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OPTIMAL ALLOCATION OF ANCILLARY SERVICE ASSETS IN RENEWABLE ENERGY - BASED MICROGRIDS FOR ENHANCED POWER SYSTEM FLEXIBILITY

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Title of doctoral dissertation: Optimal Allocation of Ancillary Service Assets in Renewable Energy -Based Microgrids for Enhanced Power System Flexibility

Abstract

Power systems (PS) with adequate operating reserves are critical to the stability of world economies. PS are susceptible to problems like load shedding or total blackouts when these reserves are inadequate. When renewable energy sources (RES) are widely used, maintaining grid stability becomes even more difficult. However, there is a lot of promise for RES as ancillary service (AS) sources when coupled via power electronic equipment. The capacity of AS provision from RES is further improved by renewable energy-based microgrids (MG), which combine several RES resources and have significant load control capabilities. The issue of how to optimally dispatch AS signals to all resources arises when there are a variety of AS resources. Single-bus MG models were used in the majority of earlier AS allocation research projects.

A thorough MG model for the best allocation of ASs among the resources using Virtual Load (VL) and an optimization process to attain the best outcomes using Genetic Algorithm (GA) are proposed in case study 1. To measure the importance of grid modeling, a comparative analysis is carried out, and the model takes into account power losses and voltage profiles for AS dispatching. The CIGRE MG benchmark model is used to test the model and suggested process. The findings demonstrate the influence that modeling can have on technical and economic indicators of MG operation and show that thorough MG modeling can influence outcomes by 11% when compared to single-bus modeling. This qualifies detailed MG modeling for all future research projects.

The case study 2 shows that the proposed GA–ANN hybrid framework is a good and quick way to predict how flexible a MG will be in real-time. The model can accurately reproduce the dynamic responses of all distributed energy resources, such as CHP units, batteries, and controllable loads, by using the GA only once off-line to create a full set of optimal dispatch solutions and then training the ANN to learn these optimal behaviours. The trained ANN shows excellent fidelity to the GA targets, with prediction errors consistently below 1% across all assets and a near-perfect match in the aggregated balancing power output. The ANN gives these predictions in seconds, while the GA needs several minutes for each optimization run. This makes it possible to quickly and reliably provide ASs. These results show that the ANN is a useful and reliable alternative to GA-based optimization. It can make good real-time operational decisions and help with MG balancing and flexibility management.

Keywords: Ancillary Service, Microgrid modelling, Renewable energy sources, Virtual load, Optimization (Genetic algorithm), Artificial Neural Network (ANN)

Scientific field: Technical science - Electrical engineering

Specific scientific field: Power systems

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Наслов докторске дисертације: Оптимална алокација системских услуга у микромрежи са обновљивим изворима енергије за потребе повећања флексибилности система

Апстракт

Електроенергетски системи (ЕЕС) са адекватним оперативним резервама од кључног су значаја за стабилност светских економија. ЕЕС су подложни проблемима као што су редукција оптерећења или потпуни распади система (блекаути) уколико су те резерве недовољне. Са широком применом обновљивих извора енергије (ОИЕ), одржавање стабилности мреже постаје још изазовније. Ипак, ОИЕ имају значајан потенцијал као извори помоћних услуга (ПУ) када су прикључени путем енергетске електронике. Капацитет обезбеђивања ПУ из ОИЕ додатно се унапређује кроз микромреже (ММ) засноване на обновљивим изворима, које обједињују више ОИЕ ресурса и поседују значајне могућности управљања оптерећењем. У случају постојања више извора ПУ, намеће се питање оптималне расподеле сигнала помоћних услуга на све расположиве ресурсе. У већини ранијих истраживања расподеле ПУ коришћени су једночворни модели микромреже.

У студији случаја 1 предложен је детаљан модел микромреже за оптималну расподелу ПУ међу ресурсима применом концепта виртуелног оптерећења (ВО), као и оптимизациони поступак заснован на генетичком алгоритму (ГА) ради постизања најбољих резултата. У циљу сагледавања значаја моделовања мреже, спроведена је компаративна анализа, при чему модел узима у обзир губитке снаге и напонске профиле при расподели ПУ. За тестирање предложеног модела и поступка коришћен је CIGRE референтни модел микромреже. Резултати показују утицај који избор модела има на техничке и економске показатеље рада микромреже и указују да детаљно моделовање може утицати на исходе и до 11% у поређењу са једночворним моделом. Ово оправдава примену детаљних модела микромреже у будућим истраживањима.

Студија случаја 2 показује да предложени хибридни оквир ГА–ВНМ представља ефикасан и брз начин за предвиђање флексибилности микромреже у реалном времену. Модел је у стању да верно репродукује динамичке одзиве свих дистрибуираних енергетских ресурса, као што су когенерациона постројења (CHP), батеријски системи и управљива оптерећења, тако што се ГА примењује једнократно у офлајн режиму ради генерисања комплетног скупа оптималних решења расподеле, након чега се вештачка неуронска мрежа (ВНМ) обучава да научи та оптимална понашања. Обучена ВНМ показује изузетну подударност са циљевима добијеним ГА методом, са грешкама предвиђања које су конзистентно мање од 1% за све ресурсе, као и готово савршеним поклапањем у агрегираној излазној снази за балансирање. ВНМ даје предвиђања у року од неколико секунди, док је ГА потребно неколико минута за сваку оптимизацију. Ово омогућава брзо и поуздано пружање помоћних услуга. Наведени резултати показују да ВНМ представља корисну и поуздану алтернативу оптимизацији заснованој на ГА, омогућавајући доношење квалитетних оперативних одлука у реалном времену и ефикасно управљање балансирањем и флексибилношћу микромреже.

Кључне речи: Помоћне услуге, Моделовање микромреже, Обновљиви извори енергије, Виртуелно оптерећење, Оптимизација (генетски алгоритам), Вештачка неуронска мрежа (ВНМ)

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AMIR

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Chapter 1

Introduction

1 Introduction

Modern power systems constitute the fundamental infrastructure of contemporary societies, facilitating the generation, transmission, and distribution of electricity derived from various energy sources to consumers [1]. These systems have undergone substantial transformation in the last century, evolving from conventional centralized grids into intricate, weather-sensitive cyber-physical systems. Presently, modern power systems function as complex systems of systems, distinguished by enhanced efficiency, adaptability, and improved economic allocation of energy resources. These developments have been propelled by the escalating complexity of power generation, transmission, and distribution networks, along with their interactions with end-users. A significant impetus behind this evolution is the increasing integration of Renewable Energy Sources (RES), including solar, wind energy, and hydrogen (fuel cells), among others [2].

In the context of escalating international initiatives aimed at mitigating greenhouse gas emissions and addressing climate change, RES has emerged as pivotal components in the evolution of power systems. The extensive implementation of RES is fundamentally altering conventional grid architectures, thereby fostering the adoption of cleaner and more sustainable energy alternatives. Nevertheless, the intrinsic intermittency characteristic of RES introduces novel operational complexities, especially concerning the preservation of grid stability and reliability [3]. Consequently, as the integration of RES expands, the imperative for power systems to exhibit greater adaptability and responsiveness to variations in energy supply and demand intensifies [4].

Flexibility has become a crucial concept in addressing these difficulties. Within power systems, flexibility denotes the grid's capacity to react to unforeseen shifts in supply and demand, especially stemming from the inherent variability of RES [5]. This flexibility enables power systems to swiftly modify their operational strategies, adjusting generation levels to align supply with real-time demand. Consequently, this characteristic is vital for preserving system stability, particularly as the integration of renewable energy sources expands and power systems must manage more frequent and unpredictable oscillations.

Flexibility can be achieved through a variety of methods, encompassing traditional power plants with rapid ramping capabilities, energy storage systems (ESS), demand-side management (DSM), and distributed energy resources (DERs). DERs, which encompass small-scale renewable energy generation, localized storage systems, and controllable loads, are becoming increasingly crucial in augmenting grid flexibility. The capacity to extract flexibility from DERs is being enhanced by advancements in monitoring, control, and communication technologies. These resources can be leveraged to deliver AS, including frequency regulation, voltage control, and congestion management, thereby bolstering the overall stability of the power system [6].

Furthermore, the adaptability inherent in contemporary power systems extends beyond mere responsiveness to transient shifts in generation and consumption. It encompasses the capacity to address the enduring variability stemming from RES. This encompasses operational flexibility, which empowers power systems to alleviate disruptions, including generator failures or forecasting inaccuracies. The preservation of operational flexibility is crucial for upholding the secure and dependable operation of power systems, particularly amidst heightened RES integration.

The increasing dependence on digital technologies and communication networks further augments the capacity of power systems to effectively manage flexibility [7]. Digitalization facilitates real-time oversight and management of grid functions, thereby promoting more efficient collaboration between Transmission System Operators (TSOs) and Distribution System Operators (DSOs) [8]. Such collaboration is crucial for maximizing the utilization DERs and preventing operational conflicts between different operators. Through the incorporation of sophisticated data analytics and machine learning methodologies, system operators can enhance their capacity to predict energy consumption and RES generation, consequently bolstering system adaptability and mitigating operational ambiguities.

The integration of Variable Renewable Energy (VRE) into electricity networks is increasing globally. In Europe, where electricity generation remains predominantly reliant on non-RES, the Clean Energy Package of the European Commission has established a target of 30% of gross final energy consumption to be met by renewable sources by 2030 [9]. The shift to renewable energy production is evident in both policy and practical implementation: from 2015 to 2017, Europe constructed 54 GW of wind and PV generation capacity [10]. This results in a novel scenario for electrical networks, wherein the proportion of renewables in electricity production is predominantly influenced by variable sources, primarily wind, with minor contributions from PV and run-of-river hydro, and is increasingly competing with conventional non-renewable generation. The fluctuation of VRE generation poses issues to the functioning of electrical networks in this new context.

To ensure a consistent and reliable supply of electricity, an electrical network has to operate in an environment free from disturbances. Over the past decade, consumers in France have had an average disconnection time of less than three minutes per year [11], demonstrating the great reliability of the electricity delivered by the network to its users in Europe. However, this degree of dependability necessitates a constant control effort: because the transmission infrastructure isn't built to hold huge quantities of electrical energy, the flows of active power generated by generators must always correspond to the network's global power consumption. Power generated by generators falls short of overall power demand if more electric loads join the network at the same number of linked synchronous generators. The network's frequency decreases due to conservation of momentum at a rate proportional to the whole power system's inertia. In continental Europe, the nominal value is 50 Hz ± 50 mHz. If the frequency deviates from this range, it is necessary to limit the deviation and then restore the frequency to prevent electrical equipment damage or blackouts, which can lead to substantial economic losses.

Frequency levels can be reinstated by modifying power flows within the transmission system: when a TSO detects a discrepancy between power generation and consumption within its jurisdiction or "control area," it solicits the activation of power reserves from flexible assets to mitigate the impact of the imbalance, counteracting the frequency deviation. The activated flexible assets comprise:

- Dispatchable power generation facilities, including nuclear, thermal, or hydroelectric plants,
- Storage devices including batteries, flywheels, supercapacitors, or pumped hydro.
- Flexible consumers.

One thing to notice is that the list above doesn't include VRE sources like wind, PVs, or run-of-river hydroelectric power facilities. Later on, we'll discover that new evidence shows that VRE have the technical ability to control their active power efficiently, even though there's a lot of doubt about their production level. At medium-term horizons, the production of VRE that follows the grid and uses inverters could account for the majority of generation capacity [12]. Because VREs are replacing classic synchronous generators in the generating mix, the amount of reserve capacity that may be activated without causing major production uncertainty is reduced. Thus, VRE's contribution to Ancillary Service (AS) balancing seems to be an essential component of power grids. Other AS, including as inertia, rapid frequency response, and voltage support, are just as important for electrical networks as balancing. Services that rely on sub-second response times to maintain system stability are likewise significantly affected by VRE integration. Improvements to renewable energy control systems have increased their grid-forming capabilities and their ability to mimic inertia [13]. According to references [14] VRE can also supply voltage support. However, AS such as frequency regulation, voltage control, and congestion management, offered by Balancing Service Providers to TSOs, will be the main emphasis of the present thesis.

Conversely, notwithstanding these technological progressions, contemporary power systems encounter a multitude of challenges that jeopardize their resilience and security. The escalating dependence on communication networks renders power systems susceptible to cyberattacks, which can potentially disrupt operations and undermine grid reliability.

Moreover, natural calamities like hurricanes, earthquakes, and floods present considerable threats to the physical infrastructure of power systems. The vulnerability to disruptions is further exacerbated by the aging grid infrastructure prevalent in numerous areas, and the operational uncertainties are amplified by the intermittency of RES.

Given these challenges, it is imperative to bolster the flexibility and resilience of power systems to maintain their reliability and operational capacity. By enhancing flexibility, power systems will be better equipped to manage the uncertainties associated with RES and to react to unforeseen occurrences, thereby fostering a more stable, efficient, and sustainable energy future. Nevertheless, AS, including frequency regulation, voltage control, and congestion management, provided by Balancing Service Providers to TSOs, will constitute the primary focus of this thesis.

1.1 Motivation and Challenges

The incorporation of renewable power plants into electricity markets necessitates accurate forecasting of their variable output before presenting this production as energy quantities and reserve capacity. It is essential to quantify uncertainty in output to make educated judgments regarding bidding volumes in the energy and AS markets. One can question how a production forecast, with the measurement of production uncertainty, might assist in formulating market bids.

The unpredictable characteristics of weather-dependent renewable energy generation prompted the creation of probabilistic forecasting techniques, providing a range of potential production outcomes. The moments of the resultant distribution are contingent upon explanatory variables pertinent to the individual energy source, geographical region, and forecasting horizon. Unlike deterministic predictions, probabilistic forecasts facilitate the identification of an ideal bid to mitigate penalties arising from discrepancies between delivered production and the proposed bid. The use of bidding optimal quantiles of the forecast distribution to renewable participation in energy markets is theoretically grounded in the portfolio theory proposed by [15]. Comprehensive reviews [16], [17],and [18] indicate that the probabilistic forecasting of power generation for wind and photovoltaic (PV) systems, albeit to a lesser degree, is a well-established area of research. Nonetheless, forecasts utilized in operational contexts continue to exhibit substantial error rates, with average absolute errors ranging from 5 % to 10%. The fines related to these forecast inaccuracies significantly affect the profitability of renewable power installations.

Production is not the exclusive source of uncertainty; before participating in AS markets, a variable renewable energy aggregator is uninformed about reserve pricing and their probability of activation. This illustrates the conventional context of bidding renewable energy in the wholesale short-term market: the aggregator must employ strategies to alleviate uncertainties in production and pricing by modifying their bidding volume across multiple markets before delivery (day-ahead, intraday, etc.) to reduce economic losses. The uncertainties in balancing ASs markets are expected to differ from those in energy markets. The characteristics of balancing AS markets significantly enhance the complexity of bidding strategies:

- bids must be highly reliable, because reserve is crucial for power systems,

- A reserve bid must be consistently accessible during the delivery duration, which may extend for several hours,
- When energy prices are more favorable than those of balancing AS, reserves may result in opportunity costs since they cause production curtailment and restrict the volumes allotted to the wholesale energy market,
- reserve activation is an uncertain variable which has a decisive impact on the revenue of producers.

In addition to the opportunity costs related to reduced production, it is important to note that implementing power regulation requires further specialized expenses. The additional capital expenditure required to enhance control capability and monitoring for balancing AS is projected to be under 1% of capital costs by [19]. The operational costs related to reserve provision may increase due to frequent regulations on power control, particularly affecting the wear and tear of wind turbines. Nonetheless, the industry's experience on this subject is limited; further research is required to incorporate these costs into the worldwide economic evaluation of reserve provision by renewable sources.

As a whole, the overarching motivation of this thesis is to develop an optimal strategy for the allocation of AS within a MG, particularly those with integrated RESs. This strategy will ensure that the MG can efficiently support the larger power system, enhancing its flexibility and ability to accommodate the variability and intermittency associated with high-RES penetration.

1.2 State of the art

In order to reduce MG losses, this section examines how to best operate a microgrid based on variable RES while taking operational expenses, AS reserves, and resource allocation into account. The utility target limitations are what drive AS constraints. Different time resolutions of AS can be provided using the model. This analysis aims to identify research gaps that will be addressed by the contributions of this thesis. Following this initial examination, more details on the most recent advancements pertaining to each contribution will be given in the different chapters.

Optimization of AS provision.

The improvement of AS delivery via flexible assets is a significant focus of research. The existing literature on this topic can be classified as follows:

- **Optimal quantile:** Based on portfolio theory literature and its significance to wholesale electricity market bidding, an optimal quantile of expected production, obtained from probabilistic forecasts, is designated for reserves, depending on the prices recorded in reserve and energy markets. This involves allocating a segment of the available electricity for reserve, showcasing operational efficiency when applied in wind-based reserve provision [20], [21]. The existing literature on optimal quantiles for reserves is deficient in a vital component for decision-making under uncertainty: it does not offer a framework for forecasting the various prices linked to reserve bidding decisions. A further disadvantage of the optimal quantile technique is its incapacity to include specific constraints, such as those stemming from control capacities or market conditions.
- **Robust optimization:** An alternative to stochastic optimization is to formulate a robust optimization problem in which uncertainties are defined by their boundaries rather than being sampled using scenarios. These boundaries provide hedging against the most adverse

outcomes of production or other uncertain variables, such as prices. In [22], an adaptive robust optimization method is given to minimize the energy procurement costs for a home aggregator of prosumers using batteries and PV production. The robust formulation facilitates hedging against risks in demand, PV production, and energy costs. The limitation of robust approaches is that they provide conservative bids, leading to suboptimal revenues that do not fully use the flexibility within a balancing ancillary services market.

- **Stochastic optimization:** The simultaneous bidding of energy and reserve is articulated as a bilinear stochastic optimization in [17]. Relaxation scheme is implemented to linearize the bilinear constraints arising from simultaneous participation in the energy and reserve markets, under the assumption of a constant ratio between energy and reserve bids; however, it is important to note that transmission operators do not necessitate such a ratio between these bids. This formulation has greater flexibility than the optimal quantile technique, as it can directly include temporal limitations, such as sustaining the reserve bid throughout the offer's validity duration.
- **Chance-constrained optimization:** Instead of conventionally weighing average profits against worst-case losses or creating strong optimization based on extreme scenarios, chance-constrained optimization governs the likelihood of adverse technical restrictions arising from variable output. The reserve bidding model of utilizes a chance constraint to maintain a stable forecasted Loss of Load Probability (LOLP) inside a micro-grid that includes variable resources.
- **Rule Sets for Linear Decisions:** Addressing stochastic and chance-constrained optimizations necessitates the generation of scenarios and their subsequent reduction to maintain the tractability of the resultant problem. An alternate approach involves approximating the limits of the uncertainty set using piecewise Linear Decision Rules (LDR). This comprehensive estimation of boundaries retains the majority of temporal information when a sufficient number of components are utilized and can function as a foundation for real-time power supply management, considering market penalties [17].

Real-time optimization of reserve dispatch to aggregated resources.

To improve the delivery of activated reserve bids during the whole validity period, aggregated flexible resources must be managed in real-time when reserve bids are accepted by system operators. The optimization of dispatch presents both technological and economic issues. Technical issues emerge from the heterogeneity of flexible resources and their collective dynamic responses to the reserve setpoint. An effective method to enhance reserve dispatch of aggregated resources is merit-order activation. The merit-order may be determined by economic or technical criteria, such as a power plant's responsiveness to prior activation. Nonetheless, more advanced approaches, such as Model Predictive Control (MPC), may be appropriate for this task. In [23], observed activation reserve signals establish a balancing energy constraint inside the rolling optimal schedule that maintains a Frequency Containment Reserve (FCR) bid presented by a consortium of flexible consumers. The limitation of MPC approaches is their dependence on an accurate state-space model of the aggregation, which can be difficult to obtain in large-scale and heterogeneous aggregations, such as a VRE-based VPP with various energy sources. This thesis will not address the optimization of reserve dispatch to aggregated resources, as it concentrates on decision-making over bidding for reserve and energy prior to delivery.

1.3 Contributions

1. *Optimization Strategy Development*
   - Develop a novel optimization strategy tailored for MG operation, enhancing their ability to provide AS effectively. The developed strategy will be usable in real-time applications within MG control platforms.
2. *Creation of a Real-Time Testable MG Model*
   - Develop a detailed MG model suitable for real-time testing and validation of optimization strategies, bridging theoretical strategies with practical applications. The developed model will be prepared for real-time platforms in order to provide the ability to test different existing or new control procedures in real time.
3. *Advancement in Renewable Energy Integration*
   - Contribute to a more flexible and resilient power system by demonstrating the feasibility of AS provision through RES-based MGs. It is expected that optimally controlled MGs can provide significant flexibility to power systems, increasing the overall hosting capacity.

1.4 Thesis Outlines

There are six chapters in the thesis format. An overview of the research is given in Chapter 1. An overview of MGs based on renewable energy sources, including their several classification schemes, is given in the second chapter. The potential of the MG to provide flexibility and ASs, as well as the importance of distributing them among different MG assets, are covered in the third chapter. The suggested methodology for allocating ASs in microgrids is described in depth in Chapter 4, with an emphasis on the creation of a hybrid GA-ANN approach intended to lower MG losses, lower operating costs, and facilitate quick real-time reaction. The results are presented in the fifth chapter, which also establishes a benchmark for comprehending the rates of involvement of RES by showing how all MG resources behave operationally under typical operating situations.

Finally, Chapter 6 concludes the thesis with a summary of the findings and a discussion of potential future research directions.

Chapter 2

RES-based Microgrids

2 RES-based Microgrids

2.1 Introduction of Microgrids

The energy demand has increased due to industrial development, population increase, and other issues in recent years. Energy crisis due to the increased demand is considered a significant problem in the world. Due to an imbalance in the electricity supply market and generation of electrical energy along with faults in the system leads to a large number of outages and blackouts in the grid all around the world which impact on the economy as well as social life [24]. Conventional power grids and generation power station are not able to meet the increasing energy demands. Also, the rising fuel cost, environmental pollution is considered as another disadvantage of the traditional power generation plants. Because of these several problems forced the governments and other private agencies all over the world to increase the penetration of RES in the power grid to meet the rising energy demands.

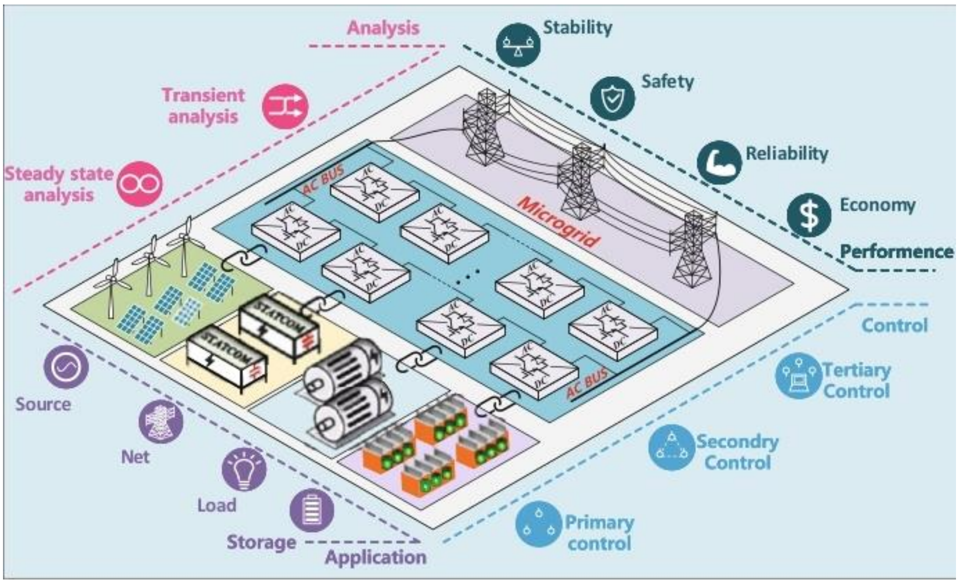


Fig. 2.1 *Structure of a MG [25].*

Methods of power generation utilizing nonconventional energy resources, including PV energy, wind energy, fuel cells, hydropower, CHP systems, and biogas, etc. are referred to as distributed generation (DG) [26]. A bidirectional network design for the transmission of electricity is produced by the digital transformation of distributed systems, which results in active distribution networks with distributed control, bidirectional decision-making, and bidirectional power flow transmission. DG units, which are small-scale power sources located close to the point of consumption, are generally easier to operate and provide more flexible and controllable performance compared to traditional synchronous generator. MGs are a novel idea for future energy distribution systems that enable the integration of renewable energy sources, and researchers have been very interested in them in recent years. [27]. This approach amalgamates DG units with energy storage systems (ESSs), demand-side management, and diverse loads into a centralized control framework, hence creating distribution networks predominantly linked to the upstream power system. Figure 2.1 shows the structure of an MG. Moreover, these networks can be disconnected from the utility grid and operated independently as isolated networks in case of grid failures or other external disturbances. In turn, this makes the power supply more reliable and sustainable. To provide the necessary flexibility within the operation of MGs and to ensure the specified power quality and power output, they have power electronic interfaces (PEIs) and appropriate control systems [25]. MGs are environmentally friendly because they utilize RES. Additionally, they can help customers and the main grid [28]. From the standpoint of the central grid, MGs can be seen as an integrated load or as a managed entity inside a power system. Power supply dependability is increased by MGs' controllability and flexibility, which make it simple to comply with grid standards without jeopardizing utility system stability. MGs also offer continuous power to satisfy customer requests for heat and electricity. They can also lower feeder losses, boost local voltage support, and increase local electrical dependability. The main grid will eventually be supported by MGs, and they may even become a trend in power systems in the future.

2.2 Basic Microgrid Components

Comprehending the frequently employed power generation technologies and their applications is essential for assessing a prospective microgrid project. Table 2.1 delineated the MG generating alternatives along with their respective advantages and limitations.

Table 2. 1 An overview of the benefits and drawbacks of the various MG generating options

RES-based MG	Advantages	Disadvantages
Gas generator	- High fuel efficiency - CHP option - Low emissions - Part load operation of 35% possible	- Limitations in transient response and slower startup - Costly fuel storage - The cost of fuel has significantly increased recently.
Solar	- Low maintenance cost - Diverse applications - Reduces carbon footprint	- Reliance on sun - Requires ESS - Capital cost - Requires inverter
Wind	- Location independent - Reduces carbon footprint - Low production costs	- Reliance on wind - Visual/noise pollution
Biogas	- Cost-effective fuel source - Minimizes pollution of the soil and water - The byproduct is fertilizer.	- Integration cost - Fuel treatment/filtration - Requires suitable biomass
Battery storage	- Neutrality concerning carbon savings. - Retrofit-able - Optimization of rates and curb - Instantaneous power availability	- Space constraint - Battery life - Limited energy storage
CHP (Fuel cell)	- Low Emissions - Extremely quiet - Useful for CHP application	- The cost of extracting hydrogen is high. - Hydrogen requires expensive infrastructure.

Generation: The MG generation system may comprise various non-dispatchable and dispatchable generation sources. A variety of dispatchable generation sources exists, including natural gas generators, biogas generators, and CHP systems. Non-dispatchable generation encompasses RES such as solar, wind, hydro, and biofuels, etc. [29].

ESS: The ESS fulfills various roles in MGs, including maintaining power quality, peak load reduction, frequency regulation, output smoothing of RESs, and supplying backup power for the system. ESS is integral to the optimization of MG costs [17].

Energy management system (EMS): The EMS facilitates the intelligent oversight of the MG through the utilization of energy meters and communication technologies. It regulates MG generation and load distribution according to economic and reliability standards [30].

Loads: MGs exhibit two primary categories of loads: (i) critical loads that must be met under all circumstances, and (ii) deferrable loads that can be modified for load balancing within the MG, hence optimizing economic power output.

Controller: The MG controller oversees the immediate functioning of the system [31].

Point of common coupling (PCC): The PCC serves as an essential link between the MG and the main grid. It functions as the interface for the exchange of electrical energy between the microgrid and the broader power system. The PCC incorporates several tools and technologies to facilitate connection, power exchange, control, and protection between the MG and the main grid. This encompasses elements such as circuit breakers, protection relays, and synchronization apparatus. The isolated MG lacks PCC [32].

2.3 Potential benefits of microgrids

Price stability: Grid investment can lower risk. It serves as a measure of protection against the unexpected and potentially excessive costs associated with emergency and contingency energy requirements. It also offers protection from fluctuating electricity bills.

Economic benefit: MGs can participate in demand response (DR) markets, reduce peak load pricing, and offer frequency control services to the wider grid, contingent on local market regulations and activities. Additionally, they can profit from participating in DR markets, reducing peak load prices, and providing frequency regulation services to the rest of the grid.

Continuous supply: Although the electrical infrastructure in numerous modern countries is generally reliable, any disruption can be expensive and perilous. Extreme weather, aging, physical assaults, and cyberattacks are increasingly threatening the nation's electrical infrastructure today. Operating in island mode can guarantee a continuous electrical supply by detaching from the main grid and utilizing on-site generation [33].

Integration of RESs: RESs play a major role in meeting some of the global energy demands. Unprecedented momentum for RESs has been created by the ongoing global energy crisis. It is expected that the predicted growth in renewable capacity over the next five years would exceed earlier projections. The International Energy Agency (IEA) predicts that between 2022 and 2027, renewable energy would increase by about 2400 GW. When compared to the growth observed over the preceding five years, this indicates a notable acceleration of 85%. In addition, the projected growth represents the largest upward revision to date, coming in at almost 30% higher than the original estimate in the report from the previous year. MGs are therefore becoming more and more crucial to enjoying the advantages of RESs [34].

Increased reliability and resilience: The ability of MGs to operate independently enables them to maintain power supply to consumers during power outages. The capability to island is also crucial for isolating errors by segregating distribution feeds.

Improve power quality: Systems could require more electricity than the electrical grid can supply. Better control over its parameters is made possible by the implementation of an MG, which is crucial for delicate equipment in labs, advanced manufacturing, healthcare, and other establishments.

Relationship between the MG and the utility grid: MGs might be considered the fundamental component of smart grids. In other words, future utility grids might consist of a network of interconnected MGs that control energy supply and demand at both the macro and micro levels.

Grid support: MGs reduce peak demand and grid congestion. They also offer additional grid services such capacity, energy, and AS.

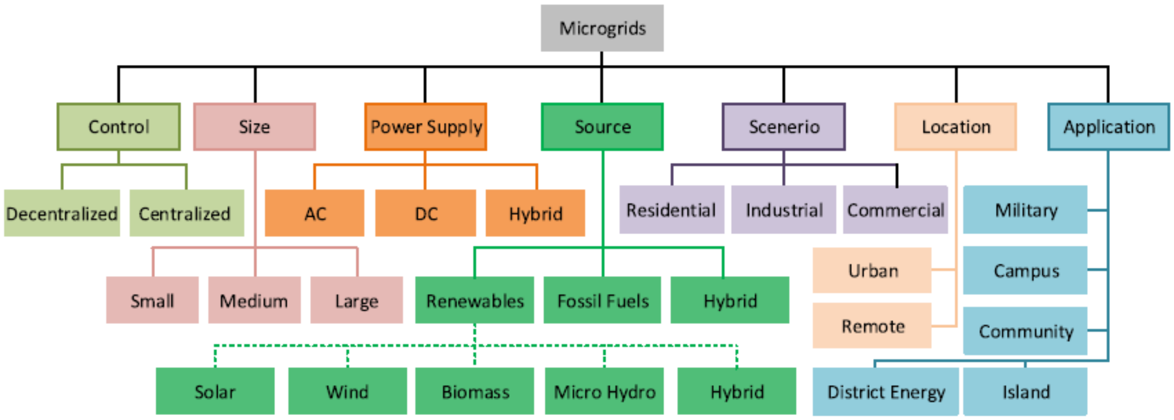


Fig. 2.2 *MGs classification [35]***.**

2.4 Microgrid Challenges

Despite the huge potential advantages of MG development, a secure and steady operation has been difficult to achieve due to a number of obstacles. A number of technical and regulatory issues need to be resolved [36].

Low Inertia Issues [36]**:** There are wider ramifications when synchronous machines are replaced. Power electronics converters provide faster dynamics than traditional synchronous machines for active and reactive power supply. This may result in unforeseen couplings, making timeframe separation-based control techniques more fragile and less valid.

Challenges with Stability and Operation Control in Multi-Resource MGs [37]**:** Various energy sources with varying capacities, transient responses, and inertia are usually included in an MG. For instance, power electronics interfaced with converter-based PV production systems have relatively little physical inertia, but hydropower generates a lot of rotational inertia because of the revolving components. The operation control method should be carefully considered in order to mitigate the interacting consequences of multi-resource MGs.

Seamless Transition Among Various Operational Modes: MGs should be able to be operated in both island-based and grid-connected scenarios. To safeguard the integrity of the utility grid and the local power supply's power quality, a smooth transition between these two modes is necessary to avoid purposeful or inadvertent damage to MGs.

Control of Power Sharing: Power sharing control techniques should consider variations in nominal capacities, transient characteristics, and the distances between loads and DG units in order to eliminate operation failures brought on by overcurrent incidents, inadvertent DG unit outages, and decreases in power transmission losses.

Problems with Power Quality: Power quality problems such as harmonics and unbalances will occur in MGs with nonlinear or unbalanced loads. Power electronic interfaces (PEIs) are designed to improve the quality of power supplies by performing a variety of tasks, including interruption rejection, voltage balance compensation, and harmonic attenuation.

Protection for Active Networks: The increasing prevalence of DG units has led to several concerns regarding MG protection. Variable infeed currents are caused by a number of issues with RESs, including bidirectional power flow, fault currents, and climatic dependence. Furthermore, high penetration distributed networks resulting from extensive joints also exhibit interaction influences.

Optimal Sizing and Placement of Multiple Sources: The efficient installation of RES, ESS, and CHP in the distribution network will reduce the economic cost as power and energy losses, voltage profiles, and redundant capacity are reduced.

Regulations for Grid-Connected MG Operation: An appropriate control approach must be put in place in grid-connected MGs to guarantee synchronized behavior, grid code compliance, and accurate regulatory compliance.

Integration of Communication: MGs require the creation of a particular communication protocol and infrastructure. The communication for media gateways and active distribution networks issued the IEC 61850 standard. There is still insufficient communication infrastructure in rural areas.

2.5 Classification of Microgrids

In order to help designers, choose safe and reliable design solutions, a thorough review of the literature was done to examine the main topologies and architectural structures of existing MGs. As shown in Figure 2.2, MGs can be divided into many classes based on their infrastructure, applications, and end-user needs.

2.5.1 Microgrids classified using control techniques

According to control methods, there are three main control mechanisms for MG systems as showing in Figure 2.3. MGs' resources have been dispersed throughout the natural world [38]. Additionally, the unpredictable and sporadic emission of RESs makes the MG's efficient operation more difficult. Therefore, to provide steady and consistent power flow, an appropriate control approach is essential. The MG is managed and controlled by the MG Central Controller (MGCC). MGCC can be set up at a distribution substation or a local control center [39]. Through communication with controllers at lower hierarchical levels, MGCC controls distributed ESS devices and local DG units. Additionally, more dispersed techniques like agent systems and droop control can be used to regulate MGs.

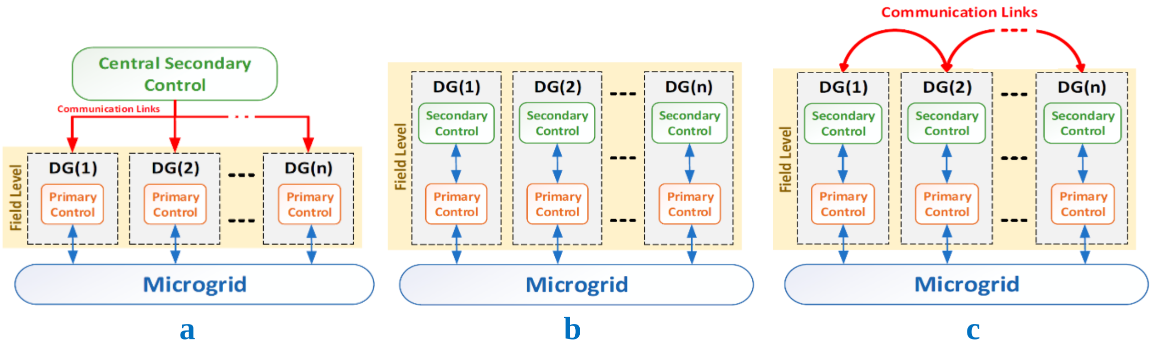


Fig. 2.3 *MG control systems: (a) centralized, (b) decentralized, and (c) distributed [38]***.**

A control strategy in an MG environment should satisfy the following characteristics [38]:

- Power balance: DG supply coordination and effective load sharing.
- Transition: MG types of operation can be seamlessly switched from by islanding to the grid-tied mode or vice versa.
- Protection: Protection includes monitoring energy flow and equipment, as well as managing grid faults.
- Power transmission: The transfer of power between the MG and the main grid is known as power transmission.
- Optimization: Enhances MG dispatch strategies for optimal economic benefit. Furthermore, depending on the MG's conditions, it provides improved energy efficiency.
- Stability: As the MG runs in different modes, its voltage and frequency are controlled. Additionally, a strong and dependable power network benefits the MG's AC and DC sides.
- Synchronization: Optimal power transmission requires synchronization between the MG and the power network.

A. Control techniques (Voltage and frequency control)

A comprehensive and systematic classification of MG control mechanisms commonly employed in MG operations is presented, providing a detailed overview of the various control strategies and their functional roles in ensuring reliable, stable, and efficient operation of MG systems under diverse operating conditions.

- **Techniques for central control:** Centralized control management makes it simple to deploy and monitor the complete system in real time. A single central controller (CC) functions as the primary controller in the context of centralized control. CC oversees the operation of various DG units in MG systems. Every DG unit uses a local controller (LC), which can communicate directly with the CC. Modern computing tools enable CC to track and evaluate the data it receives from the LC in real time [38]. It is not too difficult to install centralized control. Additionally, it has shown outstanding reaction in the MG system's functioning. But there are still a lot of unanswered questions, especially when dealing with a large-scale hybrid system. The functionality of the entire system is impacted by CC failures. Furthermore, the control method's flexibility and expandability are limited [31]. The controller has two operating modes: (1) event based meant during islanding of MG or tripping of a generator. (2) response based during sudden rise in load demand. It is divided into four modules to calculate event and frequency, state estimator and load shedding modules. This modular design can facilitate easy modification of controller task in future. However, usage of distributed state estimator (DSE) makes it quite sluggish.
- **Decentralized control techniques:** In recent years, decentralized control has been extensively explored to enhance the autonomy of micro sources and loads in MGs. Reliability, cost-effectiveness, and stability are the core goals of this control strategy. Limited local connections are needed to make the control choice, which is based on the local measurement [38]. Moreover, a high degree of connection and high-performance computer units are not necessary. However, it is not possible to guarantee global optimal solutions for the entire MG system.

- **Distributed control:** Distributed control improves overall performance by sharing some information among controllers so that each may better comprehend the behavior of the others. The various control techniques and their benefits and drawbacks were compiled in Table 2.2.

Table 2.2 A summary of the available MG control strategies.

Control Method	Benefits	Drawbacks
Centralized	Global optimal solutions.	Needs communication infrastructure. A considerable computing load is required. Reduced scalability. Communication network affect stability
Decentralized	There is no need for communication infrastructure. Higher reliability. Decreased complexity of computing. Enhanced scalability.	No worldwide optimal solution
Distributed	Decreased complexity of calculation. Better reliability. Enhanced scalability.	Sub-optimal solutions. Infrastructure for communication is necessary. Stability is affected by communication networks.

B. MG control system advancements

The most recent developments in MG control and supervisory systems have been influenced by the need for more grid flexibility, the complexity of MG operations, and the increasing integration of RESs. Enhancing the performance, dependability, and efficiency of MGs is the main goal of these technological developments, which will also guarantee the smooth integration of DERs and efficient grid management. The following are some noteworthy developments in MG control and supervision systems:

- **Intelligent Energy Management System:** Advanced EMS systems utilize artificial intelligence, machine learning, and optimization algorithms to proficiently regulate the production, storage, and consumption of energy within MGs. [40]. In order to attain optimal operational efficiency, these systems dynamically optimize energy dispatch, continually monitor and anticipate energy generation and demand, and facilitate real-time decision-making.
- **Advanced ESS management:** Complex control strategies have been created to maximize the use and effectiveness of ESS in MGs. These tactics include sophisticated ESS scheduling and control based on grid circumstances, renewable energy availability, and real-time capacity demand [41]. This enables grid support, load shifting, peak reduction, and effective energy balance.
- **Grid-forming inverter control:** The ability of grid-forming inverters to independently control MG voltage and frequency, thereby removing reliance on the main grid, has garnered attention [25]. With the growing popularity of RESs, this feature is especially important.

Advanced grid-forming inverter control algorithms improve MG resilience, increase grid stability, and facilitate smooth transitions between islanded and grid-connected modes [42].

- **Cyber-physical security:** As MG control systems become more networked and reliant on digital communication and control technologies, it is critical to guarantee their cybersecurity and resilience. To defend against cyberattacks, control and supervisory systems are incorporating advanced security features like encryption, authentication protocols, anomaly detection, and intrusion prevention systems [43].
- **DR integration:** To enable customers to actively participate in load management, control systems in MGs are integrating DR techniques. Real-time communication between the MG operator and end customers is made possible by sophisticated DR algorithms and communication protocols, which minimize total energy consumption and enable load shedding or load shifting during periods of peak demand [11].

2.5.2 Classification of MGs Based on Size

MGs can be divided into three groups according on their size: small, medium, and large-scale MGs [35].

- **Small-scale MGs:** These MGs generate low-capacity electricity using RESs. However, some MGs may use diesel generator sets as a power source in addition to or instead of RESs. The highest generation capacity of a small-scale MG is 10 MW. Small-scale MGs can provide isolated locations, residential structures, and small regional power systems.
- **Medium-scale MGs:** These plants use coal, oil, and RES to produce medium-capacity power. A medium-sized MG's generation capacity can range from > 10 MW to 100 MW. Applications for this kind of MG can be fed into industrial zones.
- **Large-scale MGs:** Large-scale MGs generate high-capacity power using coal, oil, and RESs. The range of generation capacity for a large-scale MG could exceed 100 MW. This type of MG can be used to feed applications in industrial zones.

