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A REVIEW OF CONTROL TECHNIQUES IN AC/DC AND HYBRID MICROGRID

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Abstract- Application of renewable energy sources for electric power generation have seen an upward surge in recent years; solar, wind and hydro based power plants lead the pack of renewable energy sources. This has led to renewed research and interest in the application of microgrids. In general, microgrids provide more advantages when compared to microgrids (traditional electric grid), some of these merits are enhanced efficiency, better suited for renewable energy sources which are clean energy at low cost. Microgrids support economic growth, provide electric power for hard-to-reach areas, eliminate or reduce transmission losses. Economically, it's more efficient to site power generating units close to the consumer. As microgrids continue to evolve, its smooth control has become an issue. The focus of this paper is a review of the control techniques in microgrids i.e., DC microgrid, AC microgrid and hybrid microgrid. This review uncovers and assembles the advantages, disadvantages and implementation challenges of existing control techniques. Thus, selection of an appropriate control technique for implementation can best be done by comparative analysis of these existing techniques focusing on system response to faults, smooth integration of various distributed generation, communication between components, system protection, and whether they are suitable for smart grid or not.

Keywords: AC Microgrid, Control Techniques, DC Microgrid, Distributed Generation, Hybrid Microgrid, Renewable Energy.

1. INTRODUCTION

The demand for energy in the past few years has increased exponentially, this can be attributed to population explosion, digitization and industrialization of most economies and improved living standards. Consequently, most conventional power systems are bedeviled with the following drawbacks; increased and stretched generation period, overage systems thus less efficient systems and huge transmission losses. Also, majority of these power systems rely on fossil fuel for power generation [1]. Currently, most electric power systems are composed of complex structures i.e., generation stations, transmission lines and distribution systems.

This increases the cost of power system installation, electric power generation, reduce efficiency and also pollutes the environments because of the use of fossil fuel. To address the above problems associated with traditional electric power systems, smaller and more efficient power systems popularly known as distributed generation systems (DGs) have been developed. Distributed generation systems (DGs) are commonly associated with microgrids and mostly use renewable energy sources (RES). Grid integration of RES such as PV, wind, hydro etc. together with DGs happen at the distribution level of the power system [2]. Investments into DG construction tend to be higher when compared to conventional power systems. This is due to the economy-of-scale of the conventional systems. Nonetheless, DG utility prices are less expensive compared national grid power prices. Developed countries have instituted hourly price rate for electric power. Electric power rates are high during peak hours and less during low peak hours. Therefore, electric power can be purchased and stored in batteries during low peak hours. The stored power is used during peak hours. The cycle is repeated to achieve sustainable power at reduced rates [3].

Although the penetration of DGs in power systems has not seen significant increase especially in Africa and other third world countries, they will soon phase out traditional electric power system because of the numerus benefits they present [4]. Distributed generation system utilizes RES such as PV system, micro turbines, wind generators and mini hydro stations to produce electric power. They also rely on standby generators that use fossil fuel.

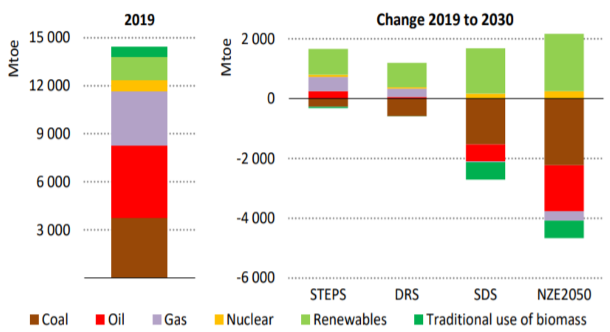

Figure 1. Energy demand and projections from 2019 to 2030 [5]

Power electric converters are required to appropriately condition the generated power for onward transfer to microgrids or national grids. Therefore, power electronic converters are essential devices required for smooth implementation of microgrids [6-7]. Based on the type of voltage at the input and output sections, power electronic converters are categorized into four groups; rectifier (AC-DC conditioning), inverter (DC-AC conditioning) chopper (DC-DC conditioning) and cycloconverters (AC-AC conditioning). These power electronic converters are used in controlling the voltage, frequency and power of microgrids in grid-tied mode and islanded mode. In the grid-tied mode, the reactive and active powers are controlled whiles the frequency and voltage are controlled in the islanded mode [8].

