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Research paper

Review of Active Synchronization for Renewable Powered Microgrid

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Abstract

Microgrid can operate in dual mode; grid-connected and islanded mode. In order to seamless transfer from islanded microgrid to grid connected mode, it is necessary to voltage, frequency and phase of microgrid to synchronize with main grid to prevent severe consequence. However, microgrid has to be controlled in a coordinated way to achieve a synchronization. This paper present a review on the existing active synchronization approach with their control strategies. There are three approach for grid-connected synchronization; active synchronization, passive synchronization and open transition transfer. However, only active synchronization approach provides the reliable reconnection for microgrid. Active synchronization approach associates with control structures and control strategies. There are three control structures of microgrid under active synchronization; centralized, decentralized and distributed and three control strategies available in the literature which are phase locked loop (PLL), droop control, and frequency locked loop (FLL). The most applicable control strategy for active synchronization is phase locked loop because of its simplicity, robustness, and effectiveness in various main grid condition. Furthermore, between three control structures of active synchronization, decentralized control is becoming more favorable by the researches based on its advantages over the other structures.

Keywords: *Active synchronization; Microgrid; Passive synchronization; Reconnection; Synchronization*

1. Introduction

Microgrid (MG) becomes a trend nowadays, which is driven by various smart-grid initiatives to enhance reliability and resilience of the power grid. An MG can be defined as low-voltage distribution systems that comprise of energy storage devices, loads and distributed generations (DG) such as solar, wind power, biomass, small hydro, and geothermal. There are a lot of advantages of MGs. The most important advantage is that MG can be connected and disconnected from the main grid to enable the MG to operate in dual mode; grid connected and islanded mode [1]. In addition, MG provides an efficient, low-cost, and clean energy. During contingencies, MG can be used as a backup system for the main grid at the same time, MG can enhance the local resilience as well as improve the stability of the regional main grid. The benefits of MG were well recognized after the super storm Hurricane Sandy in 2012 that destroyed the electricity supply across a few highly populated areas in the North America. Hurricane Sandy left approximately 7.5 million customers without power across 15 states and Washington, DC, after it hit the eastern shore of the U.S.[2][3]. In response with the vulnerable of power system under extreme weather, MG concept becomes a critical features in power system resilience concept [4].

Typically, MG is interconnected to the main grid via the point of common coupling (PCC). When the main supply is disrupted, MG becomes an autonomous entity operating in islanded mode [5]. In grid-connected mode, MG exchanges power with the main grid while following the frequency and voltage set by the main grid. In case of emergency, an MG is disconnected from the main grid and starts to work autonomously which balancing its own generation and load in a similar way to the physical island [6]. Islanding an MG is an effective measure to prevent power outage and maximize the usage of renewable energy sources (RES) [1].

Despite of its advantage, islanding operation is not reliable because the generation is limited and if the load changes rapidly, the generation might go into outage which leads to blackout of the entire island. To certain extend, an MG islanding operation has a potential to damage equipment and compromise power system security [7]. Therefore, MG must be reconnected to main grid after islanding operation as soon as possible to preserve the reliability of power supply to customer. In order to guarantee uninterruptible and reliable power supply in MG, a seamless transition between two modes is required [8] [9].

When reconnecting an MG operating in the islanded mode to the main grid, voltage, frequency and phase criteria must be satisfied according to IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems (1547.4-2011) [10]. There are three possible methods of MG synchronization; (i) active synchronization, (ii) passive synchronization, and (iii) open transition transfer. Details discussions regarding the MG synchronization are given in Section III.

The main objective of this paper is to review the existing MG synchronization approaches in terms of the structure and control strategy. The paper is organized as follows: Section II presents hierarchical control of an MG, Section III presents overview of MG synchronization method. Section IV presents analyses active synchronization methods; Section V presents the passive synchronization and open transition transfer in Section VI. Section VII overviews the summary of MG synchronization and Section VIII concludes the review.