2.5.3 MG classification according to power supply

MGs can be classified into three groups based on their connected power supply: AC, DC, and hybrid MGs [38].

A. AC Microgrids:

An AC MG is a conventional MG system with an AC power supply and linked loads powered by the AC electricity as shown in Figure 2.4. At the PCC, this MG can be connected to the main grid or run independently. The AC bus connects power sources, storage devices, and other system components to meet the demands of the AC load. These MGs don't need any additional control mechanisms and are simple to integrate into current power systems. Single-phase, grounded three-phase, and ungrounded three-phase are the three types of AC MGs [33], [38]. Additionally, these MGs can be divided into three groups according to frequency: standard-frequency AC MGs, low-frequency MGs, and high-frequency MGs. In practical applications, AC MGs have been the most popular and extensively used architecture. It is difficult to maintain voltage magnitude, phase angle, and frequency while synchronizing with the host grid. They are also not very reliable or efficient. AC MGs require complex control and architecture.

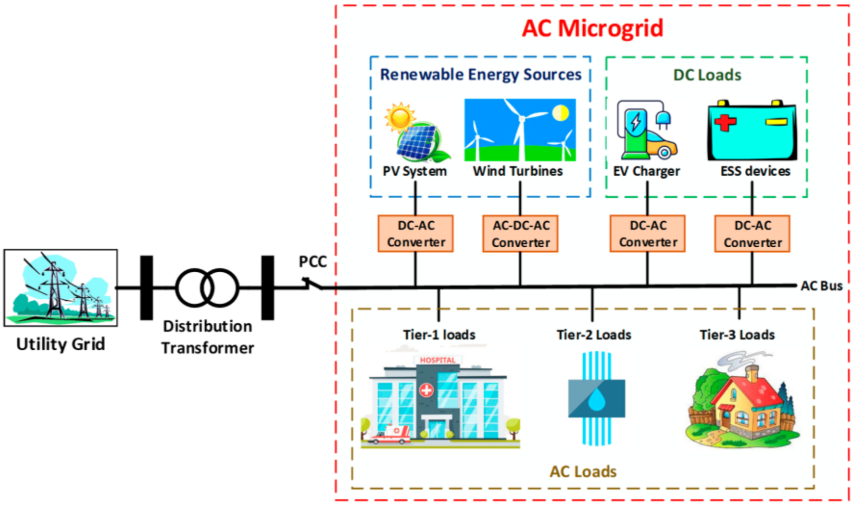


Fig. 2.4 *Basic example of a standard AC MG [38]*.

B. DC Microgrids:

DC MGs are designed to produce and store DC electricity. DC power will follow the supply power of these MGs, and DC power will drive the attached loads according to Figure 2.5. Since these MGs don't need to be synchronized and power quality problems are uncommon, they are more beneficial than AC MGs. Regarding the power factor enhancement, they have no worries. These MGs connect to the existing distribution networks via a variety of converters and power electrical components. When feeding DC loads, DC MGs are more efficient and undergo a lower conversion process than AC MGs. Examples of commercial uses for DC MGs include naval power systems, electric vehicles, telecommunication, and other fields. There are three varieties of DC MGs: mono-polar, bi-polar, and homo-polar MGs [33], [38]. One benefit of DC MGs is their ability to directly link DC loads to the DC bus. Consequently, only a small number of power converters are required. Conversely, DC MGs lack a standardized voltage. To produce AC voltage, an extra power step is needed. Additionally, DC MGs cannot be altered using the current grid. It's difficult to protect them.

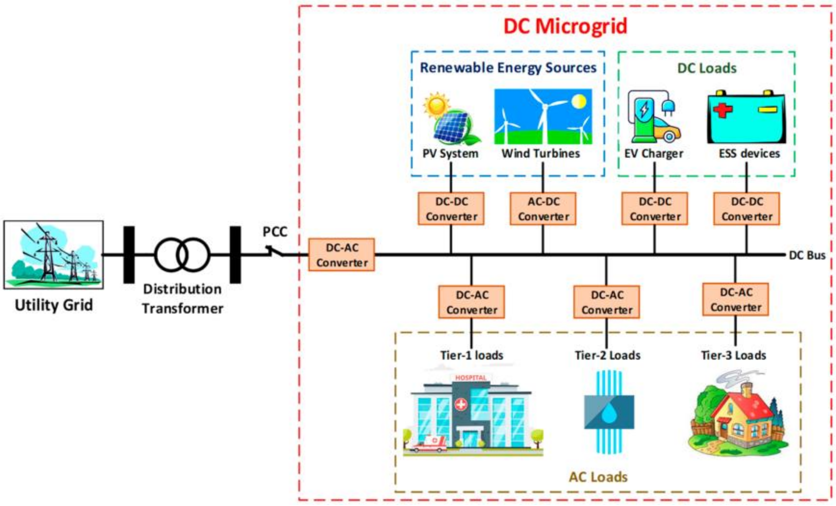


Fig. 2.5 *Basic example of a standard DC MG [38]*.

C. Hybrid AC/DC Microgrids:

Hybrid MGs have an AC and DC distribution system, and the connected load will be supplied by both AC and DC power sources as illustrated in Figure 2.6. A hybrid MG aims to reduce the number of interface devices and conversion steps while maintaining low energy costs [33], [38]. Consequently, the overall effectiveness and dependability of the system can be enhanced. Customers can tailor their power consumption to suit their demands by using hybrid MGs, which can incorporate both AC and DC loads. An MG's AC and DC components are separated by power electronic converters. Without requiring synchronization, DG units in AC-DC hybrid MGs can be connected straight to the DC and/or AC networks. This arrangement does not, however, always result in lower energy losses in the MGs. Numerous factors, including converter inefficiencies, transmission losses, and system management constraints, can still result in energy losses within the system. However, especially in an islanded mode, hybrid MGs require a complex controller and administration system. Because interface power converters are incorporated into the distribution network for DC-link generation, these MGs are also less reliable than AC MGs [38]. However, the interconnected devices become more reliable when the number of converter steps is decreased.

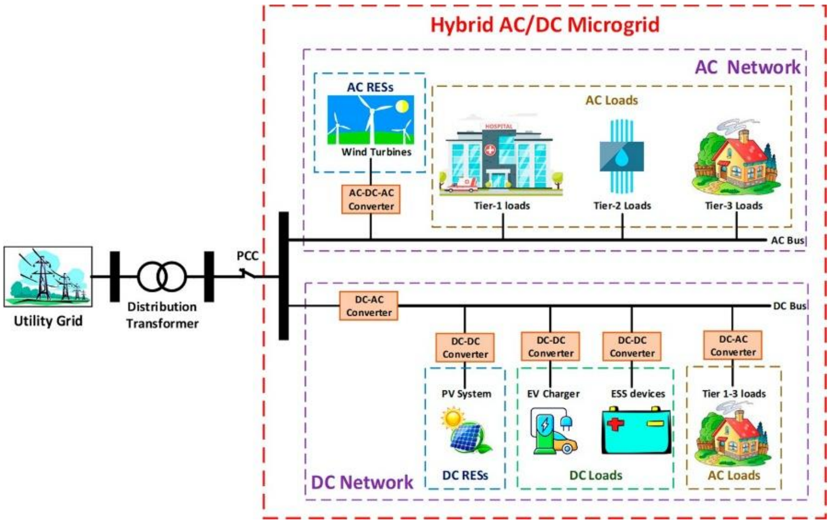


Fig. 2.6 *Basic example of a standard Hybrid AC/DC MG [38].*

2.5.4 Classification of MGs Based on Source

A. Renewable MGs

A renewable MG is one that operates on distributed RES. Renewable MGs typically include RES and batteries. They supply electricity to end consumers with a minimal carbon footprint. As a result, these MGs are growing more popular and being deployed over the world. However, the variable and intermittent output of RESs complicates the effective operation of the MGs. Furthermore, meeting the time-varying demand is a critical difficulty for an isolated MG. ESS is one of the most appealing technologies for maximizing the usage of renewable energy and is widely utilized to balance demand and supply in MGs. The major problem is to combine storage systems, distributed renewable energy sources, and fluctuating power demand. Thus, an EMS is critical for renewable MGs [35].

Renewable MGs can be categorized into five subgroups based on their renewable sources: biomass, wind, solar, micro-hydro, and hybrid MGs.

- **Solar MGs:** Solar MGs provide a compelling renewable energy solution due to their scalability and adaptability for various applications. Consequently, they are broadly considered a viable and sustainable solution for rural electrification globally. Solar microgrids operate well in regions with ample sunlight, as they depend on solar energy for electricity generation. To address inclement weather, most systems incorporate storage capacity that enables operation during intervals of limited sunlight [35]. Solar microgrids possess the capacity to serve as an environmentally sustainable energy alternative. The output of solar PV is limited by its variable characteristics. Consequently, an appropriate control technique is essential. Solar microgrids are frequently utilized to supply energy to educational institutions, street lighting, residential properties, commercial enterprises, healthcare facilities, and agricultural irrigation systems.

  The output power of the photovoltaic panel is influenced by meteorological factors, including net solar irradiation and the temperature of the solar panel. Consequently, these variables are interrelated as follows [44]:

  $$P_{PV}(t) = P_{PV}^{rated}\left(\frac{R(t)}{R_{stnd}}\right)\left[1+\alpha_p\left(T_{amb}-T_{ref}\right)\right] \tag{2.1}$$

  Where P_{PV}^{rated} denotes the nominal output of the solar cell, $\mathrm{R_{stnd}}$ represents the amount of solar radiation under normal circumstances. Standard conditions for solar irradiation are frequently higher around the equator, at about $2\ \mathrm{kW/m^2}$ but the value of $1\ \mathrm{kW/m^2}$ is usually relevant to the northern sections of the Earth. $\mathrm{R(t)}$ is the solar radiation at time t and α_p is the temperature coefficient of output. T_{amb} stands for the ambient temperature, and $\mathrm{T_{ref}}$ is the standard temperature of a solar panel, which is 25^0 Celsius.

- Wind MGs: Within well-defined electrical limits, a wind MG is an electrical distribution system that consists of a collection of connected load and wind turbines that function as a single controlled source. In order to balance the supply and store extra energy for later use in the MGs, wind-based MGs usually use an ESS. The wind turbine's output power ($\mathrm{P_w}$) is a function of the air density (ρ), turbine swept area ($\mathrm{A_{wt}}$), turbine efficiency (η_{wt}) and wind velocity ($\mathrm{V_w}$). It is possible to calculate $\mathrm{P_w}$ by [44]:

  $$P_w = \rho\left(\frac{1}{2}\right)A_{wt}\times V_w^3\times\eta_{wt} \tag{2.2}$$

- Biomass MGs: A biomass MG is an MG that runs on biomass. In this MG, biomass is partially burned in biomass gasifier systems to create syngas, which is subsequently used in an engine to power a generator [44]. Although solar and wind power are more common MG generation options, bioenergy MGs are becoming more popular in many places. They use biomass gasifiers, which are less expensive than solar PV, hence their capital needs are quite minimal. Conversely, biomass gasifiers are limited to locations that have an adequate supply of biomass. Compared to other kinds of systems, they also need a substantial amount of labor, a large amount of feedstock, and good storage practices. Everyday activities can be hampered by tar accumulation or wet husk. These systems frequently experience bottle coil failure, spark plug failure, and battery discharge (an inadvertent current to the spark plug). Another difficulty is keeping the husk dry throughout the monsoon season.
- Micro hydro MGs: Run-of-the-river projects, which use water diverted from a river or stream via a conduit to power a turbine for energy generation, make up the majority of micro-hydro

MGs. Per kWh, the cost of energy production is comparatively low. However, micro-hydro systems can only be installed in areas with sufficient water supplies.

- Hybrid MGs: An MG that can use hybrid renewable energy sources including photovoltaic, wind, biomass, and micro hydro to supply electricity to a remote location [44].

B. Fossil fuels MGs

MGs that are powered by fossil fuel generators (natural gas or diesel) can supply electricity to far-flung locations. They can operate in both remote and grid-connected environments. For many years, diesel generators and energy sources like steam and gas turbines have been the standard way to produce localized power in a MG. These, however, adversely affect both the environment and the economy. The fossil fuels necessary to operate these MGs are costly to acquire and transport, and transportation alone carries a significant carbon footprint. Numerous towns utilizing diesel generators encounter this issue consistently. Manufacturers are investigating cleaner alternatives because to these effects [44].

When the battery bank approaches the minimum permitted depth of discharge, a DG in MGs can operate as a backup supply. Based on its fuel consumption (FC), which is measured in liters per kilowatt-hour ($\mathrm{L/kW}$), it can be computed as:

$$FC(t) = A_G P_{DG}(t) + B_G P_{DG}^{r} \tag{2.3}$$

where P_{DG} denotes the generated power in kW while $\mathrm{P_{DG}^{r}}$ refers to the rated power in kW of the DG. The coefficients $\mathrm{A_G}$ and $\mathrm{B_G}$ denotes the fuel curve slope ($\mathrm{L/h/kW^{out}}$) and fuel curve intercept ($\mathrm{L/h/kW^{rated}}$) of DG, respectively.

C. Hybrid MGs

A hybrid MG system can operate in both isolated and grid-connected configurations by combining RESs, fossil fuel generators (diesel/gas), and/or batteries. Hybrid MGs utilizing renewable energy and fuels are supplanting entirely diesel or natural gas microgrids as a more favored alternative. Hybrid vehicles significantly reduce fuel use while also being more cost-effective, dependable, and environmentally sustainable throughout their lifespan. Nevertheless, hybrid systems necessitate fuel-powered generators, so rendering noise and pollution unavoidable.

D. Energy storage system (ESS)

As an energy buffer that smoothes variable generation, an ESS is essential for decarbonizing the power system and has the ability to change energy and power over time. They can offer both short- and long-term capacity, improve system flexibility to reduce peak load, postpone grid improvements, and regulate voltage and frequency. Mature methods like pumped hydropower storage (PHS), more recent innovations like flywheels and battery energy storage systems (BESS), and more current technologies like supercapacitors and hydrogen storage are among the possibilities available. It is also feasible to create a hybrid system that combines two or more technologies [45].

In producing mode, a PHS is a flexible technology that offers frequency-related AS. To boost the load's inertia, fixed-speed PHS can use their SG as a synchronous condenser while in pumping mode. A quick response to frequency variations following a disturbance can also be facilitated by variable-speed PHS connected by an inverter interface. Electric Vehicles (EVs) are cost-effective for power system applications since they run on batteries. Because there are no moving parts, BESS can react to changes in system frequency rapidly. The authors of [45] provide the best state of charge plan for PFC supply. In a similar manner, SFC with BESS is examined to assess how continuous cycling affects battery aging. Because of its high ramp capabilities, BESS are also useful for improving short-term flexibility and, if placed properly, can aid in system restoration. Small frequency imbalances can be easily followed by flywheels, and inertia emulation control can be aided by the short-term storage of supercapacitors. Furthermore, as demonstrated in [45, 46], long-term hydrogen storage may be able to lessen seasonal variations and restrict variable generation.

The battery's behavior is described by the state of charge (SOC) in percentage, which correlates with the battery energy level, BL(t), at time t as follows [44]:

$$SOC(t) = \frac{BL(t)}{BLcaps} \times 100\% \tag{2.4}$$

Subjected to

$$SOC_{min} < SOC(t) < SOC_{max} \tag{2.5}$$

Where $BLcaps$ denotes the battery's initial nominal capacity; $\mathrm{SOC}_{\mathrm{min}}$ denotes the minimum limit of the battery, and $\mathrm{SOC}_{\mathrm{max}}$ denotes the upper threshold of the battery's state of charge. Limits must be established to mitigate the impact on battery aging, hence prolonging battery life [44].

2.5.5 Classification of MGs Based on Scenario

MGs have different energy needs for different deployment circumstances. Commercial MGs focus on power quality and cost reduction for company operations, industrial MGs guarantee process continuity and high reliability, and residential MGs optimize household energy consumption and rooftop PV integration. EMS techniques and control architectures must be customized for each circumstance [47].

A. Residential

A typical residential MG consists of an advanced management system, or "controller," that integrates user electricity demands, manages distributed resources like solar PV and energy storage, and interacts with the distribution networks. During power outages, a residential MG reduces a customer's reliance on a centralized electrical source by providing emergency power to critical circuits. With the help of the MG controller, a home can be transformed into a dynamic, adaptable, and quick-reacting network resource that can offer services to network operators for transmission and distribution of electricity. Since these MGs are intended to service residential clients, they will have many users and be overseen by a different business. It could be urban or rural in character.

B. Industrial

The power supply's dependability and security are the main justifications for installing an industrial MG. Many manufacturing processes can be disrupted by power outages, which can lead to significant revenue losses and long startup times. Examples include the manufacturing of chips, the chemical industry, and the food and paper sectors. If their use is economically justified, several industrial sites are currently installing uninterruptible power supplies. Additional advantages of the

MG architecture could include the utilization of RES and a dependable power source with high energy efficiency.

C. Commercial

These MGs are widely used by commercial clients, including data centers, hospitals, and airports, to service individual users. In addition to being self-sufficient, this kind of power system can function separately from the main grid. They might occasionally be linked to the utility grid. Facilities linked to public grids can reduce energy costs and increase self-sufficiency by diversifying their energy sources, utilizing time-of-day electricity pricing, and having backup power supplied when needed.

2.5.6 Classification of MGs Based on Location

MGs can be divided into urban and remote systems based on their geographic location [48], [35]:

A. Urban MGs

MGs situated next to utility infrastructures in urban areas are known as urban MGs. These microgrids can operate in both islanded and grid-connected setups. To maintain the utility grid system's stability and electricity quality, they follow all rules, control strategies, and synchronization techniques. Urban MGs are used in both business and residential settings, including hospitals, colleges, workplaces, shopping centers, and neighborhoods.

B. Remote MGs

MG systems deployed in remote locations where utility power systems are geographically unavailable are known as remote MGs. Remote MGs include places like islands, high areas, and military installations. Because the utilities are not present, these MGs function in isolation. They are installed less frequently than urban MGs due to economic, political, and technological challenges. Remote MGs allow access to energy sources that are not connected to the grid. Remote MGs, like island MGs, have traditionally used diesel, but are increasingly incorporating solar and storage.

2.5.7 MG classification according to application

The MGs can be categorized into various groups according on their applications. The subsequent categories are as follows [35], [48], [49].

A. Campus and institutional MGs

Campus and institutional MGs are frequently composed of a certain number of buildings located in a particular region. The type of institution may have different requirements for the quality of the power supply. Research institutes might need a higher-quality power supply, although the majority of government and academic facilities might be content with a moderate level of power supply reliability. There is usually only one decision-maker in this kind of MG, and all participants and structures are owned by the same organization. This structure allows for quick decisions, and if there are obvious advantages, the real estate owner can take action.

B. Community MGs

A community MG is a coordinated local grid area that has a high penetration of local RESs and other DERs and is serviced by one or more distribution substations. In affluent nations, they are often used to assist communities in achieving their renewable energy objectives. "Community and utility" MGs are made up of private end users, mostly in residential areas, but also occasionally business and industrial clients. It may encompass rural feeders, urban areas, and villages. These MGs can supply electricity to both rural and urban areas when they are connected to the extensive utility system. These MGs may include a variety of distributed energy sources powered by fossil fuels or renewable energy sources. National and international regulations and standards will determine whether or not these MGs are commercially acceptable. Decisions will take longer than in other MG structures because of the large number of participants.

C. Island and remote ‘‘off-grid’’ MGs

An island MG and a community or utility MG are typically quite comparable. The main difference is that, for the most part, there won't be a link to the electrical grid. In certain cases, if the distance between the island and the mainland allows it, a cable connection to the mainland utility grid may be possible. However, given the island's actual power supply infrastructure, the decision-making process might go more quickly. "Off-grid" MGs prioritize scattered and varied power sources for rural and physically isolated communities as well as poor nations. As developing nations strive to upgrade their electrical infrastructure, many remote MGs are being installed in order to eventually join a bigger grid system. To maintain energy security, other distant MGs are made to be self-sufficient.

D. Industrial and commercial MGs

This category of MGs resembles the previously referenced instance of sole ownership. The development of a microgrid in an established business or industrial zone with several stakeholders complicates the situation. In a greenfield project designated as a "commercial–industrial park" with both premium and standard power supply capabilities, the investor may choose an MG structure to accommodate all client needs. Facilities connected to public grids can reduce energy expenses and enhance self-sufficiency by diversifying energy sources, utilizing time-of-day electricity pricing, and maintaining readily available backup power.

E. Other applications

In addition to their typical uses, MGs can be employed for the following purposes [31], [35]:

- District energy MGs: These MGs supply thermal energy and electricity for the heating (and cooling) of different facilities.
- Military MGs: In a military base camp, military MGs are small-scale electrical infrastructures that can function nearly independently. Ships, ferries, vessels, and other maritime equipment have marine power systems that run in islanded mode at sea and are grid-connected in ports. As a result, marine MGs are genuine commercial microgrids with a market and a reasonable cost. With ships becoming more electrical, maritime MGs are becoming more and more crucial.

- Aerospace: In recent years, the aerospace MG concept has become more significant. Electrical sources are gradually taking the place of mechanical, hydraulic, or pneumatic power sources in a number of aerospace applications, including airport MGs and e-aircraft, or more electric aircraft.
- Space: The success of a very expensive space mission depends on the availability of a spaceship's or satellite's power system components. A sustainable way to satisfy the energy needs of space applications is through space MGs.
- Biological: To support extended human space missions, artificial ecosystems can be used as life support systems (LSSs). Food production and garbage disposal are not possible in space. As a result, food and waste treatment from Earth are necessary for an open LSS. Closed ecological systems (CESs) are ecosystems that do not engage in any kind of matter exchange with their surroundings. CESs are necessary for long-term manned space missions in order to reduce Earth support. They consist of several separate compartments that continually and under controlled conditions replicate the essential processes of an ecological system.
- Water: The increasing dependence on electricity has rendered extended power outages detrimental to impacted populations. Additionally, power outages can impair water treatment plant operations, resulting in a shortage of drinkable water a critical component of post-disaster recovery efforts. One strategy to address this issue is the temporary reorganization of water and electricity systems into localized networks, such as water MGs and electric MGs, which use local resources to meet local demand independent of the central water network and/or power grid.

2.6 Architecture of MG

The rapid growth of distributed energy resources and the increasing demand for reliable, efficient, and sustainable power supply have driven significant interest in MG technology. DG units, ESS, and local loads are all integrated into a MG, which is a localized electrical network that can function independently of the main utility grid in either grid-connected or islanded modes. This flexibility makes MGs a promising solution for modern power systems, remote communities, and critical infrastructure applications.

To accommodate the diverse requirements of various applications, different architectural configurations of MGs have been developed, each offering distinct characteristics in terms of power flow management, power quality, control complexity, and scalability. Among these configurations, three fundamental types have emerged as the most widely studied and implemented: the Parallel-Type MG, the Series-Type MG, and the Hybrid Series–Parallel MG.

The Parallel-Type MG connects distributed sources and loads in a parallel fashion to a common bus, offering simplicity and modularity. The Series-Type MG arranges its components in a series configuration, providing enhanced control over power quality and compensation capabilities. Meanwhile, the Hybrid Series–Parallel MG combines the advantages of both configurations, offering a more versatile and robust architecture suited for complex and demanding power system environments.

In order to build optimized MG systems that satisfy specified performance, reliability, and economic objectives, engineers and researchers must have a thorough understanding of the structural distinctions, operational principles, and technical trade-offs of these three architectures. These three MG topologies are thoroughly reviewed and analyzed in this work, with an emphasis on their salient characteristics, benefits, drawbacks, and possible uses.

2.6.1 Parallel-Type MG

The most prevalent MG in the architecture of the power system today is the parallel-type MG. Each DG unit is connected in parallel to the common bus via the converter, as seen in Figure 2.7. Each unit in this parallel-type MG may be controlled separately, and energy can be dispersed efficiently, allowing for far more flexible power electronic regulation. The parallel-type MG, on the other hand, possesses the traits of a distributed network, which can be plug-and-play, widely available, and fault-tolerant. However, because of the DG unit's relatively low voltage grade, its extensive applicability in medium and high voltage domains are constrained.

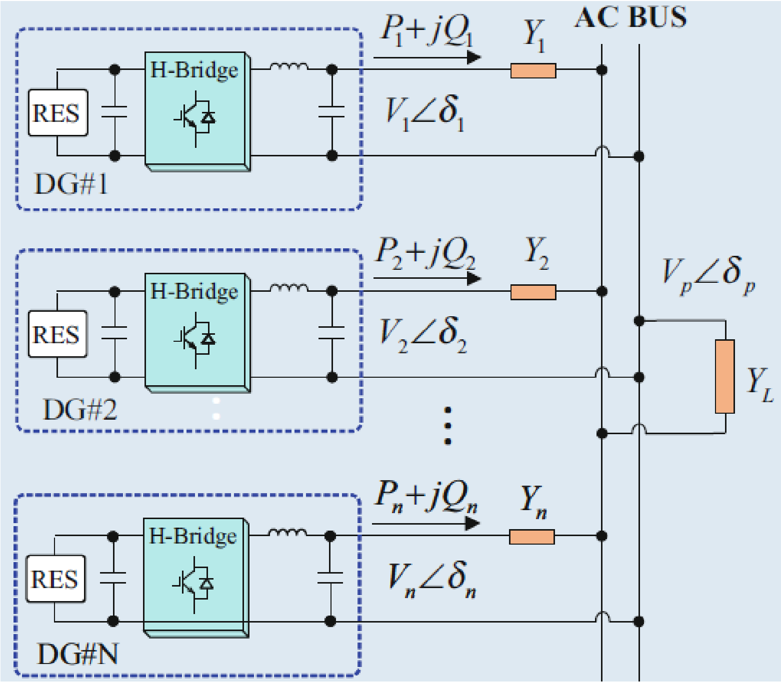


Fig. 2.7 *Parallel-type MG [25].*

2.6.2 Series-Type MG

A new kind of MG system is the series-type microgrid, which is a vertical evolution of the conventional single-node in parallel MG to multi-nodes in series. Through the converter in series, each DG unit immediately creates a MG system with a greater voltage level, as shown in Figure 2.8. In addition to being straightforward and quick to use no complicated boost circuits or large, costly transformers are needed, this method of increasing voltage also makes controlling the microgrid system as a whole simple. In a series-type microgrid, each distributed generation unit may be independently managed, and the power electronic devices can be adjusted flexibly to enhance power control and optimize management capabilities. The malfunction of a single unit in a series-type MG might result in the operational failure of the entire system, necessitating the implementation of more intricate hardware circuits or control algorithms to maintain the durability of the series power electronic system.

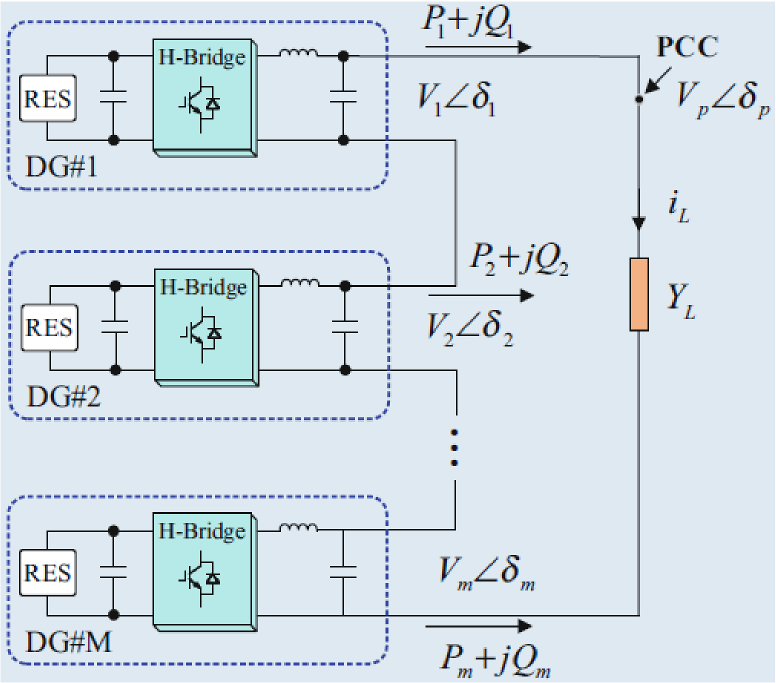


Fig. 2.8 *Series-type MG [25].*

2.6.3 Hybrid Series–Parallel MG

The hybrid series–parallel MG system, as seen in Figure 2.9, has garnered significant interest because of its three key characteristics: high voltage level, high energy density, and robust control flexibility. The series-parallel hybrid connection is used by the hybrid series-parallel MG system. Through the converter, each DG unit is linked to the public bus in a hybrid series-parallel configuration. This layout incorporates all the benefits of series and parallel MGs, including control flexibility, module redundancy, conversion efficiency, and medium to high voltage characteristics. The analysis and controller design of this structure are significantly complicated by the intricate physical transmission characteristics and interaction mechanisms of each distributed generation unit in both series and parallel configurations. The investigation into the hybrid series-parallel MG is in the preliminary exploration phase.

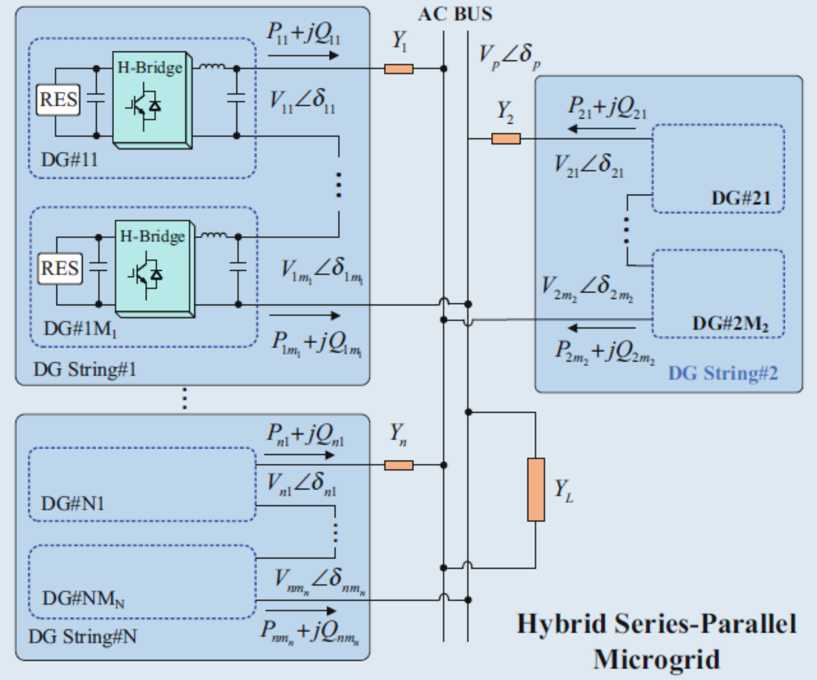


Fig. 2.9 *Hybrid series–parallel MG [25].*

2.7 Microgrid System Stability

There are two main parts to MG stability that are related to each other: frequency stability and voltage stability. Frequency stability means that the system can keep the nominal operating frequency even after a sudden change in the generation-load balance. Because inverter-dominated MGs have low inertia, frequency changes can happen quickly. This means that primary control systems like droop control need to work quickly. Voltage stability, on the other hand, is about keeping the MG network's voltage profiles within acceptable limits when the system is running normally and when it is changing. Reactive power management, generator excitation control, and the coordination of DER are in charge of it [50].

We look at both stability dimensions over a range of time scales, from transient dynamics that last for milliseconds to steady-state behavior that lasts for years, and in two main operational modes. When connected to the grid, the main grid serves as a reference for voltage and frequency, helping during problems. When the microgrid is in islanded mode, it can only use its own internal control systems, which makes managing stability much harder.

2.7.1 Classification of Microgrid System Stability

The stability of MGs can be categorized based on the underlying physical reason of instability, the magnitude of the disturbance, the physical components involved, the duration of the instability, and the methodologies employed for analysis or prediction. The stability classification of MG systems is shown in Figure 2.10. Two different phenomena define stability for MG systems: those related to the power supply and balancing and those related to the equipment control systems [51]. MG instability can also be classified as either a short-term or long-term problem. Within a few seconds, the system's short-term stability can be affected, but problems that persist after this point have an impact on the system's long-term stability [52].

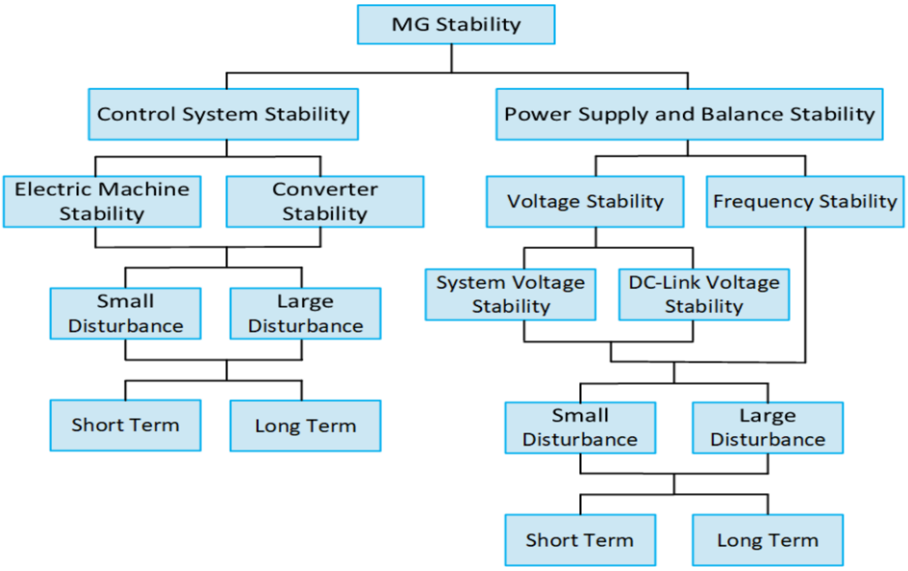


Fig.2.10 *Structure of MG system stability [53].*

A. Power Supply and Balance Stability

The ability of the system to sustain power balance among DERs and efficiently distribute demand power so that the system satisfies operational needs is what is meant by system balance and power supply stability. When a generating unit fails, DERs are overloaded, power sharing between many DERs is chosen wrong, slack (s) resources are not allocated adequately, or DERs are exceeded, this kind of stability problem arises [51]. Either voluntary or involuntary load tripping is possible. Furthermore, some load types, including induction motors or steady power loads, might result in system instability like voltage swings. This class of stability includes subgroups for stability in terms of voltage and frequency [52].

- **Frequency Stability:** Frequency regulation is a key issue in islanded MGs. Due to their small number of generating units, MGs are especially susceptible to significant disruptions when generators fail. As a result, the system frequency may undergo significant excursions quickly due to such disturbances, which could jeopardize the stability of the system frequency. Even with adequate generation reserve, the standard frequency control methods and procedures might not be enough to handle the system's quick frequency shift [51]. Such events have been reported all throughout the world.
- **Voltage Stability:** The limitations of DERs and the sensitivity of load power consumption to the provided voltage in MGs are the main causes of voltage instability. Because of their low voltages in both dynamic and steady states, these systems may experience voltage instabilities. Depending on how the system reacts and the load characteristics, voltage instability could result from an abrupt generator failure or an unanticipated shift in the output or demand of renewable energy resources. Small disturbances, like slight variations in demand, can also cause voltage instabilities for systems that are at their loading limits or extremely imbalanced [25], [51].

  Voltage instability is a potentially short-term or long-term phenomenon, depending on the time frame. An active and/or reactive power mismatch can result in short-term voltage instability due to poor coordination of control actions. Long-term voltage instabilities, on the other hand, occur when DER output limits are gradually reached by a steady increase in demand, such as in the case of thermoelectric loads.

B. Control System Stability

Control system stability problems may result from inadequate tuning of particular equipment controllers or from a lack of control strategies (such as harmonic resonance of parallel DERs). A poorly adjusted controller is the main cause of the system's instability. Either the entire system needs to be disassembled or this controller needs to be adjusted. This kind of stability is advantageous for phase locked loops (PLLs), LCL filters, and control loops for electrical machines and converters [25], [51].

- **Electric Machine Stability:** These kinds of stability studies usually look at how synchronous machines recover from angular acceleration after a malfunction in order to return to their initial synchronization. However, this phenomenon has not been seen in MGs. Because microgrids are resistive, synchronous machines, for instance, may slow down owing to short circuits if they encounter issues at the feeder's end.

  The rotor angle of traditional synchronous generators can oscillate without concern when subjected to minor perturbations in the system [25], [52]. The first kind arises from inadequate synchronizing torque, whereas the second is due to insufficient damping torque. Microgrids, however, do not encounter synchronization and damping torque issues when generators are fitted with properly calibrated voltage regulators and governors. The stability of microgrids is predominantly ascribed to poorly calibrated exciters and regulators of synchronous machines.

- **Converter Stability:** In MGs, converter instabilities can be classified as either tiny perturbations or large perturbations. The inner voltage and current control loops, whose tuning is a difficult problem, are a fundamental concern in small perturbation stability of a system. DER-induced blackouts are also a major worry, particularly for low-frequency and undervoltage protection systems. In contrast to low-frequency oscillations brought on by outer power control loops [52], harmonic oscillations can be produced by exchanges between inner current and voltage control loops and are known as harmonic instability.

  Harmonic instability, or harmonic oscillations, is a spectrum of phenomena in technical literature that result in elevated harmonic frequencies or resonances. Multi-resonance peaks arise when numerous converters are situated in proximity to one another. Harmonic instability may also arise from high-frequency switching, leading to parallel and series resonances produced by LCL power filters or parasitic feeder capacitors [25], [54]. The resonance of an LCL converter filter can be activated either by direct control or by collaborating with adjacent controllers. Active damping solutions can be employed to avoid and/or mitigate harmonic instability.

2.7.2 Stability Analysis and Performance Assessment

A. Time-Scale Separation and Model Reduction:

In order to enable tractable design of multi-machine systems, power systems are usually analyzed and controlled using reduced-order models of varying degrees of realism that take use of the difference between the dynamics of synchronous machines and the transmission network [25]. To lower the model order in traditional multi-machine power system models, fast dynamics, such as transmission line dynamics, are approximated or ignored using integral manifolds and singular perturbation theory.

Although beneficial for stability studies, these simplified ad hoc models have been challenged for microgrids. The swing equation model fundamentally depends on the characteristics of synchronous machines, rendering it problematic for microgrids characterized by low inertia and converter dominance. The dynamics and control loops of converters are rapid, necessitating a comprehensive analysis to confirm that reduced-order results are applicable to the complete system dynamics [38].

The timeframes of the various dynamic processes overlap and cannot be analyzed independently when comparing the dynamics of converter-dominated power systems with traditional power systems with low inertia. For instance, transmission line dynamics cannot be ignored when rapid acting grid-forming power converters take over power systems. Additionally, the overlapping timescales may result in unfavorable interactions with power system stabilizers, converter DC buses, grid-following controls, and control loops within converters [51].

A method that further simplifies the study is to suppose that voltage dynamics and frequency dynamics are decoupled, allowing for separate examination. This technique is typically warranted when the X/R ratio is elevated (e.g., during extensive transmission) and the nominal operating range is limited (e.g., when voltage magnitude and phase angle variations are minimal). While few analytical studies have investigated the general issue, evaluations of converter-dominated systems indicate a correlation between voltage dynamics and frequency dynamics that affects stability bounds [25].

B. Stability of a Single Converter Connected to an Infinite Bus

Grids are frequently represented as constant voltage sources in power electronics modeling, commonly referred to as infinite buses, due to the relatively rigid voltage frequency and magnitude at the converter terminals, particularly on the rapid timescales pertinent to power converter design and analysis. The methodologies for large-signal nonlinear stability analysis of grid-connected converters comprise three parts [25], [38].

- In order to provide reliable and scalable analysis techniques that surpass these basic models, nonlinear stability models typically employ Lyapunov/LaSalle functions, broader concepts of energy to inflexible grids in a rotating frame. It is essential for nonlinear stability analysis to be able to analyze nonlinear stability using a single rotating reference frame that is typically connected to the angle in converter control designs (for example, the angle used for grid-forming control or calculated by a PLL).
- This grid can also be modeled as a synchronous machine or variable voltage source, and the analysis techniques are applied in this scenario as well. Since these approaches tend to overestimate a system's integrity limit, the results are frequently overly hopeful.
- To elevate the analytical techniques in (2) to a hybrid multi-converter/multi-machine framework. Numerous studies have been undertaken about the stability of converter-based resources constrained by current limits and faults. Grid-following converters with an infinite bus have been well studied in terms of the current limiting problem. When grid-forming control is combined with current limiting, synchronism and stability are usually compromised [25], [51]. In an ad hoc engineering approach to this problem, the current limiting of a single converter has been examined in the infinite bus setting and employs simulated increasing impedances for converters as their currents approach their limits but has not been widely studied beyond this strict setting.

C. Stability of Multi-Converter Systems

Additional stability analysis is necessary for a multi-converter system with 100% grid-forming converters, each of which has frequency/active power and voltage/reactive power droop controllers [55]. It was assumed that the preliminary literature would concentrate on ideal models, wherein each closed-loop converter would operate in alignment with its theoretical reference behavior, meaning that a decline in output performance would correspond with any input to output converter. This assumption is validated by the separation of timescales: the inner control loops operate effectively, transcending the network's dynamics to avert the emergence of undesirable interactions. The initial presentations adhered to conventional decoupling assumptions and introduced innovative stability analysis techniques; for instance, methods designed for synchronizing coupled oscillators and networked control were advantageous for examining the transition of voltage and voltage fluctuations in a multi-converter system. The Lyapunov/LaSalle methods were extended to the coupled active/reactive power and voltage frequency/amplitude dynamics in later research by combining them with passivity arguments. In summary, while these methods generalize traditional energy functions created for the transient stability of power systems, many of their presumptions—such as that transmission lines are in a steady state and that they are lossless—need models that are sufficiently simplified. In summary, these techniques work well for basic models but have drawbacks when transmission line losses occur, much as traditional energy function-based techniques.

