Enhanced transient response and seamless interconnection of multi-microgrids based on an adaptive control scheme

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Abstract
The interconnection of microgrids to form a network known as the multi-microgrid (MMG) brings higher resilience and support in providing power to the loads. The dynamic response during interconnection is usually bypassed with the addition of synchro-checkers installed on all the microgrids and the exchange of critical setting points between the microgrids prior to interconnection via a low-bandwidth communication. This paper introduces a novel decentralized framework for maintaining the voltage and frequency of the microgrids within permissible operating range during the interconnection. The proposed control strategy is triggered when the microgrids violate the defined states of operation and the fast control action from each type of Distributed Generation (DG) in the microgrid is designed to tackle the transients in the voltage and frequency in order to regulate them within the IEEE standards. Moreover, the study is extended to evaluate the performance of interconnecting single microgrids to form MMG using the decentralized proposed control strategy and then sectionalizing the MMG back into separate autonomous microgrids. The results have been verified using PSCAD/EMTDC. The proposed control strategy demonstrates superior performance and simplicity for carrying out the energy management for interconnecting and sectionalizing of MMG without any kind of communication and synchro-check infrastructures.

1 | INTRODUCTION

A microgrid is a sub-grid that contains its own distributed generation for delivering power to the loads. A unique feature of a microgrid is that it can work in either grid connected or islanded state [1]. The independent microgrids can be connected together to form a larger microgrid. Over the years, lots of projects are supporting community-based microgrids that are autonomous such as the IEEE SMART Village [2], USAID project ‘Make cities work’ [3], world bank projects involving smaller villages. It becomes clear that the near future envisions islanded microgrids that are owned and operated by local entrepreneurs which are located in close proximity to each other. This justifies the need to interconnect them for higher resilience and power back up in case of outages in the weaker microgrids or for meeting load requirements.

Connecting several microgrids together involves: (1) Synchronizing the setting points of each AC microgrid so that all the microgrid can be linked via a single bus/point of common coupling (2) The use of back to back converter, static converter, circuit breakers to physically connect the AC microgrids. (3) The use of hybrid or DC microgrids to avoid the synchronization process of interconnecting AC microgrids.

To synchronize the AC microgrids prior to interconnection includes exchange of information for precise chronological coordination of time-variable setting points at high penetration level comprising multiple microgrids [4]. Most of the power balance in literature among parallely connected microgrids occur by exchanging information of voltage and frequency set points alongside optimizing the cost of power generation [5]. The study in [6] uses the minimal cut-set (MCS) method for the optimal interconnection planning of probabilistic microgrids taking
into consideration variability of renewable resources, uncertainties in network- and resource-based and the flexibility of adapting to various operating concerns. Thus, with the proliferation of low bandwidth communication, the accuracy of voltage and frequency regulation prior to communication can be achieved [7] [8].

The interconnection strategies relies on communication that can be the basis of achieving various different objectives and a thorough overview has to be done before connecting different microgrid with different operating conditions to avoid complexities and system outages. Furthermore, studies also use small signal analysis to assess the overall stability of the resulting MMG after interconnection. The study in [9] determines the stability of possible microgrid clusters based on the criteria of dynamic security assessment that exchanges/broadcast information to alleviate the potential instability. A tradeoff is usually implemented in the information that is exchanged over the benefits of sharing setting point information for different microgrid prior to interconnection [10] [11]. The authors in [12] propose a decision making criteria to interconnect two separate microgrids based on small signal stability analysis. Thus, communication is employed via a self-healing agent that decides the power deficiency and range of droop control coefficients in case of instability in the analysis prior to interconnection. All the above interconnection strategies require the exchange of crucial and confidential information between the microgrids. However, these strategies do not discuss the transient analysis during the interconnection process.

A large number of studies alternatively use hybrid AC/DC microgrids to avail the benefits of interconnection via a DC line [13]. Other studies resort to completely DC microgrids to (a) bypass the complexities of different yet close range of frequency of different microgrids, (b) reduced power loss because of corona effect, (c) higher current carrying capacity and (d) higher efficiency because of zero reactive power during transmission. DC microgrids can also be controlled to connect a cluster of different islanded microgrids operating at different operating voltages. [14, 15]. However, the use of two inverters of large capacity and DC tie-line cost a lot and presents an economical challenge to microgrid operators. In addition, the main challenge in the DC microgrid is the non-zero crossing areas that are critical for the breakers [16].

