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Review

Model Predictive Control Based Energy Management System Literature Assessment for RES Integration

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Abstract: Over the past few decades, the electric power industry evolved in response to growing concerns about climate change and the rising price of fossil fuels. The usage of renewable energy sources (RES) rose as a remedy for these problems. The increased penetration of RES in the existing generation system increased the need for an intelligent energy management system (EMS) so that the system can operate in any possible circumstances. Many sectors of society, including the education sector, are working to realize the importance of this sustainable energy system. This paper reviews the process of selecting an efficient control technique for continuous power flow from different RES to meet the load demand requirement using an enhanced model predictive control (MPC)-based EMS framework. This EMS is a software platform to provide fundamental support services and applications to deliver the functionality needed for the effective operation of electrical generation and transmission facilities to ensure adequate security of energy supply at minimum cost. The centralized EMS with technical objectives focusing on power quality and seamless power flow can be achieved through dynamically enhanced MPC.

Keywords: model predictive control (MPC); energy management system (EMS); renewable energy (RE); renewable energy sources (RES); energy storage system (ESS); solar photovoltaic (PV); microgrid (MG); distributed energy resources (DERs)

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1. Introduction

Renewable energy sources (RES) such as solar, wind, hydroelectric, and geothermal are the key to sustainable future growth for all countries, particularly those relying strongly on coal, oil, and gas [1]. Asia's largest countries, including China and India, are moving progressively toward this clean energy, where wind and solar are considered the most effective and affordable RES. As one of the Asian countries, Malaysia does not wish to lag behind in terms of this cutting-edge technology. In Malaysia, crude oil, coal, natural gas, and hydro were the primary power generation sources. However, the country is also blessed with abundant RES potential, including solar, wind, hydro, biogas, and biomass [2]. Renewable energy (RE) implementation is part of sustainable development objectives to reduce fossil fuel dependency and help minimize the effects of climate change. Malaysia is known as a country with tremendous solar-generating potential due to its strategic location near the equator. The monthly solar irradiation for Malaysia is estimated at 400 to 600 MJ/m^2, which can reach up to 6500 MW of power generation [2]. On the other hand, Malaysia is noted for having low wind speeds, with an average of below 3 m/s, which is insufficient for continuous wind energy generation. Most of the wind turbines in the market have a cut-in speed of over 3 m/s, which is beyond Malaysia's annual average wind speed. However, there is a possible potential for wind generation as the maximum wind speed is recorded between 6 and 12 m/s, which varies according to the monsoon season and location [3,4].

Integrating or combining RES into a single system, known as a microgrid, is one strategy for balancing its advantages and disadvantages. A microgrid is the new fundamental technology that facilitates integrating RES with existing power generation [5]. The integration aims to reduce environmental impact, increase the reliability of the power supply, and improve energy efficiency. Furthermore, due to the intermittent nature of RE, an energy storage system (ESS) can be a solution for ensuring power system security and stability [6]. In ref. [7], a microgrid integrates different energy sources, such as solar PV, wind turbines, ESS, diesel generator sets, and small hydropower plants. Others define a microgrid as an interconnection of distributed generators, either a set of dispatchable generating units (e.g., gas turbines and fuel cells) or non-dispatchable generators (e.g., wind turbines and solar PV) integrated with electrical and thermal energy storage devices with the ability to operate both grid-connected or islanded from the grid, thus maintaining a high level of service and reliability [8]. Researchers in [9] defined a microgrid as the concept of integrating and roaming small-scale RES to improve the reliability and energy efficiency of the electricity network [10]. Microgrids can also be considered small-scale power grids consisting of distributed energy resources (DERs), loads, and controllers [10]. These clusters of microgrids will be the next generation of power system smart grids [10,11]. A microgrid can be classified into three types based on voltage characteristics, which are alternating current (AC) microgrid, direct current (DC) microgrid, and hybrid AC/DC microgrid [5,7,8]. The AC microgrid can operate in both grid-connected and islanded modes.

In islanded mode, to ensure the microgrid's stable and economical operation, distributed generators' real and reactive powers (DG) should be split proportionately to their power rating [7]. Since the main power grid does not affect the microgrid in islanded mode, the voltage and frequency system depend on DG. The power-sharing among DGs has to deal with power quality issues, especially due to intermittent power generation from renewable energy sources, load variation, and voltage frequency fluctuation [12].

The microgrid's performance can be enhanced by employing a sophisticated control scheme. The conventional control scheme method may no longer effectively deal with fluctuating output from renewable energy sources. With its fast transient characteristics, the model predictive control (MPC) strategy emerges as a solution [5,13]. MPC is one type of control scheme suitable for microgrids due to its features that have low complexity, no modulator used, variable switching frequency, online optimization, nonlinearity, and constraint availability [14,15]. MPC is widely studied due to advanced microprocessor technology in the market. Based on an optimality criterion, this scheme predicts future behavior and selects the most appropriate control action. The prediction load model, cost function (quality or decision function), and optimization algorithm are three essential components of MPC strategies.

Microgrid systems face new challenges due to the fluctuation of load demand and the volatility of RES. An effective EMS is a means of managing and coordinating the energy distribution among these energy sources. Optimizing the EMS can help maintain demand and supply balance, increase reliability, and reduce the cost of energy production [16]. EMS using a predictive control scheme, can forecast the power generation capability of DGs and minimize errors in the behavioral pattern of renewable energy sources.

This paper aims to review and summarize the MPC controller-based EMS framework technique and its architecture. The limitation and research gap are briefly discussed in Section 2, and the modern microgrid in Section 3. EMS is depicted in Section 4. Control strategies are described in Section 5. A review of past research papers is discussed in Section 6, and the conclusion is in Section 7.

2. Limitation and Research Gap

Microgrid control strategies are significantly influenced by factors such as power quality, power sharing, communication links, and economic considerations. The intermittent nature of RES introduces a high level of generation uncertainty, which can be further worsened in isolated or island microgrids due to their lack of inertia. This results in rapidly changing dynamic behavior, often leading to system instability.

The intermittent nature of RES and lack of inertia in isolated microgrids can lead to frequency fluctuations, compromising system stability. Furthermore, integrating RES into microgrids can also impact power quality by causing voltage fluctuations, harmonics, and transient disturbances. Whereas uneven power sharing among distributed energy resources can stress the system and reduce efficiency. Another limitation of other control strategies is the lack of efficient and reliable communication infrastructure. Economic considerations, especially in return on investment, operational costs, and potential benefits, such as energy savings, improved grid reliability, and reduced greenhouse gas emissions, are still lacking in findings.

3. Modern Microgrid

The electrical infrastructure is transforming from a conventional to a modern grid. Modernizing the electrical grids benefits utilities, governments, corporations, and consumers. A more resilient and dependable system can be established using the modern grid. It allows for the incorporation of new clean energy sources and ensures energy affordability. Smart grids and microgrids are the two primary categories of modern grids. The primary distinction between a smart grid and a microgrid is the scale. Compared to a smart grid, a microgrid is designed for a smaller area. In the following section, these modern grids are explained in greater detail.

3.1. Smart Grid

The transformation from a conventional power grid into a smart, user-friendly, and responsive grid is due to new technologies in terms of transmission, distribution, generation, and consumption [17]. A smart grid is an enhanced electrical grid in which communication technology and data are used to improve the power system and increase the profit of distributors, customers, and generation companies. Smart grids can accommodate a variety of electricity resources, including diesel generators and renewable energy sources, such as wind turbines and photovoltaic arrays. The characteristics of smart grid infrastructure are efficiency, dependability, sustainability, adaptability, and demand response [18]. Additionally, such infrastructure serves as a foundation for enhanced services and enhances resource management [19]. The smart grid in Figure 1 is comprised of residential buildings, offices, factories, a storage system, plug-in hybrid electric vehicles, and renewable energy sources, such as wind, hydro, and solar.

Smart grid components include integrated two-way communication, advanced control methods, measurement techniques, advanced component, sensing technologies, and the application of smart grid technology. In addition to conventional power generation, the portion of a smart grid where renewable energy sources are utilized is in a more significant proportion. On the transmission side, measurement units are installed to monitor real-time, wide-area system conditions to ensure dependability. Grid-level energy storage functions as a power flow buffer, functioning as a load when charged and a generator when discharged. On the distribution side, grids integrate with distributed energy sources to connect consumers to utilities. On the utilization side, intelligent appliances can be managed via a network. The smart grid infrastructure enables the development of numerous new applications and services, including smart homes, smart buildings, and microgrids [17].

