators is inadequate, the energy from the storage system will be utilized to meet the energy balance constraint.
  2. If the cost of energy provided by the storage system is lower than the cost of energy produced by other sources, the storage system will participate in providing the load and provide maximum energy equal to its discharging power rate limit.

The following graph shows how the price of a kWh imported from the grid varies during 24h day:

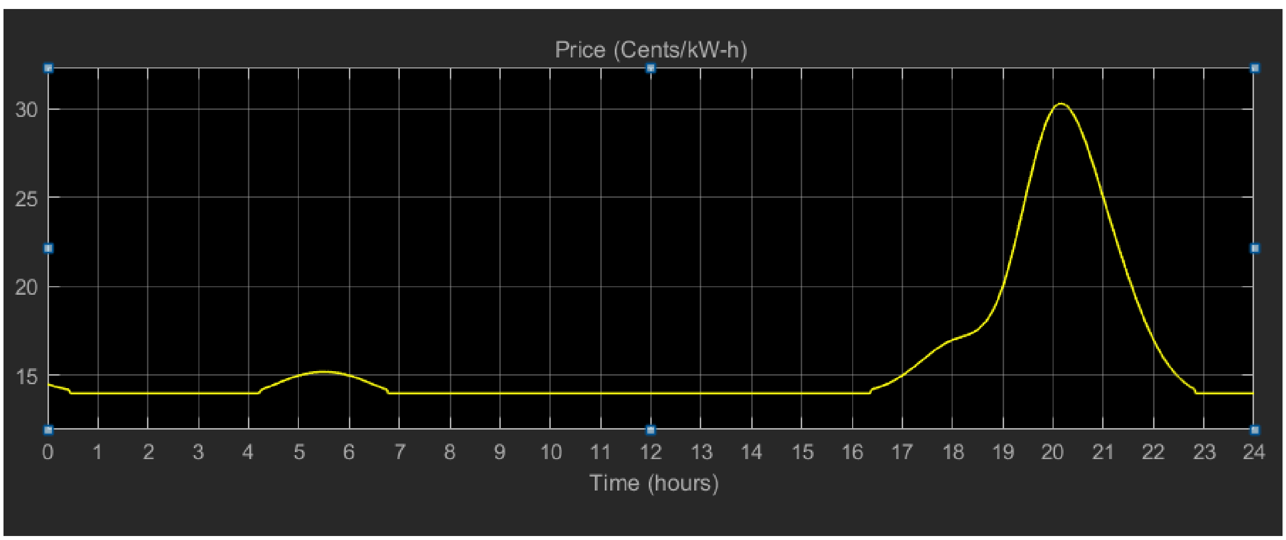


Fig 2.7: Plot of varying grid energy cost during a day [58].

4. Energy management approaches:

An energy management system is required for the microgrid's central control. The microgrid presented in this paper is made up of distributed resources, a storage system, and the main grid; their simultaneous operation necessitates an energy management system whose main function is to determine, in an autonomous manner, the optimal quantity of energy that will be supplied by the microgrid and the main grid to meet demand in terms of the energy required by the load per hour while ensuring the lowest cost of energy and lowering emissions.

4.1. Heuristic approach:

This method is based on time dependent assumptions regarding previously seen data for example: peak demand time and generic load profiles, thus it schedules its actions depending on these previous data, It measures PV output power, Load power consumption, and energy storage system state of charge (SOC %), and take them as inputs.

The time intervals which actions depend on are (t in hours):

- $0 \leq t \leq 5$: ESS is unutilized (idle) and the load is fed from the grid.
- $5 < t \leq 15$: the net power is calculated from equation (2.10), then decides whether the battery bank is to be charged or discharged. When the PV output power exceeds the loads demand, the remaining energy is used to charge the ESS.
- $15 < t \leq 23$: peak load demand phase, at this period the EMS sends a signal to extract the full potential of ESS and if there is any shortage in supply, it is compensated from the grid.
- $t > 23$: the grid prices are at their lowest and load demand start to decrease, ESS is set to be recharged and load fed, both from the grid.

This is all where ensuring the user’s comfort is a top priority.

In this approach, Matlab's tool "Stateflow" is used in order to construct the necessary algorithm, which consists mainly on Fig 2.6, the following figure shows how it is designed:

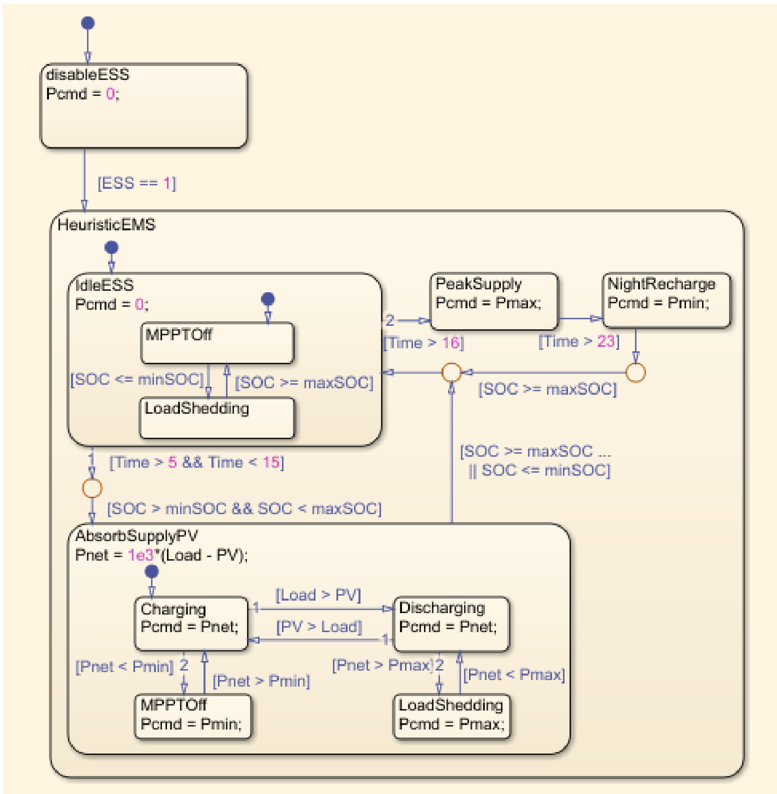


Fig 2.8 : Heuristic Approach for EMS

"Heuristic" technique or approach is any problem-solving that uses practical method or various shortcuts in order to produce solutions that may not be optimal but are sufficient given a limited time frame or deadline.

