A Comprehensive Review of the Smart Microgrids' Modeling and Control Methods for Sustainable Developments

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Abstract: - Estimation strategies and hierarchical control measures are required for the successful operations of microgrids. These strategies and measures monitor the processes within the control variables and coordinate the system dynamics. State-of-the-art frameworks and tools are built into innovative grid technologies to model different structures and forms of microgrids and their dynamic behaviors. Smart grids' dynamic models were developed by reviewing different estimation strategies and control technologies. A Microgrid control system is made up of primary, secondary, and tertiary hierarchical layers. These architectures are measured and monitored by real-time system parameters. Different estimation schemes and control strategies manage microgrid control layers' dynamic performances. The control strategies in the developed technologies dynamics were accessed in the grid environment. The control strategies were modeled for microgrids using six design layers: adaptive, intelligent, robust, predictive, linear, and non-linear. The estimation schemes were assessed using microgrid controllers' modeling efficiency. Hierarchical control strategies were also developed to optimize the operation of microgrids. Hence, this research will inform policy-making decisions for monitoring, controlling, and safeguarding the optimal design strategies for modeling microgrids.

Key-Words: - Control strategies, estimation schemes, renewable energy system, energy storage system, distributed energy system, smart grids.

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1 Introduction

The practice of incorporating distributed energy resources (DERs) into the power grids gives rise to microgrids, which are the prospects of electricity grids. The DER combines distributed energy generations (DEGs) and energy storage systems (ESSs). These standalone or grid-connected microgrids are the sources of efficient future system operations because of their suitable control approaches and estimation structures. Integrating DERs in either AC or DC form simplifies microgrid development, [1]. Links between many DERs are established using power electronic converters. The factors responsible for converter interfaces vary from the control loop features, the number of converters involved, and the network's topology. Also, the interactions between converters can affect the dynamic performance of microgrid control loops, [2]. Microgrids encounter challenges in conforming with the system's operational requirements and ensuring safe power-sharing. To ensure microgrids' robustness and reliability, it is essential to coordinate power-sharing at every sample interval in grid-connected mode, [3]. The major challenge is in coordinating multiple microgrids with many DERs integrated, ensuring the flexibility of control and protection systems, managing the unreliability of DER supplies caused by renewable energy sources (RESs) fluctuations, and dealing with the uncertainties around the sizing and placement of ESSs in response to demand, [4]. These challenges require harmonizing a real-time demand management system with an energy management system (EMS). The research articulates stability models by analyzing different DERs to evaluate their performances under different loading conditions. Innovative techniques are used by smart grid technologies to address these challenges. Demand-side management gives a reasonable performance and reduces peak power, conserves energy, mitigates greenhouse gas emissions, and produces operations that are cost-effective, [5]. In [6], strategies such as peak shaving, load shifting, load development, and conservation are included in the primary distributed management system (DMS). Different DMSs are represented using the smart grid application of the demand response method.

In [7], current flow in DERs, grid-connected inverters, and microgrids are controlled using a developed method. The study analyzed a range of linear and non-linear controllers. Evaluating the current control mechanisms can help address grid synchronization and power quality problems in a microgrid. The article [8] provides a comprehensive explanation of a hierarchical control system for a DC microgrid. This system is designed to effectively regulate and restore current and voltage, as well as efficiently manage power across primary, secondary, and tertiary control layers. In their study, [9] conducted a comprehensive evaluation of several control strategies for AC microgrids. They focused on three key aspects: active and reactive power control, frequency and voltage control, and droop control. These control techniques were analyzed within the microgrids' architectural control hierarchy. These three control strategies are utilized in the construction of microgrids' system control. They may be regarded as methods for designing the control schemes, as explained in [10] for droop control. The study evaluates four control strategies, specifically fuzzy, predictive, robust, and proportional integral derivative (PID), for their effectiveness in managing distributed power generation. Hence, this research seeks to evaluate various control approaches applicable to all categories of microgrids. The control approaches utilized in several research endeavors for the deployment of intelligent microgrids often rely on control procedures. In addition, a microgrid controller necessitates precise data to achieve a higher performance index and guarantee the power networks' efficiency. A microgrid experiences different abnormalities and power outages due to equipment deterioration, cyber security breaches, and unpredictable power generation. Therefore, it is necessary to acquire and supervise DEG, distributed energy storage (DES), and load flexibility in an efficient manner. Additionally, it is important to categorize and identify different types of risks, as well as manage numerous energy supplies to minimize risks and safeguard microgrid equipment.

This study establishes and categorizes six control strategies as the primary conceptual foundation for developing control models for new microgrid applications. The control approaches mentioned are adaptive, intelligent, predictive, robust, linear, and nonlinear. The architectural choice of a certain control approach takes into account the formulation's capability to manage microgrids' control strategies. The estimate strategies for microgrid variables and parameters involve the use of a measuring and monitoring system to enhance the dynamic performance of control procedures with precision. The design and modeling of estimate approaches in microgrids enhance the dynamic behavior of system operation, [11]. The functioning of an intelligent microgrid is influenced by a range of factors and characteristics that might vary in different situations. These include cyber-attacks, erroneous data, power quality, changing demands, internal disturbances, external disturbances, faults, line parameters, and energy supplies. Therefore, an evaluation of crucial estimation is carried out in an intelligent microgrid that provides support for these control approaches. This work also offers a comprehensive viewpoint on architectural and hierarchical oversight and estimate strategies for the efficient functioning of microgrids. These approaches efficiently synchronize microgrids' components encompassing the energy resources and the end-users, irrespective of their system structure or whether they are AC or DC.

The primary contributions of this study can be enumerated as follows:

- Evaluation of the key dynamic elements necessary for the efficient functioning of a microgrid. Development and execution in the cutting-edge grid environment, irrespective of whether they are AC or DC. These rely on system management and monitoring to efficiently manage microgrids and create self-sufficient power networks.
- An examination of the primary control methods to be utilized in smart grids capable of managing various control criteria is established according to the system variables and microgrids' power quality. Thus, this addresses the inherent process of system modeling and the design of optimum control.
- This paper addresses the development of a perspective approach for optimizing smart microgrids' operations by integrating control approaches. This effectively resolves several issues. The text addresses the difficulties, sets out the future direction for microgrid growth, and offers a structure for a digital thread that can facilitate efficient control approaches and digital modeling of microgrids.

2 Insights on Intelligent Microgrid Systems

Smart grids utilize a diverse range of services and technology to update conventional power systems. As a result, an advanced power system is created that is characterized by sustainability, security, cooperation, automation, and control, [12]. The microgrid is an efficient current operating system that allows for the integration of both AC and DC power networks. A microgrid links different DERs at a specific place, known as the point of common coupling (PCC). A comprehensive categorization approach is required to elucidate the microgrid structures, methodologies, and obstacles to comprehend the operational scheme. The microgrid topologies consist of islanded and grid-tied operating modes, [13] and the precise functioning of the microgrid necessitates the harmonization of the control systems, the load management system (LMS), and the EMS, [14]. Hence, the primary operational difficulties faced by microgrids are the stability, robustness, resilience, reliability, and optimization of the system, [15]. These issues need the use of real-time estimation, which relies on measuring and monitoring the network to track the parameters and variables of the system. This approach may effectively assist control approaches for the sustainable functioning of microgrids.

2.1 The Distributed Energy Resources and the Distributed Energy Storage

The DERs refer to a collection of small-scale power generation units that are located close to the point of consumption. These units can include renewable energy sources such as solar panels, wind turbines, and fuel cells, as well. The most prevalent energy redessources utilized in microgrid operation are DEG and DES. The power grid is adopting a new trend (the DES) that helps to efficiently distribute excess produced power throughout the network, [16]. DESs must provide substantial energy capacity and rapid power response to serve grid support functions effectively. If the load demand exceeds the maximum scheduled generation, the DES system can release electricity to reduce the peak load. If the load demand is below the minimum scheduled generation, the DES system can store the surplus energy, [17]. The DEG encompasses both renewable energy resources (RERs) and non-renewable energy resources (non-RERs), whereas the DES consists of a battery energy storage system (BESS) as well as non-BESS components. BESSs typically utilize electrochemical technology, but non-BESSs employ other ESS (Energy Storage System) technologies, including electrical, mechanical, thermal, and chemical technologies, [18]. The disparity between BESS and non-BESS technologies highlights a significant gap between standard battery-dependent electrochemical technology and other ESSs based on different technologies. In certain situations, the energy demand is included in the category of DERs because some loads are dynamic and allow for electricity to flow in both directions within the electric network. DER operations can have detrimental and beneficial effects on the system frequency and voltage profile. Control measures in power converters can help reduce the detrimental effects of DERs on the network, [19]. RERs, specifically variable renewable energies (VREs) like solar photovoltaic and wind power, are widely utilized as the primary source of DEG in microgrids. BESS technologies are crucial for enhancing the reliability, stability, and flexibility of the power grid because of the unpredictability of VRE supplies and the requirement to meet the whole power demand on an hourly basis, [20]. In addition, electric vehicles (EVs) are equipped with a portable ESS technology, which is widely utilized in many applications of DER deployment to effectively manage the electric grid, [21].

2.2 Enhancing the Reliability and Resilience of the Power Grid using Microgrids

A microgrid is an electrical network that incorporates DER, either fully or partially. The interdependence between providers and customers is a pivotal facet of electrical network advancement. The primary aspect in maintaining the optimal functioning of any electrical system is the balance between reliability and resilience, irrespective of energy security and equality goals that aim to enhance the power grid's efficiency. Microgrids enhance the reliability and resilience of the electricity grid by using the capabilities of DERs. This benefits several stakeholders, including distribution network operators, providers, and customers, [22].

Resilience refers to the ability of the electrical system to adjust to stressful occurrences effectively. The system's reliability addresses grid recovery while considering potential system compromise. Microgrids provide a chance for client participation, as their reliable systems allow for sufficient flexibility in both energy transmission and distribution, [23]. Ensuring a compelling balance between the production and usage of energy is a necessity. An optimal correlation between energy supply and demand alleviates superfluous strain on the transportation system. The article [24] introduces many methodologies and models for monitoring the reliability of the electricity system. These tactics are derived from the most pertinent developing technologies utilizing stochastic processes and frequency-based approaches. It is crucial to ensure the resilience of the power grid under certain circumstances, including system malfunctions, heat waves, and hydrologic drought conditions. Reliability ensures the long-term viability of the electrical system in the face of severe occurrences such as cyber security threats, climate change, and adverse weather conditions, [25]. The grid-tied microgrid effectively enhances the robustness and reliability of the power network. The integration of DERs facilitates a strong connection between energy distribution, transmission, generation, and end users, [26]. The microgrid provides a method for managing power consumption in industrial, commercial, and residential sectors in order to address various grid functions. In the residential segment, this involves the three fundamental aspects of building energy flexibility, which are satisfying the inhabitant's requirements, adjusting to the surrounding conditions, and enabling flexible operations. Dynamic management systems are employed to create grid-interactive and energy-efficient systems that provide energy flexibility. These structures are implemented across all customers to ensure the efficient functioning of microgrids. Furthermore, several EMS methods can effectively address the challenge of real-time coordination and monitoring in a microgrid. The EMS methods utilize microgrids with varying power capacities, configurations, and classifications, [27]. Figure 1 provides a concise overview of notable characteristics that facilitate the adoption of microgrids and their creation and implementation. It contains the energy production concept, elements, functions, and constituents of microgrids; the types and advantages of adopting microgrids are also expressed therein. Microgrids have the potential to greatly enhance the utility network and offer a reliable source of electricity in developing nations.