Thus, use of hybrid AC/DC microgrids are gaining popularity. The limitation pertains to the interlinking converters that are used in the synchronization at the distribution level. A detailed survey of the various power converter topologies used to overcome the control issue in the hybrid AC microgrid is being discussed in [17]. The power sharing of the hybrid microgrid is based on the communication between the different microgrids in the MMG. The use of communication-free system that involves multiple cascaded loops and complicated droop techniques; however, they are relatively less economical. Similarly, the power management strategies are discussed in [17, 18]. The use of droop to optimize the power management in the microgrid and interlinking converters are carried out in [19]. The study in [20] proposes a novel strategy for distributed secondary control of hybrid AC/DC microgrids that coordinates the control actions of the AC and DC sides. The use of droop is also used in [21] to optimize the droop characteristics of DGs and interlinking converters for global power sharing in a multi-DG microgrid regardless of DG location and type by proposing an optimal-power-flow-based optimal power sharing (OPS) scheme. Due to the uncertainty in load variations, main grid failures, intermittent power generations from renewable energy sources (RESs), the synchronization and interconnection of different power converters are the paramount issues in the control of AC/DC microgrid [22]. This work covers AC microgrid and does not use interlinking converters to synchronize the microgrids.

For synchronization of AC microgrids, the use of back to back converters are employed in literature to interconnect the microgrids. The study in [23] uses an isolated back to back converter (BTB) to trigger the interconnection between the two microgrids. The two microgrids in [23] operate at different angle droop thus cannot be connected directly through a tie-line and communicate via the BTB converter. Similarly, interconnection based on interlinking converters is also explored in [24] where a distributed power management scheme harnesses the active power and the power converters meets the load reactive power demand. Similarly, a small signal model of single microgrid to form a large interconnected system is proposed in [25] via a back to back converter. The proposed method in [25] uses Robust Control Toolbox and Prony method to validate the interconnection technique.

Static switches and circuit breakers are used as interlinking devices to physically connect the microgrid. The focus in literature with networked microgrid connected via static switches is usually on energy management strategies based on optimization objectives [26–28], stability assessment [29], minimize dynamic interaction between coupled microgrids in the resulting MMG [30]. All these works aim at discussing operations in microgrids after interconnection and do not discuss the dynamics during the interconnection process. Moreover, the switches can only connect AC microgrids with the same nominal voltages and frequencies. Thus, the need to explore the possibility of using the decentralized control scheme that can incorporate the interconnection between the microgrids without the need for synchronization or communication prior to interconnection.

To sum it all up, the following problem has been identified and the contribution follows:

**Problem motivation:**

- Connecting microgrids with different yet close range of frequencies together requires a synchro-check to synchronize frequencies, voltage and phase prior to interconnection. This results in exchange of critical and sometimes confidential information via low-bandwidth communication. If a decentralized system is devised it can bypass the requirement for complex means of communication.
Contribution:

- A novel technique is used to interconnect autonomous microgrids using a completely decentralized voltage and frequency coordination scheme. The proposed adaptive voltage and frequency coordination scheme is designed in consideration of the different multi-states of microgrid operation like over/under frequency/voltage regions. These multi-states in return triggers different virtual coordinated control strategies by each type of DG present in the microgrid. This results in voltage and frequency regulation as per the IEEE Standard 1547.

- Thus, the interconnection of the microgrid is possible without the conventional synchro-checkers, which heavily depends on exchange of information between the microgrids, and allows a communication free interconnection coordination scheme for islanded microgrids.

2 FRAMEWORK OF COORDINATED CONTROL STRATEGIES PROPOSED FOR THE MMG

Each microgrid comprises a mix of different renewable and non-renewable energy source of power generation to better emulate the practical microgrid setup. The MG used for the simulation consists of a PV, BESS, Capacitor banks, an Induction motor, a DFIG-WT and loads. The parameters of the given system are included in the appendix. All the distributed generation are connected to the 11 kV bus through step up transformers. Figure 1 shows the microgrid system used for the simulation of the MMG. The two microgrids are connected via circuit breaker, CB2, which is used for connection to each other while circuit breakers CB1, CB3, are used to connect the subsystems to the main grid as shown in Figure 1. Since the control is proposed for autonomous microgrid CB1,3 are considered to be always open.

The two microgrids are equipped with a variety of renewable energy sources with different loading conditions. The concept of developing the controlled topology is to ensure that during interconnection the two essential parameters that are voltage and frequency are regulated as per the IEEE Standard 1547.

- Thus, the interconnection of the microgrid is possible without the conventional synchro-checkers, which heavily depends on exchange of information between the microgrids, and allows a communication free interconnection coordination scheme for islanded microgrids.

1. This paper distinguishes the regions of frequency and voltages based on the standards. The normal operating voltages are between 0.9 and 1.1 p.u. and normal operating frequency is defined between 0.96 and 1.008 p.u. Anything beyond the normal operating zone is termed as over/under voltage/frequency.

2. The conventional P-f and Q-V droops have been modified and designed separately for each individual type of DG. Current limiters are employed to control the active and reactive power limits of the DG to modify the droops.

3. Thus, each region in the multi-state operation triggers different combination of DG control. Every DG is allotted a specific action under each state of operation. For example: Over frequency will be taken care by the PV curtailing its power output. The PV operates in faster dynamics in curtailing the power generation than a diesel generator and is thus...
used for over frequency regulation which has to be regulated rapidly. Similarly, under voltage can trigger the diesel generator to increase the DG excitation and increase the steps in capacitor banks. These combination of operation by respective DGs will be clearly explained in section below.