All of the aforementioned approaches arrive at qualitatively comparable findings, despite seemingly having distinct models, various controllers, and different methodological approaches. When each converter is reduced to its reference dynamics, these traditional lessons learned about power system stability essentially apply to converter stability; that is, there shouldn't be any transmission bottlenecks. These findings are supported by going to more intricate models using singular perturbations, so long as the dynamics of the transmission network are adequately isolated from the converter's current and voltage control loops, as is customary in engineering [25].

The stability of small signals in multi-converter power systems has also been the subject of numerous analytical investigations, with representative findings for grid-forming and grid-following converters. The converter and line dynamics need to be adequately separated across time, and the large-signal stability results are qualitatively identical.

The stability of the DC bus (or a DC network in the case of high- and medium-voltage DC components) cannot be analyzed using standard stability analysis methods for multi-converter systems because they assume the DC bus is connected to an infinite source [25], [56]. Although the so-called machine matching control can be used to get around this restriction and shows encouraging results when the DC bus is not strictly controlled, there are yet no quantitative findings on analytical stability.

D. Stability of Multi-Converter Multi-Machine Systems

Using the model-reduction methods, the (linearized) swing equation can approximate the majority of grid-forming controls. The frequency dynamics of multi-converter multi-machine systems can be analysed by using standard energy function-based stability analysis [25]. This baseline method has a number of serious drawbacks, even if it can be regarded as a fair place to start and grid-following resources could work inside this framework. For instance, fast dynamics and control loops with overlapping timescales (such as PLLs) are disregarded when mapping a variety of converter-based resource dynamics to a single swing equation model. Additionally, instability brought on by power converter restrictions, such as DC and AC currents, cannot be taken into consideration by this framework. Volatility and frequency dynamics are among the several converter, machine, and network dynamics that cannot be taken into account by any generic framework. We can now investigate small-signal frequency stability for a greater variety of machine and converter dynamics thanks to recent findings.

Due to the limits of analytical methodologies, contemporary stability analysis of converter-based resources and synchronous machines prioritizes numerical methods. This study encompasses two primary categories: theoretical methodologies for examining transient stability (i.e., significant contingencies) and small-signal techniques for assessing performance through linearized models and other stability and performance measures (such as eigenvalues and eigenvectors). Utilizing the rapid reaction attributes of converter-based resources, these studies illustrate enhanced performance and resilience in low-inertia and converter-dominated systems [25].

However, many factors are no longer relevant in large systems that have a combination of machines and converters, and common presumptions that were developed for systems with synchronous machines may no longer hold true. Although the concern of diminishing inertia has garnered a lot of attention, small-signal systems' performance and resilience metrics might be weakened by excessive virtual inertia in the wrong area. Characterizing the stability of a multi-machine multi-converter system with different converter types and levels may not be simple [25], [57].

The possibility of small-signal instabilities resulting from interactions between PLL, inner converter controls, network dynamics, and grid-forming controls of power systems is also highlighted by numerical studies that investigate the shift from traditional multi-machine systems to converter-dominated power systems. Slow machine dynamics and unfavorable interactions with conventional current limiting systems might result from grid-forming converter controls [57].

Chapter 3

Flexibility and ancillary services

3 Flexibility and Ancillary Services

3.1 Introduction

Flexibility has emerged as a fundamental characteristic of modern power systems. This denotes an electricity system's capacity to swiftly and dependably adjust to fluctuations in supply and demand across diverse temporal and spatial scales. Essentially, flexibility encompasses the system's capability to accommodate both predictable and unpredictable alterations in generation and consumption while ensuring system security, maintaining high power quality, and preserving overall system stability. Its significance is steadily increasing, particularly with the expanding integration of variable renewable energy sources. This is attributable to its role in enabling the system to manage the inherent variability and intermittency associated with these resources [58]. Conversely, a power system lacking sufficient flexibility may encounter operational challenges, including frequency deviations, voltage instability, congestion, and diminished reliability. This aspect may hinder the delivery of electricity to end customers.

AS encompass a suite of technical functions essential for the secure and stable operation of the electricity system, thereby facilitating practical flexibility. Frequency control, voltage or reactive power regulation, black-start capability, oscillation damping, loss compensation, and congestion management exemplify ancillary services. These services are crucial for maintaining system voltage and frequency within acceptable ranges, enabling rapid recovery from disturbances, and ensuring the reliable transmission of electricity from generation sources to consumers, all while adhering to technical and operational stipulations. Frequency control reserves, categorized as primary, secondary, and tertiary, are designed to address system imbalances across varying timescales [14].

Reactive power management is essential for voltage control, ensuring that each network node maintains voltage within specified parameters. The ability to restart the system after a complete or partial outage is provided by black-start capability. Furthermore, oscillation damping and congestion management are crucial for maintaining dynamic stability and optimal power flows amidst fluctuating conditions.

Historically, traditional synchronous generators served as the primary source of AS. Physical inertia and controlled active and reactive power outputs are fundamental features of these generators. Conversely, the evolving power system environment has created new opportunities for service providers [59].

The proliferation of RES is a significant factor. Advanced power electronics and sophisticated control methodologies facilitate the provision of ASs by RES, including wind and solar PV systems. Contemporary inverters enable synthetic inertia, rapid frequency response, and reactive power support, thereby allowing VRE plants to contribute to system stabilization. Furthermore, ESSs, encompassing batteries, pumped hydro storage, and other emerging technologies, are capable of rapidly and precisely modulating power [14], [16]. These systems also offer short-term balancing, peak shaving, and temporal energy shifting capabilities. Controllable loads and demand response offer a greater degree of control, allowing for real-time adjustments to electricity consumption. This helps with frequency regulation, alleviates congestion, and ultimately strengthens the system's resilience.

The integration of RES fundamentally alters the procurement and utilization of ASs. The power system gains considerable flexibility by merging RES, ESS, and controllable loads with conventional generation methods. This integrated strategy ensures the system can adapt to fluctuations in supply and demand, maintain stability during disruptions, and enhance operational efficiency, all while accommodating an increasing share of renewable energy. Understanding the mechanics of flexibility, the role of AS, and the interplay of various assets is crucial for building reliable and sustainable electricity systems in the future [16].

Essentially, the capacity for flexibility constitutes the paramount attribute requisite for the secure and efficient operation of power systems, particularly in the face of dynamic conditions and uncertainties. AS represent the practical mechanisms through which this flexibility is realized. These encompass voltage regulation, frequency control, black-start capabilities, loss compensation, oscillation damping, and congestion management. While conventional synchronous generators have historically fulfilled these functions, RES, ESS, and controllable loads are also capable of providing them [16], [8]. Consequently, the development of a robust, flexible, and enduring electricity system, capable of accommodating substantial renewable energy integration, necessitates the strategic and coordinated deployment of these diverse resources.

3.1.1 Definitions of Flexibility

In recent years, the idea of flexibility has drawn significant attention because to the growing integration of VERs in energy systems. Specialists in this field have attempted to offer comprehensive definitions of this idea. According to [5], flexibility refers to a power system's ability to control supply and demand unpredictability and uncertainty while maintaining a satisfactory level of reliability at a fair cost over a range of time periods. According to a different interpretation in [60], flexibility should adapt to a wide range of potential scenarios at a specific marginal cost. To elaborate on this idea, flexibility refers to the ability to manage net-load forecast mistakes over a variety of timescales in a consistent and profitable manner. Despite the fact that this research has offered credible definitions of the idea of flexibility, the literature lacks the definition's crucial function.

According to the authors in [61], it is necessary to accurately specify the time periods in which flexibility is provided and to debate the flexibility within these time frames. In order to achieve the proper notion of flexibility, it is necessary to know the time scales. [62] depict flexibility time scales as seconds (the inertia response as a barrier against system frequency disproportions to multiple years) (system planning possibility). The definitions of flexibility needed to be developed with the specific definition of time scales because, in contrast to research in [16], research in [5] does not provide a better explanation of the notion.

Deliverable energy flexibility, according to another definition in [58], is the entire amount of flexibility that may be offered to daily energy markets without jeopardizing the technical limitations of the distribution system. Disparities in definition can be seen in and linked to variations in how energy systems facilities are operated. Therefore, it is important to identify each sector's potential for offering flexibility. In addition to the idea of flexibility that has already been established and addressed in the literature, thermal flexibility is another type of flexibility that can be studied in the energy systems' heating sector. Flexible heat generators, interconnections, and the combination of heat generators and thermal storage units are the primary sources of thermal flexibility [9]. As a result, flexibility can be defined as a system's capacity to continue operating in the face of abrupt changes and to control all of its components to avoid exceeding their operational limitations, all the while utilizing the full potential of its infrastructure across time periods, from seconds to years, without resulting in additional expenses for the system owner.

3.1.2 Main Potential in Providing Flexibility in Power Systems

Power systems are traditionally seen as flexible if the operators use AS to manage unforeseen events, like unplanned transmission line or generator breakdowns, and real-time supply-demand imbalances brought on by inaccurate demand projections. In order to afford regulation AS, power system operators must take into account a certain level of reserved capacity. Distribution System Operators (DSOs) and Transmission System Operators (TSOs) oversee this capacity, which is also used to restore the frequency to its nominal rate and recover the power system in the event of imbalances through Frequency Containment Reserves (FCRs) [63]. However, power systems are regarded as flexible in contemporary energy systems with extensive VER integration if they [1], [4], [64]:

- Achieve the peak net-loads quickly and economically.
- Minimize supply and load constraints.
- Maintain a balance between supply and demand over various time periods.
- Verify the reliability of ramp up/down capacity for accessibility.
- Ensure the availability of sufficient fast-ramp and fast-start units.
- Effectively integrate demand response programs while functioning authentically inside an Active Distribution Network (ADN) that includes participation from smart loads.
- Provides an adequate level of AS over various time scales.
- Maintain a carefully thought-out transmission network to guarantee that flexibility is both available and delivered.
- Operate under an elegant market, in which the flexibility is not compromised by market ineptitudes.
- The main sources of energy system flexibility can be divided into:(Supply Side, ESSs, Demand Side, Grid Facilities, and Market Products).

A. Supply-Side

The way facilities around the generating sector are presented in power systems is known as the supply side. Large steam turbines, such as those found in nuclear power plants, are likely to offer flexibility, although gas turbines are thought to be the most adaptable generators. Additionally, in order to provide levels of electrical and thermal flexibility, CHP units are viable resources to connect the electrical and thermal assets in energy systems. The probabilistic nature of VER has heightened the demand for flexibility services, necessitating the implementation of a flexible generating maintenance scheduling system on the supply side [5]. It is also apparent that a flexible system can result from the use of appropriate tools for supply-side infrastructure modeling and scheduling [63]. For example, applying deep learning techniques to accurately model and forecast the production of renewable energy resources will improve the precision of supply-side utilities' maintenance scheduling [65].

B. Energy Storage Systems

Energy storage systems (ESSs) can adjust to the real-time fluctuations of RESs and demand, while simultaneously decreasing day-ahead operational expenses, resulting in enhanced flexibility, resilience, scalability, and privacy, among other advantages. Furthermore, the ramping up and down of generators will incur additional costs to the system, which could be mitigated through the strategic use of ESS [5], [64]. By reducing their effects on grid functioning, ESSs can be used to support greater

VER penetration when it comes to VER generation [9]. The penetrating effects of VERs are described throughout a range of time spans, from seconds to years.

The ESS may reduce the role of generators in terms of system frequency response services by providing inertia in the event of abrupt power fluctuations on time scales of seconds [5], [59]. In its broadest definition, inertia refers to the kinetic energy that the synchronous generators' rotational mass stores in order to offset frequency deviations from their nominal values during significant disturbances. Because wind turbines cannot react to frequency changes, a higher penetration rate of wind energy in power systems results in a large reduction in average power inertia [60].

ESSs are mostly used to supply operational reserves at the intra-minute prospect. For example, thermal storages, compressed air energy storage (CAES), battery ESSs, and pumped-storage hydropower all offer flexibility over long periods of time. When power and thermal systems are connected, thermal energy storage devices (ESSs), such as hot water storage units and, more recently, Concentrating Solar Power Storage (CSPS) systems, are essential for supplying both thermal and electrical flexibility [66].

At the minutes to hours timescale, battery ESSs can hypothetically provide numerous services, i.e., the ones pumped- storage hydropower offer, for instance, providing multiple AS simultaneously [66], offering the mobility by utilizing batteries in EVs, empowering the penetration of renewables in microgrids, among others. However, at high VER levels, sole dependency upon ESS to eliminate load/supply curtailments might become economically and practically futile [5], [59]. Significance of the ESSs in Italian AS Market’s Balancing Market (BM) is a real-world example of their role in endowing flexibility when balancing services are deployed.

Battery ESSs can theoretically provide a wide range of services at the minutes to hours timescale, such as those that pumped-storage hydropower offers, such as providing multiple AS at once [66], enabling the penetration of renewables in microgrids, and providing mobility through the use of batteries in EVs. However, relying only on ESS to remove load/supply curtailments may become practically and economically pointless at high VER levels [5], [59]. An actual illustration of the ESSs' function in providing flexibility when balancing services are implemented is the BM of the Italian AS Market.

C. Demand Side

Together with ESSs, demand response (DR) programs or demand-side flexibility are utilized to lessen the potential harm that VER could cause to the electrical grid. In order to address the mismatch between supply and demand, DR programs allow for the shifting of the demand pattern. With the help of financial incentives or long-term contracts, DR is a potential strategy that allows power users to modify their energy usage [67]. These clients may be innovative energy system structures in contemporary energy systems, such as energy hubs that are capable of executing a price-based demand response model based on the elasticity of the energy market. The use of DR can be distributed among AS providers, such as regulation services. Coordination of loads in distribution grids with varying voltage levels is a significant DR challenge. Specifically, coordinating loads of different sizes could make it more difficult to meet reserve capacity reduction targets and the system's anticipated frequency response rates [68]. Energy users enter into contracts with aggregators to increase their flexible output or consumption; aggregators then combine the flexibility of energy consumers and update it for market services, such as Balance Responsible Parties (BRP) [69]. Additionally, aggregators incorporate VER technologies, which relieve the requirement for extra capabilities by providing energy system operators with a lucrative structure. Additionally, they contract with the demand sites to take advantage of the demand-side flexibility [9].

D. Grid Facilities

The intermittency and variability of VERs are frequently considered a primary barrier to their full integration into the power system. The aforementioned issues result in a VER penetration cap known as the "economic carrying capacity of the energy grid," which can compromise grid performance if it is violated. The ability of grid infrastructure to enhance VER penetration and allow power transfer while preserving acceptable operating parameters, such as frequency profile, and maximizing network benefits is referred to as flexibility. Managing power flows using high-voltage direct current (HVDC) in a hybrid HVAC/HVDC transmission grid is a significant example of this service due to its adaptable regulatory capabilities and HVAC transmission switching [70]. Additionally, [5] present a comprehensive framework for acquiring and cautiously managing flexibility services from dispersed energy resources in distribution networks in order to collaborate with grid facilities in an efficient manner.

E. Market Products

Demand Side Response (DSR) enables energy consumers to modify their energy consumption in real-time using smart metering, allowing for increases, decreases, or adjustments. DSR also aids in maintaining a secure, sustainable, and cost-effective energy supply by implementing demand peak shaving during periods of power output deficits, resulting in an abundant and economical power influx. A large demand site, small business, or aggregator serves as the supplier of this product [5]. The flexibility metric commonly associated with this product is response time. The Flexible Ramping Product (FRP) is a market offering specifically engineered to tackle real-time flexibility concerns. Figure 3.1 illustrates that the FRP guarantees ramping availability to address the anticipated net-load resulting from its prediction uncertainty.

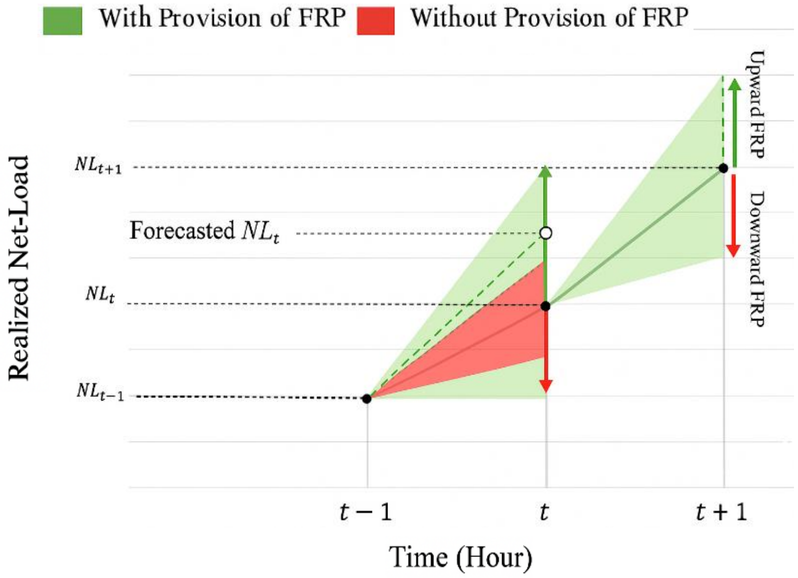


Fig.3.1 *Role of Flexible Ramping Product (FRP) provision in power systems [5].*

The FRP provides a potential ramp due to uncertainties arising from net-load inaccuracies. The FRP is consistently associated with Flexible Ramp Up (FRU) and Flexible Ramp Down (FRD), which seek to meet the system's upward and downward ramp capacity demands. The FRP reduces the system's operational costs by mitigating potential real-time energy price surges and load reductions. The FRP providers, such as the California Independent System Operator (CAISO), receive compensation for delivering flexibility through FRP in both planning and operational procedures, determined by their energy opportunity costs. This product is acquired to address anticipated net-load discrepancies and related uncertainties up to a specified confidence level. The capacity market, like other market products, provides resource availability for power supply during system disruptions. This ensures that the grid will always be reliable and that there will be enough resources to meet future energy demands. An illustration of how to handle such a market service is the Midcontinent Independent System Operator (MISO), where suppliers stimulate the market by raising electricity output and lowering usage. Regional Transmission Enhancement Planners (RTEP), DR aggregators, rehabilitated and enriched generators, and new generators are among the contributors [71]. Market products are typically derived from policies that are potential solutions to increase the flexibility of the power grid. For example, using the resources that are already available, such as dispatchable power plants' ramp capacity, rapid response ESSs, spinning reserves, DR, power facility reinforcement, and the introduction of new flexibility products in the electricity market to provide specific levels of flexibility holistically [67].

3.1.3 Cost of Flexibility Options

As previously stated, the flexibility choices are set up to keep the system economical. As countries work to reduce emissions and implement Net Zero Energy (NZE) initiatives, it has become increasingly important to provide flexibility in many power system sectors [72]. In this way, it is expected that greater VER proportions will boost the value of options to increase energy system flexibility, while it is crucial to reflect the economic benefits of energy system flexibility alternatives. According to a comparative analysis conducted by the researchers in [5], the implementation of demand response (demand side), supply-side thermal unit retrofitting, ESSs, and the construction of new grid facilities and interconnections are arranged from top to bottom in terms of economic and technical factors, respectively. According to related studies by [59], when climate targets are modest, the provision of demand-side flexibility options has a significant impact on system costs. However, when climate targets are more ambitious, sector coupling with the district heat sector and investment in grid facilities have an increasing impact among other flexibility options. Because of this, the sector coupling must precisely determine the storage demands, which allows ESSs to be more flexible at a higher system cost [58]. It may be inferred that governments can use the flexibility options based on the energy supplies' availability, financial constraints, and climate goals.

3.1.4 Flexibility Metrics

The present research and state-of-the-art research mostly evaluate power system flexibility in terms of power and energy capacity, as well as ramping capabilities [63]. However, whereas response time does reflect the consequences of DR action and system contingency response delays, these terms do not. A number of flexibility indices are recognized in [66]. Response time was presented by the authors as a novel way to measure system adaptability [73]. Similarly, the authors of [74] suggested a new flexibility metric called Insufficient Ramping Resource Expectation (IRRE), which assesses how well the power system manages demand and supply fluctuations. A conceptual metric based on the general operating standards of the system-power limit, ramp rate, start-up time, and dispatchability was introduced in [75]. Lack of Ramp Probability (LORP), which does not take into account inter-zonal transmission constraints, is another measurable flexibility metric that was presented in [76]. Intertemporal ramping flexibility is measured using this operational index at the dispatch time scale in real time.

Based on the System Capability Ramp (SCR), another index established in [77] measures the flexibility's accessibility by indicating the potential for a ramping capability deficit brought on by significant system uncertainties, such as Failure of Power Plants (FoPP) and VERs forecast error within a given time frame. Ramping Capability Shortage Expectation (RCSE), another metric discussed in [78], represents the potential for ramp shortages after encountering uncertainty at specific time intervals. The Flexibility Area Index (FIA), a novel flexibility metric established by the authors in [79], is defined as the sum of the flexibility of power system units and represents the overall system's capacity to control the curtailment of VERs by FRU and FRD components. The amount of thermal flexibility that may be obtained from thermal storages inside buildings can be represented by a new measure called the Building Energy Flexibility measure (BEFI) [80]. Table 3.1 provides a brief explanation of the technical underpinnings of the aforementioned flexibility indicators and indexes.

3.1.5 Flexibility Services

Voltage and frequency response time, reserves, reactive power services, and system security are the different categories of flexibility services [73]. These services ensure that the flexibility will always be available and delivered consistently. To help and expand the standard's implementation, several studies recommend changes to these services, such as reevaluating the IEEE standards' allowed trip clearing time setting ranges [81]. These modifications help the system by giving the power system greater flexibility.

Table 3.1. Flexibility indices.

Name	Basis on time	Basis on Ramp	Basis on power
Ramp rate		✓	
Start- up time	✓		
Response Time	✓		
Insufficient Ramping Resource Expectation (IRRE)		✓	
Lack of Ramp Probability (LORP)		✓	
System Capability Ramp (SCR)		✓	
Ramping Capability Shortage Expectation (RCSE)		✓	
Flexibility Area Index (FIA)	✓	✓	
Building Energy Flexibility Index (BEFI)		✓	
The minimum power limit			✓

3.1.6 Frequency Response Services

Through active power generation or demand modification, frequency response services maintain system constancy and offset frequency variations. These services fall mostly under the categories of static and dynamic products. Static frequency response concentrates on degradations below a specific frequency limit, whereas dynamic frequency response concentrates on response ability in intraminutes (or even seconds) [5], [82]. Rapid Frequency Response (RFR), Primary Frequency Response (PFR), Secondary Frequency Response (SFR), High Frequency Response (HFR), and Rapid High Frequency Response (RHFR) are further classifications of Dynamic Frequency Response (DFR), with corresponding accessibility times of 5, 10, 30, 5, and 10 seconds. Figure 3.2 provides an illustration of these operational timeframes.

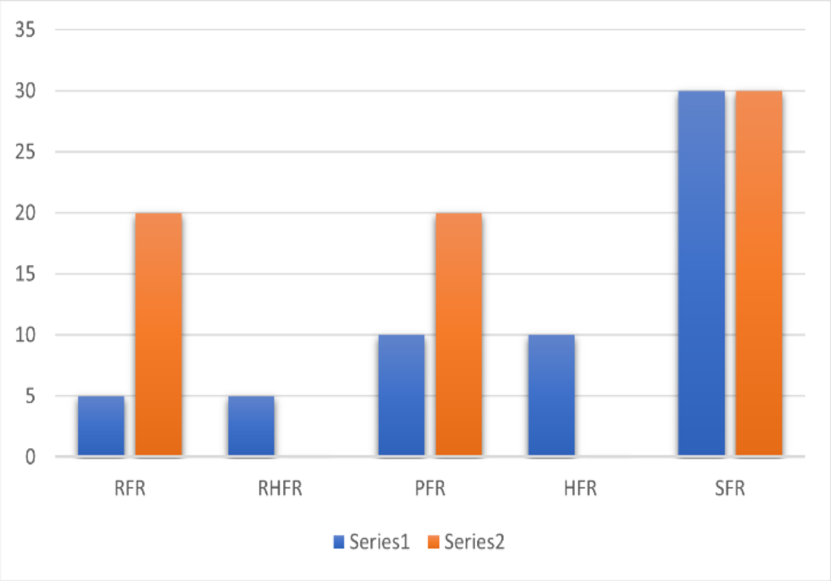


Fig.3.2 *DFR services time action [5]*.

Active power adjustments of generators, particularly large generators coupled to transmissions, result in Mandatory Frequency Response (MFR). In response to a predetermined frequency deviation limit, they ought to be able to deliver sustained power. Examples of MFR service providers are the Australian Energy Market Commission (AEMC) and the UK national grid Energy System Operator (ESO). Through online Frequency Response Price Submission (FRPS), providers enter the market once a month [83]. Balancing Mechanism Units (BMUs) and non-BMUs can access the Firm Frequency Response (FFR) service, which is available to small generators (less than 1MW). It should be mentioned that usage metering and producing units make up BMUs [82]. Through the monthly-tendered process of PFR, SFR, and HFR frequency services, providers report the energy flows of the transmission and distribution system. The term "tender" often refers to platforms wherein providers are asked to verify that, to the best of their knowledge, all of the information and their technical specifications are correct prior to submission in order to be eligible to enter into a contract in the market. The suppliers can submit bids for Short-Term Operating Reserve (STOR) services through an electronic platform, such as Systems, Applications, and Product Corporation's (SAP) Ariba platform [84].

Large frequency variations are caused by high effect contingencies, such as the loss of big generating units. The delivery of services to customers is thus impacted by these aberrations, which must be addressed by frequency control by demand management (FCDM). In order to lessen the strain on the network, FCDM providers are contracted to automatically react in the event of a frequency deviation and help restore the system frequency within a reasonable range by temporarily stopping some of their operational procedures [5].

Enhanced Frequency Response (EFR) service offers a fast response in supporting the power grid during low system inertia times sustained for 15 minutes. The service enhances the transition back to the normal frequency after sudden fluctuations. EFR reduces the grid charges and is procured through economic offers [85]. A summary of frequency response services is presented in Table 2.

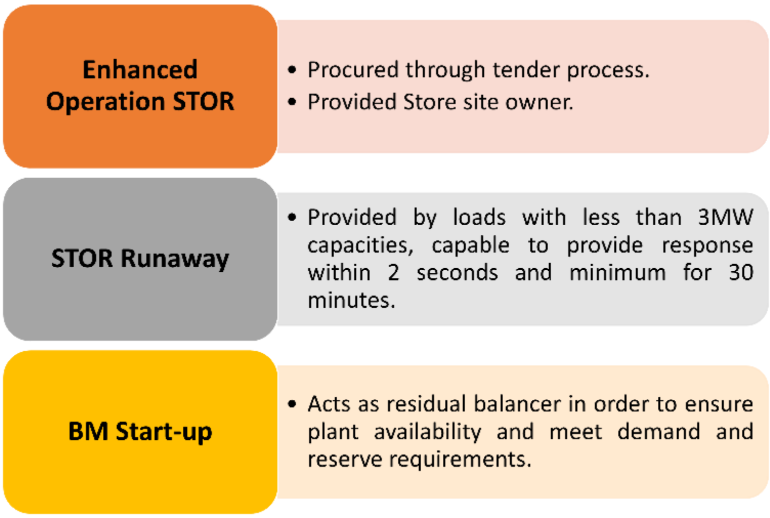
The power grid can be quickly supported by enhanced frequency response (EFR) service during periods of low system inertia that last for 15 minutes. The service facilitates the return to the typical frequency following abrupt oscillations. EFR is purchased through competitive offers and lowers grid fees [85]. Table 3.2 shows an overview of frequency response services.

Table 3.2. Frequency response services.

Name	Operational Timeframe	Base Service	Specifications
DFR	5-30 seconds	RFR-PFR-SFR-HFR-RFHR	The foundation of certain frequency response services
MFR	10-30 seconds	PFR, SFR or HFR	Applied specific days of month
FFR	10-30 seconds	PFR, SFR or HFR	Depending on the terms of the contract with ESO, one or more months may be applied.
FCDM	Within 2 seconds of instruction	SFR	Delivering minimum 3MW within 30 minutes
EFR	Within 1 second of frequency deviation	DFR	Capacity of delivering 1MW up to 50MW

3.1.7 Reserve Services

When the power system encounters sudden energy imbalances, reserve service signals the need for more resources. Reserve services can be divided into two broad categories: short-term and quick items. Providers of fast reserve products are required to provide a minimum of 50 MW of power for a maximum of two minutes [86]. Further research can be done on the use of reserve services in the energy systems' heating sector. A district heating system model is presented in [87] to increase the CHP units' thermal flexibility by allowing them to participate in reserve services. In the event of a generating shortage or surplus, STOR is provided. STOR suppliers must be accessible during market openings, which are the hours of the day when the supply margin is anticipated to be narrower. They must also be able to provide full active power for up to two hours upon request. Figure 3.3 highlights other short-term operating reserves that are not included in the STOR category, such as Enhanced Operation STOR [84], STOR runaway, and Balancing Mechanism (BM) start-up [88]. In the odd event that there is not enough capacity to meet demand, the Demand Side Balancing Reserve (DSBR) offers additional reserve. Large energy users who could choose to use less electricity, only during the winter, in exchange for a payment are the focus of DSBR. While DSBR gives large energy consumers and aggregators the chance to receive compensation for their efforts to moderate energy consumption during peak periods, Supplemental Balancing Reserve (SBR) offers generating capacity [89].When all market-based measures have been exhausted, SBR is used, in which generators are sent out in economic order (i.e., utilization price and length necessary).



Enhanced Operation STOR

- Procured through tender process.
- Provided Store site owner.

STOR Runaway

- Provided by loads with less than 3MW capacities, capable to provide response within 2 seconds and minimum for 30 minutes.

BM Start-up

- Acts as residual balancer in order to ensure plant availability and meet demand and reserve requirements.

Fig.3.3 *Various classifications of short-term operating reserves*

Contingency Balancing Reserves (CBR) are a transitional product that DSBR and SBR combine to control the grid frequency in the event of an emergency. DSBR providers can be commercial and industrial organizations that have the ability to structure the rules of AS programs. As they move to capacity markets, the energy system operator in National-grid ESO is no longer acquiring this service.

3.1.8 Services for Reactive Power Balance and Voltage Control

The availability of generators with relatively high nominal ratings, the connection of DGs, and the configuration of DGs all contribute to the need for reactive power services [90]. As a result, numerous services have been launched. Under specific operating conditions, providers of Obligatory Reactive Power Services (ORPS) are required to produce their rated output power in order to maintain voltage variations at a predetermined level. When reactive power capability surpasses the minimal requirement of MVAr lagging capabilities, Enhanced Reactive Power Service (ERPS) is purchased and used [91].

3.1.9 Security Provide Services

Some flexibility services, such as VER units' support for Black Start, inter-trip guarantees that the generators will disconnect from the power grid, and constraint management, are purchased to ensure the power transmission system operates efficiently and economically. These services can help prevent consecutive tripping of the generating units, generator disruption, transmission congestion, and power shortages [91].

3.1.10 Timelines for Flexibility

The ability of a system's utilities to control net-load fluctuation and uncertainty under deep VER integration is praised by operational flexibility [92]. A more secure power system results from increased operational flexibility, according to Reference [5]. Therefore, defining appropriate measurements to assess the network's current degree of flexibility and the related inefficiencies is a prerequisite for improving operational flexibility. Three broad kinds of current approaches visualized methods, metrics, and complete models are presented. Visualization techniques, such as the dynamic upward and downward ramping capability curve representation [93], are simple to comprehend but require a lot of data. When overall margins on accomodation of VERs' variability and uncertainty are sought, comprehensive approaches are frequently employed. Lastly, measurements like operational flexibility are another way to assess the degree of flexibility that exists now and provide insight on how to increase the system infrastructures' adaptability.

Different time scales, such as long-term, long to medium term, medium to short-term, and short to very short-term, can be used to describe operational flexibility. Figure 3.4 shows a quick schematic with analytical solutions and related highlights. The planning timeframe is the most cost-effective method of accounting for flexibility, according to experiments. The system needs enough flexible resources to function well with high shares of VER generation, taking into account the annual horizon. Over years, power system operations face dependability issues due to the unavoidably stochastic output of VERs. To keep supply and demand balanced, considerable volumes of output may be cut in power grids with limited levels of flexibility during times of high VER generation surges [80], [94].

To overcome this challenge, regulators might need to encourage investment in flexibility enhancement programs by providing certain tariffs/incentives, increase time and space granularity in market design, and re-designing capacity markets. Energy system operator should balance the seasonal energy capriciousness on monthly basis operations, arising from uncertainties of hydro units scheduling [95]. With high penetration of VERs in power systems and their impacts on net-load uncertainty and variability in hours and intra-hours prospects, market operations should be analysed in real-time.

To address this challenge, regulators may need to promote investment in flexibility enhancement programs through specific tariffs or incentives, increase time and spatial granularity in market design, and restructure capacity markets. The energy system operator must manage the seasonal variability in energy on a monthly operational basis, stemming from the uncertainties associated with hydro unit scheduling [95]. Given the significant integration of VERs in power systems and their effects on net-load uncertainty and unpredictability over hours and intra-hours, market operations must be evaluated in real-time.

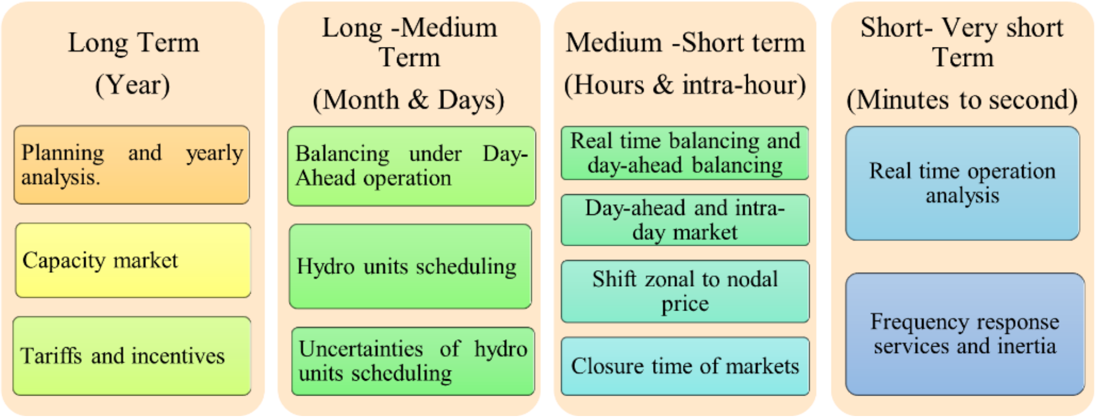


Fig.3.4 *Operational flexibility timescales***.**

The requirement for day-ahead decisions arises from the inadequacy of hourly scheduling protocols in real-time operations to furnish system operators with the necessary flexibility for effective system management [11]. Designing intra-day markets is essential for maximizing the full flexibility potential of the power grid. Moreover, establishing a reduced interval between gate closing and actual market transactions can significantly improve flexibility during this timeframe. As indicated in [58], this configuration is favored because the fluctuations in VERs, particularly wind, can be quite substantial in real-time, a phenomenon not captured in the offline (day-ahead) operational perspective of the system. This vision pertains to the operational timeline of the system, which directly influences its adaptability. In seconds, the utilization of ancillary services is essential for dependable and adaptable grid functioning, especially in addressing unforeseen discrepancies between demand and supply. Regulators must implement new products and allocate operating reserves to motivate flexibility providers to participate. Typically, an innovative service implemented by many ISOs, such as National Grid ESO, is the Fast Frequency Response (FFR) provided by Battery ESSs and VERs [96]. Flexibility is allocated in PJM, CAISO, and EPEX through day-ahead, intraday, and continuous intraday market auctions [97].

3.2 Impact of Increasing RES Penetration

According to [98], a flexibility requirement is recommended as the Electric Reliability Council of Texas (ERCOT)'s RES penetration surpasses 1 GW. For example, the maximum 1-hour ramp demand increases to 135% and the 3-hour ramp requirement increases by 30% when 14.5 GW of solar generation is added to the ERCOT. According to Reference [99], flexibility becomes much more important when RES account for more than 30% of the total, particularly solar power. Additionally, according to a Philippine Department of Energy assessment, mid-range and peaking generating units must provide roughly 50% of the additional generation capacity needed as future reserve capacity [100]. According to an analysis in [101], a generating mix with a nominal capacity of more than twice maximum demand is needed for 100% renewable electricity supply scenarios at 2030 and 2050. All of these studies show that the demand for greater flexibility coincides with increased penetration. Recognizing the different impacts of renewable resources on the electricity system is crucial for diagnosing flexibility issues and offering appropriate solutions. These impacts are categorized and described in the following. Effects can be classified as short-, mid-, or long-term types based on the time sequence of flexibility as shown in Figure 3.5.

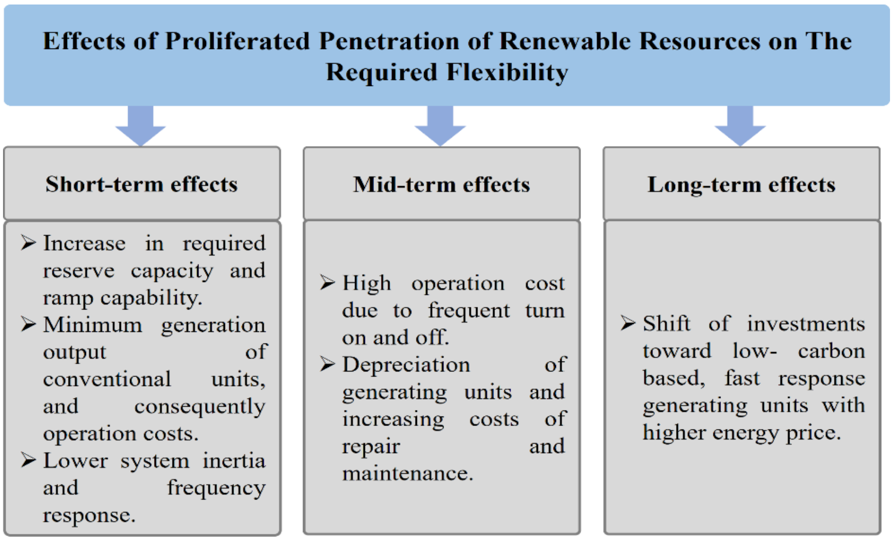


Fig.3.5 *Effects of penetration of RES on flexibility requirement*

3.2.1 Short-term effects

The General effects of flexibility in the short-term horizon include the improvement of required reserve capacity, ramp capability, inertia, frequency response, and minimum generating output limits [102], [14]. To compensate for fluctuations in demand and generating availability, suitable reserves must be allocated to ensure secure and dependable power system operation. In the existence of sustainable resources, system uncertainty will increase due to imprecise generation forecasts. As a result, additional conventional resource capacity is set aside as a reserve to ensure power balance during operational periods. During the time frame under consideration, however, the ability of the producing unit to yield the reserve fluctuates in relation to the ramp capability. As a result, in addition to determining the quantity of reserve, the required ramp capability should be planned to account for the changes and uncertainties caused by the availability of renewable resources. The penetration of renewable resources has resulted in increased changes in net demand at the hour and sub-hour levels. Traditional generating units in this situation need to be able to modify their set points in relation to changes in net demand. Therefore, in conventional generating units, the slope of changes in net demand should be smaller than the sum of changes in ramp capacity. If not, flexible units are needed to provide sufficient ramp capability [14].

Generating units are designed to be able to respond to changes in net demand during the economic dispatch time horizon. The regulation service is the only option for reacting to changes in net demand in operations with time steps that range from seconds to minutes. Regulatory services are used by the electrical system to compensate for area control errors (ACEs) and/or frequency variations. Power interchange across locations, loads, and VER generation loss would all be affected by a regulation service shortfall. In such a case, the energy price differs from the market price, which may have an impact on the market's long-term efficiency. Thus, as the variability and uncertainty of renewable generation increase, the regulation reserve and its flexibility will be modified by compensation for renewable generation deviation.

In addition to the increased reserve and ramp capacities required by the expanding penetration of renewable resources, another barrier is the conventional units' minimum generating power constraint. Imagine a world where all demands are satisfied by renewable energy. Nuclear and steam units, as well as all other conventional units, must not commit. However, this may be impossible due to the units' extended turn-on and turn-off intervals. If renewable generation drops, expensive rapid start units will be used instead of low-cost basic load units. This is not cost-effective. Besides the protracted start-up duration of traditional units (many hours for combined cycles, days for steam plants, and weeks for nuclear units), frequent activation and deactivation would incur significant expenses related to fuel, delivery, repairs, and maintenance [59]. Furthermore, the energy price may be transformed to a negative value, requiring these types of units to pay users in order to avoid repetitive turns on/off.

System inertia and frequency response may be changed when renewable resources become more widely used. In modern power systems, traditional units will automatically supply the required frequency response and inertia in the event of a disruption. Conventional units would have a modest portion of the energy supply in the case of low demand and high renewable generating. On the other hand, low-inertia power electronics are used in the majority of sustainable resources. Consequently, system inertia and frequency response may be insufficient to activate frequency load shedding relays in the event of a striking scenario.

3.2.2 Mid-term effects

As previously mentioned, a significant increase in renewable energy would require conventional power plants to frequently turn on and off. This increased use of base-load units could lead to higher costs for parts, a greater chance of unexpected outages, and higher costs for the plants themselves. These amortization costs could then increase maintenance and repair expenses, reduce income due to longer periods of no power, and lower efficiency because of less generation [59], [102].

3.2.3 Long-term effects

In the long term, fossil fuel and environmental limitations will redirect investments towards low-carbon baseload generation technologies, including nuclear power, geothermal energy, and carbon capture and sequestration. These units' low flexibility prevents them from being integrated into the network at any time because of their high minimum generation threshold and constrained ramping capability. As a result, the return on investment for these units would diminish, rendering them unattractive as an investment option. In this context, agile rapid reaction units will become increasingly prevalent, but at an increased energy cost. Regarding the aforementioned effects, certain indicators that demonstrate the inflexibility of a power system include [92], [103]:

1. Challenges in maintaining a balance between generation and demand, resulting in frequency fluctuations and load loss.
2. An increase in renewable energy curtailment due to transmission limitations and excess generation.
3. Sudden and frequent ACEs between various control areas brought on by changes to the planned power exchange. The system's inability to execute power trading and wheeling responsibilities is reflected in the variance.
4. Negative market prices caused by things like transmission line congestion, excess VERs, generating units' limited ability to ramp down, and demand's incapacity to absorb extra generation. While a system without renewable resources may experience negative price emergence, the addition of renewable energy will exacerbate this problem.
5. Price volatility, or the fluctuation between high and low prices, indicates the lack of demand responsiveness, fast reaction peak unit shortages, and limited transmission line capacity.