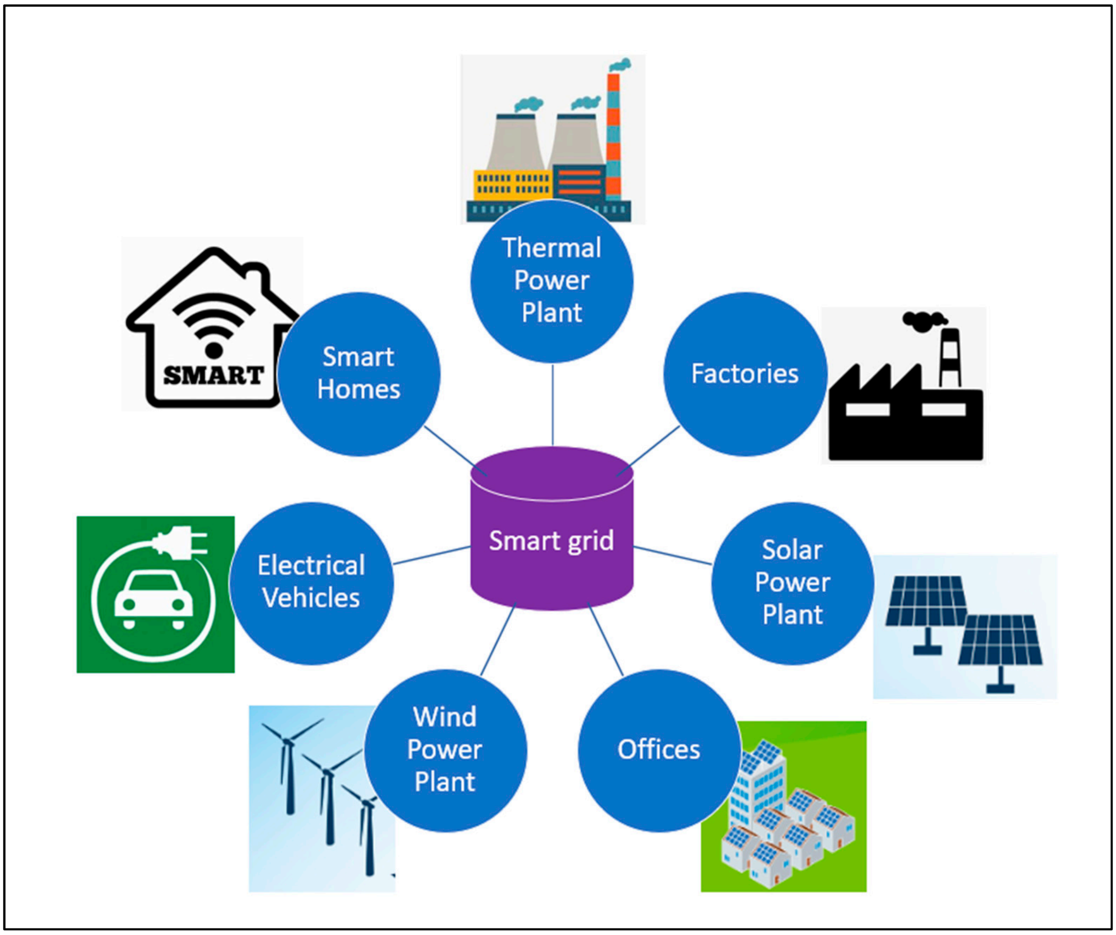

Figure 1. Smart grid diagram.

3.2. Microgrid

3.2.1. Microgrid Definition

A microgrid is a localized power system that can operate independently or in coordination with the main power grid. It typically consists of a combination of DERs, loads, and control systems that enable it to autonomously generate, distribute, and regulate power.

Its concept entails a collection of loads and small sources that function as a single system to provide electricity and heat to their local environment. The small sources are low-voltage, cost-effective, and highly dependable units installed with power electronic interfaces at user locations. Microgrid implementation could be as simple as installing a small electricity generator on the customer side to generate backup power. Alternatively, it could be as complex as integrating a power management system, electricity generation, and energy storage into the electricity grid. In addition, microgrid devices can provide a cost-effective use for waste heat in applications such as combined heat and power (CHP), thereby improving energy efficiency and reducing emissions [20]. Figure 2 depicts a microgrid comprised of multiple renewable energy sources, such as photovoltaic arrays and wind turbines, whose power is collected, processed, and distributed to meet the demand load [20,21]. In other words, a microgrid contains microgeneration sources, a control and management system, and controllable loads. MG considers the building blocks of smart grids where they can meet the challenges of smart grids. Microgrids are capable of functioning and operating in both grid-connected and island modes.

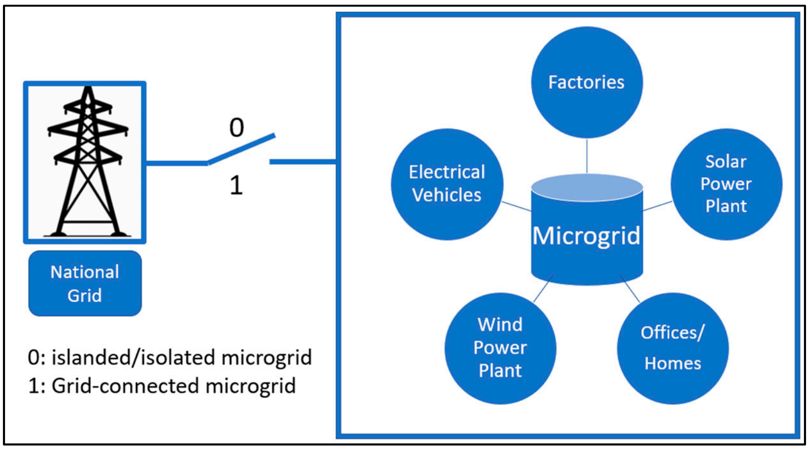

Figure 2. Microgrid Diagram.

Microgrid loads can be AC or DC, and the energy sources are DER units, including DG and RES [20]. The conventional layout of a large power grid has numerous advantages. Typically, large producing units are cost-effective and can be operated by a small staff. The integrated high-voltage transmission network reduces generator reserve demand, installs the most cost-effective producing plant at any time, and transfers excess electricity over long distances with minimal electrical losses. Typically, the distribution network is designed to handle one-way power flows and client loads. Microgrids emerged as a result of many of these effects, such as the ease of locating locations for small generators, network voltage changes, reduction in transmission costs as generation sites are closer to load, lower capital costs, shorter construction times as these are small plants, rational energy use, and reduction in greenhouse gas emissions [20,21]. The differences between microgrids and power networks are closely related, such as the power generated from micro sources being significantly less than power from a conventional power plant. Therefore, microgrids are more acceptable for distributing electricity in rural areas where the national network is nearly ineffective. In terms of voltage supply and frequency profile, microgrids are significantly more productive than centralized power plants with transmission and allocation arrangements. The conventional method for repairing power networks is time-consuming. Immediate and frequent physical and gradual intervention is required. Due to the limited number of controllable components in microgrids, the repair procedure is straightforward [20,21]. The following section will discuss the three topologies of a microgrid and its operation mode.

3.2.2. Microgrid Topology

Microgrid topologies are classified into three: alternating current (AC), direct current (DC), and hybrid microgrid.

AC Microgrid

Figure 3 depicts an AC microgrid architecture. The concept of an AC microgrid requires that the AC sources supply AC loads [22]. In the case of providing DC loads, the inverter is used. Most of the power systems operate on AC systems. Therefore, an AC microgrid offers minimum modifications to integrate into the existing system. An AC microgrid is connected to medium- or low-voltage distribution systems to reduce transmission line power losses [9]. One of the main drawbacks [8] is that more power electronic interfaces are required to synchronize distributed energy resources (DER) with the AC utility grid. It led to system stability and power quality issues.

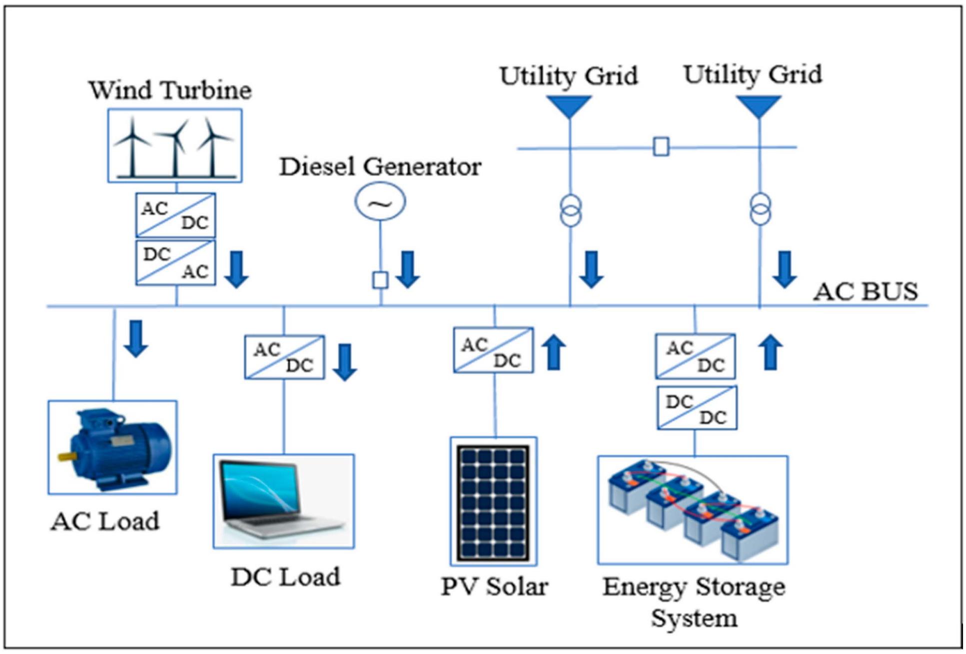

Figure 3. Alternative current (AC) MG architecture.

DC Microgrid

Figure 4 depicts a typical configuration for a DC MG architecture. DC microgrids are favored for supplying vital loads due to their safety and cost-effectiveness. Computers, human-machine interface (HMI), fire and gas systems, communication systems, etc., are examples of critical loads. This design reduces DC-AC inverters for PV solar and energy storage systems (ESS). Alternatively, these two inverters are necessary if the AC bus is chosen. Due to the energy storage system, DC microgrids are unaffected by an unplanned power outage (such as a voltage dip or sag) in the utility grid [8,9]. On the other hand, the disadvantages of the DC microgrid are its incompatibility with the existing power system, immaturity standards, and different DC protection schemes.

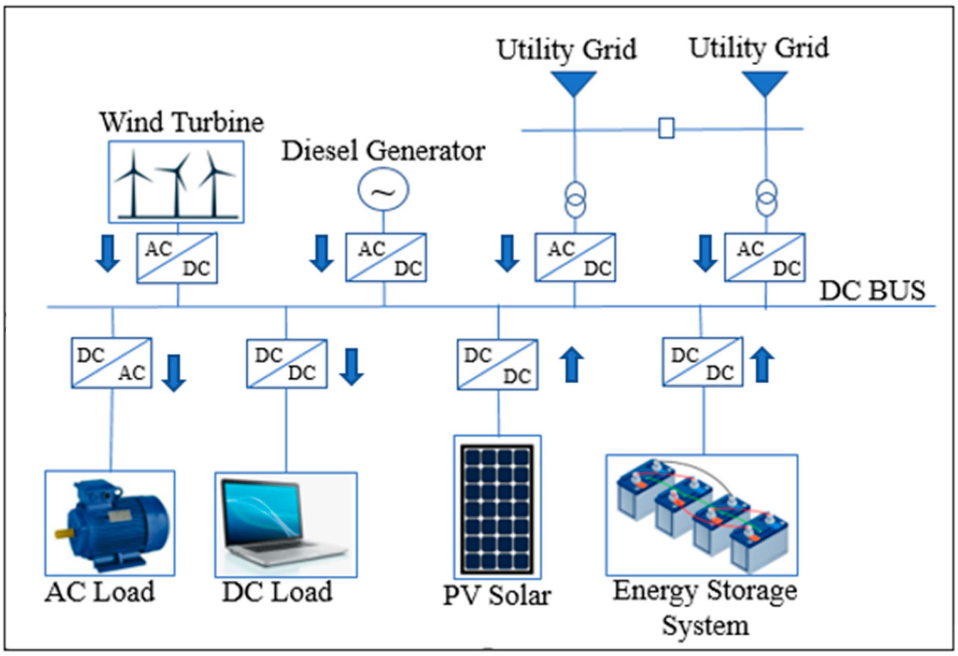

Figure 4. Direct current (DC) MG architecture.