The individual control of each DG takes into account the local signal or measurement to regulate the voltage and frequency and thus the whole system is decentralized and no exchange of confidential information is required between the microgrids during steady state and dynamic condition. Each controller is calibrated to trigger the voltage and frequency control with the help of active and reactive power injection into the PCC.

This paper identifies the multi-states of operation on the basis of the regions of frequency and voltages that violate the IEEE standard 1547. Each DG control is designed to take respective action in the demarcated defined region. The resulting action taken in each violation region by the corresponding DG is shown in Figure 2. As can be seen in Figure 2, during over voltage the capacitor banks are frozen and the diesel excitation is reduced. During over voltage when the capacitor banks are frozen, the inverter-based DG may now absorb the reactive power and operate in inductive mode. Thus, it maximizes the fast dynamic reactive power reserve by moving from inductive mode to maximum capacitive mode of operation. On the other hand, diesel generator contributes to the under voltage state by increasing the excitation field.

In the proposed work, we are using the droop control for coordinating the DGs and the loads in a microgrid. However, the basic droop control is modified from the conventional $P$-f/Q-V droop for each individual DG to implement the proposed strategy of voltage and frequency regulation. Some key features of the proposed control are:

- Figures 3 and 4 shows how the basic QV and PF droops are modified to implement the control strategy of each individual DG. Figure 3(a) shows for the diesel generator that at 0.9 p.u. the reactive power 100% and varies with the voltage of the bus. For the inverter-based DG the droop is adjusted to absorb or inject the reactive power when the voltage varies from 1 p.u as shown in Figure 3(b). This is controlled in coordination with the mechanical switching capacitor bank (MSCB) and applying the hard limit to $I_{q, ref}$. During the operation between 0.9 and 1.1 p.u., the $I_{q, ref}$ is set to 40%. Then the MSCB is forced to take more action in terms of switching the capacitor banks steps to alter the voltage. This results in maximizing the fast dynamic reactive power reserves in PV, DFIG-WT and BESS.

- The frequency of the autonomous microgrid is also regulated with the droop adjusted between 1.002 and 0.99 for diesel generator with the corresponding active power regulated between 30% and 100%. For the PV, the droop varies from 1.008-1.002-0.99 where PV injects 0 active power at >1.008 p.u. whereas, for the BESS the droop is 1.008–0.99 as can be seen in Figures 4(a), 4(b) and 4(c) respectively. The frequency droop from 1.002 to 1.008 p.u. is the curtailment mode of the PV. The fast frequency regulation is achieved by the help of the droop control in BESS and PV during transient state and the slow dynamic of the diesel is utilized for the regulation at steady state condition.

- During over frequency, the PV starts curtailing the power to maintain the frequency and frequency triggers the BESS control to cause the State of Charge (SOC) of the battery to be 95% in order to increase the charging consumption. On the other hand, during under frequency, the BESS lowers the SOC to 20% to cover up the active power and the diesel operates at 100% rating to bring the frequency back up to the acceptable limit.
In addition to this, for each respective DG, a separate algorithm is implemented to ensure voltage and frequency regulation as will be discussed in the section below.

2.1 Battery energy storage system

During interconnection the BESS is one of the devices that have a fast dynamic response. It is coupled with the slow, medium and fast dynamic operation of the diesel, WT and PV respectively. Figure 5 shows a detailed decoupled active and reactive power control implemented for the inverter control. Park’s transformation is applied to the three phase voltage and current measured from the line. The d-axis controls the active power and the q-axis controls the reactive power. The frequency is compared with the reference frequency and the error is sent to PI controller which in turn generates the \( I_{dref} \) of the current to be injected to the microgrid. Similarly, the terminal voltage is compared with \( V_{ref} \) and error is sent to PI controller, bounded by current limiters tuned according to the \( I_{dref} \). This ensures proper reactive and active power sharing during steady and dynamic state of operation of the microgrid.

The dynamics of the droop controller are represented by the following equations:

\[
i_{d,ref} = K_{pv}(F_{ref} - F_{meas}) + K_{p} \int (F_{ref} - F_{meas}) \, dt, \tag{2}
\]

\[
i_{q,ref} = K_{pv}(V_{ref} - V_{pcc}) + K_{i} \int (V_{ref} - V_{pcc}) - v_{d} \, dt, \tag{1}
\]

where \( K_{pv} \) and \( K_{pi} \) are the proportional and integral gains, respectively.

The dynamics of the current control loop are given by the following equation:

\[
v_{dout} = K_{pi}(i_{d,ref} - i_{d}) + K_{ii} \int (i_{d,ref} - i_{d}) \, dt - wL_{f}i_{q,ref}, \tag{3}
\]

\[
v_{qout} = K_{pi}(i_{q,ref} - i_{q}) + K_{ii} \int (i_{q,ref} - i_{q}) \, dt + wL_{f}i_{d,ref}, \tag{4}
\]

where \( K_{pi} \) and \( K_{ii} \) are the proportional and integral gains, respectively and \( L_{f} \) is the filter inductance gain.