2.3 Perspective of Smart Grid Technologies

The Smart Grid (SG) is an advanced electricity system that offers security measures, improved safety, environmental sustainability, cost-efficiency, and enhanced reliability. This power grid is characterized by its lowered cost, specified demand, optimal utility, reduced emissions, improved energy efficiency, and revolutionary design. The European Regulators Group for Gas and Electricity has defined the smart grid as an energy system that efficiently integrates the operations of all connected users, including consumers and producers. The goal is to create an economically efficient and sustainable power system with safety, security, exceptional quality, and minimal losses, [28]. Upgrading the traditional power grid enhances the electrical networks' sustainability, security, efficiency, and connection.

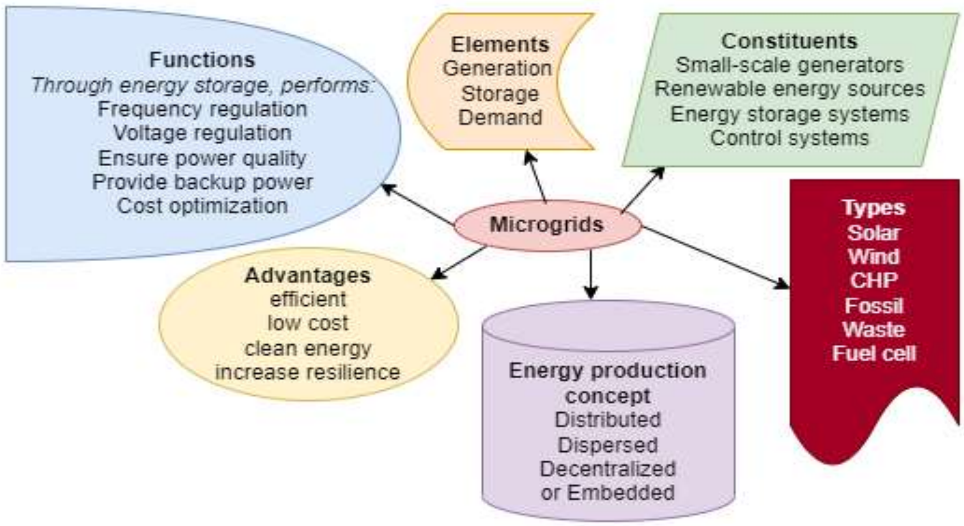

Fig. 1: Overview of microgrids

Advanced technologies digitize the power grid infrastructure and convert polluted urban areas into green landscapes. The shift from traditional power networks to innovative power grid environments incurs significant economic expenses. Furthermore, it has social obstacles due to the entrenched conventional power structure prevalent in the ancient cities, to which people are accustomed. Nevertheless, several benefits are assured in terms of enhancing the functioning of microgrids in different areas. A comparison study is discussed in [29] between the conventional electrical network and an intelligent power grid. The deployment of cutting-edge grid technology is intricate and necessitates many stages to establish an intelligent power grid ecosystem. The microgrid is a new architectural feature of a power system that efficiently incorporates many cutting-edge grid technologies. Using smart grid technology has the benefit of enhancing the efficiency of electricity flow and diminishing carbon emissions, [30]. The advanced electrical power grid incorporates several applications and technology to address most microgrids' drawbacks.

The viewpoint of novel grid technologies encompasses many modeling techniques and implementation strategies to regulate and efficiently assess microgrids' dynamic features. The utilization of cutting-edge grid technology to enhance the performance of microgrids is illustrated in Figure 2. This approach aims to achieve microgrids' Phase 5 (independent) functioning. The microgrid is now functioning in response-predictive Phases 2 and 3. Phases 1-2 represent the previous stages of the electrical system, while Phases 4-5 will correspondingly represent the intelligent grid's imminent and subsequent future. In Phase 4, artificial intelligence (AI) effectively manages the dynamic interactions between components of the power system, such as power production and transmission, distributed energy generating sources, electric vehicle (EV) integration, EMS, DMS, and battery energy storage systems (BESS). Phase 5 represents the evolutionary concept of the preceding phase, characterized by complete full autonomy in the functioning of all system components.

3 Microgrid Control Modeling and Design

Dynamic microgrid modeling relies on state, control, and modified variables with disturbances in the system. Hence, the control strategy's design must effectively manage all system disturbances and variables while adhering to certain limits. The operation of a microgrid is governed by three control layers, which work together to manage system variables and ensure the operation process' optimal efficiency. The microgrid's architectural control features are managed by three control layers, namely the primary, secondary, and tertiary. The control strategies of microgrids, particularly in the smart grid setting, may be perplexing to the technological and scientific communities.

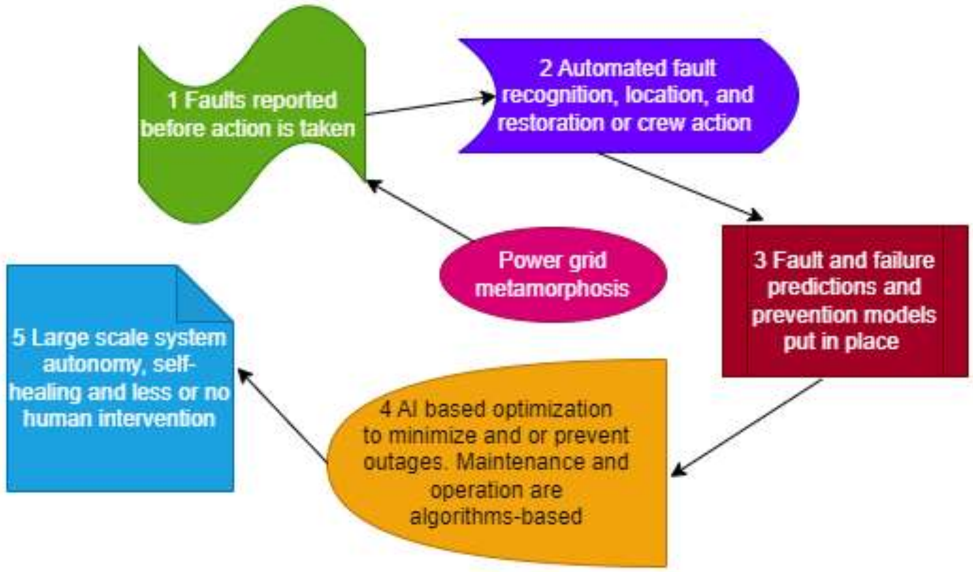

Fig. 2: Power grid metamorphosis

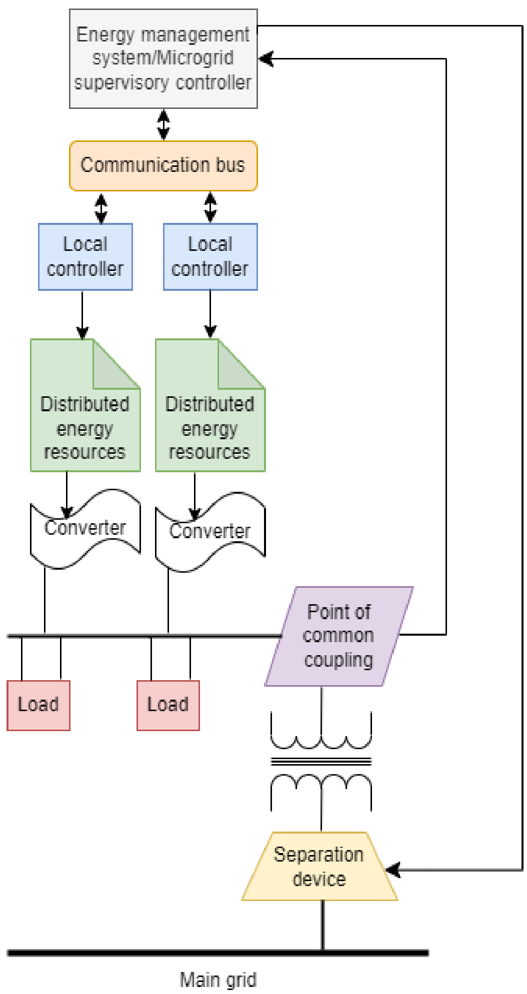

Fig. 3: Structure of a microgrid control system

Nevertheless, some methods, including active and reactive power, droop controls, voltage, and frequency, are essential for developing a design system to implement control strategies, [31]. Figure 3 displays the microgrid applications' block diagram for the control design, where the control modeling is greatly exemplified by distributed generators (DGs). This demonstrates the integration of the most pertinent control modeling and design methodologies with any estimating methodology, [32]. The efficacy of this control architecture in microgrids is contingent upon the stages of the digital revolution, as seen in Figure 2.

3.1 Model of the System

A microgrid model control system applications may be formulated [33]; the time domain, state space equation is:

$$\begin{bmatrix} x(t+1) \\ y(t) \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} x(t) \\ u(t) \end{bmatrix} \quad (1)$$

where y(t), t, A, B, x(t), C, D, and u(t) stand for the manipulated variable, sample time, state matrix, input matrix, state vector, output matrix, disturbance matrix, and control variables.

The frequency domain system transfer function, in the form of $(s) = y(s)/x(s)$, is expressed as:

$$G(s) = C(SI - A)^{-1} B + D \quad (2)$$

The time domain impulse response is expressed as:

$$y(t) = \int_0^t h(t-\tau)u(t)dt \tag{3}$$

where $h(t)$ stands for the control system's impulse response.