Using this method will allow to have some desired outputs but not optimal ones, especially it does not support cost optimizations, which is a top priority in any energy management system, thus the following section will discuss a more sufficient approach to energy management system.

4.2. Optimization approach:

This approach is developed to aim to minimize the cost of power from the grid while maintaining power balance between load demand and supply (PV, battery and grid). It is a more sufficient methodology but it required a more complex system and hardware to be ran or implemented because it uses more computational potential to be executed. In this model, the optimization is set to be done every 5 min (300 seconds) which means during 24h it would have been executed 288 times. Each iteration, it reads the previous inputs as shown in Fig 2.9 and performs the necessary calculation depending on the net power and also the grid pricing at that specific time.

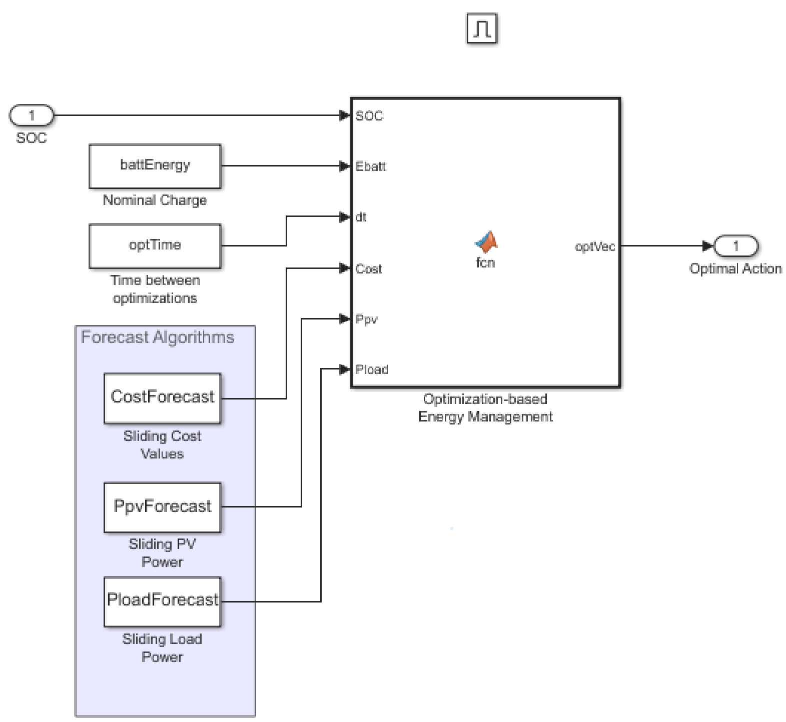


Fig 2.9 : Input and output to the optimization-based EMS.

In order to implement it, a linear programming code is used which basically optimize the total cost function of the whole system as best as possible to minimize the energy imported from the grid, by maximizing the usage of the solar array alongside with the Energy Storage System, which means a cheaper total cost with less emissions to harm the environment which is a win win situation.

In the model, both heuristic and optimization approaches, fig(2.10) shows that we can switch in between them and run the simulation and do a comparison.

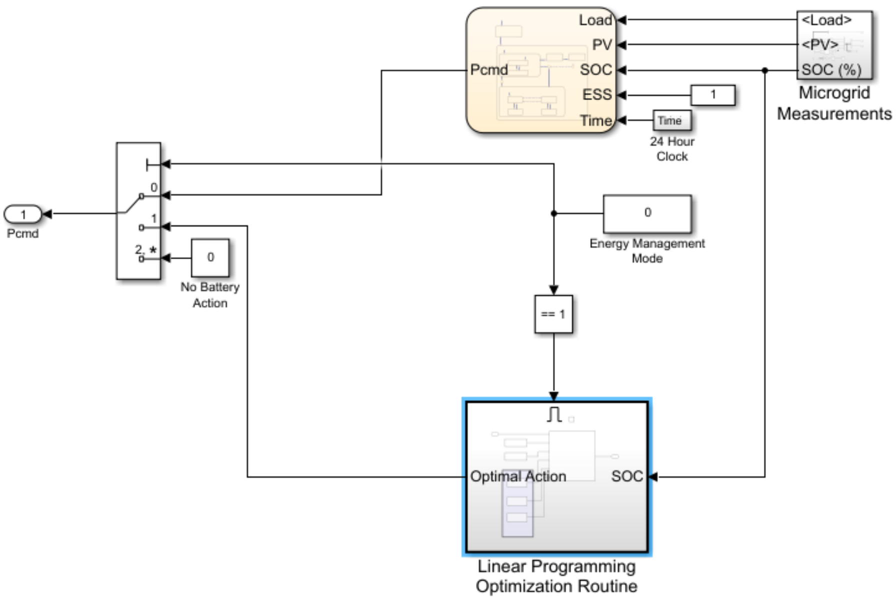


Fig 2.10 : Energy management mode selection in Matlab

As a result, there are two profiles for the solar array (clear and cloudy day data) and two different energy management approaches (heuristic and optimization) that can be implemented with the previous data, then the four following case studies are obtained:

- **Case study (1):** Heuristic energy management in a sunny clear day.
- **Case study (2):** Heuristic energy management in a cloudy day.
- **Case study (3):** Optimization energy management in a sunny clear day.
- **Case study (4):** Optimization energy management in a cloudy day.

5. Conclusion:

Energy management system offers ways to cut off costs alongside satisfying the user demand all the time and also with less emissions to harm the environment. The four Case studies mentioned above will be implemented, simulated and discussed in the next chapter using *Matlab/Simulink.*

Chapter 3: Simulation, Results and Discussion.

1. Introduction:

This chapter presents the simulation results obtained and its discussion after applying Energy Management System (EMS) to the two study scenarios (clear and cloudy day) ,using both heuristic and optimization approaches and demonstrating the difference between the two methodologies. The microgrid model is implemented using *MATLAB/Simulink* programming platform. The results are displayed in graphical form and numerical values to show the main objective described in the previous chapter.

2. Objectives:

The main objective of this study is to determine the best way to minimize the cost of importing electricity from the grid by maximizing the use of the solar array alongside the ESS, without sacrificing the user's comfort.

3. Methodology:

The two main methods used in this study are presented below:

3.1. Heuristic method:

As presented in the previous chapter, this method is a time dependent method which basically relies on previously obtained data to schedule the more appropriate action to be made.

Based on the time of the day and whether the net power is positive or negative (whether PV power satisfies the load alone or not), it decides whether the ESS is charging or discharging or if the grid is to be used or not.

Refer back to section 2.4.1 where Fig 2.8 shows the proper Stateflow algorithm that was used to implement this method.

