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Optimization techniques and microgrid control strategies based on renewable energy sources

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Abstract

Microgrids (MGs) play a pivotal role in seamlessly integrating Renewable Energy Sources (RESs) and Energy Storage Systems (ESSs) into the electrical grid, offering enhanced efficiency, reduced transmission losses, and economic benefits. However, the intermittent nature of RESs due to the stochastic availability of renewable resources introduces challenges to power quality across the grid. Addressing these challenges necessitates the application of optimization techniques and control strategies to power converters. This comprehensive review delves into three crucial dimensions: (i) The power-quality issues arising in MGs during both islanded and grid-connected operations; (ii) Optimization techniques employed within MGs to achieve optimal Energy Management System (EMS) performance; and (iii) Control strategies executed in MGs to ensure stability, mitigate power-quality concerns, achieve power balance, and synchronize with the grid. Significantly, this paper underscores the significance of hybrid MGs (HMGs), which amalgamate the strengths of AC–MGs and DC–MGs to enhance system reliability. As the utility grid gravitates towards refined MG structures, this review lays the groundwork for forthcoming research, comparative evaluations, and the advancement of pioneering techniques in the realm of HMGs.

1. Introduction

In an era marked by burgeoning global energy demand, driven by population growth, improved living standards, and extensive infrastructure development, the transition towards sustainable energy solutions has gained paramount importance [A1]. The period between 2019 and 2020 witnessed a remarkable milestone - the growth of renewable energy sources (RESs) outpaced the increase in global energy demand. However, the momentum shifted in 2022, as energy demand experienced a significant surge due to multifaceted factors such as economic recovery, population expansion, and technological advancements [A2]. As per the International Energy

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Agency (IEA), global electricity demand was projected to escalate by approximately 4% by the close of 2022, primarily fueled by the worldwide economic revival [A3]. Notably, India and several Southeast Asian nations were poised to exhibit a soaring energy consumption rate that could amplify by up to 11% by 2040[A4], thereby significantly impacting the global energy landscape [A5].

In response to this escalating energy demand, a transformative evolution of electrical energy distribution systems becomes imperative. The future of the electrical grid is envisioned to be an amalgamation of digital technologies, renewable energy sources (RESs) [A6], and an intelligent network of distributed generation (DG) [A7]. This paradigm shift necessitates a comprehensive exploration of innovative solutions that ensure reliable, efficient, and sustainable energy distribution. Among these solutions, the integration of renewable energy sources (RESs) has garnered substantial attention, fostering the need for resilient energy management systems that can strike a balance between cost-effectiveness and reliability [A8].

Microgrids (MGs) have emerged as one of the most promising alternatives for propelling the energy landscape into the next generation [A9]. These small-scale electrical power systems, comprising a cluster of loads and RESs, are intricately interconnected through sophisticated software and devices to facilitate optimal energy management. With the capacity to enhance local energy supply efficiency, MGs offer a decentralized approach to energy distribution, augmenting system reliability and minimizing investment costs [A10]. Furthermore, the integration of renewable sources within MGs aligns seamlessly with the global drive towards sustainability [A11], thereby reducing the carbon footprint and advancing the green energy agenda [A12].

Among the MG classifications, the alternating current microgrid (AC–MG) holds a dominant position due to its compatibility with existing infrastructure, protection mechanisms, and grid technologies [A13]. Nonetheless, AC–MGs confront certain challenges, including the synchronization of distributed generation units (DGUs) and losses incurred during reactive power circulation. Conversely, the rise of direct current-based RESs, such as photovoltaic (PV) systems, fuel cells (FC), and energy storage systems (ESSs), has paved the way for the emergence of direct current microgrids (DC–MGs). These DC–MGs, while efficient, require substantial modifications to the existing electrical grid, introducing complexities associated with various conversion processes [A14].

Hybrid microgrids (HMGs) offer an elegant solution that bridges the advantages of both AC–MGs and DC–MGs, enabling the creation of intelligent grids within conventional distribution networks. The distinctive architecture of HMGs confronts the challenge of accidental or programmed disconnections from the utility grid. These disconnections necessitate the establishment of scenarios to address situations of varying demand levels and manage abnormal operational instances. Consequently, the exploration of HMGs gains paramount significance in enhancing the robustness and adaptability of the future energy distribution landscape [A15].

The academic community and industry experts have embarked on a journey to dissect the intricacies of HMGs, leading to the emergence of numerous studies, reviews, and analyses. However, this review distinguishes itself by undertaking a holistic approach, encompassing multiple dimensions critical to the success of HMGs [A16]. The focal points of this comprehensive exploration include power quality challenges, optimization techniques for enhanced power output [A17], and control strategies vital for ensuring seamless HMG operation within dynamic energy ecosystems [A18].

