A Review of Control and Stability of Microgrid during Transitions

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Abstract**: The technological developments on Renewable Energy Sources have lead to research in control methods to make them useful electricity generators for feeding the loads in Microgrids and Utility grids. The Microgrid with all its Distributed Generators, Battery Energy Storage Systems and Loads has to be stable to supply power to the connected loads, maintaining frequency, voltage at Point of Common Coupling and sharing the load proportional to their capacities. The Microgrid with all its Distributed Energy Resources, which include distributed generators, battery systems and loads along with utility grid connection, constitute a mini power system network. This network has got different states, islanding, transition from grid to island and resynchronization to grid. The two transition states in which Microgrid has to be controlled and make it stable are, grid to island and synchronization back to grid. The different methods based on control techniques of synchronizing controller which monitor voltage, phase and frequency of Microgrid and main grid on either side of Static Switch and brings stability in the system. In this paper these two have been discussed elaborately, which gives fairly a good idea about control and stability of Microgrid.**

Keywords: **RES- Renewable Energy Sources; DER- Distributed Energy Resources; DG- Distributed Generators; DOE-Department Of Energ; BES-Battery Energy Storage systems; PCC-Point of Common Coupling; NDZ-Non-Detection Zone; CERTS- Consortium of Electric Reliability Technology Solutions; PLL-Phase Locked Loop; SRF-PLL- Synchronous Reference Frame-PLL**

I. INTRODUCTION

The Microgrid as per DOE, is a cluster of DGs, BESs and loads connected within a clearly defined electrical boundaries, which acts as a single controllable entity with respect to grid. The Microgrid can connect and disconnect from main grid to operate in grid or islanded mode. The general condition of Microgrid is in connection with utility grid. The Microgrid is connected to the PCC through parallel interfacing inverters and to the main grid via static switch as shown in Fig.1. In the event of fault on the main grid, the Microgrid has to be islanded seamlessly with the aid of any of the islanding detection methods and operate autonomously in island[1], [2]. There are basically intentional and un-intentional islanding modes.. Intentional are meant to isolate Microgrid for any maintenance work either on Microgrid.

On Grid. Again the unintentional islanding is, if there is any fault or transient state on the main grid, the Microgrid is to be islanded. Either intentional or un-intentional islanding is to be done through static transfer switch. For any type of un-intentional fault, the Microgrid has to sense the fault on main grid and isolate the Microgrid smoothly without injecting transients into network. As this is already defined as Microgrid is a mini power system, and an “Active Power Network”. Hence the Modern Microgrid is a bi-directional network. The Microgrid can export or import depending on the situation [3],[4].

II. LITERATURE REVIEW

The heart of any Microgrid is the controller. The controller must be capable enough to be stable in synchronous mode, to be stable in transition from grid to island mode, stable in island mode and must be ready to synchronize to grid again for exporting and importing for economical benefits [7]. Nowadays , the Microgrids may be owned by consumers and they can become prosumers by supplying power to another Microgrid with agreed tariff arrangements A thorough review is done with references indicated in the following sections.

It is suggested in the reference paper, a method of intentional islanding. It has very elaborately discussed different modes of operation of inverters. Under grid connected mode the inverters should be in CCM mode to share the loads proportionally. But in islanded mode they will revert to VCM mode to maintain constant voltage and frequency at PCC [24].

It is also pointed out different scenerios of photo voltaic and wind turbine sources during grid, islanded and transition states [22].

It is discussed in the reference paper about MPPT and battery control. It has suggested different maximization techniques like V-f, P-Q methods. [24]

A special controller is proposed, which detects both positive and negative sequence components during unbalanced faults [23].

A remarkable work is done by focussing on stability during grid mode only.. The modelling was done in PSCAD/EMTDC platform [25].

Discussed in the references, about the stability of three phase grid connected and islanded mode with linear load with and without anti-islanding controller [26].

