Synchronization Controller for Seamless Interconnection of Mirogrids with Heterogeneous Sources

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***Abstract*—Microgrids are becoming inevitable establishments in modern power systems, may be to address energy needs in remote locations or to improve resiliency or for any other reason in the smart grid scenario. Over the time, during different operating scenarios, these microgrids need to be interconnected with another microgrid or with the main grid which is a challenging task. In this connection, this paper investigates the necessity of following the synchronization protocol and the flexibility one can have when interconnecting different microgrids with inverter and rotating machine based systems, as well as homogeneous and heterogeneous sources. In addition, a simple controller is proposed to have seamless, quick and stable interconnections when the microgrids consist of rotating machines.**

Keywords— Distributed Generators, Grid code, Interconnection, Master-slave control, Microgrids, Synchronization controller.

I. INTRODUCTION

As per World Bank Global Electrification Database from *Tracking SDG 7*, at a global level, the percentage of population with access to electricity has been steadily increasing over the last few decades [1]. In 2010, around 83% of the world's population had the access; this increased to 91 % in 2020, inferring that still 9 % of world's population do not have the access to electricity in 2021. Moreover, a village is declared 100% electrified when 10% of all homes and public offices get electricity. Hence, 100% electrification of a place does not mean that 100% of the population in that area is getting electricity.

Due to cost considerations and location accessibility issues, providing electricity to remote locations is cumbersome task. Thus, in many cases the electrical power is supplied to these areas in islanded mode, representing a microgrid operating autonomously with its own generation sources and loads. Microgrids have been considered a significant part of the smart grid and are useful in the electrification of remote areas as well as resiliency improvement [2]. Besides the cost factor, it has merits of enhancing power quality, reliability, self-dependence, and energy efficiency. Micro-grids should be designed so that their local distributed generators (DGs) have enough generation capacity to meet their demand. A remote area or town can be supplied collectively by several independent microgrids. In this scenario, each microgrid might have an individual operator and be in charge of meeting the demand of a specific zone inside the remote area. However, a microgrid may experience a power generation demand mismatch (imbalance) due to the intermittent nature of solar and wind-based non-dispatchable DGs as well as demand uncertainty. Voltage and/or frequency drops will occur as a result of any insufficient electricity generation or microgrid overload. There are various solutions to address this deficiency, such as load shedding, usage of storage device, and interconnection of neighbor microgrids. In economic and stability aspects, the best solution, among others, is the interconnection of the microgrid. In addition, if the main grid comes in the vicinity of microgrid, it is almost evident to have integrated operation of microgrid and main grid. In addition, as part of resiliency planning, the power system needs to be operated into multiple mini/microgrids [3]. In all such scenarios and the future smart grid prospective the interconnection of different microgrids and integrated operation of microgrid with main grid is inevitable [4]. However, the interconnection of multiple microgrids having generating units of varying dynamics and/or having generating units of heterogeneous nature without affecting the stability of the system demands for critically designed synchronization protocol and advanced controller which can adopt and execute the protocol [5].

Thus, before interconnecting the microgrids or microgrid and grid, they must be controlled for frequency, phase angle, and voltage magnitude, such that the differences in these parameters must stay within the acceptable ranges. Therefore, the interconnecting grids must go through the synchronization process before being interconnected.

An emerging research area involves in the synchronization of multiple microgrids to create a big cluster of multigrid arrangement. Reconnection to robust utility grids is covered in the majority of research articles on microgrid synchronization. Key technologies and problem associated with the parallel connection of different sources in microgrid are briefly discussed in [3]. Droop-based synchronization controllers have been discussed in [6]–[9] for synchronization with utility grid in which the frequency and voltage are defined by the utility grid. However, in island interconnection operation of microgrid deciding the reference voltage and frequency is critical. In [10], master- slave based pre-synchronization of parallel DGs of microgrid is presented. It used temporary master slave strategy to synchronize DGs before integrated with grid. However, it considers microgrid with only converter-based system and is interfaced with the utility grid, no attention given for microgrids having the conventional rotating DGs. Active synchronization schemes using particle swarm optimization (PSO) techniques to integrate rotating machine with utility grid is proposed in [11]. Indeed, discussing the integration of rotating machines is emphasized, however, the concept of island operation and effect of interconnecting generating unit with different range of synchronization limits are not considered in [9]. In [12], a microgrid with both converter-based and synchronous generating unit is described. Here, the task of reaching synchronization with the external utility grid is divided between several of the controllable units. The phase angle, frequency and voltage deviations are calculated in an intelligent electronic device situated at the connection point, making the control implementation complex. In [13], a renewable energy based microgrid synchronization with the Diesel generator set during low renewable power generation is explored. More precisely, the inverter-based DG is synchronized with diesel generator. In [14], [15], the control actions are implemented to correct the frequency difference and phase difference in sequential manner. As it is evident, this approach involves multi-step process and delays the synchronization. On contrary, in [12] , the simultaneous corrective actions are derived to achieve the satisfactory condition for closing the interconnection switch. However, the phase difference is fed more or less directly to the controller to generate the corrective control action in these works. As result, a highly nonlinearly varying error signal is processed in the controller, eventually cannot achieve the quick synchronization.