The operating droops shown in Figure 5 describe how the reactive power component \( I_{q} \) varies between 40% and 100% when the terminal voltage changes from this operating range 0.9 – 1.1 p.u. The reactive power is injected when the terminal voltage < 1 p.u. and absorbed from the microgrid if the terminal voltage > 1 p.u. Moreover, when the \( F < 0.96 \) p.u. the SOC’s lower limit is set to 20% and for \( F > 1.008 \) p.u. the SOC is set to 95%. Algorithm 1 summarizes the strategy for voltage and frequency regulation between the above stated limits.


Algorithm 1  Algorithm for voltage and frequency control for BESS

Input the local measurements for Voltage and frequency

if \( V_{BESS} > 1.1 \text{ p.u.} \)

Maximize the reactive power reserve \( Q \), by restricting the \( I_q \) to 40% and forces the MSCB to take more action.

else if \( V_{BESS} < 0.9 \text{ p.u.} \)

Release the \( I_q \) limit up to 100%

else if \( f_{BESS} < 1.005 \text{ p.u.} \)

Release the SOC upper limit to 95%

else if \( f_{BESS} < 0.95 \text{ p.u.} \)

Release the SOC lower limit to 20%

else

Normal Operation \( I_q \) limit up to 40% & 40% < SOC < 80%

end if

Algorithm 2  Algorithm for voltage and frequency control for PV

Input the local measurements for Voltage and frequency

if \( F_{f} > 1.1 \text{ p.u.} \)

Maximize the reactive power reserve \( Q \), by restricting the \( I_q \) to 40% and forces the MSCB to take more action.

else if \( F_{f} < 0.9 \text{ p.u.} \)

Release the \( I_q \) limit up to 100%

else if \( F_{f} > 1.002 \text{ p.u.} \)

Activate PV Power Curtailment

else

Normal Operation \( I_q \) limit up to 40%

end if

2.2  PV power system

The inverter control of the PV is similar to the BESS described above. However, in addition to the inverter control the droop also carries out PV power curtailment when 1.002 p.u. < \( F \) < 1.008 p.u. On the contrary, if \( F \) < 1.002 p.u. rated power is injected into the microgrid. This is clarified in Figure 5(c). The curtailment equation is as follows:

\[
X_{pr,curt} = \begin{cases} 
1 & \text{if } \frac{F}{F_{rating}} < 1.002 \text{ p.u.} \\
0 & \text{if } 1.002 \text{ p.u.} < \frac{F}{F_{rating}} < 1.008 \text{ p.u.}, \end{cases}
\]

(5)

\[
i_{d,ref,pr} = K_{p,pr}(F_{ref} - F_{meas}) \ast F_{pr,curt},
\]

(6)

\[
i_{q,ref,curt} + K_{i,pr} \int (F_{ref} - F_{meas}) \ast F_{pr,curt}.
\]

(7)

For regulating the voltage, the \( I_{ref} \) hard limit is set to 40% of the available \( I_{pr,ref} \) capacity for the voltage range 0.9–1.1 p.u. forces the MSCB to take more steps resulting in maximizing the fast dynamic reactive power reserve in the inverter. In an event of under voltage, the \( I_q \) maximizes the reactive power and releases the limit to 100%. Algorithm 2 clarifies the above described strategy for PV distributed generation.

2.3  DFIG wind turbine

The wind turbine is a doubly fed induction generator. The modelling of the wind turbine is found in Figure 6. The dynamic of the rotor side is governed by the following equations:

\[
i_{d,ref,rotor} = K_{p1}(P_m - P_2) + K_{i1} \int (P_m - P_2) dt,
\]

(8)

\[
i_{q,ref,rotor} = (K_{p2}(v_{ref} - v_m) + K_{i2} \int (v_{ref} - v_m) dt) \ast I_{q,comp}.
\]

(9)

The Grid side control is given by the following equations:

\[
i_{q,ref,grid} = (K_{p2}(v_{ref} - v_m) + K_{i2} \int (v_{ref} - v_m) dt) \ast I_{q,comp},
\]

(10)

\[
i_{d,ref,grid} = K_{p2}(v_{dc,ref} - v_{dc,m}) + K_{i2} \int (v_{dc,ref} - v_{dc,m}) dt,
\]

(11)

where \( K_{p1}, K_{p2}, K_{i1} \) and \( K_{i2} \) are the proportional and integral gains, respectively and \( I_{q,comp} \) is given by:

\[
I_{q,comp} = \sqrt{I_{comp}^2 - I_{d,ref}^2}.
\]

(12)

This signal is then cascaded to current control loop in the grid control and rotor control as shown in Figure 6. Moreover, the wind turbine in the proposed control schemes is used to explicitly carry out voltage regulation as described in Algorithm 3. The rotor-side converter (RSC) is dedicated to voltage regulation and maintaining the electromagnetic torque so that maximum power can be achieved. The grid-side converter (GSC) regulates the DC link and the active power flow to the DC link. The \( I_{q,linear} \) is altered corresponding to the voltage measurements.

