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Review of Applications of Fuzzy Logic in Multi-Agent-Based Control System of AC-DC Hybrid Microgrid

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ABSTRACT High penetration of renewable energies to smart grid technologies has lead the traditional electrical transmission and distribution network to undergo a significant evolution. Here, advanced control strategies are required to ensure the load balance in order to keep the voltage and frequency variation within an acceptable range. With the integration of dc energy sources and storages, another control constraint would be added due to the limitations in a storage system. Among recent developments in control techniques, fuzzy logic and multi agent systems have emerged due to its strong control action in an uncertain environment. Researchers have made satisfactory efforts in optimizing hybrid renewable energy sources using these technologies. This paper strives to highlight the approaches of controlling the energy storage systems, dc voltage, frequency, and ac voltage with the aid of the fuzzy logic and multi agent systems related controllers.

INDEX TERMS Microgrid, fuzzy logic, multi agents, battery energy storage system.

I. INTRODUCTION

As of late, the traditional energy network is being heavily decentralized as a result of the world's attention moving towards high penetration of renewable power sources such as solar and wind at the customer's site. This is an alternative to the fuel fired generators, which cause high carbonic emissions. Along with the advancement of the recent research work, combination of such micro-sources forming clustered generation units, was introduced to address some challenges, such as: reliability and energy loss in the transmission system. Distributed renewable sources, termed as distributed generators (DGs) are usually connected to the local AC utility grid, near the low voltage side to supply local loads, eliminating the need for high voltage transmission [1], [2]. This aggregated system with AC and DC micro-sources, power controllers and loads are termed the Microgrid (MG). The compactness of this system and the low voltages at their interface of connection create a new set of problems which require innovative approaches in managing operation of the DGs. Hence numerous control topologies of the MG have been evolved recently with the aid of the number of recent extensive research studies.

This paper reviews the current status of the control of MGs with the aid of the primary Artificial Intelligence (AI) technique called Fuzzy Logic in Multi Agent Based control systems. It also provides a brief description on the components of an MG, an overview of the control aspects of the MG and a literature review of the control with Fuzzy Logic techniques that have been introduced, simulated and validated. Moreover, this review consolidates the evolution of control strategies up to present with Fuzzy Logic and their pros and cons. Furthermore, final conclusions are made upon critical comparisons of control strategies which pave the way for future research work.

II. HYBRID MICROGRID MODEL AND ITS SIGNIFICANCE

An MG can be considered as a sub power system in a small-scale scenario, which has two modes of controls; namely: grid and isolated. The grid mode is where the connection is set up with the main power grid and the isolated mode is where there is no connection with the utility grid. Therefore, control is more critical here. In the isolated mode, controllability over all of its attributes is done locally unlike the conventional system and more knowledge-based control aspects are used for this case.

Customers can enjoy potential benefits like improved reliability by supplying power to the islanded section during utility outages. Utilities are granted benefits from being able to resolve overload problems by disconnecting the load from the power system through unintentional islanding and intentional islanding where maintenance on the utility system at outages is allowed easily [3]–[5]. In such a scenario, it is obvious that the centrally controlled conventional grid hierarchy is no more suited for the future needs. Most of the MG related technologies are converging towards the smart grid options, which brings efficiency, stability and flexibility in the hardware, software and communication [6], [7].

Although MG inherently is an AC system, since there is a considerable DC integration, and an AC-DC hybrid system is formed. Conversion losses and harmonic additions are omitted due to the removal of inverters which leads to power quality of utility finally [8]–[10]. Further, the DC distribution system is more suitable for distributed generation with DC outputs such as, photovoltaic panels and secondary batteries, as rapid isolation from the bulk power system is possible to serve the DC loads continuously in the event of an accident in the bulk power system [11]. However, DC power transmission causes more losses than high-voltage AC transmission. Common configuration for such AC-DC hybrid Microgrid can be depicted as given in Figure 1. Micro-sources, Energy Storages, coordinating devices and loads are the main contributors of the MG formation.

A. MICRO-SOURCES

MG consists of several distributed energy resources such as, photovoltaic (PV) system, mini or micro hydro and wind turbines which are connected to the loads via AC and DC bus bar through a suitable power electronic interface called micro-source controllers (MCs). All the main DG sources are renewables; hence advanced growth in controlling technology is needed in integration. In scenarios where generation failure of renewables and absence of power electronic interfaces occur, the backup generator which is often a diesel generator is introduced into the system in order to avoid blackouts.

B. COMPOSITE ENERGY STORAGE SYSTEMS

Due to the intermittent nature of the renewable energy sources and load variations, Composite Energy Storage Systems (CESS) like batteries are vital in MGs. Fuel Cell (FC) is another mode of energy storage, which has a higher capacity and larger response time compared to battery system. DC bus voltage is an important attribute which depends directly on the state of CESS.

C. COORDINATING DEVICES

With the development of advanced topologies, power electronic devices can convert any form of electrical energy into a desirable form. Due to the fast response time, they can respond to the instantaneous disturbances and power quality issues within a very short time lapse. For instance, DC-DC converter is recommended to interface the Solar PV to the DC bus bar. Another example would be where the bidirectional inverter is required to couple AC and DC bus bars. Generally, inverters and converters are promising configurations for controllable power transfers.

D. MICRO GRIDS LOADS

Load levels can be classified under several basics. In general, it can be categorized as residential, commercial and industrial loads. Industrial users are bulk users who require high levels of power with a high-power quality for their specialized equipment. Residential and commercial loads are particularly sensible to the voltage and frequency variations due to the low inertia. Another form of load categorization is critical and non-critical, which is important particularly in load shedding because non-sensitive loads can be used as controllable loads.

III. OVERVIEW OF THE CONTROL ASPECTS OF MICROGRID

The development of a supervisory control scheme for power management of a hybrid Microgrid, becomes much more challenging when economic and renewable aspects must be considered. Therefore, this issue has attracted the attention of many researchers in the recent years and most of them have come up with a predefined function set to the controller, which neglects the uncertainties of the power flow of renewable energy sources.

Central controller-based control scheme is managed by the Microgrid Operation while the Control Center (MGOCC) is managed by coordination of an agent for each source, inverter and converter [12]. Such control schemes adopt autonomous control, Multi-agent systems, and hierarchical control which are described in 3.1, 3.2 and 3.3 respectively. As this review is constructed on the Fuzzy Logic based control techniques, section 3.4 depicts the basics of the Fuzzy Logic Controller (FLC).

A. AUTONOMOUS CONTROL

Performance of conventional control schemes is not superior under indeterminate scenarios hence intelligence is integrated in to controller to perform control actions without any external intervention [13]. Adaptation to the changes in the plant and the environment is one of some desirable characteristics of an intelligent controller. As Micro-source controllers show such features in unintentional islanding and control; an autonomous type of control is preferred over conventional methods [14], [15].