The author discussed about voltage source inverters with DGs, on the control of constant voltage and frequency [27].

Pointed out different scenerios about stability of islanding when a grid fault occurs and also stability after islanding [28].

Reference papers also discussed about different protection methods against different faults [29].

Islanding detection has got two types [5],[6],

1. Intentional method – for any maintenance on either grid or Microgrid
2. Un-intentional method – during faults

Again un-intentional method have got two ways,

1. Local method – with local measurements
2. Remote method – these are with communication

Local techniques are again devided like,

1. Active islanding detection methods
2. Passive islanding detection methods

1. Active Islanding Methods

These methods, the limitations in the passive techniques of large NDZ area, is reduced. Active methods inject perturbances at PCC to find out deviations in the voltage, frequency and impedance parameters.With this, it can be concluded that the grid is disconnected [8]. This is done by injecting disturbances through d-axis controller. Some active islanding detection methods are discussed blow.

1.1. Impedance Measurement or Harmonic Injection(IM)

This method is dependent on the variations in the high-frequency impedance of the voltage and current measurements. This signal becomes substantial during the island mode. This islanding detection is based on Impedance Measurement is commonly used in power systems with synchronous machines. This method also possesses a little NDZ area with one inverter of DG. The local loads will have larger impedance than the main grid. By this injection huge voltage and current harmonics are produced in the system. Hence the quality may deteriorate. Also the threshold selection is not an easy thing for island detection.

1.2. Active Frequency Drift Method (AFD)

In this method a distorted current wave form is injected at PCC. As long as the grid is in connection with Microgrid, there is no change in the waveforms of voltage and frequency. But in the absence of grid, a phase error occurs between the output voltage and current of inverter. Hence, a frequency drift is created. This reduces the phase error. The frequency drift crosses at another zero crossing threshold limit. This detects the island condition.

1.3. Sandia Frequency Drift Method (SFD)

The SFD technique is extension of the AFD. In this a positive feedback is applied to the inverter voltage frequency when connected to grid. If the grid is not available, the frequency change gives rise to inverter phase angle error. This goes on till the frequency crosses a threshold value. The parameters like chopping frequency CFO and accelerating gain k are essential for island detection.

1.4. Sliding Mode Frequency Shift Method (SMFS)

The SMFS technique utilizes the phase angle of the inverter output current and voltage frequency. This method uses positive feedback to change the phase voltage at DG terminals by monitoring the frequency deviations to detect island situation. The change in the phase angle of the inverter output current is in relation to the grid output voltage. The frequency of the grid voltage changes from its nominal value with respect to mains.

1.5. Sandia Voltage Shift Method (SVS)

In this the positive feedback is applied to the voltage magnitude at DG output terminals. There is no effect in grid mode. But, if grid is not available, there is reduction in PCC voltage. This reduction is sensed by anti-islanding protection relays and stops DG sending power. The Sandia Voltage Shift technique is supposed to be the most efficient one. By integrating the the SVS and SMS, a better islaning detection can be deviced, so that the power quality and performance will not effect.

These active methods are advantageous to reduce the non-detection zone (NDZ).But in so doing, the quality may be reduced or may lead to instability. Most of the techniques are based on inverter topologies.

The Micogrid has to be stable and robust for all practical engineering application.

2. Passive Islanding Methods

In these methods normally NDZ is large enough, so that the trip time is more and nuisance tripping may be activated. But these passive islanding detections are based on local measurements like voltage, current, frequency, power, impedance etc. These parameters show significant variations during grid disconnection. These methods sense the fluctuations and isolate Microgrid from main grid. These These methods do not deteriorate the power quality. The following techniques are a few passive methods of islanding detection methods.