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2. Hierarchical control structure of microgrid

Standardization operation and functions of MG have been proposed in hierarchical control structure as shown in Figure 1[11]. Each control level has its own function and provides the supervisory control over lower level systems. It is necessary to ensure the control from one level to the lower levels has a low impact in the stability and robustness performance. The bandwidth of the hierarchical control is deceased with an increase in control level [11]. MG hierarchical control can be classified by three control levels; primary control, secondary control and tertiary control [12][13][14][15] :

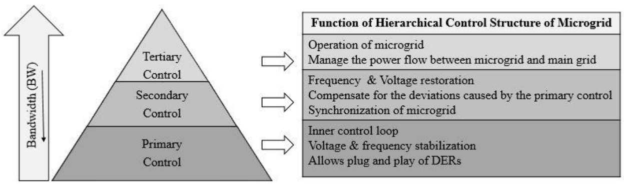

Fig. 1: Hierarchical control structure of microgrid.

2.1. Level 1: Primary Control

Level 1 is responsible to adjust the voltage and frequency references that are input for the inner current and voltage-control loops, and to reduce the circulating currents at local level of DG [15]. The main idea of the primary control level is to mimic the behaviour of a synchronous generator by reducing the frequency when the active power increases [16]. The primary control should have the fastest response within millisecond to any variation in the source or demand of the system in order to maintain the power stability and reliability. It is also provided for controlling the performance of energy storage systems such as batteries.

2.2. Level 2: Secondary Control

Level 2 is responsible to monitor and control the voltage and frequency of an MG. The secondary control ensures that deviations of voltage and frequency in an MG are within the allowed limits regardless of source and load changes [16]. This control also can be used for an MG synchronization to main grid by added a synchronization control loop. For reconnection an MG to the main grid, the voltage and frequency of the main grid will be measured and used as reference to the secondary control loop. The phase angle between the main grid and an MG will be synchronized by means of a synchronization control loop. Synchronization control loop is disabled when main grid not available. The secondary control is designed to have slower dynamic response to variation, compared to primary control in order to justify the dynamic between both levels [17].

2.3. Level 3: Tertiary Control

Level 3 applied at energy market level to control the operation and manage the power flow between main grid and an MG [11]. This control level is the last and slowest level of control. Technically, if there is a failure problem, this control will respond by absorbing the power from the main grid and if the main grid is not accessible, frequency will start to decrease. When the value exceeds the allowed limit, an MG will be disconnected from the main grid and the tertiary control will be disabled [16].

3. Microgrid synchronization method

Synchronization of MG can be defined as the process of reconnection of MG with the main grid after unintentional or intentional islanding. The purpose of synchronization is to monitor, access, enable, and automatically take the control action to prevent the abnormalities of voltage and frequency [18]. Synchronization is usually accomplished by detecting the voltage magnitude, phase and frequency difference between the main grid and an MG [19].
The IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems (1547.4-2011) has a brief discussion on MG synchronization [10]. The standard recommends that in order to initiate a connection of an islanded MG and the main grid, voltage of main grid should be within the Range B of ANSI/NEMA C84. 1-2006 [20], Table 1 the frequency range is between 59.3 Hz to 60.5 Hz, and phase rotation is correct [10].

Table 1: Service voltage.

For 120 V - 600 V Systems				
Nominal Voltage (V)	Service Voltage (V)			
	Range A		Range B	
	Max	Min	Max	Min
120	126	114	127	110
240	252	228	254	220
480	504	456	508	440

The voltage, frequency and phase angle between the islanded MG and main grid are specified in the IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems (1547-2003) [21]. According to IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems, the connection of islanded MG to the main grid should be delayed to five minutes after steady-state voltage and frequency of main grid are restored based on recommended range in order to maintain the stability [10]. The guidelines also recommends three different methods of reconnection islanded MG to the main grid which are active synchronization, passive synchronization and open-transition transfer as shown in Figure 2.

