A state of charge-based linearised frequency–voltage droop for interlinking converters in an isolated hybrid microgrid

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Abstract
A battery-dominated hybrid microgrid architecture where various battery modules are linked to the ac bus via converters is presented. A novel frequency–voltage droop scheme is proposed for the interlinking converter connecting the dc and ac grids. The ac grid frequency and dc grid voltage are linked together in outer controller loop through two factors, the ratio of which defines the frequency–voltage droop. This enables autonomous bidirectional power flow and regulation where each grid is supporting the other grid through its surplus power. A state of charge (SOC)-based control scheme is also proposed for the battery units linked to ac bus which ensures power sharing based on the SOC of individual storage units. The system small-signal model is developed and a stable range of operation is defined. The impact of number of battery units and SOC of an individual battery on the system performance is also analysed. In addition, the proposed strategy is compared with normalised SOC-based control to evaluate its feasibility. Simulations in PSCAD/EMTDC show that the proposed SOC-based scheme helps maintain charge balance while regulating the voltage and frequency and ensuring power flow among battery units and grids.

1 INTRODUCTION

Hybrid microgrids have been the center of attraction for power system researchers as they aim to bring the advantages of ac and dc microgrids under one roof [1]. The system consists of one or multiple dc and ac grids which are linked together through converters. Such a coupled ac–dc system offers many advantages such as higher flexibility, reliability and reduced cost and power losses [2]. It facilitates coupling of similar sources which reduces the power conversion stages and improves power quality [3]. The advancements in semiconductor industry have been a key factor in this evolution with increasingly efficient components and devices that help develop bond between ac and dc technology.

The hybrid microgrid configuration is usually dependent on its application. Conventional hybrid grids consist of a single ac grid tied to a dc grid via interlinking converter (ILC) which controls bidirectional power and maintains ac frequency and dc voltage within acceptable limits [4]. The ac grid can be linked to the main utility through a static transfer switch (STS) which helps the hybrid grid switch between grid-connected mode and standalone mode. In grid-connected mode, the utility grid can help satisfy additional loads of hybrid grid but local power generation is the only available source in standalone mode [5]. Thus, a strict supply of balance has to be maintained between power generation and demand. Battery storage gains significance in such operating conditions as it can support the grid during power shortage [6]. Similarly, these units can absorb surplus power which reduces system stress and improves power efficiency. Focusing on these advantages, this paper proposes a battery-dominated hybrid grid topology shown in Figure 1 where ’n’ multiple battery units are connected to the ac bus through converters. The ac grid consists of ’y’ ac sources and ’z’ dc sources while the dc grid is modelled by ’x’ dc sources and ’y’ ac sources, respectively. Such a topology offers various advantages: (1) battery module voltages can be different from the dc grid voltage which offers different voltage levels to analyse the hybrid grid, (2) weak ac grids can be supported by battery units which improves system efficiency, and (3) the battery units can absorb surplus power at low-demand intervals which offers flexibility in supply–demand balance of standalone hybrid grids. It should be noted that these advantages can also be realised by
connecting the battery units to dc bus. Since the existing power system is predominantly ac and is more mature as compared to dc grid, it becomes imperative to connect the battery units to the ac bus of hybrid microgrid.

The ILC is the focal point of a hybrid microgrid as it regulates dc voltage and ac frequency while maintaining power flow between overloaded and underloaded grids. Various control schemes have been employed to achieve these goals which can be broadly classified as autonomous control and communication-based control. A centralised system can be employed in a hybrid microgrid which uses high-bandwidth communication channel for transferring real-time data from sensors to the controller which, in turn, regulates the control variables [7]. A two-level communication network is proposed in [8] where local communication monitors individual modules and devices and provides power references for each device. The global communication exchanges information between subgrids for an optimised performance. A TCP/IP-based central server is studied in [9] where a power flow algorithm is used to obtain grid currents and voltages. An active power sharing scheme is analysed in [10] where battery storage units operate under constant frequency mode while other distributed units utilise active and reactive control. This system employs communication architecture for data exchange among units. The rapid availability of data in communication-based control helps to reduce voltage and frequency errors and improves the overall system performance. However, there are serious issues of point-of-failure and security.

Droop strategy is the most common autonomous control scheme where power management is based on local information. A per unit droop scheme is proposed in [11] where a common scale is employed for ac frequency and dc voltage. The active power reference to the ILC is adjusted by feeding the difference between these values to a proportional or PI controller. However, this strategy suffers from poor voltage quality, reduced stability and large frequency deviations. An improved decentralised control strategy is discussed in [12] where ILCs are operated as current sources in power mode. In this scheme, the ac grid frequency is coupled with the square of the dc grid voltage for autonomous power sharing but the converter is unable to operate in ac and dc grid support modes. To achieve this, the ILC has to switch from current control mode to voltage control and this involves mode detection and switching for a seamless transfer as proposed in [13] and [14]. A voltage droop scheme for photovoltaic generator-based hybrid microgrid is analysed in [15] that couples ac voltage and dc voltage to avoid continuous variations in active power reference. This leads to large voltage variations and system is prone to instability. Parallel ILC operation is studied in [16] that aims to allow a larger power exchange and minimise the circulating currents among converters while maintaining the ac grid frequency but the scheme can only be used for a one-sided power flow from dc to ac side and no mechanism is discussed for supporting dc grid via ac grid sources. A similar topology is adopted in [17] where an external variable decouples power and droop control to meet multiple operating conditions but the system is dependent on secondary control for better compatibility and flexibility.