3.2. Optimization method:

As already discussed in the previous chapter, this technique is used for more efficient result where the linear programming optimization routine (optimal action) is done every 5 minutes to supply the load with the cheapest cost possible while maximizing the usage of Battery Bank (Energy Storage System) and PV panels (Solar Arrays) without threatening the consumer comfort .

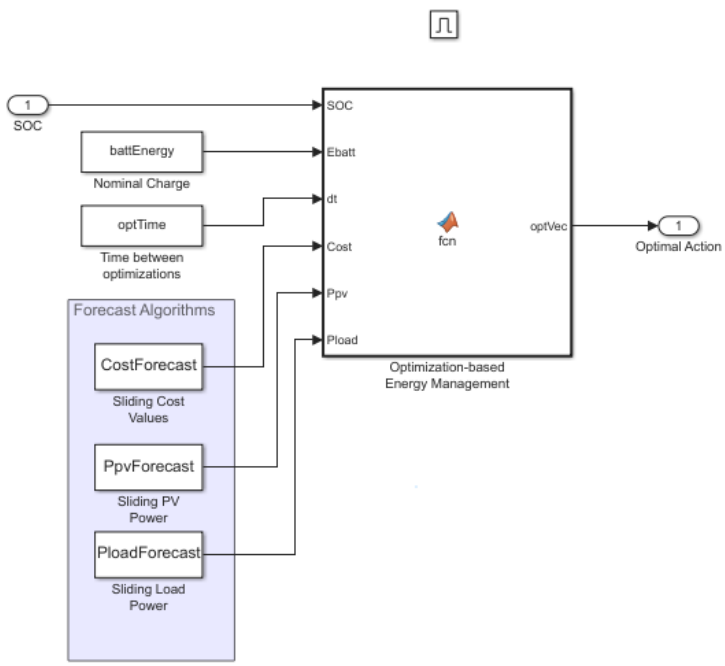


Fig 3.1: Optimization approach Energy Management

As can be seen in Fig 3.1, the optimization algorithm reads the input values each minutes, then performs the more suitable action (utilize the grid or not, charge or discharge the battery bank, ...etc.)

4. Application:

This microgrid model consists of Renewable energy resources represented by Photovoltaic system (Solar Array), an Energy Storage System (ESS), a static and a variable load, Power electronics devices (Inverters, Converters,… etc.), A utility grid with PCC (point of common coupling), and an Energy Management system.

- Load profile:

  The total daily consumption of the load is shown in figure 2.3, the simulation is performed to this specific load only.

- Photovoltaic model:

  The solar array has an area of 2500 m^2, and a efficiency of 30%.

  The output power is shown in fig 2.4 and 2.5.

- ESS model:

  Energy storage capacity is rated at 2500 kWh Lithium-ion battery bank, with a charge and discharge rate of 400kW. As mentioned in the previous chapter, it should be noted that battery capacity must be kept between 20% and 80% (initial SOC = 50%).

- Microgrid model:

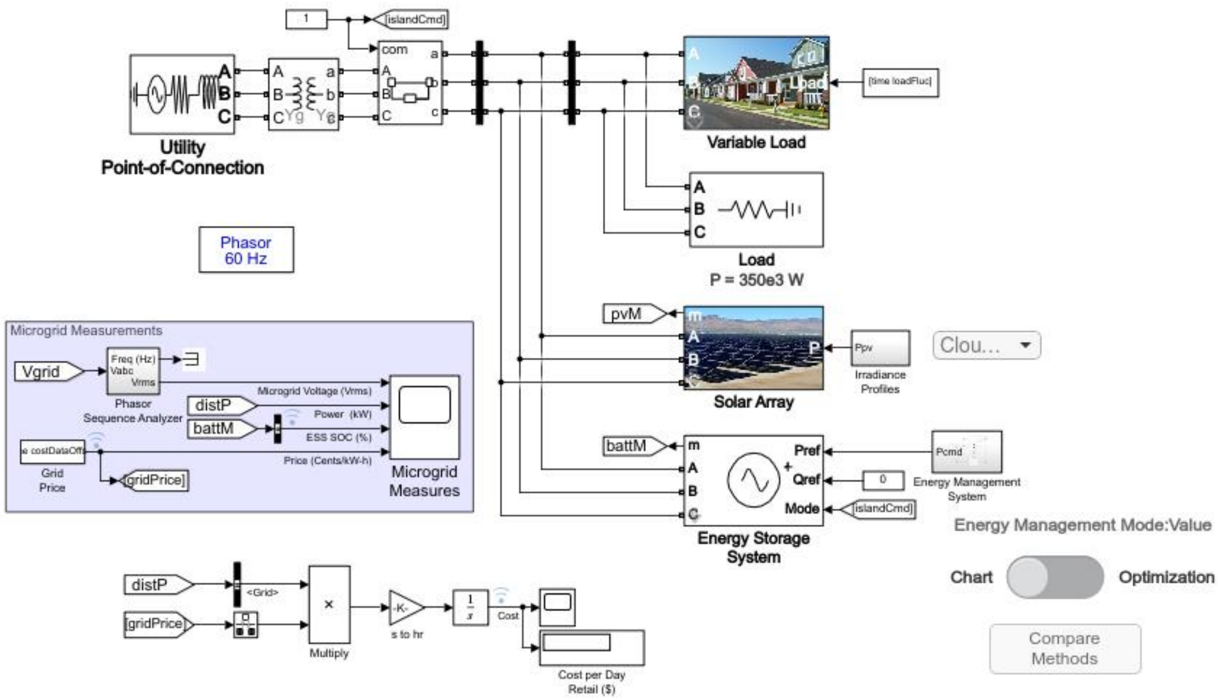


Fig 3.2: Microgrid model

5. Results:

The results presented in this section are based on the case studies shown in the previous chapter:

5.1. Case study (1): Heuristic energy management in a clear day

Using the previous data mentioned in the previous chapter, the following results are obtained and demonstrated in graphs for Power of Grid, PV, ESS, and load, ESS state of charge (SOC %), Microgrid's RMS voltage and the plot for the cumulative Cost function:

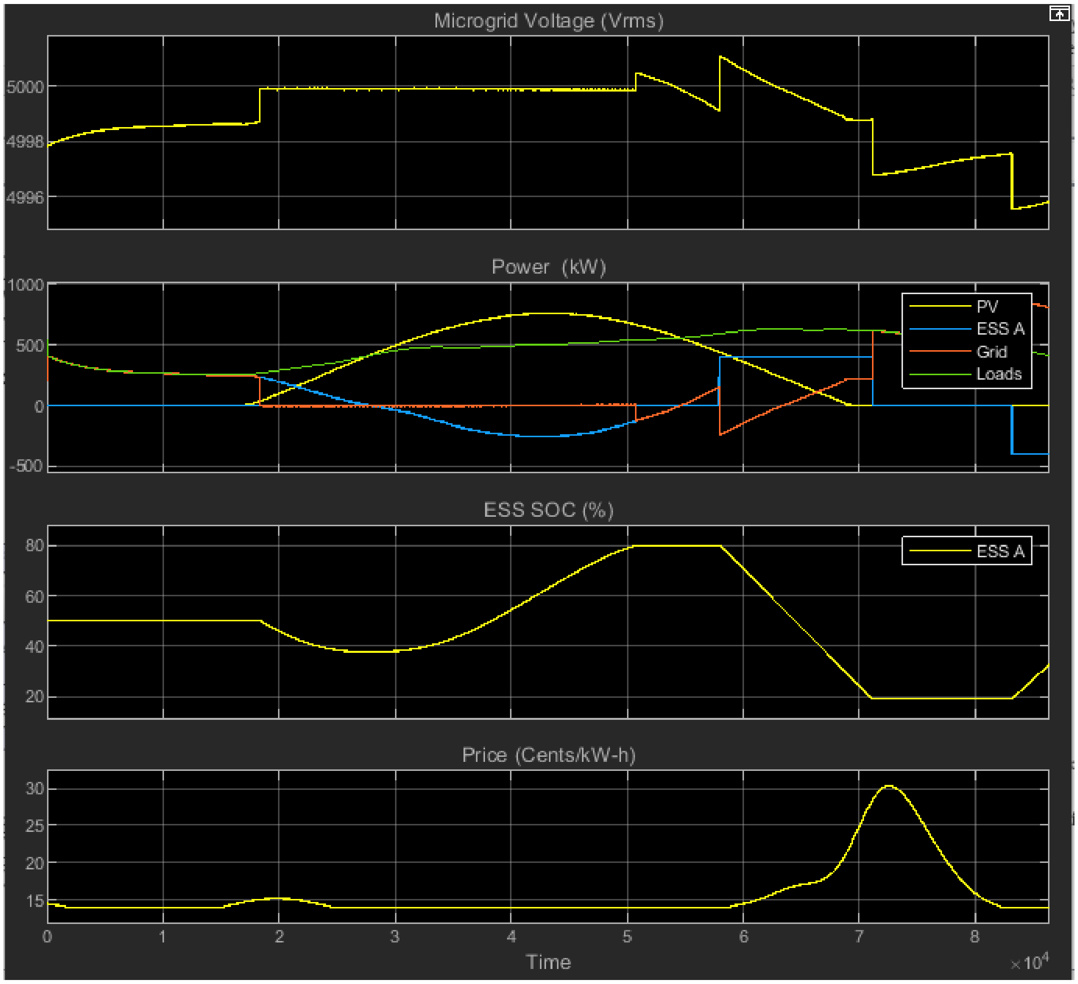


Fig 3.3 : Results for case study 1

Fig 3.3 represents microgrid's RMS voltage fluctuation (Vrms), PV, Grid, ESS, and loads power (kW), ESS state of charge (SOC %), and grid's price of energy in Cents/kW-h.

It is clear that the grid's voltage (Vrms) is inversely proportional to the grid's power (kW) due to the fluctuations in the load, which leads to small changes in the rotational speed of the generator, in addition to some power losses that may slightly affect the microgrid's voltage.

From the second graph we can deduce the following time intervals:

- No solar irradiance (from midnight until 5 o'clock in the morning):
  - The grid is the only source to the load.
  - ESS is OFF (see heuristic figure (Fig 2.8)).

- Sun is up and no peak load demand (From 5AM up to 3PM):
  - Load is fully fed from the solar array (except from 5AM until around 8AM, PV power is less than the load's; ESS is deployed (graph 3 shows that in this period the SOC is dropping)).
  - Grid is completely unutilized.
  - When PV power exceed load demand, the extra power is used to feed the ESS to charge the battery bank (as shown in graph 3).
  - When SOC reaches SOC_{max} (80%), the extra power goes back to the grid instead of ESS.
- Peak demand period (between 3pm and 11pm):
  - At this period the load demand will reaches its maximum while the PV power decreases.
  - Load demand will be mostly fed from PV and Battery bank power "with small contributions from the grid starting from 6PM due to decreasing solar irradiance thus less output power from the solar array", then both the grid and ESS will contribute to feed the load.
- Night recharge (starting from 11pm):
  - Grid's electrical energy price will be at its lowest, then grid can be used to feed both the ESS battery bank and the load.

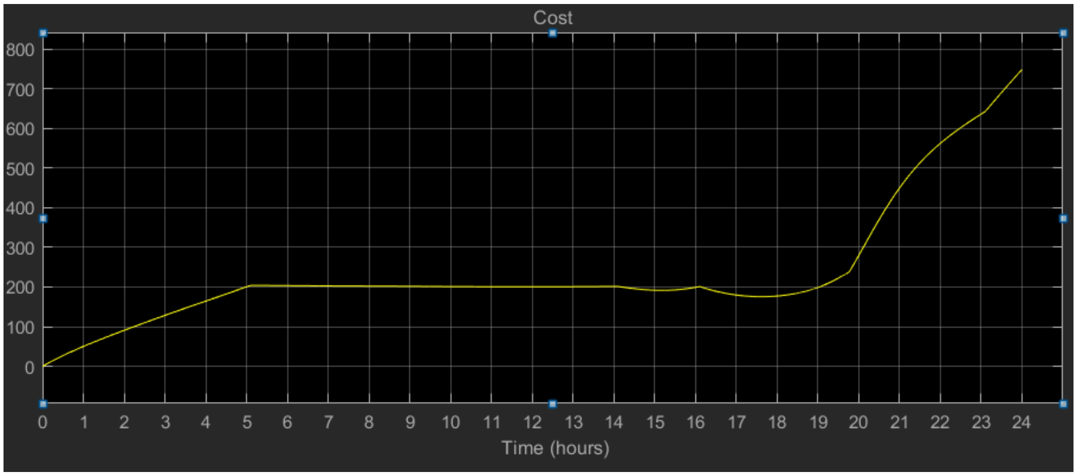


Fig 3.4 : cumulative cost function plot for case study 1

The total cost using this method is 748.4$ during this 24hrs. As seen in fig 3.4, the total cost increases significantly during the night due to grid's utilization in feeding both the load and the 2500 kWh battery bank.