The review commences with a comprehensive overview of microgrids, with particular emphasis on the burgeoning realm of hybrid microgrids (HMGs) [A19]. This foundational section sets the stage for a deeper dive into the challenges posed by power quality in the integration of HMGs [A18]. The review expounds upon issues such as current and voltage harmonic distortion, voltage fluctuations, and the malfunctioning of protection devices, underscoring their significance in the context of HMGs [A20]. Novel devices and techniques aimed at mitigating these challenges are discussed, shedding light on cutting-edge solutions developed in experimentation laboratories [A21-A25]

The optimization techniques employed in HMGs to bolster power flow, enhance energy generation, and address design and topology intricacies are meticulously examined [A26]. The review dissects a plethora of optimization methodologies, offering critical insights into their application and potential within the HMG framework [A27]. By addressing uncertainty reduction, increased power output, and minimized operating costs, these optimization techniques present a compelling case for their integration into HMG operations [A28-A29].

Control strategies constitute the backbone of any functional energy distribution system. In the context of HMGs, control strategies play a pivotal role in ensuring voltage and frequency stability, harmonious transition between operational modes, and effective participation in transient energy markets. This review meticulously analyzes an array of control methods and strategies, underscoring their importance in realizing the full potential of HMGs within the broader energy landscape [A30-A32].

A distinguishing feature of this review lies in its comparative analysis with existing reviews on the subject of HMGs. By juxtaposing its findings with contemporary literature, the review contributes to a richer understanding of the current state of research, identifying novel research areas with untapped potential [A33, A34].

In summation, this comprehensive review embarks on a journey to decipher the intricacies of hybrid microgrids (HMGs) - a pivotal component in the future of electrical energy distribution [A35]. By addressing power quality challenges, optimization techniques, and control strategies, this review aims to be a beacon for researchers, industry experts, and policymakers navigating the ever-evolving landscape of sustainable energy distribution. Through its thorough analysis and synthesis of critical parameters, this review seeks to pave the way for innovative advancements in hybrid microgrid technology, offering a roadmap for the development of intelligent grids for generations to come [A36].

2. Microgrids: Unveiling the Landscape of Distributed Energy Solutions

The relentless pursuit of sustainable and efficient energy solutions has ushered in an era of transformation within the global energy sector. Microgrids (MGs) [A37], emerging as the epitome of distributed energy systems, stand poised to redefine energy distribution by harmonizing renewable energy sources (RESs) [A38], energy storage systems (ESSs) [A39], power converters (PCs), buses, loads, control units, and sophisticated software interfaces. This comprehensive synthesis delves into the realm of MGs, unraveling their general characteristics, classification, and significance within the contemporary energy landscape.

MGs, the cornerstones of modern energy decentralization, epitomize small-scale electrical power systems that encapsulate the essence of hybrid RESs, ESSs, and advanced control systems [A40]. Operating seamlessly in both islanded and connected modes, MGs epitomize the convergence of technical prowess and innovation, as evidenced by a plethora of national and international MG projects spanning various RES configurations. These projects, exemplified in Table 1 and Table 2, are pioneering technological solutions that cater to diverse regional realities, bridging the gap between regulatory mandates, social needs, and economic viability [A41].

Table 1: Different types of operational hybrid RESs.

Rated Capacity of the RES	Project Details	Ref.
150 MW (WT), and 35 MV (PV)	Pacific (WT) and Catalina Solar, EE.UU.	[40]
10 kW (PV), 5 kW (DG), and 50 kWh (BESS)	Kythnos Island, Greece	[41]
30 MW (GeoT), and 25 MW (PV)	Enel Green Hybrid MicroGrid, EE.UU	[42]
35 MW (BM), and 22.5 MW (CSP)	TermoSolar Borges, Spain.	[43,44]
100 MW (WT), 40 MW (PV), 35 MW (BESS)	Zhangbei National, China	[45]
10 MW (WT + PHESS), and 11 MW (PV)	El Hierro Island, Spain	[46]
90 kW (WT), 10 kW (WP), and 5 kW (PV)	Dangan Island of Guangdong, China	[47]

PV = Photovoltaic; BESS = Battery Energy Storage System; GeoT = GeoThermal; BM = Biomass; PHESS = Pump Hydro Energy Storage System; BD = Bio Diesel; CSP = Concentrated Solar Thermal Power; WP = Wave Power; WT = Wind Turbine.

Project Location	Year of Installation	Generator Power (kW)			ESS	Population Served	Ref.
		PV	WT	Diesel			
Ma. Magdalena	1991	4.3	5	18	BESS	168	[48]
Nv. Victoria	1991	8.6	−−	28	−−	355	[49]
Oyamello	1991	0.76	5	4	BESS	122	[50]
X-Calak	1992	11.2	60	125	Revers. hydraulic	232	[50]
El Junco	1992	1.6	10	−−	Battery	250	[51]
Gruñidora	1992	1.2	10	−−	−−	230	[51]
Agua Bendita	1993	12.4	20	48	BESS	250	[52]
Isla Margarita	1997	2.25	15	60	BESS	200	[52]
San Juanico	1999	17	70	85	Revers. hydraulic	400	[48]

Table 2: First MG projects

MG initiatives encapsulate a gamut of objectives ranging from sustainability and cost-efficiency to resilience and self-consumption. These projects, elucidated in Table 1 and Table 2, collectively trace the historical evolution and prevailing trends within the MG market. The Navigant Research database bears testimony to the exponential growth of MGs, with a cumulative installed capacity of 26.8 GW across 4475 projects globally. Asia-Pacific and North America dominate this landscape, projecting substantial growth in the foreseeable future.

