Abstract—This paper deals with the voltage and frequency restoration problem for a droop controlled islanded microgrid (MG). A consensus based distributed control is proposed for voltage/frequency restoration of MG which allows all the distributed generator (DG) unit voltage magnitude and operating frequency to converge to the nominal values even with different communication topologies. The proposed control scheme is distributed in nature thereby eliminating the risk of single point failure because no central controller is required. Here, DG units need to communicate with their immediate neighbors only over a distributed communication network. The communication network has inherent transmission delays which can adversely affect the controller performance. Here, the impact of time delay is investigated on the proposed secondary controller of MG system. An islanded MG test system consisting of five DG unit, their respective loads, and transmission lines is simulated in MATLAB/Simulink to verify the performance of the proposed technique.

Keywords—Consensus algorithm, distributed generation, droop control, distributed secondary control, communication latency.

I. INTRODUCTION

The modern power system has been continuously increasing penetration of DG units, thereby making the operation and control quite challenging [1]. The MG being an integrated energy system organize the power system in a coordinated manner. The MG comprises of various technologies like inverters, DGs, storage systems and communication network that can operate either in the grid-connected mode or autonomously in islanded mode [2]. In grid-connected mode, the main grid forming units i.e. synchronous generators of the main grid provides operating voltage and frequency for the entire system. In islanded mode, because of the absence of main grid as a reference, MG maintains its stable operation by regulating all the components of its own. Thus, the control structure is an important part of an MG system with entirely inverter-interfaced structure with no inertia for its stable and efficient operation.

This paper focuses on the islanded mode of operation after scheduled maintenance or faults in a MG. The control design is intended to achieve the voltage/frequency restoration after islanding or load disturbances, energy management, and economic optimization [3]. Hierarchical control scheme has been suggested in literature to standardize MG operation [4]. In the hierarchical control approach, three levels of control have been specified. The first level is the primary control, which is independent and realized locally at each DG unit via droop functions, voltage, and current control loops. Though droop control has a distributed structure and provides good power sharing, it is incapable of removing voltage and frequency disparities without the secondary control level. The secondary control brings back the voltage and frequency to their nominal values. The tertiary control layer is more related to the economic power dispatch and optimization within the main grid.

The secondary control atone the voltage and frequency fluctuations induced by the droop control loop. It is conventionally implemented via MG central controllers (MGCC), which uses a complex two-way communication and a central computing unit. It also suffers from the risk of single point failure. To address the above drawbacks, distributed control for multi-agent system has been suggested [5]. The distributed control needs sparse communication network where only neighboring DGs information is required, which reduces the communication infrastructure cost and makes the system more reliable and secure. Different distributed type of secondary control techniques have been reported in [5]–[7]. In [5], a feedback linearization based pinning control scheme is proposed for voltage restoration. More recent studies consider the consensus-based control of multi-agent system for different areas of MG like power sharing etc. However, more research is necessary in consensus-based control, in view of fully exploiting its advantages, we employ the consensus algorithm for voltage/ frequency regulation with inclusion of time delays. The proposed scheme uses simple sparse communication structure and does not have a central computing unit thereby reducing the risk of single point failure.

Rest of the paper is as follows. In Section II, the primary control structure of MG is described. In Section III, the proposed consensus based control strategy is given, which covers voltage and frequency restoration. Section IV
gives the simulation results and case studies incorporating communication delays to validate the proposed algorithms. Section V concludes the paper.

II. PRIMARY CONTROL FOR MG

An inverter-based MG comprises of various elements able to operate in parallel either in grid-connected mode or islanded mode. In a MG test system, each DG unit have primary DC power source, voltage source inverter (VSI) an LC filter and an output RL connector as shown in Fig. 1. The primary control of inverter-based MG consists of voltage, current and droop control loops. The droop control generates the reference input $V_{s,ref}$ for the voltage controller, which further provides the reference input, $i_{s,ref}$ for the current controller block. The current controller generates the input reference for the pulse width modulation (PWM) block, which control the output of the VSI [7]. The primary control level is liable for controlling voltage, and frequency deviation after islanding process where the generated power does not meet user demand. The droop control is an independent and wireless control that eliminates the requirement for communication links at the primary level of control.