Hybrid Microgrid

Figure 5 shows a typical example of hybrid architecture. The hybrid AC/DC MG combines AC and DC MG concepts [22]. The advantages of a hybrid AC/DC microgrid are increased reliability, efficiency, and economic operation [9]. Moreover, a hybrid AC/DC microgrid reduces the number of power converters and reduces power losses. The main drawbacks of hybrid AC/DC MG are protection and energy management issues. In [8], the researchers mentioned that the major challenge relates to power balance when power AC and DC are exchanged.

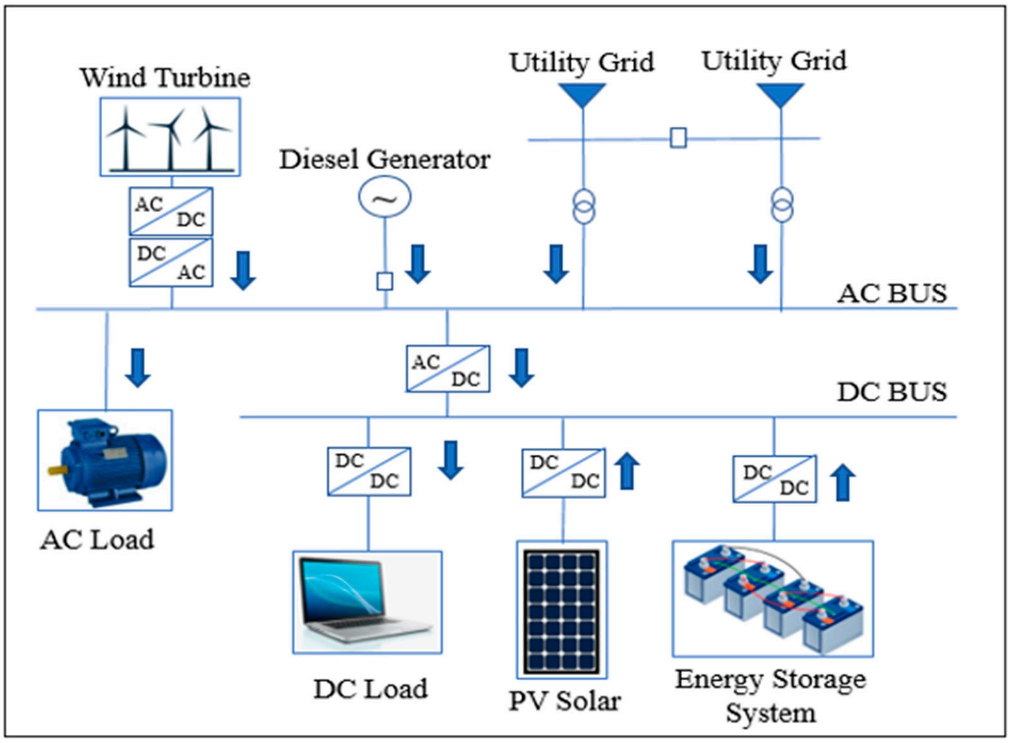

Figure 5. Hybrid AC/DC MG architecture.

3.2.3. Microgrid Operation Mode

A microgrid can operate in two modes: islanded mode and grid-connected mode. In both modes, it can integrate with the following elements [19]:

A. The source of electricity in microgrids is commercial, industrial buildings, residential, and offices;
B. Microgrid communication is a two-way communication composed of sensors, smart meters, etc., where this structure is used to know the current power profile of the consumer and respond as needed;
C. Microgrid co-generation micro-plants, such as PV arrays, wind turbines, and hydropower micro-plants, produce energy for local use within the microgrid;
D. Utilizing renewable resources is one of the benefits of a grid. However, intermittent renewable power is one of the most significant causes of concern. Consequently, a microgrid must be able to compensate for fluctuations in renewable energy using its local storage system, such as batteries;
E. A microgrid can connect to a smart device and end-user components to manage them (off/on) as required. In addition, plan a load of these devices to decrease energy consumption during peak hours;
F. Microgrids utilize the communication infrastructure to transmit and receive data between consumers and utility companies via data cable or wireless transmission.

Grid-Connected Microgrid

Grid-connected MGs are physically connected to the utility grid through a switching mechanism. In grid-connected scenarios, effectively integrated microgrids can provide grid services (e.g., frequency and voltage regulation, real and reactive power support, and demand response) that address potential capacity, power quality and reliability, and voltage issues on the utility grid. Grid-connected devices can switch between island and grid modes [22].

Islanded Microgrid

Islanded MG or off-the-grid MG is physically separated from the primary utility grid and operates in island mode due to the lack of nearby transmission and distribution equipment that is both accessible and affordable. MG will disconnect from the power grid and switch to an islanded mode to power the necessary loads when the power grid fails. Renewable energy sources, such as solar and wind, will provide an economical and environmentally friendly solution for these microgrids. Moreover, these microgrids utilize batteries as backup power sources [22].

Many review papers were written related to energy management and microgrids. Table 1 shows the review papers focused on energy management systems in microgrids.

Table 1. Existing reviews related to the energy management system of microgrids.

Ref	Contributions
[23]	A comprehensive review of microgrid energy management systems, including optimization objectives, solution approaches, and software tools.
[24]	A comprehensive review of hybrid renewable energy systems that are both grid-connected and independent. Strategies based on linear programming and intelligent techniques are reviewed.
[25]	A literature review of potential mini/microgrids for distributed generation systems. This study highlighted the challenges faced by multiagent systems and their applications, trends, and deployment strategies for renewable energy sources in emerging scenarios.
[26]	Technical literature focused on microgrid planning in terms of optimization methods related to economic feasibility, scheduling, environmental, and reliability issues.
[27]	The authors reviewed the concept of hybrid renewable energy systems and energy storage systems in microgrids. Their review analyzed the optimization and software methods used to control hybrid renewable energy systems, energy storage systems management, and power quality.

In summary, this paper will focus on the islanded DC microgrid, which gives an added advantage for rural electrification and thus can help remote areas reduce investment costs and power losses while providing a reliable power source.

3.3. Distributed Generator in Microgrid

Distributed energy resources (DER) refer to small-scale, modular energy generation and storage technologies that can be located close to the load they serve. Frequently, conventional power plants, such as coal or gas, are situated far from their consumers. However, microgrid distributed generation systems are decentralized, modular, and more flexible technologies located near the consumers. This system includes numerous generation and storage components, including energy storage [28].

DERs can be integrated into microgrids to improve efficiency, resiliency, and environmental performance. Typically, a distributed generation system consists of renewable energy sources, such as wind, solar, hydro, geothermal, and biomass. This enables the collection of energy from various sources, thereby directly enhancing supply security.

3.3.1. Wind Energy

Wind energy is the first conceivable source, as it considers to be both clean and renewable, and it is abundant throughout the world. In recent years, wind power surpassed hydropower as the primary renewable energy source. Wind turbines convert this energy into electricity, covering an extensive power range depending on the demands and generation chosen. For instance, offshore wind turbines can be several tens of meters tall to generate several megawatts (MW). In contrast, domestic wind turbines are designed with a height that does not exceed tens of meters and are placed near points of supply to generate hundreds to thousands of MW.

The wind is an inexhaustible, unrestricted resource available wherever atmospheric air moves. Installing a wind turbine system necessitates careful consideration of the wind fluctuations at a particular location. The fundamental limitation of wind energy is its intermittent and highly variable nature. As a result, it is not a dependable energy source and depends on wind speed, density, and other weather parameters [19,28].

- Wind turbine types—There are two types of wind turbines used in microgrids: horizontal-axis wind turbines (HAWT) and vertical-axis wind turbines (VAWT). The horizontal-axis wind turbine is the most common and widely used, as it is less expensive and less prone to mechanical stress than the vertical one. A comparison between vertical and horizontal wind turbines is shown in Table 2.

Table 2. Types of wind turbines.

Parameter	HAWT	VAWT
Axis of rotation	Rotation parallel to the air stream	Rotation perpendicular to the air stream
Wind direction	Dependent	Independent
Yaw mechanism	Required, adjusting the rotor around to keep facing the wind	Not required, the rotor can generate power with the wind from any direction.
Machinery location	Tower top	Base
Noise	High noise produced	Less noise

Malaysia considers a low-speed wind area, and many studies have been made to overcome this issue. For instance, the authors in [29] proposed a small wind turbine's blade design as a partial solution for low-speed wind. Small wind turbines offer an excellent opportunity to bring renewable energy to a regional scale while also utilizing existing high-rise building structures, such as towers or high-rise buildings. However, they are less efficient than large wind turbines.

3.3.2. Solar Energy

Solar power is a sustainable energy source that converts sunlight into electricity using a photovoltaic (PV) array. This type of energy is the most commonly used in residential buildings. The primary difficulty with solar power is that it produces no electricity at night. Furthermore, in countries such as Finland and Sweden, during the winter, the operational duration might be as little as a few hours [19].