Battery storage has been considered in both ac and dc microgrids as a rapidly available energy source that helps maintain supply-demand balance. In the literature, the battery state of charge (SOC) in dc microgrid is incorporated in traditional voltage droop control where dc bus voltage is coupled with active power [18, 19]. Similarly, in an microgrid, the battery SOC is implemented with traditional frequency droop [20]. In a hybrid microgrid architecture, battery units can be located in ac or dc subgrid for achieving energy balance but the natural dc interface encourages the storage deployment at dc side. The units can be connected to the dc bus by boost converters and bidirectional power flow is still managed by ILC. A model predictive voltage power control for ILC is discussed in [21] which aims to stabilise ac voltage and regulate power flow but the system requires extensive measurements via voltage and current sensors and produces current spikes in transition mode. A robust power management system for a battery-based hybrid microgrid is studied in [22] where battery SOC, power generation and dynamic constraints of sources are coupled in a cost function. Communication lines are used to convey the power set-points to the resources and the proposed scheme is costly for large-scale hybrid grids. A cascaded ILC arrangement with battery storage is proposed in [23] where droop characteristics of the battery and individual subgrids are used to define the charging and discharging pattern of the converters. A comparison of the literature schemes with the proposed control is given in Table 1. Among autonomous schemes, the normalised SOC droop scheme for series arrangement of dc/dc and dc/ac converter proposed in [24] also utilises battery charge to define the power flow through the units. However, this arrangement increases system complexity and cost. Moreover, the coupling of ac grid frequency, dc grid voltage and power output of battery in one equation implies that any one variable can affect other two variables which reduces system control and flexibility. A battery unit with direct linkage to ac frequency and dc voltage can rapidly respond to load variations and reduce transient time which is necessary in future power systems.
TABLE 1 Comparison of ILC schemes for hybrid microgrids

| Method     | Principle of operation | Communication-based control | Regulates ac frequency and dc voltage | Incorporates battery SOC | Considers relative strengths of subgrids | Power quality dependent on TCP/IP |
|------------|------------------------|-----------------------------|--------------------------------------|--------------------------|------------------------------------------|----------------------------------|
| Ref. [9]   | ✓                      | ✓                           | ✓                                    | ✓                        | ✓                                        | ✓                                |
| Ref. [15]  | ✓                      | ✓                           | ✓                                    | ✓                        | ✓                                        | ✓                                |
| Ref. [21]  | ✓                      | ✓                           | ✓                                    | ✓                        | ✓                                        | ✓                                |
| Ref. [23]  | ✓                      | ✓                           | ✓                                    | ✓                        | ✓                                        | ✓                                |
| Ref. [24]  | ✓                      | ✓                           | ✓                                    | ✓                        | ✓                                        | ✓                                |
| Proposed scheme | ✓                  | ✓                           | ✓                                    | ✓                        | ✓                                        | ✓                                |

1.1 | Shortcomings

Based on the literature review, the following deficiencies are highlighted:

1. The majority of the ILC schemes employ multi-mode control where local measurements are used to switch the control. This increases power losses and produces undesirable current spikes. A simplified converter scheme is required which can manage power between subgrids and regulate dc grid voltage and ac grid frequency.

2. The battery SOC is an important parameter while considering the power balance and it can be incorporated in the droop control of ILC so that battery units can rapidly respond to loading conditions within individual grids. Thus far, the performance of hybrid microgrid has not been analysed from the perspective of number of battery units and SOC of an individual unit.

3. Similar to frequency and voltage droop for ac and dc microgrids, a droop coefficient should also be defined for ILC. This will help incorporate relative power production in individual subgrids and give more flexibility in the design of hybrid microgrid.

1.2 | Key features and contributions

This paper analyses power sharing control in a battery-dominated hybrid microgrid where multiple battery units are linked to the ac bus through converters. A frequency–voltage droop scheme for ILC is proposed where dc grid voltage is coupled with ac grid frequency in outer controller loop via two scaling factors, the ratio of which define the droop coefficient. This arrangement translates frequency into voltage (and vice versa) and the local droop control within individual subgrids can adjust its power accordingly. State-space model of the system is developed and eigenvalues are used to define a stable range of operation for the scaling factors. The concept is extended to the bidirectional converters linking battery units to ac grid and a SOC-based droop is adopted which enables a battery with higher charge to supply more power as compared to a battery with lower charge. Similarly, the battery with lower charge will absorb more power compared to higher SOC battery. The impact of number of battery units and SOC of an individual battery on the system performance is also analysed. In addition, the proposed strategy is compared with normalised SOC-based control to evaluate its feasibility. The advantages of this scheme are as follows:

1. Bidirectional power management with dc voltage and ac frequency regulation. No communication lines are required as only local information is utilised.