The time domain deterministic model is expressed as:

$$\begin{bmatrix} x(t+1) \\ y(t) \end{bmatrix} = \begin{bmatrix} A & B \\ C & 0 \end{bmatrix} \begin{bmatrix} x(t) \\ u(t) \end{bmatrix} \tag{4}$$

While the time domain stochastic model is expressed as:

$$\begin{bmatrix} x(t+1) \\ y(t) \end{bmatrix} = \begin{bmatrix} A(t) & B(t) & B_v(t) \\ C(t) & 0 & I_v \end{bmatrix} \begin{bmatrix} x(t) \\ u(t) \\ v(t) \end{bmatrix} \tag{5}$$

where I_v is an identity matrix, $B_v(t)$ represents the mixing and scaling matrix for process noise input; $v(t)$ (defined by $v(t) = [v_1(t), v_2(t)]$), is vector/matrix noise, where $v_1(t)$, the process noise is attached to $u(t)$, and $v_2(t)$, the measurement noise attached to $y(t)$.

It is important to note that matrix D can also be included in some design situations of Eq. (5). Therefore, the deterministic formulation refers to a traditional model of a state-space model that does not consider any uncertainty, as shown in Eq. (4). Nevertheless, the stochastic formulation incorporates system uncertainty that encompasses probabilistic characteristics, [33].

Figure 4 illustrates the progress and advancement of control systems in the intelligent microgrid. The shown representation is a beneficial framework for categorizing and designing the system approach, as seen in Figure 3. The control strategies examined in this study may be applied and enhanced in any approach, configuration, and layer, irrespective of the microgrid's kind and operational structure. The control system secures critical loads, automatically detects islanding, enables seamless transition, provides a safe supply to non-linear loads, maintains power balance, and verifies voltage and frequency restoration.

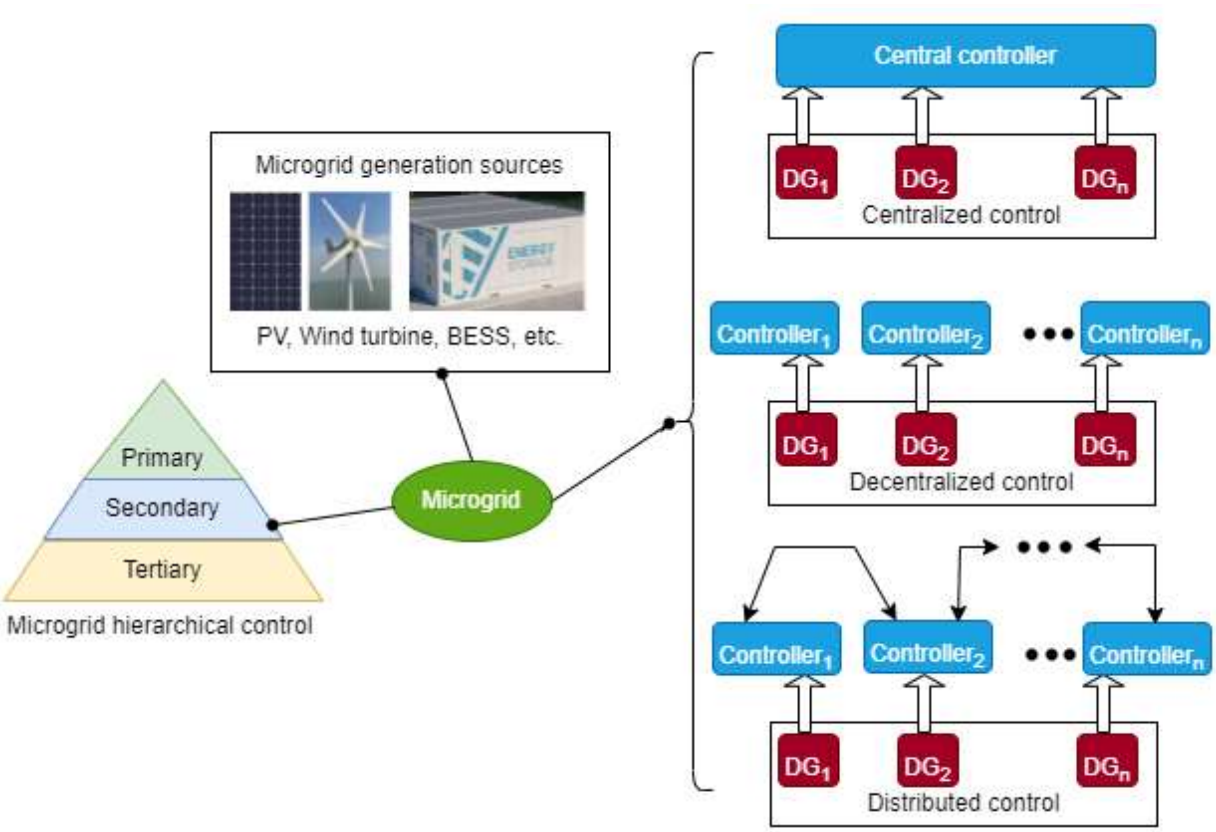

Fig. 4: Hierarchical control strategies

3.2 System Design

The design modeling technique, comprising the design (described in section 3.1) of the specified control system, illustrates microgrid sources, control hierarchies, and structures. The prevalent design modeling techniques are primarily derived from the state-space and transfer function model equations (1) and (2), respectively. The microgrid control modeling is structured in several levels and configurations, as seen in Figure 4. This section describes the different microgrids' control layers, including their complexity level, design domain, and formulation. The microgrids' control layers encompass the hierarchical control modeling and design. The optimum control techniques utilized in the microgrid are explicitly created inside the control layer's design domain. Figure 3 comprehensively describes the control implementation process for establishing a microgrid. Microgrids are designed to encompass several DERs in terms of structure and physical components. Hence, the development of the design model, as depicted in this section, pertains to the interlinkage and synergy of many DERs to achieve an effective microgrid operation. For instance, a specific DEG located at the *ith* location interacts with all *j* DERs, as seen in the distributed control shown in Figure 3.

The design domain of the primary control layer, with a low complex framework, encompasses power quality, power-sharing, voltage, and frequency stability. The model representations [33] for frequency stability (AC) are expressed as follows:

$$f(E_k, J, J_{vi}, \omega_e^*, \omega_i, \dot{\theta}_{si}, \dot{\omega}_{si}, D_{pi}, P_i^*, P_i, p_i, t) \quad (6)$$

the voltage stability is expressed as:

$$f(\delta E_i^1, k_{pE}, k_{iE}, E^*, E_{id}, \dot{e}_i, \dot{e}_j, t) \quad (7)$$

the power-sharing is expressed as:

$$f(u_{Qi}, C_{Qi}, \delta\omega_i, C_{Pi}, a_{ij}, \frac{Q_i}{Q_i^*}, \frac{Q_j}{Q_j^*}, \frac{P_i}{P_i^*}, \frac{P_j}{P_j^*}) \quad (8)$$

while the power quality is a function of Eqs. (6)-(8), expressed as:

$$f(Eqs.((6)-(8)) \quad (9)$$

From equations (6)-(9), the primary control layer, operating inside the microgrid, regulates many aspects such as frequency, voltage, reactive and active power. Its main objective is to stabilize microgrids and ascertain the electricity's high quality. Most of the variables in this layer are the same and can also be recognized in the second layer. For instance, in equation (6), E_k, J_{vi}, ω_e^*, ω, D_{pi}, and J represent the kinetic energy, virtual inertia, nominal frequency, rotational speed, virtual friction coefficient, and the synchronous generator's rotational inertia, respectively. According to equation (7)-(8), the voltage compensation provided by the reference voltage E^*, compared to the observer output, is denoted as δE_i^1. The $\bar{e}i$ and δy are the voltage-observer output and the transient deviation produced by the synchronization of the active power, respectively. C_{Qi} and C_{Pi} refer to the coupling gain, while k_{pE} and k_{iE} represent the control gain used in proportional-integral (PI) control. It should be emphasized that the extent of these gains relies on the control approach employed to develop the design model. The u_{Qi} voltage of DEG i is used to control the reactive power, whereas P_i/P^*_i represents the normalized power of the *ith* DEG.

The secondary layer is expressed mathematically via equations (10)-(12). The design domain of the secondary control layer, with a moderately complex framework, contains frequency restoration, voltage restoration, and power-sharing improvement. The model representations [33] for frequency restoration (AC) is expressed as:

$$\begin{cases} \omega_i = \omega^* - m_i P_i + \Omega_i \\ k_i^{\omega} \dfrac{d\Omega_i}{dt} = (\omega^* - \omega_i) - a_{ij}(\Omega_i - \Omega_j) \end{cases} \quad (10)$$

the voltage restoration is expressed as:

$$\begin{cases} E_i^{ref} = E^* - n_i Q_i + \partial E_i \\ k_i^E \dfrac{d(\partial E_i)}{dt} = \beta_i (E^* - E_i) - a_{ij}(\dfrac{Q_i}{Q_i^*} - \dfrac{Q_j}{Q_j^*}) \end{cases} \quad (11)$$

while the power-sharing improvement is expressed as:

$$\begin{cases} P_i(active\ power) = f(Eq.(10)) \\ Q_i(reactive\ power) = f(Eq.(11)) \end{cases} \quad (12)$$

In equation (10), ω, Ω, m, $k^{\omega}{}_i > 0$ and P r P, ω, m, Ω, and $k^{\omega}{}_i > 0$ represent active power, frequency, droop coefficient, frequency restoration parameter, and the secondary control's velocity regulation coefficient. All parameters and variables can be related to DEG *i*. The elements of the adjacency matrix, a_{ij}, represent the weights used to assess the communication architecture. These weights, a_{ij}, can be utilized to estimate the stability of the microgrid. Node *j* represents the agent that communicates with node *i*. In equation (11), Q_i/Q_i^*, *n*, δE_i, and *E are the* normalized reactive power of the DEG_i, droop coefficient, secondary control variable, and the regulating voltage, respectively. Modification of the dynamics is achieved using the positive gains β_i and k^E_i. The objective of the secondary control mechanism is to address the vulnerability of a centralized control system to solve the single-point failure. This concept is implemented to provide equitable power distribution among microgrids. Within the secondary control layer, an improved design of a single domain has the potential to address the issues present in other domains as well. An example of a distributed control system in the second layer is responsible for managing both the restoration of frequency and voltage in AC microgrids, [34].