- Photovoltaic solar energy—Photovoltaic solar energy is derived from converting sunlight into electricity within semiconductor materials, such as silicon, which is entirely covered by a thin metal layer. Photosensitive materials have the property of releasing their electrons under the influence of external energy. This energy is supplied by photons, a fundamental component of light, which strikes the electrons and causes them to release. The photovoltaic solar generator is composed of photovoltaic modules, which are composed of interconnected photovoltaic cells [28]. Three types of solar PV panels are used in microgrids: polycrystalline, monocrystalline, and thin film. A comparison between the three types is in Table 2. Table 3 shows that a monocrystalline solar panel is the best option for this project due to its longer life span and higher efficiency compared to polycrystalline and thin film-type solar PV panels.

Table 3. Types of PV solar panels.

Parameter	Polycrystalline	Monocrystalline	Thin film
Material	Pure silicon	Melted silicon crystals	Variety of materials
Life span	Moderate	Longest	Shortest
Efficiency	~15%	~20%	~7–10%
High-temperature performance	Poor	Poor	Better
Cost	Least expensive	Moderate cost	Most expensive
Glass color	Blue	Black	Brown, black, gray
Size	Large (less space efficient)	Small (most space efficient)	Largest (least space efficient)

Table 4 shows related works of sustainable energy systems used for MG's energy management operation.

Table 4. Sustainable energy systems in microgrids.

Ref.	Solar (PV)	Wind (WT)	Fuel Cell (FC)	Combined Heat and Power (CHP)	Biomass	Hydro	Tidal
[30]	×	×					
[31]	×					×	
[32,33]	×		×				
[34]		×	×				
[35,36]	×		×				×
[37]	×	×			×		
[38,39]	×	×		×			
[2]	×				×	×	

3.3.3. Energy Storage System

Energy storage systems (ESSs) play a crucial role in resolving issues arising from the intermittent nature of renewable energy sources. It is accomplished by increasing their efficiency and consumption, improving system continuity and dependability, and decreasing their reliance on dispatchable generation. Due to their quick dynamics, some energy storage technologies may be suitable for compensating for the lack of inertia in microgrids. Consequently, ESSs enhance the microgrid's power quality, stability, dependability, and imbalance [40]. Energy storage is an indispensable element of energy management systems. They have several benefits, including improving energy utilization efficiency by reducing energy waste and reducing raw-materials consumption required for primary energy sources, such as fossil fuel and natural gas. In turn, it reduces CO_2 and greenhouse gas emissions and preserves exhaustible raw materials. Energy storage provides balancing demand with supply, maintaining energy stability, load shifting, and enhancing power quality, particularly in microgrids. In addition, it encourages the utilization and effectiveness of renewable energy sources.

- Energy storage forms—Based on the stages of transformation of electrical energy into different forms, energy storage systems are classified as mechanical (pumped hydro, flywheel), electrochemical (flow batteries, batteries), chemical (hydrogen), thermochemical (solar hydrogen), electrical (capacitor), or thermal (sensible and latent heat storage). This research focuses on the use of batteries as an energy storage system [28,40]. Numerous types of batteries are used in energy storage systems, including lithium-ion (Li-ion), lead-acid, and sodium-ion batteries. The comparison of these batteries is presented in Table 5.

Table 5. Comparison between batteries.

Parameter	Lithium-Ion	Lead-Acid	Sodium-Ion
Power cost (USD/kW)	~900–4000 [41]	~200–600 [41]	~300–500 [42]
Efficiency	High (>90%)	Low (<75%)	High (>90%)
Material	Scarce	Toxic	Earth-abundant
Safety	Low	Moderate	High
Energy density	High	Low	Moderate
Temperature range	−25 °C to 40 °C	−40 °C to 60 °C	−40 °C to 60 °C
Cycling stability	High (negligible self-discharging)	Moderate (high self-discharging)	High (negligible self-discharging)

In conclusion, an islanded DC microgrid emerges from integrating renewable energy sources such as solar, wind, and energy storage systems into the existing traditional grid. Solar photovoltaic and wind turbine generators have the lowest installation and maintenance costs.

4. Energy Management System

4.1. Energy Management System Definition

In the 1960s, the evolution of the EMS started, and it was called the "Control Center"; then, during the 1970s, the name changed to "Energy Control Center (ECC)." During the 1990s, the name finally changed to real-time, known till now as EMS. EMS has many control techniques, such as distribution management systems (DMS), load control (LD), and demand side management (DSM) [43]. The definition of EMS was set in International Electrotechnical Commission standard IEC 61970. EMS is a "computer system containing software platform to provide fundamental support services and applications to deliver the functionality needed for the effective operation of electrical generation and transmission facilities to assure adequate security of energy supply at minimum cost."

EMS aims to develop a system that can optimally collect different energy sources for consumers while including sustainable power sources without sacrificing the system's security, reliability, and safety. EMS can monitor, optimize, supervise, and manage the customers, transmission, distribution, and generation facility [44]. So, the primary function of EMS relies on creating a system that can provide a balance between demand and supply efficiently. In other words, it should be cost-effective while working under operational restrictions and uncertainties. EMS can work on control, energy scheduling, and transmission security management. It is becoming more sophisticated as the grid evolves with the integration of RES, ESS, PEV, high-power requirement buildings, and other factors. EMS for the smart grid will help maintain the supply–demand balance while maintaining the system constraints to achieve reliable, secure, and economic operation of the power system. Another part integrated with EM is optimization. Optimization in EMS guarantees that the cost of energy generation is reduced. Finally, an energy management system can minimize and control the amount and the cost of the energy required to perform specific applications by integrating all systematic techniques.

4.2. Energy Management System Objectives

There are many objectives behind the idea of an energy management system, such as economic, technical, social-economic, and environmental. Although many studies were made regarding the goals of EMS, researchers mainly focus on financial objectives. The total operating cost [45], profit maximization [46], and cost of customers are examples of studies made to serve economic purposes [47]. In addition to the financial objective, the studies revealed that the technical issues should also be considered, as EMS optimization may seek to produce the best economic outcome. However, the system may experience blackouts, brownouts, or distribution network equipment may be damaged. The technical objectives can be focused on the equipment performance [48], power quality, and degradation of transformers [49]. The importance of technical objectives relies on providing a system with better power quality, improving performance, and reducing downtime and maintenance. Social-economic goals [50] affect economic activities through social processes, such as agents, network operators, and end users, which affect achieving the best financial outcomes. Finally, the environmental objectives [51] are mainly to reduce greenhouse gas emissions. In this instance, the system aims to reduce carbon footprint generation by utilizing renewable energy sources and various fossil fuel-based generation. Table 6 provides a summary of the objectives of energy management systems that take renewable energy sources into account.

Table 6. Objectives of the energy management system for a microgrid.

Ref.	Mode of Operation	Distributed Generator Used	EMS Objectives
[52]	Islanded microgrid	PV/ESS/FC	Convert the energy excess of PV to the electrolyzer
[53]	Islanded microgrid	FC/ESS	Minimize cost and maximize profit
[54]	Islanded microgrid	DER	Minimize investment and operational cost
[55]	Grid-connected	PV/WT/ESS	Minimize emission, cost of load loss, and lifecycle cost
[56]	Islanded	DG/PV/WT	Maximize reliability and optimize capacity

4.3. Energy Management System Architecture

The efficacy of an EMS is determined by its control architecture and the employed solution method. Figure 6 shows three control architectures for energy management systems: centralized, distributed, and hierarchical. Following is an explanation of each architecture.

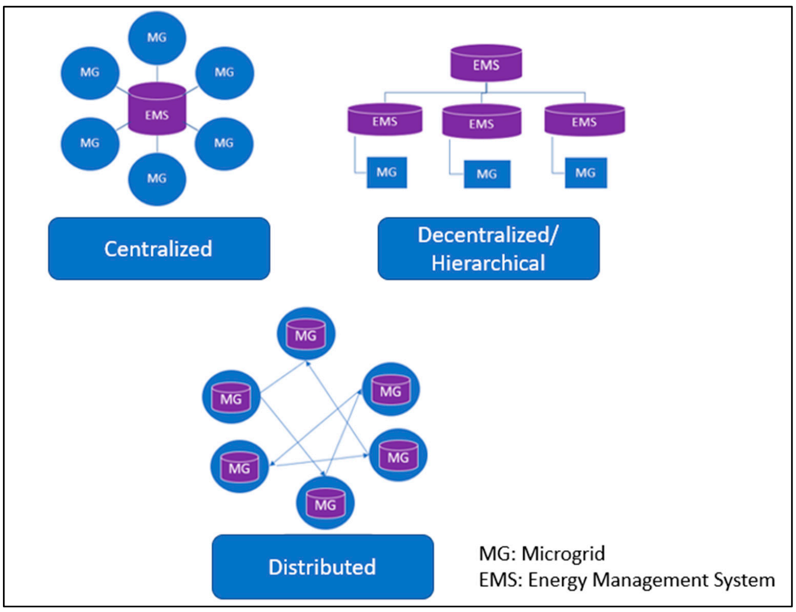

Figure 6. EMS architecture.

A. Centralized EMS

To manage energy consumption, the centralized EMS consists of one central controller with a high-performance computing unit and a secure communication line. This architecture's controller collects data from all nodes to optimize the system and achieve the best possible results. The required information includes the energy consumption of each consumer/load, the generation of energy, and market operator-relevant information, among others. This centralized control provides optimal global performance but has a few drawbacks. In this architecture, all data converge at a single point, which increases computational costs, primarily if a large number of assets must be managed. It will reduce the effectiveness of the control process for real-time communication needs. The structure is not easily scalable and may be disrupted by adding a new source with variable operational costs and limits. Additionally, there is a single point of failure [57,58].

B. Distributed EMS

Distributed EMS architecture, also called decentralized EMS architecture, is a distributed processing system in which each node is capable of autonomous control and peer-to-peer communication. Distributed architecture overcomes the scalability limitation of centralized architecture, permitting greater operational flexibility and removing a single point of failure. This architecture supports three modes of operation based on the level of distribution and communication between nodes: fully independent, partially independent, and fully dependent. A mode in which a distributed controller communicates with other distributed controllers only through a central entity, and a mode in which distributed controllers can communicate freely with one another. In the partially independent mode, distributed controllers talk to the central entity [57,59].

C. Hybrid EMS

Hierarchical EMS is based on decentralized EMS, especially for a multi-microgrid system in which microgrids are interconnected to form a microgrid community. The hierarchical EMS structure consists of multiple control levels with distinct objectives. Typically, structures consist of two or three levels, such as the supervisory level, the execution control level, and the optimization control level. No information is shared between single and neighboring levels [16].