B. MULTI-AGENT SYSTEM (MAS)

If there is a population with different sets of people and organizations with different goals and proprietary information, then we need to have a system which can handle such different interactions, in order to meet the diverse requirements., Such a system with agents possessing different intentions as well as a cordial effect due to the correlation between the

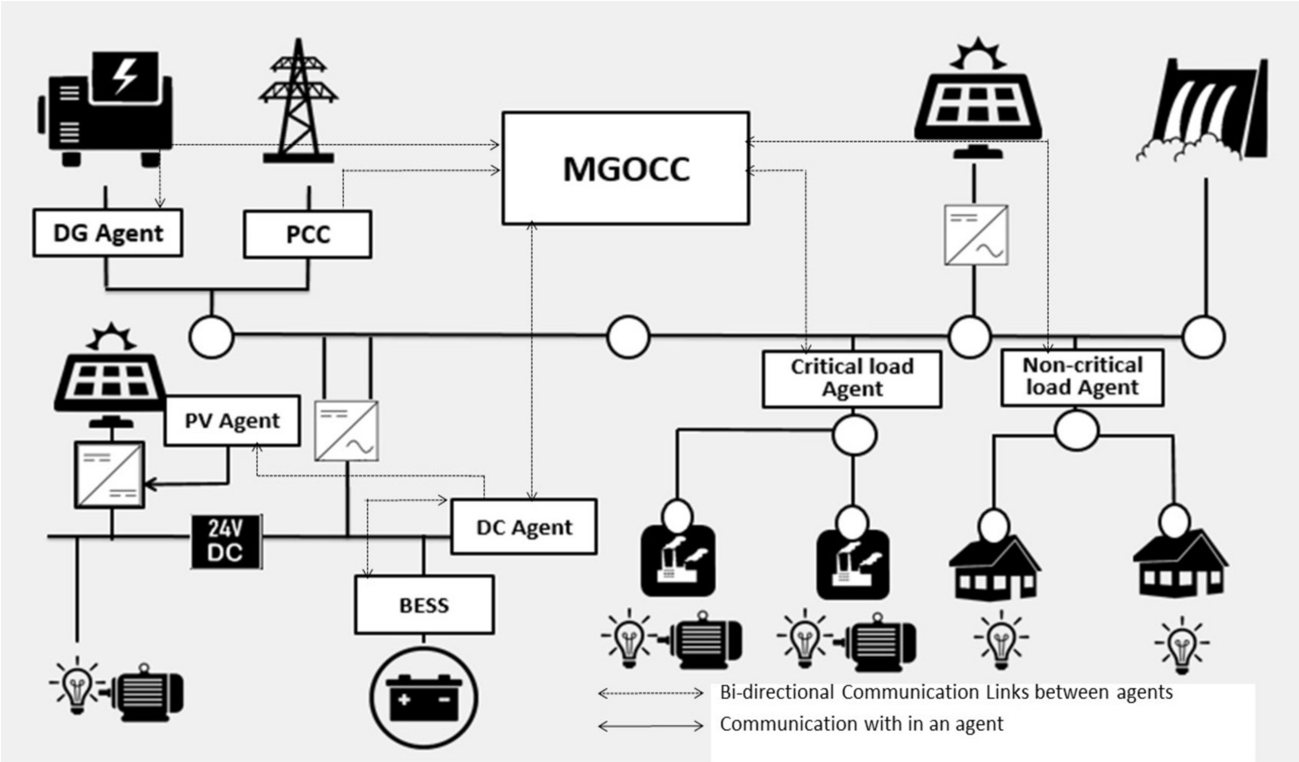


FIGURE 1. Common configuration for MG.

agents is known as a Multi Agent System (MAS). None of the agents have the authority to represent others since each has a single task of their own and has to collaborate with the others for an effective output. Possible advantages of such system would be speedy operation due to the parallel processing and proficiency in relevant area of operation [16]–[18]. Another advantage is the ability to make comprehensive and reliable decisions since there is no need of a centralized controller.

C. HIERARCHICAL CONTROL SCHEME

Figure 2 shows the hierarchical control scheme for the Microgrid operation which comprises of Central Autonomous Management Controller (CAMC) and Central Controller (MGOCC) and a number of other agents categorized into Micro-source agents, load agents and coordinators. Under the power demand request made by CAMC, MGOCC works as a coordinator in the multi-agent environment and the next hierarchical control level is supported by the embedded local controllers who are mainly parallel inverters and source agents consisted of MCS. System state estimation, overall system monitoring, security evaluation and active and reactive power balancing are the main duties of MGOCC.

Apart from the main operations here, Microgrid consists of enhanced intelligence and other advanced functions such as: load forecasting; optimization in economic operation and stability assessment. Local controllers in the MCs take the secondary control steps based on the primary higher level of rules obtained from the MGOCC [19], [20].

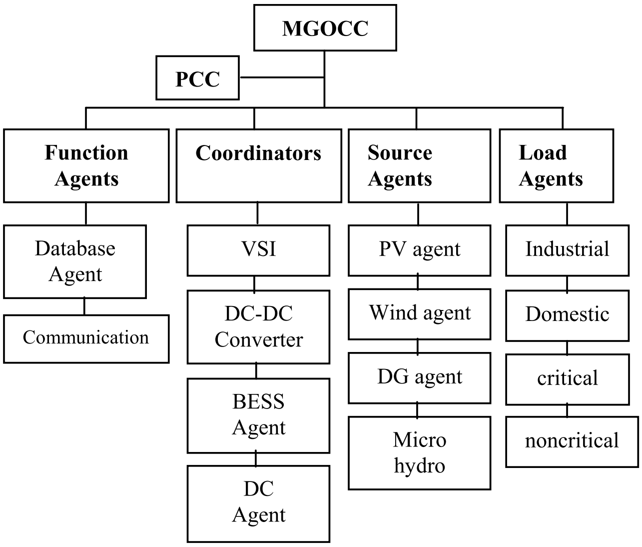


FIGURE 2. Agent based environment for Microgrid.

D. FUZZY LOGIC BASED CONTROLLER

As conventional on-off controller is based on the binary inputs and output, this may cause transition from one state to another state with hard boundaries between transition states which is not suitable to represent the real-world applications. Therefore, it is more convenient to use a control type which has a decision-making algorithm closer to human nature.

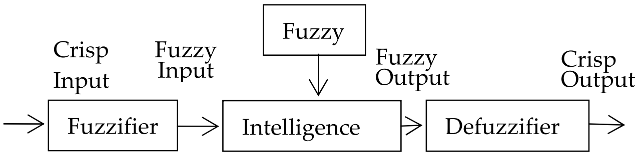


FIGURE 3. Basic structure of the fuzzy system.

In such scenario, FLC brings quantitative expression between zero and one for the particular parameter. Mathematical expression used here is simplified to the rule based if- then statements so that simplicity is brought to the model with more complex input output scenarios [21].

MacVicar-Whelan [22] constructed the linguistic control protocol for first FLC algorithm. Since, design requires expertise and experience knowledge application would be limited of this type of FLC though they were successful compared to classical controllers [23]. The general structure of Fuzzy consists of three steps named as fuzzification, fuzzy inference process and defuzzification as shown in Figure 3.

In the first step, the degree of crisp inputs is based on each fuzzy set is decided. These fuzzified inputs are then fed to the inference engine in order to evaluate the fuzzy rules stored in the fuzzy rule base. Set of membership functions are used for this transform based on the suitability of the application [24], [25]. Inference engine based on the fuzzy rules, generates the Fuzzy output values. Defuzzifier transforms the fuzzy set obtained by the inference engine into a crisp value. Defuzzifier achieves output signals based on the output fuzzy sets obtained. Furthermore, FLC performed exceptional character in evolving conventional PI, PID controllers by providing certain advancements in adaptive nature [26], [27].