5.2. Case study (2): Heuristic energy management in a cloudy day:

Similar graphs are plotted for this case as well, comparing with the last case study, only the irradiance profile is changed, the following results are obtained:

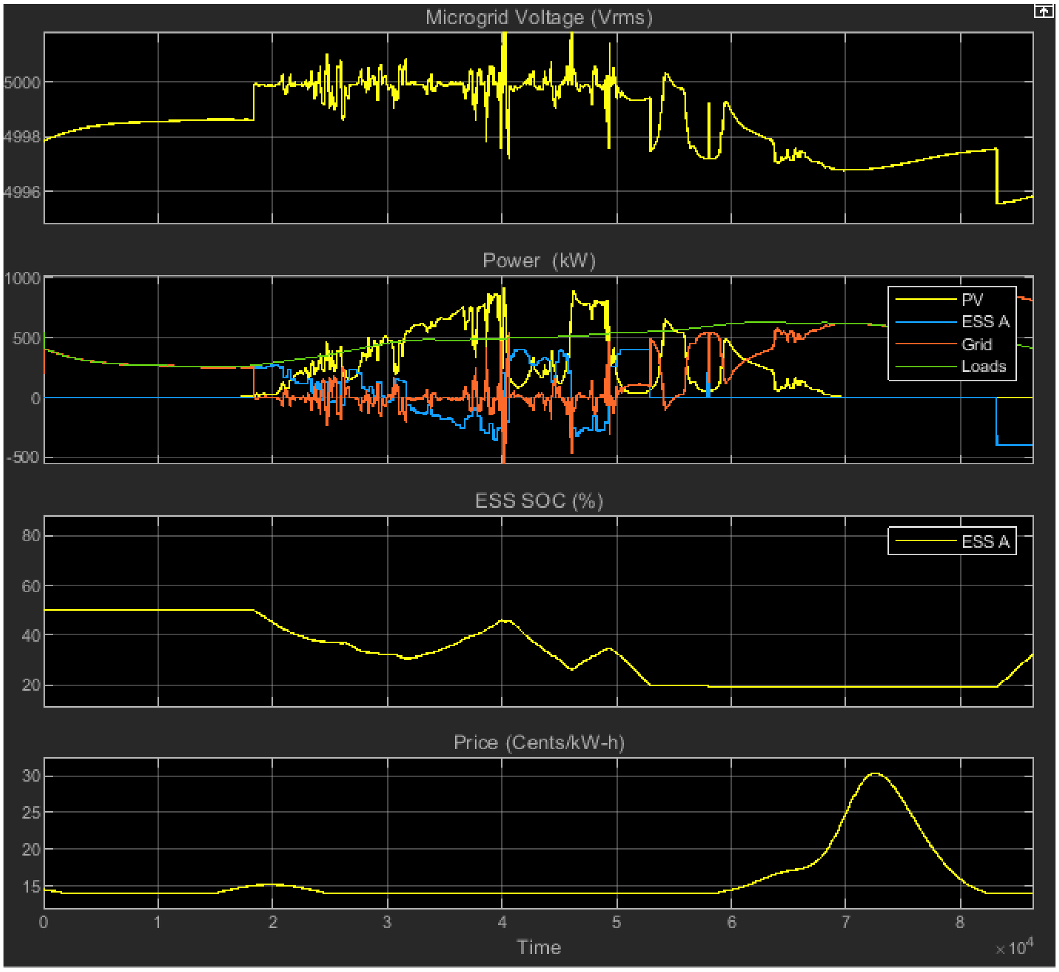


Fig 3.5 : Results for case study 2

As previously said in the first case study and since this is the same Energy management approach only different solar irradiance profile (cloudy day), the same time intervals and principles are applied.

The fluctuations observed especially in microgrid's voltage and power curves exist due to the fluctuating solar irradiance (Fig 2.5), the previous results were obtained while obtained the heuristic method (Fig 2.8).

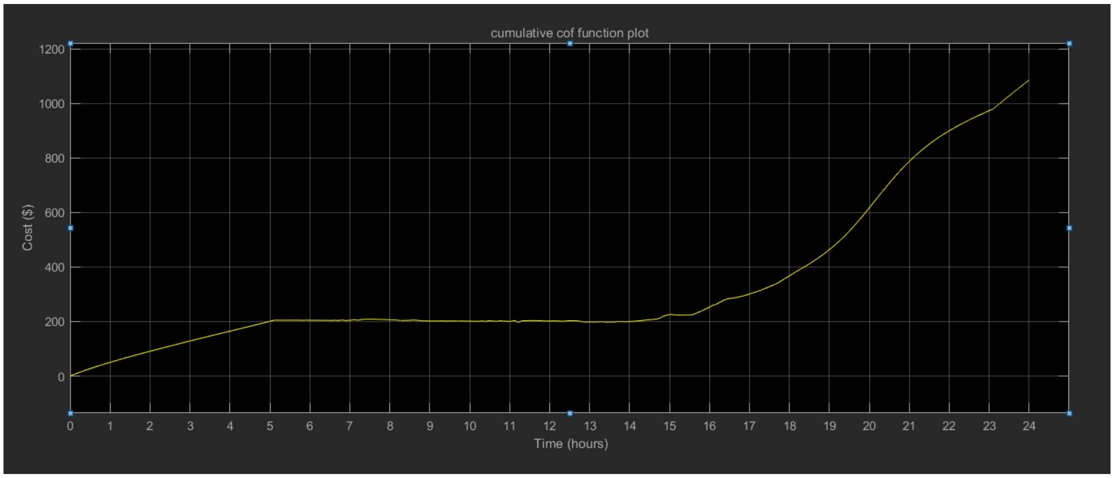


Fig 3.6 : cumulative cost function plot for case study 2

The total cost in a cloudy day is 1086$, which is logically higher than the first case study due to less overall output power from the solar array. As noticed in Fig 3.6 and due to the increasing load demand and the night charge phase of the battery bank, the cost increases significantly during the night.

5.3. Case study (3): Optimization energy management in a clear day:

For this case study, the whole EMS mode is changed, instead, now the optimization algorithm is applied, which is designed to optimize the total cost function while maximizing the use of ESS:

Each 5 minutes, The optimization is performed, which means this method does not rely on time intervals to perform the necessary actions. It measures and reads all the necessary inputs (SOC, battery energy, Cost, output power from the solar array, load consumption, all at that specific moment.), then performs the most suitable action each time, according to the inputs read.