Planners and operators are searching for the most cost-effective and efficient ways to provide the necessary amount of flexibility to systems that exhibit a lack of it. The upcoming section will introduce the many ways to improve system flexibility.

3.3 ASs and their Classification

Activities related to guaranteeing the security of distribution systems are included in ASs. These services include things like ensuring the stability of frequency response, providing backup, delivering reactive power, assisting with system restoration, and starting black start processes. ASs are usually supplied by power plants that are connected to the transmission system in conventional electric PSs, where power mainly moves from transmission systems to distribution systems [14]. The TSO is frequently cited as the main player in defining and overseeing AS. According to this framework, an AS is defined by the European Network of TSOs as the execution of several tasks meant to preserve the system security of the TSO [104].

The system operator must guarantee the requisite quality and safety standards to uphold the system's integrity and reliability, implement preventive measures for contingency management, and execute other additional responsibilities. The operator must regulate the system's frequency and voltage within specified limits, ensure system reliability, prevent transmission system overload, and, if required, restore the system [67]. To ensure system reliability in light of events and eventualities, a proposed list for the system operator is provided in Table 3.3. It has been determined that all ASs are essential and fulfill the prior requirements. Figure 3.6 presents a comprehensive classification of ASs. ASs are facilitated through the provision of power, commerce, and dispatch. They are typically defined by the advantages they offer to market participants [60]. The following Table 3.3 lists the different classifications of ASs in the literature from various sources.

Table 3.3. Important features of ASs

References	Source	Contribution
[105], [106], [107], [108], [19], [109], [110]	CIGRE/ IEEE /FERC/ Power System Economics and other Authors	Black start. Scheduling and dispatch. Frequency and voltage control services. Transmission security. Operating reserve. Load-Following. Financial trade enforcement. System security. Loss Compensation. Energy imbalance. Reactive power control. Real-power balancing.

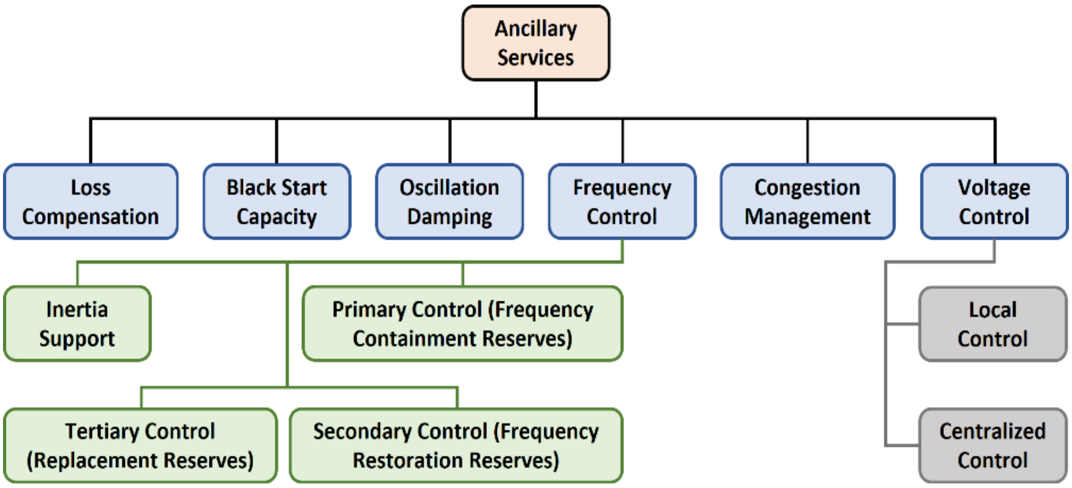


Fig.3.6 *Classification of ASs [19]*.

The previously mentioned categories of ASs mostly pertain to the categorization and integration of diverse service types. Generally, these services can be categorized into one of the following three main categories:

- Network control services,
- Frequency control services, or
- System restart services.

3.3.1 ASs for Frequency Control

The active power generated and consumed are quantified by frequency, and both must be balanced for an AC system to operate. The basic operations of the power system are shown in Figure 3.7.

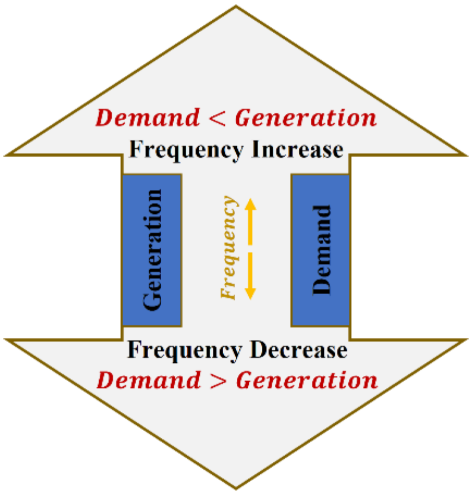


Fig.3.7 *The power system network's basic behavior.*

Consequently, frequency is regarded as an indicator for standardizing active power output to achieve equilibrium. Frequency control is essential for system security. For the electrical system to operate securely and for connected devices to operate reliably, the frequency variation usually stays within an acceptable range. Because power usage varies, it's important to adjust the active power output accordingly. Figure 3.8 illustrates the process at different frequency levels [109].

A. Frequency Control Levels

Frequency control services are supported for technical reasons. One of the most important and distinctive features of frequency-related ancillary services is deployment timing. 'Deployment Start' refers to the entire time between a particular network operator's request and the service provider's answer [41], [111]. ‘Deployment End’ refers to the maximum duration for which the service can be provided following a demand.

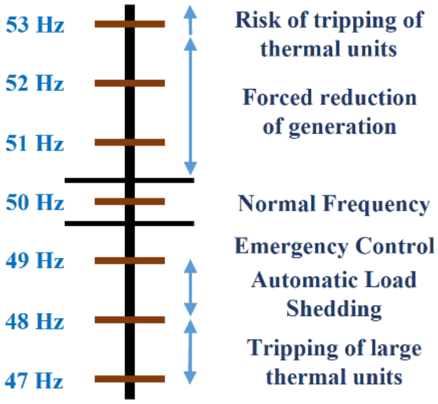


Fig.3.8 *Different frequency levels of operation.*

Frequency Control Levels To sustain balance between generation and demand, the further layers of controllers are employed [41], [111], [112], as illustrated in Figure 3.9:

- Primary,
- Secondary,
- Tertiary,
- Time control.

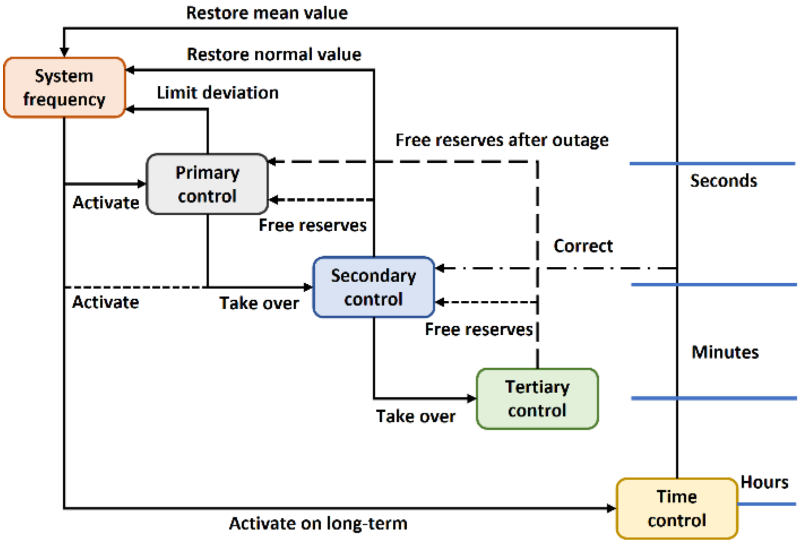


Fig.3.9 *The function of various types of frequency reserve controls region [41].*

All control levels differ with changes in temporal reaction and the methodology employed to comprehend the fundamental operational perspective [41], [113].

- Primary control is activated within seconds as a coordinated effort by all relevant parties or TSOs.
- Secondary control replaces the primary control over minutes and is enforced by the responsible parties/TSOs.
- Tertiary control initially fulfills secondary control and subsequently substitutes it with generation rescheduling, imposed by responsible entities/TSOs.

- As a long-term collaborative effort by all parties involved, time control rectifies the global synchronous time deviations.

i. Frequency Control for Primary

The generating unit's active power output serves as the primary control to regulate frequency variation and usage in controllable loads. It is specifically made to regulate the frequency during significant load and generation disruptions. As such, it is critical to the power system's stability. Every generator in the synchronous area that has a speed governor installed automatically performs this regulation. The self-regulation effect of frequency-sensitive loads, such as induction motors, or the operation of frequency-sensitive relays, which connect or disconnect specific loads at preset frequency limits, are also included in this control [102].

Primary control source: Primary frequency reserves should be evenly dispersed throughout the network to minimize unexpected transits following a major disruption. The uniform distribution also contributes to the system's stability in the event of islanding. Hydraulic turbines and stations are especially well-suited for primary control and load monitoring. These machines allow for easy adjustment of the unit load and installation/completion of the units without substantial stress or production loss. In certain situations, further water release considerations (irrigation, minimum flow, etc.) ought to be limited to the load that follows. Without a free board, primary control and load following are not possible for canal-based hydro plants [114].

Because they can be managed in and out, gas turbine stations are appropriate for load following. However, because they need to be run at a constant firing temperature (equal to efficiency and life), they are not suited for primary control [115]. The firing temperature will rise above what it can tolerate continuously if fuel injection is increased in order to increase megawatts. Thermal over-stressing results from lowering the fuel injection to lower the MW, which lowers the firing temperature and alters the fast/frequent firing temperature. Efficiency is also decreased by increasing the firing temperature. Steam turbine efficiency slightly decreases under partial load since the steam parameters can be kept at rated levels and can also serve as primary control and load monitoring. In a short time, the valves that provide the principal response can increase the steam turbine's active power. It is crucial to modify the major input power, such as the fuel flow, for extended periods of time [116]. High-voltage DC transmission can also be utilized as a principal controller when two systems are connected, especially in existing power systems with sufficient spinning reserves and tightly controlled frequency.

ii. Frequency Control for Secondary

Secondary frequency control is a centralized automated system that enhances the active power output of generating units to reestablish their target values after frequency deviations and connections with other systems. This process can be executed by modifying the generator set point or reference point, or by initiating and ceasing operations of power plants. Secondary control should be utilized exclusively for generating units located within the control region where an imbalance has transpired. The objective of secondary frequency control is to minimize the area control error (ACE). The primary frequency control must be adjusted to maintain active power balance after a sudden change in load capacity. This will lead to a frequency alteration in the power plants due to a sustained decline in primary frequency regulation. However, this may result in a discrepancy between the actual power transfer and the intended power transfer inside the control system throughout the control areas. Automatic secondary frequency control reinstates the planned power transmission.

Secondary frequency control employs a proportional-integral (PI) controller and filters to reduce the ACE to zero. In the UCTE (Union for the Coordination of Transmission of Electricity), secondary frequency control is referred to as load frequency control (LFC), while in North America, it is termed automatic generation control (AGC) [41], [117].

iii. Frequency Control for Tertiary

Tertiary frequency control pertains to the human adjustments in the allocation and management of generating units. The control is used to recover primary and secondary frequency control reserves, manage transmission network congestion, and restore frequency or interchange their target value when the latter function cannot be accomplished by the secondary control [102], [114].

iv. Time Control

According to time control, the average frequency is the same as the normal frequency of 50 Hz. If the average frequency change exceeds the above threshold point, the fixed frequency point in the whole synchronous zone is set at either 49.99 Hz or 50.01 Hz for full, one-day periods [41], [111]. Figure 3.10 shows how these controlling frequency phases are implemented for a generating unit with the help of feedback control loops.

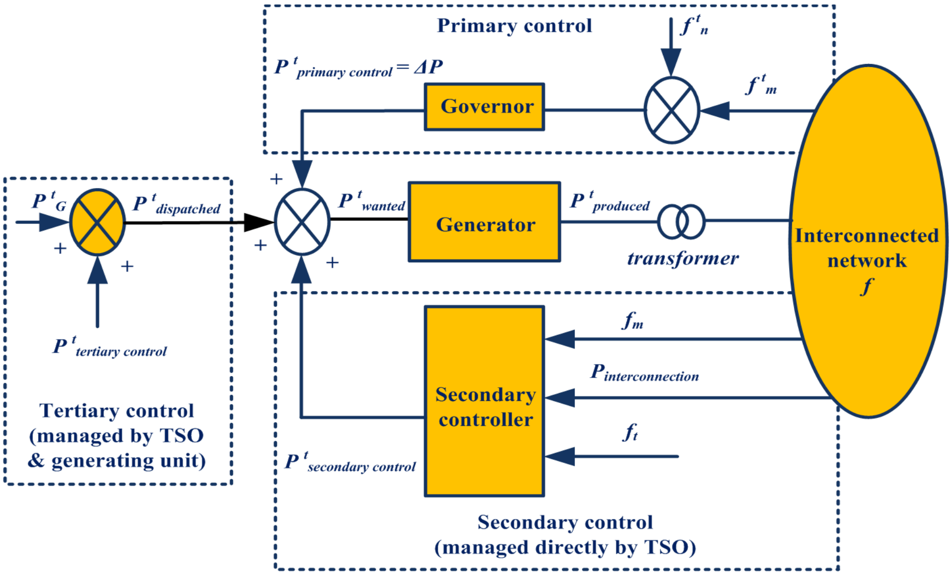


Fig.3.10 *Three operational frequency regulations of a generator [41].*

B. Frequency Reserves

In the event of active power consumption and production deviations, frequency reserves are required to preserve the system's integrity. Variations in load or generating failures may be the cause of these circumstances. The likelihood of repeated generation failures and load changes determine how much reserve is needed. For example, a system's reserve need rises when it is loaded with more arc furnaces due to the highly unpredictable nature of the arc furnace load. The necessary reserves won't alter if a generator experiences repeated outages, but the amount of reserves used will increase. The review's above-mentioned frequency control methods feature certain reserves that manage frequency fluctuations brought on by load/generation capacity management [19], [110]. The usage of reserves for several kinds of frequency controls for a typical generating unit is depicted in Figure 3.11. The following general categories can be used to classify frequency reserves:

i. Spinning Reserves/Reliability Reserves

The extra generating power needed to increase the power output of the generators already connected to the power system is known as the spinning reserve. Spinning reserves are essential because short-term standards require quick reactions and demand may fluctuate. Controllable loads or very fast operation units fall into this category [41], [118]. At higher power use, such reserves cannot last for extended periods of time. As a result, more reserves will unavoidably be added to them. This can be supplied by hydro units or coordinated internal combustion engines.

ii. Supplementary Reserves

Their response time need not be as fast as that of spinning reserves, but they must be able to run for longer periods of time at higher power output. They frequently need human intervention to be activated. The production of hot standby units also contributes to the reserve [111], [118].

iii. Backup Reserves

These reserves can be sustained for an extended duration (within hours) but should not be activated for a specified period (often 30 minutes or more) [19], [114].

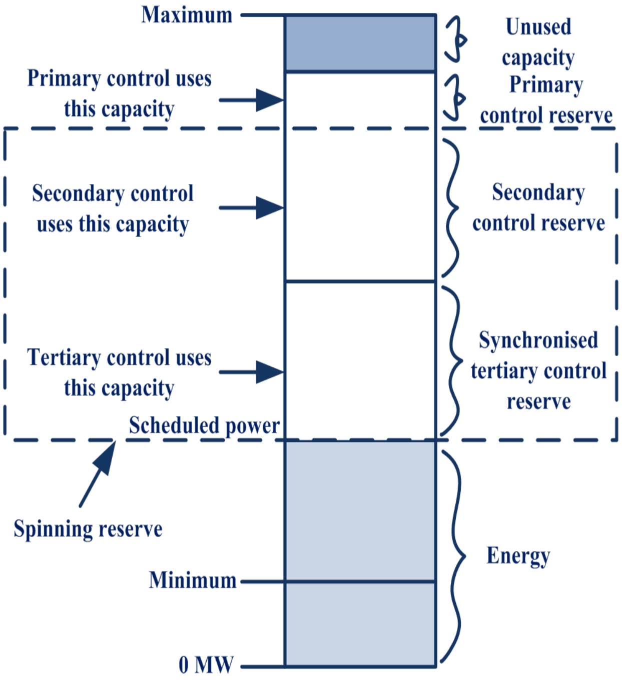


Fig.3.11 *Control levels for a generating unit [41].*

3.3.2 ASs for Voltage Control

System voltage is an extra standard measure for power quality. To regulate the voltage, the power system's reactive power injection and drawl are managed. Network flows interact with transformer line inductance and capacitance to produce voltage increases and decreases.

A. Requirements for Voltage Control

The system's reactive power and accurate boundaries are necessary for the system voltage control, which is utilized to maintain the voltages at many nodes. Reactive power is supported as much as feasible because it is not well transmitted via the grid due to high inductance lines and transformers. The following justifies the need for voltage regulation [119]:

- The voltage supply equipment must operate within its design parameters to ensure safe processing and prevent excessive implementation.
- The fluctuation in system voltage causes variations in reactive power, significantly impacting system losses.
- The system's transfer capacity may also be limited by voltages.
- Reactive power injection and absorption are crucial for preserving system stability, particularly in preventing eventualities that may result in voltage collapse. Reactive power needs to have sufficient capacity to meet demands and keep a buffer for unforeseen circumstances. Local voltage control is a consumer service aimed at fulfilling reactive power demands and assessing each consumer's influence on network voltage and system reliability. Consequently, power factor issues at a customer location do not impact power quality in other areas of the system.

B. Stages of Voltage Control

The comprehensive voltage regulation function can be organised into a hierarchy including three levels.

- Primary voltage control may involve local automated regulation, which maintains the voltage at the producing bus at predetermined levels. The task is accomplished by an automated voltage regulator (AVR).
- The secondary voltage control is an automated integrated system designed to minimize the actions of local controllers. Therefore, it is efficient for the addition of reactive power into a localized power network.
- The methodical optimization of reactive power flow within the power system is known as tertiary voltage control.

Acceptable voltage controls for the creation of a power system network using a single unit are shown in Figure 3.12. Reactive power management instruments including capacitors, reactors, static-VAR compensators, generators, and occasionally synchronous condensers are used inside the transmission network to control voltage, as are ratio-adjusting devices like transformer taps. The system operator regulates and oversees the voltage while supplying the grid's reactive power needs. VAR absorption during low-load periods is essential to avert excessive voltage levels. Conversely, VAR production can assist in averting excessively low voltage levels during periods of heavy demand [41], [120]. In certain regions, acquiring reactive power support from a customer or producer is more cost-effective than delivering immediate reactive support. Depending on their ability to sustain VAR output quickly or effectively, either dynamic or static VARs can be used to maintain or provide units (mostly units). A dynamic device in VAR is substantially more expensive than a static device.

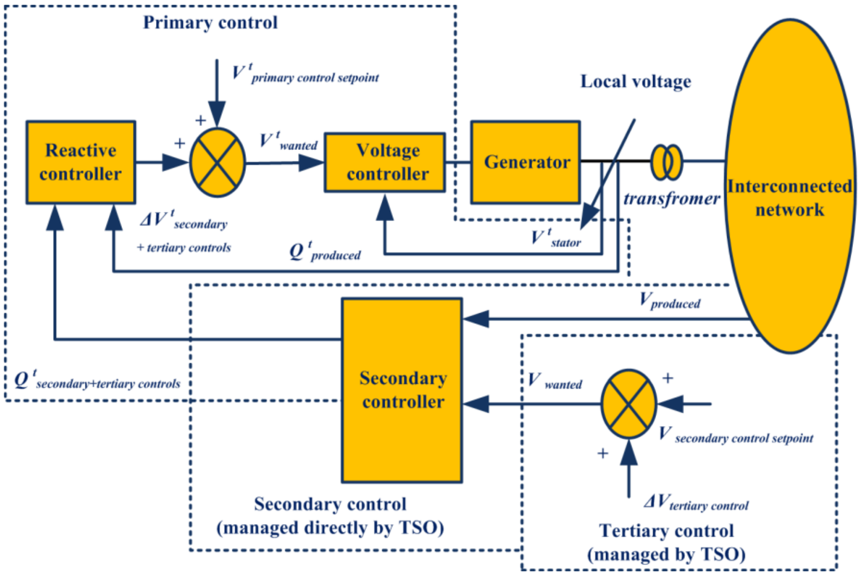


Fig.3.12 *Three functional voltage controls for a generator [41].*

C. Voltage Management Cost

The capital costs of equipment such as generators and capacitors make up the majority of the cost of delivering reactive power, which may lower the anticipated capital flow for backup. Additionally, the operational costs related to the excess or underexcitation of producing units should be allocated to reactive support. The primary expense associated with generator voltage support refers to losses in the rotor, stator, exciter, and step-up transformer. In some cases, the opportunity cost is linked to the reduction of VAR production or the absorption of real-time power generation capacity. Regarding reactive power, the actual cost of service production predominantly comprises fixed costs, which are typically aggregated or segregated. Generally, variable cost components are quite minimal [115], [121].

3.3.3 Capability of Black Start

Without an external power source, black start stations can start from a shutdown at any cost to their production units, integrate into the system to support a section of the system, and coordinate with the system under processes. In contrast, it is referred to as a technique for reviving a system after a complete or partial failure. Therefore, the producing units with black start ability must be present [11]. The black start unit is measured as a generating unit that can run at a lower level with a unit load or be started without a power supply. Consequently, grid separation occurs. It has a minimum of one black start unit so that the power system can be powered by a black start reserve system generating unit. As a result, it will supply power to local needs in the event of a system power failure. All producing stations, with the exception of a few tiny hydro units, require an electric supply to start.

For the ancillary unit's work, these stations have required some supplies. Thus, the turbo generator aids in this operational procedure. Small diesel generators typically get this supply from batteries. The start-up supply for gas turbines is supplied by diesel engines and compressed air for big diesel generators (the start-up supply needed for gas stations is typically 1% of installed capacity and 2% of installed capacity for hydro stations). As a result, the subsystem/producing stations can be powered by such a generating unit. Meeting the related performance requirements is crucial [11], [41], [120]:

- Depending on demand, it can turn off its circuit breaker for a dead bus.
- It requires to maintain the frequency under various load conditions.
- It can provide a voltage supply for unpredictable loads.
- The system operator's selected output rate within the time limit is optimal.

3.3.4 RES's Inertia Response

In general, RESs that are developed as an alternative energy source in the near future will present new issues with the quality of the power supply when generating plants are connected to the network. Nonetheless, in distributed networks, a well-managed DG can greatly enhance service continuity in particular geographic areas [122]. High-RES penetration creates serious problems with frequency stability.

First of all, RESs usually have weak or nonexistent inertial responses. For instance, a power electronic converter typically links a variable-speed wind turbine to a network in order to efficiently distribute wind turbine inertia from diminishing transient systems. Furthermore, solar PV plants don't provide any inertia response to the power grid. The entire electrical system's inertia is decreased when RESs are used in place of conventional sources [123]. Consequently, fewer industrial units supply primary and secondary control reserve power as the RES penetration rate rises. As a result, the frequency variance will rise, as indicated in Figure 3.13 and described in [124]. To solve the frequency stability issues brought on by the weak inertial response and reserve power, the RESs must develop new frequency control strategies that would allow them to take part in frequency regulation operations.

The typical frequency response with operational restrictions is displayed in Figure 3.13. When the machine is operating normally, its frequency is around 50 Hz. However, as demonstrated by the swing formula, the frequency of the system starts to decrease with the frequency levels when an event causes an imbalance in generation and demand. This is dependent on the total system inertia and total unbalanced energy [125], [124]:

$$\frac{df}{dt} = \frac{f_0}{2H_{sys}S_B}(P_m - P_e) \tag{3.1}$$

Where df/dt is the frequency shift speed, H_{sys} is the maximum inertia constant of the unit, S_B is the rating of generator power, $P_m\ and\ P_e$, are the mechanical power and electrical power, and f_0 is the frequency of the system. Due to the inertia reaction, the synchronous generator releases kinetic energy stored in its spinning mass before any controller activation and for up to approximately 10 seconds [126]. After that, the primary frequency controller is activated immediately if the frequency deviation exceeds a certain value.

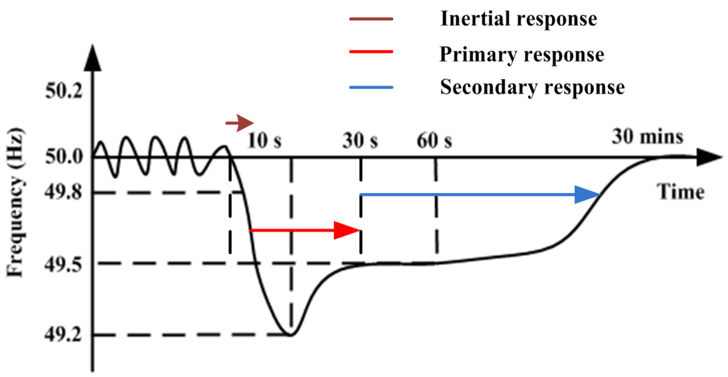


Fig 3.13 *Time stages involved in responding to system frequency [124]***.**

This controller returns the frequency to store values in 30 seconds [127] using the generator governor. After the 30s, a new control known as secondary control will be activated to return the system frequency to its nominal value. The secondary controller takes several minutes to return the system frequency to its nominal value, as shown in Figure 3.13. Currently, backup capacity is adequate to meet the rise in power needs. Lastly, it makes it possible to use residual power deviation to alter the tertiary frequency. In contrast to main and secondary controllers, the tertiary controller needs to be manually adjusted for scheduled scheduling changes or when generators are sent [128]. Frequency and inertial control methods for RES are generally divided into two fundamental groups: RES control techniques with ESS and RES control techniques without any ESS assistance. The benefits and drawbacks of the frequency/inertia command [41] for RES with and without ESS are shown in Table 3.4.

Table 3.4. Benefits and drawbacks of using ESS and frequency/inertia control for RES.

ESS	Source Type	Methods	Merits	Demerits
Without	Solar	Deloading	There is no need for an extra element. There is inertia and frequency regulation available.	A certain percentage of energy is lost. It is contingent upon the environmental circumstances.
	Wind	Inertial response	Power directly derived from the rotating mass.	The second drop in frequency may occur in losses.
		Deloading	There is primary frequency control available.	It loses some energy percentage.
With	Solar	Deloading MPPT	The system is highly effective. Removes instabilities in power.	Increased cost as a result of the battery's expense and energy loss.

				The battery cannot take in electricity from the grid if it is completely charged.
	Wind	Inertial response	The method is quite reliable.	The value is significantly higher than with the aforementioned methods. high energy and battery prices.

3.3.5 Oscillation Damping

During or following internal (excitation loss, generator instability, etc.) or external (transmission line failure, loss of generation or load, etc.) disruptions, it is preferred that the frequency and voltage values in the power system stay within the stable operating range. The electricity system experiences low frequency oscillations as a result of these disruptions. These oscillations may be inter-area (geographically dispersed and involving multiple distant generators) or local (to a single plant, generator, or region). Fast exciters in the power system cause local oscillations (0.7–2 Hz), while overloading weak transmission connections causes inter-area oscillations (0.1–0.7 Hz) [129]. Partial or complete power system blackouts could result from these oscillations if they are not adequately damped. To reduce these oscillations, the power system uses automatic voltage regulators with a power system stabilizer and flexible AC transmission system (FACTS) components [130] such static VAR compensator and static synchronous compensator (STATCOM).

3.3.6 Congestion Management

Congestion in a power system occurs when the transmission infrastructure is unable to support all desired transactions due to the physical and operational constraints of the power system. These physical and operational constraints may include heat limits of transmission lines and transformers, voltage restrictions, and transient or other stability limitations [131].

In grid codes for Capacity allocation and congestion management [132], 3-types of congestion i.e., market, physical, and structural congestion has been defined. A situation when cross-zonal capacity or allocation constraints limits the economic surplus for single day-ahead or intraday coupling is termed as ‘Market congestion’. When the thermal limits of grid elements and voltage or angle stability limits of power system are breached during forecasted or realized power flows, it is defined as ‘Physical congestion’. ‘Structural congestion’ has been defined as transmission system congestion that is predictable, geographically stable over time, and occurs frequently under normal power system conditions. Power system congestion causes pricing disparities between different regions in electricity markets. One such instance occurred on October 3, 2018, when the day-ahead wholesale pricing differential between Belgium and Germany was between 105 and 152 per MWh. Physical traffic between Belgium and Germany was the cause of this price discrepancy [119].

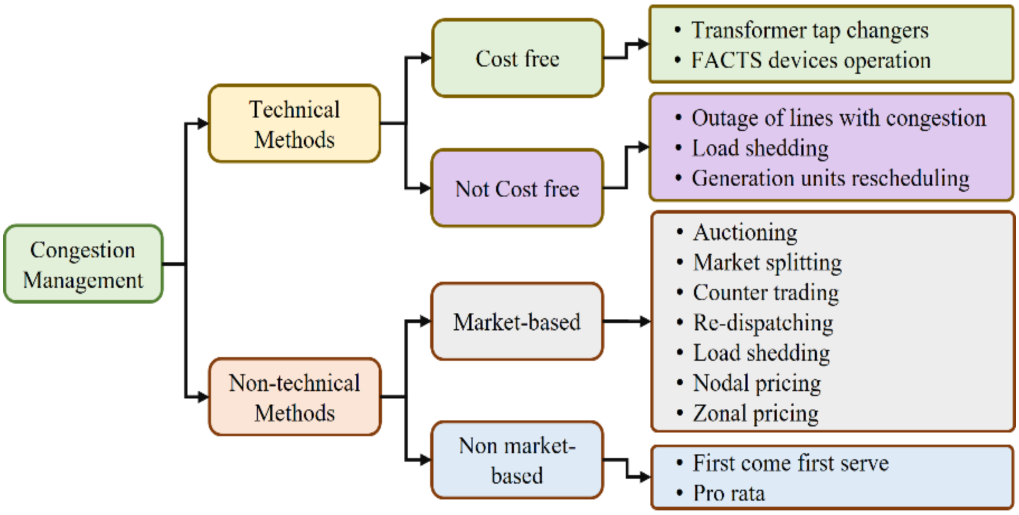


Fig.3.14 *Congestion management classification [119].*

Congestion management is the practice of utilizing the existing power system infrastructure (economical and operational) while operating within system limitations [133]. Congestion management provides the TSO with long-term investment signals for bolstering the transmission system infrastructure, either locally (to a single TSO) or cross-zonally (shared with other TSOs). The expense of corrective measures for congestion management must be covered by a TSO in charge of a specific control area or by many TSOs in charge of the relevant control area [134]. Numerous approaches have been put forth for managing traffic in [82], and they can be roughly divided into two categories: technological and non-technical approaches. Both cost-free and non-cost-free technical approaches to congestion control are possible. Phase-shifters, transformer tap changes, and FACTS devices are examples of cost-free congestion management techniques. These techniques are easily accessible through the TSO, don't involve other parties like distribution or generation companies, and have no financial impact. In order to manage congestion, load shedding and producing unit rescheduling fall under the category of non-free techniques. The TSO orders technical methods. Market-based (auctioning, counter-trading, nodal, or zonal pricing, etc.) and non-market-based (pro rata or first come first serve) are two examples of non-technical congestion management techniques. The TSO just observes non-technical congestion management techniques; it is not involved in them. Figure 3.14 shows the classification of different congestion control techniques.

3.4 The procurement process for energy and ASs

Depending on when they operate, how much information each participant gives the System Operator (SO), and how the SO facilitates or regulates these markets, the market structure may vary. The two-auction markets for energy and/or AS dispatch are called forward markets and real-time markets [102].

3.4.1 Forward market design

The hour-ahead forward market is used to correct deviations from the day-ahead timetable, and forward markets function according to a day-ahead timeline, in which suppliers or retailers provide their generated or required power one day prior to actual power delivery [91]. The terms "day-ahead" and "hour-ahead" are commonly used to describe these energy markets. Sequential and simultaneous are two approaches to energy and AS distribution that depend on the control granted to the SO.

- The sequential strategy entails the successive dispatch of energy and AS markets, wherein one market, primarily the energy market, is cleared first, establishing the foundation for the subsequent AS market [102]. It comprises distinct AS markets, each featuring unique offerings for individual products. This technique leads to pricing issues such as price reversal.
- The simultaneous approach entails distinct mechanisms for both energy and ancillary services markets. It comprises a singular AS market with distinct offerings for each product. It offers advantages over the sequential approach but does not provide a perfect solution regarding energy and ASs dispatch.
- The simultaneous co-optimized plan includes the joint co-optimization of the AS and energy markets. In this case, the AS and energy markets are dispatched simultaneously. Since simultaneous approach appears to be more efficient, markets of PJM, ISO-NE, NYISO, CAISO or ERCOT employ this approach for market clearing [135].

Figure 3.15 illustrates how the auction method for the energy and AS markets changed from a sequential to a co-optimized approach.

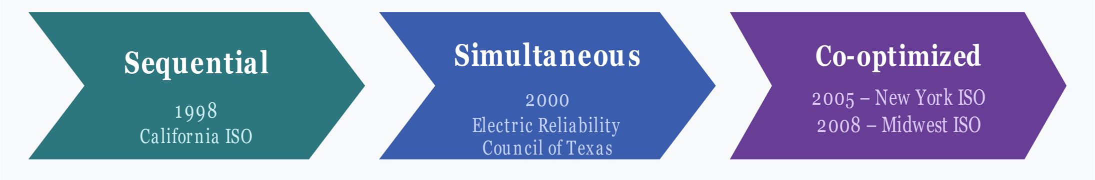


Fig.3.15 *Evolution of auction mechanism for energy and AS markets [102]*.

3.4.2 Real-time market design

Supply and demand are connected in real time using the real-time market. One of the key duties of the SO in this market is to maintain the electricity market balanced in real time. The goal of these markets is to successfully obtain the resources needed to ensure system reliability. The SO must obtain the necessary resources, such as AS, if the market is unable to fully meet dependability requirements [110], [115]. As seen in Figure 3.17, AS trading is conducted in both forward and real-time markets, whereas energy trading is typically conducted in forward markets.

3.5 RES's effect on the AS and energy markets

An electric power system's generating mix has a significant impact on its potential to incorporate renewable energy generation. Due to its domestic availability and numerous additional advantages over alternative energy sources, a number of nations are incorporating RES into their energy mix. Numerous factors have contributed to their widespread use, including: i) the steadily declining cost of renewable energy per unit, which is getting close to grid parity for some RES, such as wind and PV; ii) government policy and regulatory obligations [136] and incentives, such as feed-in tariffs. Because of this, even if these resources are essentially distinct from one another, they can compete with traditional energy resources in the market [137].

Power plants are the primary providers of this service through bilateral long-term contracts established with the SO, contingent upon meeting specific performance criteria. This service is acquired on an annual basis in both the Electric Reliability Council of Texas (ERCOT) market and Ontario's market through competitive mechanisms within electricity markets. Table 3.5 presents the response speed, duration, and dispatch frequency associated with various AS, while Table 3.6 outlines the procurement mechanisms for AS capability across different electricity markets. Figure 3.16 depicts the general AS in modern power systems as defined by both the Union for the Coordination of the Transmission of Electricity (UCTE) and the Federal Energy Regulatory Commission (FERC). Voltage control and load following are classified as continuous services, whereas system protection services distinct from device protection encompass reliability-based non-spinning and spinning reserves, which must be fully available within ten minutes, as well as replacement reserves that are required to be fully available within thirty minutes [102], [136].

Table 3.5 Response time of various AS

Type of AS	Requirement	Response speed	Duration	Dispatch frequency
Regulation	Normal Operation	<1 min	Minutes	Hours to days
Load Following		<1 min	Minutes	Hours to days
Operating Reserves (Ten Minute Spinning Reserve (TMSR))	Abnormal Operation	Seconds to <10 min	10 min to 2 h	Hours to days
Operating Reserves (Ten Minute Non-Spinning Reserve (TMNSR)		<10 min	10 min to 2 h	Hours to days
Replacement Reserves		<30 min	2 h	Hours to days
Reactive Power Support	Normal Operation	Seconds	Seconds	Continuous
Black-Start Services	Abnormal Operation	Minutes	Hours	Months to years

Table 3.6 Procurement mechanism in different AS markets [102].

Name of market (Grid operators)	AS Types			
	Reactive Power Support	Frequency Regulation	Emergency Services	Operating Reserves
CAISO (California)	Long term contracts	purchased on an hourly basis in the futures market by ISO	Annual bilateral contracts	-

ISO-NE (England)	Basic payment for operation and capacity	Annual bilateral contracts and competitive auctions	-	-
NORDEL (Nordic Countries)	Annual contracts	Competitive offers	-	-
ERCOT (USA)	Dispatched through the Out-of-Merit Capacity (OMC) deployment method	Scheduled and procured in forward market	Procured competitively on annual basis	-
NYISO (New York)	Resources under control of SO	Competitively procured in IDM	-	Competitively procured in FM, Occasionally in RTM
India	FM Competitive procurement through bid-based auction/pay-as-bid pricing method	FM Competitive procurement using bid-based auction with a pay-as-bid price model.	Flexible generators will receive incentives comprising fixed and energy prices.	No market yet
PJM (USA)	Scheduled in FM and compensated for engagement in RT on a cost basis	Real-time Competitive market	No established market; compensation is based on incentive rates.	Competitive market mechanism on FM and RTM basis
Russia	Real-time procurement occurs as the system operator immediately accesses resources when required.	Competitively procured on bid-basis	-	No market exists for this service; however, it was acquired from the capacity market when needed.
China	Provided by the resource as an obligation	Transacted through long-term contracts or self-supplied.	Traded via bilateral long-term contracts	Auction based markets
Spain	Annual bilateral contracts	Competitive market	Not rewarded	Competitive offers
AEMO (Australian Energy Market Operator)	Annual bilateral contracts	Bilateral contracts	Annual bilateral contracts in different zones	Annual bilateral contracts

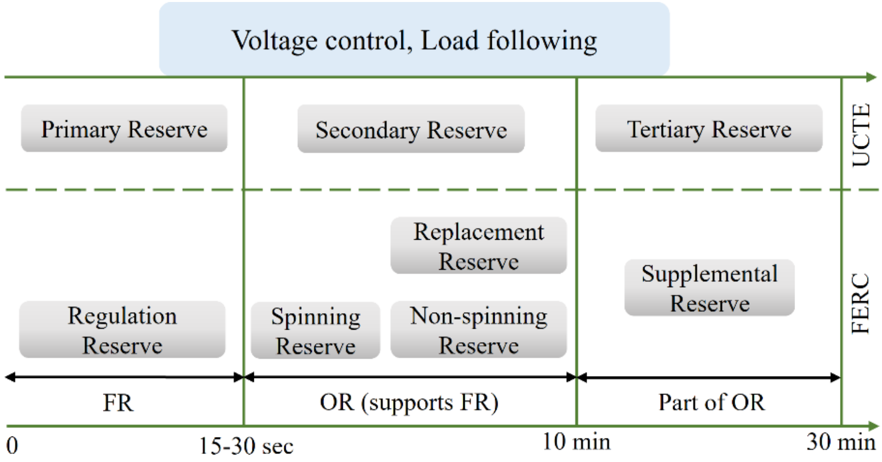


Fig.3.16 *General AS in modern power systems as per UCTE and FERC [102].*

3.5.1 Impact on market price

Marginal cost pricing applies in a competitive electricity market. In an attempt to satisfy demand, the many potential suppliers bid energy supplies into the pool. The dispatchers choose the least costly combination of generation or demand reductions in order to balance the system. The market clearing prices are established by this optimal dispatch. This price is given to generators for the energy they supply, and consumers pay this price into the pool for energy they purchase from the spot market [138].

In a competitive energy market, locational marginal prices are used to represent individual prices that are established for various nodes and/or within zones. It is the marginal cost of delivering the further addition of electric energy at a particular bus while taking into account the limits of the transmission and generation systems in addition to the marginal cost of generation. The marginal cost of energy production and delivery are both reflected in LMPs. Locational marginal pricing can differ substantially between locations due to the effects of both transmission losses and transmission system congestions [15].

Another significant element that supports the growing use of renewable energy sources in AS markets and the energy sector is the falling cost of electricity generated from RES [139]. As seen in Figure 3.18, the market clearing price is impacted by zero or even negative [102] marginal costs for RESs like wind and photovoltaics. The market clearing price in both single and double auction markets is determined by the point where the supply and demand curves converge.