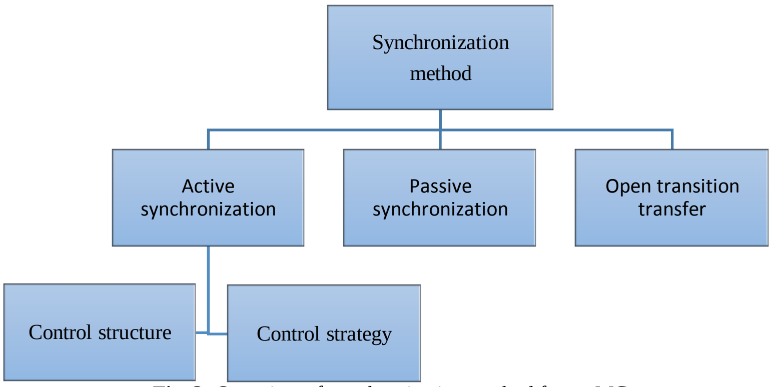

Fig. 2: Overview of synchronization method for an MG.

4. Active synchronization

Active synchronization can be defined as an automatic control technique for synchronization. In active synchronization, a control mechanism is used to match the voltage, frequency and phase angle between an MG and main grid. This method requires information on both sides of MG and main grid to be delivered to the control mechanism. Illustration on the general concept of active synchronization control that applied in most of published paper is shown in Figure 3 [22].

The connection of MG and main grid is through a static switch. A static switch is an electrical device that provide instantaneous transfer of power sources to the load. In order for the static switch to operate, it has to get information from IED. The IED will communicate with the MGCC which acts as a central controller for this process. IED is responsible to monitor and compares the frequencies, voltage magnitudes and the phase angles difference across the static switch, and initiates the synchronization control signal once the synchronization criteria is met [22].

Based on the received information from the main grid and an MG via the intelligent electronic device (IED), the MGCC transmits appropriate commands to controllable power sources and energy storage devices to control the frequency and voltage of the MG. Uncontrollable devices operate normally acting as a disturbance in maintaining the stable voltage and frequency of the system.

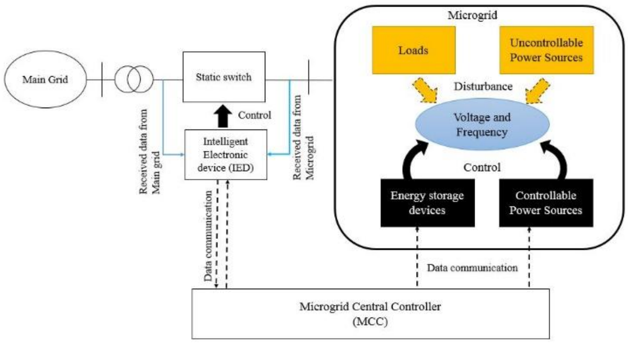

Fig. 3: Basic scheme of active synchronization [22].

4.1. Control Structure

There are three types of control structures of an MG under active synchronization approach; centralized, decentralized and distributed as shown in Figure 4. A detail explanation of each structure is discussed below:

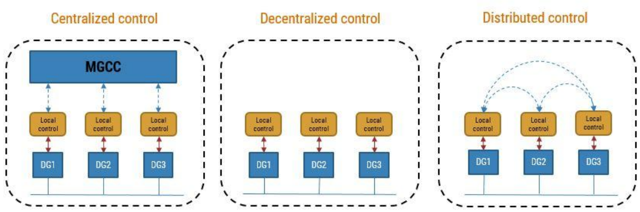

Fig. 4 : Control structure of an MG.