The tertiary layer is defined by equations (13)-(15). The design domain of the tertiary control layer, with a highly complex framework, is made up of economic dispatch, energy, and congestion management. The model representations [33] for economic dispatch are expressed as:

$$f(C_i(P_i), \alpha_i, \beta_i, \gamma_i, P_i, P_L, \lambda_i) \tag{13}$$

the energy management is expressed as:

$$\min_{u} \sum_{t=1}^{k} F(x_i(t), u_i(t), d_i(t), z_i(t)) \tag{14}$$

while the congestion management is expressed as:

$$\min f = (pr, \Delta S_{G_i}, \Delta P_{ll_i}, \Delta S_{L_i}, \Delta S_{L_s}, t) \tag{15}$$

In equation (13), $C_i(P_i)$ represents the operating expense, related to a certain *ith* DEG unit. Therefore, the coefficients of the cost function are represented as α_i, β_i, and γ_i, where with α_i, and β_i are the values of the quadratic cost functions that are related with the generation i; λ_i provide the assessment of the additional cost for each generation. P_i represents the active power from DEG_i, and P_L represents the system's power demand. In equation (14), $x_i(t)$ stands for the discrete time-varying variables, encompassing the battery state of charge (SOC) and the energy cost; $u_i(t)$ is the control parameter; $d_i(t)$ denotes the parameter vector comprising the most accurate assessment of demand at a specific time, intermittent generation, fuel cost, etc.; z_I is the time-invariant variables, such as voltages, phase angles, and frequency. In equation (15) *pr* represents the fluctuating price of electricity in the market, determined by the bid prices for each load demand and generation source. From equations (6)-(9), the primary control layer, operating inside the microgrid, regulates many aspects such as frequency, voltage, reactive and active power. Its main objective is to stabilize microgrids and ascertain the electricity's high quality. Most of the variables in this layer are the same and can also be recognized in the second layer. For instance, in equation (6), *Ek, Jvi, ωe*, ω, Dpi*, and *J* represent the kinetic energy, virtual inertia, nominal frequency, rotational speed, virtual friction coefficient, and the synchronous generator's rotational inertia, respectively. According to equation (7)-(8), the voltage compensation provided by the reference voltage E^*, compared to the observer output, is denoted as $\delta Ei1$. The $\bar{e}i$ and δy are the voltage-observer output and the transient deviation produced by the synchronization of the active power. The energy management planning domain is widely implemented in various tertiary control levels of various microgrids. In [35], a highly efficient combinatorial control scheme is developed to represent the economic dispatch of a freestanding microgrid. This system depends on an energy management structure and aims to maximize the use of ESS. In [36], a decentralized structure is created by utilizing energy management techniques to optimize the charging process of electric vehicles in off-grid microgrids. Moreover, the energy market has evolved into a complex ecosystem where various players have substantial influence. Congestion management establishes a hosting domain that ensures fair participation of all stakeholders, including end-users, distribution, transmission system operators, etc., in the energy market, which involves the comprehensive integration of DERs [37].

Optimal functioning necessitates the consideration of microgrid stability. This is because microgrids are composed of linked systems where ensuring dynamic stability is the primary need to ascertain the stability of DEG. Implementing inertia control is a viable method to ascertain microgrids' frequency stability. An efficient primary layer control ensures optimal power distribution and DC microgrids' voltage stability, but frequency stability in AC microgrids is an additional factor included [38]. The primary layer serves as the fundamental basis for the operational functioning of microgrids [39]. The hierarchical control structure is a combination of two or more layers; this control architecture improves the performance of microgrids in terms of coordination, stability, regulation, and power quality. Architectural control with two levels, primary and secondary, is proposed to mitigate power oscillations of various distributed generators (DGs) in microgrids [40]. In the first layer, two current controllers were designed to produce the current reference and mitigate the active power oscillations. In addition, the second layer is designed using an ideal model to effectively reduce the fluctuating magnitudes of both active and reactive powers simultaneously. Thus, in most cases, an effective control design for microgrids relies on a hierarchical control architecture.

4 Control Methods

The control strategies for a microgrid are built using the hierarchical design concept. The existing control architecture of the microgrid is focused on transitioning the predictive power network (phase 3 of Figure 2) into a prescriptive electrical grid (phase 4 of Figure 2), aligning with the eventual vision of the autonomous power grid (phase 5 of Figure 2). The most relevant control methods identified for microgrid applications are the intelligent, robust, predictive, adaptive, linear, and non-linear control methods. The benefits of categorizing control strategies in this manner are that all design methodologies may be tailored to the specific needs of microgrid modeling and enhancement. This may be accomplished by employing deterministic or stochastic modeling techniques to manage the optimum control approach's dynamic feature effectively.

4.1 Smart Control Method

Smart or intelligent control approaches utilize hardware and software technologies to accurately represent the dynamic nature and manage the operational efficiency of microgrids, [41], [42], [43]. Soft computing technology is commonly called the programming language, and its models are based on intelligent control techniques. The data-driven method is a smart control technique that suggests many options for both non-linear and linear models, [44], [45] and the experiment can involve either one or more state and control variables. Data-driven approaches provide various advantages, including the capability to develop a model based on data, the capacity to learn control behavior, and the flexibility to place sensors and actuators in systems with multiple variables. The intelligent control approach is scalable and resilient, allowing for constant and precise monitoring of power grid functioning and user behavior in real-time. This technique also enables great dynamic control, [46]. The mildest computing methods employed to regulate intelligent microgrids are wavelet transform, particle swarm optimization, machine learning, fuzzy neural network, fuzzy logic control, deep neural network, deep learning, artificial neural network, artificial intelligence, etc., [47], [48], [49], [50], [51], [52]. Soft computing is primarily regarded as a framework encompassing several intelligent technologies and an instrument that can enhance the resilience and efficiency of control procedures. Their applications are commonly being processed in the realm of power electronics, as well as active and reactive power, to maintain the functioning of microgrids and significantly reduce the complexity of computation in the system performance index. The hardware technologies utilize advanced communication networks based on innovative technology to manage microgrids intelligently. The Internet of Things (IoT) technology is a visionary approach to managing microgrids intelligently. This innovative control system spans from power generation sources to the ultimate consumers. The Internet of Energy utilizes the concept of linking various elements such as services, devices, individuals, and energy sources through the Internet of Things (IoT) to develop intelligent models for energy distribution. These models aim to address the current difficulties in the energy sector, [53].

4.2 Robust Control Method

The robust control approach employs many control mechanisms to facilitate the interconnection control of DER units and ensure appropriate energy conversion. This control approach primarily focuses on the inverter control’s feedback loops of the microgrid. It regulates frequency and voltage during imbalanced situations, typically using the concept of infinite horizon, [10]. The robust control approach may be used to design slide mode and direct control techniques for DGs in microgrids, [54], [55]. The robust control approach is capable of functioning well under various loading circumstances. This control strategy is designed to handle both unbalanced and balanced loading scenarios. This resilient control strategy provides precise and rapid performance irrespective of system fluctuations. Robust control modeling employs the identical approach of stochastic formulation as stated in Eq. 4. Nevertheless, the robust construction only considers the uncertainty in the system description without considering any probabilistic characteristics. The robust control method could be modeled as [33]:

$$x(t+1) = Ax(t) + Bu(t) + B_d \omega(t) \tag{16}$$

where $w(t)$, t, B_d, are the unknown disturbance vector, time, and the known parameters matrix.

The controller for microgrids often incorporates many layers to ensure its resilience. Consequently, a hierarchical control system smoothly transitions between different microgrid operation modes. A hierarchical control strategy effectively addresses the robust control issues that arise in the efficient functioning of microgrids. The model's structure is generalized and does not necessitate a mandatory transition between inverter-interfaced district control DEGs.

4.3 Predictive Control Method

Predictive control approaches utilize forecasting and prediction to anticipate the future dynamic behavior of a particular system. It can be modeled using quadratic or linear quadratic models, model predictive control (MPC), statistical or deterministic time series, neural networks, etc. The predictive control model can be expressed as [33]:

$$J(k) = \sum_{i=0}^{N} \begin{bmatrix} x^T(k+i \mid k) Q x(k+i \mid k) \\ +u^T(k+i \mid k) R u(k+i \mid k) \end{bmatrix} \tag{17}$$

where Q and R are positive elements diagonal matrices, N and $J(k)$ are the control horizon and the objective function of predicted sequences, respectively.

Authors in [56] discussed the critical trends in the development of MPC and showcased MPC as a competitive alternative to conventional techniques in economic operation optimization, power flow management, frequency control, and voltage regulation. Several factors, including demand constraints, DEG restrictions, output, input, and state variables, can constrain the MPC performance index. MPC is commonly implemented at the tertiary control level. Furthermore, MPC is a resilient and robust control strategy that may effectively manage system uncertainty and disturbance. Therefore, the utilization of predictive control methods that rely on Model Predictive Control (MPC) and Artificial Neural Networks (ANN) may be effectively applied to model all three tiers of smart microgrid controllers, namely primary, secondary, and tertiary, in both DC and AC power systems. The dead-beat concept can likewise be implemented using predictive control techniques. The predictive control technique offers a significant advantage, which has resulted in the development of different execution strategies within machine learning (ML) methods. These strategies include using support vector machines, linear regression, regression trees, and neural networks (NN).

4.4 Adaptive Control Method

The adaptive control approach encompasses a diverse array of techniques with varying characteristics. The adaptive control approach is applicable for creating the intelligent microgrid controller on many levels, including primary, secondary, and tertiary, [57], [58]. The accuracy of power-sharing between DGs is compromised when there is a mismatch in the impedances of the feeders/lines in islanded microgrids. This can be attributed to the disadvantages inherent in decentralized approaches for managing active power through reactive power and inverse droop control through conventional droop control. Virtual impedance is a widely used solution for addressing this difficulty, necessitating the use of optimal valuation of the environment. Hence, a method for adaptive control is devised to modify the virtual impedance based on the output current of DGs. This method enhances the power-sharing capabilities of isolated microgrids without the need for extra parameters, predictions of network load, sensors, or communication equipment. The method further ensures precise power distribution and attains a balanced state of charge (SOC) among the distributed energy storage systems (DESS).

4.5 Linear Control Method

Regarding the development of the control models, the linear model has the potential to be stated as a linear time-invariant expression, [33].

$$\begin{cases} \dot{x} = f(x,u,t) \\ y = h(x,u,t) \end{cases} \quad (18)$$

Equation (18) functionally represents the state-space model of Equation (1). A linear control approach may be used to control the current and regulate the frequency of a microgrid. Equation (2) is also used to design a linear control mode. Various control strategies, including repetitive current controllers, proportional-resonant, proportional derivative, and proportional-integral (PI), can be employed using linear control techniques. This method efficiently develops a proportional integral derivative (PID) control strategy. The linear control approach may create current and voltage control loops in the microgrids' primary and secondary control layers, [59], [60]. Linear control approaches can be further evolved into a tertiary control layer to address energy harmonization issues [8] effectively. Quadratic problems related to the distribution of DER electricity, including ESSs, may also be effectively addressed by employing linear quadratic modeling, [61]. The distinguishing characteristic of these strategies is their capacity to convert a non-linear system into a manageable linear system.