2.1. Classification of the Microgrids

AC–Microgrids (AC–MGs): The paradigm of AC–MGs, the most prevalent microgrid configuration, entails a web of interconnected distributed generators, ESSs, and loads tied to AC grids via power converters [A42]. Although some generators like microturbines and wind turbines can be connected without power converters, DC RESs necessitate DC–AC inversion for grid integration. The benefits of AC–MGs, including compatibility with existing AC infrastructure, are counterbalanced by complexities associated with control and grid synchronization. These AC–MGs, despite challenges, remain the cornerstone of contemporary microgrid solutions[A43].

2.2. DC–Microgrids (DC–MGs): The ascension of DC–MGs, an innovative departure from traditional paradigms, presents an opportunity to mitigate conversion losses inherent in AC–MGs. DC generation, converted into AC for grid compatibility, introduces inefficiencies[A44]. However, DC–MGs streamline this process, minimizing conversion stages and enhancing system efficiency. The inherent simplicity of primary control and seamless integration of distributed energy resources (DERs) positions DC–MGs as a preferred choice for residential distribution systems. Their resilience and ease of design in islanded mode bolster their appeal[A45].

2.3. DC–AC MG or Hybrid MG (HMG): Hybrid MGs, the epitome of harmony between AC–MGs and DC–MGs, epitomize adaptability and versatility. By coalescing AC and DC buses, HMGs offer a conducive environment for diverse energy generation and ESS integration. The synergy between multiple load types and power systems enhances the potential of HMGs. However, the intricate control mechanisms and synchronization complexities pose challenges, particularly in islanded mode. HMGs are poised to be transformative agents, facilitating dynamic energy distribution[A46].

In summation, this synthesis unfurls the rich tapestry of microgrids, portraying them as the nexus of sustainable energy distribution. MGs, with their hybrid RESs, energy storage systems, and advanced control systems, embody the culmination of technical innovation and global energy aspirations. As AC–MGs, DC–MGs, and HMGs vie for supremacy within the microgrid landscape, their collective potential to reshape energy distribution and consumption is undeniable. This exploration underscores the pivotal role of microgrids in ushering in an era of decentralized, efficient, and resilient energy systems[A47].

3. Characteristics of Microgrids: Unveiling the Nuances

Microgrids (MGs) stand as intricate systems, driven by a tapestry of characteristics that define their operations, efficacy, and adaptability. Delving into the intricate fabric of MGs reveals a matrix of defining features that span from grid connection to voltage and frequency regulation, encompassing power sources, energy storage systems (ESSs), demand dynamics, and more. This exploration unfurls the multi-dimensional nature of MGs, providing insight into the complexities that underpin their architecture and functionality[A48].

3.1. Grid Connection Dynamics: The essence of MGs lies in their connectivity with the larger electrical grid. The conventional MG definition pertains to grids connected to the larger network, yet capable of autonomous operation in islanded mode. In this context, a distinct subgroup emerges - islanded grids that mimic the operational characteristics of MGs. Contrasting these are traditional islanded grids centralized around diesel generators. Distinctions also arise based on the regularity of grid connection. While some MGs maintain consistent connections, others are designed for prolonged islanded operation, necessitating dispatchable generation or robust storage infrastructure. The decision to operate in islanded mode hinges on grid reliability and contractual relationships between grid owners, thereby orchestrating a delicate interplay between reliability and economic considerations[A49].

3.2. Power Source Dynamics: The backbone of MG operation resides in power sources, whose characteristics wield significant influence. The presence of renewable energy sources (RESs) and their dispatchability shape MG management. RESs confer cost-efficiency to MGs while necessitating a delicate balance to maintain supply quality during islanded operation. Dispatchable generation reduces the reliance on intermittent renewables, ensuring continuity and equilibrium between generation and demand. Beyond supply characteristics, the decentralization of generation, whether centralized or diversified among owners, fuels a cascade of implications ranging from MG management intricacies to contractual relationships among stakeholders[A50].

3.3. Energy Storage Systems (ESSs): The interplay between ESSs and RESs is a pivotal factor dictating MG functionality. The prevalence of ESSs hinges on the reliance on RESs. While exclusive reliance on RESs mandates ESSs for stability, systems with dispatchable generation employ storage to optimize costs and facilitate energy exchange with the larger grid. ESSs act as a buffer during the transition from islanded to connected mode, mitigating transient disturbances that might compromise system integrity. The physical disposition of ESSs, centralized or decentralized, and ownership patterns significantly impact MG management and stakeholder dynamics. Notably, ESSs transcend electrical domains, extending to thermal vectors, catalyzing efficient energy utilization[A51].