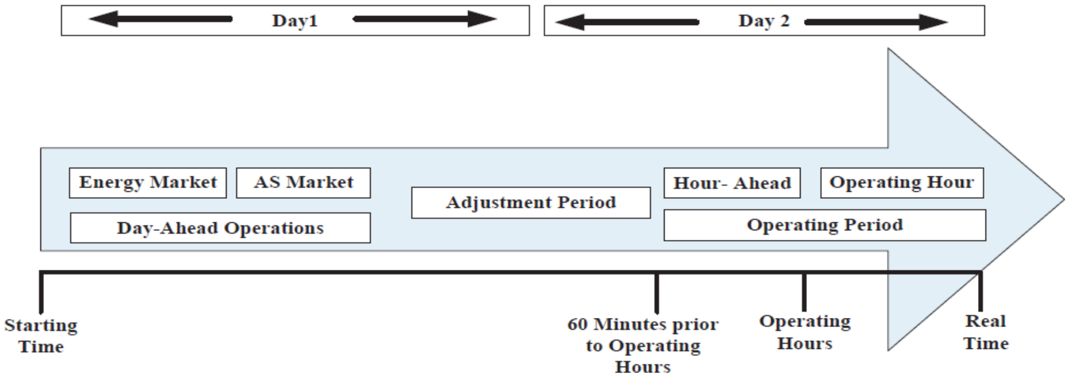


Fig.3.17 *Energy and ASs dispatch auction market design [102].*

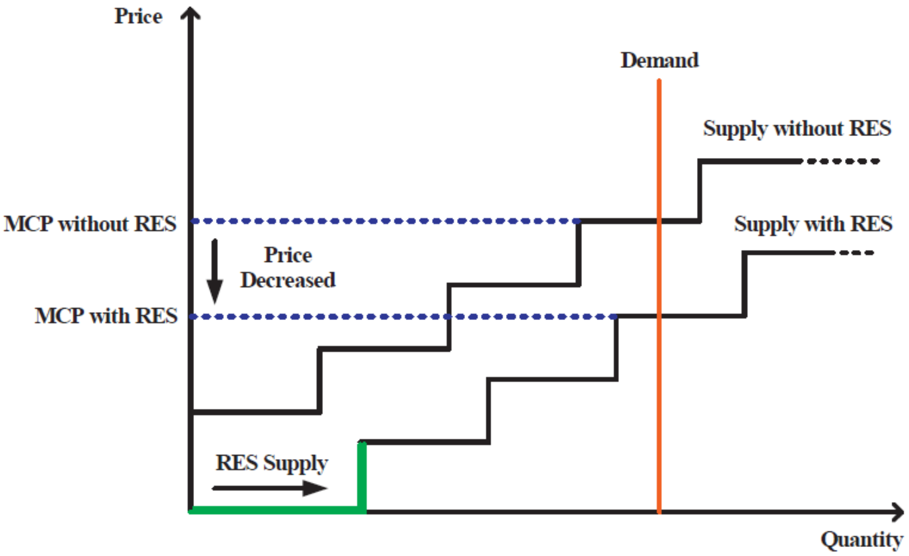


Fig.3.18 *Theoretical Merit order dispatch with and without RES [140].*

Renewable generation in such markets will lower down the market price by eliminating more expensive generating sources in merit order dispatch. [18] investigated the impact of RES as wind power integration to power system on the total generation costs and electricity market prices. Pereira et al. [141] showed that by increasing penetration of wind power in Iberian market results in declination of the average price of electricity by around 4.5 €/MWh and reduction in operational hours of thermal plants. The ability to store and dispatch electricity from Concentrated solar power plants promises cost advantages when it comes to integrating into electricity markets. Similarly, [142] presented an approach for optimal placement of RES like wind and PV for profit maximization and to reduce government subsidy on these variable generations in the competitive electricity market.

3.5.2 Impact on operation of power system

Because of their unpredictable output and extremely varied diurnal pattern, these resources not only have the potential to reduce the system's electricity price but also have a big influence on how the power grid is planned and operated [16]. Maintaining a balance between generation and demand requires the variable technologies to communicate with the other generating units in the system.

Fossil fuel-based plants ramp up or ramp down their output to meet the fluctuation of RE generation, operating at production levels above or below their ideal schedule. Additionally, these ramps may frequently result in the generating units' commitment to ON and OFF. Because of this, a lot of papers only discuss the unpredictability that comes with integrating renewable energy sources into power system operations. The effects of renewable integration on thermal producing units can be measured using stochastic unit commitment models. Stochastic unit commitment models were used in References [143] to estimate the effects of renewable integration on thermal producing units while accounting for the variability of RE generation. Additionally, the widespread use of RES in the electrical market will lower the start-up costs of traditional units and save fuel.

[138] discussed on the role of RES like wind, solar, waves, and biomass in developing sustainable development strategies. He talked about three main tactics, which usually include efficiency gains, demand-side energy savings, and switching to different RES in place of fossil fuels. Further, [144] illustrates difficulties and strategies during large scale integration of wind power into existing 50% CHP based electricity generation to reduce CO2 emissions in Denmark.

Regarding the challenges and energy-saving measures needed in Macedonia to transition to a 100% RES-based electricity market, a similar study has been conducted by [145]. Various obstacles and potential fixes for RES integration in the electrical markets of France, Italy, Denmark, Greece, and the Netherlands. [146] examined how the integration of wind and photovoltaics into the California energy market affected the day-ahead and real-time power prices in a merit order manner. The main conclusion indicates that by enhancing the effectiveness of the day-ahead forecasts, trading efficiency in California's day-ahead market and real-time market energy marketplaces can be increased. The detrimental effects of RE, which has historically been supplied to the electrical market at the low marginal cost, are described by the merit order effect.

A more methodical and balanced expansion of renewable capacity alongside conventional power generation is required, with a focus on system economics and security, according to the results of his analysis and the influence of wind and solar energy modeling on the electricity market. In order to identify the ideal balance of renewable energy sources for the current fossil fuel-based Mexican electrical system, [147] suggested a revolutionary methodology based on Minimum Total balance Capacity. By creating several biomass mix scenarios, this methodology has been utilized to explore the possibility of integrating RES into the electrical grid and reach the goal of utilizing 35% of RE generation by 2024.

3.6 Development of an effective market framework for RE integration in energy and AS industries

The establishment of an effective market for the integration of these variable energy sources in CEM for the procurement of AS has received comparatively little attention. Renewable power producers offer power in a marketplace with unpredictable supply and prices [148]. Their involvement in the energy market may entail significant departures from the original obligations, which results in a revenue drop that must be paid by the owners due to the stochastic nature and limited predictability of RES. Hence an efficient market needs to be established so that the effect of imbalances caused by Conventional power producers and renewable power producers on market will be discouraged and the associated parties will be penalized.

Certain methods are implemented based on market regulations that vary from market to market in order to deter this unequal behavior of the players. Before entering the auction, the bidder in the Netherlands must post a performance bond of a specific amount, which is forfeited if the bidder does not operate the plant on time[149].

According to the Central Electricity Regulatory Commission's Unscheduled Interchange regulations, sellers in India are responsible for paying a penalty if they do not supply capacity as scheduled in the frequency support AS market. In Argentina, generators are required to have OR available. When these generators are unable to supply the specified reserve, they are punished. NYISO penalizes nonperforming resources against decreased generating quantity and sets real-time prices using ex-ante prices, which are prices based on predictions made close to real-time [150].

Similar to this, generating units in Italy that have rated power beyond 10 MVA are subject to imbalance penalties based on the RTM's marginal price, whereas plants with rated power under 10 MVA are subject to fines based on the day-ahead market or AS-market average price [151]. Penalty payments are made using the pool market price since RES, like wind, are hard to arrange in the day-ahead market. Additionally, these producers who make less accurate offers are not penalized.

3.7 Renewable energy-based procurement of AS

By incorporating unit commitment into power system operation, power system operators have historically attempted to reduce their overall cost of generating. The SO aims to maximize the social welfare of both customers and generation utilities as a result of the liberalization of the electricity markets. The use of green energy for energy and AS worldwide has become the focus of energy-based research due to worries about fossil fuel-powered power plants and their contribution to global warming.

With the greater integration of RE generation like wind and solar PV power into existing grids, research efforts must be devoted to creating market-based environment for the procurement of both energy and AS. Several publications and studies have verified that dispatchable RES like hydro and pump-storage plants along with non-dispatchable RES like wind, solar PV, concentrated solar power are also capable of and well-suited to supply various types of AS.

The conventional plants, renewable power producers are also proficient in providing energy as well as several AS in order to maximize their profits due to their fast-responding ability [152]. In general, these sources agree to a production level in these markets, which they delivered in the contracted periods. This section discusses several RES types that offer various AS.

3.7.1 RES based procurement of frequency regulation services

Conventional generation units are insufficient for addressing rapid or nearly instantaneous frequency regulation challenges when compared to RES [153]. Conventional units exhibit reduced ramping capabilities, leading to a sluggish response in regulation provision. Consequently, renewable energy sources can significantly contribute to the provision of these services.

the potential for wind energy to be integrated with an existing small-scale CHP plant in order to provide the entire spectrum of pertinent frequency and voltage regulation in the Danish electrical system. The function of wind farms is to give minute-by-minute control. the availability of wind-generated AS-based frequency regulation and the financial effects of various wind power plant control architectures on frequency responsiveness. The variable speed wind turbine generator's ability to regulate generator torque and take part in main frequency regulation [153].

In order to boost system security and boost their profit under wind power penetration, the combined energy and regulation reserve market provides quick reserves. In order to regulate the trade of wind power in the day-ahead California energy market, [154] suggested an economic-based wind participation in the Spanish secondary regulatory market. [155] examined the grid coding requirements and wind turbine control techniques for their involvement in frequency control in the UK and Ireland.

Wind turbines powered by doubly fed induction generators use a variety of control techniques to achieve frequency regulation, primary control, and initial response. [156] To achieve frequency regulation, an interconnected wind-thermal integrated power system's control parameters were optimized. With the wind farm, control techniques like maximum power limiting and delta control lower the system's overall generation costs. Because their output may be adjusted to reduce frequency oscillations soon after a large generating unit fails, wind farms with sophisticated controls provide greater control over actual power [21].

Other control systems have been covered in [157], including pitch angle control, sub-optimal control, and optimal model predictive control methodology. These control techniques help the wind plants generators to maintain instantaneous power balance as well as frequency regulation services in electric power systems. The advanced control of wind turbines are used in order to guarantee low-cost, high-performance, and safe electrical energy production whereas pitch angle control related with the wind turbine is designed that makes the wind power plant to have a long-term frequency regulation capability. The implementation of optimal controllers in wind turbines offers good dynamic performance as well as ensures system dynamic stability. A supervisory control approach for Permanent Magnet Synchronous Generator based grid connected wind farms has been proposed to deliver grid support services, particularly primary frequency control using the pitch regulation mechanism in [158].

Other renewable energy sources provide regulation services in addition to wind-based alternatives. By modifying their active power outputs, a novel control technique for frequency regulation from PV generators without energy storage devices has been proposed in [159]. Large-scale photovoltaic power plants' contribution to Denmark's frequency support services. [160] has examined the effectiveness of the wind-solar isolated system in Spain to supply frequency regulation by pumped storage hydro plant.

However, by offering regulation, DGs based on RES sources also work with the major conventional power plants to improve the security and dependability of the power system [160]. [161] looked at a new control system that was used to regulate frequency from a microgrid in grid-connected mode using a wind-based distributed generator as the primary energy source and a super-capacitor as a storage device.

3.7.2 RES based procurement of load following services

These services become chiefly important at times of day when the demand for electricity increases considerably. This may be provided through a group of AS depending on the SO. Additional ramping requires are needed to provide load following, which can be satisfied by operating flexible generators, such as hydroelectric generators or generators that run on natural gas or oil [162]. [158] investigated the load-following capability from modern Permanent Magnet Synchronous Generator within wind energy conversion systems. Pumped storage hydro plants also provide emergency reserve when operated in pumping mode [163].

ERCOT has developed unique proficiency on generation capabilities, deliverability and impact of generation from variable sources on power system by constantly improving wind power forecasting tools that allow ERCOT to better predict AS needs. The recognition of the nodal market in 2010 was one of the key factors that contribute to the successful integration of intermittent resources into the ERCOT system. Wind power has been successfully integrated, allowing it to closely follow variations in net load while simultaneously increasing AS capacity to a minimal degree [164].

3.7.3 RES based procurement of operating reserve services

Traditionally, conventional fossil fuel-based generators are the contributors to supply these reserves. Spinning reserves as a part of the operating reserve are provided by online and synchronized generating units like coal-fired plants, hydro and pumped storage plants whereas non-spinning reserves are provided by fast responding units like oil or gas-based plants and by interruptible loads [165]. Due to their fast-ramping rates and reduced marginal cost of providing these services, renewables are currently making an appearance in reserve-based markets.

The prospect of wind power to provide frequency control or delivering active power reserves within technical, regulatory and economic aspects have been investigated by [166]. [167] described the possibility of spinning reserve from Doubly Fed Induction Generator based wind turbines.

Different methods for the determination of an optimal amount of various type of operating reserves with high wind penetrations are discussed in [168]. The effect of wind producers to become price-maker and to provide a positive spinning reserve in the single electricity market for Northern Ireland and the Republic of Ireland has been examined by [168].

[169] developed two-stage stochastic programming formulation to determine the reserve generation and cost association with power system operation under large-scale wind power penetration in California system. In order to reduce day-ahead and real-time adjustment costs, a disaggregated market clearing method for energy and spinning reserves has been developed, taking into account the impact of uncertainty in wind power generation [170]. [171] proposed a combined energy and regulation reserve market model to encourage trading of the wind power in the market to incentivize wind producers and to favour grid security.

[172] examined techno-economical procurement of downward and upward reserve from wind power producers in the day-ahead market. [173] discussed about how PV generation affects reserve AS and balancing markets. Sensitivity study of distributed solar battery systems' ability to provide primary control reserve has been presented by [115]. [23] addressed different policy framework, legal provisions and grid codes for supplying active power reserve from PV based distributed RES. Major technical and regulatory provisions include policy frameworks, legal provision, and grid codes, as they affect the role of distributed RES system in the distribution network.

With highly ambitious targets of Indian government for achieving 175 GW of RE installed capacity by 2022 necessitates the introduction of AS like Spinning Reserves. As per national electricity policy , the country must have at least 5% of the total installed capacity as spinning reserve which includes primary, secondary and tertiary reserves [174]. [34] discussed the possibility of EV to supply spinning reserve to electrical systems. A novel optimization technique has described by [175] for EV to participate in reserve markets by minimizing contracted and real-time participation.

3.7.4 RES based procurement of reactive power support

Hydro plants without large reservoir signs long-term contracts with ISO to provide secondary reserves. In the Brazilian system, most of the hydroelectric plants provide reserves along with reactive power support [176]. Wind power plant can provide reactive power control [21]. [177] investigated the economic and technological aspects of acquiring reactive voltage control assistance from modern wind farms. In order to provide reactive power regulation in central Sweden, the VPP, which consists of the wind park, hydro plant, reservoir, solar PVs, and battery energy storage, has been studied by [178].

Different control actions like absolute power constraint, power ramp rate control, power spinning reserve, frequency response, inertia response, reactive power and power factor control, voltage control and fault ride-through associated with Doubly Fed Induction Generator based wind power plants can provide frequency and voltage control [179]. [180] investigated an optimal management of grid-connected PV units to provide reactive power and system losses. DG with grid-connected PV plants to provide reactive power control has been presented in [181]. [182] discussed the capability of renewable energy-based ESSs for providing voltage support in real-test network by maximizing active power production.

The pumped storage plants seem to be the most promising way to address the problems of RE storage and grid penetration. The best option for providing frequency regulation reserve, or reactive power support, is a pumped storage unit combined with RES.

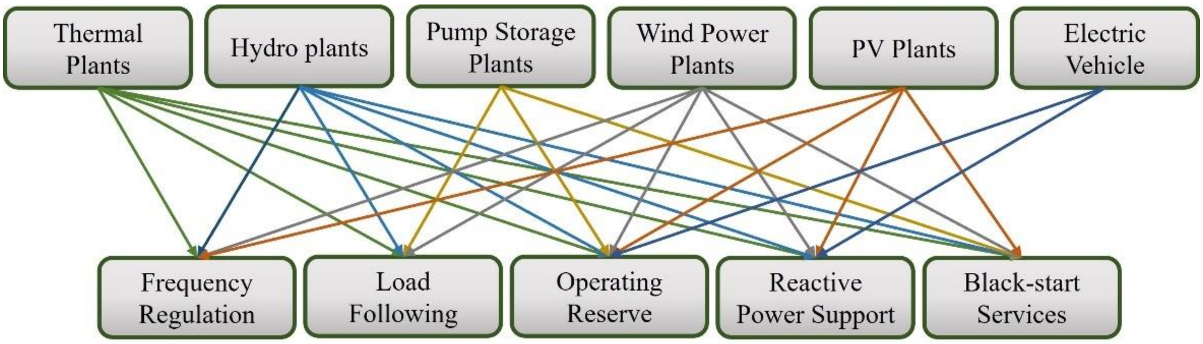


Fig.3.19 *Renewable based procurement of various AS [102]*.

3.7.5 RES based procurement of black start services

Black start restoration as an AS has been mainly examined in the context of thermal generators and very less work has been reported that examines how renewables could contribute to such requirements. Conventional power plants' Fast Cut Back feature ensures that ancillary equipment will run in order to restore the system after a blackout [183]. In contrast to traditional energy sources, RES like wind has very low startup times, which aid in the restoration of the power system during blackouts. [184] investigated the role of wind and PV to enhance the sustainability of the system by providing power system restoration services. Procurement of different AS from traditional as well as RE based resources are shown in Figure 3.19.

3.8 Renewables in joint energy & AS market clearing

Traditionally, conventional plants are providing both energy and AS services. These days, hybrid systems are used to provide energy and AS in addition to simply variable sources like hydro, wind, and PV. The role of renewables in provision of joint energy and AS are discussed in [185] presented a market-based approach for integration of RE like wind and PV to procure energy and AS. The objective of the proposed method is to reduce the AS procurement cost with integration of these sources in energy and AS markets. They further developed a penalty based Short-Term Market (STM) for the procurement of energy and AS while considering the stochastic behaviour of wind power on Social Benefit and Procurement Cost for obtaining any services. [186] proposed energy and spinning reserve market clearing process for wind integrated thermal system while considering uncertainties in the variable generation and load forecasts. [20] presented an optimization framework to find the optimal scheduling simultaneous clearing of both of energy and regulation reserves markets from cascaded reservoir system in order to maximize the expected profit from these markets.

[60] proposed a methodology that uses VPP-based distributed generation and demand response to provide energy and reserves inside a distribution network. [187] examined various technical and legal requirements for the use of Concentrated solar power technology in tertiary reserve and power markets. The involvement of Concentrated solar power with thermal energy storage systems and wind power plants in the day-ahead clearing of joint energy and spinning reserve markets. Concentrated solar power plants with thermal energy storage systems can offer both energy and AS, such as frequency regulation, operating reserves, and reactive control services.

The variable generation like wind and PV power producers, Plug-in EV can participate in the joint day-ahead energy, spinning reserve and regulation markets by incorporating stochastic programming approach for Plug-in EV profit maximization [188]. [189] proposed a novel approach to obtain energy and reserve market clearing scheme from EV aggregator based on wind power and

Plug-in EVs. [190] examined the participation of biogas plants electricity markets to provide energy and reserve markets. Biomass-fuelled CHP plants are able to provide energy in electricity spot market as well as in control reserve market [191].

3.9 MG Classification of Converters

Based on their interactions with the distribution grid, converters can be divided into two main groups: grid-forming converters and grid-following converters. Grid-forming converters are capable of power sharing across parallel converters in numerous source contexts in addition to setting and controlling the bus voltage of the distribution grid for the load. Grid-following converters function as planned when they supply electrified power to a grid.

3.9.1 Grid-Following Converter

Grid-following converters have a high parallel output impedance and act as current sources. In general, grid-following converters based on phase-locked loops (PLLs) can work in parallel with these converters. Similar to PV or wind power units, DG units' power converters usually run in the grid-following mode. By modifying the references of active and reactive powers, P^* and Q^*, at a higher-level control layer, these converters can take part in the regulation of the MG AC voltage amplitude and frequency. The grid-following converter's control structure and analogous circuit are depicted in Figure 3.20. Grid-following converters cannot function in island mode without a grid-forming converter or an AC MG with a local synchronous generator producing the voltage amplitude and frequency [192], [193]. Additionally, the stability of grid-following converters coupled to a weak grid will be impacted.

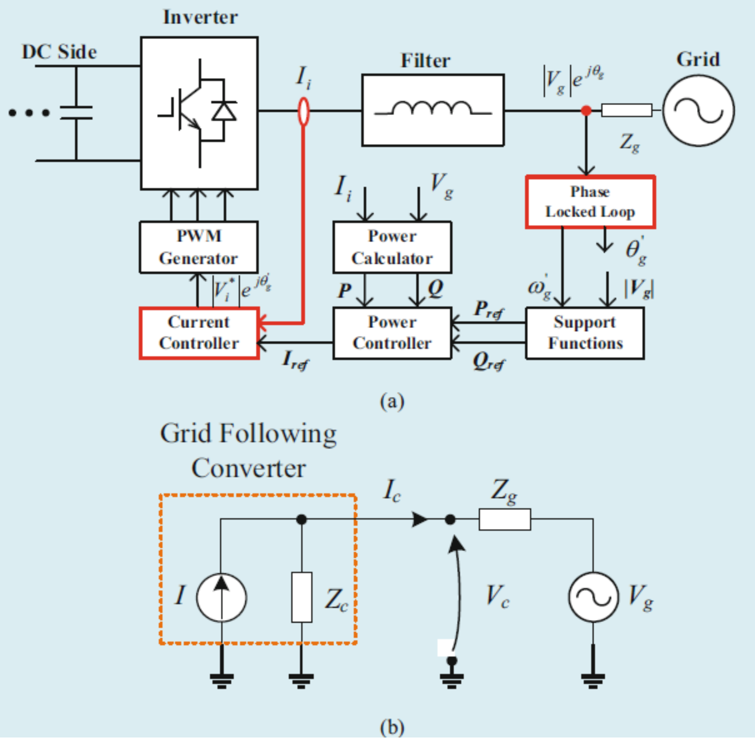


Fig. 3.20 *Grid-following converter. (a) Block diagram. (b) The equivalent circuit [25].*

3.9.2 Grid-Forming Converter

The closed-loop control of a grid-forming converter allows it to function as a perfect source of AC voltage with a given frequency and amplitude. Extremely precise synchronization systems are necessary for parallel operation with other grid-forming converters since they generate low voltages. Power sharing in parallel grid-forming converters is contingent upon the converters' output impedances. Grid-forming converters can follow loads in the standalone mode as long as the voltage and frequency remain constant. Various control mechanisms, such as virtual oscillator control [194], droop control, virtual synchronous machines, etc., have been proposed to parallelize the operation of numerous grid-forming converters. As an actual instance, standby UPSs can use grid-forming converters. The system stays disconnected from the main grid under specific operational conditions. In the event of a grid loss, UPS power converters supply grid voltage. The DC voltage produced by the grid-forming converter will serve as the foundation for the generation of the remaining grid since it will serve as a reference for the grid-following converters that are connected to it. Figure 3.21 displays the control structure of the grid-forming converter as well as the comparable circuit.

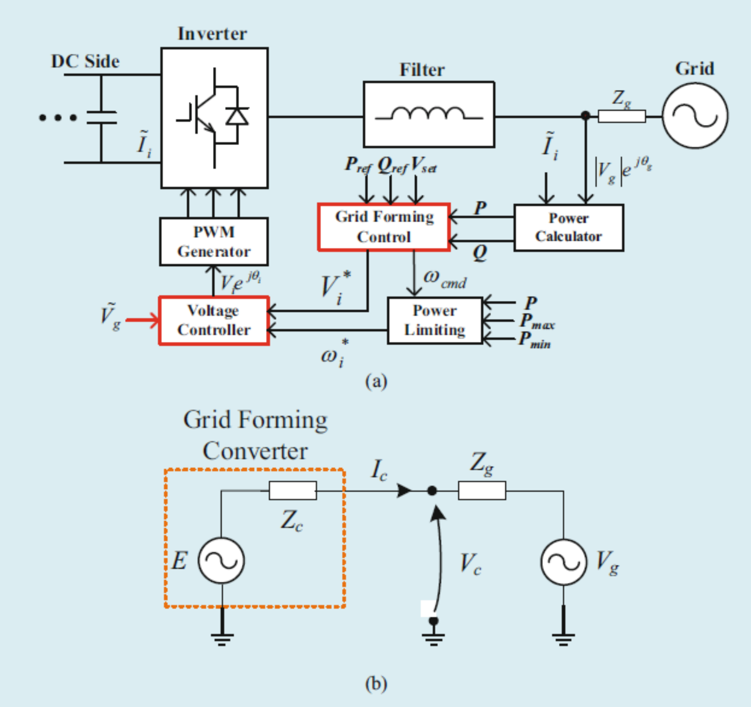


Fig. 3.21 *Grid-forming converter. (a) Block diagram. (b) The equivalent circuit [25].*

Grid-forming converters function more like voltage sources than current sources, which has several drawbacks. Simple grid formation-based control methods have weak converter existing regulations. As a result, grid-forming converters could find it difficult to manage overcurrent when loads fluctuate or when unusual circumstances, like faults or grid transients, arise. To accomplish current limiting, sophisticated control systems like virtual impedance current limiting, etc., might be required. However, in the majority of circumstances, such methods will impact the overall stability of the system. Large current flows brought on by concurrent events, like a grid voltage sag or surge, could overload the converter.

Chapter 4

Methodology for AS allocation in a MG

4 Methodology for AS allocation in a MG

4.1 Modelling

The proposed approach is designed to optimize the operation of a MG, taking into account operational expenses, AS reserves, and resource allocation to minimize microgrid losses. The utility target limitations are what drive AS constraints. Different time resolutions of AS can be provided using the model. The model's originality is in its ability to model MG power losses and the AS request at the PCC of MG to the distribution grid as a virtual load (VL), which sets it apart from earlier studies on this subject. In other words, a VL is added to the PCC node with the restriction that it can be supplied by MG assets only (RES, discharging batteries, or lowering MG controllable load) in the event that a request for active power balancing arises, as illustrated in Figure 4.1, where the MG must increase its power exchange with the distribution grid. The load curve of the VL matches the balancing requirement.

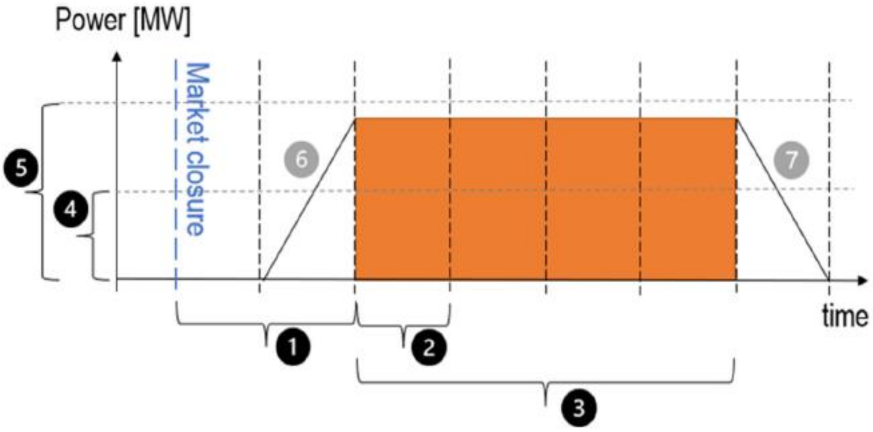


Fig.4.1 *Balancing requirements: (1) Time to delivery; (2) and (3) minimum and maximum time; (4) and (5) minimum and maximum power; (6) and (7) ramping and de-ramping rates [195].*

The objective of this problem is to minimize the operational costs of the MG while considering its power exchange with the utility grid, as described in equation (4.1).

$$min \sum_{t} \left[OC_{MG}(t) + \rho^{grid}(t)\, P^{grid}(t) + \rho^{as}(t)\, P^{VL}(t)\right] \tag{4.1}$$

Where, $(OC_{MG}(t))$ represents the MG operation costs as showing in equation (4.2), $(\rho^{grid}(t))$ and $(P^{grid}(t))$ represent the electricity exchange price with the utility grid and power exchange with the utility grid. $(\rho^{as}(t))$ is AS price from RES and $(P^{VL}(t))$ represents change of power exchange with the utility grid in response to AS requirements.

$$OC_{MG}(t) = \sum_{i \in G} f_i\left(P_{g_i}(t)\right) + \sum_{j \in L} f_j\left(P_{l_j}(t)\right) + \sum_{k \in S} f_k\left(P_{s_k}(t)\right) \tag{4.2}$$

It should be mentioned that the load cost function is defined for the controllable part of the load. The objective is subject to technical constraints, including MG power losses and AS requirements.

In this context, the symbols (f_i, f_j, and f_k) represent cost functions of individual generation (fuel cost), load (power consumed by adjustable load), and storage assets, respectively.

The power balance in Equation (4.3) guarantees that the total power produced by the DERs and the power exchanged with the utility grid corresponds to the load side, which includes the power of the virtual load (P^{VL}), the load (P_L), power charging the storage unit (P_S^{ch}), and power losses (L).

$$P_G(t) + P_S^{dch}(t) + P^{grid}(t) = P^{VL}(t) + P_L(t) + P_S^{ch}(t) + L(t), \qquad \forall t \tag{4.3}$$

The power flows of ESSs may be positive (discharging), negative (charging), or neutral (zero). The utility grid's power can be negative (export), positive (import), or neutral (zero).

In (4.4, 4.5, 4.6, and 4.7), the minimum and maximum constraints for the output power limits from the generators (P_{gi}), power load (P_{lj}) limits, power charging (P_s^{ch}) limits, and power discharging (P_s^{dch}) limits respectively.

$$P_{gi}^{min} \le P_{gi}(t) \le P_{gi}^{max}, \qquad \forall i \in G \tag{4.4}$$

$$P_{lj}^{min} \le P_{lj}(t) \le P_{lj}^{max}, \qquad \forall j \in L \tag{4.5}$$

$$P_{sk}^{ch,min} \le P_{sk}^{ch}(t) \le P_{sk}^{ch,max}, \qquad \forall k \in S \tag{4.6}$$

$$P_{sk}^{dch,min} \le P_{sk}^{dch}(t) \le P_{sk}^{dch,max}, \qquad \forall k \in S \tag{4.7}$$

Constraints for the ramp-up and ramp-down rates in (4.8, 4.9, 4.10, 4.11, 4.12, and 4.13), and $(t-1)$ denotes the previous time step (The rate at which each generator can increase or decrease its power output between two successive time intervals).

$$P_{gi}(t) - P_{gi}(t-1) \le \Delta P_{gi}^{up}, \qquad \forall i \in G \tag{4.8}$$

$$P_{gi}(t-1) - P_{gi}(t) \le \Delta P_{gi}^{down}, \qquad \forall i \in G \tag{4.9}$$

$$P_{lj}(t) - P_{lj}(t-1) \le \Delta P_{lj}^{up}, \qquad \forall j \in L \tag{4.10}$$

$$P_{lj}(t-1) - P_{lj}(t) \le \Delta P_{lj}^{down}, \qquad \forall j \in L \tag{4.11}$$

$$P_{sk}(t) - P_{sk}(t-1) \le \Delta P_{sk}^{up}, \qquad \forall k \in S \tag{4.12}$$

$$P_{sk}(t-1) - P_{sk}(t) \le \Delta P_{sk}^{down}, \qquad \forall k \in S \tag{4.13}$$

The dynamics of storage unit charging over time takes into account charging and discharging activities and adjusting the efficiency of the storage process. It ensures that the state of charge (SoC) is accurately updated based on the energy flow in the charging and discharging of the storage unit during each time step (4.14), as well as the minimum and maximum limits (4.15).

$$SOC_{sk}(t) = SOC_{sk}(t-1) + \left(P_{sk}^{ch}(t) - P_{sk}^{dch}(t)\right) \cdot \eta_k \cdot t, \qquad \forall k \in S \tag{4.14}$$

$$SOC_{sk}^{min} \le SOC_{sk}(t) \le SOC_{sk}^{max}, \qquad \forall k \in S \tag{4.15}$$

Equations (4.16, 4.17) represent the minimum charging (T_{sk}^{ch}) and discharging (T_{sk}^{dch}) time, and these limits ensure that storage units are charged and discharged for a sufficient duration to meet operational requirements or avoid damage to the unit from charging and discharging periods that are too short.

$$T_{sk}^{ch}(t) \geq T_{sk}^{ch,min}, \qquad \forall k \in S \tag{4.16}$$

$$T_{sk}^{dch}(t) \geq T_{sk}^{dch,min}, \qquad \forall k \in S \tag{4.17}$$

In (4.18), the minimum energy required (E_{lj}^{min}) when the load is energized is considered. This inequality assures that each flexible load receives at least the amount of energy it requires throughout the optimization period. ("At the end of the day, the total energy consumed by this load must not be less than the minimum need"). The constraint that the VL is supplied only by MG (RES) assets is given in Equation (4.19).

$$\int_{t_0}^{t_f} P_{lj}(t)dt \geq E_{lj}^{min}, \qquad \forall j \in L \tag{4.18}$$

$$P^{VL}(t) = \Delta P_S(t) + \Delta P_L(t) + \Delta P_G(t) + \Delta L(t) \tag{4.19}$$

Equation 4.20 represents the voltage constraint (this limitation maintains the voltage magnitude at each node within safe and regulatory limits), and in equation 4.21 the power flow constraint has to be respected at all times throughout the MG (the power flow through each line must not exceed its rated maximum).

$$V_n^{min} \leq V_n(t) \leq V_n^{max}, \qquad \forall n \in N \tag{4.20}$$

$$P_{flow,m}(t) \leq P_{flow,m}^{max}, \qquad \forall m \in M \tag{4.21}$$

4.2 Optimization

Algorithms for optimization are mathematical processes created to identify the optimal solution to a problem while taking specific limitations into account. These algorithms are essential to several fields, such as data science, engineering, machine learning, and operations research. They are a group of algorithms used to determine the optimal solution to a particular issue. Finding the best solution that minimizes or maximizes a specified objective function is the aim of an optimization algorithm. Optimization algorithms come in many different forms, each with unique advantages and disadvantages. ANN, Simulated Annealing, Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), GA, and others are some of the most widely used optimization techniques. Algorithms for optimization are effective instruments for resolving complicated issues. They could completely change the way we work with data. Depending on the objective function being optimized, the optimization process entails taking a set of parameters and determining the best solution that either maximizes value or minimizes cost.

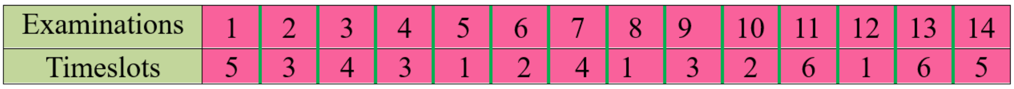
4.2.1 Genetic Algorithm

One of the greatest optimization techniques for resolving a variety of issues, particularly optimization issues, is the genetic algorithm. Since GA is a general algorithm, it will function effectively in any search area and generate an excellent result. GA uses the concepts of evolution and selection to provide several solutions for a given issue.

GA is a search algorithm that is based on genetics and natural selection. It draws inspiration from the "survival of the fittest" idea of natural evolution, which applies to a population of individuals. GA uses chromosomal encoding to reflect the fundamental functions of the individuals [196].

A. Chromosome Encoding

To encode potential solutions to any problem in a format that a computer can process, chromosome encoding is necessary (i.e. chromosome representation is called encoding). The genes that make up a chromosome contain information about the issue that has to be resolved. In the search space for this problem, every gene is a variable. Encoding frequently varies depending on the issue. Binary digits are used to encode chromosomes [197]. However, a chromosome's gene can be represented in a variety of various ways that may be more useful for problem-solving [198]. The first step in putting the genetic algorithm into practice is chromosome encoding, which depends on the situation. The number of inspections for each dataset determines the chromosomal representation in this study. Every gene is represented by the two variables (i.e., the number of examinations and timeslot), and each gene contains information on which examinations are planned for a specific timeslot. Since permutation encoding only works with numbers, it is utilized in this instance. The chromosome encoding utilized in this study is shown in figure 4.2, where the selected crossing site is represented by a vertical line “ | ”.



Examinations	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Timeslots	5	3	4	3	1	2	4	1	3	2	6	1	6	5

Fig.4.2 *Chromosome encoding*

B. The operations of GA

GA's fundamental functions are population, crossover, and mutation. Every potential solution to a given issue is included in the population (sets of chromosomes). Each pair of chromosomes is crossed across to create a new chromosome, and the selection of chromosomes is based on the fitness value as shown in figure 4.3. On the other side, mutation is used to alter the new chromosome in order to produce high-quality chromosomes until the best or most suitable answer is found. The two most crucial genetic algorithm operators that have the biggest impact on the algorithm's performance are crossover and mutation [197].

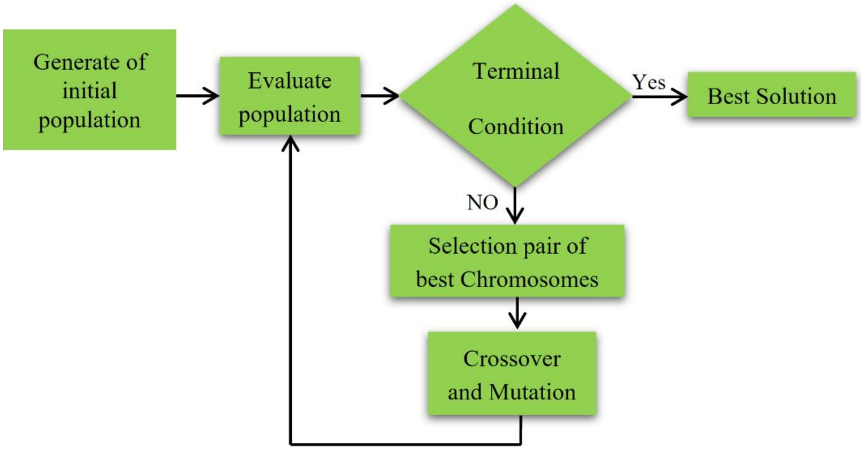


Fig. 4.3 *Operations of General Genetic Algorithm*

1. Initial population

The accepted solutions that initiated the GA are referred to as the beginning population. A chromosome is used to represent each solution. In order to yield every potential answer, this initial population is typically created at random. However, it will take the algorithm longer to get an estimated solution.

2. Fitness Function

The fitness function is among GA's most crucial components. Its objective is to guide the GA toward a better solution by enabling the algorithm to describe the chromosome that fits the data the best [197]. To determine which chromosome is the best fit among the others, each one must be assessed in accordance with the presumptive limitations. A fitness value is a number assigned to each solution in the population for evaluation. GA can choose the chromosome for crossover and mutation processes based on this value.

3. Selection

Appropriate chromosomes are selected from the population based on the fitness value of each chromosome. The objective of selection is to furnish parents (chromosomes) for crossover and mutation processes to generate a new population. These chromosomes may be utilized in the subsequent iteration of the algorithm. There are several forms of genetic algorithms, each possessing distinct characteristics. Chromosomes exhibiting high fitness are likely to be selected multiple times, whereas those with low fitness have a diminished probability of selection.

• Roulette Wheel Selection

Fitness Proportionate Selection is another name for roulette wheel selection as shown in figure 4.4. It is the best conventional method for choosing parents and is utilized to choose potentially helpful crossover solutions [197]. The most common kind of selection is thought to be roulette wheel selection. The chromosomal selection is governed by the fitness values. A chromosome with a high fitness value is more likely to be chosen more than once.

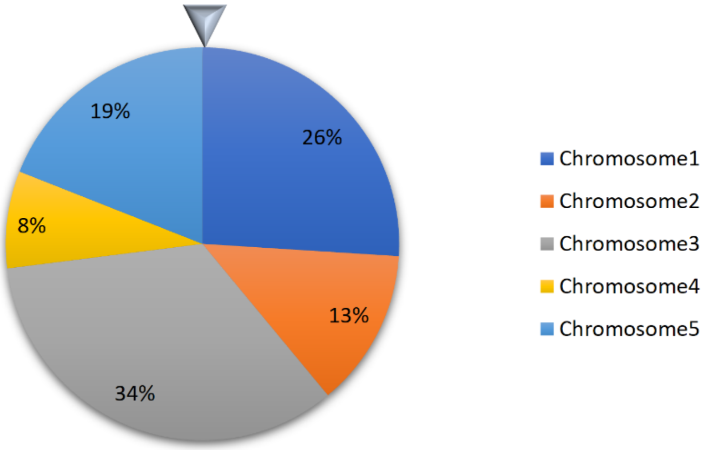


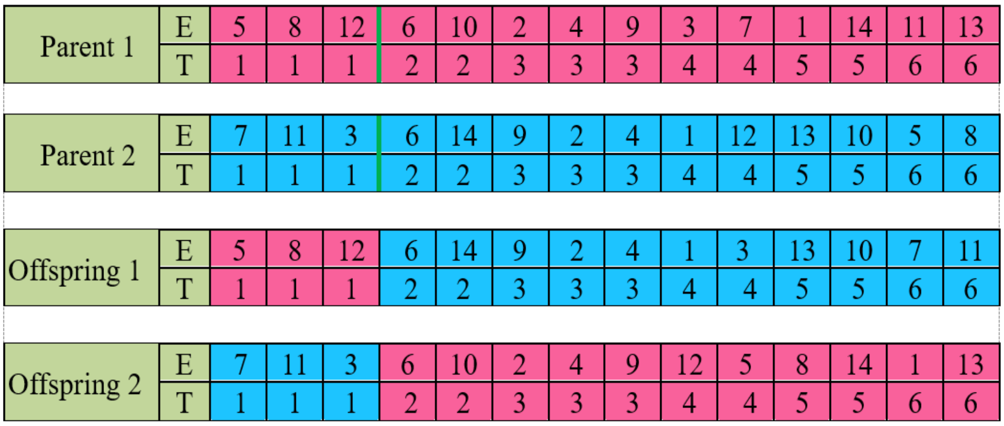
Fig.4.4 *Roulette Wheel Selection*

4. Crossover

Crossover is a principal mechanism in genetic algorithms that merges two chromosomes (parents) to generate a new chromosome (offspring) [196], wherein genes are selected from both progenitors to form the new offspring. The primary objective of crossover is to generate a novel chromosome that may surpass its progenitors by incorporating the advantageous traits of each parent. Numerous varieties of crossover operators exist:

- **Single Point Crossover**

One-point crossover is another name for single point crossover. It is the most basic type of crossover in which genes from the first chromosome (parent) are taken from the beginning of the chromosome until the crossover site. However, depending on the crossover rate, the remaining offspring are taken from the second parent to generate the first offspring, and vice versa [196], [197]. The chromosomes are switched at the segment level. The single point crossover following the repair procedure is seen in Figure 4.5.