The droop control method can be described by considering a simplified model for power flow from a VSI to MG, as shown in Fig. 2. If the high frequency ripples are overlooked, the VSI is modeled as an voltage source with $V_{MG}$ and the lumped line impedance is $Z \angle \theta$. The common MG bus voltage $V_{bus}$ can be derived as

$$V_{bus} = \frac{V_{MG}V_{oi} \sin \delta}{Z}$$

$$Q_i = \frac{V_{MG}V_{oi} \cos \delta - V_{MG}^2}{Z}$$ (3)

If the difference of phase angles between the inverters output voltage and MG bus voltage, $\delta$, is considerably smaller, then, $\sin \delta \approx \delta$ and $\cos \delta \approx 1$. Equation (3) can be reduced to

$$P_i \approx \frac{V_{MG}V_{oi}}{Z} \delta$$

$$Q_i \approx \frac{V_{MG}V_{oi} - V_{MG}^2}{Z}$$ (4)

Equation (4) gives direct relationship between active power $P_i$ and phase angle $\delta$ and reactive power $Q_i$ and output voltage $V_{oi}$. Thus, voltage and frequency droop equations can be utilized to tune the operating voltage and frequency reference of inverter [8]. As seen from Fig. 3(a), in the steady state, nominal operating point is $a$ ($P_{old}$, $\omega_{nom}$). Once the $P_{old}$ increases to $P_{new}$, the angular frequency $\omega$ will decrease because of the $P - \omega$ droop characteristic and settle down on the point $b$ ($P_{new}$, $\omega_{new}$). Further, the triggered secondary level of control will restore $\omega$ to its original value $\omega_{nom}$ by adjusting the transient point $c$ ($P_{new}$, $\omega_{nom}$). The restoration of operating voltage magnitude shown in Fig. 3(b) is analogous to Fig. 3(a). It is observed from the above analysis that the voltage and frequency droop control scheme employed in the primary stage of distributed control is given as

$$V_{oi} = V_{n1} - k_{V}Q_i$$ (5)
\( \omega_i = \omega_{ni} - k_P^p P_i \) \hspace{1cm} (6)

where \( V_{ni} \) and \( \omega_{ni} \) are the nominal set point of \( i^{th} \) DG's voltage magnitude and angular frequency, \( Q_i \) and \( P_i \) are the measured reactive and real powers, \( k_Q \) and \( k_P^p \) are the droop coefficients for the voltage and frequency control scheme.

The power controller is shown in Fig. 4. By using d-q reference frame transformation [8], dynamics of every DG unit is converted into their respective d-q reference frames. The power controller includes the primary control stage and provides direct and quadrature terms of reference voltage \( V_{odi}^* \) and \( V_{oqi}^* \) for voltage control loop and operating angular frequency \( \omega_i \) for the VSI.

The active and reactive powers can be calculated by

\[
P_i = \frac{\omega_c}{\omega_c + S} (V_{odi}^*odi + V_{oqi}^*oqi) \hspace{1cm} (7)
\]

\[Q_i = \frac{\omega_c}{\omega_c + S} (V_{odi}^*odi - V_{oqi}^*oqi) \]

where the power controller has the low-pass filter with cut-off frequency of \( \omega_c \). The primary control stage aligns the voltage magnitude to the direct-axis of the corresponding DG’s d-q reference frame and quadrature axis reference is, set to 0 as follows

\[
\begin{align*}
V_{odi}^* &= V_{ni} - k_Q Q_i \\
V_{oqi}^* &= 0 \\
\omega_i &= \omega_{ni} - k_P^p P_i
\end{align*} \hspace{1cm} (8)
\]

The primary droop control keeps the voltage and frequency deviations close to the original values once user demands changes, whereas the secondary control strategy restores the deviations induced by primary control. Thus, secondary control scheme has to be formulated such that \( \lim_{t \to \infty} V_{odi}(t) = V_{nom} \) and \( \lim_{t \to \infty} \omega_i(t) = \omega_{nom} \) for all \( i \in N \), where \( V_{nom} \) and \( \omega_{nom} \) are the reference values of the operating voltage magnitude and angular frequency.