4.6 Non-linear Control Method

The control approach of a non-linear state model can take several shapes based on a specific system model. Equation (x) serves as an exemplar of a non-linear design concept:

$$\begin{cases} \dot{x}(t) = f(x(t)) + g(x(t))u(t) + \omega(t) \\ y(t) = x(t) \end{cases} \quad (19)$$

where *f(x(t))* and *g(x(t))* are the non-linear functions that may require linearization for the control design's optimal solutions and *w(t)* represents the bounded disturbance respectively. Utilizing a nonlinear control approach allows for the creating diverse control schemes, including hysteresis controllers, deadbeat (DB), PI, and PID. Fuzzy logic, PI, and PID controllers are optimal nonlinear strategies for achieving equilibrium in Energy Storage Systems (ESSs) and stabilizing the bus voltage of DC microgrids. In addition, they can manage the limitations of current distribution and the synchronization of power transmission. The control schemes are designed specifically for the primary control level, [62]. A passivity-based control approach is considered an efficient and feasible nonlinear control method for bidirectional DC-DC converters.

Furthermore, the strategy is easy to put into practice, [63]. Implementing a droop control mechanism enables the autonomous recovery of cluster microgrids. Implementing DER control using nonlinear primary control stabilizes the system frequency and voltage at the point of common coupling (PCC) while regulating the active power. In addition, this technique provides a solid and uncomplicated setup.

5 Discussions

Table 1 concisely overviews various control approaches used in smart microgrids. It is essential to mention that data-driven approaches are an alternative term for soft computing techniques. A soft computing technique encompasses various intelligent tactics rooted in data-driven and evolutionary computation approaches. Data-driven refers to the utilization of data sciences to replicate the behavior of an ideal control method. Typically, this pertains to Artificial Intelligence (AI) and Machine Learning (ML). This technology is a powerful method that will enable the next generation of the power grid to function as an independent electrical system, as presented in Figure 2, and effectively enable the implementation of Multi-Agent Systems (MASs). Deterministic optimizations for microgrids primarily rely on an appropriate optimum control method to manage the dynamic performance of tertiary control. A stochastic optimization technique can create an optimal control scheme. However, it is more appropriate to categorize it as a fusion of control methodologies since it can account for the many uncertainties present in the system. The classification of deterministic optimization-based optimum control methods depends on the equations used and may be categorized as either linear (Eqn. (18)) or non-linear (Eqn. (19)) control approaches. In addition, it is possible to create either a deterministic or stochastic optimization control system based on a framework of control techniques.

Table 1 displays the most significant research studies conducted in the past five years that address control methodologies for an intelligent microgrid. This demonstrates the implementation of several different methods. Intelligent microgrids' precise and efficient functioning necessitates a meticulous evaluation of the potential power generated by DERs. The control hierarchy's bandwidth and time scale exhibit an inverse relationship with microgrids from the primary to the tertiary level of control. This implies that primary control needs a significant amount of data transfer capacity in a lower range. Time scale computation is required for tertiary control structures, which operate at a more significant time scale with a low bandwidth.

Furthermore, semantic technologies are employed in cutting-edge grid systems to achieve precise estimates and optimal efficiency during runtime [64]. It is essential to recognize that the manipulated parameters for running microgrids rely on the control and state variables to provide optimal control behavior. Monitoring the output reference is crucial for ensuring optimal performance and reliable operation of islanded and grid-tied microgrid modes. Hence, it is crucial to use appropriate control to ensure an intelligent microgrid's efficient functioning.

6 Future Works

The advancement of microgrids necessitates control methods that can independently implement any dynamic idea depicted in Figure 4 to manage variables and parameters' monitoring and protection. Therefore, microgrids can function at phase 5, as depicted in Figure 2. The robust management of all system variables is achieved by implementing control methodologies. The intelligent grid environment offers a diverse range of control capabilities for the power network. In this context, the bidirectional connection between remote terminal units, phasor measurement units, intelligent electronic devices, and control centers enhances the robustness of the power network. Precision in data is crucial when managing the integration of innovative power generation with the growing use of real-time sensor-based decision-making.

Nevertheless, the intelligent microgrid is susceptible to cyber-attacks, in which a meticulously planned assault might introduce inaccurate information into the microgrid during the process of state estimate, hence impacting the functioning and management of the electrical system [95]. This can lead to significant technological, economic, and societal issues. Standard approaches like Newton-Raphson can mitigate the effects of fake data injection assaults on essential sensors in the microgrid. Implementing a plan to identify hacked meters effectively eliminates potential hazards to the electricity system. The intelligent microgrid operation should quickly identify false information and adjust the process according to dynamic behavior. The internet of energy is a sophisticated notion within intelligent grids, [96]. This can be efficiently accomplished and implemented using a hybrid control framework inspired by the concept of cutting-edge microgrid control.

The hybrid control structure refers to amalgamating all three suitable control structures. The Internet of Energy uses a distributed design to maintain a balanced power network. Thus, the system can function autonomously without relying on the primary transmission and distribution network, [97]. However, this architectural design primarily focuses on DERs with the potential for large-scale ESSs and a significant number of integrations into electric vehicles (EVs). Furthermore, implementing robust and resilient control in an intelligent grid environment would face challenges related to many variables, characteristics, and elements. Hence, developing a system that can effectively meet all the requirements is necessary. The proposed system will incorporate a hierarchical model to manage protection, monitoring, and system control. It will handle state estimations, resources, cyber security, self-healing, fault recognition, and location tasks. The system will also include an instantaneous communication network to enable real-time and fast data transfer within a MAS conglomerate.

7 Conclusion

Cutting-edge grid technology has revolutionized the power system's modeling and design. These technologies incorporate innovative ideas for bidirectional communication and efficiently control energy distribution across several independent entities. The smart grid may be defined as the amalgamation of DERs integrated with optimum control strategies. The deployment of microgrids serves as the foundational framework that enables the adoption of advanced technologies. An intelligent microgrid operation necessitates hierarchical coordination among diverse technologies to assess and manage several parameters and variables in a real-time setting, irrespective of the system's complexity, kind, and structure.

Table 1. Recent trends of control methods in smart microgrids

Year	Application description	Control method	Methodology	Ref.
2021	A predictive control applying parallel converters in islanded microgrids	Predictive	Parallel converters	[65]
2020	A power power-sharing control approach for AC microgrids	Predictive	MPC	[66]
2021	A model predictive control in islanded microgrid for distributed energy sources	Predictive	Finite control model	[67]
2021	A predictive control using virtual inertia emulator in AC microgrids	Predictive	MPC	[68]
2020	A model predictive control in microgrids' real-time operation	Predictive	MPC	[69]
2020	Microgrids' network voltage tracking and damping using robust control method	Robust	Linear-quadratic-Gaussian (ILQG) controller	[70]
2020	A robust control method for microgrids using linear matrix inequality	Robust	Linear matrix inequality	[71]
2020	A robust control method for DC microgrids using disturbances and parametric uncertainty	Robust	Lebesque-measurable matrix and disturbance rejection.	[72]
2020	A robust control method for DC microgrids using communication network delay	Robust	Lyapunov-Krasovskii theorem and linear-matrix	[73]
2020	A control method for islanded microgrids using H_∞ robust approach	Robust	linear matrix inequality	[74]
2021	A smart control method for microgrids using distributed fuzzy cooperative controller	Smart	Model predictive voltage and current	[75]
2021	A DC microgrid applications of DC/DC converter	Smart	ANN	[76]
2021	Microgrids model reference voltage controller	Smart	Fuzzy PI model	[77]
2021	Smart microgrids battery energy storage energy controller	Smart	ANN	[78]
2021	Frequency and voltage controller in an AC microgrid	Smart	PSO tuned PI	[79]
2021	A microgrids' voltage controller using droop control	Nonlinear	Load boundary and negative droop resistances	[80]
2021	A DC microgrids' controller design	Nonlinear	Lyapunov theory of Linear Matrix Inequality (LMI).	[81]
2020	An energy storage systems and renewable resources DC microgrids' controller	Nonlinear	Integral backstepping	[82]
2021	A distributed event-driven power sharing controller design	Nonlinear	Partial feedback linearization	[83]
2020	A microgrid systems' droop-like behavior control mapping	Nonlinear	External droop control architecture	[84]
2022	A DC bus voltage stabilizing controller design	Adaptive	Active damping scheme	[85]
2022	An AC microgrids' master-slave controller design	Adaptive	Backstepping control (BSC) scheme,	[86]
2022	A shipboard's DC microgrids control design	Adaptive	Neural network linear parameter	[87]
2022	A controller design for remote microgrids	Adaptive	Continuous mixed P-norm (CMPN) algorithm	[88]
2020	An incremental filter-control for rural microgrids	Adaptive	Incremental adaptive filter	[89]
2021	Microgrids' multiple models' controller design	Adaptive	Multiple models	[90]
2020	Isolated microgrids' linear quadratic controller design	Linear	Power sharing control	[91]
2022	A rural PV microgrid controller for DC-DC converters	Linear	Exact linearization technique	[92]
2020	A hybrid AC-DC microgrid using improved voltage oscillation damping	Linear	Linear quadratic Gaussian method	[93]
2023	An isolated hybrid AC-DC microgrids frequency controller	Linear	Linear parameter varying (LPV) method	[94]

Distinguishing between control methodologies and modeling of microgrids in the novel grid context might be challenging. This study evaluates several control methodologies for advanced microgrids. The study categorizes the control approaches into six distinct categories: intelligent, robust, adaptive, predictive, linear, and non-linear control systems. This control categorization evaluates the inherent implementation capabilities of microgrids in terms of their novel techniques, layers, modeling structure, and dynamic design. It has been noted that some control approaches may be applied inside a framework that simulates two or more methods. The hierarchical control refers to the organization of the microgrid into primary, secondary, and tertiary levels to achieve efficient operational performance. In addition, this introduced a secondary layer that examines the plausible assessment of DER potential since microgrids serve as the driving force behind DER deployment.

Furthermore, microgrid controllers often consist of hierarchical control layers that synchronize, enhance, regulate, and stabilize the system's behavior. This research proposes a unique control structure, namely a hybrid, to differentiate itself from the widely available control structures. The control structures may be classified into three types: centralized, decentralized, and distributed. The hybrid control structure refers to amalgamating all three suitable control structures. This is the viewpoint of the entire self-governing electric network comprised of Multi-Agent Systems (MASs). A successful hierarchical control architecture requires exceptional monitoring behavior to safeguard microgrids against unforeseen occurrences.