3.4. Demand Dynamics: In MGs, demand occupies a central role, accentuating the importance of meticulous management. As MGs are relatively smaller in scale, demand imposes stricter operational parameters, particularly during islanded mode. Critical loads assume prominence, necessitating robust supply to ensure essential services. The design of MGs accommodates critical loads, integrating uninterrupted power supply systems as an additional safeguard. The proximity between generation and demand in MGs fosters an active role for demand management, enabling it to serve other components or users within the system[A52].

3.5. Voltage and Frequency Regulation: Voltage and frequency regulation constitute pivotal dimensions in MG dynamics. MGs predominantly operate at low voltage levels, with certain instances featuring medium voltage distributions. Voltage paradigms encompass AC and, in some cases, DC. The voltage choice shapes component compatibility, control systems, and overall grid management. Frequency regulation aligns with grid frequency in AC systems and voltage levels in DC systems. High-frequency MGs have been proposed as vehicles to facilitate renewable integration, capitalizing on enhanced filtering capabilities and improved efficiency [A53].

In conclusion, the characteristics that define microgrids transcend mere technical specifications, embracing a holistic orchestration of grid connection, power sources, energy storage, demand, and voltage and frequency dynamics. The symphony of these attributes coalesces to shape the operational efficiency, resilience, and sustainability of MGs. Unraveling the nuances of microgrid characteristics lays the groundwork for informed decision-making, underpinning the evolution of energy distribution systems towards a future replete with innovation and adaptability[A54].

4. Optimization Techniques for Hybrid Microgrids

In the intricate realm of Hybrid Microgrids (HMGs), the pursuit of optimal operations has emerged as a pivotal endeavor. Optimization techniques, wielding their prowess, encompass a diverse array of objectives, ranging from amplifying the power output of Renewable Energy Sources (RESs) to enhancing the longevity of Energy Storage Systems (ESSs), curtailing environmental impact, and streamlining operational costs [A55]. The orchestration of constraints and objectives within optimization strategies orchestrates a symphony of improved Efficiency Management Systems (EMS), yielding short- and long-term benefits that conduce to cost reduction. This exploration unravels the optimization tapestry enshrouding HMGs, elucidating the techniques that galvanize their evolution and potential [A56].

4.1. Diverse Optimization Techniques: A panorama of optimization techniques adorns the landscape of HMGs, each catering to specific objectives and constraints. Linear and Non-Linear Programming (LP and NLP), Mixed Integer Linear and Non-Linear Programming (MILP and MILNP), Quadratic Programming, Linear Least Squares Programming, Dynamic Programming, and artificial intelligence techniques stand as vanguards of this optimization journey [A57]. To carve the path toward minimized carbon emissions, reduced energy consumption, enhanced economic viability, and augmented reliability. Linear Programming, a cornerstone technique, navigates linear constraints to optimize linear functions. Algorithms like the Simplex Method and Linear Interior Point Solver bolster its implementation. NLP programming, on the other hand, delves into extreme value pursuit of nonlinear objectives under constraints that might traverse linear or nonlinear domains. MILP, an extension of NLP, ventures into more complex territories with mixed variables, demanding computational dexterity [A58].

The schematic diagram of a hybrid PV-Wind renewable network is shown in Figure 1. The basic graphic depicts the architecture of an IHMS in general [A48]. It represents the block of each module with the connections and co-relation and synchronization. The AC bus is connecting the sources and loads according to the sequence of transformers and converters. The combination of AC wind turbine, AC diesel generator, DC PV, and DC BESS create the islanded/grid connected IHMS, in which the AC and DC loads converge each other in between the AC and DC bus system.

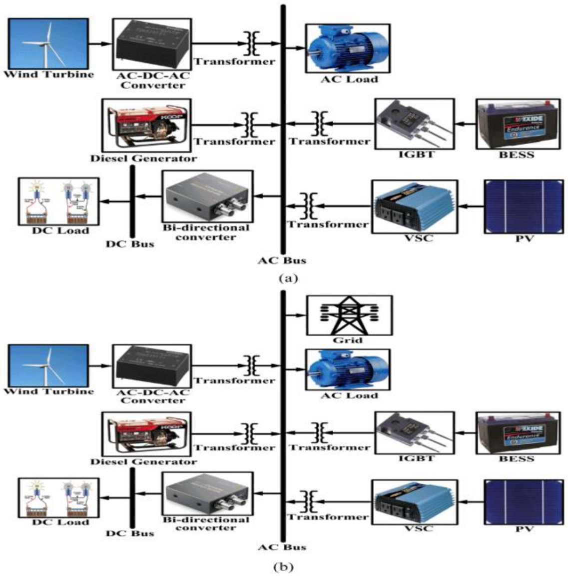

Fig. 1: Schematic diagram of solar-wind hybrid microgrid (a) islanded and (b) grid-connected [A49].