### III. Consensus-based Distributed Restoration

In this section, we first introduce the consensus algorithm [9] and then design the consensus based voltage/frequency restoration scheme in sections III-C and III-D respectively. In recent years, consensus algorithm has been applied in multi-agent and multi-vehicle system to achieve coordination among number of distributed agents. The basic idea of consensus is to enable a set of distributed agents to attain an agreement on the quantity of interest via information exchange on the communication network. The secondary control selects the references \( V_{ni} \) and \( \omega_{ni} \) to update the primary control for the restoration of voltage and frequency respectively. The low bandwidth communication links are mandatory to implement the distributed secondary control for the restoration of voltage and frequency to their original values. The information exchange between DG units can be implemented either using wireless network or power line carrier communication. The delay used in power electronics systems are in the order of \( \mu s \), whereas the delays in communication networks can easily reach to the order of milliseconds or even seconds. Let us assume these communication channels have a delay of \( \tau_d \) seconds. The communication topology in MG can be explained using a directed graph. The following section gives brief review on graph theory, which is used to develop the controller.

#### A. Review on Graph Theory

Consider an islanded MG as a multi-agent system working as agents, the required communication network can be modeled by a weighted undirected graph (digraph) \( G = (\mathcal{V}, \mathcal{E}, \mathcal{A}) \) where the set \( \mathcal{V} = \{v_1, v_2, \ldots, v_n\} \) denotes the set of nodes (DGs), the set of edges \( \mathcal{E} \subseteq \mathcal{V} \times \mathcal{V} \) denotes the communication links between the DG’s and \( \mathcal{A} = [a_{ij}]_{N \times N} \) is a weighted adjacency matrix defined as \( a_{ii} = 0 \) and \( a_{ij} \geq 0 \). \( a_{ij} > 0 \) if and only if the edge \( (v_i, v_j) \in \mathcal{E} \). The set of neighbors of the \( i^{th} \) DG \( V \) is given by \( N_i = \{v_j \in V : (v_i, v_j) \in \mathcal{E}\} \). The in-degree matrix \( D = \text{diag}\{d_1, \ldots, d_N\} \) with \( d_i = \sum_{j \in N_i} a_{ij} \) and then \( \mathcal{L} = D - \mathcal{A} \) is the Laplacian matrix. \( \mathcal{L} \) has all row sum equals to zero i.e. \( \mathcal{L} 1_N = 0 \), where \( 1_N \) is vector of ones with length \( N \) [10].

#### B. Consensus Algorithm

Consider a MG network with \( N \) agents (DGs) having first-order linear dynamic system:

\[
\dot{x}_i = u_{xi}, \hspace{1cm} i \in \{1, \ldots, N\} \hspace{1cm} (9)
\]

where \( x_i \) is the agreement state of \( i^{th} \) agent (i.e. voltage and frequency), and \( u_{xi} \) is the control command. If agent \( i \) have access to the reference input \( r_i \), then the consensus algorithm can be stated as

\[
\begin{align*}
\dot{x}_i &= \dot{r}_i - k_1 (x_i - r_i) - k_2 \sum_{j=1}^{N} \mathcal{L} x_j - y_i \\
\dot{y}_i &= k_1 k_2 \sum_{j=1}^{N} \mathcal{L} x_j
\end{align*} \hspace{1cm} (10)
\]

where \( x_i \) and \( y_i \) are the states associated with agent \( i \), \( \mathcal{L} \) is Laplacian matrix of communication digraph. The first and second terms of the algorithm help the agents to reach the reference input signal \( r_i \), while the third and fourth terms cause consensus among neighboring agents via proportional-integral feedback. The constants \( k_1 \) and \( k_2 \) are the design parameters, can be tuned for achieving improved performance.
C. Secondary Voltage Restoration

For an inverter based DG unit $i$, single integrator dynamics can be given as,

$$\dot{V}_{ni} = u_i$$

(11)

where $u_{vi}$ is the control input has to be formulated using the consensus algorithm as follows

$$\dot{V}_{ni} = \dot{V}_{odi} - k_1 (V_{odi} - V_{nom}) - k_2 \sum_{j=1}^{N} L V_{odj} - y_{vi}$$

(12)

$$\dot{y}_{vi} = k_1 k_2 \sum_{j=1}^{N} L V_{odj}$$

where $V_{odj}$ is the neighbor information obtained from the communication network, $L$ is the Laplacian matrix of considered topology and $k_1, k_2$ are the design parameters for tuning the performance of proposed control scheme. A typical choice is to make $k_1$ and $k_2$ adequately large enough to precisely tune the response of the secondary control and achieve fast consensus among DG units. However, a high degree of freedom is available to the designer to find the perfect combination of $(k_1, k_2)$ via extensive simulations. It is worth mentioning that (12) guarantees that the voltage return to its specified reference value ($V_{nom}$). Fig. 5 shows the block diagram of the proposed consensus-based distributed secondary voltage controller.