Overall, EMS is a software platform that provides essential support services and applications to deliver the functionality required for the efficient operation of electrical generation and transmission facilities to ensure adequate energy supply security at the lowest possible cost. Stabilizing and balancing the generation and load demand is the objective. Thus, the best consideration for this project is a centralized EMS with technical goals focusing on power quality and seamless power flow.

5. Control Strategies

5.1. Control Strategies for Power Converter

Due to the unpredictability of load variation and intermittent power generation from renewable energy sources, synchronization and interconnection of various power converters are the primary concerns in the microgrid. Since they define the active (P) and reactive (Q) power flows from the energy resources, these inverters are the key actuator element in controlling AC microgrids. The P and Q injected by dispatchable generating units (e.g., diesel engine generator and ESS) are determined by the MG control system and are dependent on the specific control strategy. P and Q are not defined for non-dispatchable generating units (e.g., solar PV/wind turbine) because they deliver as much power as possible, typically with a power factor of 1 [4,59,60].

5.1.1. Power Converter Control Strategies for DC Bus

On the DC bus voltage, constant voltage control, constant current control, and DC droop control are frequently implemented. The goal of constant current and voltage control is to regulate the DC bus voltage in accordance with sinusoidal current and voltage references. In the event that the required power (P) is too low or too high, causing voltage instability in the DC bus, the power (P) control will generate the reference, as depicted in Figure 7. DC droop is utilized to regulate and equalize load distribution among converters.

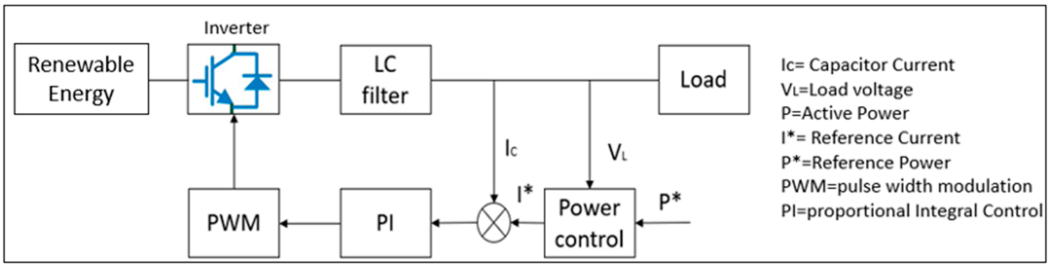

Figure 7. Example of constant current control with power control.

5.1.2. Power Converter Control Strategies for AC Bus

PQ control, V/f control, and droop control are frequently implemented on the AC bus voltage. The objective of the PQ control is to maintain constant active and reactive power at the terminal sources when the frequency and voltage fluctuate within the specified parameters. The aim of V/f control is to maintain frequency and voltage within the assigned reference value regardless of DG's active and reactive power. Figure 8 depicts an example of a V/f control strategy. The disadvantage is that it cannot respond to load variations. Typically, the final droop control strategy is implemented in the islanded mode. P/f droop and Q/V droop characteristics are the two droop characteristics. P/f droop, also known as active power control, is achieved by adjusting P/f sag based on the load-induced frequency deviation. In the meantime, Q/V droop or voltage control is accomplished by adjusting the reactive power output of DG resulting from voltage deviation.

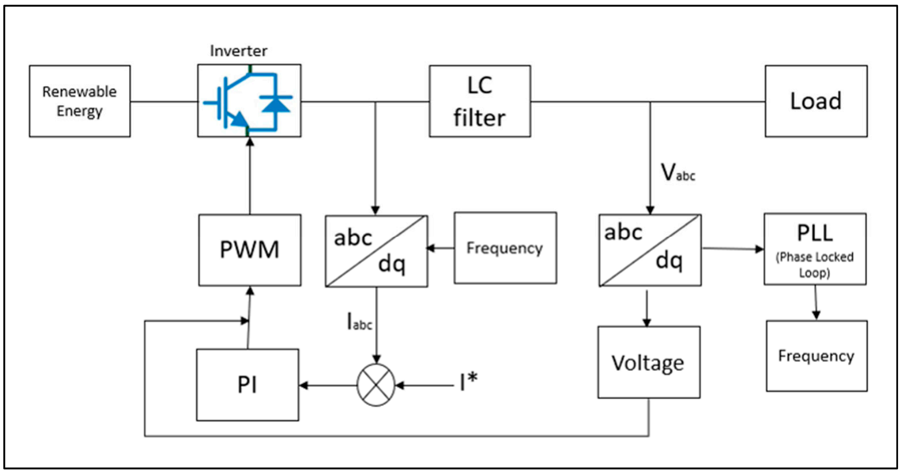

Figure 8. Example of V/f control strategy using I* (reference current) in AC bus.

5.2. Control Strategies for Microgrid

Control strategies for microgrids can be divided into master–slave control, peer-to-peer (P2P) control, hierarchal control, multiagent control, and predictive control [7].

5.2.1. Master–Slave Control

In this control strategy, one or more distributed generators (DGs) or energy storage system (ESS) units can behave as master units. In contrast, the other DGs or ESS units act as slave units, as illustrated in Figure 9. The master unit is capable of partially controlling the slave units. In islanded mode, the master unit adopts the V/f control to provide reference voltage and frequency to the slave units operating in PQ control [7]. However, the master–slave control strategy has disadvantages, such as single-point failure problems, poor power quality in remote buses, and large capacity requirements for the master DG [61–65].

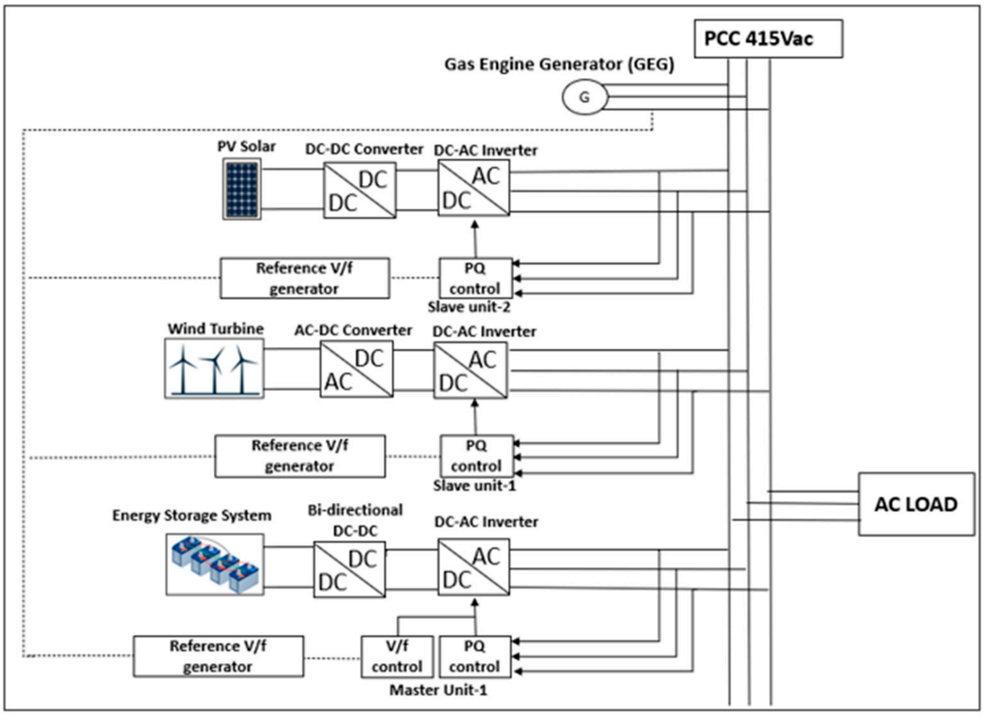

Figure 9. Sample architecture of master–slave control energy in microgrid.

5.2.2. Peer-to-Peer (P2P) Control

P2P control, as illustrated in Figure 10 shows that it is controlled in the droop control decentralized method to provide support of voltage and frequency to the MG busbar and regulate the output power based on local information [7]. The advantages are communication infrastructure savings and reduced complexity. The multi-layer and multiagent peer-to-peer control architecture can increase the flexibility and resilience of microgrids [66]. The power flow tracing control method for accurate P2P trading in DC microgrids was introduced to provide reliable data for electricity trading [67].

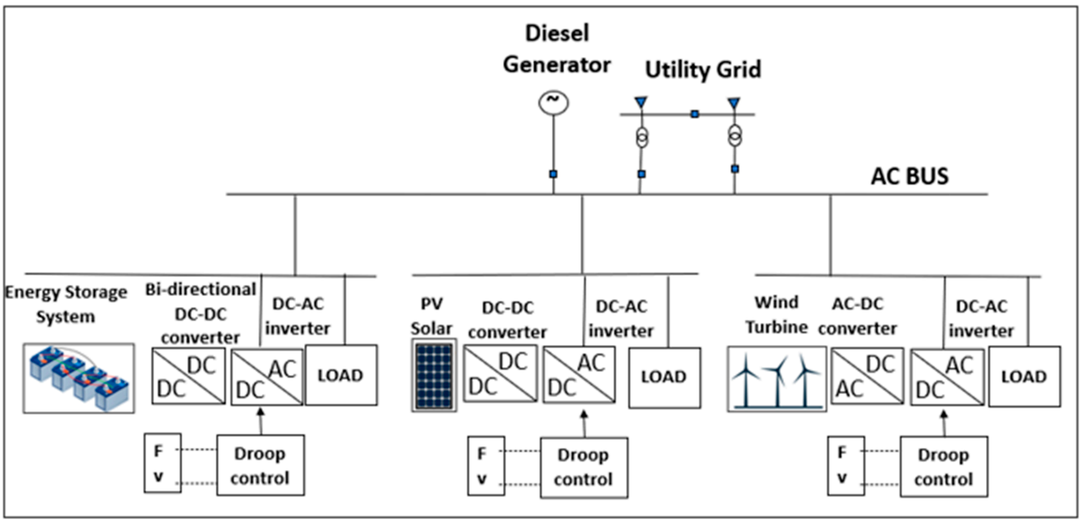

Figure 10. Sample architecture of peer-to-peer (P2P) control in microgrid.