IV. DC BUS BAR

With the introduction of the DC loads and DC sources into the system, DC bus bar is formed where it needs a control topology in DC voltage restoration [28], [29]. Battery Energy Storage system (BESS), which is playing the key role in balancing power, needs to maintain required capacity which is denoted by its State of Charge (SOC) level. Therefore, the additional requirement should be included to control the battery SOC level and to maintain it in a proclaimed range for safe operation [30]–[32].

A. BATTERY SOC LEVEL MANAGEMENT

Due to large time constants of some Micro-sources, a storage device is the most suitable integration in power grids to balance the supply and demand, particularly when disturbances are created. Moreover, this includes an economical aspect by discharging the battery in peak hours where the cost of energy purchased from the upper grid can be high. Maintaining the correct Depth of Discharge (DOD) improves the lifetime of the battery. A large amount of research work had been carried out over last several years to evaluate the benefits of integrating energy storage systems into power system [33], [34]. To meet the aforementioned objectives, Battery Management System (BMS) which is accompanied with enhanced controlling criteria has been introduced to monitor the available capacity of the battery which is termed as Battery's SOC. This is usually expressed as a percentage of capacity of the battery.

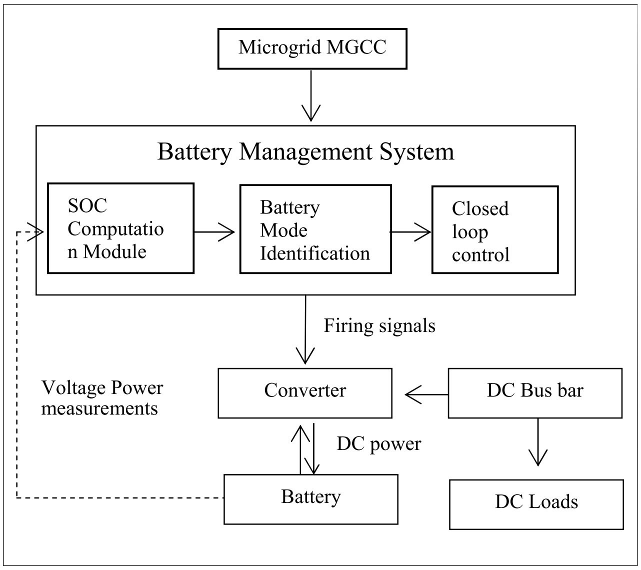


FIGURE 4. Battery management system for Microgrid.

Hierarchical Control System for BESS control is introduced for this, by Miao *et al.* [35] which comprises of three modules, named: SOC Computation Module, Battery Mode Identification System (BMIS) and Closed Loop Feedback Controller, as given in Figure 4. As the name implies, SOC Computational Module works as an SOC level disclaimer from the available battery data. BMIS works as a central system which determines the appropriate state of operation based on SOC and the islanding status of Microgrid. According to the control output given by the BMIS, secondary controller performs the control action in two separate control systems, namely: Power Control Loop and the Voltage-Frequency Control Loop.

Same state transition architecture is proposed in [34] considering five states with three main components in control namely: PV converter, battery converter and fuel cell converter. Additionally, the load variation of the MG is used to vary the role of the PV and battery summarized in Table 1.

Deciding on the charging or discharging rate of the BMS is challenging. Hence, Yoo *et al.* [36] decided the charging or discharging state according to the state transition diagram shown in Figure 5, with the aid of the inputs as load level, EDR (Energy Demand Request) signal and the SOC level of the battery. Then Fuzzy Logic is integrated in-to the charging current controller with a Sugeno type fuzzy inference system, in order to determine the charging/discharging rate precisely. To mitigate the power peaks and unnecessary fluctuations of above system, similar Fuzzy Logic

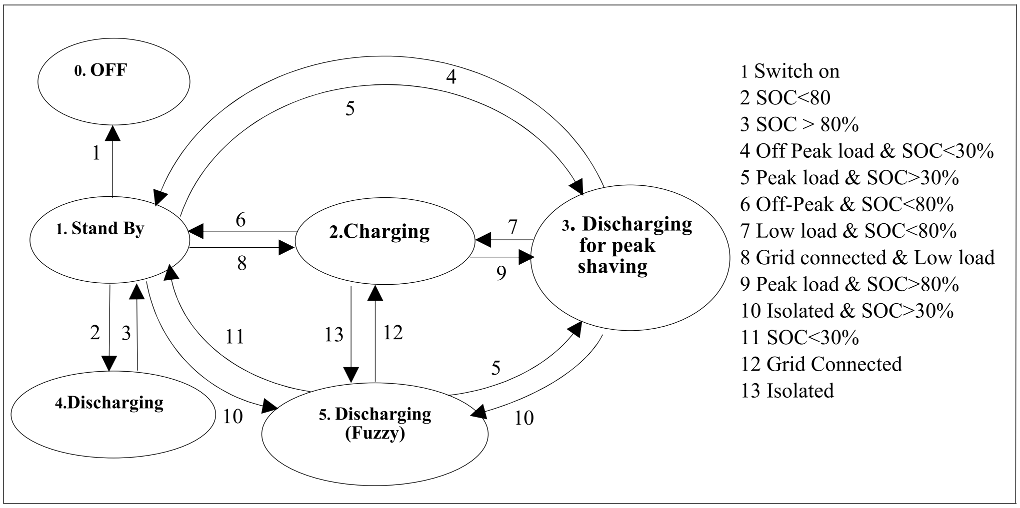


FIGURE 5. Agent based environment for Microgrid.

TABLE 1. PV and Battery action according to the load variation.

Load Condition	PV	Battery
Light	DC bus voltage control	Fixed current charging state
Moderate		Charging, Voltage control
Higher than PV output		Discharging

implementation has been done in [37] for the residential grid connected Microgrid which takes more dynamic parameters as inputs.

Stepping forward from here, ESS is used to play a role in maintaining the frequency in the grid by balancing generation and consumption [38]. Here the coordinated control between ESS and other controllable Micro-sources are proposed which is set up under centralized MGCC and other local controllers. As the control is limited by the available battery capacity, secondary control should be initiated to bring back the power output to zero. Since frequency and voltage variation is still highly considerable even in the presence of battery, Fuzzy Logic has been used for such control scheme in [38] to facilitate the rule-based control system.

Primary BESS is supported by a supercapacitor or secondary battery to preserve the SOC of the battery further in [39]. This inspired researchers to set up a droop control between several parallelly connected BESS units to the DC grid [41]. In [43], study proposed a rule-based control method for BESS to be integrated with renewables where mathematical modelling is not required Basic control architecture is shown in Figure 6. Since, in this type of rule-based models, mode switching boundaries are more rigid, Reddy and Reddy [44] set up the FLC to smoothen the rule base operation of Wind Solar integrated system. Badwawi *et al.* [45] further proceed from here by applying a dual Fuzzy controller with a gain scheduler as a secondary controller. This approach is so comprehensive in terms of accuracy however the time taken for settling is too long. Researchers integrated the MAS architecture into the BESS control scheme so as to provide a much powerful control scheme in [46]. Then this was further optimized by the Fuzzy integration to the MAS system for BESS control in [47]. Disadvantages of conventional PI controllers have made researchers to focus on adaptive control methods. As PI controllers only deal with the error, the rate of change of error cannot be included in the algorithm, which is a major drawback. This can be overcome by using Fuzzy Logic Controllers that use the error and the rate of change of error as inputs [48].