D. Secondary frequency Restoration

For the $i^{th}$ DG unit single integrator dynamics can be given as

$$\dot{\omega}_{ni} = u_{\omega i}$$

(13)

where $u_{\omega i}$ is the control input has to be formulated using the consensus algorithm as follows

$$\dot{\omega}_{ni} = \dot{\omega}_{odi} - k_1 (\omega_{odi} - \omega_{nom}) - k_2 \sum_{j=1}^{N} L \omega_{odj} - y_{\omega i}$$

(14)

$$\dot{y}_{\omega i} = k_1 k_2 \sum_{j=1}^{N} L \omega_{odj}$$

where $\omega_{odj}$ is the neighbor information obtained from the communication network. The controller in (14) guarantees that the operating frequency return to its predefined reference value ($\omega_{nom}$). Fig. 6 shows the structure of the consensus-based secondary frequency controller. The proposed consensus based secondary control uses low bandwidth communication network and sparse communication structure which increases overall system reliability over the conventional secondary control structure and decreases the risk of single point failure. Also, the proposed method does not use excessive computation thereby increasing the operation speed. For an MG in the small geographical area, power line carrier communication can be used provided the physical structure of the MG is known. For simulation study, an intrinsic communication network delay has been considered.

IV. RESULTS AND DISCUSSION

To verify the performance of the designed consensus based secondary controller, we simulated 380 V, 50 Hz islanded MG shown in Fig. 7. The simulation is carried out in MATLAB/SimPowerSystem environment. The islanded MG consist of five DG units and their respective loads, and four transmission line. The simulation parameters of DGs, loads, and lines of the MG test system are summarized in Table I and Table II. Two different communication topologies have been considered as shown in Fig. 8. The secondary

![Fig. 7. Islanded MG test system.](image-url)
controller parameters are chosen as $\alpha = 100$, $\beta = 100$. This section is divided into three segments, starting with performance evaluation, then, under communication network changes, and, finally impact of communication latency is shown with different time delays.

### TABLE I. SPECIFICATION OF MG TEST SYSTEM

<table>
<thead>
<tr>
<th>Grid</th>
<th>DG 1 &amp; DG 2 &amp; DG 3</th>
<th>DG 4 &amp; DG 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{ref}$</td>
<td>380 V</td>
<td>380 V</td>
</tr>
<tr>
<td>$f_{ref}$</td>
<td>50 Hz</td>
<td>50 Hz</td>
</tr>
<tr>
<td>$k_p^d$</td>
<td>$9.4 \times 10^{-3}$</td>
<td>$12.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>$k_p^f$</td>
<td>$1.3 \times 10^{-3}$</td>
<td>$1.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>$R$</td>
<td>0.03 $\Omega$</td>
<td>0.03 $\Omega$</td>
</tr>
<tr>
<td>$L$</td>
<td>0.35 $mH$</td>
<td>0.35 $mH$</td>
</tr>
<tr>
<td>$B_j$</td>
<td>0.1 $\Omega$</td>
<td>0.1 $\Omega$</td>
</tr>
<tr>
<td>$L_f$</td>
<td>1.35 $mH$</td>
<td>1.35 $mH$</td>
</tr>
<tr>
<td>$C_f$</td>
<td>50 $\mu F$</td>
<td>50 $\mu F$</td>
</tr>
<tr>
<td>$K_{PV}$</td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>$K_{IV}$</td>
<td>420</td>
<td>390</td>
</tr>
<tr>
<td>$K_{PFC}$</td>
<td>15</td>
<td>10.5</td>
</tr>
<tr>
<td>$K_{IC}$</td>
<td>20000</td>
<td>16000</td>
</tr>
<tr>
<td>$\omega_c$</td>
<td>31.41 rad/s</td>
<td>31.41 rad/s</td>
</tr>
<tr>
<td>$Z_{Linc 1}$</td>
<td>0.23 + j 0.1$\Omega$</td>
<td>0.35 + j 0.1$\Omega$</td>
</tr>
<tr>
<td>$Z_{Linc 2}$</td>
<td>0.23 + j 0.1$\Omega$</td>
<td>0.35 + j 0.1$\Omega$</td>
</tr>
<tr>
<td>$Z_{Linc 3}$</td>
<td>0.35 + j 0.58$\Omega$</td>
<td></td>
</tr>
<tr>
<td>$Z_{Linc 4}$</td>
<td>0.35 + j 0.58$\Omega$</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE II. MG LOADS