5.2.3. Hierarchal Control

In the context of microgrids, hierarchical control refers to a multi-layered control structure that aims to achieve different objectives at different time scales and levels of abstraction. A common hierarchical control structure consists of three layers: primary, secondary, and tertiary control. Primary control focuses on fast, local control actions, such as voltage and frequency regulation. Secondary control deals with power sharing and system restoration, while tertiary control manages the economic dispatch, demand response, and optimal scheduling of DERs.

The hierarchal control structure is implemented in the microgrid to minimize the operation cost while maximizing efficiency, reliability, and controllability [7,68]. According to Figure 11, the hierarchical control structure is divided into primary, secondary, and tertiary levels.

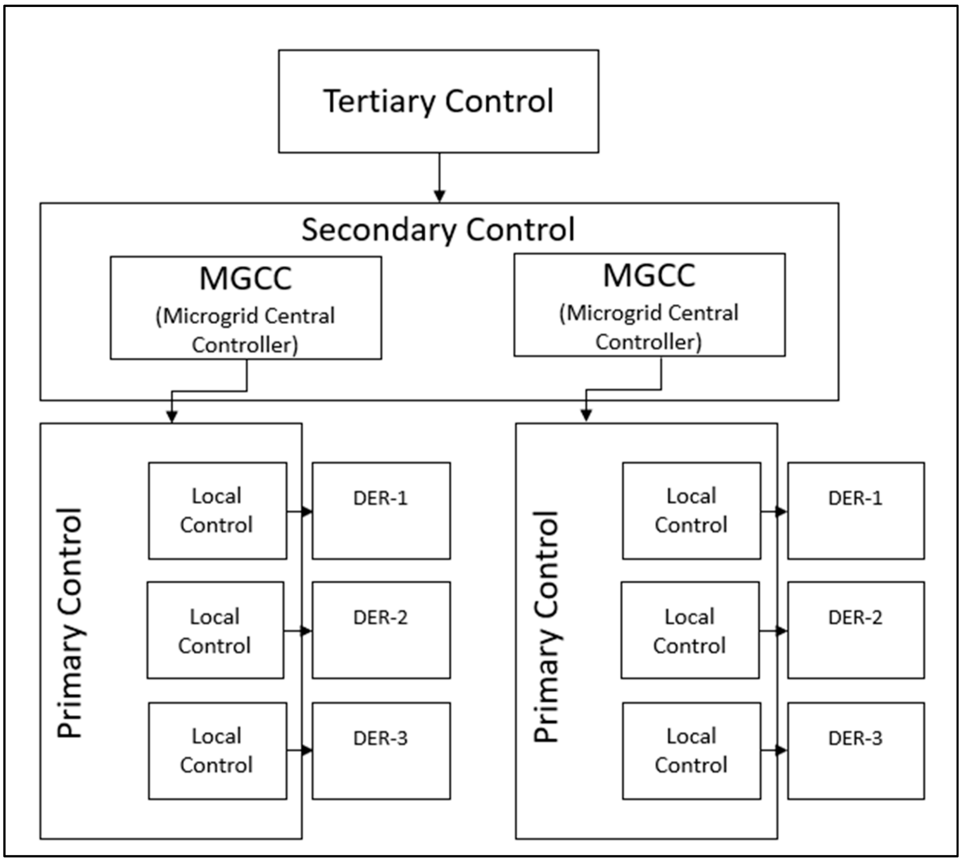

Figure 11. Sample architecture of hierarchal control in a microgrid.

A. Primary control: the lowest level and the fastest response, also known as local control. Primary control is responsible for ensuring power quality (e.g., voltage and frequency within the acceptance limit) and coordinating the power-sharing among DGs;
B. Secondary control: the intermediate level and slower than primary control due to complex mathematical calculation. This level utilizes the microgrid central controller (MGCC) to optimize the economical operation and reliability of the microgrid. It also refers to the energy management system (EMS). It can be in a centralized or decentralized mode;
C. Tertiary control: the highest level to maintain power flow control and security of the entire system. The tertiary control has a large timescale in the order of minutes.

5.2.4. Multiagent Control

This control strategy involves multiple intelligent local agents and calls for agent-to-agent communication, as shown in Figure 12 [7]. Intelligent electronic devices or software are used as a control agent. An agent can respond automatically to environmental changes and take action to alter the environment. An agent is capable of carrying out its mission without human intervention. The distributed frequency control of isolated microgrids based on multiagent quantum machine learning can reduce the number of parameters and regulate the frequency with improved time delay tolerance and display [69]. A cooperative multiagent system that considers each agent to be embedded in the battery inverter control unit can manage proper power sharing [70].

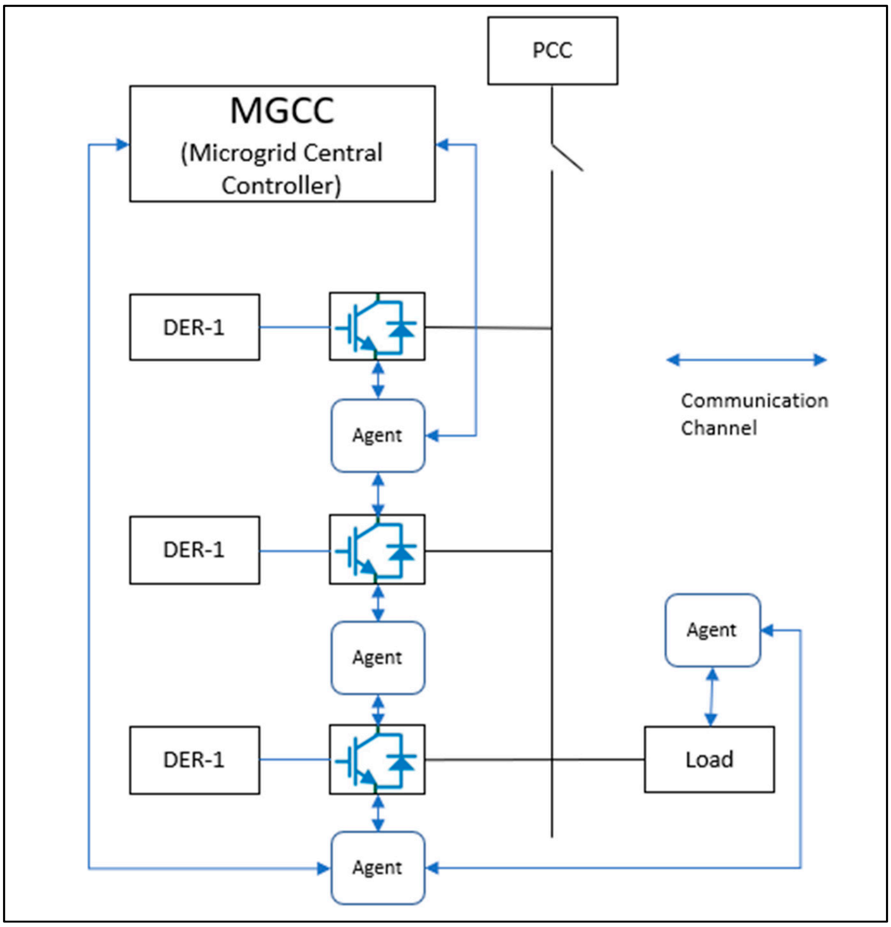

Figure 12. Sample architecture of multiagent control in a microgrid.

5.2.5. Predictive Control

MPC is an advanced control strategy that uses a dynamic model of the system to predict its future behavior over a finite prediction horizon. At each time step, the control inputs are optimized based on the predicted system states, subject to the constraints imposed on the system. Once the optimal control inputs are determined, only the first control action is implemented, and the process is repeated at the next time step, thus allowing for real-time adaptation to changing conditions.

This model predictive control is a solution to minimize power loss for multiple operating modes in the islanded AC microgrid. The typical model predictive control (MPC) control scheme in an AC microgrid is shown in Figure 13 [70].

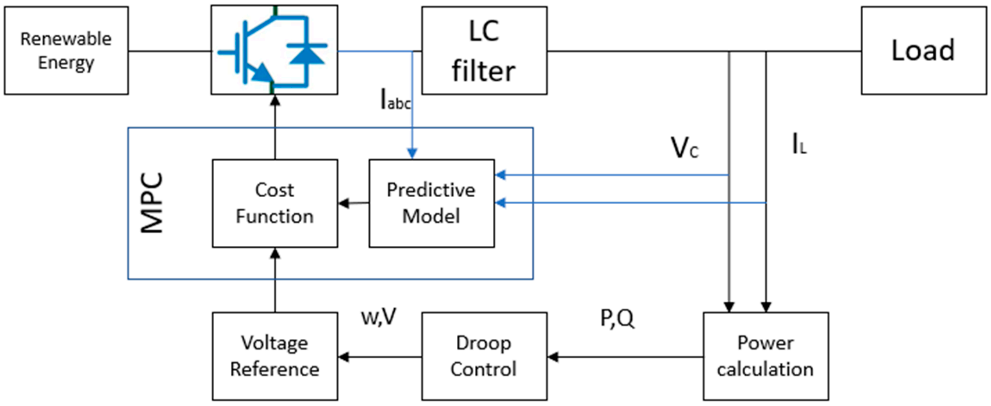

Figure 13. Typical MPC control scheme in AC MG.

MPC control strategies can be divided into three control models, also known as objective function, cost function, and optimization algorithms [5,14]. First, the prediction load model is used to predict the behavior of controlled variables (e.g., current, voltage, power, etc.).

Objective function: The objective function is used to minimize the cost or maximize the microgrid's performance. It can be formulated as:

$$J(x,u) = \sum_{k=0}^{N-1} c(x_k, u_k) + x_N \tag{1}$$

where $J(x,u)$ is the objective function, $c(x_k, u_k)$ represents the instantaneous cost at time step k, x_N denotes the terminal cost at the final time step N, and x_k and u_k are the system states and control inputs, respectively.

