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Frequency Regulation in Islanded AC Microgrids Using Intelligent Controllers: Techniques, Challenges, and Future Trends

R. Sethuraman[1*], Dr. V.J.Vijayalakshmi[2]
[1*]Department of Electrical and Electronics Engineering, Karpagam Academy of Higher Education, Coimbatore, India.
ramansethueee@gmail.com
[2]Department of Electrical and Electronics Engineering, Karpagam Academy of Higher Education, Coimbatore, India.
Corresponding Author: ramansethueee@gmail.com

Abstract

Frequency regulation in islanded microgrids is much harder due to the absence of the relatively large conventional generation, low system inertia and addition of variable renewable energy sources. It is important to keep the frequency stable so that microgrids can operate reliably, particularly in standalone mode without a connection to the main grid. Classic control methods, such as droop control and Proportional-Integral (PI) controllers, are typically not able to cope well with fast changes in load and generation. To solve these problems, intelligent controllers such as Fuzzy logic controllers (FLC), Artificial neural networks (ANN) and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) came up as potential solutions. This study provides a good review in regards to control methodologies designed for frequency regulation of AC microgrids. We investigate the limitations of classical approaches and present motivation for intelligent controllers, including flexibility, stability, and dealing with nonlinearity and uncertainty that occur in renewable power generation. This review demonstrates the promise of intelligent controllers for frequency control in islanded microgrids and thus a more resilient, sustainable energy system.

Keywords: *Microgrid, Distributed Energy Resources, Fuzzy Logic Control, Artificial Neural Network, Adaptive Neuro-Fuzzy Inference Systems (ANFIS).*

I. INTRODUCTION

A microgrid is a self-sustained power infrastructure that can operate in parallel with or on islanded mode from a larger power grid [1]. Usual suspects generally include distributed energy resources, such as solar panels, wind turbines, batteries and combined heat and power systems. The design of microgrid should be based on the principles of easy installation, commissioning and maintenance. " By minimizing network congestion, line losses and associated costs, a microgrid may cut the overall cost of electrical energy supply by more than 30-50%. Micrograds are more flexible and reliable, which can operate interconnected with grid and islanded, as well as being dispersed or dense in its location [2]. To meet the increasing electricity demand and to improve energy efficiency, power generation has gradually gone through new technology developments such as renewable sources, clean and efficient fossil one or decentralized generation. The microgrid concept is based on interconnected multiple microgenerators to a local distribution system that can partially or completely be disconnected from the high voltage transmission and grid [3]. Microgrids can support integration into the distribution system, but they also may present threats to the secure and reliable operation of the grid that could affect line flow, voltage stability and power quality.

Microgrids have two primary operating modes, Grid-Connected and Islanded. [4]

In grid connected operation, the microgrid is on a power grid. It can receive power from the grid t when it needs, and return excess energy on the grid [5]. The microgrid improves the distribution between local demand and resources with higher flexibility behavior and reliability. It also encourages the use of renewable sources of energy, and lessens total carbon emissions. The microgrid is able to operate in islanded mode [6] when the main grid is not available such as under a blackout or some other incidents. Here in this state, it can function on its own, tapping into local sources of energy such as solar panels, wind turbines or batteries. This capability improves resiliency, which means critical services and buildings will still be able to operate during extended grid failures. Both modes can adjust microgrid operations according to different energy requirements and working environments, so they play the important role in present power systems [7]-[11].

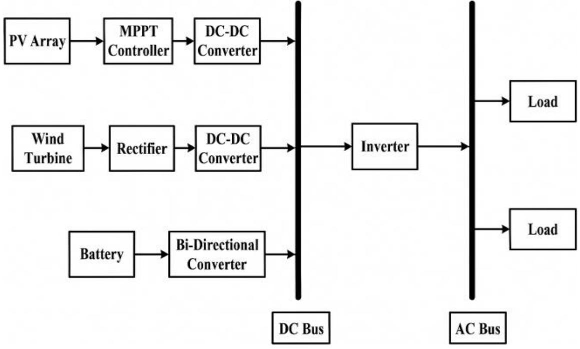

Fig- 1 Islanded Microgrid

II. OBJECTIVE OF THE REVIEW

The aim of this work is to provide a comprehensive review and comparison between traditional and smart control strategies that have been proposed for frequency regulation in islanded microgrids.

- To Investigate the shortcomings of traditional control approaches i.e droop and PI controllers to preserve the frequency stability in islanded micro grid.
- To investigate whether highly-developed intelligent controllers such as Fuzzy Logic Controllers (FLC), Artificial Neural Networks (ANN) and Adaptive Neuro-Fuzzy Inference system (ANFIS) are suitable for meeting the challenges of low system inertia, the intermittency of renewable energy, and dynamic load changes.
- To compare the performance of traditional (non-intelligent) versus intelligent controller in terms of adaptability, robustness and its ability to handle nonlinearities and uncertainties that exist for energy from renewables.
- To address the framework for integration of BESS and their coordination with control algorithms to supply fast frequency services and enhance system stability.