4.1.1 Centralized control

Centralized control is defined as a hierarchy decision-making structure where all decisions and processes are handled strictly by one single controller known as microgrid central controller (MGCC). Centralized control system relies on information data gathers in MGCC [15]. The MGCC is responsible to accomplish calculation, determine the control actions for all DGs unit and send the information back to main systems [13]. Centralized controller uses communication network for exchange the information between an MG and main grid. This control is suitable for small scale MGs. However, this type of control has a low reliability and redundancy. Other drawbacks of this control are severe communication problems, and requires shutdown the whole system in case of system maintenance [23]. With the evolution and advancement of technology in an MG, centralized control does not seem appropriate in processing and making a decision for a large amount of information system. Therefore, decentralized approach are suggested in order to reduce the complexity of the network [24].

4.1.2 Decentralized control

Decentralized control can be defined as a systematic delegation of decision making where one MG has multiple controllers, where each of local controller has an access to different information [25]. This type of control enables DG units and loads to act independently [23]. Therefore, all local controllers are connected with communication bus. This communication bus is used to exchange information among each DG controller [26]. In decentralized control, communication with other DG units is not necessary as this control enables plug and play capability [27]. This kind of control allows a flexible system that can adapt to change system structures and situations. Hence, this control significantly reduces the computational need and releases the stress on the communication network [28]. Despite its advantages, inability of local DGs in different areas to share information and data is the main drawback for this control. Therefore, distributed control is suggested to improve the performance of the system.

4.1.3 Distributed control

Distributed control is operated based on delegation of decision making powers and flexible processes. A key point about distributed control scheme is that there is no central point of control. Based on the proposed distributed control in [29][30], the information is sent to the leader DGs and the leader DGs will share the information to their neighbours. Each DG only requires its own and adjacent information to adjust the voltage at PCC. In this control, sparse communication network can be used and the complexity of the system can be reduced. The summary of three different control structures of active synchronization is tabulated in Table 2.

Table 2: Characteristic of control structure under active synchronization approach

Control Structure	**Centralized**	**Decentralized**	**Distributed**
Structure & Expansion Capacity	Suitable for small scale MG & Low scalability	Suitable for big scale of MG & Moderate	Suitable for big scale of MG & Infinite
Decision making	Central controller DER depend on single central controller to send and receive information	Multiple controller for one MG	No central point of control
Communication network	Command & control Need high bandwidth of communication	Peer-to-peer Local controllers are connected with communication bus.	Peer-to-peer Reduces the stress on communication network
Reliability	Low	Medium	Optimum
Cost	High	Moderate	Moderate
Single point of failure	Yes	No	No

4.2. Control strategy

Nowadays, synchronization of an MG to main grid is quite challenging due to the advancement of technology and rapid increase of power demand. Synchronizing an MG which consist of several DGs including renewable energy (RE) and energy storage is greater challenge because the frequency and voltage of an MG are determined by multiple DGs and loads. The synchronizing criteria for synchronization can be satisfied only by controlling the frequency and voltage of an MG. For MG synchronization, the voltage, frequency and phase angle of main grid must be equal with the voltage, frequency and phase angle of an MG. This section analyses the grid-connected synchronization method of an MG that are available in the literature such as phase locked loop (PLL), droop control, and frequency locked loop (FLL).

4.2.1. Phase locked loop (PLL)

Phase locked loop (PLL) is the most acknowledged concept since it was published in 1932 due to their simplicity, robustness, and effectiveness in various main grid condition[31]. PLL are widely used for various industrial fields such as communication system, control system and instrumentation. Nowadays, PLL techniques have been used for MG synchronization. Generally, PLL is a closed loop feedback control system which synchronizes its output signal with the reference input signal in frequency and phase [32][33][34]. As illustrated in Figure 5, a basic PLL structure comprises three main blocks, which are phase detector (PD), a low-pass filter (LF) and voltage controlled oscillator (VCO). In [35], the proposed synchronization method used a typical PLL structure, so the parameter can be designed. The tracking principle of frequency and phase control is similar as in a PLL and as a result, the proposed method can adjust the fundamental positive and negative sequence components as well as low-order harmonic components of an MG to accurately track the voltage of main grid.