Furthermore, the control techniques safeguard the whole system from various abnormal occurrences, such as malfunctions and cyber-attacks, while also offering the chance to identify suitable areas for adding DERs and ESSs to enhance system efficiency. In addition, microgrids have yet to be fully commercialized, and their new applications need to be integrated into the future of the digital revolution of the smart grid. Future studies will investigate the hierarchical coordination and vision perceptions of novel microgrids.

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References:

[1] X. Liu, Y. Liu, J. Liu, Y. Xiang, and X. Yuan, "Optimal Planning of AC-DC Hybrid Transmission and Distributed Energy Resource System: Review and Prospects," *CSEE Journal of Power and Energy Systems*, vol. 5, no. 3, pp. 409-422, 2019, https://doi.org/10.17775/CSEEJPES.2019.00540.

[2] A. M. Jasim, B. H. Jasim, V. Bures, and P. Mikulecky, "A Novel Cooperative Control Technique for Hybrid AC/DC Smart Microgrid Converters," *IEEE Access*, vol 11, no 1, pp. 2164-2181, 2023, https://doi.org/10.1109/ACCESS.2023.3234011.

[3] M. Mottaghizadeh, F. Aminifar, T. Amraee, and M. Sanaye-Pasand, "Distributed Robust Secondary Control of Islanded Microgrids: Voltage, Frequency, and Power Sharing," *IEEE Transactions on Power Delivery*, vol. 36, no. 4, 2021, https://doi.org/10.1109/TPWRD.2021.3076761

[4] A. Muhtadi, D. Pandit, N.. Nguyen, and J. Mitra, "Distributed Energy Resources Based Microgrid: Review of Architecture, Control, and Reliability," *IEEE Transactions on Industry Applications*, vol. 57, no. 3, 2021, https://doi.org/10.1109/TIA.2021.3065329.

[5] H. H. Shalaby, Y. G. Hegazy, A. M. Azmy, F. M. Bendary and M. N. Ali, "A review on demand side management applications, techniques, and potential energy and cost saving," *Journal of Electrical Engineering*, vol. 20, no. 1, 2021, 21-33, 2021.

[6] N. Irtija, F Sangoleye, and E. E. Tsiropoulou, "Contract-Theoretic Demand Response Management in Smart Grid Systems," *IEEE Access*, vol 8, no 1, pp. 184976-184987, 2020, https://doi.org/10.1109/ACCESS.2020.3030195.

[7] A. M. S. Alonso, L. D. Arenas, D. I. Brandao, E. Tedeschi, R. Q. Machado, and F. P. Marafão, "Current-Based Coordination of

Distributed Energy Resources in a Grid-Connected Low-Voltage Microgrid: An Experimental Validation of Adverse Operational Scenarios," *Energies*, 2022, vol. 15, no 1, pp. 6407. https://doi.org/10.3390/en15176407.

[8] A. Abhishek, A. Ranjan, S. Devassy, B. K. Verma, S. K. Ram, A. K. Dhakar, "Review of hierarchical control strategies for DC microgrid," *IET Renewable Power Generation*, vol. 14, Issue 10, pp.1631-1829, 2020, https://doi.org/10.1049/iet-rpg.2019.1136.

[9] A. Mohammed, S. S. Refaat, S. Bayhan, and H. Abu-Rub, "AC microgrid control and management strategies: Evaluation and review," *IEEE Power Electronics Magazine*, vol. 6, Issue 2, pp. 18-31, 2019, https://doi.org/10.1109/MPEL.2019.2910292.

[10] F. Mohammadi, B. Mohammadi-Ivatloo, G. B. Gharehpetian, M. H. Ali, W. Wei, O. Erdinc, and M. Shirkhani, "Robust Control Strategies for Microgrids: A Review," *IEEE Systems Journal*, vol. 16, no. 2, pp. 2401-2412 2022, https://doi.org/10.1109/JSYST.2021.3077213.

[11] A. K. Onaolapo, G. Sharma, P. N. Bokoro, T. Adefarati, and R. C. Bansal, "A Comprehensive Review of the Design and Operations of a Sustainable Hybrid Power System". *Computer and Electrical Engineering Journal*, vol. 111, part A, pp. 108954, 2023, https://doi.org/10.1016/j.compeleceng.2023.108954.

[12] G. Dileep, "A survey on smart grid technologies and applications," *Renewable Energy*, vol. 146, no 1, pp. 2589-2625, 2020, https://doi.org/10.1016/j.renene.2019.08.092.

[13] A. K. Onaolapo, G. Sharma, S. Sharma, and T. Adefarati, "The Economic Feasibility and Cost Reduction of Grid-linked Solar PV Systems in South Africa," *International Conference on Innovative Sustainable Computational Technologies (CISCT), Dehradun, India*, pp.1-5, 2022. https://doi.org/10.1109/CISCT55310.2022.10046464.

[14] J. Singh, S. P. Singh, K. S. Verma, A. Iqbal, B. Kumar, "Recent control techniques and management of AC microgrids: A critical review on issues, strategies, and future trends," *Energy Systems*, Vol. 31, Issue 11, pp. e13035, 2021, https://doi.org/10.1002/2050-7038.13035.

[15] M. H. Saeed, W. Fangzong, B. A. Kalwar, and S. Iqbal, "A Review on Microgrids' Challenges & Perspectives," *IEEE Access*, vol. 9, no 1, pp. 166502-166517, 2021, https://doi.org/10.1109/ACCESS.2021.3135083.

[16] O. K. Olajiga, E. C. Ani, T. M. Olatunde, and Z. Q. Sikhakane, "Assessing the potential of energy storage solutions for grid efficiency: a review", *Engineering Science & Technology Journal*, vol. 5, no. 3, pp. 1112-1124, 2024. https://doi.org/10.51594/estj.v5i3.974.

[17] L. Chang, W. Zhang, S. Xu, and K. Spence, "Review on distributed energy storage systems for utility applications," *CPSS Transactions on Power Electronics and Applications*, 2017, vol. 2, no. 4, pp. 267-276, 2017. https://doi.org/10.24295/cpsstpea.2017.00025.

[18] M. M. Rahman, A. O. Oni, E. Gemechu, A. Kumar, "Assessment of energy storage technologies: A review," *Energy Conversion and Management*, vol. 223, no. 1, pp. e113295, 2020, https://doi.org/10.1016/j.enconman.2020.113295.

[19] J. Caballero-Pena, C. Cadena-Zarate, A. Parrado-Duque, and G. Osma-Pinto, "Distributed energy resources on distribution networks: A systematic review of modelling, simulation, metrics, and impacts," *International Journal of Electrical Power & Energy Systems*, vol. 138, no. 1, pp. 107900, 2022. https://doi.org/10.1016/j.ijepes.2021.107900.

[20] S. Han, Y. Yuan, M. He, Z. Zhao, B. Xu, D. Chen, and J. Jurasz, "A novel day-ahead scheduling model to unlock hydropower flexibility limited by vibration zones in hydropower-variable renewable energy hybrid system," *Applied Energy*, vol. 356, no. 1, pp. 122379, 2024. https://doi.org/10.1016/j.apenergy.2023.122379.

[21] S. R. Salkuti, "Advanced Technologies for Energy Storage and Electric Vehicles," *Energies*, vol. 16, no. 1, pp. e2312, 2023, https://doi.org/10.3390/en16052312.

[22] J. Sora, I. Serban, and D. Petreus, "Enhancing Microgrid Operation through Electric Vehicle

Integration: A Survey," *IEEE Access*, vol. 12, no. 1, pp. 64897–64912, 2024. https://doi.org/10.1109/ACCESS.2024.3397587.

[23] M. H. Imani, P. Niknejad, M. R. Barzegaran, "The impact of customers' participation level and various incentive values on implementing emergency demand response program in microgrid operation," *Electrical Power and Energy Systems*, vol. 96, no. 1, pp. 114–125, 2018. https://doi.org/10.1016/j.ijepes.2017.09.038.

[24] P. Balducci, K. Mongird, and M. Weimar, "Understanding the Value of Energy Storage for Power System Reliability and Resilience Applications," *Current Sustainable/Renewable Energy Reports*, vol. 8, no. 1, pp. 131–137, 2021, https://doi.org/10.1007/s40518-021-00183-7.

[25] A. K. Onaolapo, G. Sharma, P. N. Bokoro, A.O Aluko, and G. Pau, "A Distributed Control Scheme for Cyber-Physical DC Microgrid Systems." *Energies*, 2023, vol. 16, no. 1, pp. 5611, 2023, https://doi.org/10.3390/en16155611, pp. e5611.

[26] J. Shi, L. Ma, C. Li, N. Liu, and J. Zhang, "A comprehensive review of standards for distributed energy resource grid-integration and microgrid," *Renewable and Sustainable Energy Reviews*, vol. 170, no. 1, pp. 112957, 2022, https://doi.org/10.1016/j.rser.2022.112957.

[27] Y. Zahraoui, I. Alhamrouni, S. Mekhilef, M. R. B. Khan, M. Seyedmahmoudian, A. Stojcevski, and B. Horan, "Energy Management System in Microgrids: A Comprehensive Review," *Sustainability*, vol. 13, no. 1, pp. 10492, 2021. https://doi.org/10.3390/su131910492.

[28] M. Fotopoulou, D. Rakopoulos, S. Petridis, and P. Drosatos, "Assessment of smart grid operation under emergency situations," *Energy*, vol. 287, no. 1, pp. 129661, 2024. https://doi.org/10.1016/j.energy.2023.129661.

[29] M. Ourahou, W. Ayrir, B. E. Hassouni, A. Haddi, "Review on smart grid control and reliability in presence of renewable energies: Challenges and prospects," *Mathematics and Computers in Simulation*, vol. 167, no. 1, pp. 19-31, 2020, https://doi.org/10.1016/j.matcom.2018.11.009.

[30] C. P. Ohanu, S. A. Rufai, and U. C. Oluchi "A comprehensive review of recent developments in smart grid through renewable energy resources integration" *Heliyon*, vol. 10, no. 1, pp. e25705, 2024. https://doi.org/10.1016/j.heliyon.2024.e25705.

[31] S. Ahmad, M. Shafuilla, C. B. Ahmed, and M. Alowaifeer, "A Review of Microgrid Energy Management and Control Strategies," *IEEE Access*, vol. 11, no. 1, pp. 21729-21757, 2023, https://doi.org/10.1109/access.2023.3248511.

[32] G. B. Gharehpetian, H. R. Baghaee, M. M. Shabestary, "Microgrids and methods of analysis," *Academic Press, Cambridge, Massachusetts, United States*, chp 8, pp. 1-131, 2021.

