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Advancements in Microgrid Systems: A Review of Recent Developments in Control Strategies and Technologies

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Abstract – Microgrids play a pivotal role in the evolving energy landscape by integrating renewable energy sources (RES) with advanced control strategies. This review highlights ten recent studies on hybrid AC-DC microgrids, covering innovative designs, intelligent control mechanisms, and practical applications. Key findings include improved stability, efficient power management, seamless state transitions, and adaptive solutions for variable conditions. These insights pave the way for developing robust microgrid solutions to address the challenges of modern power systems.

Keywords: *Microgrid, Renewable Energy Sources, AC-DC Systems, Frequency Control, Stability, Adaptive Control.*

I. INTRODUCTION

With the increasing adoption of renewable energy sources (RES) like solar photovoltaics (PV) and wind turbines, microgrids have emerged as a critical solution for localized energy generation and distribution. Unlike conventional energy systems, microgrids offer the flexibility to integrate diverse energy sources and efficiently manage power in both grid-connected and islanded modes. Hybrid AC-DC microgrids, in particular, have gained significant attention for their ability to combine the strengths of AC systems—widely used in power grids—with the efficiency and simplicity of DC systems.

However, hybrid microgrids face several technical challenges, including power fluctuation, voltage synchronization, frequency stability, and the seamless transition between operational modes. Addressing these challenges requires the implementation of advanced control strategies, intelligent algorithms, and robust energy management systems. For instance, solar PV systems are prone to variability due to changes in temperature and irradiance, necessitating the use of storage systems and sophisticated power controllers to maintain stability. Similarly, islanded microgrids require precise synchronization mechanisms and adaptive control solutions to manage distributed generators effectively.

Recent studies have proposed innovative approaches to tackle these issues, ranging from neural network-based frequency deviation control to improved voltage loops and adaptive synchronization schemes. These developments aim to optimize performance, enhance stability, and ensure reliable power distribution under dynamic conditions. This review synthesizes insights from recent literature, focusing on novel control techniques, hybrid microgrid architectures, and the practical implications of these advancements in modern energy systems.

II. LITERATURE REVIEW

Saurabh Babu (2023) The study proposes an AC-DC microgrid powered by a combination of renewable energy sources. Appliances that require either direct current (DC) or alternating current (AC) can be powered using this system. Solar photovoltaics and wind power systems are the most practical alternatives because of their widespread availability and low maintenance requirements. Solar PV electricity fluctuates owing to the altered in temperature and irradiance and is unable to generate consistent power, so a storage battery system is required to meet up the power demand and preserve the fidelity of the hybrid microgrid. Thus, a DC microgrid system has been built, comprising BS plus the solar PV system with DC load, and an AC micro grid system, comprising a wind turbine generator, a connection to the grid, and an AC load. A power regime controller is used to regulate the ratio of AC to DC current. As a further step towards validating the suggested system's efficacy, it has been built in MATLAB/Simulink.

Luwei Wang (2023) With the continuous construction of new power systems, it is characterized by a high proportion of renewable energy and high-power electronic products. The grid-forming converters have the advantage of flexibility and controllability, which can provide voltage and frequency support for the new power system with low rotational inertia and weak damping. A model of an islanded AC microgrid (MG) with time-delay based on grid-connected converters is established. Utilizing Artstein transformations, the model is subsequently transformed into a model without any delays. Then, considering the problem of communication link disturbance and information delay, a distributed fixed-time controller (DFTC) for the islanded AC MG based on the grid-forming converters is proposed. The proposed strategy can guarantee that the frequency and voltage are restored to its rated value and accurate power allocation is gained within a fixed time. Furthermore, the fixed-time stability of the proposed method is analyzed using the Lyapunov stability principle and the fixed-time theorem. Finally, the effectiveness and excellent performances of the DFTC strategy are verified by MATLAB/Simulink simulation.

Lin He (2023) Microgrids have two operational states: grid-connected and islanded. Ensuring seamless transition between these different operational states is a critical measure for enhancing the stability of microgrids. Under the above background, this paper proposes a hybrid AC-DC microgrid system and a smooth switching control strategy based on improved voltage loop. First, the typical topology, operation mode and traditional control method of the proposed microgrid

are introduced. Secondly, an improved voltage loop based on current compensation is proposed to reduce the current reference shock. Finally, the control of voltage amplitude and phase Angle pre-synchronization is added to the AC/DC converter of microgrid to realize smooth grid connection. Through simulation analysis, it is verified that the proposed microgrid system and the improved voltage loop control mode can coordinate the switching of each control mode, reduce the influence of current, and improve the operating stability of the microgrid.

K. Nosrati (2023) Variable output power in isolated microgrids (MGs) threatens frequency stability and may even degrade power quality. In response, intelligent control methods have been developed and applied to frequency deviation control systems with excellent results. Nevertheless, a potential problem is that the application of such advanced techniques with a large search space is not enough to deal with highly dynamic environment and real-time operations of MGs. In this light, the present study introduces a flexible artificial neural network (ANN)-based frequency deviation control solution in a constrained structure that operates as follows. First, the stable controller parameter space of the PID-based AC microgrid is derived by using the stability boundary locus method. Then, the controller parameters are tuned and updated online by searching for an optimal combination of the coefficients with consideration of output variations sensed by a constrained ANN in the derived reduced parameter space. To accomplish this step, a reinforcement learning technique is applied to train the ANN-based tuners. The performance of the proposed technique has been verified under a given scenario to demonstrate how the reduced parameter space should facilitate the optimization procedure.