Till date, various synchronization strategies are proposed, however, they are focused on interconnection of inverter based system with inverter or inverter based system with diesel generator or utility grid. Moreover, they did not consider the effect of changing the synchronization protocols on the system condition and parameters. In addition, either multi-step synchronization process or simultaneous corrective controls using nonlinearly varying error signals are implemented. In this connection, this paper proposes a synchronization controller to enable a seamless transition from standalone to interconnected operation of two microgrids. A dedicated synchronization controller is proposed for both inverter and rotating machine based generating units for interconnection with other microgrids, taking the benefit of their respective dynamics. In case of microgrid with rotating machines a smoothing function is implemented before processing the phase difference as error. In case of inverter based system, taking the advantage of their fast dynamics, a simple synchronization controller is implemented. The synchronization technique centers around synchronizing the frequency and phase angle of one of the microgrids to match with that of the other microgrid considering that the voltages are equal. This controller is studied in all the possible combinations of generating sources available to observe the nature of the response of a system with the interconnection of DGs having different dynamics. The two modeled microgrids are connected through a static switch/circuit breaker, which allows interconnection only when the parameters of both microgrids are in the range as specified in IEEE 1547.

II. SYNCHRONIZATION PROTOCOLS

Synchronization is a process that realizes satisfactory and stable interconnection of two electrically isolated systems with generating units, may be with loads as well. In order to have successful synchronization, differences in voltage, frequency, and phase have to be within safe limits prior to the synchronization. If not, the system may go out of step and the associated devices/equipment may get damaged.

- If the systems with phase difference out of specified limits are interconnected, there will be heavy inrush current flowing in the systems, creates a very high torque in the generator and damages the generator equipment. It also may cause overheating in the armature core of the generator.
- If the systems with voltage difference out of specified limits are interconnected, there will be heavy inrush currents, however, due to reactive power flows from one generator to the other.
- If the systems with frequency difference beyond the specified limits are interconnected, there will be varying phase differences and resulting high inrush currents, capable of damaging the generator and associated equipment.
- With incompatible phase sequence, either or all of the above three conditions will arise and will be a severe threat to the systems to be synchronized.

Therefore, it is must achieve the synchronization conditions before interconnecting two systems with DGs. There are multiple standards across the globe that define the interconnection protocols. For example, the IEEE 1547 [16] defines the protocol as in Table 3 to achieve successful synchronization. The synchronization limit should only be applicable once DGs are within the voltage and flicker limit of standard IEEE 1547. Other international standards like Canadian grid code C22.3 No.9-08 [16] and CAN/CSA-C22.2 No. 257-06 [17] and California Electric Rule 21 [18] accepted the synchronization limit of IEEE 1547.

According to CEA, all the interconnecting resources shall have an automatic synchronization device, while the induction generators (other than self-excited induction generators) and resources with inverter (with inherent synchronization mechanism) shall not require this. Paralleling device of DG shall withstand 220% of the nominal voltage at the interconnection point [19]. The synchronization process shall not cause voltage fluctuations beyond ± 5%. For higher capacities of DGs, a manually operated isolation switch shall be provided while following other technical and visual requirements.

Table 1 Synchronization parameter limits for synchronous interconnection (IEEE 1547) [16]

Aggregate rating of DR units (KVA)	**Frequency (Δf, Hz)**	**Voltage (ΔV, %)**	**Phase angle ($\Delta \Phi$, °)**
0-500	0.3	10	20
>500-1500	0.2	5	15
>1500-10 000	0.1	3	10

III. SYNCHRONIZATION CONTROLLER

The proposed controller for synchronization with rotating machine systems and with inverter based systems are described in this section.