Then, the cost function will be the decision function to represent the desired behavior of the system, which consists of system dynamics and constraints.

System dynamics: The system dynamics describe the evolution of the microgrid state, considering the physical constraints of the system. The system dynamics can be expressed as follows:

$$x_{k+1} = f(x_k, u_k) \tag{2}$$

where x_k and u_k are the system states and control inputs, respectively, and $f(\ )$ is a function that represents the system's dynamic behavior.

Constraints: The system constraints can be related to generation, demand, grid limits, or other factors and can be formulated as follows:

$$g(x_k, u_k) \leq 0 \tag{3}$$

where $g(x_k, u_k)$ represents the constraints at time step k, and x_k and u_k are the system states and control inputs, respectively.

Lastly, the optimization algorithm is to select the switching state that minimizes the cost function.

MPC optimization problem: The MPC optimization problem can be described as:

$$min_{(u_0 \ldots u_{N-1})} J(x,u) \tag{4}$$

Subject to:
$x_{k+1} = f(x_k, u_k)$ for $k = 0, 1, \ldots, N-1$
$g(x_k, u_k) \leq 0$ for $k = 0, 1, \ldots, N-1$

These equations can provide a mathematical basis for understanding the MPC-based EMS and its operation. They can be further customized to suit specific microgrid configurations and energy management objectives.

The typical predictive current control scheme is shown in Figure 14 and consists of the following steps [71]:

1. Measurement of load current;
2. Prediction of the load currents for the next sampling instant for all possible switching states;
3. Evaluation of the cost function for each prediction;
4. Selection of the switching state that minimizes the cost function;
5. Application of the new switching state.

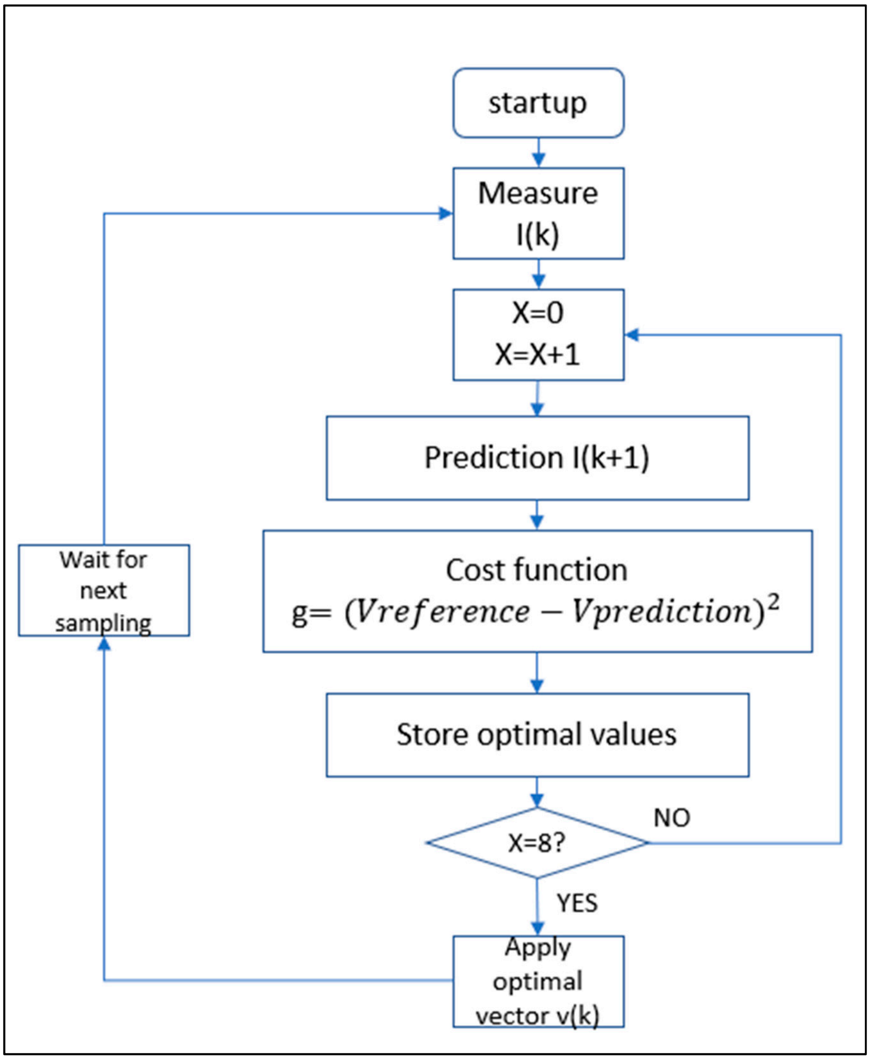

Figure 14. Flowchart of predictive current control.

A simple solution to compensate the above delay is to consider the calculation time and apply the selected switching state after the next sampling instant, as shown in Figure 15 [71]. In this way, the control algorithm is modified as follows:

1. Measurement of the load currents;
2. Application of the switching state (calculated in the previous interval);
3. Estimation of the value of the currents at the time (k + 1), considering the applied switching state;
4. Prediction of the load currents for the next sampling instant (k + 2) for all possible switching states.

$$\hat{i}_c(k+1) = \hat{i}_c(k) + T_s \begin{bmatrix} \frac{1}{L_f}(v_i(k) - \hat{v}_c(k)) \\ +k_e(v_c(k) - \hat{v}_c(k)) \end{bmatrix} \tag{5}$$

T_s = sampling time
$\hat{i}_c(k)$ = estimated current capacitor
$\hat{i}_c(k+1)$ = estimated current capacitor at (k + 1)
$\hat{v}_c(k)$ = measured voltage capacitor
$v_i(k)$ = optimal voltage vector calculated at the previous step
$v_c(k+1)$ = predicted capacitor voltage
$v_b^*(k)$ = reference voltage
k_e = observer gain
L_f = inductance
g = cost function

5. Evaluation of the cost function for each prediction.

$$g = |v_c - v_b^*(k)| \tag{6}$$

6. Selection of the switching state that minimizes the cost function.

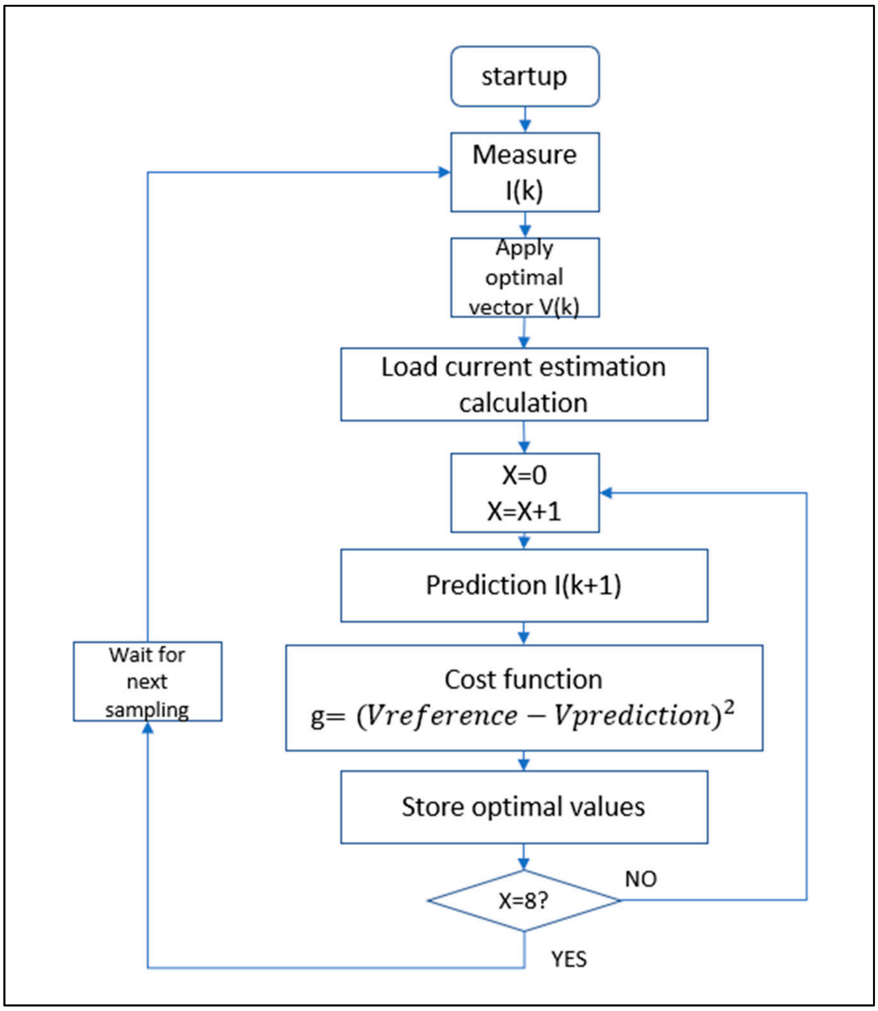

Figure 15. Flow chart of predictive current control with delay compensation.

Figure 16 shows an additional theoretical concept for a model predictive control (MPC)-based energy management system.