[33] T. N. Mbungu, A. A. Ismail, M. AlShabi, R. C. Bansal, A. Elnady, A. K. Hamid, "Control and estimation techniques applied to smart microgrids: A review," *Renewable and Sustainable Energy Reviews*, vol. 179, no. 1, pp. 113251, 2023. https://doi.org/10.1016/j.rser.2023.113251.

[34] I. Poonahela, S. Bayhan, H. Abu-Rub, M. Begovic, M. Shadmand, "On Droop-based Voltage and Frequency Restoration Techniques for Islanded Microgrids," *IECON, Toronto, Canada*, pp. 1-8, 2021, https://doi.org/10.1109/IECON48115.2021.9589772.

[35] X. Li and S. Wang, "Energy Management and Operational Control Methods for Grid Battery Energy Storage Systems," *CSEE Journal of Power and Energy Systems*, vol. 7, no. 5, pp. 1026-1040, 2021. https://doi.org/10.17775/CSEEJPES.2019.00160.

[36] W. K. Meteab, S. A. H. Alsultani, and F. Jurado, "Energy Management of Microgrids with a Smart Charging Strategy for Electric Vehicles Using an Improved RUN Optimizer," *Energies*, vol. *16, no.* 16, pp. e6038, 2023, https://doi.org/10.3390/en16166038.

[37] J. Hu, X. Liu, M. Shahidehpour, and S. Xia, "Optimal Operation of Energy Hubs with Large-Scale Distributed Energy Resources for Distribution Network Congestion Management," *IEEE Transactions on Sustainable Energy*, vol. 12, no. 3, pp. 1755-

1765, 2021. https://doi.org/10.1109/tste.2021.3064375.

[38] M. Ahmed, L. Meegahapola, A. Vahidnia, and M. Datta, "Stability and Control Aspects of Microgrid Architectures—A Comprehensive Review," *IEEE Access*, vol. 8, pp. 144730 - 144766, 2020. https://doi.org/10.1109/access.2020.3014977.

[39] M. Carpintero-Rentería, M. Carpintero-Rentería, D. Santos-Martín, and J. M. Guerrero, "Microgrids Literature Review through a Layers Structure," *Energies*, vol. *12, no.* 22, pp. e4381, 2019, https://doi.org/10.3390/en12224381.

[40] S. O. Mohammad, R. Aghamohammadi, S. Oshnoei, S. Sahoo, A. Fathollahi, M. H. Khooban, "A novel virtual inertia control strategy for frequency regulation of islanded microgrid using two-layer multiple model predictive control," *Applied Energy*, vol. 343, pp. e121233, 2023. https://doi.org/10.1016/j.apenergy.2023.121233.

[41] J. Viola and Y. Chen, "Digital Twin Enabled Smart Control Engineering as an Industrial AI: A New Framework and Case Study," *International Conference on Industrial Artificial Intelligence (IAI), Shenyang, China*, pp. 1-6, 2020.

[42] M. Khaleel, "Intelligent Control Techniques for Microgrid Systems," *Brilliance: Research of Artificial Intelligence*, vol. 3, no. 1, 2023, https://doi.org/10.47709/brilliance.v3i1.2192.

[43] Y. Boujoudar, M. Azeroual, H. Elmoussaoui, and T. Lamhamdi, "Intelligent control of battery energy storage for microgrid energy management using ANN," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 11, no. 4, pp. 2760~2767, 2021, https://doi.org/10.11591/ijece.v11i4.pp2760-2767.

[44] S. S. Zehra, A. U. Rahman, H. Armghan, I. Ahmad, U. Ammara, "Artificial intelligence-based nonlinear control of renewable energies and storage system in a DC microgrid," *ISA Transactions*, vol. 121, no. 1, pp. 217–231, 2022, https://doi.org/10.1016/j.isatra.2021.04.004.

[45] M. V. Kazemi, S. J. Sadati, and S. A. Gholamian, "Adaptive Frequency Control of Microgrid Based on Fractional Order Control and a Data-Driven Control with Stability Analysis," *IEEE Transactions on Smart Grid*, vol. 13, no. 1, pp. 381-392, 2022. https://doi.org/10.1109/tsg.2021.3109627.

[46] M. Davari, W. Gao, Z. Jiang, and F. L. Lewis, "An Optimal Primary Frequency Control Based on Adaptive Dynamic Programming for Islanded Modernized Microgrids," *IEEE Transactions on Automation, Science, and Engineering*, vol. 18, no. 3, pp. 1-14, 2021. https://doi.org/10.1109/tase.2020.2996160.

[47] Z. Chu and Y. Wang "Efficiency improvement in energy consumption: A novel deep learning-based model for leading a greener Economic recovery," *Sustainable Cities and Society*, vol. 108, no. 1, pp. 105427, 2024. https://doi.org/10.1016/j.scs.2024.105427.

[48] R. Escudero, J. Noel, J. Elizondo, and J. Kirtley, "Microgrid fault detection based on wavelet transformation and Park's vector approach," *Electric Power Systems Research*, vol. 152, no. 1, pp. 401-410, 2017. https://doi.org/10.1016/j.epsr.2017.07.028.

[49] M. Kurucan, M. Ozbaltan, Z. Yetgin, and A. Alkaya "Applications of artificial neural network based battery management systems: a literature review," *Renewable and Sustainable Energy Review*, vol. 192, no. 1, pp. 114262, 2024. https://doi.org/10.1016/j.rser.2023.114262.

[50] A. O. Aluko, R. P. Carpanen, D. G. Dorrell, and E. E. Ojo, "Robust state estimation method for adaptive load frequency control of interconnected power system in a restructured environment," *IEEE Systems Journal*, vol. 15, no. 4, pp. 5046-5056, 2021, https://doi.org/10.1109/jsyst.2020.3005979.

[51] A. O. Aluko, A. M. Knight, and D. G. Dorrell, "State-Space Modeling and Analysis of Distributed Secondary Control of DC Microgrids," *International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME), Tenerife, Canary Islands, Spain*, 2023.

[52] A. K. Onaolapo, R. Pillay Carpanen, D. G. Dorrell, and E. E. Ojo, "Forecasting Electricity Outage in KwaZulu-Natal, South Africa using Trend Projection and Artificial Neural Networks Techniques." *IEEE PES/IAS PowerAfrica, Nairobi, Kenya*, pp. 1-5, 2021,

https://doi.org/10.1109/POWERAFRICA52236.2021.9543182.

[53] B. N. Alhasnawi, B. H. Jasim, Z. S. A. Rahman, J. M. Guerrero, and M. D. Esteban, "A Novel Internet of Energy Based Optimal Multi-Agent Control Scheme for Microgrid including Renewable Energy Resources," *Int. J. Environ. Res. Public Health*, vol. 18, no. 15, pp. e8146, 2021. https://doi.org/10.3390/ijerph18158146.

[54] M Gursoy and B Mirafzal, "Direct vs. indirect control schemes for grid-forming inverters–Unveiling a performance comparison in a microgrid," *IEEE Access*, vol. 11, no. 1, pp. 75023 – 75036, 2023. https://doi.org/10.1109/access.2023.3297551.

[55] M. I. Ibraheem, M. Edrisi, H. H. Alhelou, M. Gholipour, and A. Al-Hinai, "A Sophisticated Slide Mode Controller of Microgrid System Load Frequency Control Under False Data Injection Attack and Actuator Time Delay," *IEEE Transactions on Industry Applications*, vol. 60, issue: 2, pp. 2117-2126, 2023. https://doi.org/10.1109/TIA.2023.3316190.

[56] J. Hu, Y. Shan, J. M. Guerrero, A. Ioinovici, K.W. Chan, J. Rodriguez, "Model predictive control of microgrids – An overview," *Renewable and Sustainable Energy Reviews*, vol. 136, no. 1, pp. 110422, 2021. https://doi.org/10.1016/j.rser.2020.110422.

[57] H. Karimia, M. T. H. Beheshtib, A. Ramezanib, H. Zareipour, "Intelligent control of islanded AC microgrids based on adaptive neuro-fuzzy inference system," *Electrical Power and Energy Systems*, vol. 133, no. 1, pp. 107161, 2021. https://doi.org/10.1016/j.ijepes.2021.107161.

[58] S. S. Khorramabadi, A. Bakhshai, "Intelligent Control of Grid-Connected Microgrids: An Adaptive Critic-Based Approach," *IEEE Journal of Emerging and Selected Topics*, vol. 3, issue 2, pp. 493-504, 2014. https://doi.org/10.1109/JESTPE.2014.2331188.

[59] K. Ahmed, M. Seyedmahmoudian, S. Mekhilef, N. M. Mubarak, and A. Stojcevski, "A Review on Primary and Secondary Controls of Inverter-interfaced Microgrid," *Journal of Modern Power Systems and Clean Energy*, vol. 9, no. 5, pp. 969-985, 2021. https://doi.org/10.35833/mpce.2020.000068.

[60] S. S. Madani, C. Kammer, and A. Karimi, "Data-Driven Distributed Combined Primary and Secondary Control in Microgrids," *IEEE Transactions on Control Systems Technology*, vol. 29, no. 3, pp. 1340-1347, 2021, https://doi.org/10.1109/tcst.2019.2958285.

[61] C. Bersani, H. Dagdougui, A. Ouammi, and R. Sacile, "Stochastic constrained linear quadratic control in a network of smart microgrids," *IET Renewable Power Generation*, vol. 14, issue 7, pp. 1193-1200, 2020. https://doi.org/10.1049/iet-rpg.2019.0992.

[62] M. Legry, J. Dieulot, F. Colas, C. Saudemont, and O. Ducarme, "Non-Linear Primary Control Mapping for Droop-Like Behavior of Microgrid Systems," *IEEE Transactions on Smart Grid*, vol. 11, no. 6, pp. 4604-4613, 2020. https://doi.org/10.1109/tsg.2020.2998810.

[63] F. Y. Toriumi and B. A. Angélico, "Passivity-Based Nonlinear Control Approach for Tracking Task of an Underactuated CMG," *IEEE/ASME Transactions on Mechatronics*, vol. 26, no. 5, pp. 2285-2293, 2021, https://doi.org/10.1109/tmech.2020.3036765.

[64] L. Ahmethodzica, and M. Music, "Comprehensive review of trends in microgrid control," *Renewable Energy Focus*, vol 38, no. 1, pp. 84-96, 2021. https://doi.org/10.1016/j.ref.2021.07.003.

[65] Y. Li, Z. Zhang, C. Hu, M. Abdelrahem, R. Kennel, J. Rodriguez, "A full state-variable direct predictive control for islanded microgrids with parallel converters," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 9, no. 4, pp. 4615-4628, 2021. https://doi.org/10.1109/jestpe.2020.3042875.