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A. *Controller for Rotating Machine*

In principle it is being adapted from a master-slave approach [12], however, modified to improve the performance. In this approach states a designated master unit defines the microgrid's set points for voltage and frequency. In general, a system with relatively more stable performance is selected to operate as a master unit. Once the synchronization controller is active, the slave microgrid deviates from its operating condition, if required, and tries to follow the master microgrid. The synchronization switch is controlled such that it gets ON only when the voltage frequency and phase differences across the interconnection point are within the limit of Grid Code.

The synchronization control for interconnecting two microgrids is developed as per the master-slave synchronization approach, as shown in Fig. 1. The microgrids' voltages (V_{MG_A} and V_{MG_B}) are sensed and the frequency and phase difference signals are derived as shown in Fig. 1. These frequency and phase deviations are processed using two parallel PI controller loops, one for the phase angle correction and other for the frequency correction. As the phase difference is highly sensitive to frequency deviations, the controller action for phase correction is initiated when the frequency deviation comes within the defined range, not necessarily the limit specified in grid code, thereby enabling the parallel control action. The quick synchronization condition can be achieved with help of parallel control action, however, the controller in phase correction loop processes only smoothened deviation.

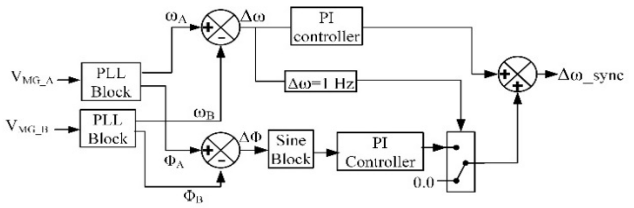

Fig. 1 Synchronization controller for rotating machines.

Thus the correction derived from this controller ($\Delta\omega\_sync$), can correct the slave microgrid frequency and the phase, thereby matching the parameters of the master microgrid.

B. *Controller for Inverter based Systems*

Prior to the interconnection with the other microgrid, the DGs system operates in standalone mode, hence, having its own frequency and voltage (phase). Once the synchronization process is triggered, the controller changes its mode from standalone mode to interconnection mode, as shown in Fig. 2. On receiving the command of interconnection, the synchronization process starts with the help of phase-locked loop (PLL) which extracts the frequency, voltage and phase signals. Since, the inverter based systems having fast dynamics and with fast acting controllers, multi-step process can be avoided as shown in Fig. 2

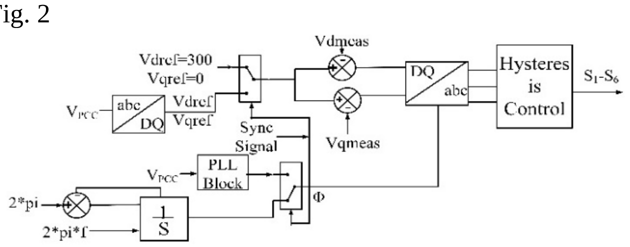

Fig. 2 Synchronization controller for Inverter based systems

IV. Results And Analysis

In this paper, a gas turbine driven synchronous generator is considered as rotating machine source, whereas the DC side voltage of the converter is supplied by a regulated voltage source, representing a renewable energy source, such as solar PV. The AC system is of 400V 50 Hz, the converter is rated at 15 kVA and the synchronous generators is rated at 100 kVA. A 10 kW local load is considered to be connected at the inverter based DGs end. To understand the controller performance better, the analysis is divided into four different integration cases, as: inverter based system with inverter based system, inverter based system with rotating machine based system, rotating machine based system with rotating machine system and microgrid with another microgrid, both of them having inverter as well as rotating machine.

Case I: Inverter interfaced with inverter-based DG

Among the two inverter systems, as shown in Fig. 3, one of them is considered as master while the other is considered as slave that adapts its parameters to match with that of the master to enable successful synchronization.