III. CHALLENGES IN FREQUENCY CONTROL

Frequency control in an islanded microgrid is essential due to the lack of main grid stabilizing action and because smaller, centralized generation systems are less capable to address frequency issues.

Unlike the case of large power systems where it is feasible to rely on high rotational inertia present in large conventional generators (e.g. hydro, thermal) for maintaining system stability, island microgrids are typically equipped with lesser rotating equipment most notably smaller distributed energy resources (DERs) based on renewable sources which lack considerable inertia [12]. This does render the system more susceptible to fast frequency changes during disturbances. Low inertia means that the system will exhibit quicker and greater frequency excursions as load or generation changes are imposed, making it more difficult to keep stable. Renewable sources of power such as solar and wind represented frequently in micro-grids are inherently intermittent where the amount of electricity they generate varies based on weather conditions [13]. These variations may result in differences between generation and load, which can compromise frequency stability. The stochastic characteristic of renewable resources makes the frequency regulation more uncertain both when it cannot meet and exceed to the load demand [14]-[15].

Under islanded operation the microgrid cannot utilize the frequency control services of the host grid [16]. In grid-connected mode, the high-inertia and stable grid is a frequency reference for converter-based equipment, which is not available in islanded operation; hence local controllers are very important. All frequency control should be performed by local generators, storage systems and controllers that may not have the capability and speed as a larger grid [17]. Fast fluctuation on the load side may cause frequency to become unstable, particularly in small microgrid systems with a bigger ratio of load-to-generation [18]. If there is a rise of demand the frequency falls and vice versa. Nonlinear loads included in the system, such as power electronics or electric vehicle chargers among others would introduce harmonics and other disturbances impacting the frequency stability.

Classic control methodologies such as droop control and Proportional-Integral (PI) controllers are mostly incapable of compensating the rapid fluctuations in frequency due to the dynamic loads and renewable generation in islanded microgrids. Hardwired controllers could be too sluggish to bring back frequency under control when sudden load or generation changes occurs which means frequency deviations may persist or the system collapse. Battery Energy Storage Systems (BESS) are commonly employed for fast frequency response when active power is exceeded or in case of shortage generation. However, the storage capabilities may be limited in the amount of energy that can be stored and releases for frequency support, more particularly for prolonged periods of time or with less available stored energy. Batteries can degrade, losing some of their ability to provide fast-frequency support which can be detrimental for long-term stability

In an isolated MG, ensuring the synchronise of DGs is essential [19]. For example, inadequate synchronization of the generators may lead to differences in frequency that can destabilize microgrid operation. It may be challenging to re-synchronize between different generation resources following a large disturbance in order to restore stable operation from a frequency perspective. Employment of more advanced frequency control techniques like energy storage or fast acting intelligent controllers can be expensive especially for smaller islanded MGs suffering from constrained financial resources [20]. Islanded microgrids composed of small islands might not achieve the diversified generation and load in order to support frequency stability, especially when high demand/high renewable shortage is continuously lasted [21].

IV TRADITIONAL FREQUENCY CONTROL METHODS

The droop control algorithm is the most popular way for frequency regulation of islanded microgrid. It is formed under the philosophy of emulating the natural response of large synchronous generations where frequency and output power are modulated subject to a balance between generation and load demand [22]. Droop control is lightweight and decentralised, and does not require inter-communication among multiple DERs to share the load. The fundamental idea behind DC lies in modulating the power generation of distributed generators or inverters according to deviations in the system frequency (for active power control) and voltage (for reactive power control). This is also applicable to small isolated microgrids, similarly with reduced communication requirements between the generators, where the load sharing takes place among lines without any control signal. However, for reasons of frequency accuracy and response time, droop control is not very suitable to high-RES integration in large scale power systems.

PI and PID controllers It is widely used to return the system frequency back to its rated value if the load shifts or disturbances in islanded microgrid environments. Such techniques are an extension over the basic control schemes, such as droop control, in which a secondary layer of control is added to alleviate steady-state errors and to enhance frequency corrective performance behind time. PI controllers are very popular in control systems because they combine two primary benefits of proportional control that reacts to the current error and integral control that responds to errors accumulated over time.