2.1. Over-voltage/ under-voltage protection (O/UVP) or Over-frequency/ under- frequency protection (O/UFP)

These are normal protection relays, which are installed on a distribution outgoing feeder. They determine the minimum or maximum values during Microgrid operation. These methods take the selective settings of of voltage and frequency relays at DG terminals. The relays operate when the voltage and frequency cross the set values. Then they disconnect the DGs from the network. The grid always depend on the changes in the active and reactive powers before disconnecting DGs. If a change in the amplitude of active power appears at PCC, the O/UVP relay disconnects the DG. But if a change in reactive power occurs a load voltage phase shift happens. This deviates the inverter current frequency. The over or under frequency relay detects and isolates the DG, which is much simpler without even much cost.

2.2. Rate Of Change Of Frequency(ROCOF)/ Rate Of Change Of active Power(ROCOP)

These relays detects the changes in the frequency or DG power in islanding. During the absence of the main grid, because of power imbalance, if the frequency of the power system is observed at DG terminals. This change in the frequency df/dt is sampled for a short period of time. Then it compares with the set value. If the deviation crosses the set limit, islanding detection is done and relay sends trips the breaker. The tripping time of the frequency relay is used in ROCOF-based islanding detection method, which is around. 0.012 cycles. During the absence of main grid, if there is a sudden load change, the ROCOP method senses the change and measures dP/dt at DG terminals and integrates for a specific time interval. If the signal strength is more, the trip setting is changed and the islanding is detected. Compared to the O/UVP and O/UFP techniques, the ROCOP-based islanding detection technique is faster and is not affected by the small active power mismatches and thus nuisance tripping is avoided.

2.3. Phase Jump Difference Method (PJD)

In this method the phase difference in voltage and current at PCC is measured during a sudden phase jump. In islanding mode , this method is very much useful and is used in the PLL controller. But this method can not detect islanding for a low active power mismatch between DG and loads. This may cause nuisance tripping.

3. Remote islanding detection methods

The methods are with communication between the grid and DG sources. These methods are efficient and with small NDZ area. NDZ can also be defined as a power region which is not protected by normal protection devices. It is obvious that conventional passive islanding detection methods have a large NDZ. The remote techniques are better but they costlier and complex. They are not reliable as the communication may fail at any time. Figure. 1 shows a schematic of the remote islanding detection method. Islanding detection depends on the collection of information from media and trip signal sending to switch. The examples of remote islanding detection techniquess are the power line communication (PLC), supervisory control and data acquisition (SCADA) etc,..