[66] T. Chen, O. Abdel-Rahim, F. Peng, H. Wang, "An Improved Finite Control Set-MPC-Based Power Sharing Control Strategy for Islanded AC Microgrids," *IEEE Access*, vol. 8, no. 1, pp. 52676-52686, 2020. https://doi.org/10.1109/access.2020.2980860.

[67] H. S. Khan, M. Aamir, K. Kauhaniemi, M. Mumtaz, M. W. Hassan, M. Ali, "Improved finite control set model predictive control for distributed energy resource in islanded microgrid with fault-tolerance capability," *Engineering Science and Technology*, vol. 24,

no. 1, pp. 694–705, 2021. https://doi.org/10.1016/j.jestch.2020.12.015.

[68] C. Zheng, T. Dragicevic, and F. Blaabjerg, "Model Predictive Control-Based Virtual Inertia Emulator for an Islanded Alternating Current Microgrid," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 8, pp. 7167-7177, 2021. https://doi.org/10.1109/tie.2020.3007105.

[69] A. Nurkanovic, A. Mesanovic, A. Zanelli, G. Frison, J. Frey, S. Albrecht, M. Diehl," Real-Time Nonlinear Model Predictive Control for Microgrid Operation," *American Control Conference, Denver, CO, USA,* pp. 4989-4995, 2020.

[70] D. Datta, S. R. Fahim, S. K. Sarker, S. M. Muyeen, M. R. I. Sheikh, and S. K. Das, "A robust control method for damping and tracking of secondary network voltage of a PV based hybrid AC/DC microgrid," *Frontiers in Energy Research*, vol. 7, no. 1, pp. 1-15, 2020, https://doi.org/10.3389/fenrg.2020.580840.

[71] E. Pathan, A. A. Bakar, S. A. Zulkifi, M. H. Khan, H. Arshad, M. Asad, "A Robust Frequency Controller based on Linear Matrix Inequality for a Parallel Islanded Microgrid," *Engineering, Technology & Applied Science Research*, vol. 10, no. 5, pp. 6264-6269, 2020. https://doi.org/10.48084/etasr.3769.

[72] M. Mehdi, S. Z. Jamali, M. O. Khan, S. Baloch, C. Kim, "Robust control of a DC microgrid under parametric uncertainty and Disturbances," *Electric Power Systems Research*, vol. 179, no. 1, pp. e106074, 2020. https://doi.org/10.1016/j.epsr.2019.106074.

[73] M. Mehdi, C. H. Kim, and M. Saad, "Robust centralized control for DC islanded microgrid considering communication network delay," *IEEE Access*, vol. 8, no. 1, pp. 77765-77778, 2020. https://doi.org/10.1109/access.2020.2989777.

[74] M. Armin, M. Rahman, M. M. Rahman, S. K. Sarker, S. K. Das, M. R. Islam, A. Z. KouzanI, "Robust extended H_∞ control strategy using linear matrix inequality approach for islanded microgrid," *IEEE Access*, vol. 8, no. 1, pp. 135883 - 135896, 2020, https://doi.org/10.1109/access.2020.3009188.

[75] Y. Shan, J. Hu, K. W. Chan, and S. Islam, "A unified model predictive voltage and current control for microgrids with distributed fuzzy cooperative secondary control," *IEEE Transactions on Industrial Informatics*, vol. 17, no. 12, pp. 8024- 8034, 2021, https://doi.org/10.1109/TII.2021.3063282.

[76] H. S. Khan, I. S. Mohamed, K. Kauhaniemi, and L. Liut, "Artificial neural network-based voltage control of DC/DC converter for dc microgrid applications," *IEEE Workshop on the Electronic Grid (eGRID), New Orleans, LA, USA,* pp. 1-6, 2021, https://doi.org/10.1109/egrid52793.2021.9662132.

[77] H. E. Keshta, E. M. Saied, O. P. Malik, F. M. Bendary, A. A. Ali, "Fuzzy PI controller-based model reference adaptive control for voltage control of two connected microgrids," *IET Generation, Transmission & Distribution*, vol. 15, issue 4, pp. 602–618, 2021. https://doi.org/10.1049/gtd2.12046.

[78] Y. Boujoudar, M. Azeroual, H. Elmoussaoui, T. Lamhamdi, "Intelligent control of battery energy storage for microgrid energy management using ANN," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 11, no. 4, pp. 2760-2767, 2021, https://doi.org/10.11591/ijece.v11i4.pp2760-2767.

[79] U. Sultana, S. H. Qazi, N. Rasheed, and M. W. Mustafa, "Performance analysis of real-time PSO tuned PI controller for regulating voltage and frequency in an AC microgrid," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 11, no. 2, pp. 1068~1076, 2021. https://doi.org/10.11591/ijece.v11i2.pp1068-1076.

[80] Y. Zhang, X. Qu, M. Tang, R. Yao, and W. Chen, **"**Design of nonlinear droop control in DC microgrid for desired voltage regulation and current sharing accuracy," *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, vol. 11, no. 1, pp. 168-175, 2021. https://doi.org/10.1109/jetcas.2021.3049810.

[81] I. Rai, R. Anand, A. Lashab, J M. Guerrero, "Hardy space nonlinear controller design for DC microgrid with constant power loads," *Electrical Power and Energy Systems*, vol. 133, no. 1, pp. 107300, 2021, https://doi.org/10.1016/j.ijepes.2021.107300.

[82] H. Armghan, M. Yang, M.Q. Wang, N. Ali, A. Armghan, "Nonlinear integral backstepping based control of a DC microgrid with renewable generation and energy storage systems," *Electrical Power and Energy Systems*, vol. 117, no. 1, pp. 105613, 2020, https://doi.org/10.1016/j.ijepes.2019.105613.

[83] J. Lai, and X. Lu, "Nonlinear mean-square power sharing control for ac microgrids under distributed event detection," *IEEE Transactions on Industrial Informatics*, vol. 17, no. 1, pp. 219-229, 2021, https://doi.org/10.1109/tii.2020.2969458.

[84] F. Colas, C. Saudemont, and O. Ducarme, "Non-linear primary control mapping for droop-like behavior of microgrid systems," *IEEE Transactions on Smart Grid*, vol. 11, no. 6, pp. 4604-4613 2020. https://doi.org/10.1109/TSG.2020.2998810.

[85] G. Melath, M. N. Hussain, and V. Agarwal, "A nonlinear adaptive backstepping controller for stabilizing the DC bus voltage of an islanded hybrid microgrid," *IEEE Journal of Emerging and Selected Topics in Industrial Electronics*, vol. 3, no. 3, pp. 538-548, 2022. https://doi.org/10.1109/jestie.2022.3160666.

[86] M. Dehghani, T. Niknam, M. Ghiasi, H. R. Baghaee, F. Blaabjerg, T. Dragicevi, M. Rashidi, "Adaptive backstepping control for master-slave AC microgrid in smart island," *Energy*, vol. 246, no. 1, pp. e123282, 2022. https://doi.org/10.1016/j.energy.2022.123282.

[87] S. Azizi, M. H. Asemani, N. Vafamand, S. Mobayen, A. Fekih, "Adaptive neural network linear parameter-varying control of shipboard direct current microgrids," *IEEE Access*, vol. 10, no. 1, pp. 75825-75834, 2022. https://doi.org/10.1109/access.2022.3191385.

[88] S. Mohamed, M. Mokhtar, and M. I. Marei, "An adaptive control of remote hybrid microgrid based on the CMPN algorithm," *Electric Power Systems Research*, vol. 213, no. 1, pp. e108793, 2022. https://doi.org/10.1016/j.epsr.2022.108793.

[89] B. Singh and S. Kumar, "Distributed incremental adaptive filter-controlled grid interactive residential photovoltaic-battery based microgrid for rural electrification," *IEEE Transactions on Industry Applications*, vol. 56, no. 4, pp. 4114-4123, 2020. https://doi.org/10.1109/tia.2020.2987000.

[90] Z. Ma, Z. Wang, Y. Guo, Y. Yuan, and H. Chen, "Nonlinear multiple models adaptive secondary voltage control of microgrids," *IEEE Transactions on Smart Grid*, vol. 12, no. 1, pp. 227- 238, 2021. https://doi.org/10.1109/tsg.2020.3023307.

[91] J. F. Patarroyo-Montenegro, F. Andrade, J. M. Guerrero, J. C. Vasquez, "A linear quadratic regulator with optimal reference tracking for three-phase inverter-based islanded microgrids," *IEEE Transactions on Power Electronics*, vol. 36, no. 6, pp. 7112- 7122, 2020. https://doi.org/10.1109/tpel.2020.3036594.

[92] R. Aliaga, M. Rivera, P. Wheeler, J. Munoz, J. Rohten, F. Sebaaly, A. Villalón, A. Trentin, "Implementation of exact linearization technique for modeling and control of dc/dc converters in rural PV microgrid application," *IEEE Access*, vol. 10, pp. 56925- 56936, 2022. https://doi.org/10.1109/access.2022.3178425.

[93] S. K. Das, D. Datta, S. K. Sarker, S. R. Fahim, M. R. I. Sheikh, F. R. Badal, "Improved voltage oscillation damping and tracking of subgrid of a hybrid ac/dc microgrid using robust integral linear quadratic Gaussian control," *International Conference on Smart Power & Internet Energy Systems, Bangkok, Thailand*, pp. 299-304, 2020.

[94] A. Aff, M. Simab, M. Nafar, A. Mirzaee, "Robust linear parameter varying frequency control for islanded hybrid AC/ DC microgrids," *Electric Power Systems Research*, vol. 214, no. 1, pp. e108898, 2023. https://doi.org/10.1016/j.epsr.2022.108898.

[95] N. Mthukuse, A.K. Onaolapo, A. Aluko, and D.G. Dorrell "Review of cyberattack implementation, detection, and mitigation methods in cyber-physical systems." *Energies*, vol. 16, issue 13, pp. e5206, 2023. https://doi.org/10.3390/en16135206.

[96] B. N. Alhasnawi, B. H. Jasim, B. E. Sedhom, E. Hossain, and J. M. Guerrero, "A New Decentralized Control Strategy of Microgrids in the Internet of Energy Paradigm," *Energies*, vol. 14, no. 8, pp. 2183, 2021. https://doi.org/10.3390/en14082183.

[97] K. Mahmud, B. Khan, J. Ravishankar, A. Ahm adi, P. Siano, "An internet of energy framework with distributed energy resources, prosumers and small-scale virtual power

plants: An overview," *Renewable and Sustainable Energy Reviews*, vol. 127, no. 1, pp. e109840, 2020. https://doi.org/10.1016/j.rser.2020.109840.

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