When microgrids are concerned, the Proportional (P) part of the controller senses the frequency deviations from its rated value and compares it against a set reference, while the Integral (I) part integrates over time the system errors to ensure constant elimination of frequency deviation leading to recovery of microgrid system frequency as per nominal value. The proportional component reacts with the present frequency error to perform fast adjustment. The integrator removes the accumulated frequency error to return the system frequency to its proper value. The derivative part predicts future errors based on the rate of change of the deviation, and (therefore) it can help ameliorate the degree of error if cut off changes occur. This predictive element allows the PID controller to react more quickly when renewable energy generation is abruptly interrupted / changed and thus it makes them suitable for highly variable systems.

P-PI controllers find special applications in microgrids with a significant fraction of renewable generation such as solar or wind plants: the large variability of their power output due to rapid changes in sunlight or wind speed can result in frequent uncontrollable frequency shifts. As with PI controllers, PID control is compatible within a secondary control system with droop control or another primary controller. The secondary controllers like PI, PID type are very important to bring back or push up the frequency at nominal value with in the islanded mode of operation when disturbances or load changes is occurred. Fast but crude frequency regulation is achieved using droop control, while steady-state frequency error and system stability are both improved with the aid of PI and PID controllers particularly in microgrids that have high renewable power source penetration. But these controllers need to be well-tuned and the use of redundant communication structure increases the complexity of the total control system. Tertiary control is an important tool when considering the optimal power flow and economic operation of a microgrid that is in either grid-connected mode with the main grid or it is controlling several DERs on islanded mode [23]. As primary and secondary control deal with frequency and voltage regulation, the tertiary control is in charge of optimisation of power flows, cost reduction, stability coordination at the whole microgrid level.

V. ADVANCED CONTROL TECHNIQUES

With the growing penetration of renewable sources into microgrids and their low inertia levels, new control techniques are required for frequency stability. Smart control systems with storage systems represent a smart, fast and adaptive approach to deal with challenges of renewable energy intermittency and low system inertia for reliable and efficient microgrid operation. Model Predictive Control (MPC) has become an attractive optimization method used in microgrids to address the frequency regulation problem, particularly in system with high penetration of RES [24]. MPC, in fact, is well adapted to microgrids as it deals with multivariable control problems and enabled prediction with on-the-fly optimization in the face of uncertainties like renewable energy resources which are intermittent. Decentralized control methods in microgrids allow for frequency regulation using local decision-making, peer-to-peer communication and distributed algorithms. Such decentralized operation will increase the flexibility, reliability and scalability of the microgrid, making it more applicable to the new types energy systems that can include renewable sources and dispersed generation.

VI. INTELLIGENT CONTROLLERS FOR FREQUENCY CONTROL

The Fuzzy Logic algorithm is a calculation approach which mimics human reasoning and hence has the ability to handle logic uncertainties as well as difficult non-linearities in structured systems like micro-grids [25]. As opposed to the conventional binary logic (which is true vs. false), fuzzy logic has a notion of partial truth (being partly true). Fuzzy logic is a powerful concept to deal with uncertainty and non-linearity in microgrid. "Based on human logic, it is able to control in both a screw-loose manner and pinned-down manner in open surroundings without dealing with specific measurements or models. The flexible use of it increases the application of fuzzy logic in advanced power control, distributed generation integration and power/frequency control for modern microgrid. FLC appears to be a viable solution for controlling VRE generation and load profile in microgrids. It is capable of increasing the stability and reliability to an acceptable level in terms of FLC, which are flexibility, restructuring options, rapid convergence rate of real-time compensating capacity and smooth operation control.

ANNs can be used to take as input streaming data such as generation levels, load demand and frequency from various components in the microgrid down to ATP losses. This has allowed them to acclimate easily to new circumstances. Using the ANN-based controllers effectively learned to predict which optimal action needs to be taken in order to maintain frequency and stability relying on system memory, on-line feedback and adaptive learning mechanisms. This ability of handling the complex and nonlinear relations as well as learning when system operating conditions vary, makes them a desirable alternative for the recent power system control. [26] ANFIS is the combination of artificial neural network and fuzzy logic schemes. This is what allows the system to cope with uncertainty and imprecise data in both data analysis and control decision. The complicated relation of generation and load can be modelled by ANFIS. This needs to be done in real-time so as to provide dynamic load dispatch and generation scheduling which can balance the demand-supply equilibrium taking into account variation. In PSO, there are some particles (potential solutions) which are wandering in the region of solution. This strong global SE detection ability can help in searching for optimal solutions very soon, and is thus very helpful in real-time system adaptation.