RES have become important commodity in the generation of electric power and will soon phase out fossil fuel-based system for electric power generation. Most European countries have set 2030 as the deadline to ban sale of vehicles with combustion engines. Various reports from reputable bodies such as international energy agency (IEA) have shown upward trajectory in the magnitudes of electric power generated from RES. Figure 1 shows a graph of energy (fuel sources) demands for the 2019 and projections from 2019 to 2030. From the graph, it's evident that fossil fuels were the major sources of fuel for the year 2019 to 2022, however, by the end of the year 2030, renewable energy sources will overtake fossil fuel sources as the main source of fuel for electric power generation [5].

2. MICROGRID

The concept of microgrids is rapidly becoming an integral part of new power systems because of the increasing use of renewable energy sources and the heightened need to limit the use of fossil fuel. Also, the successful implementation of DGs has immensely contributed to the rapid deployment of microgrids. Microgrid system was introduced by CERTS (consortium for electric reliability technology solutions) to improve efficiency, sustainability and reliability of modern power systems [9-12].

A microgrid is a small-scale electric power system usually composed a few hundreds of kilometers of transmission lines, generation units, storage systems, control units and loads. The generation units are mostly DGs. Microgrids enable decentralization of power systems, they can be coupled or decoupled from power grids with ease. They therefore boast of the following merits; better power quality, minimized power losses, better system reliability, application of RES and less system cost. Micrgrids can either be a complete DC microgrid, an AC microgrid or a hybrid (AC-DC) microgrid. Hybrid microgrids provide the advantages of both DC and AC microgrids. Hybrid microgrid is a propitious power system of the future.

2.1. AC Microgrid Structure

Figure 2 shows the structure of a typical AC microgrid. As depicted, the structure is composed of generation units such windfarms or wind-turbines, battery systems, PV systems, fuel cells and mini hydro-dams, power electronic converters, bus voltage and the grid point of common coupling (PCC). Usually, Conventional transformers or power electronic transformers (PET) are used to couple the microgrid to the grid at the PCC. Based on the type of generation unit, various architectures have been proposed by researchers. A hybrid generation unit consisting of wind-turbines and PV systems for residential use was proposed by the authors [13-14]. To improve the output power of the presented hybrid wind-PV system, the authors in [14] make use of MPPT (maximum PowerPoint tracking) in the PV system and an induction generator in the wind system. The authors in [15] improved the generation capability of their presented PV system by including a double axis tracking and MPPT.

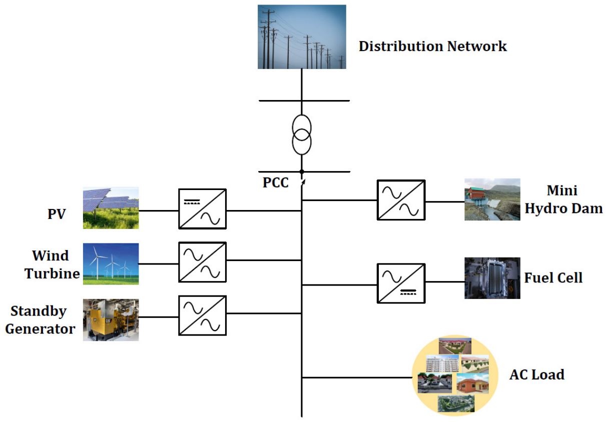

Figure 2. Typical AC microgrid structure

2.2. DC Microgrid Structure

As shown in Figure 3, a DC microgrid can provide power for DC and AC loads. It also coupled to the grid via switch. Power electronic converters (bidirectional) are used to provide voltage conditioning for onward transmission between the grid and microgrid. Renewable energy sources are essential generation sources for DC microgrids. The control of DC microgrid is designed for grid-tied and islanded modes. In the grid-tied mode, the bidirectional converter controls the voltage whereas the energy storage devices control the voltage in islanded mode.