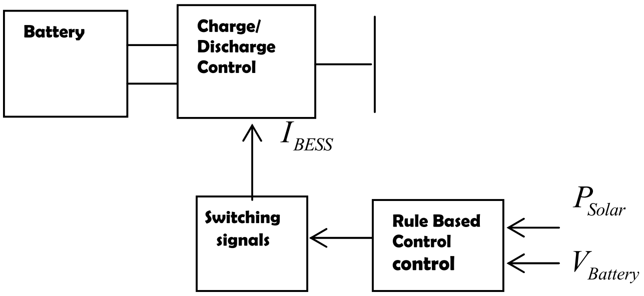
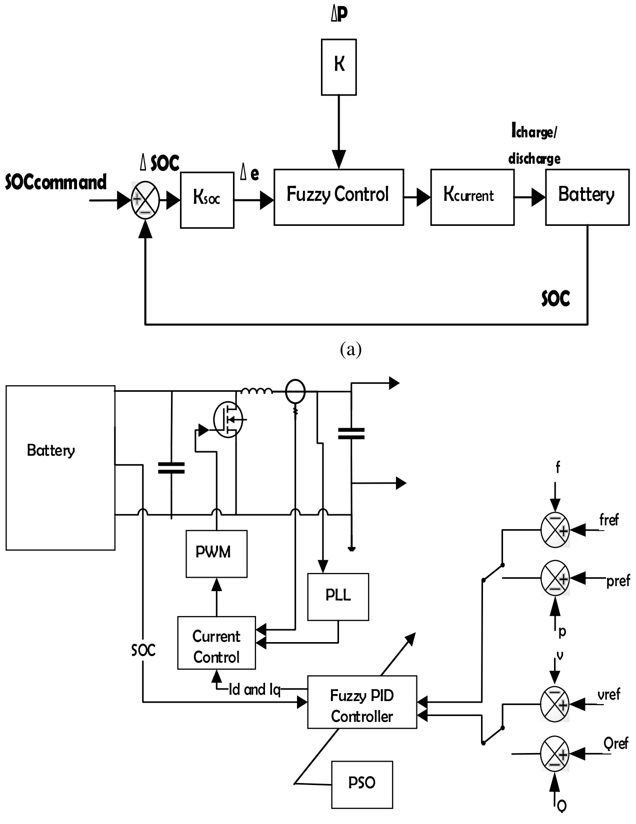


FIGURE 6. Fuzzy Logic implementation for battery charging current control.

7.a) depicts the simple fuzzy integrated control of PID for SOC control for a DC MG. Prasad and Dawood [48] depict the FLC and conventional PID controller which are tuned by the Particle Swarm Optimization (PSO) algorithm so as to enhance the power quality of the AC MG in islanded operation. Fig 7.b) depicts the control architecture of the interface of Battery and AC bus bar.



(a)

(b)

FIGURE 7. a) Fuzzy implemented control algorithm for SOC. b) Optimization of Fuzzy PID with the PSO.

In [50], comprehensive architecture is proposed compared to the aforementioned methods, as six inputs namely; the status of the battery, time of the day, state of charge of the storage system, electricity price, wind power generation and load demand are used as inputs of the FLC. The output of FLC is the power output of the battery. The actual time is represented by the linguistic variables morning, midday and night. Hence, it has the learning capability to update fuzzy rules and membership functions.

B. DC BUS BAR VOLTAGE CONTROL

DC voltage, which is the basic controllable attribute of the DC bus bar, should be kept within predetermined limits by the remedial control actions provided by the controllers. Here, several controllers are considered, namely: DC/DC converters at the interface of DC bus bar, the DGs and the Voltage Source Inverter (VSI) at the DC bus bar and AC bus bar interface. Meanwhile, battery SOC level limiter also keeps the DC voltage within the nominal range by its control actions. The voltage variation problem and the voltage drop problem make a coordinated voltage control system necessary for the DC bus bar [38]–[40].

The other important aspect is the impedance of the DC distribution line which is a more important parameter compared to AC distribution as the voltage drop is considerable. Voltage compensation is required in response to the bus voltage deterioration, which can be compensated by the introduction of the controllable DG and the energy storage device. In [51] battery converter decides the charging or discharging mode, based on the power imbalance. The system operating state DC voltage is maintained by either the battery or boost converter. Hossain *et al.* [52] and Liang *et al.* [53] proposed to use DC voltage droop control system by controlling the AC/DC converter, which was an alternative to a high frequency communication line to transmit the signal. This vastly improves the system redundancy and reliability. As simple droop controlling does not give the required level of voltage control; advanced steps for DC MG has been proposed using a cooperative voltage control scheme with a distributed generator (DG) and a grid connected converter (GCC) in [54]. There, a novel control method using gain scheduling and fuzzy control is proposed in order to fulfill voltage control through DC/DC converter. Simulation results show that the DC voltage regulation and stored energy balancing control are achieved simultaneously.

Since the controller design is simple with mathematical modelling and a rule-based system is more appropriate for such a case; a combination of Fuzzy Logic and the gain scheduled techniques is used in [55]. Similar type of work is presented in [56], with hardware implementation of the gain scheduled and fuzzy control techniques. Discrepancy in load resistance and solar irradiance variation as well as variations in converter's parameters have made researchers introduce a high-performance local linear controller (LLC) for the DC voltage control in the Microgrid [57].

In [58], the main focus is to depict that a Fuzzy Logic controller can stabilize a DC MG within a given tolerance range, in a manner comparable to that of a PI controller. In [59], voltage balancing is done by a Fuzzy PID controller, where the constants of the conventional PID control are further tuned by Fuzzy Logic. Here, two inputs are considered, namely: DC grid voltage error and Integral of DC grid voltage error whereas the outputs are the three constants for the PID. Results prove that FL-PID is superior and better for voltage control of the DC MG studied. In [60], study is targeted to come up with Fuzzy Logic based DC-DC converter for voltage stabilizing. Least voltage variation proves that this successfully compensates the effect of the non-uniform irradiance on the PV panel.

In [61], a study had been done on the improvement of the Maximum Power Point Track (MPPT) algorithms by the Fuzzy Logic in order to deliver constant voltage in bus bar and harness maximum power from the PV panel. Hence, Fuzzy based system can be used for solar power optimizer where it shows a considerable efficiency improvement compared to the conventional control methods.

C. COLLECTIVE LOOK AT THE DC BUS BAR CONTROL

This review section describes the Fuzzy Logic interference to the DC bus bar control scheme, mainly on how the battery discharging technologies and DC voltage controlling were

TABLE 2. Summary of the DC bus bar control using Fuzzy logic.