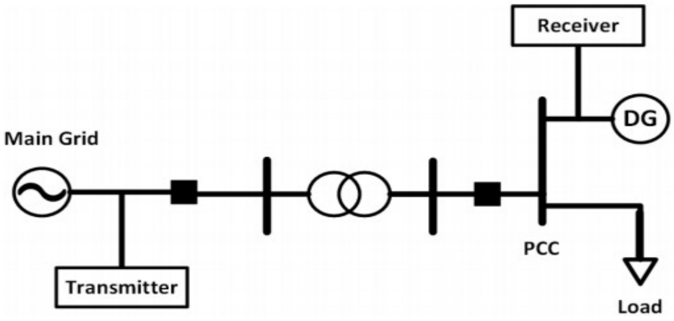

Figure.1 Remote islanding detection method with Communication

III. MICROGRID STRUCTURE

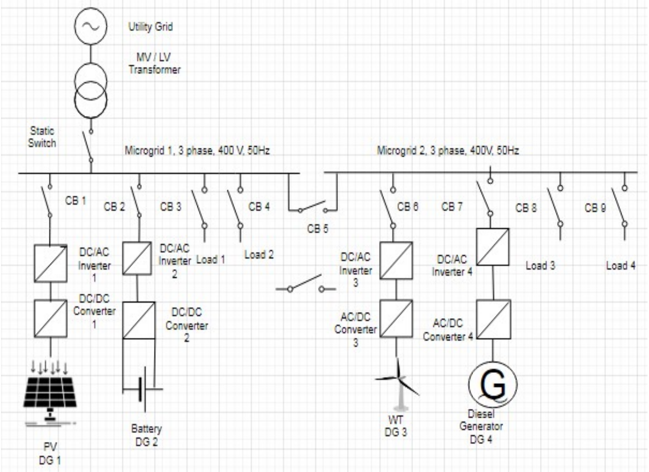

Figure.2 Typical Microgrids single line diagram

The Microgrid consists of a power control centre, in which grid incomer is connected through a static transfer switch for smooth transition between the transitions and all outgoing breakers are connected to DG interfaced inverters (PV, WT, and Battery Energy storage System)and loads as shown in Figure.1. All these lines are connected via distribution lines or cables depending on requirement. The loads are segregated as essential and non-essential loads which are prioritized based on the customer’s specifications [9], [10].

The Microgrid has to operate either with utility grid synchronized or has to independently work in islanded mode sharing the load power and maintaining voltage and frequency at PCC as per the DOE and CERTS.

The islanding is detected much before instability of Microgrid with the islanding detection method and brings back stability through smooth changeover from grid mode to island mode. Also it should reduce introduction of transients, through filters [11], [12].

The battery is utilized to regulate voltage and frequency and DGs will try to supply active and reactive powers to the load proportional to their ratings in islanded mode . The reverse droop control method will cover this phenomena.

The loads are also prioritized as essential and non-essential loads. In the event of very serious perturbations the non-essential loads can be avoided by means of automatic load shedding panel. The Microgrid stability can be achieved through the control of voltage and frequency[13], [14].

IV. DIFFERENT TOPOLOGIES OF CONTROLLERS

1. Pll Model

This controller is used in grid tied power converters for synchronizing to main grid. PLLs are required to ensure proper power flow from the source converter to grid. PLLs are utilized in power converters with renewable energy sources [15, [16].

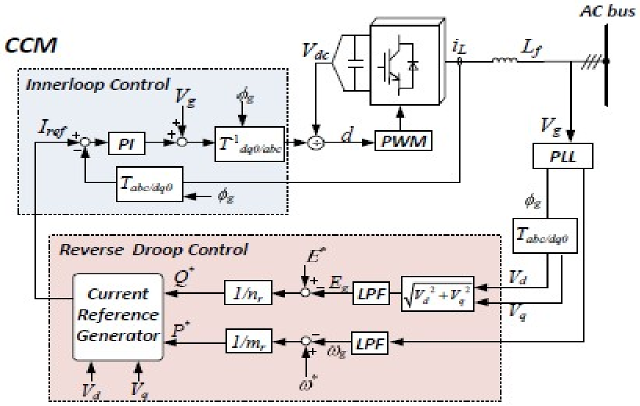

Figure.3 Simple Grid connected PLL controller

During the synchronization, the capacitor monitors the PCC voltage. The PLL synchronization controller unit consists of three elements, sequence detector, PLL and a voltage comparator, which is shown in Figure.3.

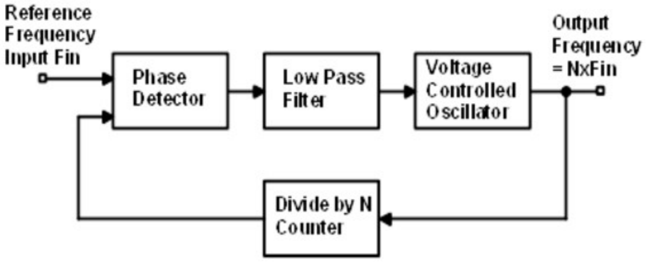

Figure.4 Simple PLL circuit

1) *Sequence detector:* The sequence detector compares frequency compare the frequency of either side of PCC and gives output as per droop reference[17].

2) *SRF-PLL:* This checks the phase angle of grid and microgrid as per the reference and gives output comparing the reference. .This controller block consists of three components, a phase detector, a low pass filter and a voltage controlled oscillator[18].

3) *Voltage amplitude comparator:* This compares voltage amplitudes of grid and Microgrid and gives output as set by reference[19].