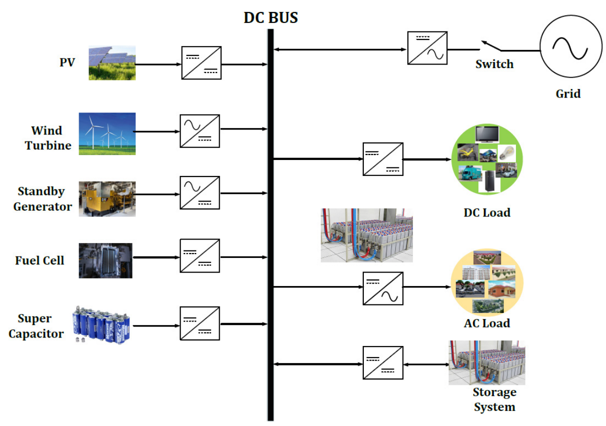

Figure 3. Typical DC microgrid structure

Supercapacitors and battery are the commonly used energy storage devices. Supercapacitors have high power density; therefore, their controllers are designed to cushion rapid fluctuations [16-17]. Also, the controller of the battery is designed to indemnify low-frequency power mismatch because the energy density of the battery is high [18]. DC microgrids are gradually receiving the needed attention. However, power management and bus voltage control are complex due to the varied generation sources and common bus voltage for DC loads. There are three conventional control techniques in DC microgrid. These techniques are distributed, centralized, and decentralized [19-21].

2.3. Hybrid Microgrid Structure

The basic topology of a hybrid microgrid is shown in Figure 4, the main components are generation units (DGs), power electronic converters, DC bus and AC bus. The generation sources of hybrid microgrid is a collection of distributed generations (DGs) such as PV and wind installations, fuel cells, battery ESS etc. and traditional centralized power generation sources. DGs are the widely preferred generation units in DC microgrids. The benefits of microgrids over conventional grids are enormous. Therefore, microgrids are capable of replacing conventional generation sources at the distribution level of power systems or they can be coupled together [22]. Conventionally, microgrid response to load disturbances is poor; this pushes the rate of load slew to be restricted so as to sustain the grid stability. On the other hand, microgrids are able to reduce load disturbances, increase power stability and quality by the use of power electronic circuits [23-24]. Due to the importance of microgrids, several studies have been conducted around the world to overcome challenges of power quality, stability and efficiency. Projects such as CERTS in the USA, the microgrid project in Senegal, Kythnos microgrid in Greece and several other projects in Japan [25].

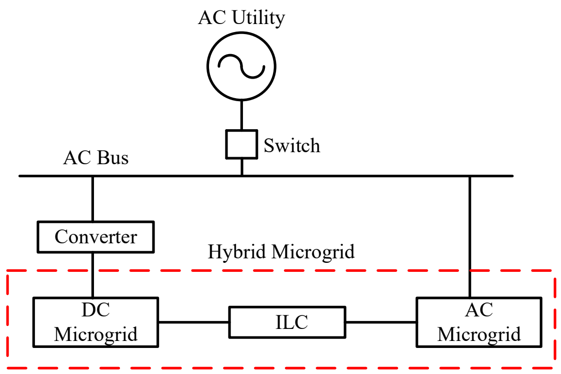

Figure 4. Hybrid microgrid structure

Hybrid microgrid are operated in two modes; grid-tied or islanded modes. A transient transition period occurs during the change in operational mode from either grid-tied to island mode or from island mode to grid-tied mode. During this transition period, voltage deviations and unbalanced current harmonics are of critical concern because they cause power quality related problems.

Also, absolute synchronization of phase and voltage between grid-tied and island mode is essential when switching from island mode to grid-tied [26]. Comprehensive literature research into control methods of DC, AC or hybrid microgrid has shown a wide variety of control techniques. PI regulators was used by [27] for microgrid control. Also [28] used a process known as Optimization-based fuzzy controller incorporated with battery and fly wheel to for microgrid control.