Authors	Fuzzy technique	Application	Drawbacks and limitations
[36] Cheol-HeeYoo, Yop Chung, Hak-Ju Lee Sung-Soo Hong	Fuzzy Sugeno type	For battery charging and discharging considering the SOC level and renewable input	Fuzzy Logic adaptation is limited to the peak shaving scenario
[39] Haoran Zhaha O, Qiuwei WU, Chengshan Wang et all	Fuzzy Logic based coordinated control	To determine the power output reference ($P_{ref,\ bess}$) of the BESS	Coordinated control scheme is not considered.
[44] A.Srikanth Reddy T. Srikanth Reddy	Fuzzy control with error and derivative of error	DC voltage control and SOC level maintenance	Scheduling based approach is used hence adaptability is limited
[47] Jérémy Lagorse, Marcelo G. Simões	Combination of Fuzzy Logic and crisp logic	Battery Fuzzy agent	Maximum power harnessing is not considered hence RES optimizing is not achieved
[49] Jong-Yul Kim Hak-Man Kim Seul-Ki Kim Jin-Hong Jeon Heung-Kwan Choi	Fuzzy PID controller tuned with PSO algorithm	For the secondary control of the active power control	DC side stability is not considered for the hybrid Microgrid
[50] Juan P. Fossati, Ainhoa Galarza, Ander Martín-Villate, José M. Echeverría, Luis Fontán	Fuzzy control with 6 inputs. Genetic algorithm for membership function tuning	Allocating the power of the storage system	Transition stability between isolated and grid connected mode is not considered
[59] Chauhan, R.K.	Fuzzy system with 2 inputs	Fuzzy PID controller for voltage control	Settling time is considerable in FL-PID
[60]Karime Farhood Hussein	Fuzzy PID control	For the DC/DC converter in DC bus	Load perturbations were not considered
[61] Ananya Guha, T.R. Narasimhe Gowda, Sridhar N.H., Shilpa R.M.	Fuzzy system with PID control	For the MPPT system and voltage control	Transient stability of the controller is not tested.

evolved over the years. In many applications, power imbalance and the SOC level were used as inputs. Battery charging current was considered as the output, while other constraints for battery charging limits and power limits of DGs were included. After the quick response was set up, the rest was done by the MGCC with collaboration of DG controller units to supply the excessive power, in order to protect the battery source power and to utilize it to the ultimate level. This brought battery power back to zero. Furthermore, this method of control improved dealing with several storage systems to enhance redundancy. Further coordination technologies were used to deal with the portion of power sharing by each ESS. Moreover, then the battery discharging takes the aspect of time domain discharge considering the economic value of the power units. Hence in peak hours, discharging is preferred and on the contrary, during off peak hours, day time battery charging is preferred where solar input is considerable. Decision making was further improved by the Fuzzy PID systems and in some cases; optimization was done with the PSO algorithm to support the adaptability of the fuzzy rules.

DC voltage controlling actions are basically performed over the DC-DC converters of DGs and the converters at the battery energy systems. The required coordinated control scheme is powered by the Fuzzy Logic PID controllers, as the controlling algorithm is much more challenging due to several reasons, such as: the MPPT algorithms of PV, constraints of BESS, load variation of DC bus loads, voltage drop in the DC bus bar, availability of the main grid and power flow from or to the AC bus bar through the bi-directional inverter. Even though some concerns were considered in research topics separately, voltage control and BESS control were not integrated considering all of the above constraints making it more problematic to apply for the hybrid MG. Hence further improvement is required with several parallel Fuzzy

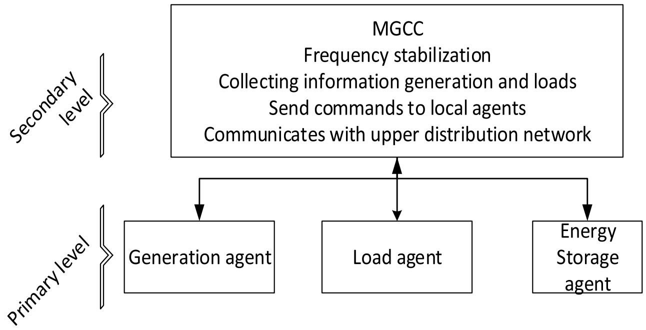


FIGURE 8. **LFC hierarchy in microgrid.**

Logic controllers mastered under a central controller, which comprises of the overall states of the Microgrid operation. Table 2 summarizes the applications of the Fuzzy Logic in DC bus bar control.

V. AC BUS BAR CONTROL

Though Microgrids are interconnected with the utility grid; scheduled isolation can take place where it would require the ability to operate firmly and maintain autonomous control over frequency and voltage in each operating state.

A. LOAD FREQUENCY CONTROL

Control of active power and frequency in power system is usually referred to as Load Frequency Control (LFC). Maintaining precise balance between generation and demand in a small and isolated system is a significant issue, as generation might be limited or intermittent. If one of the generating units fail, emergency conditions will arise, where load shedding is required. Hence it is crucial to have a robust LFC mechanism implemented to ensure a stable system operation under all conditions. In this literature review, study has been done in the several LFC strategies for Microgrid concepts, which have been very interesting and contemporary research topics in the world. As shown in the Figure 8, MGCC holds the key functions in hierarchical control scheme of LFC [65].

MGOCC coordinates the hierarchical control scheme for LFC by providing the secondary control which exploits different inverter control modes, which is similar to the Automatic Generation Control. Meanwhile, in the primary level, each Micro-source generator and storage device are locally controlled, which is performed in two ways [66].

1. Local PI controller: - This method is used when the MG is interconnected. Centralized control is disabled here.
2. Centralized automatic way mastered by the MGOCC: - In the isolation, LFC coordination is done by the central control by giving necessary set point to the local controllers.

MGOCC specifies active power set-points based on the frequency error and partition factor details. These control signals are sent back to the MCs in order to adjust the production levels and consequently correct the frequency offset. Additionally, some economical viable controlling methods are possible with the economic set points provided by the MGOCC with the collaboration of micro generators. Once it is identified for MG islanded operation, VSI can react to that by providing primary voltage and frequency regulation in the Microgrid. Two main control scenarios are possible here, namely: Single Master Operation (SMO) where one master VSI is working as a controller while others operated in PQ mode and the Multi Master Operation (MMO), where several inverters operating as VSI with predefined frequency and voltage characteristics [69]. Another approach of LFC is proposed with an inverter and BESS. Oudalov *et al.* [70] presented a decentralized LFC mechanism to control a BESS and DGs incorporated in an isolated MG system to regulate the system's frequency. By controlling the DC/AC inverter attached to a BESS, LFC is performed where inverter control system tracks the system's frequency error signal and controls the active power injected or absorbed by the BESS. The frequency error signal is the input of the inverter control system, and the output is the d-axis current signal. This system extensively explained in 4.1. Figure 9 depicts the Schematic diagrams for control which are presented in [71]. In [32], real power sharing is facilitated in multiple inverters with BESS by using the droop controllers against the variable load and DG.

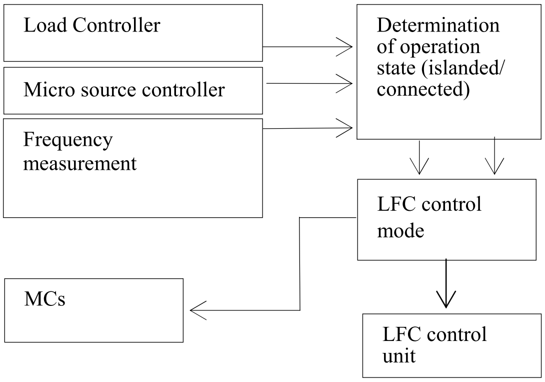


FIGURE 9. **Load Frequency control in MGCC.**

Droop controlling is the widely-used method in frequency controlling with parallel inverters, which has both advantages as well as drawbacks.

- Every inverter here contributes to frequency adjustment. Loads are shared according the droops inherited, which is an advantage.
- Due to proportionality between load variation and frequency variation, frequency variation is high when load changes significantly, which is an inherent drawback.