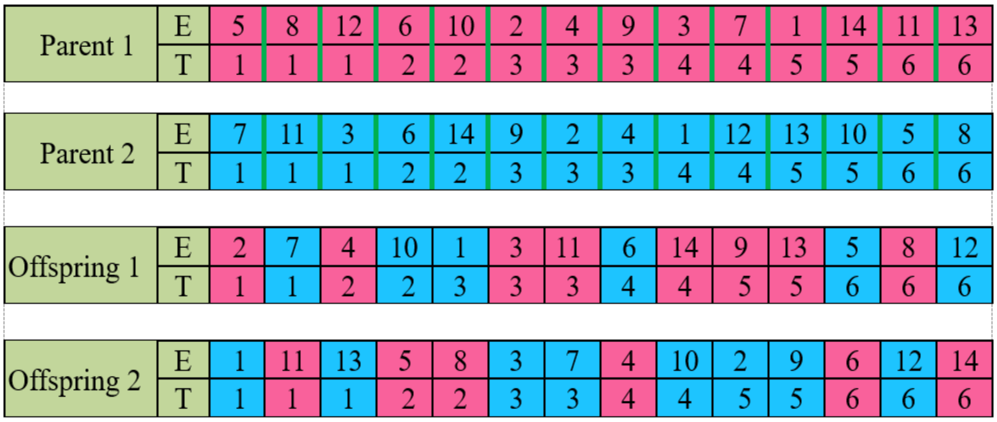


Parent 1	E	5	8	12	6	10	2	4	9	3	7	1	14	11	13
	T	1	1	1	2	2	3	3	3	4	4	5	5	6	6
Parent 2	E	7	11	3	6	14	9	2	4	1	12	13	10	5	8
	T	1	1	1	2	2	3	3	3	4	4	5	5	6	6
Offspring 1	E	5	8	12	6	14	9	2	4	1	3	13	10	7	11
	T	1	1	1	2	2	3	3	3	4	4	5	5	6	6
Offspring 2	E	7	11	3	6	10	2	4	9	12	5	8	14	1	13
	T	1	1	1	2	2	3	3	3	4	4	5	5	6	6

Fig. 4.5 *Single point crossover*

- **Uniform Crossover**

This type of crossover, sometimes referred to as the crossover rate, establishes the values assigned to genes in the child chromosomes with a certain likelihood. In contrast to certain crossover types that combine the parent chromosomes at the segment level, it also allows for the combination of the genes. A set of genes will be taken from the first parent and the remaining genes from the second parent if the crossover rate is approximately 0.7. The uniform crossover pseudo code illustrates how the genes (chromosomes) from both parents are chosen at random. The consistent crossing following the repair procedure is shown in Figure 4.6.

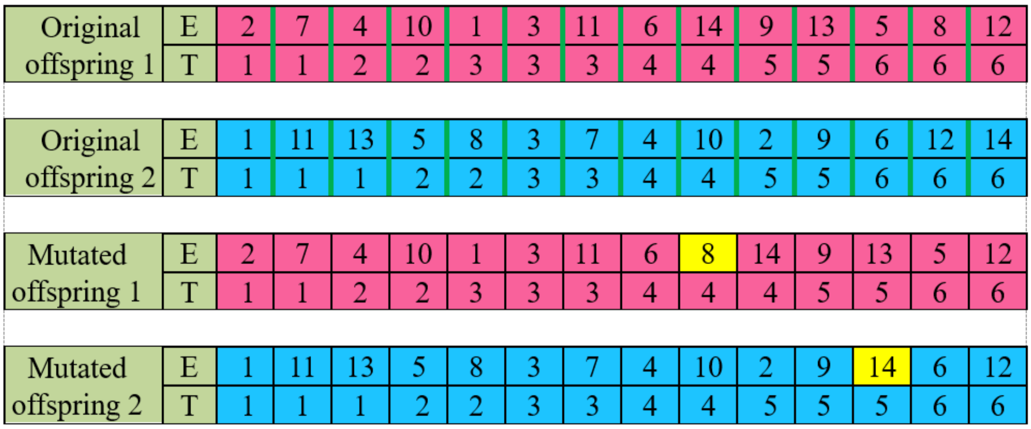


Parent 1	E	5	8	12	6	10	2	4	9	3	7	1	14	11	13
	T	1	1	1	2	2	3	3	3	4	4	5	5	6	6
Parent 2	E	7	11	3	6	14	9	2	4	1	12	13	10	5	8
	T	1	1	1	2	2	3	3	3	4	4	5	5	6	6
Offspring 1	E	2	7	4	10	1	3	11	6	14	9	13	5	8	12
	T	1	1	2	2	3	3	3	4	4	5	5	6	6	6
Offspring 2	E	1	11	13	5	8	3	7	4	10	2	9	6	12	14
	T	1	1	1	2	2	3	3	4	4	5	5	6	6	6

Fig. 4.6 *Uniform crossover*

5. Mutation

To maintain genetic variation throughout generations of chromosomal populations, mutation is used. A mutation modifies the original values of one or more chromosomal genes. As seen in figure 4.7, the altered gene values will be added to the chromosome's gene pool. The genetic algorithm might be able to produce a better answer than the one that was previously obtained thanks to the new gene values. Generally speaking, the mutation keeps the genetic algorithm from becoming trapped in local optima. The selected gene value is essentially inverted by the mutation operator. This kind of mutation is known as an insertion mutation, in which the test is chosen at random from one time slot and inserted into another time slot without creating a conflict.



Original offspring 1	E	2	7	4	10	1	3	11	6	14	9	13	5	8	12
	T	1	1	2	2	3	3	3	4	4	5	5	6	6	6
Original offspring 2	E	1	11	13	5	8	3	7	4	10	2	9	6	12	14
	T	1	1	1	2	2	3	3	4	4	5	5	6	6	6
Mutated offspring 1	E	2	7	4	10	1	3	11	6	8	14	9	13	5	12
	T	1	1	2	2	3	3	3	4	4	4	5	5	6	6
Mutated offspring 2	E	1	11	13	5	8	3	7	4	10	2	9	14	6	12
	T	1	1	1	2	2	3	3	4	4	5	5	5	6	6

Fig. 4.7 *Mutation operator*

C. Parameters of GA

1. Crossover Rate

The goal of crossover is to produce new chromosomes that might be superior to the parent chromosomes in terms of attributes. If there is no crossover, the children can be regarded as being exact replicas of their parents. If there is crossover, the child can be regarded as having both parents' chromosomes because the crossover rate is often between 60% and 70% [198]. All offspring can be regarded as having been created by crossover if the crossover rate is 100%. But the chromosomes will remain the same and pass on to the following generation.

2. Mutation Rate

The mutation rate is used to determine the amount of the mutated chromosome part. The offspring are created directly after crossover without any alteration (replica) if the mutation does not exist. The mutation will occur based on the mutation rate which lies between 0.1% to 1% [198]. If the rate of the mutation is 100%, then the entire chromosome will be altered. Mutation should not occur frequently; otherwise, the genetic algorithm will turn out to random search.

The extent of the altered chromosome portion is determined by the mutation rate. If there is no mutation, the offspring are produced immediately following crossover without any modification (replica). According to the mutation rate, which ranges from 0.1% to 1%, the mutation will take place[198]. The entire chromosome will be changed if the mutation rate is 100%. If mutations happen too often, the genetic algorithm will become a random search.

3. Population size

The number of chromosomes in the population (in one generation) is determined by this parameter, which is regarded as one of the crucial parameters in the genetic algorithm. Because only a small portion of the search area is covered, the genetic algorithm's search process is quick in cases when there are few chromosomes (small population size). However, if there are many chromosomes (a large population size), the search process slows down since there are more explorations.

4.2.2 Artificial intelligence techniques

The majority of power system research techniques rely on physical modeling and analysis, which has proven difficult to manage given the growing complexity and uncertainty of the system. Consequently, self-learning Artificial Intelligence (AI) methods that rely less on mathematical representations of physical systems can offer practical answers [199], [200].

A. Overview of AI Techniques

AI primarily refers to the creation of systems, such as computers, computer-controlled robots, or software, that exhibit human-like intelligence, reasoning, problem-solving, and the capacity to think and learn from previous experiences.

Power systems primarily address the substantial data produced by system evolution and the incorporation of various components, including DERs, electric vehicles, smart meters, ESSs, and communication infrastructures. AI techniques are utilized in power systems to solve the issue since traditional computing approaches are unable to effectively handle and process large amounts of data [201], [17]. The following classes are the primary categories into which AI techniques in power systems can be divided [202]:

1. Algorithms for machine learning, encompassing:
    - Supervised learning: a class of machine learning (ML) which learns a function to map inputs to outputs according to labeled datasets/example input-output pairs.
    - Unsupervised learning: a class of ML that learns patterns from unlabeled datasets.
    - Reinforcement learning (RL): a category of machine learning pertaining to the actions of intelligent agents aimed at maximizing cumulative reward.
2. Ensemble methods: techniques that integrate the output of several AI algorithms to overcome an algorithm's shortcomings while producing better outcomes.

3. Expert Systems (ES): a computer program that simulates a human expert's decision-making process to address issues.

Figure 4.8 displays the schematic representations of a few common AI techniques. These methods can be applied to various power system applications to enhance its efficiency, performance, and other characteristics.

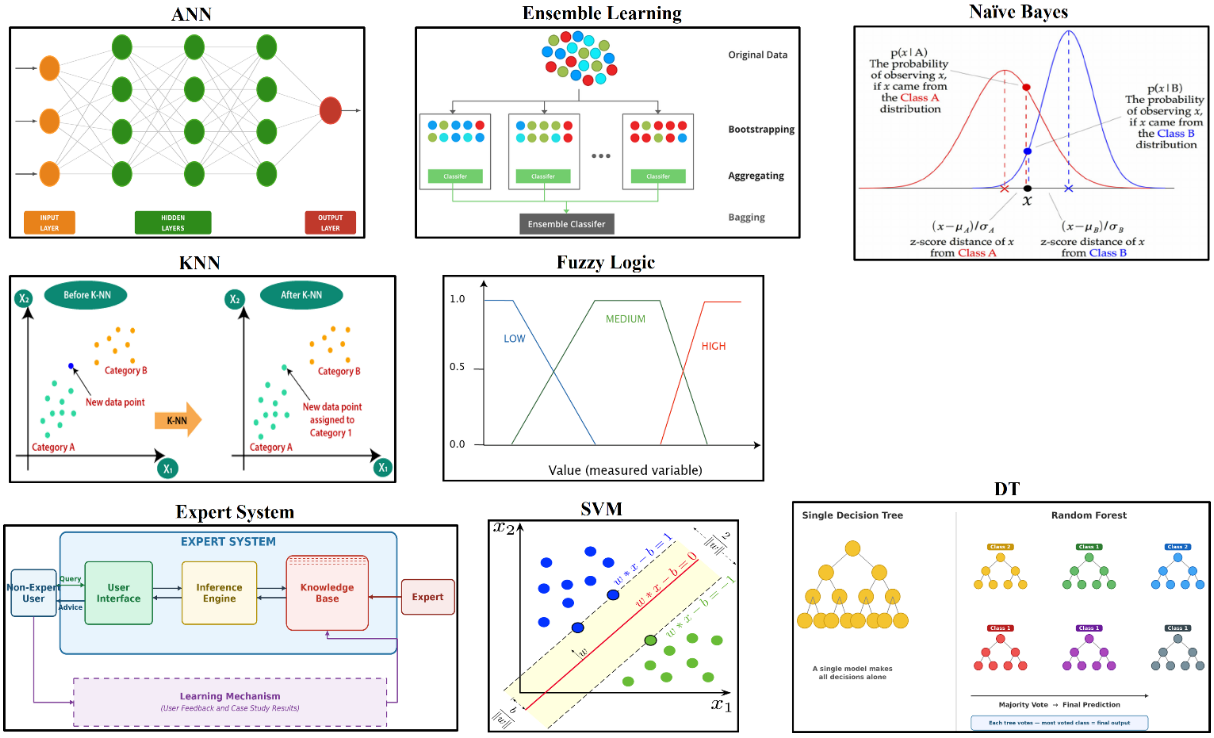


Fig. 4.8 *Diagrams for various typical AI methodologies.*

B. Using AI for Power System Problems

Energy conversion systems can be divided into two categories that aid in defining the need for sophisticated control systems: (i) unconstrained energy systems and (ii) constrained energy systems, which are those that are approaching a finite energy and, typically, a finite maximum power. Systems based on RES (wind, solar, tidal, geothermal) and fossil fuels (gas, coal, oil, hydrogen) and thermodynamic cycles. Renewables are only sustainable if the amount of energy conversion is less than the amount of energy recovered by the environment. However, they are still limited because the energy derivative needs to be optimized, and a convex function would normally define such a real-time based optimization.

A number of factors will need to be taken into account, and AI will progress effective energy conversion for electrical power systems based on these assumptions:

1. Variability in parameters that can be made up by using designer judgment,
2. Procedures that are not mathematically modelable but can be modeled linguistically,
3. Using operator discretion to set the goal of increasing efficiency,
4. When the system relies on the abilities and focus of the operator,
5. Every time a process parameter influences another,

6. Data-intensive modeling (using parametric rules): Temperature, density, and impedance are among the variables that vary.
7. Impacts that independent PID control cannot achieve,
8. Deadband, time delay, non-linearities,
9. Input and output variable cross-dependence.

Three paradigms are commonly employed for energy conversion systems utilizing AI/ML: (i) function approximation or input/output mapping, (ii) negative feedback control, and (iii) system optimization.

The initial step involves model development, the subsequent step entails comparing a set-point with an output capable of driving the system, and the last step consists of searching for parameters and system circumstances that will optimize or minimize a specified function. AI methodologies, like fuzzy logic and neural networks (NN), facilitate a robust and dependable deployment. The incorporation of contemporary power electronics, power systems, communications, information, and cyber technologies, alongside a significant integration of RESs, is at the forefront of microgrid and smart grid design and implementation[203], [204].

The next part provides a brief overview of machine learning techniques and their applications in power systems due to their significance and broad range of applications.

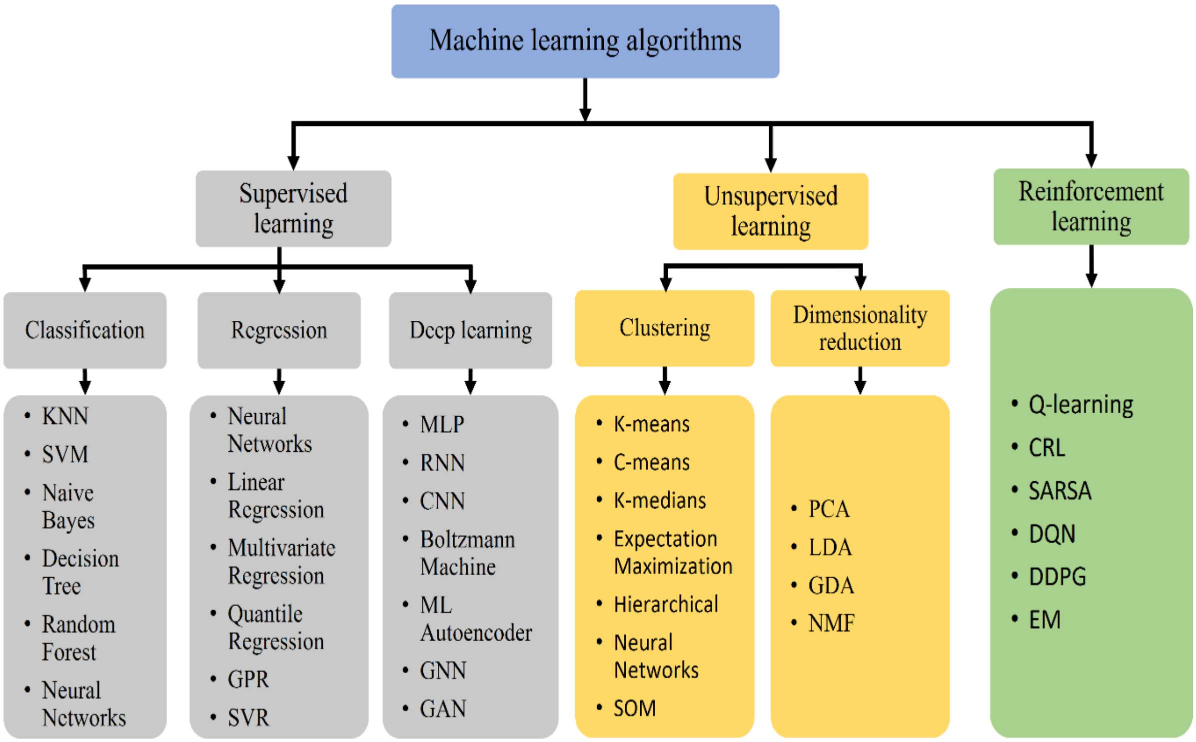


Fig. 4.9 *Different types of algorithms for machine learning [205],[206].*

C. Machine Learning

Supervised learning, unsupervised learning, and reinforcement learning are the three primary categories of machine learning. These methods are applied to a variety of applications, including dimensionality reduction, clustering, regression, and classification. Types of machine learning algorithms are depicted in Figure 4.9 [207]. For network admittance, parameter and topology estimation, fault diagnosis, load forecasting, renewable power forecasting, energy price forecasting, power flow modeling, and power system online sensitivity identification, regression-based algorithms with a real or continuous output variable were employed in power systems [207]. For defect detection and classification, power quality disturbance classification, power system security assessment and classification, power system stability classification, and islanding classification, classification algorithms with a discrete value as the output variable were employed. Among these techniques, decision trees, support vector machines (SVM), and ANNs have shown reliable and suitable performance in classification tasks.

Deep learning uses numerous layers to extract various properties from raw input, relying on ANNs for representation learning. Power system transient stability prediction, voltage instability prediction, load forecasting, and renewable power forecasting are among the issues that deep learning algorithms have been applied to [208]. One of the most promising approaches for unsupervised learning in complicated distributions is the generative adversarial network (GAN), a deep learning model that was first presented in 2014. The generative model and the discriminative model are the two modules that make up the GAN. Power system dynamic security assessment with missing data [209], short-term power system scheduling [210], risk assessment [211], power system dynamic state estimation [212], and phasor measurement unit data production for better event classification are all applications of GAN approaches.

Conventional deep learning methods are suitable for extracting features from Euclidean data, however several practical applications use data collected from non-Euclidean domains. To address this issue, researchers devised graph neural networks (GNNs). A graph is a type of data structure, often comprising nodes and edges. The node encompasses entity information, whereas the edge conveys relational information between entities. GNNs can be classified into five groups, as illustrated in Figure 4.10.

GNNs are deep learning algorithms that leverage the qualities of nodes and edges to enhance feature extraction capabilities GNNs have been employed in power system analyses for many applications. Figure 4.11 illustrates several applications of GAN and GNN as sophisticated AI methodologies in power system analyses.

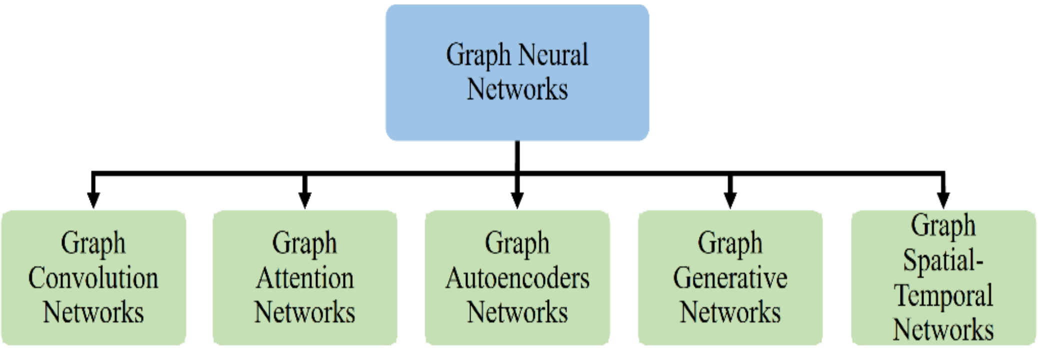


Fig. 4.10 *Different categories of GNNs.*

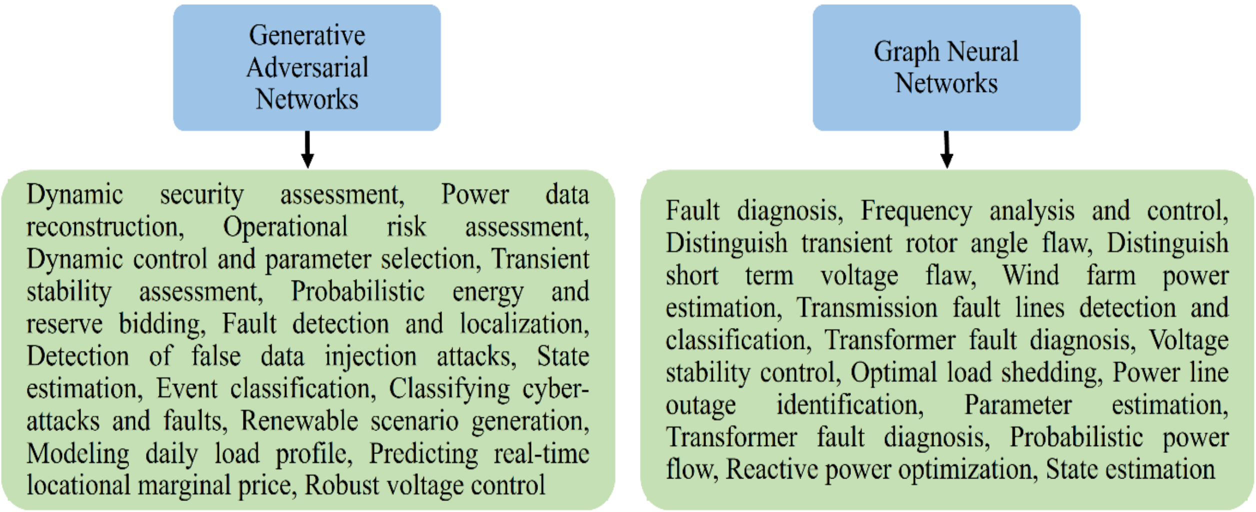


Fig. 4.11 *Different applications of GANs and GNNs in power system.*

Energy management, attack detection, load frequency control, power system resilience, power flow analysis, and power system stability regulation have all made use of reinforcement learning as a machine learning technique [213]. As unsupervised algorithms, clustering and dimensionality reduction techniques have been applied to a variety of problems, including power plant predictive control, electricity customer classification, load curve pattern recognition, power plant reliability modeling, power quality evaluation, power system capacity expansion modeling, electricity price forecasting, and load profiling [214].

4.2.3 Application of AI techniques in MGs

AI is applicable to MG/smart grid and RES. Here are a few examples of these applications: (1) EMSs, (2) PV and wind generation curve forecasting, (3) Forecasting the grid's consumer load, (4) Fault-tolerant control, protection plans, and online fault diagnostics, cyberattack detection, (6) delay-less and noise-free signal filtering, (7) robust feedback signal estimation without a sensor, (8) NN modeling of static and dynamical system components, and real-time simulation using DSPs and FPGA chips, (11) Real-time energy pricing predictions with demand-side management; (10) Intelligent scheduling of generation and storage; and (9) High performance intelligent control of system elements. The parts that follow go over some of the most significant uses of AI in MGs.

A. Microgrid Energy Management

In light of both technological and financial operational considerations, energy management in MGs is a crucial issue. Model-based and model-free EMSs are two types of EMSs that fall under this category. In order to create precise models and parameters for an MG, model-based EMS depends on domain expertise. Therefore, this approach has high development costs because it is neither scalable nor transferable. However, the MG uncertainties could result in parameter redesign, which would raise maintenance costs considerably. [215].

Learning representations of nearly ideal control schemes in the MG from its operational data is one example of a model-free or data-driven approach. Using learning-based techniques can improve the EMS's scalability, save expenses, and lessen need on an explicit system model.

In [216], a data-driven stochastic energy management system based on GANs for isolated MG was developed, taking into account the reactive power cost and the reactive power capability of DERs.

To model the uncertainties in the output power of the RESs to be used in the formulation of stochastic programming, the GAN was employed as a data-driven scenario generation technique. In [217], the use of GANs to secure optimal energy management in MG was covered. It was looked into how data integrity assaults affected the MGs' central control, which can lead to serious load shedding and blackouts. A probabilistic power flow technique based on Graph Convolutional Networks (GCN) was proposed in [218]. The study's two primary contributions are the GCN framework, which uses only the power grid's topology and no prior electrical knowledge. Second, compared to traditional Monte-Carlo approaches, it significantly cuts down on computation time while maintaining good accuracy.

Due to their independence from the nonlinearities of MG components, fuzzy logic controllers (FLCs) do not necessitate complex mathematical modeling. This results in a comprehensive EMS based on simplified linguistic rules and lowers the control complexity, particularly for an MG with numerous components and various operating modes. An energy management method based on FL supervision for electric cars with a fuel cell (FC) and two ESSs, such as batteries and supercapacitors (SCs), was tested in [219] using an experimental MG. In [220], the FL-based EMS method was proposed for optimal control of a home MG's battery system. For FLC design in EMS research, low complexity, including input and rule numbers, must be considered [221].

For EMS of MGs, uncertainty management is a problem. In [221], the battery was too big to handle this issue, which is not the best way to handle it. Using techniques like radial basis function NN, a combination of several ANNs, or ANN with other methods, load and renewable power sources like solar and wind can be forecasted to manage uncertainties in EMS [222]. The primary goals of EMS-based research using various ANN types are to reduce production costs, improve RER utilization, and reduce emissions [222]. Because online EMS can address uncertainties by examining real-time data, it is more favorable when taking into account the sporadic nature of RESs and the high degree of stochasticity in market pricing and loads. Traditional online methods such as model predictive control employ a separate forecaster, but reinforcement learning techniques [223] can train a function from historical data. However, RL techniques usually suffer from lengthy training, complex restrictions, and dimensionality problems caused by the continuous state and action space. An overview of AI-based techniques for EMS in MGs is given in Table 4.1.

Table 4.1 Summary of AI-Based techniques for EMS in MGs

Ref.	Proposed method	Contribution	Limitation	Demonstration
[224]	Fuzzy logic	For MG's EMS, a low-complexity FL controller with just 25 rules minimizes variations in the grid power profile.	The battery is too big to manage uncertainties, and degradation is not taken into account.	Simulation and real-world MG experiment.
[213]	Reinforcement learning and dynamic programming.	maximizing client pleasure, battery life, environmental friendliness, self-sustainability, and dependability.	Coordination of active and reactive power dispatches, real-time implementation, and dynamic state prediction were not taken into account.	Simulation models.
[225]	Imitation learning	Reduce training time and address dimensionality problems in Reinforcement	Only the economic element of MGs is taken into account; battery	Numerical studies,

		learning (RL) EMS caused by the continuous state and action space, complicated restrictions, and slow training.	degradation, complex formulation, and system losses are ignored.	simulation models.
[226]	Fuzzy logic	Using multi-agent FL, a distributed EMS that can be configured in a chaining fashion is used to regulate the energy flow in hybrid energy systems.	System losses and battery deterioration are not taken into account.	Simulation models.
[222]	Bee colony and ANN and Markov chain	Demand response is taken into consideration, along with lowering manufacturing costs, speeding up convergence, and enhancing accuracy and efficiency in unpredictable situations.	Battery deterioration and voltage and frequency control are not taken into account.	MG test bed in experimentation.

B. Load and Generation Forecasting in MGs

Considering the fluctuating nature of loads and the growing penetration of RESs like solar and wind in MGs, MGs are confronted with problems and greater uncertainty. For system operation and planning, load and generation forecasting are thought to be a way to increase MG stability and dependability. However, given the extremely non-smooth and nonlinear character of the load/generation time series, forecasting load/generation is difficult. Load forecasting (LF) can be divided into three categories based on the time horizon of the studies: short-term LF (STLF), which predicts the load from minutes to hours, mid-term LF (MTLF), which predicts the load from hours to weeks, and long-term LF (LTLF), which predicts the load for years. A number of variables, including metrological data, time, season, event, and client type, affect the electric load [207].

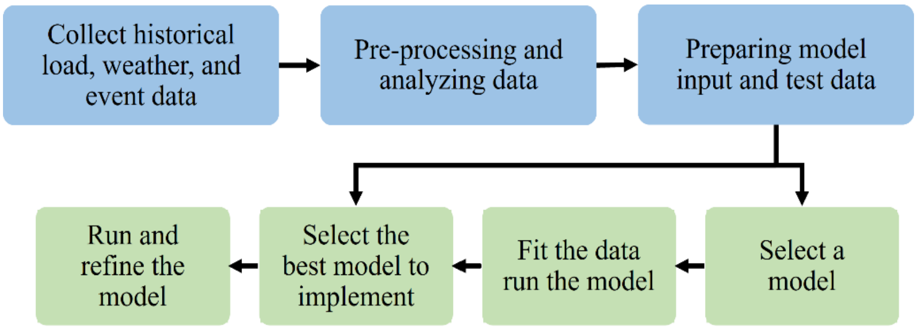


Fig. 4.12 *Diagram of developing a load forecasting model [205].*

The literature on load and generation forecasting encompasses various tasks, including data collection, data preprocessing, model design and selection, implementation, and validation. Figure 4.12 illustrates the design diagram of the load forecasting model.

To increase the dataset's dependability, the initial step in load and generation forecasting is data preparation, which reduces noise and separates trend data. Numerous methods, including as wavelet decomposition, principal component analysis, empirical mode decomposition, fuzzy information granulation, and singular spectrum analysis, have been applied in this situation [227].

Following data preprocessing, a forecasting algorithm is used. By doing this, academics have attempted to create new algorithms or enhance those that already exist. One of the most often used approaches for load and generation forecasting in MGs is AI-based methodology. These techniques fall into two categories: single and hybrid models. ANN, SVM, FL, adaptive neuro-fuzzy inference system, self-organizing map, and extreme learning machines have all been used in single models [228], [229]. In contrast, hybrid approaches have combined a number of algorithms, including ANN with wavelet, ANN with FL, ANN with SVM, ANN with metaheuristic algorithms, and SVM with other algorithms.

The use of ANN in MGs has drawn the most interest among the LF approaches. The proper tuning of parameters such as layers and nodes affects how well ANN-based forecasting algorithms function. Furthermore, many ANN learning techniques, including gradient-based approaches, may experience overfitting while extracting the mapping functions or become stuck in the local extremum [230]. Combining ANN algorithms or ANN with other methods has been suggested as a solution to this problem [231], [232]. Nevertheless, hybrid approaches have more parameters even though they can boost performance. Therefore, techniques like metaheuristics and trial-and-error were employed to fine-tune the ANN's parameters.

Since intermittent RESs like wind and solar are an integral part of MGs, improving the prediction accuracy of these sources is crucial for a variety of activities, including management and control. For predicting wind speed/wind energy and irradiance/solar energy, studies have employed a variety of AI-based algorithms, including ANN [233], SVM, and hybrid approaches like ANN and SVM. For day-ahead short-term PV power forecasting, a weather categorization model based on GANs and CNNs was proposed in [234]. A data-driven approach based on two interconnected deep neural networks for scenario development with GANs was introduced in [235]. In [236], a sequence GAN-based distribution-free method for creating wind power scenarios was introduced.

A convex optimization problem defines load and generation forecasts, which is aided by support vector machines. SVM avoids local minima, which is a benefit over ANNs. Support vector regression (SVR) machines were presented for generation forecasting and load forecasting in several studies [231] in order to overcome the two main problems with ANNs for load forecasting in the real world: overfitting and the curse of dimensionality. Other metaheuristic algorithms, such as GA and particle swarm optimization (PSO), have been used to enhance SVM's performance. Another important consideration in load or generation forecasting using SVR is the selection of kernel functions, which can affect calculation time and accuracy. In this regard, a different study uses four kernel functions-linear, radial basis function, polynomial, and sigmoid-to analyze how well SVR performs for load forecasting. Multiple kernel learning was investigated for load forecasting in [232]. In SVM-based models with numerous datasets, the execution and storage of the matrix consumes a significant portion of the computer memory and computing time. This makes it difficult for SVM-based algorithms to train large datasets. This problem was resolved using recurrent neural networks [237]. An overview of AI-based techniques for MG load and generation estimates is shown in Table 4.2.

Table 4.2 An overview of AI-based methods for MG load and generation forecasting

Ref.	Proposed method	Contribution	Limitation	Demonstration
[238]	ANFIS model, MLP-ANN, and RBF-ANN	lowering MG operating costs by accurately predicting the load, sun irradiance, wind speed, and ambient temperature.	model's intricate structure, large number of parameters, and tuning challenges.	Simulation
[239]	ANN	By creating a data fusion method that uses many ANNS, wind speed forecasting has the unusual ability to predict the overall trend of the upcoming year.	Low accuracy when there is a deficiency of current data and a reliance on recurring updates to build the model.	Simulation with actual metrological data from Malaysian regions
[233]	ANN	Four ANNs—non-linear autoregressive, feedforward, long short-term memory, and echo state network—are used to forecast global horizontal irradiance; the echo state network has the highest accuracy.	The method's application may be limited because it filters the data each time a fresh forecast is requested; the speed at which algorithms converge has not been covered.	Simulation using real data
[240]	PSO and SVM	For load forecasting with spikes, the least square SVM and PSO algorithms offer a higher accuracy than SVR, SVM, and ANN while avoiding issues with data volatility, insufficiency, and quality.	Large-scale dataset training is challenging for SVM since storing and computing the matrix requires a substantial amount of computer memory and processing time.	Simulation with data from Peng-Hu Island
[237]	Recurrent Neural Network	LSTM recurrent neural networks perform better than other approaches when used to forecast the load of non-residential users using multiple correlated sequence information.	load forecasting that ignores certain external elements, such as the region's existing economic stance and policy support.	China's simulation with actual data

C. Microgrid Fault Detection and Protection Systems

Because of their unique features, MG protection differs from traditional methods and distribution system protection. The following problems [241] may prevent the conventional protection methods from functioning properly in MGs: (2) Bidirectional power flow; (3) Dynamic characteristics of DGs operating in MGs; (4) Topological changes in the power grid due to the intermittent nature of DGs; (5) Type of DGs; (6) Location, number, size, and control type of DGs; (7) Variation of fault currents in various operation modes.

The primary obstacles to MG protection include increased fault current, variable short-circuit level, blinding protection, false tripping, automatic prohibition of reclosing, unsynchronized reclosing, relay interoperability, and a decrease in the range of remote relays [241].

1. Using AI Techniques for MGs' Fault and Islanding Detection and Classification

Fault detection is a crucial component of MGs protection. The existence of DERs and varied topologies may make it difficult to directly apply traditional fault detection and classification techniques used in distribution systems to MGs. As a result, these techniques ought to be modified or updated in light of various elements, including the dynamic nature of MGs, their topology, their modes of operation, and the features of the generating unit. There are three primary categories of methods used in the literature for defect detection and classification in MGs: model-based methods, AI-based methods, and signal processing-based methods [242].

In the literature, many AI-based methods were used, including type-2 FL [243], fuzzy rule-based intelligent protection system inspired by decision trees [244], FL for islanding detection [245], and ANNs and SVMs for defect detection and classification. For all electric ship MVDC power systems, a real-time defect detection and localization technique based on GANs was proposed in [246]. The findings demonstrated the classification method's 99% accuracy and anti-noise capacity. For DC series arc defect diagnosis in PV systems, a domain adaption and deep convolutional generative adversarial network (DA-DCGAN)-based methodology was presented in [247].

Transmission line transient faults [248], transformer faults [249], and power line outages are just a few of the MG and power system defects that graph convolutional networks have been utilized extensively to diagnose. In [250], GCN was utilized to locate distribution network faults. The suggested approach takes system topology into consideration while integrating multiple measurements at different busses. In [251], the effectiveness of a number of machine learning (ML) techniques, including decision trees, K-nearest neighbor (KNN), support vector machines, and Naive Bayes, was evaluated for fault classification in MGs while taking the optimal wavelet function into consideration. The KNN performed better than the other techniques, achieving an accuracy of 95.63%.

2. Protection Schemes Based on AI

For MG protection, several adjustments may be necessary to traditional protection techniques such distance protection, differential and directional protection, overcurrent relays, under/over voltage, and under/over frequency [242]. Adaptive protection, which updates the settings based on the dynamics and variations of MGs, is one technique used for MG protection. A overview of adaptive protection of MGs, which makes use of several AI approaches, was presented in [241]. An adaptive overcurrent protection approach for distributed systems with fault current limiters and distributed generators was covered in [252]. A rule-based adaptive protection solution using machine learning techniques was introduced for MGs in [253].

A hybrid ANN-SVM model is used for state recognition, where adaptive reconfigurations can be implemented with improved decision-making to change the relay settings and the grid topology to achieve the intelligent reliable operation. From a data mining perspective, the Pearson correlation coefficient can be used to analyze the uncertain elements in MG. Based on fuzzy logic and graph algorithms, a central protection system with overcurrent protection capacity was put into place for reconfigurable MGs in [254]. A hybrid fuzzy-optimization method for adaptive relay settings and optimal coordination was used in [255] to construct a numerical relay. Table 4.3 provides an overview of AI-based MG protection strategies.

Table 4.3 An overview of AI-based methods for research into MG protection

Ref.	Proposed method	Contribution	Limitation	Demonstration
[251]	Naive Bayes and decision trees.	The J 48 decision tree performs better than Naive Bayes when appropriate characteristics are extracted from local electrical data and Naive Bayes and decision tree classifiers are used for improved fault discrimination and localization.	Fault direction, topology change, grid-connected mode, and the switch from grid-connected to islanded modes are not taken into account (HIF).	Numerical simulation.
[243]	FL	Less processing is required compared with training-based methods when detecting, classifying, and localizing MG errors using an interval type-2 fuzzy logic system.	Only single-phase faults are taken into account; topology changes, fault direction, and high impedance faults (HIF) are not.	Simulation
[245]	ANFIS	Accurate and quick, ANFIS-based islanding detection for microgrids reduces the NDZ through a combination of passive measures without compromising power quality.	reliance of the method's performance on the quantity, quality, and duration of training samples.	Simulation end experimental
[252]	DT and ANN	Distributed systems with DGs and FCL can benefit from overcurrent adaptive protection, which allows OC relays to communicate based on data produced by FFT to assess their own operating conditions.	There is no discussion of FCL's transient response.	Simulation
[253]	ANN and SVM	Analysis of unknown elements in an MG by Pearson correlation coefficients from data mining, topology change, and fault location are taken into consideration using a rule-based adaptive protection mechanism that uses ANN-SVM methodology.	Numerous data sets, intricacy, a heavy computing load, and training.	Simulation using an IEEE 9-bus system and an MG model at Aalborg University.

D. AI Methods for Power Electronic Control in MGs

A MG's power electronic components, which link RESs, ESSs, and other loads to the AC or DC busses, are a crucial component. Applications of AI in power electronics, including design, control, and maintenance, have been documented in the literature [256]. AI is being used to control power electronic devices through modulation, energy management, Maximum Power Point Tracking (MPPT) in wind and photovoltaic systems, and PID controller parameter tuning.

Conventional control has provided several methods for designing controllers for dynamic systems. For the system to be regulated, each of them needs a mathematical formulation and a specific methodology for designing a closed-loop control. These control strategies will use data from mathematical models in a number of ways. Certain heuristic information may not always be taken into account during the design phase; instead, heuristics are used to fine-tune the controller after it is put into use. This is always necessary because the model used to construct the controller is not entirely accurate. By allowing heuristics and learning from previous case studies or numerical data, fuzzy logic and NN address precisely these lack of real-life understanding by heavily math-oriented control designers. They typically retrofit an excellent performance controller, which frequently outperforms heavily mathematical control design approaches. To install an ANN-based controller, first during the system identification phase, a NN model of the plant that has to be managed is made. In the control design stage, a NN plant model will be used to train a controller. One of three designs-model reference control, adaptive inverse model-based control, or model predictive control may be used after the system has been identified. Heuristic methods can be used to fine-tune parameters. In the literature, FL controllers were used to regulate the duty ratio of DC/DC boost converters integrated with PV systems [257] and the output voltage of a phase-shifted PWM (PS-PWM) soft-switching DC-DC converter [258]. The computational demand of fuzzy controllers can be one of their disadvantages, since it can impact the converter's reaction to abrupt changes in load. By using look-up tables and appropriate interpolation techniques, this problem can be resolved.

The output voltage of the converter was controlled by adjusting parameters like the duty cycle of switches using other techniques such an adaptive fuzzy neural network control [61], optimized back propagation ANN, and a neuro-fuzzy controller [259]. By fine-tuning and refining the controller parameters, some research used optimization algorithms like GA [260] and whale optimization [261] to further enhance the efficiency of converters controlled by AI techniques. One of the most important issues with RESs is tracking the maximum power point, which is achieved by controlling the power electronic converters. Consequently, a number of AI-based MPPT techniques were proposed, such as FLC and ANNs. FLC is more effective than other MPPT techniques and provides greater flexibility in modifying PV system MPPT parameters. Because FLCs make it easier to modify the control system, the system will be more compatible with the uncertainties and nonlinearities of the system [262].

Machine learning has been applied to MPPT control systems. The modules' inputs, which include temperature, irradiation, open circuit voltage, and short circuit current, can be used as inputs for an alternate controller or as inputs for the ANN that controls the converter [265]. As shown in wind and PV systems, ANNs can provide an MPPT that is sufficiently accurate without requiring in-depth knowledge of the system model or parameters. Table 4.4 provides an overview of AI-driven approaches for controlling microgrid power electronics.

Table 4.4 A review of methods for controlling power electronics in MGs that use AI

Ref.	Proposed method	Contribution	Limitation	Demonstration
[258]	FLC	Using lookup tables built from the original FLC to suppress high computational demand and lower expenses, FLC is used to control the output voltage of a phase-shifted PWM soft-witching DC-DC converter.	The optimization parameters of the lookup table, the lack of fuzzy information, and the high computing demand while employing the original FLC.	Laboratory setup for simulation and experimentation
[257]	FLC	In order to reconcile the duty ratio of the DC-DC boost converter, a fuzzy logic-based controller is used in conjunction with MPPT approaches such constant voltage controller and FLC to study duty ratio control of the boost converter.	There is no discussion of controller convergence, dynamic performance of the system under different situations, or stability of the system.	Simulation
[259]	Back propagation ANN controller.	Sharp variations in temperature and irradiance are taken into consideration when using back propagation ANNs to operate boost converters in photovoltaic systems. ANN structure optimization is done for easy hardware implementation and improved performance.	The ideal structure is determined by trial and error of a few options that might not be a global answer; stability analysis is not provided; and a systematic approach for ANN design is not taken into consideration.	Commercial PV array models are simulated.
[263]	ANN-based reinforcement learning for MPPT in wind turbines	When ANNs and the Q-learning technique are used for MPPT in PMSG wind turbines, the MPPT algorithm can learn online, increase efficiency, and adjust to system aging.	The transition from the MPPT to the constant power region is not covered, and the wind speed range is constrained.	An emulator for simulation and experimentation
[264]	ANN for MPPT in PV systems	For MPPT in PV systems, ANN-based Levenberg-Marquardt (LM), Bayesian Regularization, and Scaled Conjugate Gradient (SCG) algorithms are employed; LM performs better.	More real data in clear and foggy settings is needed to assess algorithm performance in real-world scenarios; optimal network design has not been covered.	simulation that trains on actual field data.