The primary goal of this study is to create a hybrid Non-dominated Sorting Whale Optimization Algorithm (NSWOA), which combines a multi-objective, non-dominated sorting approach with a swarm-based Whale Optimization Algorithm (WOA). This is done to create an algorithm that can search for optimal solutions quickly and efficiently. It has also been reported how NSWOA may be used to optimize the controller settings of an island microgrid with both static and dynamic load. When optimizing the controller parameters of an island microgrid model with multiple objectives, SPSS software was used to compare the performance of the proposed NSWOA method with that of the non-dominated sorting genetic algorithm-II (NSGA-II) and Strength Pareto Evolutionary Algorithm (SPEA) technique. It is discovered that NSWOA needs, on average, four iterations to arrive at the best possible outcome [50].

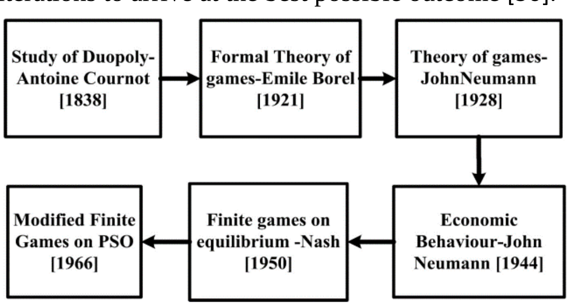

Fig. 2: graphically demonstrates the revolutionization of the hybrid energy system's game theory strategy.

The advantages and disadvantages of the popular optimization techniques and algorithms for the hybrid solar-wind energy system are shown in Table 3.
In Table 4, the optimization and prediction of solar-wind IHMS has been represented in a nutshell.

Table 3: Stochastic optimization techniques adopted by researchers for IHMS.

Optimization Techniques	Advantages	Disadvantages	Convergence Rate	Complexity
Genetic Algorithm [70,71]	Can take care of issues with different arrangements, effortlessly transferable to existing re-enactments and models. Solve issues with numerous arrangements; accessible in MATLAB tool kit.	The convergence rate is slower than other stochastic calculations; it cannot guarantee consistent advancement reaction times and so on.	Faster	Simple
Particle Swarm Optimization [63,64]	The speed of the examination is quick; computation in PSO is straightforward in contrast with different techniques; it can be finished effortlessly.	It cannot work out the issues of the non-facilitated framework; effectively experiences the fractional good faith and so on.	Faster	Simple
Loss of Power Supply Probability (LPSP) [65,66]	Easy to understand; more focused on a single system	Difficult to investigate; complex; less writing accessible.	Slower	Relatively Complex
Metaheuristic search method [67,68]	Upgrades the exhibition of nearby pursuit; quick calculation.	Complex process.	Slower	Relatively Complex
Artificial Bee colony [69,70]	The calculation has a neighborhood look and worldwide hunt capacity; actualized with a few enhancement issues; simple to utilize; accessible for hybridization mix with different calculations	Irregular statement: the calculation has a few parameters.	Relatively faster	Complex
Ant colony algorithm [51,52,53]	The calculation has the quality in both neighborhood and worldwide pursuits; executed with a few improvement issues.	Arbitrary installation: calculation has a few parameters; parameters should be tuned; probabilistic methodology in the neighborhood search.	Relatively faster	Complex

Table 4. Optimization and prediction of solar-wind IHMS [84].

Investigation	Sizing Restraint	Yield
Probabilistic [55,56,57]	Loss of Power Supply Probability (LPSP)	Probabilistic analysis with optimal sizes of solar PV and BESS, COE, and NPC calculation
Techno-economic [58,59,60]	Total Cost/kWh, level of self-rule	The best and worst case in terms of LCOE, LNPC, and minimum CO2 emissions.
Economic [61,62]	Net Present Value (NPV)	Lowest NPV and the best renewable energy combination for remote and decentralized areas.
Techno-economic [63,64]	Total cost and load energy requirement	Proper load supply management with minimum cost and environment friendly.
Probabilistic [65]	Vitality file of dependability	Calculation of probabilistically advanced IHMS for decentralized hospital and school.
Economical [69]	Lack of life cycle cost, power supply probability	Optimal sizes of solar PV, wind, DG, and BESS; cost analysis of electricity production.

Fig. 3: shows the methodological approach of a typical IHMS. In the last decade, the application of different software tools for renewable energy-oriented IHMS and HRES has increased at a huge rate. The popularity of software tools has increased due to the vast industrial applications and complex free conclusions. HOMER is the most efficient and most popular software tool **for renewable** energy-oriented IHMS and HRES. HOMER gained popularity due

to its easy iteration steps and great convergence rates with the highest accuracy. The results generated from HOMER Por have already been recognized and published by many reputed international journals.