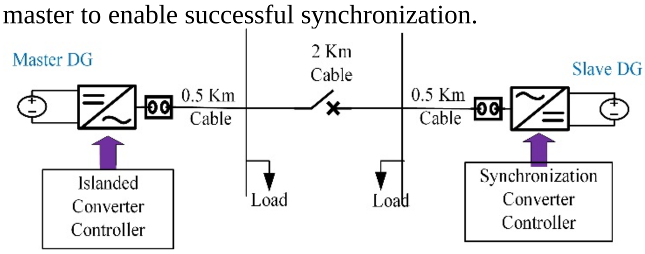

Fig. 3 Reference configuration for case I

The following Fig. 4 shows the response of the system in which the synchronization controller is activated at 3.75s. At this instant, it can be observed that the frequency and phase difference between the system are -2 Hz and 180°, respectively. If the synchronization switch/circuit breaker is closed at 3.8s, when the frequency and phase differences are outside the synchronization limit as per the IEEE 1547, resulting in high inrush currents. As both the systems consists of inverters, the controller could correct the frequency and phase in due course. However, due to high inrush currents and due to powers going beyond the rated capacity of 15kVA, the protection system of converter operates and disconnects the source, thereby makes the system unstable, confirming the necessity of following integration protocols.

In another test case as shown Fig. 5, the synchronization process started at 4s when the frequency and phase difference between the DGs are 2Hz and 0°. However, the synchronization switch/circuit breaker is activated at 4.2s, when the slave DG achieved the synchronization limits as per IEEE 1547. A smooth transition from standalone to interconnected DGs as can be seen in Fig. 5, confirms the stable interconnection.

To investigate the relative importance of achieving frequency and phase limits, the switch is ON at 4.02s, when the frequency is out of the limit as per the synchronization code, but the phase difference is within the limit as shown in in Fig. 6. It can be observed almost zero inrush current flow in between the DGs, and a smooth transition from standalone to interconnected DG. On contrary, when the breaker is ON without meeting the phase difference requirement, however the frequency deviation is within the limit, as shown in Fig.

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7, resulting in high inrush current and can make the system unstable.

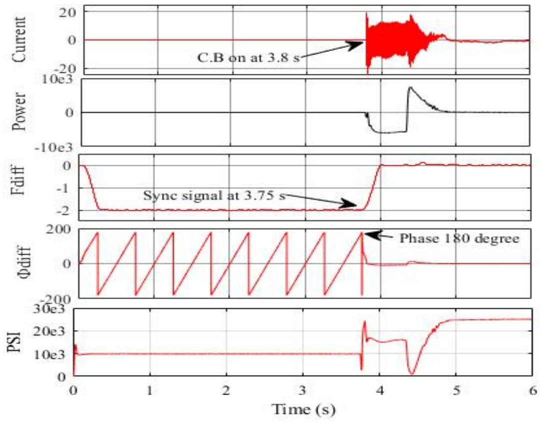

Fig. 4 Response of system when Circuit breaker is ON without following synchronization protocols.

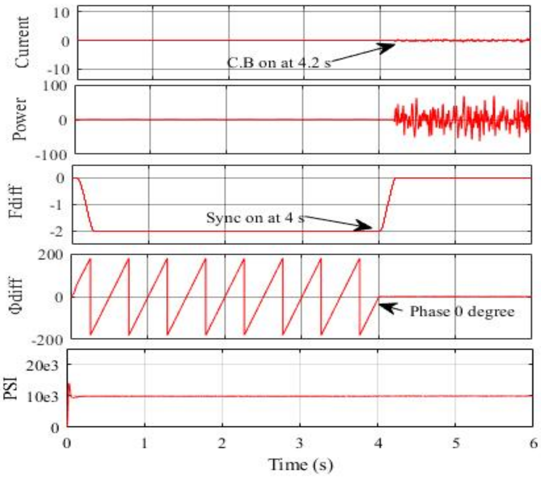

Fig. 5 Response of system when Circuit breaker ON after following synchronization protocols.

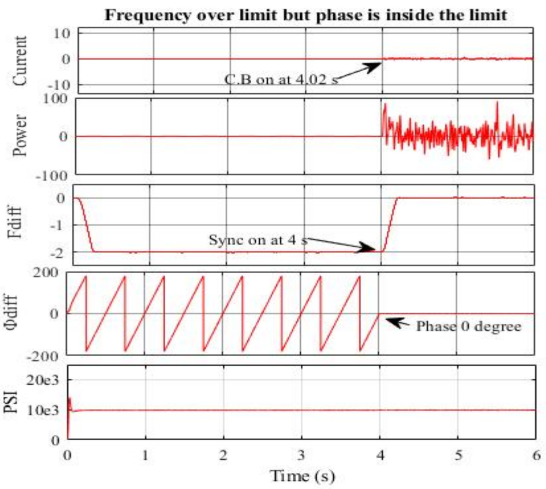

Fig. 6 Response of system for case I when frequency is out of synchronization limit.