This method maximizes the utilization of the battery bank (ESS) as you can notice in the following graphs it either charges or discharges at its full potential (charge/discharge rate) depending on the situation.

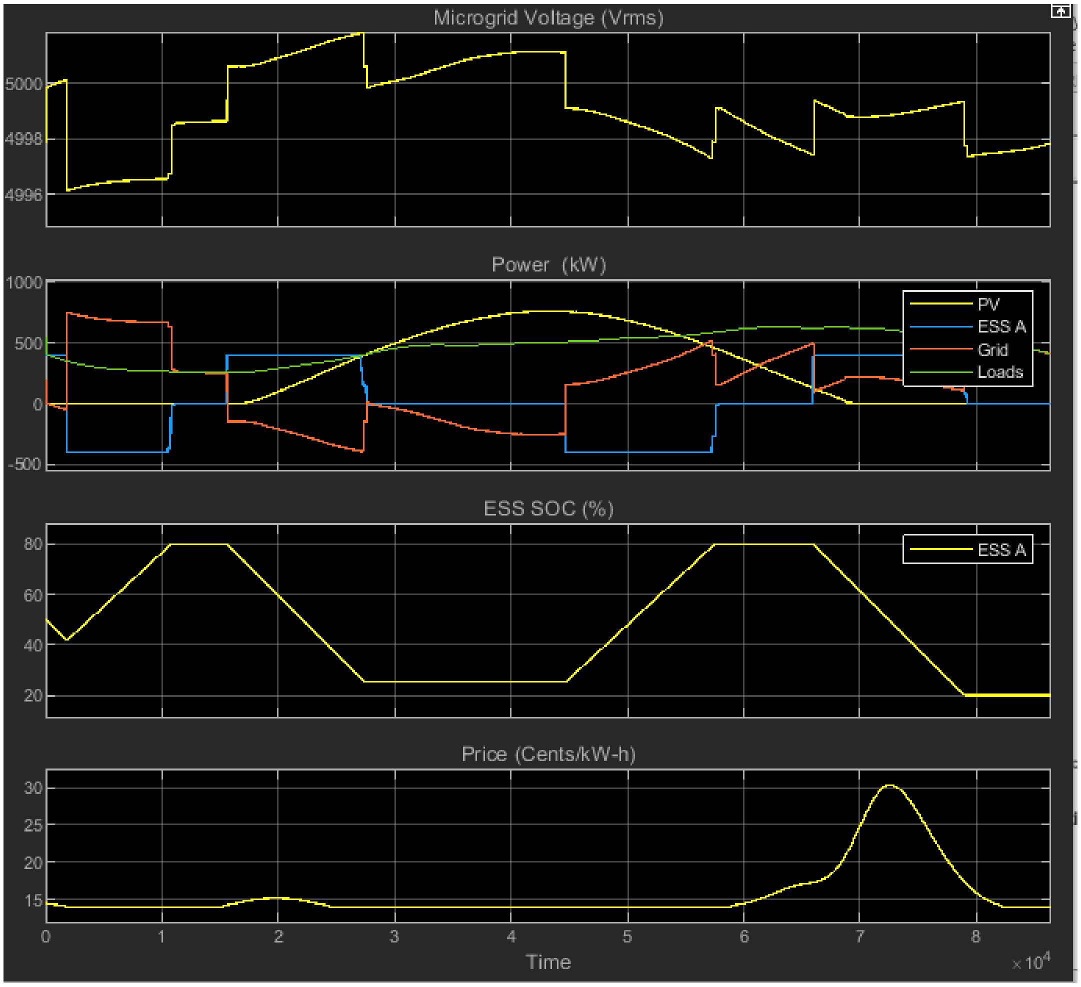


Fig 3.7 : Results for case study 3

As previously mentioned, the ESS charges or discharges at its full potential depending on the need, in the early hours when the grid's energy pricing is low, it uses the grid to power both the load and charge the battery bank, then when the prices start rising it changes it priority to feeding the load from the solar array and battery. When the PV's output power exceeds the load's, it uses the extra power to feed it back to the grid (to compensate the cost) and charge the battery bank.

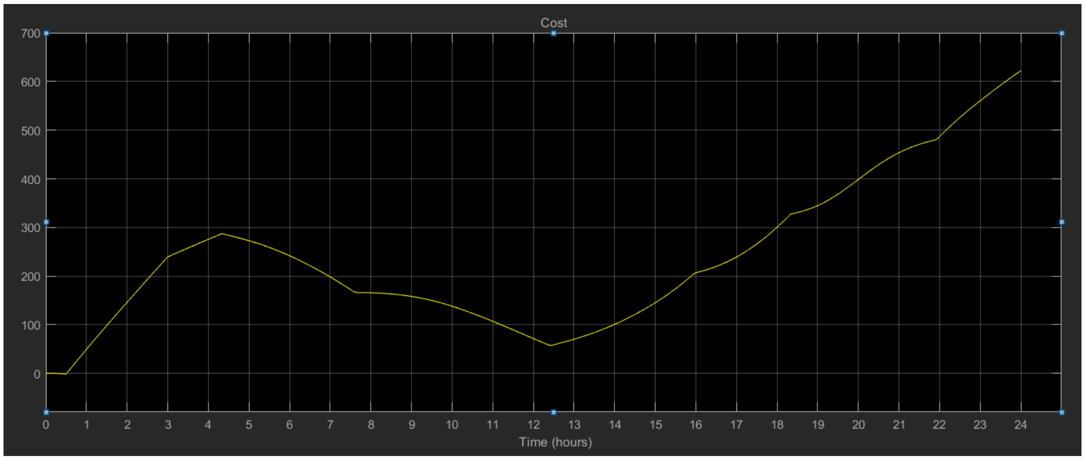


Fig 3.8 : cumulative cost function plot for case study 3

As you might have noticed, the cumulative cost function in this method, increases during the morning period (when the prices are low) due to the usage of the grid to power both the load and charging the battery bank. The total cost of the energy from the grid is 622.5$.

5.4. Case study (4): Optimization energy management in a cloudy day

Similar graphs are plotted for this case as well, comparing with the last case study, only the irradiance profile is changed, the results are shown in Fig 3.9 .

As viewed in case study 2, the fluctuating solar irradiance during a cloudy day affects both the voltage and power curves due to the fluctuating output power from the PV system (solar array).

But, for the ESS SOC% is the same as the previous case study because even though the power from the solar array is fluctuating, it is completely compensated from the grid, thus the ESS stays unaffected, thus logically we will have a larger total cost of the day due to larger grid usage.