2.4  Diesel generator

The diesel generator is equipped with a speed governor to regulate the system frequency. A governor system is used to control the generator speed, an AVR provides the exciter field voltage that regulates the terminal voltage of the diesel generator. The response from BESS/PV is relatively faster than diesel and capacitor banks. The rapid response of the fast devices is tackled by activating the slow response devices through delaying the voltage signal using the low pass filter. The mechanical dynamic equations of the diesel generator are:

\[
\frac{dw_r}{dt} = \frac{1}{2H_1}(T_m - T_r),
\]

(13)

\[
\frac{d\delta}{w_{base}dt} = w_r,
\]

(14)
Algorithm 3  Algorithm for voltage and frequency control for DFIG wind turbine

Input the local measurements for Voltage and frequency

if \( V_{WT} > 1.1 \text{ p.u.} \) then
    Maximize the reactive power reserve \( Q \), by restricting the \( I_q \) to 40\% and forces the MSCB to take more action.
else if \( V_{WT} < 0.9 \text{ p.u.} \) then
    Release the \( I_q \) limit up to 100\%
else
    Normal Operation \( I_q \) limit up to 40\%
end if

where \( \omega_r, \delta, H_1, T_m, T_e \) are the rotor angular speed, rotor angular position, rotor angular constant, mechanical torque and electrical torque of the diesel generator, respectively. \( T_e \) is given by

\[
T_e = \psi_d * i_d - \psi_q * i_q, \quad (15)
\]

where \( \psi \) is the flux linkages of the windings. The droop controllers for the diesel generator are implemented as:

\[
w = w_n - K_p P_e, \quad (16)
\]

\[
V = V_n - K_q Q_e, \quad (17)
\]

where \( K_p \) and \( K_q \) denote the droop gains; \( P_e \) and \( Q_e \) are the diesel generator active and reactive power output, respectively; \( w_n \) and \( V_n \) are the reference speed of the governor and reference voltage of the exciter, respectively. Algorithm 4 below discusses the control strategy of the diesel generator:

Algorithm 4  Algorithm for voltage and frequency control for diesel

Input the local measurements for Voltage and frequency

if \( V_{DZ} > 1.1 \text{ p.u.} \) then
    Low Pass Filter
    Reduce the DZ excitation Operation
else if \( V_{DZ} < 0.9 \text{ p.u.} \) then
    Low Pass Filter
    Increasing the DZ excitation Operation
else if \( f_{DZ} > 1.002 \text{ p.u.} \) then
    Reduce the DZ Operation by reducing the active power by 30\% of its rated capacity
else if \( f_{DZ} < 0.96 \text{ p.u.} \) then
    operate DZ at rated capacity
else
    Low Pass Filter
    Normal Operation
end if

2.5  | Capacitor bank

The CAP banks increase the steps and the diesel increases the excitation during under voltage state of operation. On the other hand, during over voltage the CAP bank decreases the steps and the diesel reduces the excitation. For the regulation of frequency, the diesel generator plays a part by operating at rated power
Algorithm 5: Algorithm for voltage and frequency control for capacitor bank

```
Input the local measurements for Voltage and frequency
if $V_{CAP} > 1.1 \text{ p.u.}$ then
    Low Pass Filter
    Freeze the CAP bank steps
else if $V_{CAP} < 0.9 \text{ p.u.}$ then
    Low Pass Filter
    Increase the CAP bank steps
else Normal Operation which includes variation on CAP banks to regulate the voltage within limits
end if
```

in event of under frequency and reducing the active power by 30% of its rated capacity in over frequency state of operation. Algorithm 5 describes the control strategy of the capacitor bank.

3 | EVALUATION OF THE PROPOSED CONTROL SCHEME

3.1 | Results considering different states of operations for a single MG

In order to test the operating conditions of the proposed scheme under different states of operation a series of load transition strategy is incorporated to achieve a state of over or under frequency or voltage. For example, when an active load is added to the system it increases the overall loading level and causes under frequency (UF), and when the active load is disconnected due to the characteristic of P-F droop this causes over frequency (OF). Similarly due to the dynamics of Q-V droop, when a reactive load is added to the system, it causes under voltage (UV) and on disconnection of a reactive load can cause over voltage (OV). According to the rating of the DGs in the microgrid and the connected loads, the value of each active and reactive load is decided respectively. Consequently, combination of different active and reactive loads can also cause for example OV and UF at the same time. Figure 9 shows the values of 10 loads are connected and disconnected at different times to achieve the multi-states of operation that are OV, OF, UF, UF and the combination of different active and reactive loads can also cause for example OV and UF at the same time. Figure 9 shows that the frequency of the microgrid during the multiple states of operation. The proposed scheme shows enhanced transient response in all the OF scenarios. It can be observed that the conventional scheme violated the IEEE 1547 standard by not regulating the frequency of the system $f > 1.008 \text{ p.u.}$ at instances $t = 150, 450, 800 \text{ s}$ whereas the proposed scheme showed frequency regulation in these respective instances. The instances of OF are countered by the proposed scheme and the Figure 8 shows minimal overshoot at these time (i.e. at $t = 150, 450\text{ s}$).