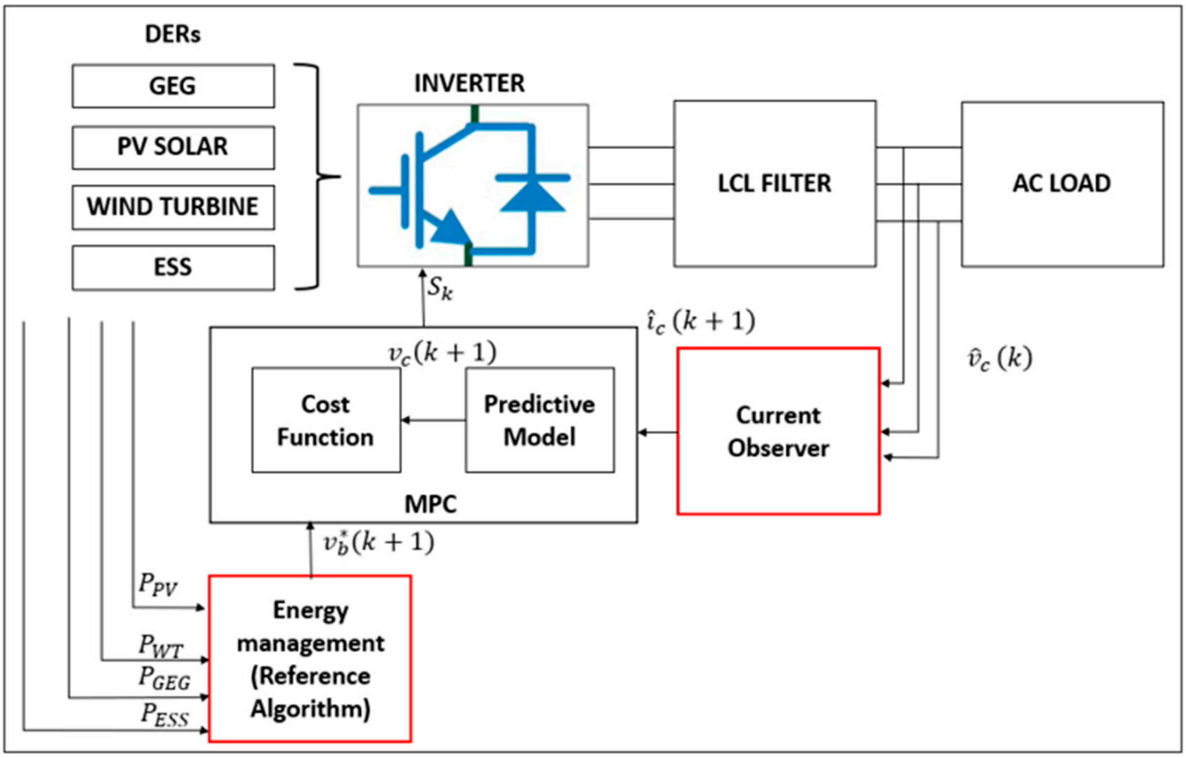

Figure 16. MPC-based EMS with the current observer.

DER = distributed energy resources
GEG = gas engine generator
ESS = energy storage system
LCL = inductance–capacitance–inductance
T_s = sampling time
$\hat{i}_c(k)$= estimated current capacitor
$\hat{i}_c(k+1)$ = estimated current capacitor at $(k+1)$
$\hat{v}_c(k)$ = measured voltage capacitor
$v_i(k)$ = optimal voltage vector calculated at the previous step
$v_c(k+1)$ = predicted capacitor voltage
$v_b^*(k)$ = reference voltage
k_e = observer gain
L_f = inductance
g = cost function
S_k = switching state (S_a, S_b, S_c)
P_{PV} = active power solar PV (Watt)
P_{WT} = active power wind turbine (Watt)
P_{GEG} = active power gas engine generator (Watt)
P_{ESS} = active power energy storage system (Watt)
P_{LOAD} = active power load (Watt)
T_s = sampling time
$\hat{i}_c(k)$ = estimated current capacitor
$\hat{i}_c(k+1)$ = estimated current capacitor at $(k+1)$
$\hat{v}_c(k)$ = measured voltage capacitor
$v_i(k)$ = optimal voltage vector calculated at the previous step
$v_c(k+1)$ = predicted capacitor voltage
$v_b^*(k)$ = reference voltage
$i_b^*(k)$ = reference current
k_e = observer gain

L_f = inductance
g = cost function

The mathematical calculation is as below:

$$\hat{i}_c(k+1) = \hat{i}_c(k) + T_s \begin{bmatrix} \frac{1}{L_f}(v_i(k) - \hat{v}_c(k)) \\ +k_e(v_c(k) - \hat{v}_c(k)) \end{bmatrix} \tag{7}$$

$$\Delta P_{PV} + \Delta P_{WT} + \Delta P_{GEG} \pm \Delta P_{ESS} = \Delta P_{LOAD} \tag{8}$$

$$v_b^*(k) = \frac{\Delta P_{ESS} - \Delta P_{PV} + \Delta P_{GEG} + \Delta P_{WT}}{i_b^*(k)}. \tag{9}$$

MPC has advantages over other control strategies, such as accommodating multiple inputs and outputs. MPC includes a prediction mode, a cost function, and an optimization algorithm.

6. Review of Past Research

In ref. [72], an MPC-based EMS is known to increase a microgrid's PV and load hosting capacity. This paper's isolated MG resembles a radial distribution system where the voltage increases or decreases with line length. Each feeder has two loads, two EV chargers, and two PVs with diesel generators as their primary sources. ESS is utilized at the end of the line to assist in grid stabilization. Using ESS and the ESS optimal operation algorithm, it is discovered that the number of PV and EVs can be increased by a factor of two. The frequent cycling of a battery can accelerate its degradation. Due to this, a weighted model predictive control was proposed [73] with a degradation cost model for BESS based on an online auction and rain flow cycle counting algorithm. The authors also considered the real-time operation with uncertainties. Through this, the SOC of the battery is kept high with only a slight economical cost to the operator. In [74], a model predictive control-based energy management scheme for hybrid storage systems in an islanded microgrid was proposed. RES penetration causes instability in the power system due to low inertia and intermittency of DER. The authors pointed out that using a single type of ESS is inefficient in providing an optimal solution for mitigating the issues caused by the high penetration of the RERs. Hence, the usage of a combination of different ESSs or hybrid ESSs is proposed in the MPC-based EMS. The authors introduce a robust MPC based on interval prediction in [75] to compensate for the issue of prediction errors of multiple uncertainties in the day-ahead scheduling for real-time operation. The proposed approach aims to produce high flexibility and highly efficient cost solutions. The performance of the proposed scheme is compared with the common MPC and hard-charging methods.

In ref. [76], the authors proposed risk-averse MPC to operate an islanded microgrid. The authors implement risk-averse MPC to protect microgrids in the event of estimation errors in the probability distributions of power generation and loads. The authors admitted that the complex nature of this scheme could lead to a computational burden. However, the authors also proved that the risk-averse problem could be reformulated to allow the problem to be solved online. The complex structure of microgrids attracted the attention of researchers to a multi-level control or hierarchical control of microgrids, with each level having its objectives. The authors in [77] proposed a hierarchical distributed MPC for a wide and dispersed isolated microgrid. Two layers are proposed: the upper layer is for economic optimization, and the lower layer is for tracking properties set by the upper layer.

The authors in [78] also proposed two layers of microgrid supervisory based on MPC. The scheme also has an upper layer and lower layer in which the latter is needed to handle and anticipate the voltage and frequency variations in the grid. They suggested that distributed and hierarchical control helps in a controlling system, such as MG, characterized by different dynamics. In ref. [78], they also acknowledged that some literature ignores that in real life, MG encompasses lines, loads, and low-level controllers, which cannot be neglected in the overall model.

Table 7 shows the previous related works for AC and DC grids using different types of MPC with different Renewable Energy Sources (RES), BESS, and generator as the inputs. These papers are summarized and compiled in the table below.

Table 7. Related works.

Paper	Type of Grid	Type of MPC	Elements	Remarks
[72]	AC	Deterministic MPC	• PV • BESS • DG • Loads • EVs	The MPC can increase the hosting capacity of PV and loads. However, the PV generation and the loads are assumed to have the same patterns with no consideration of the worst case.
[74]	DC	Deterministic MPC	• DG • PV • BESS • SC • RFC • Loads	The forecasting is incorporated during the decision-making by the MPC; however, the uncertainty of the forecasting is not considered.
[75]	DC	Robust MPC (RMPC)	• PV • WT • BESS • Loads • DGs	The author proposed RMPC based on interval prediction. Online learning will be used alongside RMPC to increase the accuracy of the prediction. The aim is to achieve optimal solutions that count on flexibility and cost efficiency. However, the quality of the power is not discussed.
[76]	DC	Risk-averse MPC	• WT • BESS • Conventional generator	The problem complexity can become more complex as more elements are introduced into the microgrid and the number of nodes in the scenario trees increases.
[77]	DC	MPC	• PV • WT • BESS • Loads	The computational burden proved to be minimized by using the hierarchical distributed MPC. However, some of the optimizations show better results in the hierarchical centralized MPC.
[78]	AC	MPC	• BESS • Inverter • DG • PV	The two layers of the model predictive controller can maintain the microgrid's stability and track the microgrid's performance. This is, however, not considering disturbances impacting the microgrid.
[79]	AC	Stochastic MPC (SMPC)	• PV • BESS • DG • Inverter	Sample-based approaches or data-driven methods for constructing representative scenario trees that capture uncertainty. Calculations involved in updating the chance constraints can be conducted offline. In contrast, SMPC has overly conservative control laws due to uncertainties often overestimated and a high number of historical samples.
[80]	AC	Hierarchical distributed model predictive control (HDMPC)	• PV • DG • BESS • Inverter	It has been used for large-scale energy systems modeled for robustness with the existence of the data uncertainty. In contrast, it needs forecasting information about the energy.
[81]	AC	MPC	• PV • DG • BESS • Inverter	MPC can significantly reduce the total operating cost (TOC) of the Mae Hong Son (MHS) microgrid from 25% to 45%. In contrast, the accuracy of data is dependent on short-term load forecasting.

This paper focuses on increasing the prediction accuracy and RES and ESS utilization while reducing the operating cost of the microgrid.

7. Conclusions

This literature review provides an overview of the modern grid, its various types, and the role of distributed energy resources (DERs) in contemporary power systems.

Furthermore, the concept and architecture of model predictive control (MPC)-based energy management systems (EMS) are reviewed, and their applications and performance based on existing research are well discussed.

The MPC-based EMS framework offers a promising approach for optimizing and managing power flow within microgrids. The framework enables more efficient and sustainable energy generation and distribution by maximizing the utilization of renewable energy sources, such as solar photovoltaic, wind turbines, and energy storage systems (ESS). The implementation of MPC-based EMS enhanced prediction accuracy and reduced the operating costs associated with microgrid management.

In conclusion, the growing interest in and adoption of RES, coupled with advancements in MPC-based EMS, offers significant potential for enhancing the performance of microgrids and supporting the transition towards a more sustainable and resilient energy future. This literature review serves as a foundation for future research, promoting further advancements and innovations in the field of microgrid control and management.

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