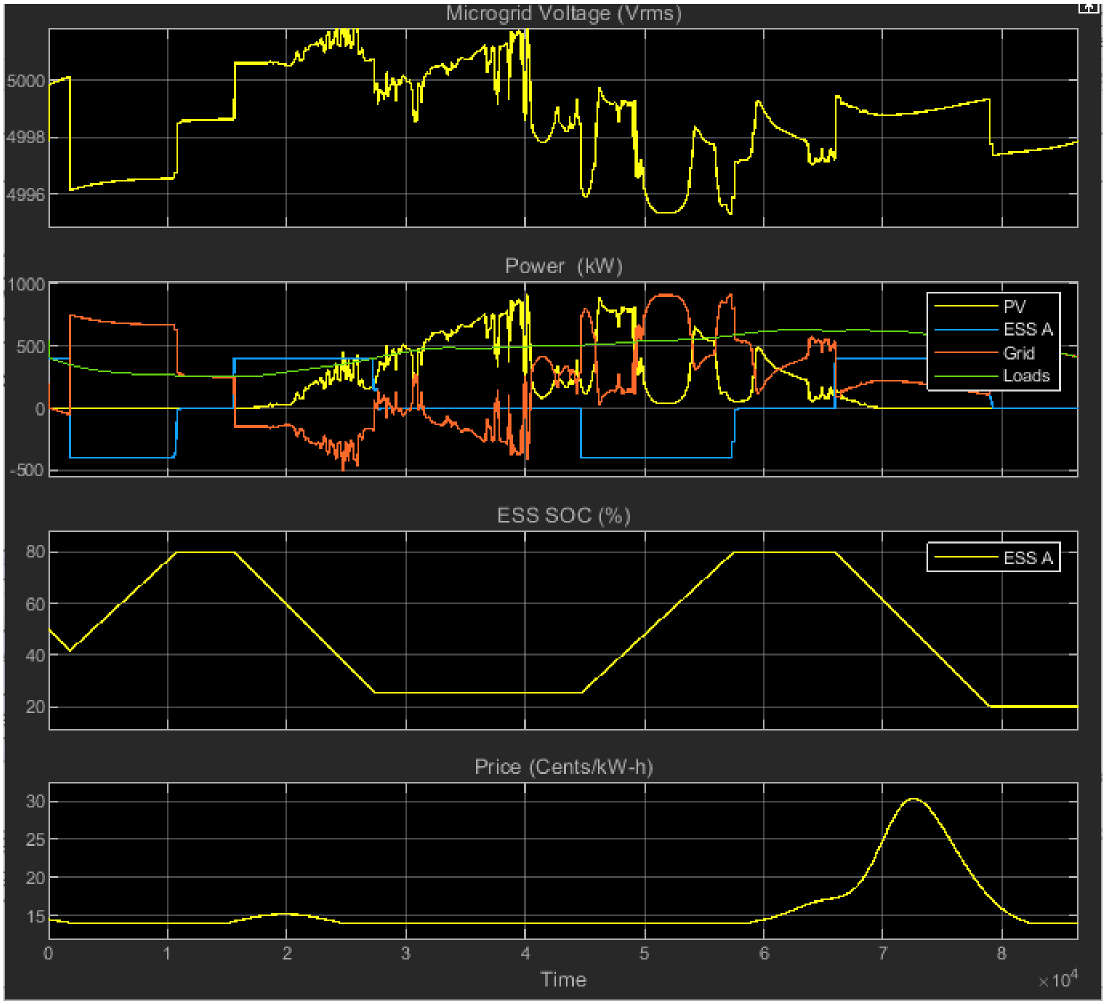


Fig 3.9 : Results for case study 4

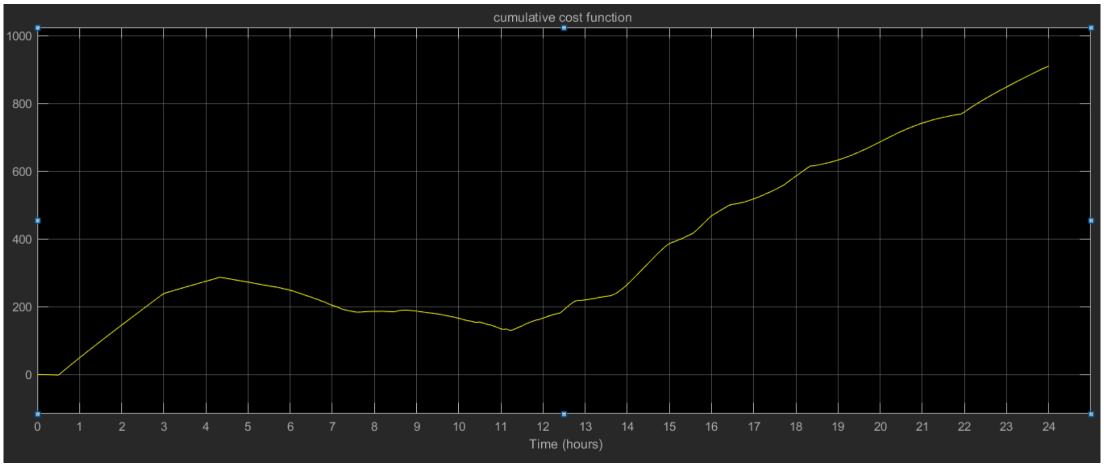


Fig 3.10 : cumulative cost function plot for case study 4

Similar to the previous case study, The total cost increase in the early hours of the morning due to the usage of the grid for powering the load and charging the battery bank at the same time. As for the evening, the EMS must compensate the lack of PV power by importing more electricity from the grid and discharging the batteries to cover the load and satisfy the user's comfort. The total cost is: 910.9$.