Battery regulation technologies i.e., charging and discharge, storage etc. are presented by [29-30] and the control of islanded power system using frequency regulation by [31]. Procedures and guidelines are given by [32-33] for optimal battery sizing and efficient battery usage to avoid power fluctuations. The authors in [34] analyzed the financial burden of using batteries as storage units. The above battery control techniques (but not limited to them) can be applied to DC, AC or hybrid microgrid provided energy storage systems such as batteries are utilized. The focus of this research is primarily on the control of DC-AC and hybrid microgrids but more emphasizes are placed on the control of Hybrid microgrids since it encompasses DC and AC microgrids. Voltage and frequency (V&F) are the two most easily controlled parameters in a microgrid. Thus, a number of V&F control techniques have been developed. These techniques are applicable to hybrid microgrid subsystems. In the hybrid microgrid structure, the DC and AC grids are connected by a system of inverters called ILC (interlinking converters). The control strategies for ILC can be based on different methodologies such as communication, droop-based control mechanism [35]. A comprehensive review of tolerant control fault diagnosis of DC-DC converters used in DC microgrids is presented by [36].

Figure 5 shows the structure of a microgrid with emphasis on power electronic converters and distributed generations. This microgrid is made up of three voltage generation sources which are all distributed generations (DG1, DG2 and DG3). The main grid and microgrid are tied together at the PCC (point of common coupling). The static transfer switch (STC), functions as a switch which is able to couple or decouple the microgrid from the main grid usually within half of a cycle or a period. An injection transformer is used to stabilize the microgrid power either sourced from the main grid or utility or from the distributed generations. Each DG has ESS and an inverter which inverts DC voltage to AC voltage. To have improved, reliable and efficient power supply system, combined heat and power (CHP) unit is incorporated into the power supply. Operation of the microgrid can be done in two modes; grid-tied mode or self-sustaining mode which is commonly called islanded mode.

In the grid-tied mode, the utility or main grid provides part of the power together with the DGs. Power is taken from the utility when the power of ESS is completely depleted of energy and during unfavorable weather conditions which makes RES not to operate accordingly. CHP plants such as micro-turbine provides power and heat to a close-by load.