2. SRF-Pll Model

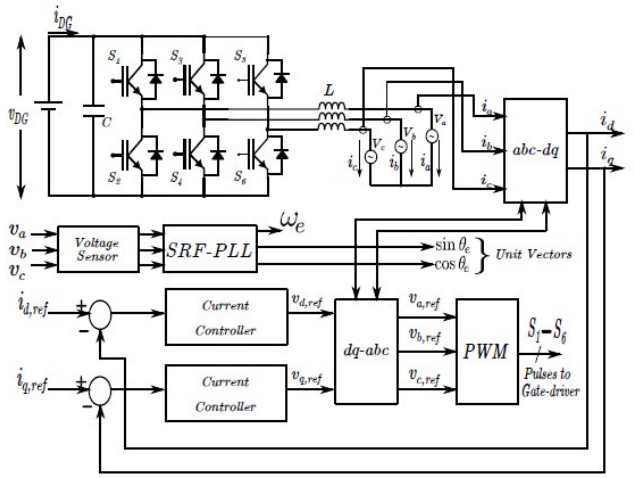

Figure. 5 SRF-PLL Inverter

The SRF-PLL controller is shown in Figure. 3. This method consists more responsive time and more dc-offsets as per IEEE-2003. Hence a modified method which eliminates these is shown in Figure. 4. The position of the switch S decides requirement of dc blocking pre-filter for Vα and Vβ. This method SRF-PLL, adopts state space variables[20], [21].

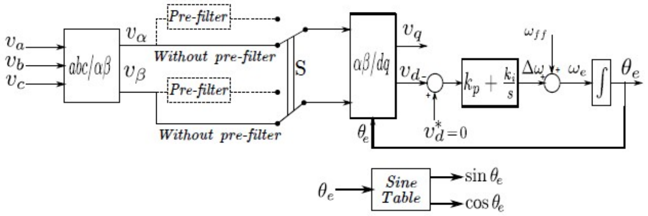

Figure. 6 Modified closed-loop control of SRF-PLL method

3. SOGI-Pll Model

SOGI-PLL is second order generalized integrator PLL, which monitors voltage amplitude[22], [23], phase and frequency of both Microgrid and grid on either side of static switch and gives synchronizing command as shown in Figure.5.

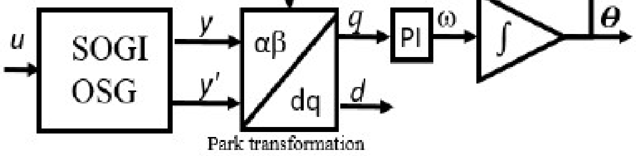

Figure. 6 Orthogonal Signal Generator based(OSG) SOGI-PLL

The input signal is *u* wave and output signals are *y* and *y'. The signals y* and *y'* are different out of phases of 90°. Hence they are transformed into park transformation [24], [25]. SOGI-

OSG is a continuous time-domain model as shown in Figure. 6.

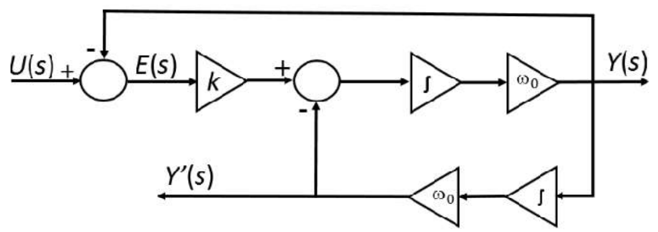

Figure. 7 Continuous time-domain SOGI-OSG

4. SOGI-FLL Model

SOGI-FLL is second order generalized integrator PLL, which monitors voltage amplitude, phase and frequency of both Microgrid and grid on either side of static switch and gives synchronizing command [28] as shown in Figure.7.

SOGI-FLL is a type of PLL which is advanatageous to SOGI-PLL in monitoring the frequency even outside 50 Hz frequency range, as per the standards.