To mitigate the aforementioned drawback, frequency error is integrated which can stabilize the system frequency at rated value [72]. But here, the integral of frequency change has a slow processing speed, which is a disadvantage. Authors consider coming up with a new equation and method called the ''improved frequency error integral regulation'', to combine the pros of the above two methods. In [73], communication

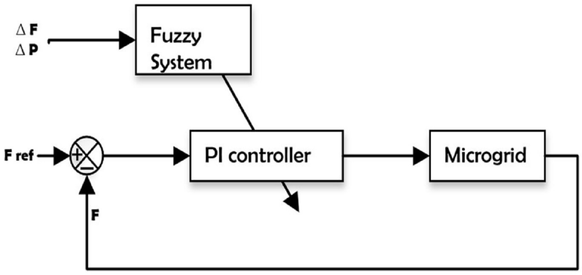


FIGURE 10. Control block for Fuzzy PI controller for LFC.

network of the MGCC implies constraints like time delays that can degrade the overall system performance and responsiveness. Load shedding is a mechanism that can be used to control frequency in case of an emergency. In [74], a novel approach to multi agent control in load shedding is presented. Novel computing techniques such as: Fuzzy Logic, Neural network-based techniques,Genetic Algorithm

Partial Swarm based techniques are increasingly used due to the satisfactory performance over conventional control methods like PID [75]. During the control, fuzzy system shows enhanced performance, bringing adaptive proper proportional and integral gains of a PI controller according to the area-control error and its change. A Fuzzy system for such an LFC is shown in Figure 10 [76].

Two FPI controllers and a Mamdani-type self-organizing controller are implemented in [77] to enhance the operational capability to handle the frequency fluctuation in hybrid Microgrid power system. Fuzzy Logic is introduced to the conventional frequency error feedback control system by the researchers so as to provide a much smoother, sophisticated and faster control strategy [78].

The LFC method is reviewed using different types of technologies for its constants, in the PID controller. Fuzzy Logic, Ziegler-Nichols and PSO algorithms are compared in the study and it was found that Fuzzy Logic shows the better response in the LFC [79]. Self-tuning nature was integrated into the conventional PID Fuzzy Logic approach, which is considered as primary AI based technique. Fuzzy Logic provides adaptive thinking which is closer to the human intuition [80]. Some drawbacks may be created in those systems as adaptability is not accepted for dynamic time varying systems. Therefore, a new intelligent control is proposed based on polar fuzzy sets in [83] where Genetic Algorithm (GA), Artificial Neural Network (ANN) and PSO are used in optimization cases.

B. COLLECTIVE SUMMARY OF FREQUENCY CONTROL

In this paper, several common frequency control techniques of a Microgrid are reviewed, before the extensive work through Fuzzy Logic is addressed. Basically, all technologies can be categorized into two main groups, based on their basic way of control.

1. Droop controlled BESS
2. Mater-Slave operation of BESS units

Droop control is where sharing the load is possible in proportion to their capacities, according to the set point derived out of droops. Though no communication is required, and expandability is supported through this, slow transient response and possibility of circulation current would result in developing novel approaches like decoupling droop control method [84]. Opposite droop control method proposes control for mainly resistive coupling impedance, which establishes a dependency of active power to local voltage [85]. By supplying a current generated by the voltage difference across virtual impedance, a new droop controlling method is developed to enhance the short circuit behavior of control [86].Secondly, Master-slave control techniques are promoted where one voltage-controlled inverter working as a master unit generates the required current commands for slaves and current controlled inverters as slave units [89]. Single point of failure tempted researchers to enhance redundancy by selecting a random master using a rotating priority window or by using extended micro-computers to work as a master or by multi-master operation techniques. Master replaced by a central control block, gives certain advances but, still the drawbacks are considerable, due to the requirement of high bandwidth communication link. Current and power sharing control techniques like circular chain control (3C) strategies are proposed. Each and every technology is greatly affected by the Fuzzy systems introduced. Response time is further reduced, and the adaptability of the rules is enhanced in all aspects. Hence recent research results showed adaptation mechanism to the prevailing techniques, rather than novel control aspect, as the control theories over the field looks lot saturated. Due to the application of Fuzzy Logic in LFC control being comparatively slow, some researchers prefer the fast response direct control over the low adaptability, where actual current from each unit and average current are considered to perform load sharing, through lower bandwidth communication link. Research papers discussed are summarized in Table 3.

C. AC VOLTAGE CONTROLLING

As per the aforementioned reasoning in 0, proper controlling action is required to compensate the voltage fluctuations when the MG is isolated from the main grid. Here, AC voltage controlling is separately considered. But it is vital to mention that this may not be the actual case as there's an effect of Q on F and effect of P on V which can't be neglected in a system where line impedances are considerable. Voltage control scheme as same as the previous control strategies, can be divided to three levels forming a hierarchical control [90]. This control scheme ensures the requirements, such as: keeping the bus voltage within specified limits, controlling the taps of transformer, minimizing the active power loss and controlling the power factor. CAMC, which is in the top of the hierarchical control, is responsible for the reactive power flow from the grid. Two types of inverter-based voltage controlling methods are described in [72].

TABLE 3. Summary of Fuzzy Control techniques in Frequency control.

Authors/Reference	Fuzzy technique	Drawbacks/Limitations
[77] Xiangjun Li, Yu-Jin Song, Soo-Bin Han	Fuzzy PID controller	Frequency variation is limited to the real power variation
[79] Nour EL Yakine Kouba, Mohamed Menaa, Mourad Hasni and Mohamed Boudour	Fuzzy PID controller ZN method and PSO	Renewables are not separately considered
[80] Saleh Ahmadi , Shoresh Shokoohi , Hassan Bevrani	Fuzzy PID controller	Dependency to the line parameters
[81]JavadFattahi, Henry Schriemer, Ben Bacque, Ray Orr, Karin Hinzer,Joan E. Haysom	Two parallel adaptive Fuzzy Logic controllers for droop control	Considered MG is too simple and too much away from real MG
[82]MohammadRezaKhalghani, Mohammad Hassan Khooban, Esmaeil Mahboubi-Moghaddam, Navid Vafamand, Mohammad Goodarzi	Fuzzy PID controller	Only frequency error and power error are considered as inputs
[99] K Mahesh Dash, Makhes Kumar Behera Vamsi Krishna Angajala	Fuzzy control for frequency error integral method	Only frequency error and power error are considered as inputs