<table>
<thead>
<tr>
<th>Loads</th>
<th>Load 1</th>
<th>Load 2</th>
<th>Load 3</th>
<th>Load 4</th>
<th>Load 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>40 $\Omega$</td>
<td>40 $\Omega$</td>
<td>50 $\Omega$</td>
<td>50 $\Omega$</td>
<td>50 $\Omega$</td>
</tr>
<tr>
<td>$L$</td>
<td>47 $mH$</td>
<td>64 $mH$</td>
<td>64 $mH$</td>
<td>64 $mH$</td>
<td>95 $mH$</td>
</tr>
</tbody>
</table>

A. Study 1: Performance evaluation of proposed controller

The performance of the consensus-based controller has been depicted in Fig. 9 and 10 for restoration of voltage and frequency disparities caused by primary control respectively. The communication topology for this case is shown in Fig. 8(a). The simulation outline of this segment is defined as follows:

- At $t = 0$ s, only primary control is active.
- At $t = 0.5$ s, load 1 is increased.
- At $t = 1.0$ s, load 4 is increased.

- At $t = 1.5$ s, secondary control is activated, and the restoration process starts for all DG units at the same instant.

It is clear from Fig. 9 and 10 that the voltage magnitude and operating frequency are restored to their nominal values ($V_{nom} = 380$ V and $f_{nom} = (\omega_{nom}/2\pi) = 50$ Hz) successfully, removing the deviation produced by primary control.

B. Study 2: Under different Communication topology

To analyze the performance of the proposed controller with different communication network, the communication topology shown in Fig. 8(b) is considered. The controller specifications remain same as in study 1. Fig. 11 and 12 show that with different communication topologies, the proposed controller performs accurately and restores the voltage and frequency of the MG to the reference values.

C. Study 3: Effect of communication latency

Communication plays an important role in preparing a framework that permits the information exchange among various elements of the MG. The influence of communication increases when consensus algorithm is used for secondary control layer of MG. In this case study, the effect of communication delay on the proposed control approach is illustrated under following three cases.

- case 1: A fixed total communication delay of $\tau_d = 0.1$ s in the MG.
- case 2: A fixed total communication delay of $\tau_d = 1$ s in the MG.
- case 3: A fixed total delay of $\tau_d = 2$ s in the MG.
Fig. 13. Voltage magnitude, $\tau_d = 0.1$ s

Fig. 14. Frequency, $\tau_d = 0.1$ s

Fig. 15. Voltage magnitude, $\tau_d = 1$ s

Fig. 16. Frequency, $\tau_d = 1$ s

Fig. 17. Voltage magnitude, $\tau_d = 2$ s

Fig. 18. Frequency, $\tau_d = 2$ s

For the sake of clarity, only one DG’s voltage and frequency response are shown for above three cases from Fig. 13 - 18. It can be seen from Fig. 13 and 14 that the controller exhibits good performance with a small time delay of 0.1 s. As it can be seen from Fig. 15 and 16 that when the time delay $\tau_d$ is increased to 1s, the voltage/frequency are restored after small deviation but the convergence time is increased. Further, when the delay continues to increase to 2 s, the proposed controller restores the voltage/frequency but with more convergence time as shown in Fig. 17 and 18. Thus, it can be summarized that the communication latency can delay the convergence rate of control system.

V. Conclusion

In this work, a consensus-based distributed control strategy for droop controlled inverter based islanded MG has been proposed. The proposed control deals with both voltage and frequency restoration issue of islanded MG. The distributed secondary control at each DG comprises every DG unit local controller and communication network, hence, providing a suitable control input, which further sent to the primary controller. The proposed controller eliminates the risk of single point failure because the failure of a particular DG unit will fail down that particular unit and all other DGs in the MG can work individually. In this sense, MG system expansion becomes simple. The proposed method is evaluated based on the numerical simulations studies in MATLAB/SimPowerSystem software environment. Results show that the control objectives voltage/frequency restoration can be accomplished even with different communication topology. Furthermore, the effect of communication latency over the MG control is investigated, if the delays are large enough, the system will not be stable. In future work maximum boundary of time delay for a stable system operation has to be investigated.

REFERENCES