It can learn by studying the past how a system will act in different scenarios. ANFIS can respond to dynamic changes continuously, and hence modifies control strategies according to the current frequency deviations and load demands. It is deemed that ANFIS-based frequency control of the islanded microgrid in this test system has certain reliability to maintain its stability during dynamic process. The capability of adapting allows microgrid operators to improve the frequency control strategy and ensuring reliable and efficient operation. GA emulates the process of natural selection and it is efficient for searching large solution spaces. It is capable of accommodating variable system aspects, including varying loads and supply. GAs is capable of considering multiple objectives like fuel cost minimization, emission optimization and system stability. By combining these parameters, they may be used to maintain control over the system through different situations. GAs operates with a population of solutions so that they can search for strong solutions that work well on various conditions and hence increase the system´s robustness PSO is popular for its fast convergence that proves to be very useful in order to maintain the stability of the system in dynamic environment. Instantaneous milling & brewing adjustments and instantaneous generation and load control modifications can be based upon real-time/modern data. PSO can adapt to generation (like renewable energy sources) and load changes, hence it is applied for real-time parameter optimization.

VII. ROLE OF ENERGY STORAGE SYSTEMS (ESS) IN FREQUENCY CONTROL

BESS may quickly discharge power to the grid or absorb surplus power. This is responded when so too or power generated much of in compared had-ow of load. Try-related frequency that a corresponding try that could require. BESS can also be discharged to increase power if the frequency is low(L) (overload (load surplus)/under generation). If on the other hand the frequency is high (oversupply) it can take power and thus help bring down the frequency to normal. In microgrids with renewable generation (e.g. solar or wind), generation could be intermittent. Flow batteries like BESS can store excess energy when generation is high, and release it during low generation periods which smoothens out the highs and lows to stabilize frequency. With the islanded mode of operation, it would provide its own response to frequency deviations without having to rely on a centralised control. Such local actions can be important for reducing response times and improving system-level resilience. BESS Fast frequency response nodes are the key of islanded microgrids. It increases robustness and reliability of the system regarding to round-off noise, magnitude error and frequency deviation. This capability is increasingly important for microgrids that are prevalent and coupled with variable renewable energy sources.

VIII. COMPARATIVE ANALYSIS OF CONTROLLERS

Table 1 Comparison of Traditional and Intelligent Controllers for frequency regulation of MGs

iteria	**aditional Controllers**	**telligent Controllers**
sponse Time	ower, may struggle with rapid fluctuations	ster, capable of responding to dynamic changes
bility	lequate under steady-state conditions, weake extreme conditions	ghly stable, even under dynamic and nonlinear conditions
bustness to Load/Generation Changes	ited robustness, struggles with larg turbances	ghly robust, can handle significant fluctuations
plementation Complexity	ple to implement, low cost	re complex to implement, requires expertise an mputational resources
aptability to Renewable Energy	ited adaptability to renewable variability	ghly adaptable, designed for nonlinearities and renewabl rgy fluctuations

This Table provides a comparison of conventional controllers and advanced intelligent controllers, highlighting key aspects such as stability, implementation ease, complexity, and resilience to variations in load or generation.

Table 2 Comparison of different intelligent controllers for frequency regulation of MGs

Control Method	Response Time	Accuracy	Complexity	Remarks
Droop Control	Fast	Moderate	Low	mple implementation; relies on proportiona ntrol based on frequency and active power fective for steady-state but may struggle with namic conditions
ızzy Logic Control (FLC)	Moderate	High	Moderate	lapts well to non-linear systems and uncertainties quires fuzzy rule design but provides good curacy. Response time can be slower due to ference processes.
rtificial Neural Networks (ANN)	Moderate	High	High	pable of learning complex patterns and dynamics quires training data and computational resources ood accuracy, but response time depends on twork complexity
Adaptive Neuro-Fuzzy ference System (ANFIS)	Moderate	Very High	High	ombines benefits of FLC and ANN; self-adapting pabilities enhance accuracy. More complex and mputationally intensive than basic FLC
Genetic Algorithm (GA)	Slow	High	Very high	ed for optimization rather than direct control; can d optimal settings but typically involves longer mputation times. Not suitable for real-time quency control
Particle Swarm Optimization (PSO)	low to moderate	High	High	milar to GA, focused on optimization; good for rameter tuning. Not ideal for immediate response t useful in pre-determined scenarios

This table illustrates a comparative analysis of various intelligent frequency control methods based on key performance criteria such as response time, precision, and complexity.

IX.CONCLUSION

Active controllers play vital roles for frequency stabilization of islanded microgrids, especially the grids integrated with high level solar or wind power. Their capability to adaptively deal with uncertainty, more flexible resource allocations and provide better system resilient-ratio are key for secure and efficient microgrid running. As the new method of energy generation continues to be developed, so will this form of controllers. Also, the rise of complexity in microgrid systems due to renewable integration and emerging technologies underscores the research need for adaptive and predictive control strategies. The research will be integral to ensuring that microgrids are both reliable and economic, and operate safely as the energy environment continues to change. By tackling these questions, the researchers can help to develop more resilient and sustainable microgrid solutions

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