The SOGI-FLL structure in continuous time-domain models is shown in Figure .8.

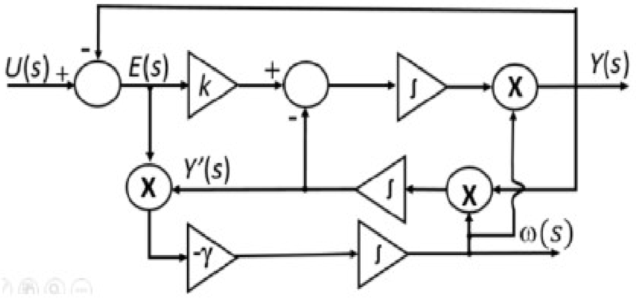

Figure. 8 SOGI-FLL in continuous time-domain

5. SOGI-QSG Model

Second-Order Generalized Integrator-Quadrature Signal Generator (SOGI-QSG) is shown in Figure.9, has got advantage not only for realizing 90 deg input phase angle offset but also can filter higher order harmonics[26],[27].

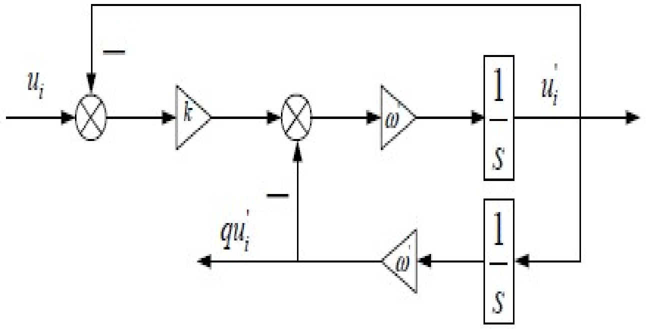

Figure.9 SOGI-QSG controller

6. Modified Sogi-Qsg Model

The DC components of input signals can not be suppressed by the normal SOGI-QSG. In order to nullify that effect, a modified version is devised which is shown in Figure.10.

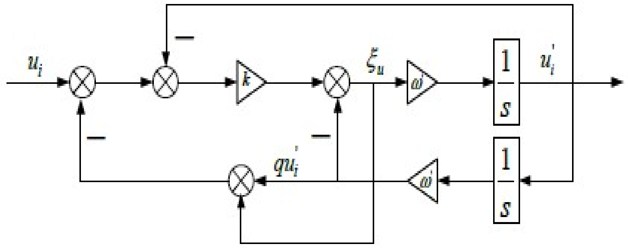

Figure.10 Modified SOGI-QSG controller

The DC components and higher order hamonics are reduced in this controller by feeding back the signals. But the response time is longer than the previous method [29].

7. DSOGI-PLL Model

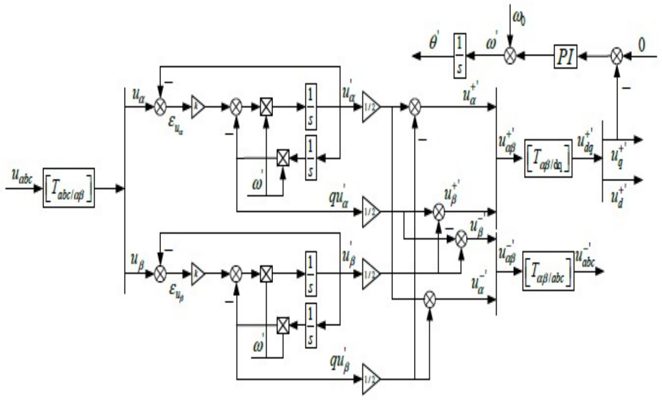

Figure.11 DSOGI-PLL controller

DSOGI-PLL – Double Second Order Generalized Integrator

Phase Locked Loop

In this method, the phase lock is realized by seggregating the positive d- axis as active power and q-axis as reactive power (positive sequence components) and then eliminating q-axis positive sequence component or making it to zero.