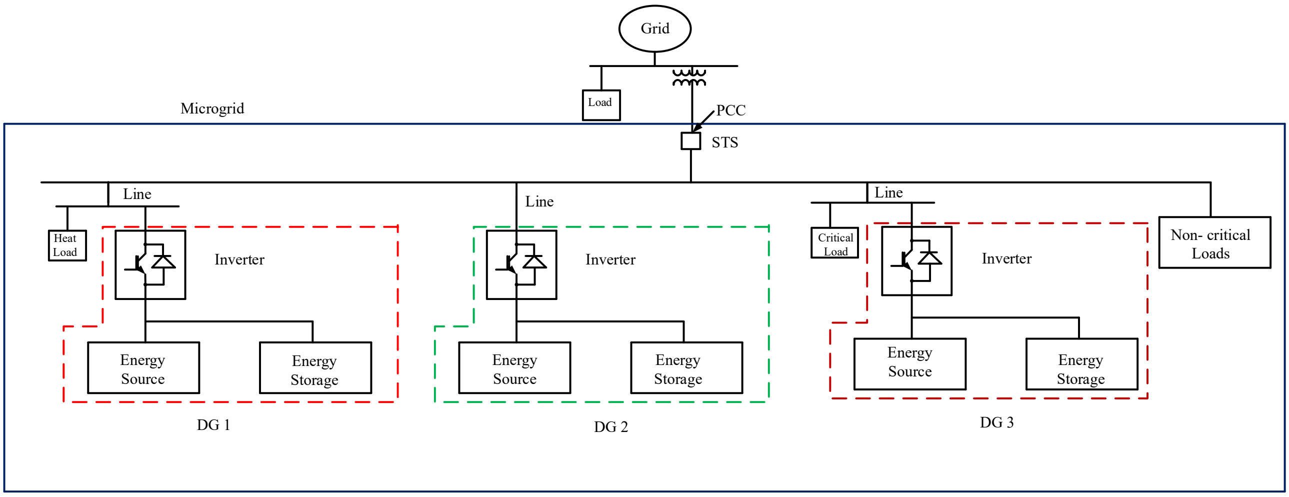

Figure 5. Microgrid structure with multiple DGs

On the self-sustaining mode, all the power required is produced by the DGs and CHP. Due power demand and quality issues, careful calculations are done before installing DGs such that they are able produce the required power at peak loads. When demand exceeds supply, non-critical loads are decoupled or standby gents are powered. Issues of phase angle of voltages and frequencies have to be critical looked at before synchronizing the microgrid and main grid [24].

Distributed generations are done on small scale, sited close to the consumer so as to provide the electric power requirements of the consumer. Sitting DGs closer to consumers eliminates or reduces transmission losses. The common components of DGs are photovoltaic power plants, wind farms, energy storage systems, fuel cells and mini-hydro dams. These DG sources when put together constitute a microgrid. Application of RES has tremendous benefits to environment; carbon emissions are reduced which causes the rate of depletion of the ozone layer to be minimized. Combining DGs and RES in power generation/microgrid introduces issues of power quality [37]. Figure 4 and Figure 6 shows two structures of hybrid microgrid. Figure 6 shows a hybrid microgrid where power is produced from RES and DGs. Also, tying the microgrid to utility or main grid is beneficial for both systems i.e., the microgrid and utility since power can be transmitted both ways. This relationship can be described as mutualism. In this disposition, the MHP energy and photovoltaic generated power are used efficiently. Thus, the utility becomes backup power as in the case of UPS. In cases where the microgrid cannot provide enough energy to meet the demands of the load, extra power is taken from the grid and when the DGs of the microgrid produces more power than the load needs, the utility absorbs the excess power [38].

The hydro and photovoltaic systems are connected to a general direct current bus; this is will reduce the cost of the system, makes it more efficient and thus eliminating complex system structures. The hybrid microgrid functions as the main power system and the utility acts as a generator to provide power in situations of power shortage in the hybrid system.

There are several factors which can account for power deficit in the hybrid microgrid; introduction of new loads, weather conditions in the case of renewable energy sources, system faults as in the case of PV system, though power production will be high in summer, system failures/breakdowns will also occur due to high temperatures which is a drawback for semiconductor materials [24].

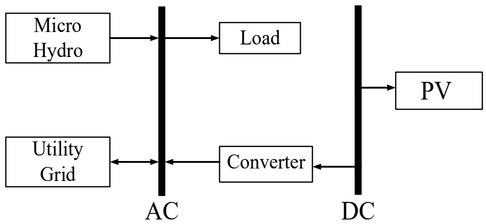

Figure 6. Hybrid microgrid

3. MICROGRID OPERATING MODES

3.1. Grid-Tied Mode

In the grid-tied mode, the converter should be able to easily switch from AC to DC (rectification) and from DC to AC (inversion), this process also helps in providing or controlling the reactive power. The DC-DC converter maintains the maximum power of the grid. Excess power produced in the microgrid is fed into the main grid. Also with good ESS, excess power can be stored; this methodology is an added cost and not really required since the grid functions as generating set and a storage unit concurrently. Energy storage system will be more useful in islanded mode; ESS will balance the power and provide a stable voltage (voltage stability) [37].

A small ESS will be more useful in the DC sub-grid of the hybrid system to support DC loads and also reduce losses produced by switching.

3.2. Islanded Mode

In the islanded or self-sustaining mode, the hybrid microgrid is not tied to main grid or utility. ESS thus becomes an indispensable part of the system by providing voltage stability and maintaining balanced power in the microgrid. Depending on the load requirements, Buck-boost converter is used to vary the DC voltage; to increase or reduce the supply to loads. High quality and stable AC voltage is provided by controlling the main converter with high quality filters [38].