Case II: Inverter interfaced with rotating machine-based DG

The reference system configuration for this case is shown in Fig. 8. The converter-based system is operating as a master and the rotating machine is needed to follow it.

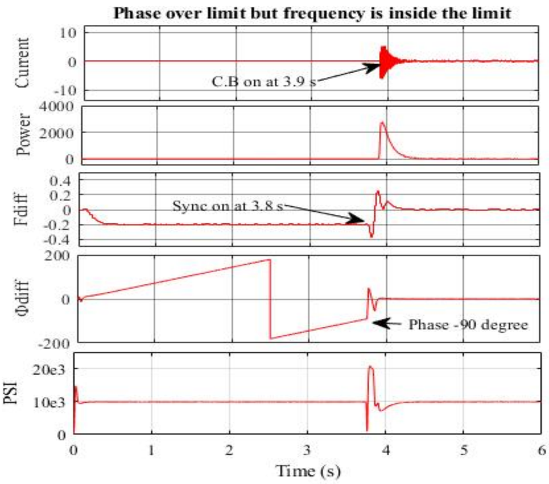

Fig. 7 Response of system for case I when phase difference is out of synchronization limit

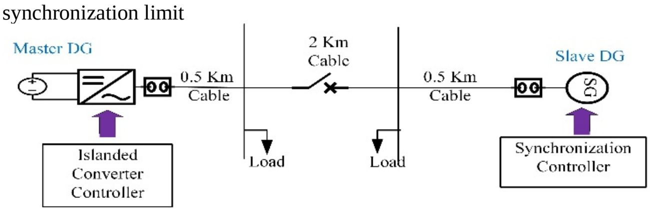

Fig. 8 Reference configuration for case II

Fig. 9 shows the response when the circuit breaker is on when the frequency, voltage, and phase difference are inside the synchronization limits. A smooth transition can be observed from the response. In this case, a small current flow between the DGs when a circuit breaker is on at 14.4 s due to differences in frequency and phase, though they are within the limits as per the code. Since no power-sharing controller is used in this configuration, the sharing of power is not defined in this paper. However, once the DGs are interconnected, synchronous generator supplies some active power to the inverter based microgrid as the inverter is a non-inertia system and does not react to a sudden changes in the system. One critical observation, one can make here is that the satisfactory synchronization condition is achieved at 14.4s, almost after 7s from the starting of synchronization process at 7s, against 0.2s as in the case I as shown in Fig. 5.

The following Fig.10 shows the interconnection of DGs when the phase difference is 180°, but the frequency is within the limit as per the grid code. In the other scenario, the synchronization signal is commanded at 7s, and the circuit breaker is on at 9.96s during which the frequency difference is 1Hz, and the phase difference is 0° as shown in Fig. 11. On contrary to case I (Fig. 6), both these scenarios are potential to make microgrid system unstable.

Case III: Rotating machine interfaced with rotating machine-based DG

Two microgrids having their own rotating machines as generators are considered in this case as shown in Fig 12. Master Generator is feeding a local load of 50 kW while slave generator is feeding a lesser local load of 20 kW. At 7s synchronization process is triggered, and the slave generator tries to follow the references of master DG from then. Since the phase and the difference between the phases keep on changing, it is challenging to tune the controller and achieve the desired synchronization limits within desired duration. Hence, a smoothing function "*sine*" is used before processing the phase error for this case as well as for case 2, as shown in Fig. 1. The responses of the system for different scenarios are depicted in Figs. 13-15. As shown in Fig. 13, the circuit breaker is closed at 13.4s, after attaining the frequency and phase differences as 0.28 Hz and 0°, respectively. A 10 A and 6000 kW peak transient power and inrush currents flow between the microgrids at the instant of circuit breaker on due to their nonzero frequency difference, and involved inertias as per their respective capacities. However, both the microgrid systems together operating stable after interconnection as shown in Fig. 13

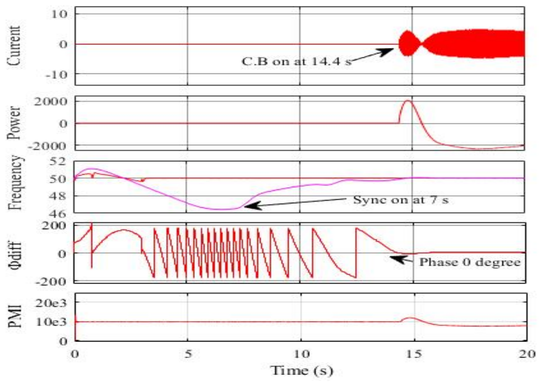

Fig. 9 Response of system for case II when circuit breaker operates following the synchronization limit.