6. Discussion and comparison:

The following graphs compare both the cumulative cost function and the cumulative grid usage function with respect to time in order to visualize the difference between the two methods (heuristic and optimization) in both cases (clear and cloudy days):

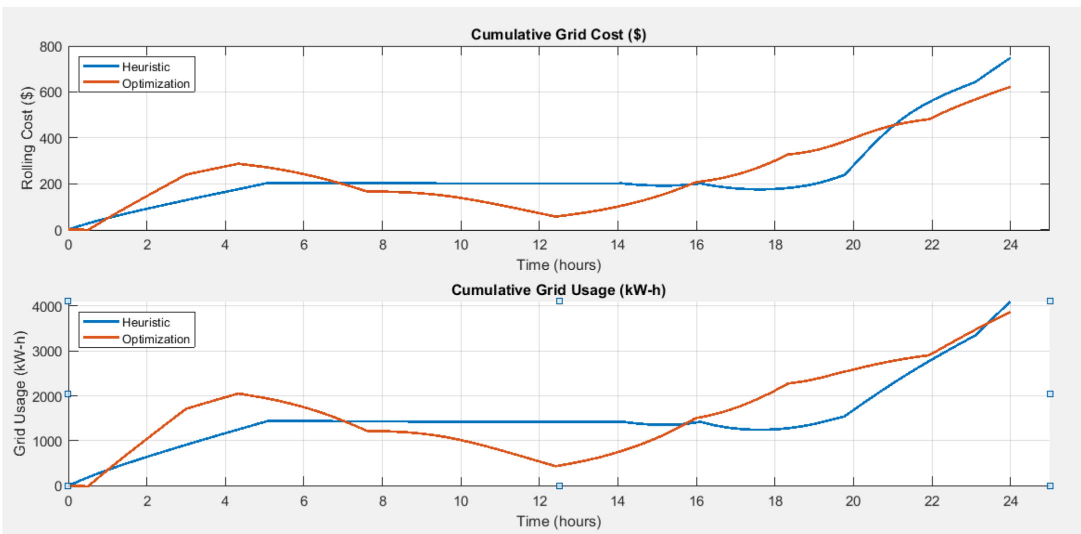


Fig 3.11 : Comparison between the heuristic and optimization methods during a clear day

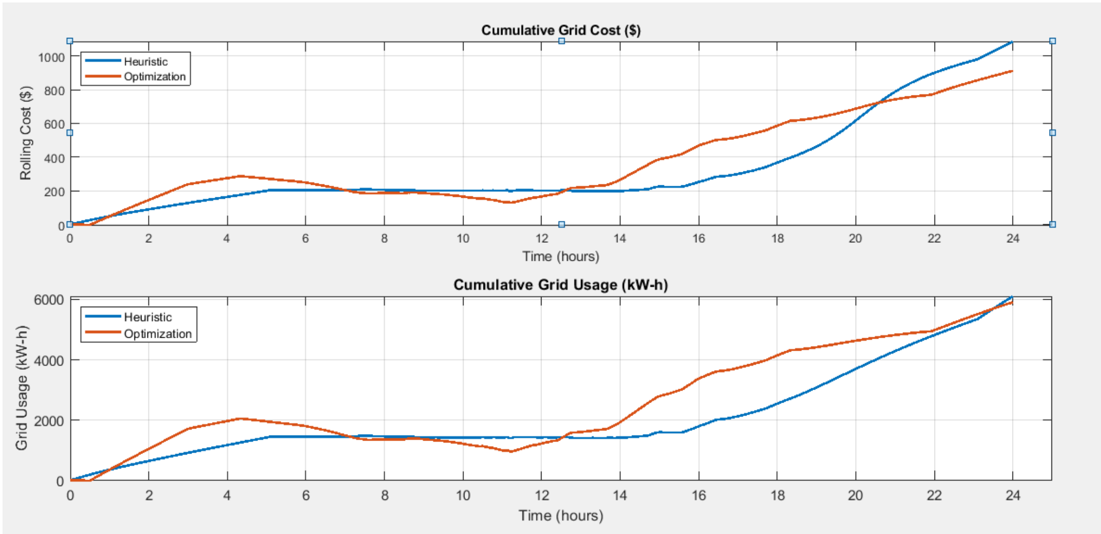


Fig 3.12 : Comparison between the heuristic and optimization methods during a cloudy day

Both Fig 3.11 and Fig 3.12 are a more precise demonstration for the difference between the two EMS approaches. The main objective was to reduce the grid usage thus the total cost.

The following table shows both the total grid usage and the total cost:

Table 3.1 : Comparison between results of the four case studies.

	Heuristic, clear day	**Optimization, clear day**	**Heuristic, cloudy day**	**Optimization, cloudy day**
Total cost ($)	748.4	622.5	1086	910.9
Total grid usage (kW-h)	4094	3861	6435	5907

- As we can notice from the table , the optimization approach is clearly better to be implemented as an Energy Management System thanks to better overall cost due to the better deployment of the Energy Storage System and the higher processing power. Optimization method is based on real time data measured then processed then come up with the best action possible, unlike the heuristic one, where all the action taken are based on previously seen data, then scheduling these actions depending on time of the day.

- Heuristic method is more of a prediction rather than a management system, unlike the optimization where it really manages the situation.
- For the cost if clear day data is considered, by switching from heuristic to optimization method, a total of 125.9$ in a day is spent on unnecessary power from the grid, thus, for a longer term application, the savings would get larger and larger. The difference is even larger in the case of cloudy day data (175.1$ difference).
- Thus, the optimization method is the more suitable Energy Management approach that can be implemented.

7. Conclusion:

This chapter was about the simulation of two different types of Energy Management inside a microgrid, this simulation shows the results and the benefits of using one over another through a comparison between the two results. The user's comfort and satisfaction was held as a top priority during all the simulation. The less the grid's power usage is, the greener the system becomes, thus the optimization method is more eco-friendly.

General conclusion

The Energy Management system approaches implemented in this study, decide whether the microgrid is to be grid connected or islanded depending on both the solar array's output and the State Of Charge of the Energy Storage System. Also, it schedules the grid usage as efficiently as possible, which means maximizing the use of the Solar array's power and the Energy Storage System, while considering grid prices. Thus, reducing the overall cost of using the grid's energy and making more eco-friendly. Implementing such a system on a large scale would result in a significant decrease in the usage of traditional sources of energy thus decrease the pollution rare on our planet.

Both of the methods implemented in this simulation show promising results, but as the third chapter clearly shows, the optimization method shows better overall results compared to the heuristic one because of the more accuracy and the more iteration unlike the time intervals implemented in the heuristic method.

Finally, an Energy Management System is a necessity regarding the implementation of microgrid to utilize any renewable energy source. There already exist many places where this has been implemented with success such as Germany, Italy, Sweden, ...etc. We wish that such a system would be implemented in our vast country where RESs are available around the year.

For future works, it is highly recommended to use additional renewable energy sources, such as Wind energy. Furthermore, Electric vehicles in the last decade have known a rapid increase in both production and use, thus considering them in the microgrid would end up in a more efficient system. In this simulation, only one load profile was implemented, which is based on the energy of a residential home area (higher electricity demand during the night than the day), it is possible to design an Energy management system that can cope with any load scenario and deduce the best action to be executed.

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