E. Microgrid Cyber-Attack Detection Using AI Techniques

The proliferation of cyber-physical systems (CPSs) has brought greater focus to the significance of these systems and prompted increased research into them. MG is susceptible to various cyber-attacks, just like any other CPS. With the proliferation of MGs in many sectors, including renewable energy, electric power distribution, and electric transportation, the problem of cyber-attack detection in MGs has grown in importance [272]. A few examples of cyberattacks are control system attacks, false data injection (FDI), communication delay, denial of service (DoS), and sensor attacks [273]. These assaults pose a danger to the secure and effective functioning of the system and have the potential to impact the economy, stability, and reliability of MG.

Methods for cyber-attack detection have been proposed in the literature among them the AI-based techniques have attracted more attention due to their efficiency and accuracy. These techniques include deep learning [267], recurrent neural network [268], Hilbert-Huang transform and deep learning [274], deep learning, wavelet transform, and singular values approach, ANN [269], SVM, AI-ES fuzzy system [275].

Cyber-attack detection in power systems and MGs was accomplished with GANs. One method for finding distribution systems with unobservable FDIAs was suggested in [276] and it relies on data-driven learning. This study successfully finds abnormalities under FDIAs by integrating autoencoders into GAN framework. In order to categorize cyber-attacks and flaws, a novel adversarial generative framework was suggested in [277] that learns from skewed class distributions.

In order to identify and avoid cyberattacks on smart grids, more ML-based techniques are reviewed in [278]. Dynamic Bayesian networks, extended closest neighbor, Q-learning, K-means, and K-NN are all examples of such techniques. There have been claims that these methods achieved accuracy levels above 93.76% when used to deep learning and the Hilbert-Huang transform, 95% when applied to the singular values approach and wavelet transform, and 96% when applied to the fast Fourier transform and singular value decomposition.

Energy system and MG cybersecurity measures are still seen as add-ons rather than built-in functions [279]. This is particularly true in light of the absence of modernized standards and shared market trends. In order to address overlooked or ignored aspects of economic and social growth, it is necessary to employ multidisciplinary techniques. The methods for controlling MG power electronics that are based on artificial intelligence are summarized in Table 4.5.

Table 4.5 Overview of AI-based methods for MG cyber-attack detection

Ref.	Proposed method	Contribution	Limitation	Demonstration
[266]	SVM	To identify covert smart grid attacks, we use support vector machines (SVMs) trained with supervised learning to train a distributed SVM. We then propose an ML-based approach that can detect measurement deviations with no computing overhead and no training data at all.	Failures and transients, such as variations in load, are not taken into account.	Simulation

[267]	Deep learning	By analyzing past measurement data and using the identified features, we can identify foreign direct investment (FDI) attacks in real-time with deep learning. We then propose a model for electricity theft that outperforms SVM and ANN in terms of accuracy.	The suggested detection system relies on pattern recognition sensitivity; however, it does not take into account the practical behaviors of FDI attacks and does not stipulate a minimum number of sensing units.	Simulation on IEEE 118-bus system and MGs.
[268]	Recurrent NN	A nonlinear auto-regressive exogenous model NN is used to estimate dc voltages and currents, and recurrent NN is used to detect FDIAs in DC MGs and identify the attacked DER units. The method relies on time-series analysis.	When there are a lot of available units or when numerous loads change at once, the system's performance could suffer; appropriately calibrated ANN is necessary for optimal performance.	Modeling in Simulink and OPAL-RT for real-time simulation
[269], [270]	ANN	A technique for FDI removal that relies on an ANN-based reference tracking applicationSimilar to DC microgrids that use parallel DC-DC converters, but with load fluctuations, variable FDIAs, and control signal latency taken into account.	False data that varies over time can impact the system, although most studies have concentrated on FDIAs where the false data value is constant.	Simulation
[271]	Coupled ANN-fuzzy expert	By employing a physical model-checking method that is integrated with AI and ES. for the purpose of identifying cyber-attacks or human-made directives that alter the circuit breaker's switching behavior.	Not taken into account are changes to the system topology, including the addition of new buses or power equipment, as well as changes to the load.	Modeling of MGs with the IEEE 14-bus system

F. AI Methodologies for Different Applications in MGs

AI is used in MGs for purposes other than power electronics. Generators and induction motors are commonly used in MGs. In order to manage torque and flux with virtual d-q currents, the inverse model of an induction motor/generator is mathematically resolved. To create the pulse-width modulation of transistors in a three-phase inverter that controls the induction machine, the controller response is then reverse-calculated in real-time. Trigonometrical Park and Clarke transformations and decoupled d-q equations form the foundation of this intricate instantaneous model. Neural networks and fuzzy logic seem to be the best options for processing information from non-linear functions, maximizing flux, and regulating the speed of induction motors.

Intelligent protection and monitoring could be another use of AI in MGs. A small-scale wind farm built within an MG, for instance, might be planned for intelligent protection and monitoring. The signals to be obtained in such an application should be:

- Wind signals: velocity, wind direction, turbulence of blade, yaw angle, shaft torque, mechanical brake signal, tip-speed- ratio.
- Gear box: oil temperature, oil viscosity, noise intensity, vibration, nacelle temperature.
- Wind signals include shaft torque, yaw angle, wind direction, tip-speed ratio, turbulence of the blade, and mechanical brake signal.
- Generator: stator voltages, phase sequence, percentage of imbalanced terminal voltages and currents, stator currents RMS, average, peak, stator frequency, active power, reactive power, shaft torque, bearing temperatures, shaft vibration, stator winding temperature distribution, rotor magnet temperatures.
- Converter: output frequency, ac line voltages, dc-link voltages, dc-link currents, dc-link power, cooling fluid velocity, converter temperatures, active power, reactive power, motoring/regeneration mode, and phase imbalance of voltages and currents.
- Wavelet and Fourier expansion of certain signals.

Sensors or adaptive sensorless estimation can be used to monitor the signals and assess the overall health of a wind farm, as shown in Figure 4.13. If the signals' variation stays within a very acceptable range, the health conditions may be "excellent." The system can be deemed "very good" if some signals are outside of this range but are still extremely safe. The health index can also be categorized as "good," "fair," "poor," "unsafe," etc. for additional ranges. The diagnostic messages for the signals can be produced separately if any of them deteriorate. The system can be protected by shutting down if any signal exceeds the safe range for a fault situation. Eventually, a real-time smart-grid platform (like Opal-RT or other potential solutions) can incorporate similar health monitoring concepts into PV or other systems. In essence, real-world function approximation problems are system modeling solutions. These solutions can be state-space, or memory-based equations, where the output depends on the internal states plus previous inputs, or algebraic, or a mapping of input to output.

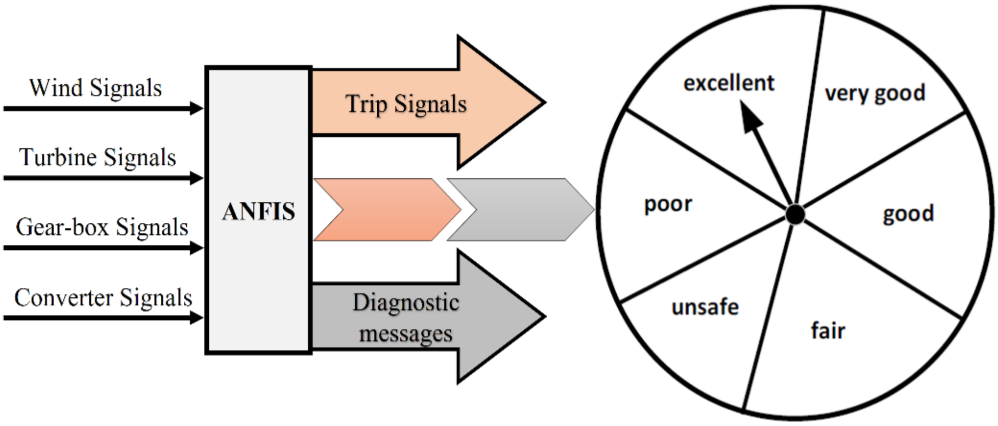


Fig. 4.13 *AI System for Monitoring Health on Wind Farms [205].*

Energy forecasting, load-flow modeling of large power systems, learning of non-linear functions in power electronics and power systems, estimation of poorly modeled systems, such as the effect of temperature variation on the resistance of the rotor of an induction motor, the non-linear response of capacitors, loss modeling of the transformer core, lifetime expectation of protection circuits, and many other applications that are typically very challenging to find a function approximation using pure mathematical theory, can all be supported by a neural network (NN), a very straightforward method for learning functions. Numerous issues pertaining to signal processing in power electronics, MG/power systems, and power quality can benefit from the use of function approximation. The estimation of warped waves is one instance.

G. Artificial neural networks Model

In this study, a MG system's power dispatch was optimized using an ANN. The network was designed and implemented using MATLAB's NN Toolbox, specifically using the $newff$ function to construct a feedforward multilayer perceptron. The model receives 16 input features representing grid conditions and produces 9 output values corresponding to the optimal power dispatch of distributed energy resources, including Battery storage, CHP units, and controllable loads.

With four hidden layers and neuron counts of [32, 64, 128, 64], the ANN design forms a symmetric diamond-shaped structure that expands and contracts the feature space. This design allows the network to first extract high-level representations and then compress them into meaningful output predictions. The input layer has 16 neurons corresponding to the 16 input features, and the output layer has 9 neurons for the 9 dispatch targets.

The trained model was evaluated using two complementary metrics: Root Mean Squared Error (RMSE) for absolute error in MW, and sMAPE for symmetric percentage error. Both metrics were computed for each of the 9 outputs individually and for the overall balancing Power.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(y_{true} - y_{pred}\right)^2} \tag{4.1}$$

The RMSE measures the average magnitude of the prediction error in the same unit as the output (MW). It is computed by taking the square root of the mean of all squared differences between the target (true) values y_{true} and the predicted values (y_{pred}) over all N samples. Lower RMSE indicates better model performance, and unlike MSE, RMSE is directly interpretable in physical units.

The Symmetric Mean Absolute Percentage Error (sMAPE) measures the average percentage error between the targete (true) values y_{true} and the predicted values y_{pred}, using symmetric denominator that averages both the target and predicted magnitudes. The small constant $\epsilon = 1 \times 10^{-6}$ is added to prevent division by zero when both values are close to zero. The result ranges from 0% to 200%, and unlike MAPE, sMAPE remains stable and unbiased even when the target values are very small.

$$sMAPE = \frac{1}{N}\sum_{i=1}^{N}\frac{2\left|y_{true} - y_{pred}\right|}{\left|y_{true}\right| + \left|y_{pred}\right| + \epsilon} \times 100 \tag{4.2}$$

The model accuracy is obtained by subtracting the sMAPE from 100%, providing an intuitive measure of correctness as a percentage. A higher accuracy indicates better model performance, where 100% represents a perfect prediction with zero error. In this study, all 9 outputs achieved an accuracy above 99% with the overall balancing power (sum of all outputs) reaching 99.88% confirming the excellent predictive capability of the proposed ANN model (the model's reliability for real-time MG dispatch optimization).

$$Accuracy = 100\% - sMAPE \tag{4.3}$$

4.3 Cases of Modelling and Optimization

4.3.1 Case Study 1

The proposed model is tested on Sub-network 1 of the CIGRE MV MG benchmark, proposed by [280], given in Figure 4.14. Neglecting the parameters of the transformer 110/20, defined as TR1 in Figure 4.14, node 1 becomes PCC between the external power grid and the MG. The grid parameters are given in Table 4.8. The grid supplies households as well as industrial load. In addition, it utilizes solar and wind DG, CHP units, fuel cells, and battery storage, as per tables in Table 4.7. Daily household load, industrial load, as well as wind and solar profiles are given in Figure 4.15, while the power of each individual resource is defined in Table 4.6. For the sake of a more realistic approach, each individual load and generation is randomly varied within the range of ±10% from the typical curves, using a 5 min resolution.

The MG has 2 CHP units, which are also capable of providing ASs. Detailed information for these generators is given in Table 4.9. Nodes 5 and 10 utilize battery and fuel cells, with parameters defined in Table 4.10. For this case study, only battery storage is considered as fuel cell units, which are of much lower power and are connected in the same nodes as battery storage units. In addition, it is considered that industry load can be controllable to some extent in order to provide ASs, as defined in Table 4.11. Finally, the hourly market price of electricity for energy exchange between the grid and the MG is shown in Figure 4.16, while the price of delivered balancing energy is 50 €/MWh downwards and 250 €/MWh upwards, averaged from the ENTSO-E report [281]. These values of the balancing prices are not selected for any specific country but are average values of the prices from the ENTSO-E report.

The proposed framework is implemented in MATLAB R2024b and optimized via GA and penalization functions to satisfy the constraints. GA is appropriate for this kind of power-balancing AS service since it can find the best answer in this situation in a matter of minutes. With the use of robust real-time simulators that are compatible with MATLAB, GA performance can be further enhanced.

The purpose of the base case simulation is to demonstrate how all of the microgrid's resources function under "normal" circumstances. This gives a starting point for understanding how much RES, such as wind, solar, CHP Full Cell, controlled load, batteries, and CHP diesel, participate in regular, efficient grid operations.

The AS provision case is conducted in two scenarios: (a) Detailed grid modelling; (b) Single-bus modelling as shown in figure 5.7. The following is a comparative analysis of these two cases, which indicates and quantifies the significance of detailed grid modelling in MG operation optimization.

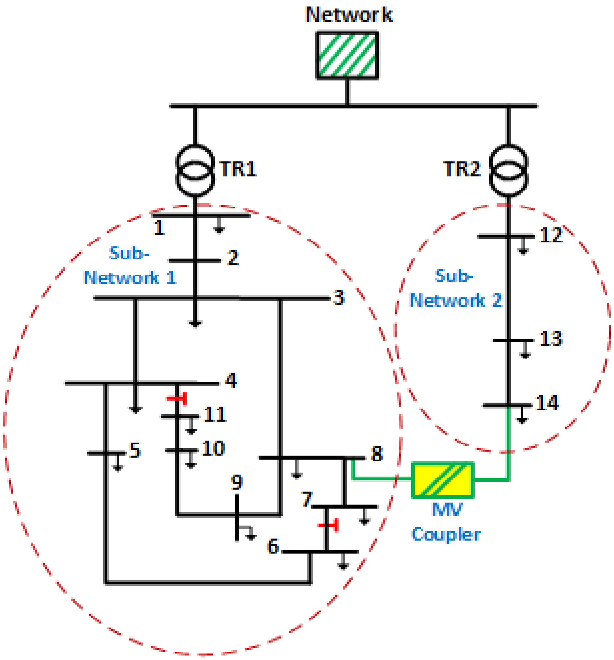


Fig. 4.14 *CIGRE MV benchmark MG model [280].*

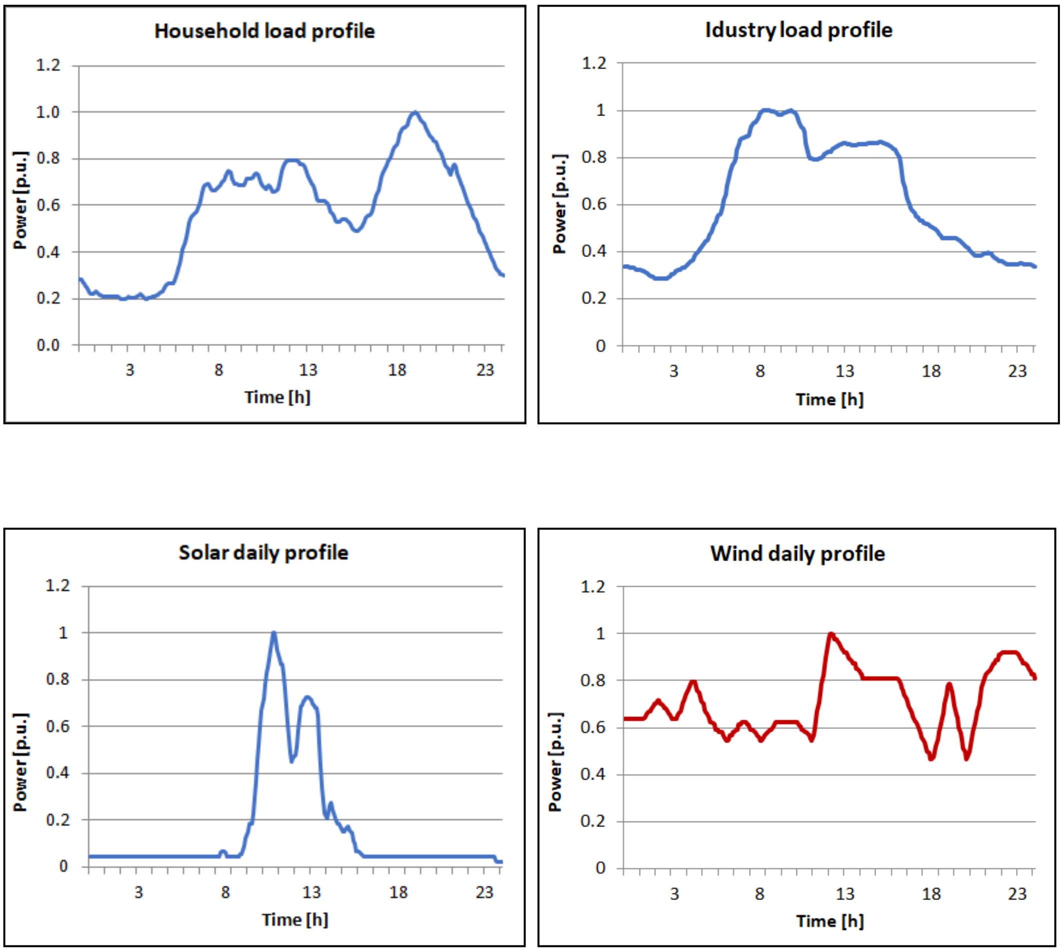


Fig.4.15 *Daily load and production curves [282].*

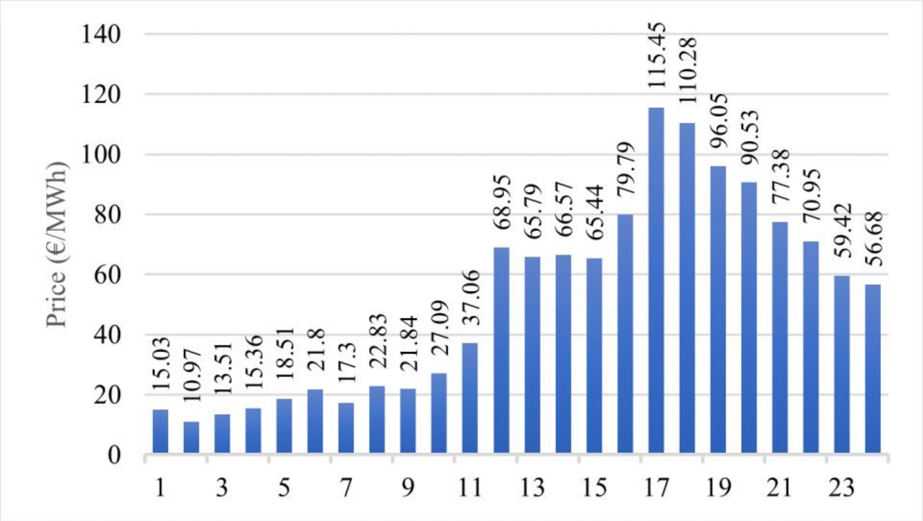


Fig. 4.16 *Hourly market electricity price.*

Table 4.6 Parameters of loads at each node [280].

Node	Load Type	P_{MAX} [MW]	Q_{MAX} [Mvar]
1	Household	13.758	8.527
1	Industry	4.984	1.012
3	Household	0.253	0.157
3	Industry	0.239	0.049
4	Household	0.396	0.246
5	Household	0.665	0.412
6	Household	0.504	0.313
7	Industry	0.077	0.016
8	Household	0.539	0.334
9	Industry	0.572	0.116
10	Industry	0.068	0.014
10	Household	0.438	0.271
11	Household	0.304	0.188
12	Household	13.75	8.527
12	Industry	4.984	1.012
13	Industry	0.032	0.006

14	Industry	0.329	0.067
14	Household	0.190	0.118

Table 4.7 Parameters of DG units [280].

Node	DG Type	P_{MAX} [kW]
3	PV	20
4	PV	20
5	PV	30
5	Battery	600
5	Fuel cell	33
6	PV	30
7	Wind turbine	1500
8	PV	30
9	PV	30
9	CHP diesel	310
9	CHP fuel cell	212
10	Photovoltaic	40
10	Battery	600
10	Fuel cell	14
11	PV	10

Table 4.8 CIGRE MV benchmark model parameters [280].

Node	Node From	Node To	R’ [Ω/km]	X’ [Ω/km]	C’ [nF/km]	L [km]
Sub-network (SN 1)	0	1	---	---	---	---
	1	2	0.579	0.367	158.88	2.82
	2	3	0.164	0.113	6608	4.42
	3	4	0.262	0.121	6480	0.61

	4	5	0.354	0.129	4560	0.56
	5	6	0.336	0.126	5488	1.54
	6	7	0.256	0.13	3760	0.24
	7	8	0.294	0.123	5600	0.67
	8	9	0.339	0.13	4368	0.32
	9	10	0.399	0.133	4832	0.77
	10	11	0.367	0.133	4560	0.33
	11	4	0.423	0.134	4960	0.49
	3	8	0.172	0.115	6576	1.3
SN 2	0	12	---	---	---	---
	12	13	0.337	0.358	162.88	4.89
	13	14	0.202	0.122	4784	2.99

Table 4.9. Characteristics of CHP units.

Unit	Node	Operation Cost (EUR/MWh)	Min–Max Power (MW)	Ramp Up/Down Rate (p.u./5min)
CHP Diesel	9	30	0–0.3	0.2
CHP Fuel Cell	9	20	0–0.2	0.15

Table 4.10. Characteristics of battery storage.

Unit	Node	Capacity (MWh)	Min Charging/Discharging Power (MW)	Max Charging/Discharging Power (MW)
Battery	5	1	0.05	0.6
Battery	10	1	0.05	0.6

Table 4.11. Characteristics of adjustable industry load.

Load	Node	Type	Min–Max Power (p.u)
L1	1	Curtailable	0–0.1
L2	3	Curtailable	0–0.1
L3	7	Curtailable	0–0.1
L4	9	Curtailable	0–0.1
L5	10	Curtailable	0–0.1

4.3.2 Case Study 2

Figure 4.17 illustrates the complete operational workflow of the proposed MG flexibility prediction system, integrating a GA for offline optimization with an ANN for real-time prediction. The architecture is designed to generate, learn, and reproduce optimal control actions for DERs under a variety of dynamic operating conditions. The process consists of three main stages: input acquisition, optimization and improvement procedures, and model output generation. Together, these components form a high-performance prediction framework capable of producing accurate results within seconds and with very low error rates relative to the target values.

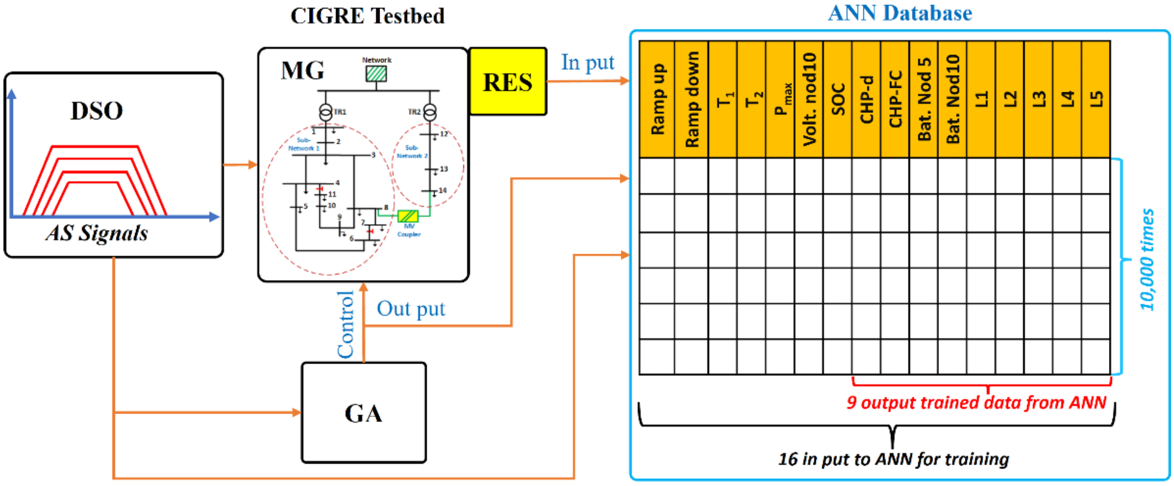


Fig.4.17 *Feedforward GA with ANN for predict system outputs based on historical input data.*

The workflow begins with the receipt of AS signals from the DSO. These signals represent system-level instructions such as ramp-up or ramp-down requests that the MG must satisfy. The AS signals define the flexibility requirements imposed on the MG at each moment. The model dynamically integrates conditions of operation and disruptions arising from the microgrid itself. These encompass fluctuations in renewable energy, temperature variations, maximum generation capacity restrictions, battery state of charge dynamics, voltage measurements, and real-time load profiles. Together, these signals constitute the complete set of 16 input variables feeding into the system. These inputs are then applied to the detailed CIGRE MG testbed, which includes multiple DERs: CHP Diesel, CHP Fuel Cell, Battery Node 5, Battery Node 10, and five controllable loads. Due to the nonlinear, interdependent, and dynamic nature of these resources, determining the optimal response to AS requirements cannot be achieved using conventional static methods. For this reason, the GA is employed as an improvement and optimization mechanism.

The GA estimate numerous potential operational configurations for each scenario, employing evolutionary processes like selection, crossover, and mutation to identify the most advantageous one. Its objective is to satisfy ramping signals, the enhancement of system stability, the adherence to voltage constraints, and the minimization of operational deviation. The GA is implemented across 10,000 MG scenarios, each of which simulates different conditions related to renewable output, load variations, voltage states, and resource availability. For every scenario, the GA ascertains the optimal outputs for all DERs. These optimized responses collectively constitute a high-quality dataset, thereby representing the most effective operational decisions available to the MG. This dataset comprises 9 output variables: the power contributions from the two CHP units, the states of battery charging and discharging, controllable load adjustments, and the total balancing power.

The ANN is then trained using this dataset. The ANN learns the nonlinear relationship between the 16 input variables and the 9 optimal outputs found by the GA. Through repeated training and error reduction, using methods like the Levenberg–Marquardt optimization, gradient reduction, and early stopping, the ANN gradually mimics the genetic algorithm's decision-making process. The training performance graph shows quick convergence, with the best validation performance occurring at epoch 14, followed by little change in error. Diagnostic plots of the gradient, damping factor, and validation checks indicate that the ANN finds a stable solution without overfitting. After training, the ANN becomes a real-time surrogate model, able to produce outputs almost instantly. This is a major advantage of integrating GA with ANN: while the GA requires substantial computation time (minutes to hours for large scenario sets), the ANN performs the same decision generation within milliseconds to seconds, making real-time operation feasible. This hybrid approach combines the optimality of GA during offline dataset creation with the speed and generalization capability of ANN during real-time deployment.

The outputs generated by the ANN include the power settings for all DERs and the total balancing power. When compared with the GA targets, the ANN predictions show extremely close agreement. Across all assets, the $sMAPE$ remains well below 1%, far surpassing the acceptable threshold of 5% for real-time control systems. The high accuracy is further confirmed through the various prediction figures presented for each asset. The predicted curve continually corresponds with the target curve, even during quick changes, sharp drops, or high-frequency oscillations. This close correspondence confirms that the ANN has successfully learned the GA-optimized responses, allowing it to produce reliable results in real-time.

Finally, the proposed GA–ANN hybrid model represents a complete and highly efficient framework for MG flexibility prediction. Through the integration of GA for offline optimization and ANN for real-time replication, the system achieves the dual advantages of optimality and speed. The ANN provides immediate predictions characterized by minimal error, thus rendering the methodology appropriate for real-time AS delivery, power estimation, and the dynamic management of microgrids. This framework's integration of high accuracy, immediate computation, and robust learning capacity establishes it as a powerful instrument for modern microgrid management and future intelligent energy systems.

Chapter 5

Results

5 Results

The proposed model in case study 1 is coded in MATLAB-R2024b and optimized using GA and penalization functions to address the constraints. GA is capable of obtaining the optimal solution in this case with a range from 3 to 30 minutes, making it suitable for this type of power-balancing AS provision. Further improvement of GA performance is possible by using powerful real-time simulators that are compatible with MATLAB.

The base case simulation is performed just to show how all the microgrid's resources operate under "normal" conditions. This provides a baseline understanding of the participation levels of RES like wind, solar, CHP Full Cell and also controllable load, batteries, and CHP diesel in optimal, routine grid operations.

The AS provision case is conducted in two scenarios: (a) Detailed grid modelling; (b) Single-bus modelling. The following is a comparative analysis of these two cases, which indicates and quantifies the significance of detailed grid modelling in MG operation optimization.

5.1 The Base Case

As the base case, a study without ASs is considered, optimizing the operation of the MG considering only DG operating costs and electricity market price. In this case, the industry load is not controllable. After running the simulation, the results shown in Figure 5.1 are obtained for all distributed assets, with nodes indicated in the legend of the diagram. The MG operation is dominated by wind, battery, and CHP units, so to present the operation more clearly, per unit representation is given in Figure 5.2.

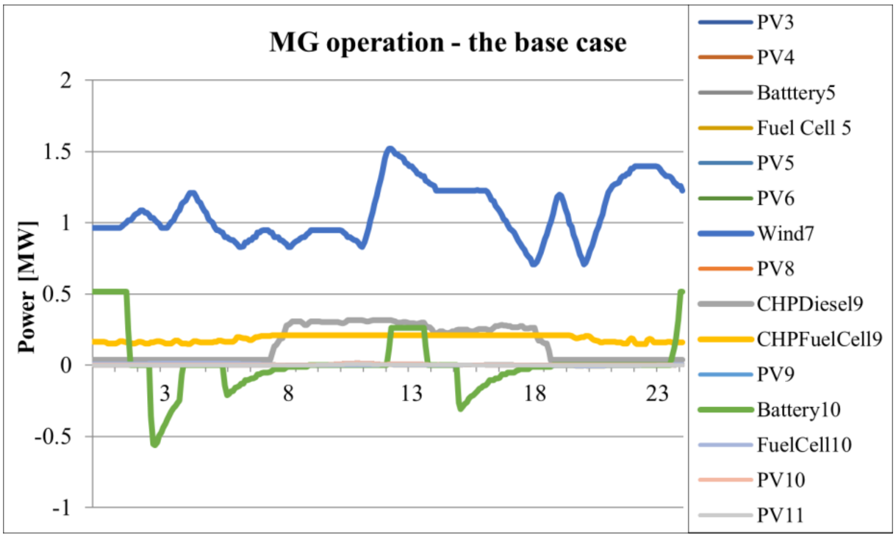


Fig.5.1 *The base case MG operation (MW).*

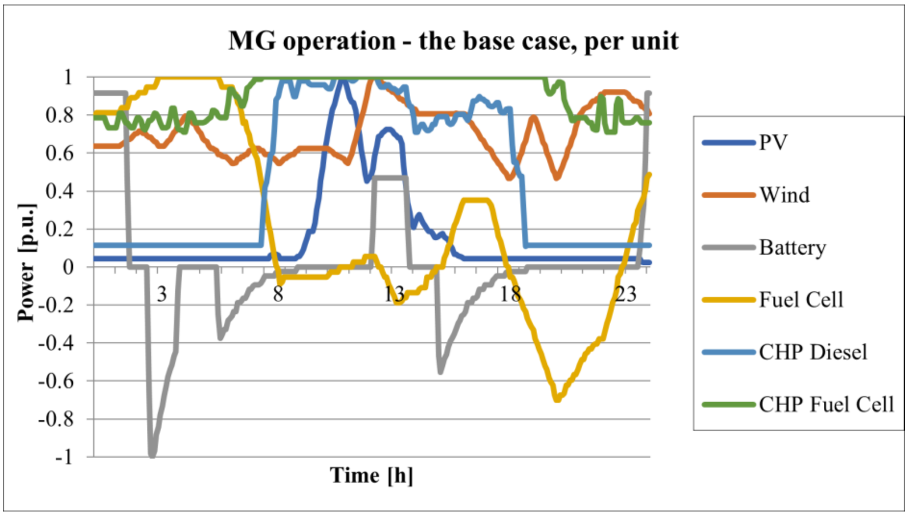


Fig.5.2 *The base case MG operation (per unit).*

5.2 The AS Provision Case

In the AS provision case, CHP units, battery storage, and industrial load control are considered as AS assets, with the parameters in previous chapter (chapter 4) defined in Tables 4.9, 4.10, and 4.11. In addition, two different sub-cases are considered: (a) The case with grid modelling, where all voltage profiles and MG power losses are considered; (b) The case without grid modelling, where MG is considered to have all assets connected to a single bus. The latter case was usually the case study of previous research papers. The goal of this paper is to show the importance of grid modelling by comparing the results of sub-cases (a) and (b). The AS request is modelled by VL in the point of connection, as shown in Figure 5.3. It represents three requests for AS provision, with different amounts of power requested in both the upward and downward directions. After running the optimization procedure for the model represented in Chapter 4, using GA, the obtained results are shown in Figure 5.4 for sub-case (a) and in Figure 5.6 for sub-case (b) as well as in Table 5.1 .

To avoid confusion, it should be noted that in single-bus modelling (sub-case (b)), the names of the assets are kept the same, so “Battery node 10” and “Battery node 5” can be seen. These are only their names, while all the assets are connected to the same bus. Therefore, nodes 5 and 10 do not exist in this case. Additionally, L1–L5 in Figure 5.4 and 5.5 refer to controllable loads, as defined in Table 4.11 in chapter 4.

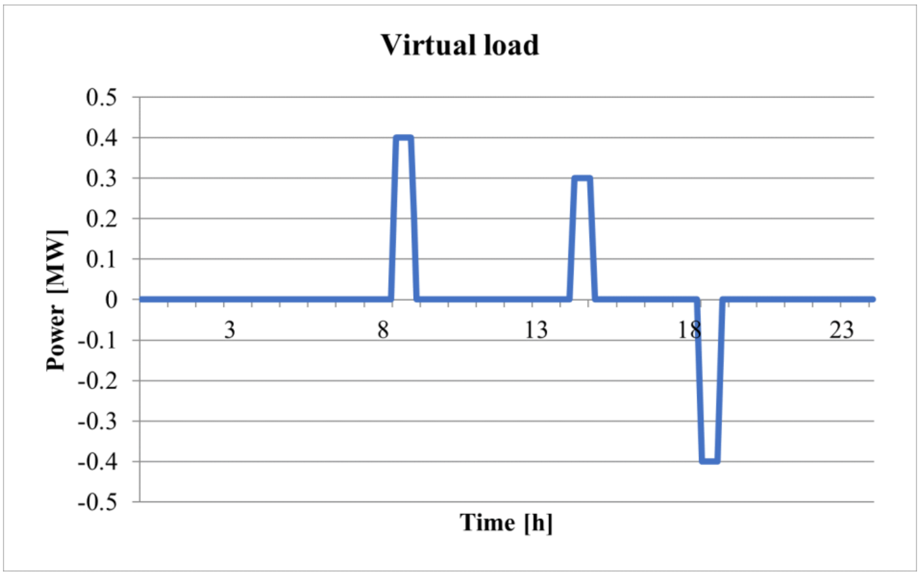


Fig.5.3 *Virtual load for AS representation.*

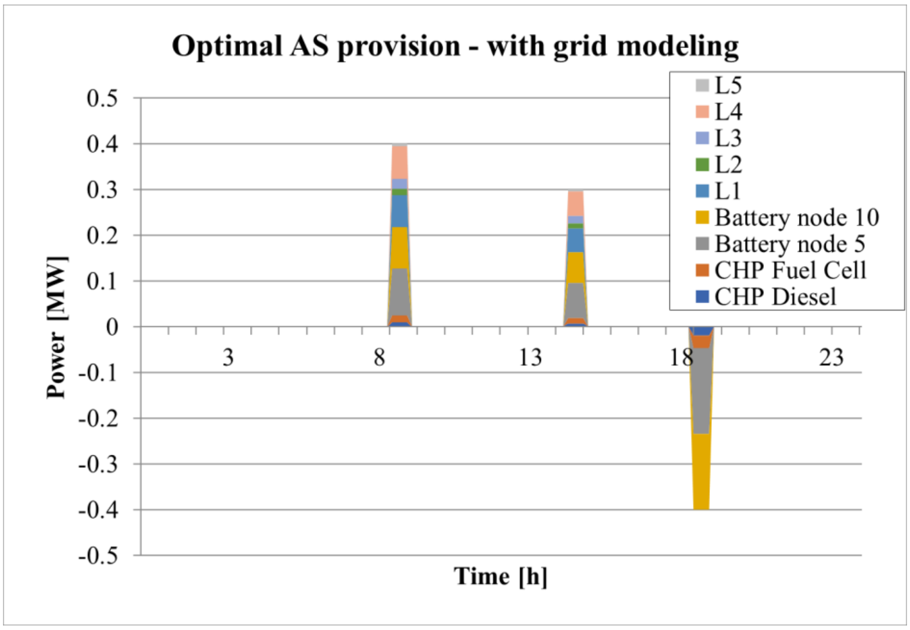


Fig.5.4 *Optimal AS provision with grid modelling (sub-case (a)).*

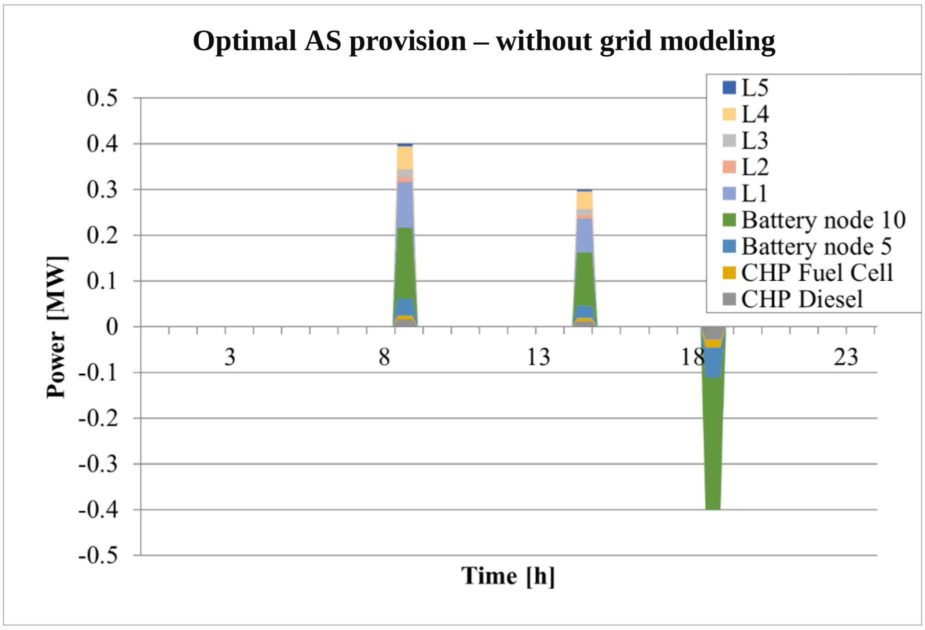


Fig.5.5 *Optimal AS provision without grid modelling (sub-case (b)).*

Table 5.1. Optimal AS provision.

Sub-Case		CHP Diesel	CHP Fuel Cell	Battery Node 5	Battery Node 10	L1	L2	L3	L4	L5
(a)	Upward	2.6%	3.8%	25.6%	22.6%	17.3%	3.7%	5.4%	17.6%	1.4%
	Downward	4.7%	7.0%	46.9%	41.4%	0%	0%	0%	0%	0%
(b)	Upward	4.0%	2.2%	9.0%	38.9%	24.9%	2.8%	4.1%	12.8%	1.4%
	Downward	7.4%	4.1%	16.6%	72.0%	0%	0%	0%	0%	0%

Fitness values are metrics proportional to the objective functions, a term specific to GA. Fitness values indicate how good a solution is, with lower values being better in the context of our minimization problem, as defined by Equation (4.1). By comparing the fitness values of both solutions, with sub-case (a) having the fitness value of 178.37 and sub-case (b) having the fitness value of 178.8, it can be wrongly concluded that the case without modelling the grid is the same for MG operation. However, it must not be forgotten that this fitness value does not consider power losses that actually exist in real MG. For this reason, another load flow procedure is conducted using the solution of sub-case (b). After obtaining the load flow results, the fitness value is recalculated, and a value of 197.99 is obtained. This procedure of comparative analysis and fitness value recalculation is shown in Figure 5.6.