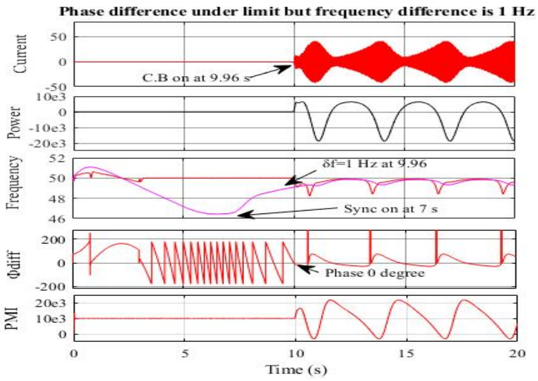

Fig. 10 Response of system for case II when phase difference is out of synchronization limit.

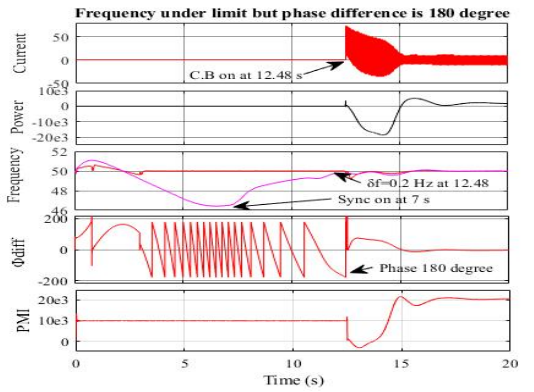

Fig. 11 Response of system for case II when frequency is out of synchronization limit.

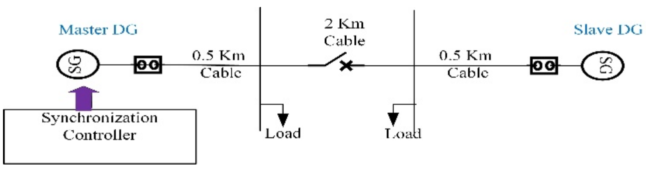

Fig. 12 Reference configuration for case III

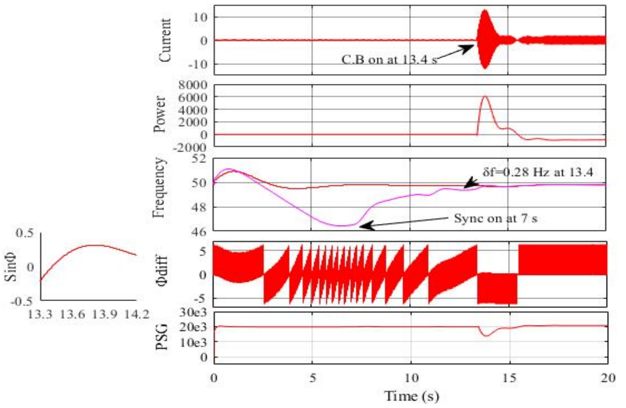

Fig. 13 Response of system when circuit breaker operated under synchronization limits.

However, when the switch is ON with unmatched frequency limit (as in Fig.14) or with unmatched phase limit (as in Fig. 15), the microgrid are experiencing high transients and power flows which can disconnect the respective DGs from the rest of the microgrid system, thereby making the system unstable. However, as can be observed in Figs. 14 and 15, the inrush current is more and is more sensitive to phase difference when compared with frequency.

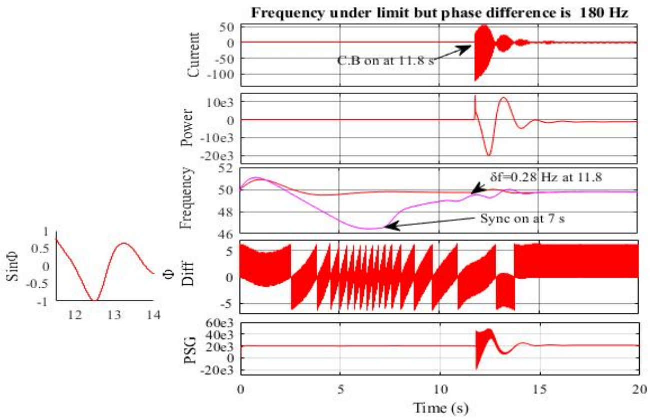

Fig. 14 Response of the system for case III when frequency is beyond the synchronization limit.