The active power generation of the DGs is shown in Figure 10 for the BESS, PV, wind turbine and diesel generator respectively. The novel aspect of the proposed scheme is the coordinated response that seems to occur virtually between the different types of DGs without any sort of communication between them. The proposed scheme is completely decentralized yet under the forced scenario of over/under frequency/voltage the wind, PV, diesel and BESS acts independently according to the devised proposed control. The following discussion highlights the features unique to each type of DG during the transition from one scenario to the next. It can be observed that in the states of OF the BESS is charging since the SOC upper limit is adjusted to allow for more charging and this restores the condition to normal state. Similarly, the PV curtailing can be observed at $t = 150, 450, 750, 800, 950 \text{ s}$ which corresponds to the OF condition as shown in Figure 8. The diesel generator takes a relatively slower action in frequency regulation. Furthermore, the active power profile for the wind turbine is mainly maintained at constant 0.74 p.u. with momentarily spikes that are caused by the sudden change in voltage.

3.2 | Results for interconnection of MGs to form MMG system

The Microgrid 1 and Microgrid 2 are operating at different loading levels. The total load connected to MG1 is $1.25 + j0.45 \text{ MVA}$
and the load connected to MG2 is $0.6 + j0.2$ MVA, in addition to fixed induction load in MG1 and MG2 (rating mentioned in appendix). In addition to this, an induction motor is also connected to each microgrid as shown in Figure 1. Due to the difference in loads the interconnection at different frequencies can be a critical step especially if there is no synchronization prior to interconnection. On the other hand, centralized control follows series of synchronization steps to match the frequency of the MG1 to MG2. The framework of the centralized controller is shown in Figure 11. As can be seen in Figure 11, a low bandwidth communication is used to measure the frequencies of the two microgrids by the centralized controller. The difference in the two frequencies is computed ($f_\delta$) which is subtracted from the over frequency state in the microgrid having higher frequency and the resulting signal is sent to the microgrid’s frequency controller to equalize the frequency to $F_{\text{synch}}$. Contrary to this, $f_\delta$ is added to the frequency of the microgrid with lower frequency to achieve frequency synchronization. Finally, the diesel generator then takes action to match the frequency to the generated $F_{\text{synch}}$ in the respective microgrid.

The following results show the effectiveness of the decentralized scheme proposed compared to a centralized scheme discussed above. In the first case study, a comparison of different response from the MG is discussed for the centralized
and proposed schemes. The centralized scheme uses communication to synchronize the frequency before interconnection. This signal is called $T_{\text{synch}}$ and is activated at $t = 26s$ in this case study. The interconnection $T_{\text{IC}}$ is carried out at $t = 30s$. To make this section clearer, the results are presented in the following series and the discussion follow suit. The interconnection occurs at $t = 30s$ and the Voltage, Frequency and phase of the two microgrids are shown from Figures 12–14. Next, the Active and reactive power injection of the four types of different DGs that are BESS, PV, wind and diesel generator are shown from Figures 15–22, respectively.

As can be seen from the Figure 12, the voltage of the MG1 and MG2 varies from 0.96 to 0.9 p.u. for centralized scheme and between 0.85 and 0.96 p.u. for the proposed control scheme at the instant of interconnection. For a decentralized control scheme the voltage dip is recovered in less than 0.1s which is acceptable according to IEEE 1547 standards.
Figures 13 and 14 show the frequency and phase of the microgrids before and after the interconnection respectively. The frequency of the system for centralized scheme is synchronized at $t = 26$ s at 1 p.u., prior to interconnection at $t = 30$ s as shown. On the contrary, the proposed scheme connects the microgrids at different frequencies that is $f_{MG1} = 0.995$ p.u. and $f_{MG2} = 1.005$ p.u. Figure 13 thus validates the effectiveness of the proposed scheme for connecting microgrids at different frequencies without any significant overshoot in the transient response.

Similarly, Figure 14 shows that the two microgrids have different phase angles prior to interconnection. Although the centralized system synchronizes the angles of the two microgrids
before interconnection, the transient response achieved using the proposed scheme ensures that two systems with different phase angles can be interconnected with no significant overshoot. The proposed scheme is completely decentralized and yet it ensures a smooth interconnection of the two microgrids operating at different voltages, frequencies and phase angle without any violation of IEEE 1547 standard for islanded microgrids. It is worth to mention that the performance of the proposed control strategy can be further enhanced by employing advanced PLL or FLL synchronization scheme for achieving faster response in locking to frequency and phase angle.

The active and reactive power of the BESS DG for MG1 and MG2 can be seen in Figures 15 and 16, respectively. The centralized and proposed schemes follow closely, but the response of active power to reach steady state in MG1 and MG2 is faster for proposed scheme than the centralized scheme. It can also be noted that the BESS is supplying 0.4 MW in MG1 before interconnection due to high loads connected whereas the BESS in MG2 is charging and absorbing power of 0.6 MW from the grid. After interconnection both the BESS absorb equal active power of 0.17 MW from the microgrid. The reactive power injected in MG1 by BESS was around 0.2 MVar whereas in MG2 it was 0.06 MVar for the proposed scheme. After interconnection both the BESS inject approximately 0.11 MVar. The steps in the reactive power are due to the change in voltage by the capacitive banks ensuring the steady state is reached.