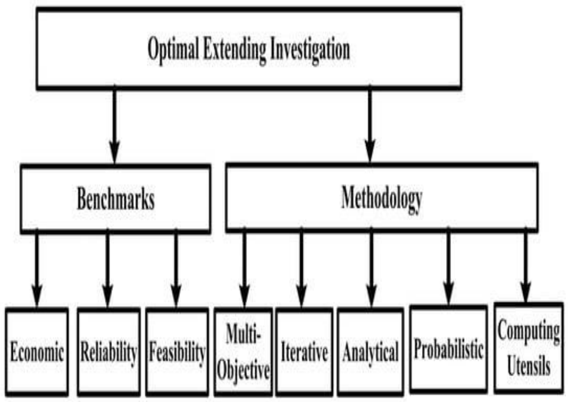

Fig. 3: The methodological approach of typical IHMS [A69]**.**

4.2. Quadratic Programming and Real-world Applications: Quadratic Programming emerges as a dynamic optimization methodology, embracing quadratic objective functions against a backdrop of linear constraints. While embracing the complexities of linear equality constraints, quadratic optimization charts a course for optimal solutions within HMGs. The efficacy of these techniques is showcased through real-world applications. For instance, in a challenging scenario at the CIESOL bioclimatic building of the University of Almería, Linear Programming was harnessed to tackle a grid power reduction issue, resulting in a staggering 48.1% reduction in electrical energy costs. Another illuminating case involved an HMG seeking to minimize operating costs and carbon emissions, deploying the MILP technique with a multi-objective solution framework[A59].

4.3. Enabling Platforms and Future Prospects: The arsenal of optimization techniques is fortified by specialized modeling platforms such as GAMS, AMPL, and AIMMS. These platforms, underpinned by deterministic solvers like IPOPT, CPLEX, SCIP, BARON, CONOPT, MATLAB, and Python, lay the groundwork for optimal decision-making within the intricate realm of HMGs. This evolution of computational prowess and modeling sophistication paves the way for a future where HMGs are empowered to navigate the complex nexus of operational efficiency, cost minimization, and sustainable practices.

In culmination, optimization techniques stand as the guiding light within the realm of Hybrid Microgrids. The fusion of objectives, constraints, and computational finesse carves a trajectory toward sustainable, resilient, and cost-effective energy solutions. As HMGs continue to evolve, optimization techniques will remain the bedrock upon which innovative energy paradigms are sculpted, solidifying their role as the catalysts of a cleaner and more efficient energy future[A60].

4.4. Exploring Diverse Optimization Techniques for Hybrid Microgrids

In the intricate landscape of Hybrid Microgrids (HMGs), a tapestry of optimization techniques is being woven to unravel the complex threads of efficient energy management. The realm of HMGs demands solutions that optimize myriad objectives - from minimizing costs and carbon emissions to maximizing renewable energy utilization and ensuring system reliability. This exploration delves into the plethora of optimization techniques that propel the evolution of HMGs towards a more sustainable and efficient future[A61].

4.5. Dynamic Optimization and Metaheuristics: Dynamic optimization and metaheuristics emerge as potent tools within the HMG optimization toolkit. The realm of metaheuristics, exemplified by Particle Swarm Optimization (PSO), orchestrates a dance of search points within a multidimensional space, gravitating towards the most promising regions. Multi-Objective PSO (MOPSO) expands this methodology into a multi-objective optimization realm. MOPSO seeks non-dominated solutions and explores optimal dimensioning, operational cost minimization, and reliability enhancement within HMGs. Applications of MOPSO abound, resonating through the optimization of HMG components, renewable generation, and overall system reliability[A62].

4.6. Genetic Algorithms and Multi-Agent Optimization: Genetic Algorithms (GAs) make their mark in the quest for optimal component sizing within HMGs. Non-Dominated Sorting Genetic Algorithm (NSGA–II) refines this approach, fine-tuning load management and operating costs. Harnessing the power of Multi-Agent Systems (MAS), HMGs transform into dynamic ecosystems where autonomous agents collaborate to achieve collective goals. Distributed control, market modeling, and optimization are domains where MAS carves its niche. These methodologies unleash a new dimension of adaptability, scalability, and decentralized decision-making within HMGs[A63].

4.7. Fuzzy Logic and Beyond: Fuzzy logic, a paradigm that embraces uncertainty, lends itself to optimizing the dynamic interplay of demand, energy storage, and operating costs. The Strength Pareto Evolutionary Algorithm (SPEA–II) channels this approach to enable Demand Response Management (DRM), mitigating peak loads and curbing customer spending. This methodology echoes through data centers, load scheduling, and dimensioning optimization, ushering in improved service quality and stability[A64].

4.8. Optimal Power Flow and Beyond: Optimal Power Flow (OPF) optimization grapples with the complexities of nonlinear power flow equations in HMGs. Tackling this non-convex challenge necessitates steady-state models and numerical methods, sculpting a trajectory towards cost-efficient and stable power delivery. This methodology synergizes with integrated optimization models and AI frameworks to create harmony within interconnected HMGs, enhancing overall system performance[A59].