Bijit Kumar Dey (2023) Popularly, the VSIs of the decentralized, islanded microgrids, use the voltage and frequency droop laws for proportional power sharing. These cause the output voltage amplitude and frequency of the VSIs to deviate from their nominal values. Because of the decentralized architecture of the microgrid, any incoming DG unit(IDG) will be unaware of these deviations. In this situation, this DG unit will initially generate an output voltage whose amplitude and frequency are at their respective nominal values. The difference in output voltage amplitude and frequency will cause a high and undesirable current to flow between the generators. In this paper, this problem is solved by introducing a novel synchronization scheme. The scheme makes any incoming DG unit operate first in the Intermediate mode and then in the Droop controlled mode. These modes are designed to meet the IEEE 1547-2003 std and make the synchronization possible for the incoming DG unit.

Pagidela Yamuna (2022) The design and the deployment methods of the microgrid design have traditionally relied heavily on alternating current (AC) systems. Over the AC microgrids, there are DC microgrids which are more popular due to numerous advantages. The advantages are that there is no need for the synchronization and no need for frequency modulation. The DC microgrids are more suitable for DC loads and in distributed energy resources (DERs). In case of hybrid microgrids, the solutions are cost-effective and are practical in nature. This is due the eliminations of power conversions between AC and DC systems. In this piece of work, an analytical method is proposed for the optimal coordination of AC and DC microgrids with IEEE 12 bus system.

Arijit Ganguly (2022) This brief proposes a new consensus based adaptive frequency tracking scheme for dispersed generation (DG) based AC microgrid that is not connected to main grid. The distinct controllers has been designed following cooperative control algorithm having sufficient amount of adaptive potential. Linear quadratic regulator (LQR) calculates the controller gain. The microgrid performance has been checked exposing it to network delays (NDs) and high frequency noise (HFN) signals. Microgrid, subjected to NDs has been analyzed with the variation and alteration of control parameters. A detailed case study has been presented and simulated to generate results satisfying the proposed control scheme.

Xiaohai Ge (2022) The cascaded-type microgrid is proposed to promote the application of microgrids at the high-voltage level. The conventional P-f droop control method cannot perform a unified characteristic to guarantee stable operation in both grid-connected and islanded modes. A novel Q-f droop control is proposed in this paper to realize a unified power control for cascaded-type AC microgrids operating in grid-connected and islanded modes in a fully decentralized manner. The power transmission characteristics of the cascaded system in two modes are analyzed, respectively. Then the steady-state performance and small-signal stability are discussed in this paper. This method has a simple control structure and satisfactory power control performance, which greatly improves reliability, and flexibility and reduces costs. Finally, the feasibility and effectiveness of the proposed control strategy are verified.

Abd Alelah Derbas (2022) This paper proposes an intelligent primary control strategy for voltage source converter (VSC)-based ac microgrid (MG). This is implemented by using a proportional resonant (PR) regulator adopted in the inner level of primary control of VSCs. An approach based on brain emotional learning (BEL) is proposed to provide an online and adaptive tuning of control coefficients of the PR regulator. The proposed BEL approach is fully model-free, indicating that the coefficients are regulated without previous knowledge of the system model and parameters. The outer level of primary control employs a droop control loop to regulate power-sharing among different distributed generators. Unlike the conventional control methods with constant coefficients, which are typically designed for a specified operating condition, the proposed approach avoids the dependency of the converter control system on the operating conditions and accommodates varying loading conditions. A sensitivity analysis is also performed to investigate the effects of PR coefficients on the system stability. Moreover, a Mesh analysis is carried out to examine the stability of dominant frequency modes of the whole AC-MG using the proposed control scheme. Simulations are provided to demonstrate the performance of the proposed control scheme.

Hari Krishnan S (2022) To tackle the ever-increasing energy demand, microgrids (MG) with higher penetration of renewable energy sources (RES) serve as an effective solution. Since these sources are highly intermittent, various maximum power point tracking (MPPT) algorithms and energy storage system (ESS) is utilized to exploit the full potential of the resources and operate reliably. This paper focuses on the power management and

voltage quality improvement of an AC microgrid with solar, wind energy generation, and battery energy storage. The variable step incremental conductance (INC) MPPT algorithm is used for solar and wind distributed generations (DGs). The ESS maintains the power balance and the DC bus voltage, which is interfaced through PI controlled bi-directional DC-DC converter. The voltage quality at the AC bus is improved by employing finite control set model predictive control (FCS-MPC) of a three-phase three-level neutral point clamped inverter. The results elucidate that harmonic distortion and unbalance in the AC bus voltage are compensated under varying load and source conditions. Furthermore, the power-sharing capability of the inverters with two DGs is investigated.

CONCLUSION

The reviewed studies collectively advance microgrid technology by addressing critical challenges such as stability, synchronization, and adaptability. Innovations in hybrid AC-DC architectures, intelligent controllers, and synchronization mechanisms highlight the potential for more efficient and resilient energy systems. Future research should focus on scaling these solutions for larger networks, integrating real-time adaptability, and reducing deployment costs. These advancements lay the groundwork for a sustainable and reliable energy future.

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