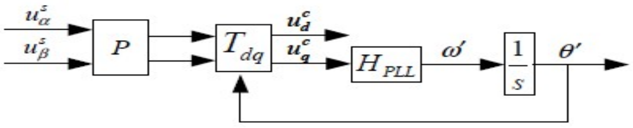

Figure.12 Generalized DSOGI-PLL controller

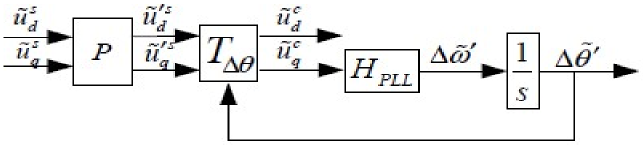

Figure.13 Average model of DSOGI-PLL controller

V. STABILITY ISSUES AND CONTROL METHODS

Any Microgrid has to operate and be stable in two modes, viz., grid to islanding and islanding to grid.

1. During grid to islanding

In grid mode active and reactive power to be injected by the inverter is decided by the PQ control method. The disturbances are basically unbalanced currents, reactive power and harmonics.

There are certain standards from IEEE-1547 for the Microgrid to detect islanding condition. The outlines are,

- Power flow magnitude and direction should be monitored
- The disconnection time of DG must be less than 2 Secs
- Proper quality of voltage, frequency and power must be maintained
- Transformer grounding configuration must be maintained as this will decide the neutral current direction

The following Table No..1 gives fairly, a good idea about the islanding detection standards.

Table No.1 IEEE-1547/ IEC-62116 Standards

Parameters	IEEE-1547	IEC-62116
Quality factor	1	1
Detection time	< 2secs	< 2secs
Frequency range,Hz	49.3≤ f ≤50.5	-1.5Hz< f <+1.5Hz
Voltage range, Vpu	0.88 ≤ V ≤1.10	0.85 ≤ V ≤1.15

The aim of any islanding detection scheme is seamless transition from grid to islanding mode. The parameters to monitor an dthe control techniques are given in the following Table No.2 and Table No.3. Table No.3 gives the control variables at inverter level and Table No.4 at Microgrid level. At Microgrid level, the three methods decentralized, centralized and distributed are also discussed. Centralized method is with communication . But again the control is at three levels, primary, secondary and tertiary .

Table No.2 Inverter level variables and control methods

Control Variables	Control Technique
Δ, E	Voltage control VSI
Vload, igrid	Grid interactive PWM
Vg, ig	PLL based sequence
Vg, ig	Load shedding method
e, Θ0	Self Synchronizing synchronvector
Tsync, ψsync	Virtual Torque/Virtual flux based Synchronizing Method
Vcf, α	Indirect current control
V LL, Θ0	SVPWM control, dither sync. signal
V0, ic	Volt an freq. sync. algorithm
Pout, Vout, Qout	MPC based hybrid objective fcn
Vout, Iout	Parallel VI control of UPS system

A comparative analysis for seamless transition of Microgrids during switching modes is shown in Table No. 2 and 3. These address the issues and suggests type of control required for each disturbance However the major challenges between Microgrid and grid can be concluded a below,

- Frequency fluctuations leading to DER power wave angle, which adversely effects the Microgrid stability Large deviations in the DER interfaced inverter output voltages and load currents switching on or off.

To address these disturbances different control schemes have been proposed at inverter and Microgrid levels. In both these cases the traditional droop control cannot cater to total control a dhas limitations,

1) V-f deviations in island mode
2) Un-regulated power injection in grid mode
3) In-accurate reactive power sharing in islad mode
4) Necessity for a central resynchronization control while connecting to grid

To obviate this, various modified droop methods proposed in the Table Nos. 2 and 3.