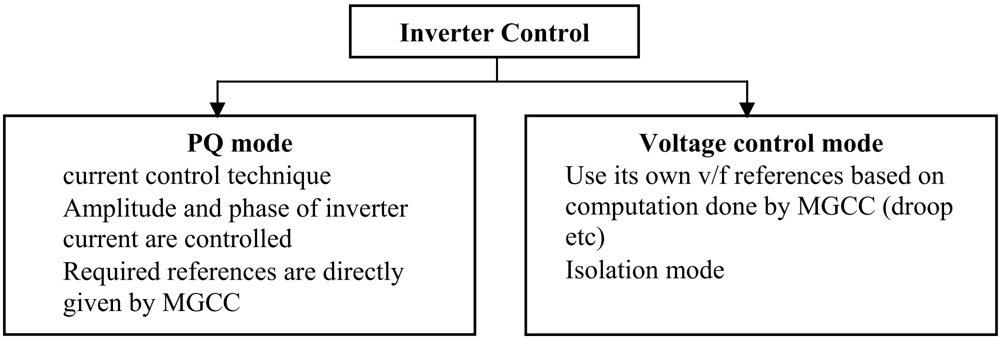


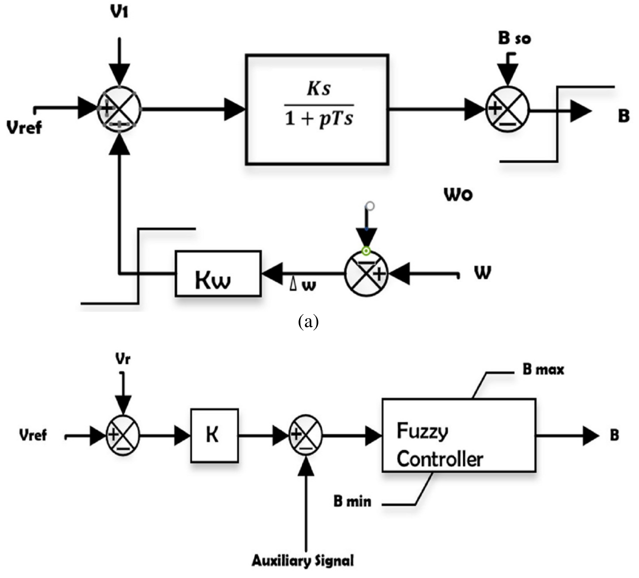
FIGURE 11. Control topologies for voltage control in Microgrid.

A novel coordinated voltage control method is proposed in [91], where the diesel generator, governor, excitation, inverter-based distributed energy sources and controllable voltage sources with DC link are meant to be working together for this purpose. If the voltage regulation is not satisfactory enough right after operation of capacitor banks, the inverter-based control comes to play by dropping the power factor and by providing the required reactive power compensation. Another coordinated control strategy is proposed with typical PI controllers for voltage controlling in [92], hence control action is not optimized.

Advances in power electronic devices brought the development of flexible AC transmission system (FACTS) devices, which have very fast responses to the instantaneous changes in the power system. Static Var Compensators (SVC), thyristor-controlled series capacitors (TCSC) and unified power flow controllers (UPFC) are important devices in creating an effective voltage and current profile [93]. SVCs are widely preferred over other reactive power compensators, due to quick response to the fast dynamics.

To control the switching operation of the SVC or FACTS controlled devices, improved techniques are being used these days where Fuzzy Logic implementation in power system stabilizer is quite commonly proposed as in [94]. Conventional VAR stabilizing control scheme is presented in Figure 12.a).

In [95] Fuzzy Logic is directly applied to the VAR stabilizer using SVC, where the primary application is to maintain the bus bar voltage in a predefined range. This works in both steady state stability and dynamic stability. Control scheme for the Fuzzy logic aided VAR stabilizer is presented in Figure12 b).



(a)

(b)

FIGURE 12. a). Control diagram for SVC control. b). Improved SVC control with Fuzzy.

Some extensive research has been done with an adaptive fuzzy controller and PI controller in [96]. It would be more suitable to develop two parallel controllers as instantaneous reactive power compensator and fuzzy controller which is equipped with the adaptation algorithm. Here Fuzzy Model Reference Learning Control algorithm performs as the learning mechanism which is always updating with the dynamic load change and the MG parameters. Another Fuzzy Logic based mechanism is proposed in [97]. Authors claimed that the quick response and fast compensation are achieved by fuzzy PID applied to closed loop to ensure the good dynamics and steady characteristics. Here the fuzzy algorithm based on the basic rule set such that if the large error exists controlling action to be targeted to diminish the error. In contrast to this if the error is relatively small then the overshoot and steady state problems are considered.

In [98], the research objective is to show the effectiveness of the Sugeno and Mamdani type fuzzy controllers for thyristor firing controls, with the aid of the proposed two input one-output FLC for SVC. Idea of fuzzy PID controller for the purpose of SVC control is discussed in [102]. Here, the constants of the conventional PID controllers are inherited with the adaptive nature of the Fuzzy Logic to develop a much comprehensive control technique adhered with learning capability.

In [103], the controller generates the appropriate firing signals to the Thyristor Controller Rectifier (TCR). In this proposed scheme, only real power flow is considered. Here, SVC fuzzy damping controller is developed by using the technique of adaptive gain factor adjustment. Hence, it is suggested that the Fuzzy PI system is a realistic solution for the damping problem.

In [104], another FACTS device called TCSC which consists of a parallel constant capacitor and thyristor-controlled reactor is controlled by its Kc gain and the time constant Tc. In [105], FLC is implemented to switch relevant number of TSCs to maintain the voltage as required. The Genetic Algorithm (GA) is also used in order to find out the optimal firing angle of SVC. Systems adaptability is highly challenging, and the compensation is degraded in the presence of the utility grid, though the optimization capability is enhanced by the inherited GA into the FLC [106]. Figure 13 depicts such control scheme for the GA aided FIS in voltage controlling.

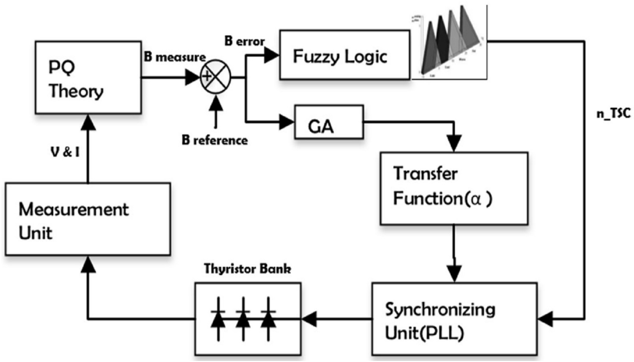


FIGURE 13. Control algorithm for Genetic Algorithm integrated Fuzzy control.

In [107] and [108] neuro fuzzy architecture is proposed for voltage control. The proposed method shows better performance in both the steady-state and transient operation. Without optimization, its performance for new operating conditions and various faults is comprehensive due to its intelligent and adaptive structure.

D. COLLECTIVE SUMMARY OF VOLTAGE CONTROL

Hierarchical control scheme is still applied to the voltage control scheme of the Microgrid due to its better organization. Voltage control methodologies are identical to the frequency controlling techniques as the droop control is common for both. Over the years, the conventional droop controlling techniques have evolved and undergone a number of optimizations with the rule-based techniques [54], [71]. Meanwhile FACTS devices like SVCs are widely used in applications for voltage compensation, as these are highly controllable, adaptive and responsive to the fluctuations in the power system. In order to combine the advantages of the above two methods, SVC is controlled by a conventional controller like PI controllers. With the advancement of fuzzy technologies, these PI controllers were further improvised to gain better commands to the SVC control. Further, these techniques were tuned by the Generic Algorithm and PSO Algorithm for fine tuning in order to form integrated responsive control architecture. Table 4 summarizes the papers discussed in this section.

VI. QUANTITATIVE ANALYSIS FOR POWERFULNESS OF FUZZY CONTROLLERS

Effectiveness of using Fuzzy logic controllers can be well manifested by analyses involved with different types

TABLE 4. Summary of Fuzzy Controlled techniques in AC voltage controlling.