Finally, the obtained results can be used to evaluate the improvement of the objective function, which also indicates technical and economic improvement of MG operation. Technically, the detailed grid modelling in sub-case (a) enhances accuracy by accounting for power losses and ensuring voltage profiles stay within safe limits. Economically, this approach leads to a more precise assessment of operational costs, reducing unnecessary energy expenditure and optimizing asset use. To evaluate the

Improvement Factor (IF), the fitness values of both sub-cases ($Fitness^a$ and $Fitness^b$) are compared as per Equation (5.1). It must be noted that fitness values are compared at the real MG level from Figure 5.6.

$$IF = \left|\frac{Fitness^a - Fitness^b}{Fitness^a}\right| \times 100\% \approx 11\% \tag{5.1}$$

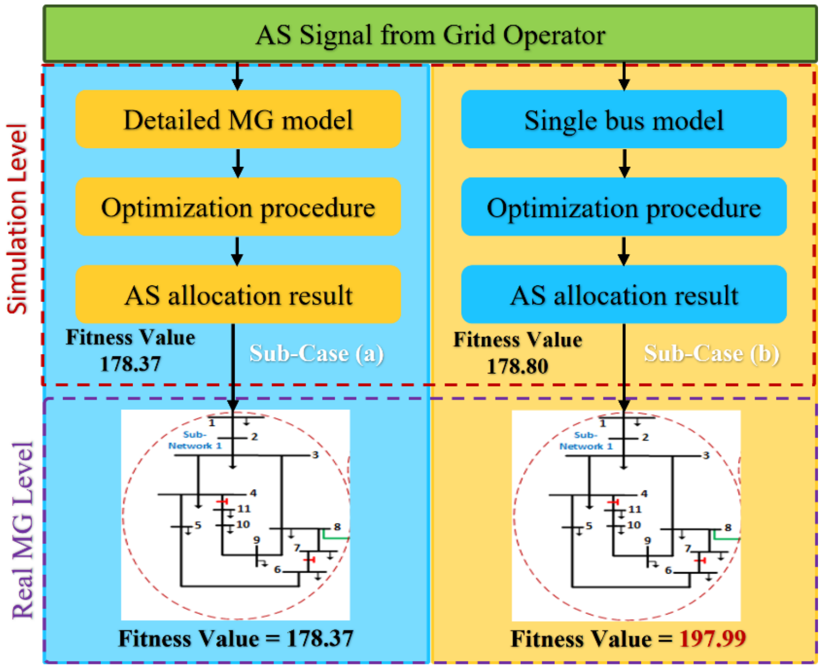


Fig.5.6 *The procedure of comparative analysis between sub-cases (a) and (b).*

5.3 Case Study 2

The proposed model in case study 2 is developed in MATLAB using a hybrid structure that integrates GA (optimized data) with a trained ANN to create a real-time flexibility prediction framework. Case study 1 uses GA directly to find the best operating point for each case. The case study 2 uses GA once offline to find the best dispatch solutions for a wide range of operating conditions. These optimized outputs serve as the training targets for the ANN. As shown in figure 4.17 in chapter (4), the ANN receives the same set of MG input variables (16 inputs) such as ramp limits, AS signals, power constraints, SOC, voltages profile, DER states, time-based inputs $t_1$and t_2, and controllable load and learns to map them directly to the optimal outputs previously computed by the GA.

Figure 4.17 in chapter (4) illustrates the complete workflow of case study 2. All operational inputs from the MG are collected, processed, and used both for GA optimization and ANN training. After training, the ANN can immediately predict 9 important output variables: CHP diesel, CHP fuel cell, battery at node 5, battery at node 10, and the controllable loads (L_1 to L_5). The figures shows that these ANN-generated predictions are very close to the target outputs from the GA. For all assets, the Target and Prediction curves are very close to each other. This means that the ANN has learned the best dispatch patterns and can reproduce them with very little error.

The GA-ANN captures the dynamic properties of all distributed energy resources. This means that the model in Case Study 2 can give real-time responses right away, while the GA needs minute or hours in off-line (non-real-time) to solve each optimization. The proposed model in case study 2 reduces the computation time to just a few seconds, making it useful for providing real-time power balancing and AS. The results show that the error between the Target and ANN Prediction stays below 1% for all 9 outputs, which proves that the trained model is reliable as shown in figures from 5.7 to 5.15, and shown in Table 5.5.

The final balancing power output, which is the sum of all 9 predicted components, also shows that the ANN prediction and the GA optimal target are very close to each other (small error less than 1%). This shows that the ANN works well to keep coordinated behaviour between multiple assets during AS provision. Case Study 2 shows that the ANN can make fast, accurate, and stable real-time operational predictions. This means that it can be used instead of direct GA optimization for balancing and managing flexibility in MGs.

Table 5.5. *Comparison between the target and the ANN-predicted balancing power*

NO	Output	RMSE (MW)	sMAPE (%)	Accuracy (%)	RMSE Rating	Accuracy Rating
1	**CHP Diesel**	0.0159	0.6565	**99.3435**	Very Good	Very Good
2	**CHP Fuel Cell**	0.0122	0.6822	**99.3178**	Excellent	Very Good
3	**Battery node 5**	0.0239	0.4326	**99.5674**	Good	Excellent
4	**Battery node 10**	0.0264	0.4494	**99.5506**	Good	Excellent
5	**Load 1**	0.0222	0.6526	**99.3474**	Good	Very Good
6	**Load 2**	0.0058	0.7277	**99.2723**	Excellent	Very Good
7	**Load 3**	0.0217	0.5751	**99.4249**	Good	Very Good
8	**Load 4**	0.0169	0.5451	**99.4549**	Very Good	Very Good
9	**Load 5**	0.0051	0.8930	**99.1070**	Excellent	Very Good
Balancing Power		**0.0190**	**0.1227%**	**99.88%**	**Outstanding**	**Outstanding**

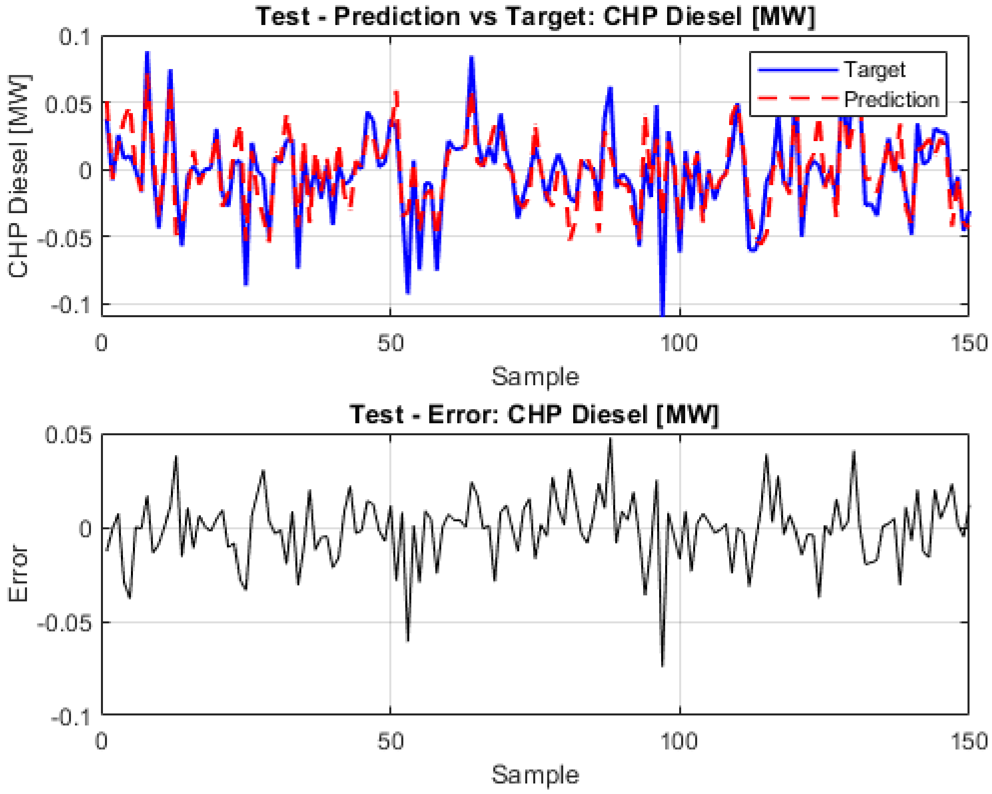


Fig.5.7 *Performance Prediction of CHP Diesel Output in R-T MG Operations Using GA-ANN.*

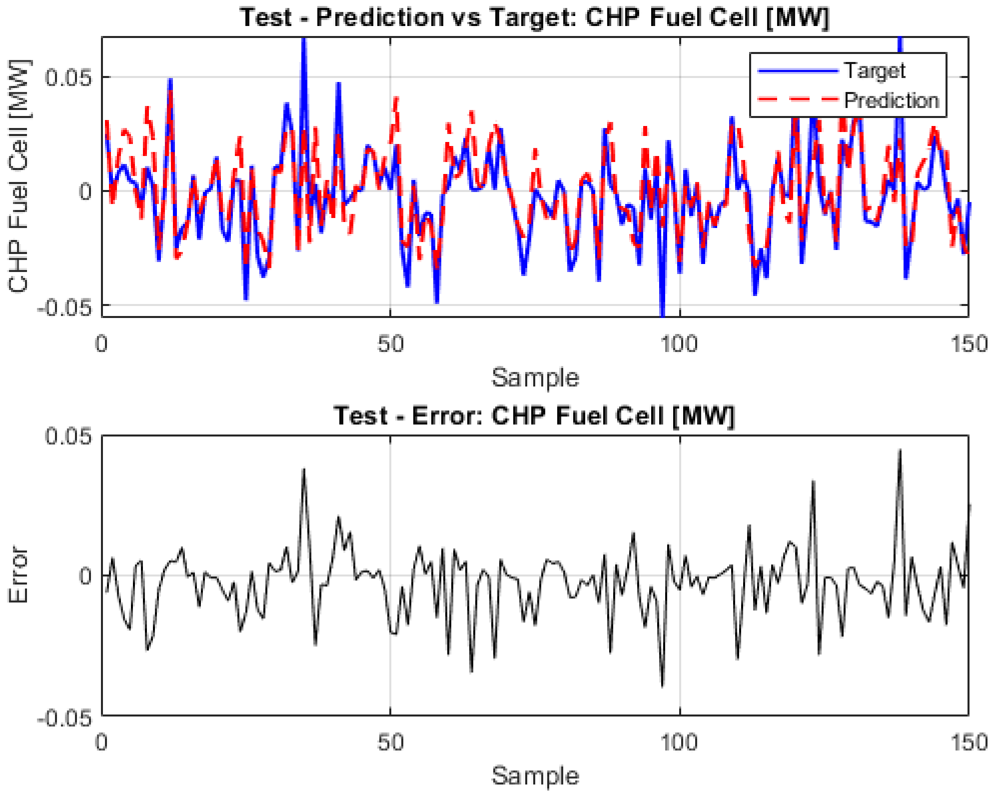


Fig.5.8 *Performance Prediction of CHP Fuel Cell Output in R-T MG Operations Using GA-ANN.*

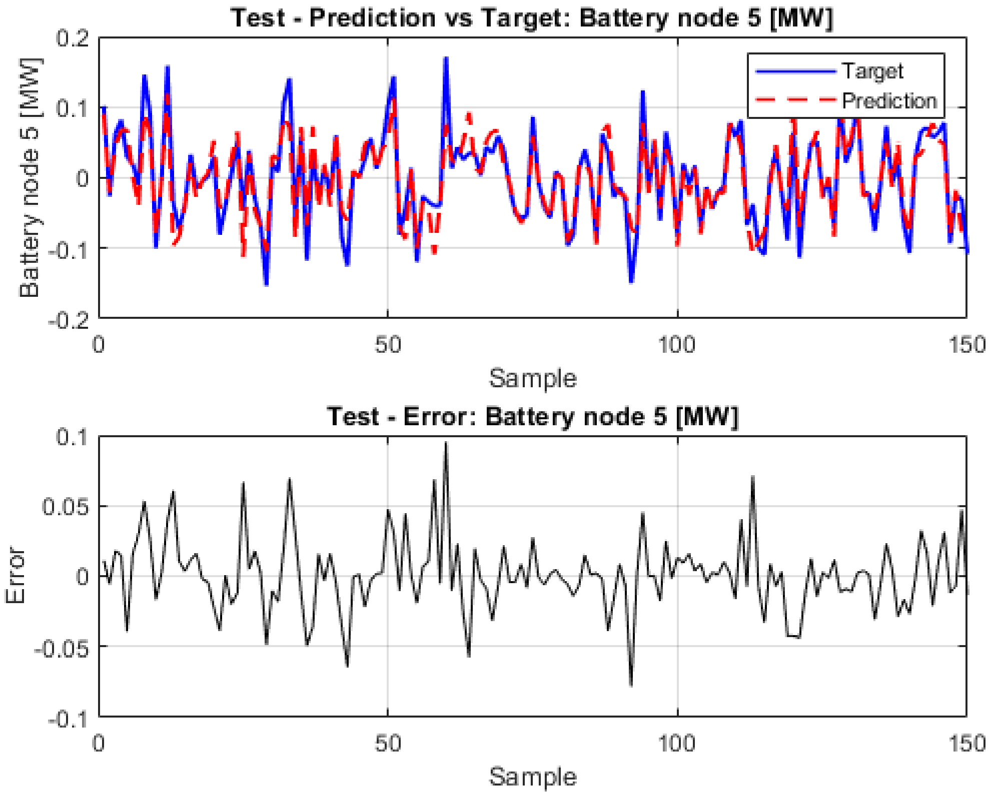


Fig.5.9 *Performance Prediction of Battery at node 5 Output in R-T MG Operations Using GA-ANN.*

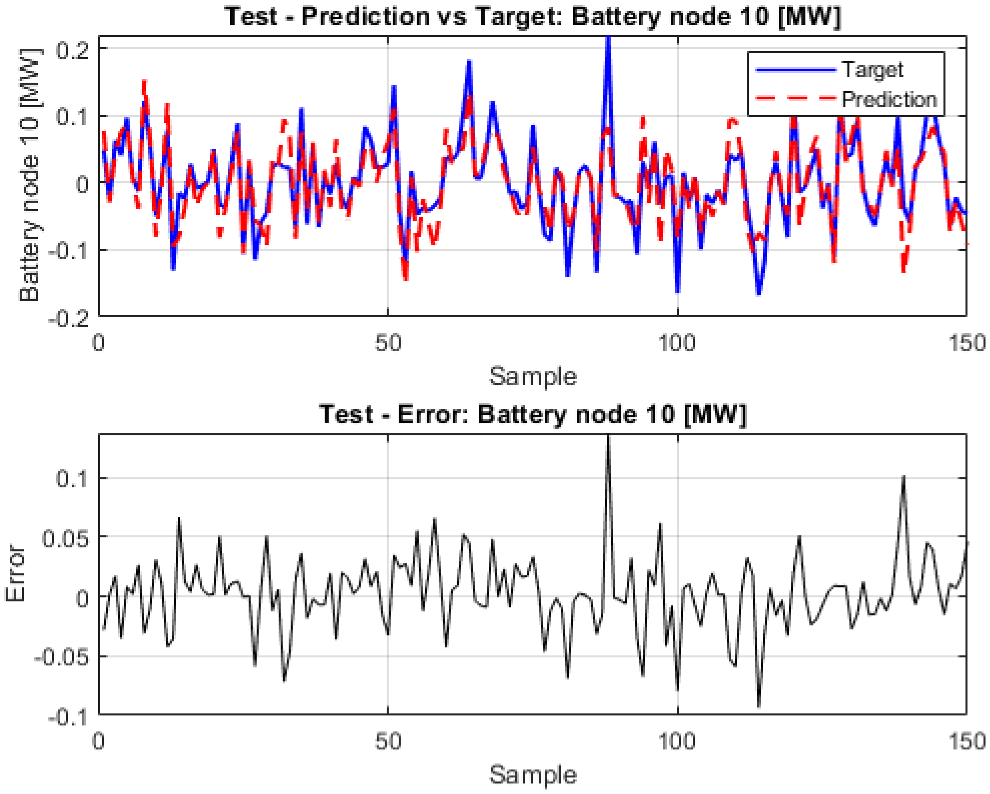


Fig.5.10 *Performance Prediction of Battery at node 10 Output in R-T MG Operations Using GA-ANN.*

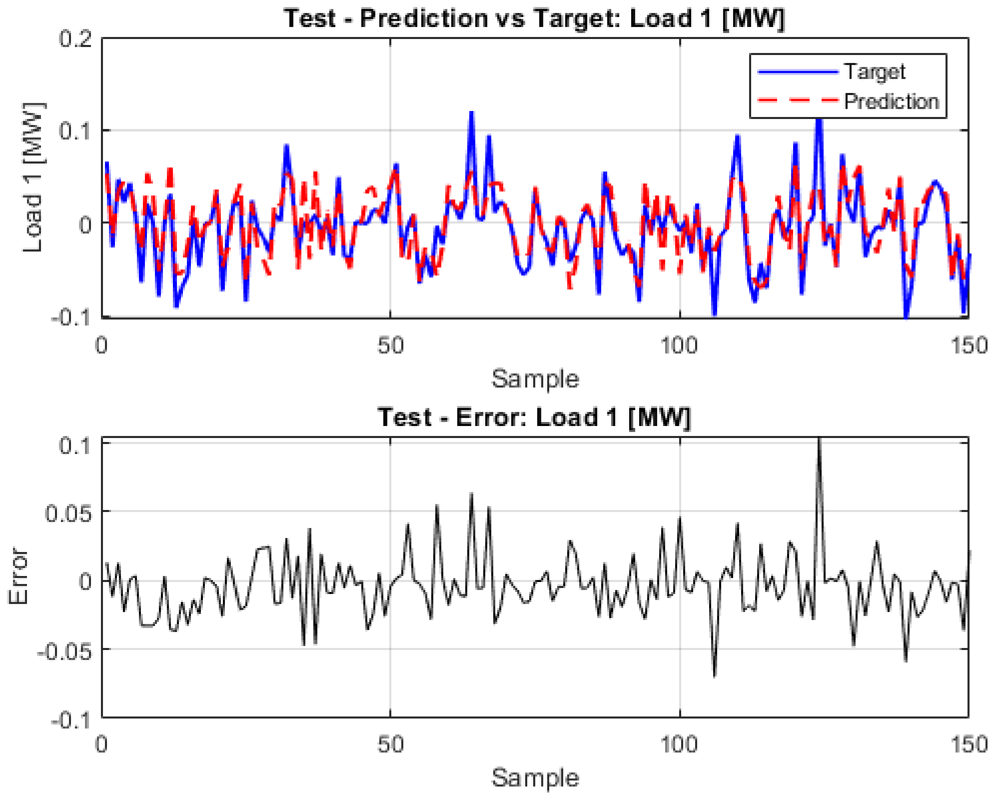


Fig.5.11 *Performance Prediction of Controllable Load 1 Output in R-T MG Operations Using GA-ANN.*

Fig.5.12 *Performance Prediction of Controllable Load 2 Output in R-T MG Operations Using GA-ANN.*

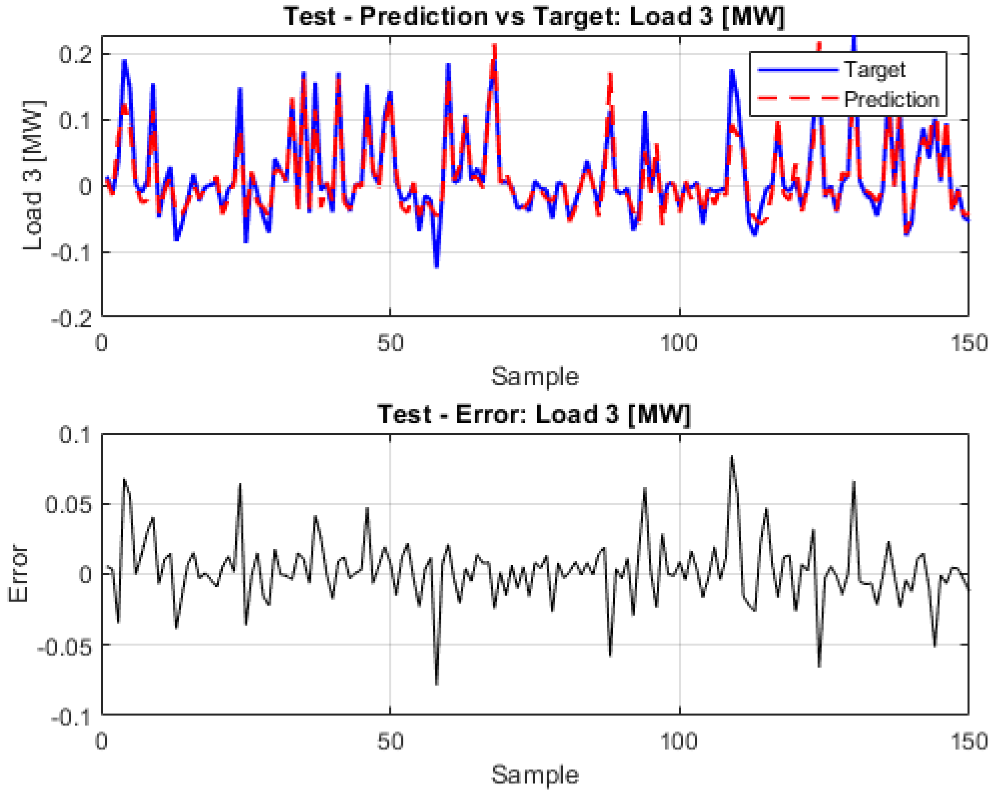


Fig. 5.13 *Performance Prediction of Controllable Load 3 Output in R-T MG Operations Using GA-ANN.*

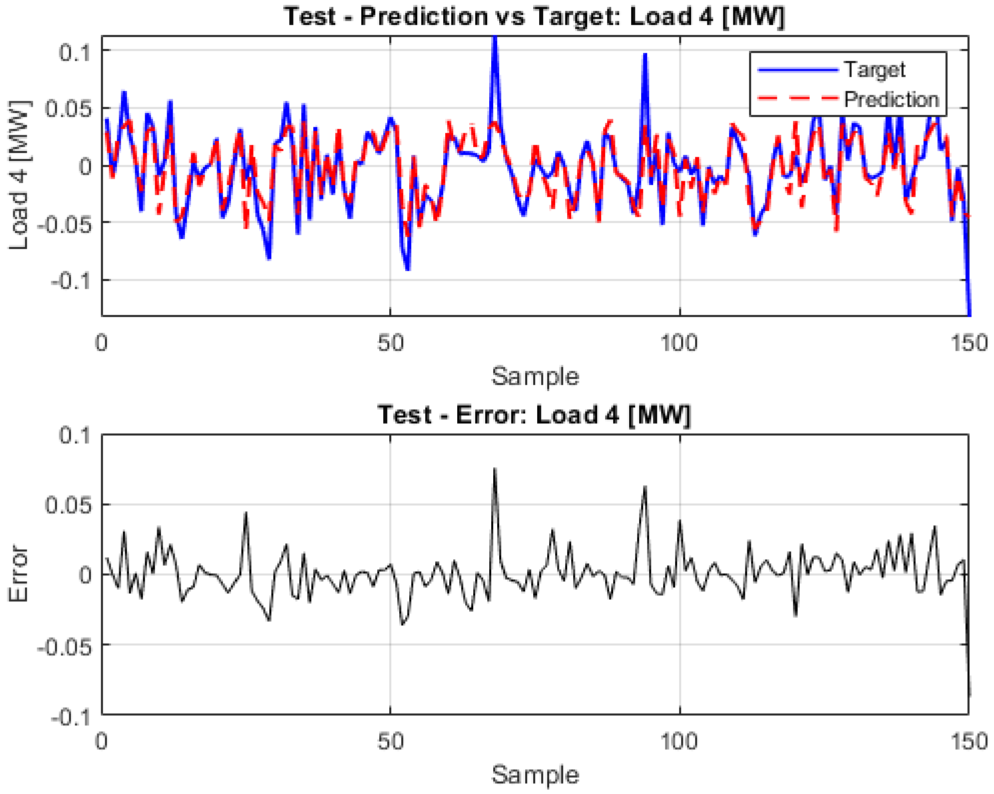


Fig.5.14 *Performance Prediction of Controllable Load 4 Output in R-T MG Operations Using GA-ANN.*

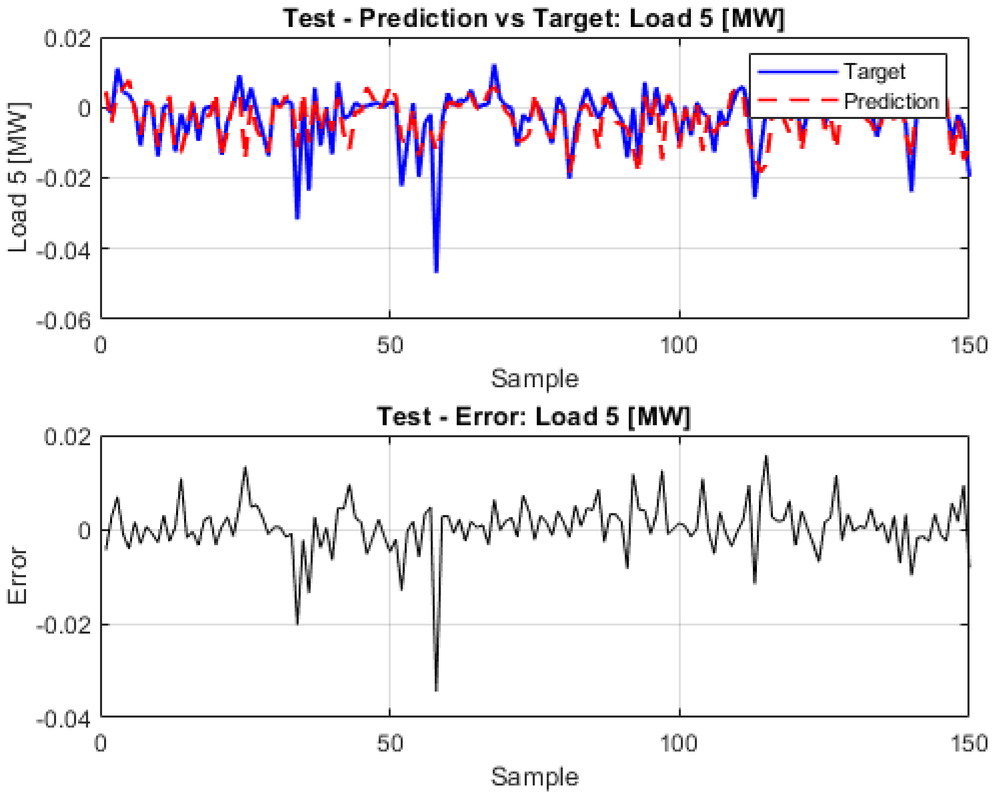


Fig.5.15 *Performance Prediction of Controllable Load 5 Output in R-T MG Operations Using GA-ANN.*

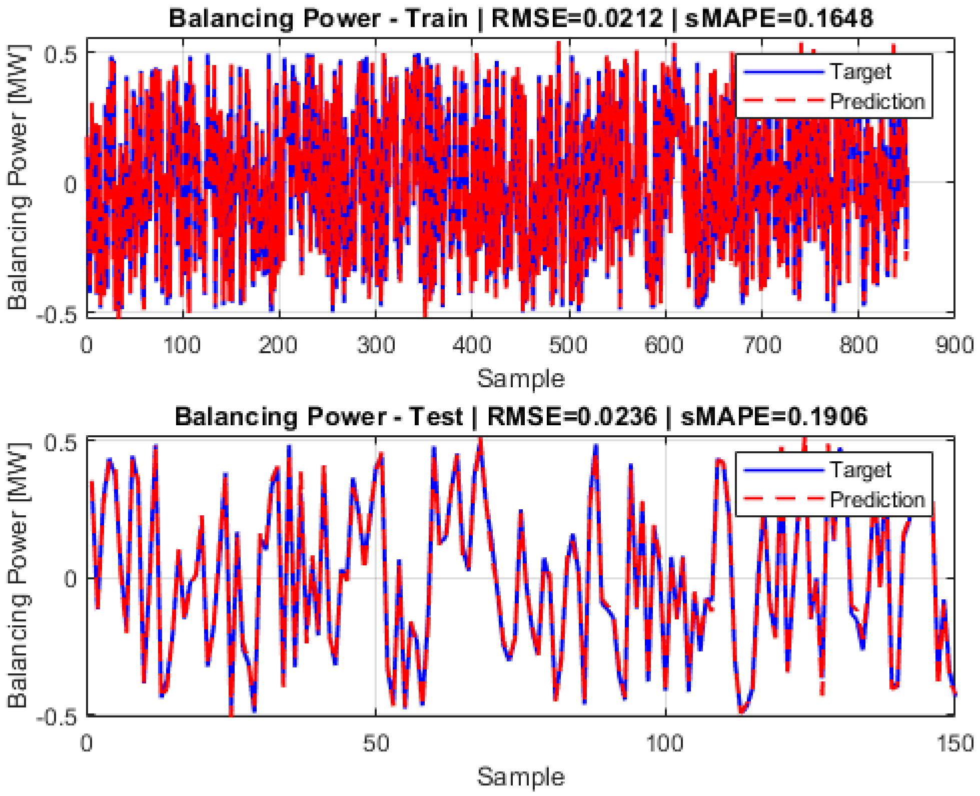


Fig.5.16 *Performance of GA-ANN Predictions for R-T Balancing Power in MG.*

Figure 5.16 illustrates the balancing power performance within the proposed GA–ANN real-time framework for MG operation. In this framework, the GA is employed in an off-line stage to determine optimal operating strategies for controllable generators, energy storage systems, and flexible loads under various operating conditions. The resulting optimal solutions are then used to train an ANN, which acts as a fast surrogate model in real-time operation.

During real-time decision, the ANN directly outputs the power set-points for each controllable unit at every time sample, ensuring an instantaneous balance between generation and demand. The balancing power shown in Figure 5.16 is obtained by aggregating all 9 ANN-generated outputs, representing the system-level response of the MG.

The close agreement between the target and predicted balancing power curves demonstrates that the ANN successfully emulates the optimal GA-based decisions in real time, without the computational burden associated with running GA online. The low error metrics (sMAPE = 0.1227% and RMSE = 0.0190 MW) further confirm the robustness and accuracy of the proposed hybrid framework at the system level.

Therefore, Figure 5.16 validates the effectiveness of the GA–ANN framework in achieving both optimality and real-time responsiveness, making it well-suited for AS provision and real-time operational control of MGs with high renewable penetration.

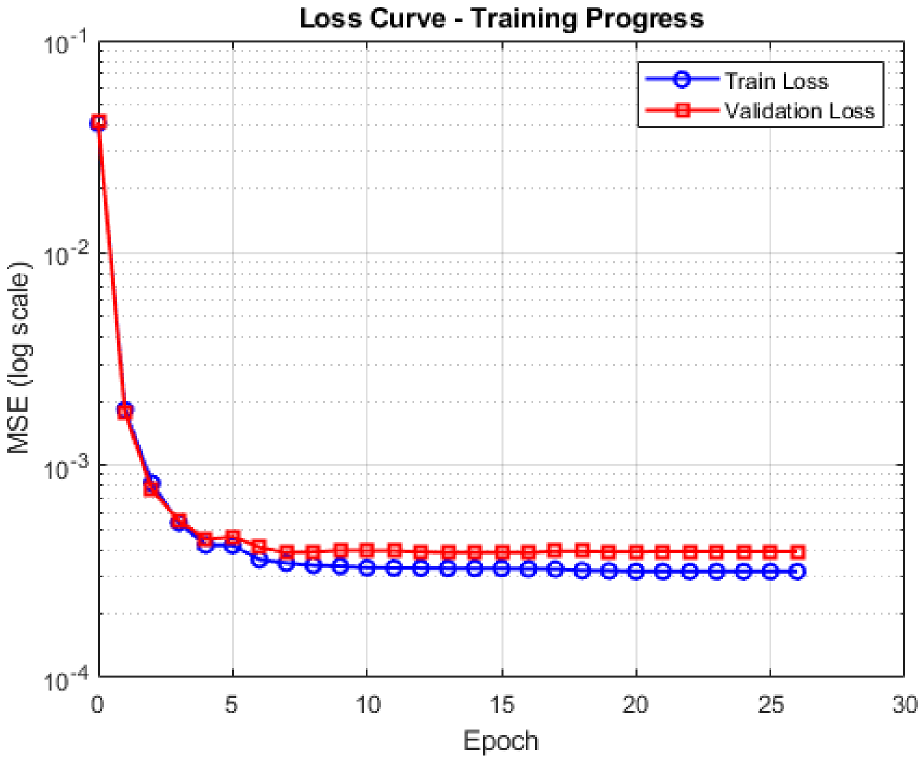


Fig.5.17 *Performance of GA-ANN Predictions for R-T Balancing Power in MG.*

The training convergence curve for the suggested hybrid model (GA-ANN) for optimizing MG power dispatch is shown in Figure 5.17. The results demonstrate that the GA-ANN model operates with high efficiency, converging to an optimal solution in approximately 27 epochs, representing only 2.7% of the maximum training budget of 10000 epochs. This accelerated convergence is directly attributed to the GA component, which optimizes the initial weight configuration of the ANN, enabling the model to start training from a strategically advantageous position in the error surface rather than a random one. All of these results demonstrate that the proposed GA-ANN model for the MG power dispatch problem achieves both improved forecast accuracy and computational economy.

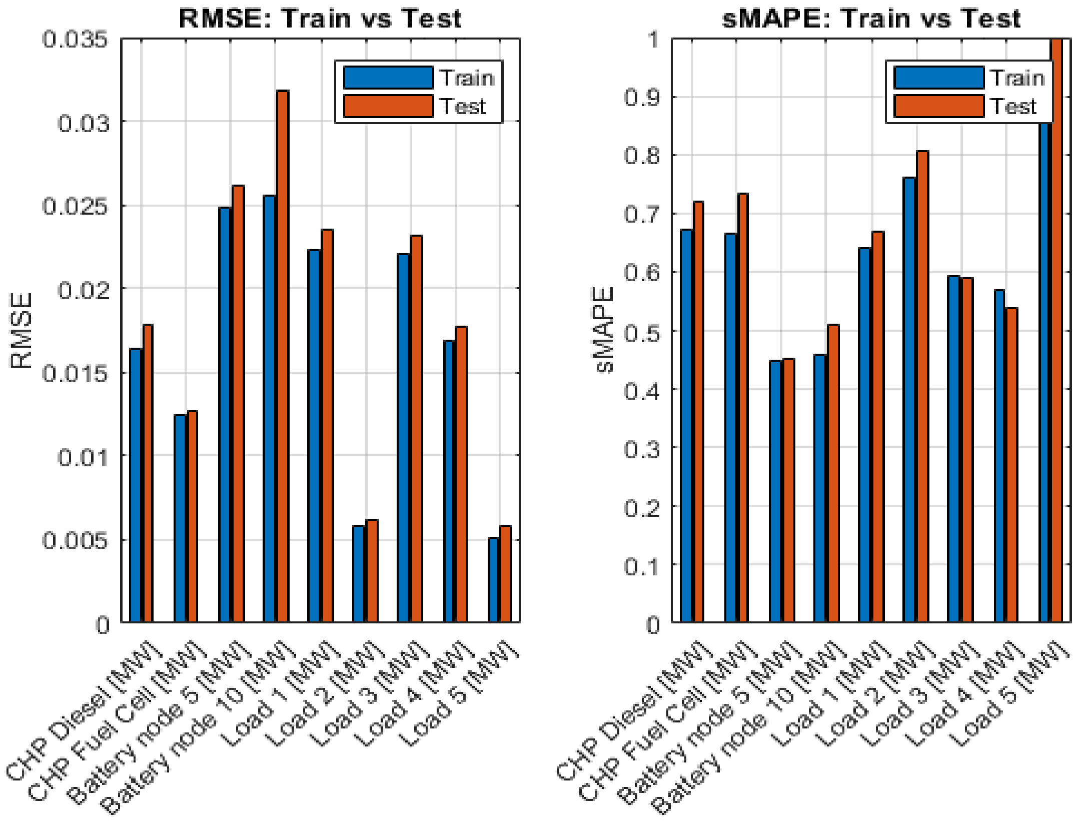


Fig.5.18 *Performance of GA-ANN Predictions for R-T Balancing Power in MG.*

Figure 5.18 illustrate that the GA-ANN model achieves excellent and consistent performance on both training and testing datasets. The close agreement between the target (blue) and prediction (red) bars for all 9 outputs is pure visual evidence of strong generalization capability and the absence of overfitting. The model successfully predicts power dispatch values for CHP units, load demands, and battery storage nodes with sMAPE values below 1.0%, and RMSE values below 0.032 MW, making it highly suitable for R-T optimization applications.

Chapter 6

Conclusions

6 Conclusions

The reliability of PS networks with enough operating reserves is critical to the stability of world economies. PSs are susceptible to problems like load shedding and total blackouts when these reserves are inadequate. A large proportion of RES makes maintaining grid stability even more difficult. However, there is a lot of promise for RES as AS sources when they are connected by power electronic devices.

AS provisions from RES can be further enhanced via MGs based on renewable energy, which can aggregate resources from several RES and offer significant potential for load control. The issue of how to distribute AS signals to all resources as efficiently as possible is brought up by the diversity of AS resources.

This work presents a comprehensive approach to optimizing AS provisions in renewable energy-based MGs. The proposed model integrates a detailed MG model, thus including voltage profiles and power losses and highlighting their critical role in accurate AS allocation. Through a detailed case study using the CIGRE MV MG benchmark, the work illustrates how these factors influence the operational efficiency of realistic MGs. The work underscores that simple MG models using a single-bus representation fail to capture the true behaviour of MG operations, leading to suboptimal resource utilization.

The case study 1 incorporates wind and solar generation units, as well as CHP units, battery storage, and industrial load control as AS assets. Two sub-cases are analyzed: (1) One with grid modelling those accounts for voltage profiles and power losses, using the CIGRE MV benchmark model; (2) One without grid modelling, treating the MG as a single- bus system. The findings reveal that ignoring grid modelling leads to a misrepresentation of the MG’s capabilities. Specifically, the fitness value, which initially seemed comparable between the two sub-cases, diverged significantly after accounting for actual power losses and voltage profiles. The results indicate that detailed modelling of microgrids can impact the results by 11%. Even though not explicitly quantified in this paper, considering that the objective function is a financial indicator of MG operation, the results consequently suggest that a well-modelled MG also maximizes financial returns from AS participation, particularly in markets with variable electricity prices.

The case study 2 shows that the proposed GA–ANN hybrid framework is a good and quick way to predict how flexible a MG will be in real-time. The model can accurately reproduce the dynamic responses of all distributed energy resources, such as CHP units, batteries, and controllable loads, by using the GA only once offline to create a full set of optimal dispatch solutions and then training the ANN to learn these optimal behaviours. The trained ANN shows excellent fidelity to the GA targets, with prediction errors consistently below 1% across all assets and a near-perfect match in the aggregated balancing power output. The ANN gives these predictions in seconds, while the GA needs 3 to 30 minutes for each optimization run. This makes it possible to quickly and reliably provide ASs. These results show that the ANN is a useful and reliable alternative to GA-based optimization. It can make good real-time operational decisions and help with MG balancing and flexibility management.

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Biography

Amir Hameed Abed was born on October 20, 1981, in Anbar – Iraq. He finished elementary and high school in 2001 in Anbar. And in 2001, he enrolled the Faculty of Science at the University of Technology in Baghdad, where he received a Bachelor’s degree in electrical and electronic department in 2005. Then He enrolled the Master studies in 2015, in the department of Electrical and Electronics at the School of Electrical Engineering, University of Turkish Aeronautical Association, he graduated with an overall average score of 9.51, where he defended his Master's thesis on October 25, 2017, entitled “Power Supply Quality Improvement Using Dynamic Voltage Restorer (DVR) In Iraqi Network” under the mentorship of Prof. Dr. Javad Rahebi. Later Mr. ABED enrolled in doctoral studies at the Department of Electrical Engineering and Computing, School of Electrical Engineering, Belgrade University, in 2021-2026, he is a third-year Ph.D. student and passed all exams with a grade point average of 9.71.

The candidate has developed his experience in a variety of technical tools, including AutoCAD, MATLAB, Multisim, Visio, and CYME DIST, as well as proficiency in Microsoft Office applications such as Word, Access, Excel, and PowerPoint. Additionally, the candidate has a solid foundation in computer hardware and software maintenance. Throughout his career, He has led multiple critical projects, such as the installation, testing, and operation of 33/11 KV electrical substations in Anbar City, the installation of underground cables and transmission lines (33KV and 11KV), electric transmission towers, switchgear systems, and circuit breakers (33KV).

образац изјаве о ауторству

Изјава о ауторству

Име и презиме аутора Амир Абед (Amir Hameed Abed)

Број индекса 2021/5050

Изјављујем

да је докторска дисертација под насловом

ОПТИМАЛНА АЛОКАЦИЈА СИСТЕМСКИХ УСЛУГА У МИКРОМРЕЖИ СА ОБНОВЉИВИМ ИЗВОРИМА ЕНЕРГИЈЕ ЗА ПОТРЕБЕ ПОВЕЋАЊА ФЛЕКСИБИЛНОСТИ СИСТЕМА

- резултат сопственог истраживачког рада;
- да дисертација у целини ни у деловима није била предложена за стицање другедипломе према студијским програмима других високошколских установа;
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Потпис аутора

У Београду, ________________

Amir

образац изјаве о истоветности штампане и електронске верзије докторског рада

Изјава о истоветности штампане и електронске верзије докторског рада

Име и презиме аутора Амир Абед (Amir Hameed Abed)

Број индекса 2021/5050

Студијски програм Докторске академске студије

ОПТИМАЛНА АЛОКАЦИЈА СИСТЕМСКИХ УСЛУГА У МИКРОМРЕЖИ СА ОБНОВЉИВИМ ИЗВОРИМА ЕНЕРГИЈЕ ЗА ПОТРЕБЕ ПОВЕЋАЊА ФЛЕКСИБИЛНОСТИ СИСТЕМА

Ментор: проф. др Горан Добрић, ванредни професор

Изјављујем да је штампана верзија мог докторског рада истоветна електронској верзији коју сам предао/ла ради похрањивања у **Дигиталном репозиторијуму Универзитета у Београду.**

Дозвољавам да се објаве моји лични подаци везани за добијање академског назива доктора наука, као што су име и презиме, година и место рођења и датум одбране рада.

Ови лични подаци могу се објавити на мрежним страницама дигиталне библиотеке, у електронском каталогу и у публикацијама Универзитета у Београду.

Потпис аутора

У Београду, ______________

Amir

образац изјаве о коришћењу

Изјава о коришћењу

Овлашћујем Универзитетску библиотеку „Светозар Марковић“ да у Дигитални репозиторијум Универзитета у Београду унесе моју докторску дисертацију под насловом:

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која је моје ауторско дело.

Дисертацију са свим прилозима предао/ла сам у електронском формату погодном затрајно архивирање.
Моју докторску дисертацију похрањену у Дигиталном репозиторијуму УниверзитетауБеограду и доступну у отвореном приступу могу да користе сви који поштују одредбесадржане у одабраном типу лиценце Креативне заједнице (Creative Commons) за којусам се одлучио/ла.

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Потпис аутора
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