Case IV: Microgrid Interconnected with Microgrid

In this case, it tried to interconnect two microgrids, A and B, both consisting of heterogeneous sources as shown in Fig. 16.

As the earlier cases in this paper established the necessity of following the synchronization protocol, the performance of the microgrid with different kinds of sources and the consequences of deviating from limits and the proactive steps that can be taken for quick and satisfactory interconnection, this case study is dedicated to understand the performance deviations with respect the synchronization limits as shown in Fig. 17. By narrowing the synchronization limits, there will be decrease in inrush currents and a seamless operation can be achieved while interconnecting, even though the microgrids are supplying their respective loads prior to synchronization as can be observed in Fig. 17. However, as can be seen, the time required for completion of synchronization process will increase with decrease in synchronization limits. The simulation results of this configuration are shown in Fig.17-20.

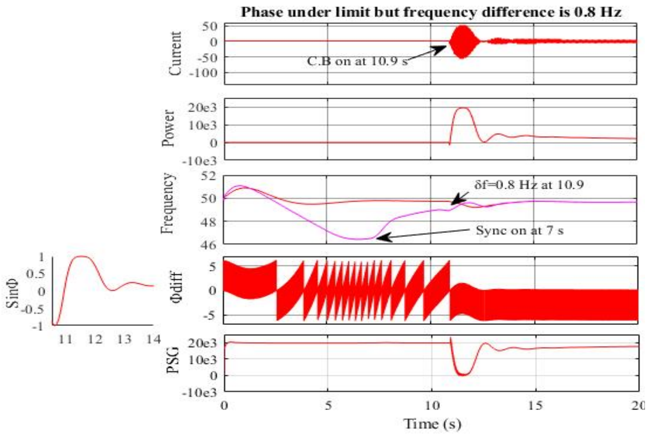

Fig. 15 Response of the system for case III when phase difference is beyond the synchronization limit.

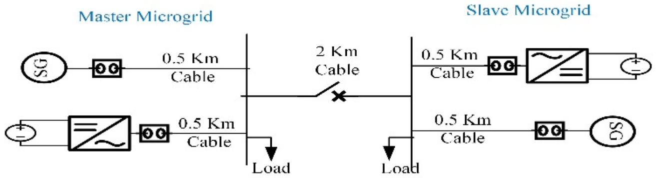

Fig. 16 Reference configuration for case IV

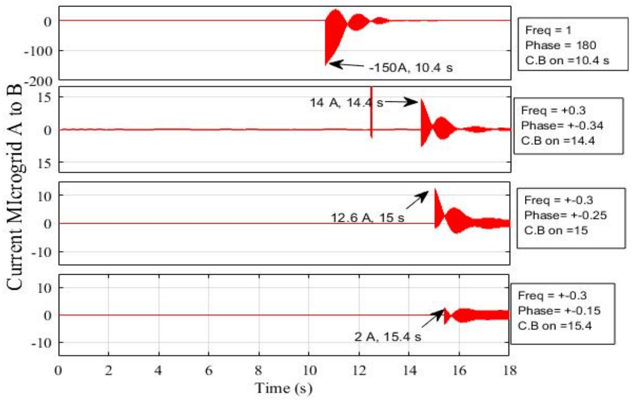

Fig. 17 Current flowing between the microgrids.

V. Conclusion

A synchronization controller for seamless interconnection of microgrids with different kinds of generating sources is developed in this paper. In order to have quick and stable synchronization a smoothing function is introduced in the control loop. In the process, the necessity of following synchronization protocol is established. Furthermore, different case studies are caried out and following inferences are drawn.

When both the microgrids are having only static devices, like inverter based systems, though it is advisable to follow the frequency and phase limits, it may not be necessary as long as the initial inrush currents are within the limits of the converter system, considering the their quick control and inertia-free response.

When any one or both the microgrids are having rotating machine, the synchronization limits have to be followed strictly before interconnection to avoid system instability and damage to the associated components. Stricter the limits, lesser will be the inrush currents. Moreover, in any case, the inrush currents are relatively more sensitive to phase difference when compared with frequency differences.

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