4.9. Robust and Stochastic Optimization: Uncertainty pervades the realm of HMGs, with user participation, energy pricing, and energy production fluctuations introducing variables that need to be tamed. Robust and stochastic optimization emerge as guiding lights, crafting strategies that navigate unpredictability. Adaptive Robust Optimization (ARO) overcomes static limitations, evolving to match the dynamism of HMGs. Stochastic models, harnessed through algorithms like Modified Flower Pollination and Chaotic Particle Swarm Optimization, illuminate pathways for optimal energy management, ensuring resilience in the face of uncertainty[A48].

4.10. Charting a Sustainable Path: Amidst this symphony of optimization techniques, the trajectory of HMGs is being mapped towards a more sustainable and efficient energy future. These techniques, honed through real-world applications, chart a course that embraces renewable energy, minimizes costs, enhances system reliability, and accommodates the intricacies of a changing energy landscape. As the evolution of HMGs continues, optimization techniques stand steadfast, guiding their journey towards a harmonious coexistence of technology and nature[A36].

In conclusion, the world of Hybrid Microgrids is being illuminated by the beacon of optimization techniques. These methodologies, spanning dynamic optimization, metaheuristics, genetic algorithms, fuzzy logic, optimal power flow, and robust optimization, imbue HMGs with the power to navigate complexity, uncertainty, and dynamic interplay. As HMGs evolve into vital nodes of our energy ecosystem, optimization techniques become the driving force propelling them towards a future characterized by efficiency, sustainability, and resilience[A16].

4.11. Control Strategies for Hybrid Microgrids

In the intricate realm of energy management, Hybrid Microgrids (HMGs) emerge as a complex frontier that demands innovative and tailored control strategies. Unlike conventional distribution grids, HMGs interweave AC and DC subgrids, demanding more intricate and adaptable control approaches. This section delves into the labyrinth of control strategies, elucidating the nuances of their application within the unique tapestry of HMGs. Notably, several strategies have originally been developed for AC and DC Microgrids (MGs) but can be adeptly adapted for HMGs with a few modifications[6].

4.12. The Landscape of Control Strategies: HMGs host a myriad of control strategies, each tailored to address specific challenges and goals. These strategies encompass stability, protection, power balance, smooth transitions between operating modes, power transmission, synchronization with the electrical grid, and optimization. These multifaceted strategies bear the responsibility of orchestrating a harmonious symphony within the dynamic energy ecosystem of HMGs [A28, A12].

4.13. Centralized Control Strategy: At the heart of the control strategies lies the centralized approach, exemplified by the Hybrid Microgrid Central Controller (HMGCC). This approach entails standardized procedures and streamlined implementation. A centralized controller communicates uninterruptibly with the Distribution System Operator (DSO) and the electricity market, while exchanging information with local controllers and processing data. The HMGCC optimizes the operation of Distributed Generators (DGs) and Energy Storage Systems (ESSs) based on market prices, grid security, and ancillary services requirements. While this approach offers simplicity, it relies on low-bandwidth communication links, which might limit its reliability in larger HMGs [A23].

4.14. Decentralized Control Strategy: The decentralized control strategy decentralizes the decision-making process, assigning each local controller the autonomy to generate control variables. With the absence of a Central Controller (CC), local controllers optimize production, meet demand, and exchange energy with the grid and other HMGs. Advantages include low computational cost, fault tolerance, and efficient power-flow management. This strategy shines in its simplicity and reliability, eliminating the need for inter-controller communication [A29, A15].

4.15. Distributed Control Strategy: The distributed control strategy, riding the wave of technological advancements, is gaining traction. This approach leverages a network of agents that collaboratively manage energy production and consumption. Real-time decision-making is empowered through distributed control architecture and multi-agent systems. The distributed strategy yields reliability, efficiency, and reduced costs, marking its ascendancy in the quest for optimized energy management [A23, A24].

4.16. Hierarchical Control Strategies: Hierarchical control strategies, featuring levels ranging from zero to tertiary control, orchestrate a symphony of power balance, quality, and cost-effectiveness. The zero-level control, nestled within the converters, operates swiftly to maintain internal stability. Primary control ensures steady-state equilibrium, while secondary control enhances power quality. Tertiary control, the orchestrator of interaction with the Electrical Power System (EPS), optimizes the operation, minimizing costs, and respecting constraints. This hierarchical approach harmonizes generation, demand, and regulation, culminating in a sophisticated energy management ballet [A26, A27].

Intricately woven, these control strategies paint a landscape of adaptability, efficiency, and optimization within the realm of Hybrid Microgrids. Their orchestration ensures seamless transitions, optimal energy utilization, and resilient operations. As HMGs continue to evolve as vital components of our energy future, control strategies stand as the guiding compass, steering the way towards a harmonious coexistence of technology and sustainability[A7].