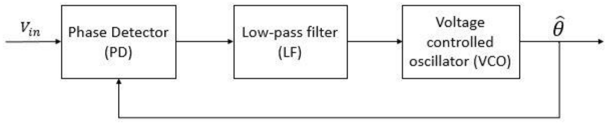

Fig. 5: Basic structure of PLL.

Various modifications and development have been made to improve PLL performances under various main grid conditions such as synchronous reference frame PLL (SRF-PLL), enhanced PLL (EPLL), fixed-reference frame PLL (FRF-PLL), and variable sampling period filter PLL (VSPF-PLL) as presented in [36]. The difference between each of the method lies in how the PD block is implemented. However, only SRF-PLL method is widely applied for MG synchronization as presented in [37][38][39][40][41]. The PLL which is used in three-phase systems is based on the use of SRF-PLL [34]. The basic structure of SRF-PLL is illustrated as Figure 6. Conventional SRF-PLL allows fast and accurate estimation of phase angle and main grid-voltage frequency in ideal condition. However, the three-phase voltage vector in *abc* natural reference frame need to be transformed to synchronous reference frame *dq* through Park's transformation [37]. SRF-PLL is preferred since it has a good frequency tracking and voltage disturbance rejection.

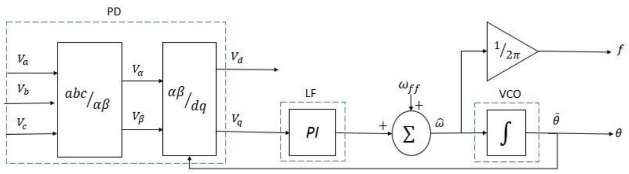

Fig. 6: Basic structure of SRF-PLL.

In [38], the proposed synchronization system makes use of three different PLL configurations known as grid PLL, GPS PLL, and local PLL based on SRF-PLL. However, in this paper, a deterministic prediction-correction filter, derived by a steady-state linear Kalman filter (SSLKF) is used as a loop filter as shown in Figure 7(a). GPS PLL and local PLL are achieved using the prediction-correction filter, same with grid PLL, however, specialized for the 1 pulse per second (1PPS) signal provided by a GPS device as shown in Figure 7(b).

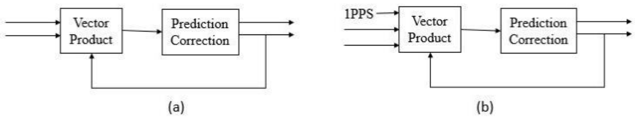

Fig. 7: Block diagram (a) Grid PLL (b) GPS PLL and Local PLL

Author in [39] used three phase software phase-locked loop (SPLL) based on SRF-PLL method where the terminal voltage phase Angle for SPLL is θg and synchronization is achieved by controlling Vgq =0. In [40], the synchronization system employs a sequence detector and SRF-PLL to monitoring the voltage of PCC and capacitor. In [41], the control strategy based on SRF-PLL is applied for frequency and phase detection. Further, simulation on synchronization of microgrid to main grid based on SRF-PLL is discussed in [42].

4.2.2. Droop control

During islanded microgrid, many inverter-based DGs adopt the droop strategy for stable power sharing [43][44]. Droop control is used to achieve DG inverters parallel operation and the power sharing between them. Generally, droop control is autonomous approach for controlling frequency and voltage amplitude of the generator and, eventually, the microgrid. The droop equation can be obtained as below:

$$f = f_o - k_P(P - P_O) \quad (1)$$

$$E = E_O - k_Q(Q - Q_O) \quad (2)$$

Where f_o , E_O, P_O, Q_O are the nominal frequency, amplitude, real and reactive power respectively. Several research [45][46][43][47][48][49][30][50] have shown that droop control is widely used in synchronization technique. A droop control technique by adjusting the voltage magnitude and frequency set point of DG in a distributed manner is proposed by author in [30]. However, the author in [50] adopts the network-based control of multiple DGs for reconnection of an MG where the algorithm will generate the frequency/voltage offset command signals for the multiple DG controllers.
In [43], droop control concept by adding two separate synchronization compensators to the external real and reactive power control loops is proposed. A seamless droop controlled DG strategy for MG synchronization based on adjusting the voltage of an MG by adjusting frequency and voltage amplitude of the DG is proposed by author in [45]. The synchronization strategies consist of two steps; frequency synchronization and phase synchronization as shown in Figure 8. Droop characteristic adjustment with low speed communication is proposed by author in [46]. The linear integration method is adopted to adjust frequency and voltage amplitude of an MG by adjusting the nominal real and reactive power of one DG or both.

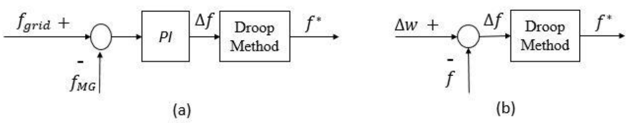

Fig. 8: (a) Frequency synchronization (b) Phase synchronization.

In [47], synchronization is achieved based on droop control by adjusting frequency and voltage amplitude of the MG through frequency and voltage restoration loop. Frequency and voltage restoration loop was used in [51]. However, in this paper, the frequency restoration loop was modified by adding synchronization block (grid synch). The synchronization block is used to reduce the phase angle between the voltage of main grid and an MG by measuring the frequency deviation. Similarly, author in [49] proposes a grid synchronization method based on the frequency restoration and voltage restoration mechanism of the P−ω and Q− ˙V droop controls. The proposed

method adjusts the Distributed Energy Resources Controls (DERC) operation frequencies and phase angles through the frequency restoration of the P–ω droop control. While, DERCs' output voltage magnitudes are adjust through the voltage restoration of Q–V droop control. Due to the proportional sharing of real power and the reactive accomplished by the droop controls, negligible transients in the process can be maintained. Further, the effectiveness of proposed method is validated by simulation based on a pilot microgrid setup having converter based DG.
Author in [48] used voltage-based droop (VBD) control to synchronize the rms voltage, phase angle and frequency of main grid and an MG by adjusting the synchronizing DG unit's voltage with respect to the PCC voltage at the main grid. In this paper, the VBD controller of synchronizing unit is modified by including an rms voltage synchronization block, a droop limiting block and a phase synchronization block. The voltage, phase angle and frequency of the synchronizing DG unit are controlled with respect to the PCC values.

4.2.3. Frequency looked loop (FLL)

Frequency locked loop (FLL) is a closed loop feedback control system which synchronizes its output signal with the reference input signal in frequency. The main component of the FLL is similar structure to the PLL. The implementation of a synchronization system based on FLL is presented in [52]. The control algorithm based on the adaptation of a dual second-order generalized integrator based on an FLL (DSOGI-FLL) is proposed for controlling the disconnection, resynchronization and reconnection of an MG with main grid. In this paper, the proposed synchronization process used two DSOGI-FLL. The algorithm is implemented in a grid-connected power converter that acts as an intelligent connection agent (ICA). However, the effectiveness of the proposed method may disintegrate due to the presence of many voltage source converters in the system. The synchronization is achieved once a new nominal frequency has been measured and applied in the main DSOGI-FLL loop which gives the new frequency reference to the islanded MG.

4. Passive synchronization

Unlike active synchronization, passive synchronization does not require control mechanism. The passive synchronization is done through synchronization check using a synchrocheck relay. The synchrocheck relay is a device which measures the magnitude, phase angle and frequency differences between the voltages on either side of the circuit breaker [22]. Figure 9 shows a general concept of passive synchronization with synchocheck relay function according to IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems (1547-2003) [21]. This device will only reconnect the system if the voltage, frequency, and phase angle are within a recommended range to ensure minimal disturbance. This method will take a longer time for reconnection process as this method requires an analysis of both MG and main grid condition.