Table No.3 Microgrid level variables and methods

Level	Control variable	Control Technique
Decentralized	P0, Q0	Linear integration method
Decentralized	fof, Vg	Hybrid VSI control w dispatch unit
Decentralized	iabc,Vgabc,frequency	Active f/b comp.and droop based
Decentralized	ω,E	EPFC scheme using SRF-PLL
Decentralized	V0 via I0, Ic	Modified Linear Voltage Compensator
Decentralized	Vpccm, Is	BESS assisted modified controller
Decentralized	Vg, Θg, f	Modified VBD(Vrms sync, droop limit, phase sync blocks)
Decentralized	Vsa, ω	Windowing factor sync. scheme
Centralized (Heirarchical)	P*, Q*	Mod. v/f restoration loops with sync. block
Distributed	Δω*, ΔV*	Active synchronization using MSC
Distributed	Vcabc, I0abc	UPS based control
Distributed	Kv, L or C	VOC based grid synchronization

2. During islanding to grid (Resynchronization to grid)

This is also called re-synchronization of Microgrid back to main grid. This is obtained by reducing the phase angle difference of voltage at PCC. This is is achieved with a synchrophasor measurements at PCC. During re-synchronization, if asynchronism occurs, may lead to voltage phase angle difference. If this is more than 60 degrees, voltage difference of 1 pu may happen an dthis induce high inrush currents at PCC between Microgrid and main grid.

To achieve a effective resynchronization to grid, voltages at PCC on the MG side must be equalized with the grid. Section IV discussed various Phase Locked Loop (PLL) methods for DG grid resynchronization. These methods regulate the voltage phase angle at the DG side and grid side. The phase angle measured is the reference and that will synchronize DG with the grid. These methods are good for local measurements.

There are certain standards for resynchronization Microgrid with main grid as per IEEE-1547 and IEC-62116. As per these, there are limitations of voltage, phase angle and frequency variations of Microgrid and main grid across breaker and these are given in Table. 4. and Figure.14.

Table.4 Microgrid resynchronization requirements as per IEEE-1547

DG Rating KVA	Frequency variation, Δf	Voltage variation, ΔV%	Phase angle variation, Δ°
0-500	0.3	10	20
500-1500	0.2	5	15
1500-10000	0.1	3	10

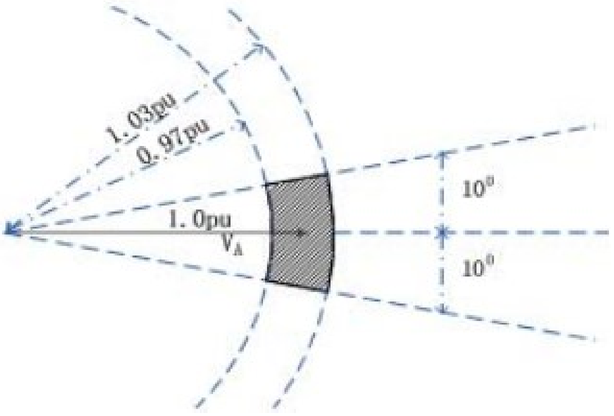

Figure.14 Interconnection requirements

It is obvious from the Table.2, as the DG rating is increased, the tolerance is becoming smaller. The voltage magnitude and phase required for re-synchronization are as shown in Figure. 14. Voltage VB should should be within the shaded area when the static switch operates. Over and above the considerations are on frequency variations. VB should enter and stay within the shaded area for at least 0.463 milliseconds.

VI. CONCLUSIONS

The paper reviews different topologies of controllers for efficiently islanding and synchronizing back to utility grid. Starting from generalized model of PLL, other topologies like SRF-PLL, SOGI-PLL, SOGI-FLL, SOGI-QSG, DSOGI-PLL have been discussed for covering larger areas and reducing NDZ areas. Based on this review, it will be helpful to devise a novel hybrid method to cover all the gaps and can be tested with the aid of Matlab / Simulink. By analysis and optimization, control and stability can be achieved. This can be the future research work on the line appropriate and which has got lot scope.

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