In summation, control strategies emerge as the linchpin in the realm of Hybrid Microgrids. They unravel the complexity, adapt to uncertainty, and orchestrate energy flows with finesse. From centralized control's simplicity to decentralized resilience and distributed strategies' efficiency, and hierarchical precision, these techniques ensure a seamless integration of renewable energy, efficient energy management, and sustainable progress. As HMGs carve their path into the energy landscape, control strategies act as the maestros, directing the symphony of power towards a harmonious and sustainable future.

5. Conclusion

In the ever-evolving landscape of energy generation and distribution, the emergence of Distributed Generation Units (DGUs) has ushered in both promising advancements and intricate challenges. As these DGUs proliferate, they introduce complexities in Electrical Power System (EPS) planning and relay protection, casting shadows on the power quality of distribution grids. This ripple effect disrupts the seamless functioning of electrical equipment, leading to premature wear and tear, accompanied by substantial economic losses. The reverberations of this cascade extend further, culminating in large-scale power supply issues. This discussion centers on the interplay of these challenges and the strategies deployed to tackle them, underscoring the pivotal role of control schemes.

The Impact of DGUs on Power Quality: As elucidated previously, the disruption stemming from DGUs takes on various forms, manifesting as long-term voltage fluctuations, deviations in RMS values of nominal voltage and frequency, voltage imbalances, and harmonic distortions. These disturbances not only impede the smooth operation of equipment but also pose a threat to economic stability. In response to these challenges, primary and secondary control strategies are harnessed to maintain voltage levels and stabilize frequencies within permissible limits mandated by grid codes.

5.1. Recent Reviews Unveiling Insights: In recent years, the scientific community has engaged in in-depth reviews that delve into diverse facets of Hybrid Microgrids (HMGs). These reviews offer a spectrum of perspectives, addressing crucial issues and paving the way for innovative solutions. One such area of scrutiny is power quality. In one instance, a review tackles control techniques to enhance power quality within the Unified Power Quality Conditioner (UPQC) integrated into HMGs [A26]. Another review [A27] juxtaposes power quality issues in HMGs, comparing problems, solutions, and standards, encompassing voltage sags, swells, harmonic distortion, system imbalances, and fluctuations. Furthermore, a critical dissection of power quality indicators, causes, and consequences in HMGs is undertaken, drawing from IEC 61000 and IEEE Std. 1159 [A28]. In the same vein, uncertainties linked to HMGs and their Renewable Energy Sources (RESs) are explored, underscoring the need for optimized operation [A29]. Delving into the nitty-gritty, a review articulates the array of power-quality challenges faced during HMG development [A30]. In the realm of DGUs driven by photovoltaic (PV) systems, harmonics emerge as a key concern, with both non-linear loads and PV inverters contributing to current harmonic content [A31, A32, A33]. Additionally, a study investigates the harmonic distortion effects of an HMG composed of PV systems and linear and non-linear loads [A34].

5.2. Navigating the Power Quality Matrix: The reviews collectively underscore the burgeoning significance of monitoring power quality in distribution grids. Rigorous measurement and analysis are imperative, revealing the dual influence of HMGs on power quality degradation and the impact of utility grid disturbances on HMG performance. A holistic view of power quality encompasses both sides of the equation, propelling the quest for stable operations and high-quality power.

5.3. Optimization Techniques and Control Strategies: Beyond merely dissecting issues, recent reviews delve into optimization techniques that promise enhanced power quality management. The evolution of power converters for DGUs is interwoven with algorithms and control strategies striving to uphold power quality. Optimization avenues manifest in the form of mathematical techniques applied to HMG planning [A64]. The economical and reliable optimization of green HMGs surfaces as a prime concern, beckoning efficient techniques to the forefront [A36]. A bibliometric analysis traverses the landscape of HMGs, spotlighting Energy Storage Systems (ESSs) and charting paths for future improvement [A63]. Transient stability analysis takes center stage, with reviews unpacking optimization and control techniques for HMGs operating in islanded and grid-connected modes [A33].

5.4. Pioneering the Future: The unfolding narrative reveals a rich tapestry of insights. Diverse optimization techniques converge on the maximization of generator output, extending equipment life, and minimizing environmental impact. The design and topology of HMGs glean advancements, while control strategies navigate intricate dynamics. Notably, HMGs operating in islanded mode present distinct challenges. The reviews collectively highlight niches of opportunity in the realm of HMGs, from protection issues to the continual pursuit of uncompromised power quality. These reviews become the springboard for future research, driving comparative analyses and pioneering novel techniques in the dynamic realm of HMGs.

5.5. Concluding the Journey: In the realm of Hybrid Microgrids, these reviews emerge as guiding beacons, illuminating challenges and charting pathways to solutions. From untangling power quality puzzles to optimizing energy management, the discourse encapsulates the spirit of innovation and adaptability. As HMGs rewrite the energy narrative, these reviews stand as pillars, supporting the edifice of a decentralized Electrical Power System and ushering in an era of sustainable, efficient, and reliable energy ecosystems.

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