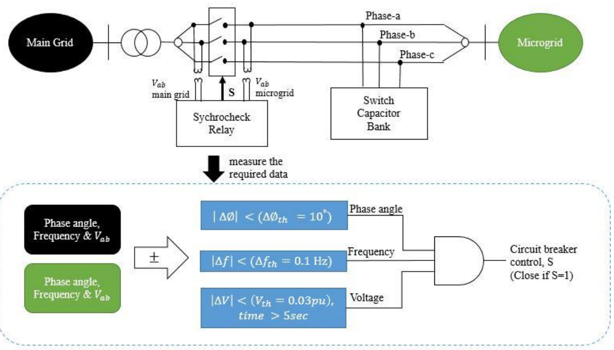

Fig. 9: Basic scheme of passive synchronization with sychrocheck relay function [22].

5. Open transition transfer

In this transition method, the load and DGs are de-energized before reconnection of MG to main grid. Once an MG is connected to the main grid, this load and DGs are brought back online. This approach will not be discussed further as this method reduces the reliability of the power system and not applicable for MG synchronization.

6. Summary of review of microgrid synchronization

For ease of reading, the features of an MG synchronization method presented in previous section is illustrated in table below:

Table 3: Summary of review of MG synchronization

Ref.	Year	Control Structure	Control Strategy	Technique	Simulation
[35]	2015	Distributed	PLL	Adjust the fundamental positive and negative sequence components as well as low-order harmonic components of an MG.	Experiment
[37]	2017	Centralized	PLL	Estimate the phase angle and main grid-voltage frequency.	Matlab
[38]	2015	Centralized	PLL	Three different PLL configurations; Grid PLL, GPS PLL, and local PLL based on SRF-PLL	Experiment

[39]	2014	Centralized	PLL	Three phase software phase-locked loop (SPLL) based pre-synchronizing unit is designed to track the voltage of main grid.	Matlab/ Simulink
[40]	2012	Centralized	PLL	Employs a sequence detector and SRF-PLL	Experiment
[41]	2011	Centralized	PLL	Measure an MG frequency at the inverter terminals	Experiment
[42]	2015	Centralized	PLL	Implementation of SFR-PLL	Matlab
[43]	2004	Centralized	Droop	Adding two separate synchronization compensators to the external real and reactive power control loops.	Matlab/ Simulink
[45]	2012	Centralized	Droop	Frequency synchronization and phase synchronization	PLECS
[46]	2012	Distributed	Droop	Adjust the nominal real and reactive power of one DG or both.	PSCAD/ EMTDC
[47]	2015	Centralized	Droop	Frequency and voltage restoration loop	PLECS
[48]	2013	Centralized	Droop	Used voltage-based droop (VBD) control	PLECS
[49]	2013	Centralized	Droop	Frequency and voltage restoration	Experiment
[50]	2011	Decentralized	Droop	The algorithm will generates the frequency/voltage offset command signals for the multiple DG controllers.	Experiment
[52]	2011	Centralized	FLL	Used two DSOGI-FLL.	Matlab/ Simulink

7. Conclusion

Various research papers on the microgrid synchronization method have been reviewed. The advantages and disadvantages of the MG synchronization methods have been analysed and discussed. Many researchers emphasize on the control method and the best chance to connect during the grid-connected process. It can be concluded that active synchronization method is widely implemented in MG due to its benefits and ability to emerge in various technology, especially for converter based distributed resources. Compared to traditional central controller, active synchronization method reduces communication costs and improves flexibility and redundancy. In terms of the control strategies, the droop control and phased lock loop are the most commons one with a lot of improvement. It can be foreseen that the application of Multi-agent system as decentralized control of MG synchronization can be utilized and deserve more attention on future work.

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