The nature of hybrid microgrids is a complex one; it involves DC power systems and also AC power systems. The control of DC microgrid is relatively easy when compared to AC microgrids. In DC microgrids, there is no need to provide power control because there is no sudden change in power, phase control is not needed because synchronization does not occur in DC power sources, and frequency control is also not an issue. There are fewer power losses in DC microgrids since only one stage conversion is done. Therefore, the efficiency of DC microgrids is relatively high juxtaposed to AC microgrids. All the above advantages are feasible with RES produced DC power making it relatively easy to tie to DC microgrids [5, 39-40]. Most control methodologies developed are as a result of the use of AC or hybrid microgrids. The next stage of our research is to review the various control strategies employed in DC, AC or hybrid microgrids. The control of microgrids is done either at the HV or LV levels, at a switchyard or substation.

4. MICROGRID CONTROL TECHNIQUES

4.1. Frequency And Voltage Droop Method

A very common method known as 'plug and play' is used to control each DG independently; in this method, the terminal voltage of each DG is controlled by using droop control method which includes the combination of the following techniques:

I. Real power vs. frequency (P-ω) and

II. Reactive power vs. voltage (Q-E)

In this method, the reactive and real power flow in a phase connecting nodes (two) isolated by line impedance. Figure 7 shows the droop control method of real power sharing of microgrids. The two voltage values are denoted E_1 and E_2 and the phase angle of E_1 and E_2 is represented by δ. The line resistance R is ignored for pure inductive line impedance. The line impedance Z, real power P and reactive power Q are computed by Equation (1) to Equation (3) [6] as:

$$Z = R + jX \tag{1}$$

$$P = \frac{E_1}{R^2 + X^2}\left[R\left(E_1 - E_2\cos\delta\right) + E_2\sin\delta\right] \tag{2}$$

$$Q = \frac{E_1}{R^2 + X^2}\left[-RE_2\sin\delta + X\left(E_1 - E_2\cos\delta\right)\right] \tag{3}$$

4.2. Reactive Power Control Algorithm with Improved Accuracy

The reactive power control algorithm with improved accuracy was introduced to solve the challenges associated with reactive power control methods. The reactive power control methodology is not precise because of the voltage drop which occurs on line impedances. To solve this problem, we ignore voltage drop across the line and understate the effect of the Q-E droop method [41].

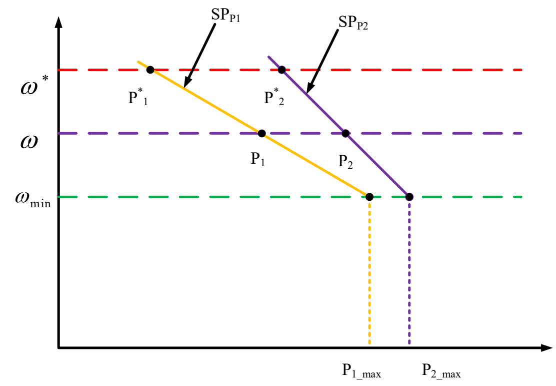

Figure 7. Droop control method of real power sharing

4.3. MG Islanded Control Operation

There are two main scenarios which cause islanded operation of MG; when there's fault in the microgrid and planned maintenance of MG or utility. In this, DG power production and load consumption are made parallel to solve load imbalances in the system. Decoupling MG from utility is done fast to protect loads and this cause microgrid dynamics. In the absence of synchronous machines to stabilize supply and demand via frequency control techniques, switching inverters are used to control the frequency. The preferred inverter topology is the VSI; voltage source inverter. But this technique only works at the terminals; two other preferred methods which are quick to react to system disturbances are;

a) Single Master Operation: In this method, the voltage source inverter functions as a master and a source to the power supply.

b) Multi-Master Operation: The number voltage source inverters are many and they have an already assigned active power/frequency and reactive power/voltage characteristics.