The two microgrids have different phase angles prior to interconnection. Although the centralized system synchronizes the angles of the two microgrids before interconnection, the transient response achieved using the proposed scheme ensures that two systems with different phase angles can be interconnected with no significant over shoot. The proposed scheme is completely decentralized and yet it ensures a smooth interconnection of the two microgrids operating at different voltages.

The PV graphs for active and reactive power are shown in Figures 17 and 18 for MG1 and MG2, respectively. The PV response can be best explained with help of Figure 13 (proposed scheme). As can be seen from Figure 13, the MG2 before interconnection is operating at over frequency (i.e. 1.008 p.u.) due to less loads connected to it and thus, the PV generator for MG2 in Figure 18 can be seen to curtail the active power to bring the frequency back to normal. After interconnection, the PV for MG2 starts to injects higher active power till it reaches steady state at 1 p.u. at t = 85 s. The active power of PV for MG1 is almost constant at 1 p.u. because MG1 is operating at normal frequency range with slight disturbance during interconnection caused due to the change in frequency of the system. The reactive power injection is controlled with the $I_q$ limit which depends on the voltage of the system. As can be seen in Figure 12 the voltage changes with capacitive banks and that in turn changes the reactive power injection of the PV of MG1 and MG2.

Figures 19 and 20 show the active and reactive power of the wind turbine for MG1 and MG2 respectively. It is observed that the wind turbine shows a constant active power injection at 1.25 MW before and after interconnection. There is a disturbance during interconnection which is due to the voltage sag. The wind turbine was initially absorbing the reactive power for MG2 of 0.02 MVar while for MG1 the reactive power injected was 0.15 MVar. After interconnection at t = 30 s the WT inject reactive power of $Q_{wt,MG_1} = 0.1$ MVar and $Q_{wt,MG_2} = 0.3$ MVar. The slight change is reflected because of the difference in voltage of the two MG and the capacitor banks account for steps in reactive power injection for wind turbine.
The response of diesel generator is shown in Figures 21 and 22, for the active and reactive power of the MG1 and MG2 respectively. The slow dynamics of the diesel can be seen to reach the steady state at around $t = 100\text{s}$. Although the active power is slightly adjusted at $t = 100\text{s}$ to $P_{DZ, MG1} = 0.75\text{ MW}$ and $P_{DZ, MG2} = 0.6\text{ MW}$. Before interconnection, the reactive power, $Q_{DZ, MG1} = 0.02\text{ MVAR}$, was injected in MG1. On the other hand, the reactive power was absorbed from MG2 where $Q_{DZ, MG1} = -0.04\text{ MVAR}$. After interconnection both the diesel generator in MG1 and MG2 absorbed reactive power from the grid and $Q_{DZ} = -0.04\text{ MVAR}$. Moreover it can be seen from both Figures 21 and 22 that the centralized response shows slower response as compared to proposed scheme which has an enhanced performance of the diesel generator for active and reactive power response.

### 3.3 Results for sectionalizing MMG to MGs

The study with the proposed scheme was extended to test the performance during sectionalization of the connected MMG system to form MG1 and MG2. In this section the results are presented in the following order: Figures 23–25 highlight the Voltage, frequency and phase of the two microgrids before and after sectionalizing. This is followed by the Active power injection of the 4 types of DGS that is wind turbine, BESS, PV, diesel in MG1 in Figure 26 and MG2 in Figure 27. Lastly, the reactive power injection of the 4 types of DGS in MG1 and MG2 are shown in Figures 28 and 29, respectively.

Figure 23 shows the voltage of the bus. The centralized and proposed scheme show similar response during sectionalization. The voltage before interconnection is $0.94\text{ p.u.}$ and after interconnection $V_{MG1} = 0.92\text{ p.u.}$ and $V_{MG2} = 0.96\text{ p.u.}$

The frequency and phase of the system are shown in Figures 24 and 25, respectively. The frequency response shows how the proposed scheme has an enhanced transient response
during sectionalizing. For the centralized scheme the frequency is violated under the IEEE 1547 standard (> 1.008 p.u.). However, the frequency of the proposed scheme is always below 1.008 p.u. Similar response is seen in the phase angles with no significant spike during sectionalizing for the proposed scheme in Figure 25.

Figures 26 and 27 show the active power of MG1 and MG2 from all the DGs. The response of MG1 for proposed scheme coincides with that of centralized scheme. There is a noticeable sag in $P_{w,t, MG1}$ due to the sag in voltage seen for MG1 in Figure 23. For the PV, $P_{PV, MG1}$ is approximately close to 1 p.u. because the frequency is under the permissible limit. The BESS was charging and absorbing active power in MMG system. After sectionalizing, the BESS starts injecting active power in MG1 with $P_{BESS, MG1} = 0.4$ MW. The diesel generator shows an increase in the active power injection for MG1.