Authors	Fuzzy technique	Application	Drawbacks and limitations
[96] Ahmed S. Eldessouky, Hossam A. Gabbar	Adaptive Fuzzy Control	SVC controlled by a learning Fuzzy mechanism	Fast compensation is not ensured due to the additional learning algorithm
[97] Juanjuan Wang, Chuang Fu, Yao Zhang	Fuzzy PID	Control number of TSC connected	Fuzzy output is a discrete
[99] P.K. Dash, S. Mishra, A.C. Liew	Fuzzy PI controller	SVC control	Accurate mathematical model of the whole system is required prior to application
[94] Takashi Hiyama	Fuzzy Logic	A Fuzzy Logic switching for a TCR type SVC with variable gain (Fuzzy Logic power system stabilizer)	Suitability for a complex MG is not recommended
[101]S.Khanmohammadi M.TarafdarHagh, M. Abapour	TSK and Mumdani type Fuzzy Logic controllers	Fuzzy controlled SVC	Platform with multiple source is not considered
[102] K.L. Lo M.O. Sadegh	Fuzzy PID	SVC based control	Considered set up is too simple. Perturbations were not considered.
[103] D. Z. Fang Yang Xiaodong T. S. Chung	Adaptive Fuzzy Logic	SVC fuzzy damping controller	Fuzzy is used to generate the auxiliary signal in the control system
[104] Ghazanfar Shahgholian, Mojtaba Maghsoodi1, Mehdi Mahdavian,	Fuzzy PI controller	For the controlling of TCSC	Controller suits limited scenarios and applications
[105]J.E. Calderon, H.R. Chamorro	Fuzzy Logic and Generic algorithm	Firing angle of TSC is controlled	Redundancy of the system is dropped due to the GA implementation
[107]RabiahBadar, Laiq Khan	Neuro Fuzzy Architecture	SSSC controlled with fuzzy	Two machines' test system is used

of controllers. It is well understood that, though the complexity of the controller is increased, performance of the different types of Microgrid is well optimized showing the pragmatic solutions. Results shown in previous research work with quantitative indexes emphasize the extensive modelling using FLC in comparison to the conventional controllers. Those controllers are implemented in both DC and AC systems where this chapter attempts to summarize the DC applications first and AC applications lately.

Arcos-Aviless *et al.* [109] have studied the design of an economical operation method for a EMS for grid connected Microgrid with fuzzy based. Authors anticipate the reduction of peak power by 67% power variation range (PVR) and maximum power derivative (MPD). Proposed Fuzzy based system supposes reduction of 95% and 78% in (APD) and Power Quality (PQ) indices respectively in comparison to the conventional SMA strategy. Garcı'a *et al.* [110] attempted the employing of FLC to a ESS consists of FC, battery and electrolyzer. This MES minimizes the utilization cost of HESS and shows that a 13% cost saving is expected with respect to the conventional EMS. Chaouachi *et al.* [111] have explored a multi-objective intelligent energy management (MIEM) scheme under low cost and low emissions with the use of optimal battery scheduling using FLC. The proposed MIEM based method outperforms the conventional methods showing cost serving of 5.76 % and lower emissions of 6.1 %. Al Badwawi *et al.* [112] highlighted the powerful employment of Fuzzy approach in DC microgrid with high PV penetration using several scenarios. Two FLC are implemented for the charging and discharging case separately where rules of the FLC are defined such that effective load shedding is minimized. It is well shown that the load shedding can be dropped by an effective percentage of 29% with the use of FLC. Kakigano *et al.* [55] have adopted the FLC for DC voltage balancing and storage SOC balancing of a DC microgrid. Proposed controller with gain scheduling achieves a 5% band of voltage variation for the DC bus bar with 340V which is not achievable through conventional control.

Studies targeting the AC microgrid show the performance indices related to voltage variation and frequency variation. Controlling the active and reactive power flow using FLC with VSC has been the research objective in Díaz *et al.* [113] which clearly depicts the smooth control over the active and reactive power flow maintaining the lowest overshoot and settling time compared to the PI controllers. It shows that a 0.26% overshoot can be achieved compared to the 9.6% overshoot by PI controllers in active power. Furthermore, 0.19% overshoot is presented in reactive power in comparison to the 4.83% of PI. Baydokhty *et al.* [114] have compared the several fuzzy inference techniques in a Load frequency controller problem handled by the PID controllers. Novel Fuzzy engine which was adopted Cuckoo Optimization Algorithm, proposed by the authors outperforms the conventional controller by clear margin in all performance indexes of tie line power flow controller. ISE is reduced from 0.7 to 0.1 due to the novel control proposed and RMS is reduced from 0.2202 to 0.0026 when the FLC is optimized.

Peak to peak oscillations of frequencies are approximately halved and oscillations of ΔP_tie are reduced by 30% with the use of optimization of FLC. Sahu *et al.* [115] have expanded the same type of analysis for LFC with a FLC with PI controller undershoot, overshoot and settling time of Δf1 is improved by 66.29%, 72.92% and 62.00% respectively, in Δf2 is improved by 86.4%, 72.56% and 64.55% respectively.

Zhang and Liu [116] have estimated the performance indexes of PSO and FAPSO using IEEE 118 and IEEE 30 bus system. Voltage deviation is dropped by 67% using FAPSO and power loss is dropped from 1. 22p.u to 1.15pu as depicted in the simulation. Direct Adaptive Fuzzy logic control has been used by Yousef *et al.* [117] to study the effective Load frequency control of multi area Microgrids with the aid of certain performance indexes like integra of time-weighted absolute error (ITAE). Superior performance in comparison to PID controllers has been exhibited by the proposed scheme by a wide margin since ITAE is reduced by almost 50% in all considered cases. Fuzzy-PI-based voltage controller has been adopted by An *et al.* [118] ensuring 48.3 % reduction of voltage variation while Ahmadi *et al.* [80] have attempted the LFC and voltage control simultaneously with a FLC which accomplished superior performance to the hybrid microgrid with conventional controllers.

This quantitative analysis perceives that the FLC are well ahead with all the measured performance indexes of the MG controllers in compared to the conventional PID controllers. Moreover, it is far clearer that the optimized FLC perform so better in all of these indexes bringing the permissible variations further lower in compared to conventional FLC.

VII. CONCLUSIONS

This paper discusses, currently available Fuzzy Logic architectures for the purpose of Microgrid control, in the aspects of BESS control DC bus bar voltage control, AC bus bar frequency control and AC bus bar voltage control; extensively; with the comparison of previously available primary control technologies. In the review, it is mentioned that the Fuzzy Logic control models are more advanced and provide better optimization compared to the conventional methods used.

In BESS control, single BMS optimization was done using Fuzzy based AI systems. Though there is a considerable potential, there is only a little research done on clustering BESS operation. Validation to a real MG operation was found only in a very few cases, even though a number of research work has been done within Fuzzy Logic integration to the BMS. Novel architectures like V2G technologies and BESS integration through Fuzzy Logic; require some attention of the researchers.

DC voltage control and control targets are not fully achieved due to the lack of adaptivity and integrity of the whole DC system, with all renewables sources such as: PV, Wind and Energy Storage Systems integrated. DC voltage stability analysis is required prior to the introduction of Fuzzy Integrated System, for such complex system. The rigidity provided by the multi-scenario operation should be eliminated by smooth transition from one state to the other.

In AC Bus bar control, frequency and voltage control techniques are sufficiently optimized due to the Neuro-Fuzzy based powerful learning algorithms, though only little work has been done in the voltage control of Multi Microgrid Operation.

In conclusion, it is important to mention that the future work should be focused on improving adaptability of the Fuzzy systems to the DC bus bar control, with the aid of a powerful learning algorithm and Multi Microgrid Operation in order to form an intelligent clustered Microgrid operation.

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