4.4. Hierarchical Control of Droop Controlled Microgrids

The hierarchical control of droop-controlled hybrid AC-DC microgrid is developed by a step-by-step control strategy. It utilizes the top to bottom control method. This idea was borne from ANSI/ISA-95 which is also known as ISA-95. This is a certified international standard control between enterprise and control systems. ISA-95 has six step multilevel control. The same idea has been established to control microgrids. Here, four levels of control strategy have been designed starting from zero

- Tertiary control (level 3): this is the power/energy production level, and control of energy flow via MG to consumer is done at this level.
- Secondary control (level 2): power quality issues are controlled at this stage. Voltage sag and swell as well other power related problems are controlled or solved.
- Primary control (level 1): this where the actually droop control method is applied. Stability over damped system control is done here.
- Inner control loop (level 0): individual module regulation issues are meshed together at this level. Voltage and current, feed forward and feedback as well as nonlinear

and linear control is done to adjust voltage output value and tune current values although maintaining a stable system. This control strategy can be done in solely AC microgrids, DC microgrids or a hybrid system [4].

4.5. Conventional and Fuzzy-PI Based Frequency Control

Conventional power system control secondary frequency by the use of proportional integral controllers (PI). The PI operates in a region which is already determined; once the boundary of operation is overcome, the PI becomes obsolete unless it's reprogrammed. [28] uses a popular PI tuning technique called Ziegler-Nichol. Detailed research on PI or PID tuning technique such as Ziegler-Nicholas is presented in [42]. An experimental result is shown by [28] in Table 1 using Ziegler-Nicholas PI tuning technique.

Table 1. Ziegler-Nichols based PI control Magnitude [42]

Controller Parameter	Magnitude
K_p	4.095
K_i	21.84

4.6. Hybrid MG Control Under Islanding Mode

A new method of controlling hybrid microgrid was proposed by [43], firstly, the control of the AC microgrid part is done separately, after, the DC microgrid part is controlled. Finally, the hybrid control is done. For the DC control method, two schemes of operation are looked at; central and distributed schemes. In the central control technique, central point of control, monitors the whole system and issues commands when necessary, monitoring of various generation sources and distribution system is done via communicating devices; this adds extra cost and reduces performance. These disadvantages make the distributed scheme the preferred choice. DC bus signaling (DBS) is the preferred choice of distributed techniques in this paper. In DBS scheme, the bus voltage is considered as the universal index to determine the converter operating levels.

4.7. Microgrid Control without ESS

The control strategy proposed by [44] is a combination of two factors; power generation control and load control for frequency tuning. The rate of frequency deviation is compared to generation and load frequencies, the variation is determined and the necessary control technique is applied. Artificial neural network (ANN) technique is applied. The ANN is trained with two target values (voltages), one for maximum power point tracking and the other for 90% power output. With the application of neural network, the system is able predict, detect and offer solutions to help control the frequency of the system.

5. CONCLUSION

Distributed generation and microgrid systems are rapidly being roped into in the design of new power systems. Also, traditional power systems are being modified to include DGs and microgrids. These developments can be attributed the numerous advantages of using distributed generation and microgrid in power systems. However, there are some challenges in the control of microgrids. These challenges are mostly experienced by AC and hybrid microgrids. These challenges are broadly categorized into power generation challenges, mostly caused by unstable renewable energy sources, grid-tied control challenges caused by voltage and frequency synchronization between grid and microgrid, islanded control challenges mostly faced in AC microgrid, voltage conversion challenges caused by converter control and load challenges caused by different load characteristics. This article reviewed these control techniques challenges in AC, DC and hybrid microgrids. DC microgrids are less susceptible to control challenges. Therefore, more emphasis was placed on the review of control techniques in AC and hybrid microgrids. Also, the control of microgrids during grid-tied and islanded modes were reviewed. Some of these control techniques are conventional droop control method, hierarchical control technique where control is done using the top to bottom approach, frequency control where the use of converters or an inverter enables the application of switching techniques to control the frequency and subsequently provide grid power control.

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