For the response in MG2, the wind turbine for centralized system shows a spike in active power injection during sectionalizing. Whereas, the proposed control shows a smooth controlled response of the wind turbine. The PV shows curtailment of active power injection because the MG2 is now operating at over frequency of 1.008 p.u. after sectionalizing. Thus, for the steady state $P_{w,t, MG2} = 0.75$ p.u. as compared to 1 p.u. in centralized scheme for MG2. The BESS which was absorbing power continues to absorb power after sectionalizing in MG2 because of less loads connected. Lastly, the diesel generator shows consistent response for MG2 approximately close by $P_{DZ, MG2} = 0.55$ p.u. before and after the sectionalizing.

Figures 28 and 29 show the reactive power of the DGs in an event of sectionalizing of MMG system into two MGs. The wind turbine in MG1 is injecting reactive power in MMG system; however, after sectionalizing the wind turbine injects reactive power for the relatively loaded MG1 but absorbs reactive power for the less loaded MG2. As can be seen from Figure 23, the voltage of MG1 is lower than MG2 thus the reactive power injection by the BESS, PV and diesel is higher as compared to MG2. For the BESS, wind turbine and diesel generators, the reactive power for MG2 is actually absorbed from the grid and the loads are met by PV and BESS injecting $P_{BESS, MG2} = 0.05$ p.u. and $P_{PV, MG2} = 0.33$ p.u. Overall, the proposed scheme shows an enhanced performance with respect to transients during sectionalizing compared to the centralized scheme which lacked the dynamic ability to smoothly sectionalize the MMG system.

4 | CONCLUSION

The paper utilizes a decentralized scheme to regulate voltage and frequency in an islanded microgrid utilizing active and reactive power injections by the variety of integrated DGs consisting of wind, diesel, BESS, PV. The proposed system show comparable response to the centralized system conventionally used in the microgrids which requires expensive synchro checker for equalizing frequencies and voltages of the two separate systems prior to interconnection. The proposed scheme is able to connect two autonomous microgrids operating at different voltages, frequencies, phases without any communication and the response shows no violation of IEEE 1547 Standards. Additionally the proposed scheme can also be used for sectionalizing and shows enhanced transient response for the proposed scheme as compared to the centralized scheme. The proposed decentralized scheme can be helpful to the MMG providers that implement energy management by interconnecting microgrids or sectionalizing MMG system.

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### APPENDIX

**TABLE A.1** Power system DFIG-WT,PV,BESS,DZ,CAP Bank parameters

| Parameter                         | Value                        |
|-----------------------------------|------------------------------|
| DFIG-WT                           |                              |
| Rated power                       | 0.9 MVA                      |
| Rated voltage                     | 690 V                        |
| Inertia (J = 2H)                  | 0.85                         |
| RSC rating                        | 0.3 p.u.                     |
| Gsc rating                        | 0.3 p.u.                     |
| DC link voltage                   | 875 V                        |
| DZ cable                          | 0.01 p.u.                    |
| Rated power                       | 1 MVA                        |
| Primary voltage                   | 69 kV                        |
| Secondary voltage                 | 11 kV                        |
| Positive leakage react            | 0.06 p.u.                    |
| Rated power                       | 1 MVA                        |
| Phase voltage                     | 5.196 kV                     |
| RMS line current                  | 0.0641 kA                    |
| Inertia constant                  | 0.5 s                        |
| Neutral series resistance         | 1.0E5 p.u.                   |
| Rated power                       | 15 MVA                       |
| Positive leakage react            | 0.08 p.u.                    |
| Primary voltage                   | 69 kV                        |
| Secondary voltage                 | 11 kV                        |
| Magnitiz Current                  | 1%                           |
| Electric grid                     | PV cable                     |
| Rated voltage                     | 132 kV                       |
| Rated frequency                   | 50 Hz                        |
| X/R                               | 7                            |
| SCR                               | 6                            |
| Dynamic load parameter            |                              |
| Rated power                       | 0.5 MVA                      |
| Rated voltage                     | 38 kV                        |
| Mechanical damping                | 0.01                         |
| MPPT model parameter              |                              |
| PV array short circuit current    | 160.1 A                      |
| PV array open circuit voltage      | 750 V                        |
| PV model parameters               |                              |
| Electron charge                   | 1.6E-19 C                    |
| Shunt resistence                  | 1000 Ω                       |
| Ideality factor                   | 1.5                          |
| STC short circuit current         | 2.5A                         |
| STC temp.                         | 298K                         |
| Initial value                     |                              |
| Sampling interval                 |                              |
| Angular moment inertia            | 0.1s                         |
| Base angular freq.                | 314 rad/s                    |
| Series resistance                 |                              |
| STC saturation current            | 1E-9A                        |
| Temp. coefficient                 | 0.001                        |
| STC solar irradiance              | 1 kW/m²                      |