2. The frequency–voltage droop coefficient helps incorporate relative strengths of individual subgrids. This is especially beneficial in microgrids with different power generation capacities.

3. Since only the outer controller loop is modified by adding ac frequency and dc voltage, the control scheme can be differentiated on the basis of its simplicity. No switching between control modes is required which reduces energy losses and improves efficiency.

4. Unlike other SOC-based droop which manages battery power in ac and dc microgrids using traditional frequency and voltage droop, respectively, the SOC-based frequency–voltage droop discussed in this paper helps connect ac and dc microgrid via ILCs and ensures that a battery with higher charge will provide more power and vice versa. This is beneficial in hybrid grid topology.

The rest of the paper is organised as follows: Section 2 presents the detailed modelling and design of battery-dominated hybrid microgrid. The droop schemes for individual subgrids, battery units and ILCs are discussed. The system state-space model is analysed in Section 3 where a stable operational range for scaling factors is defined. Section 4 presents the time-domain simulation results in PSCAD/EMTDC. The main conclusion and future work are presented in Section 5.

2 | SYSTEM CONFIGURATION AND PROPOSED CONTROL SCHEME

The detailed structure of the battery-dominated hybrid microgrid under consideration is shown in Figure 2 where two
battery units are attached to ac bus via bidirectional ac/dc converters. Local loads are connected within individual grids which reflect the total system demand. An LCL filter is used at the output of ILC to improve power quality. Droop control is used to manage power within ac and dc grids and afterwards, ILC controls power flow at system level while regulating ac grid frequency and dc grid voltage. Thus, it becomes imperative to analyse the power sharing within individual ac and dc grids before proposing the converter control schemes.

### 2.1 AC and dc grid droop control

In conventional synchronous generators, frequency droop characteristics of governor help regulate the ac grid frequency by adjusting the active power output according to the loading conditions. This behaviour can be emulated in inverter-based ac grid so that the parallel converters work together at the reference frequency as [25]:

\[
\omega_{ac} = \omega_{max,ac} - mP_{grid,ac},
\]

where \(\omega_{ac}\) and \(\omega_{max,ac}\) are the reference and maximum frequency of the ac grid and \(m\) is the droop coefficient, respectively.

To share power proportionally among converters, the droop coefficient is selected as:

\[
m = \frac{\omega_{max,ac} - \omega_{min,ac}}{P_{rat,ac}},
\]

where \(\omega_{min,ac}\) is minimum ac grid frequency and \(P_{rat,ac}\) is the rated power of converter, respectively.

Droop control in dc microgrid utilises dc voltage as the control variable to maintain power sharing among the converters. The dc voltage is linked to active power as [26]:

\[
v_{dc} = v_{max,dc} - nP_{grid,dc},
\]

where \(n\) is the converter droop coefficient and \(v_{max,dc}\) is the maximum allowable dc voltage, respectively. Similar to ac grid, the droop coefficients of multiple parallel converters are based on their rating.

### 2.2 Proposed converter schemes

#### 2.2.1 ILC connecting ac and dc subgrids

The ac grid frequency is a useful indicator to determine the loading condition inside the ac grid. Similarly, the dc grid voltage can help predict the loading inside the dc grid. The ILC can measure these two quantities and control the power flow from an underloaded grid to overloaded grid. If the ILC senses a drop in frequency, it allows the active power flow from dc grid to ac grid. In a similar manner, if loads in the dc grid are increased, the dc bus voltage drops and ILC provides power support to dc grid via ac grid. Thus, any control strategy of ILC should involve both ac grid frequency and dc grid voltage.

The proposed ILC control scheme is shown in Figure 3. The angle \(\theta\) is extracted from the ac bus voltage by using a phase-locked loop (PLL). In standalone mode, \(\Theta\) is a periodic ramp with frequency \(f_{ac}\) and varying between zero and \(2\pi\). It decomposes three-phase output converter currents \((i_{a}, i_{b}, i_{c})\) and voltages \((v_{a}, v_{b}, v_{c})\) into dq-frame currents \((i_{dq}, i_{dq})\) and voltages \((v_{dq}, v_{dq})\), respectively. The traditional two-level six-switch
Figure 3: Proposed ILC control linking ac and dc subgrids

Figure 4: Droop control of individual subgrids and ILC

architecture is adopted where the outer control loop is modified to include both ac frequency and dc voltage. These two quantities are coupled together through scaling factors $a$ and $b$. The outer loop generates a current reference for the inner current controller. Since reactive power is not required at dc end, the q-axis current reference ($i_q^{ref}$) is set to zero. The modulating signals produced by the current controller are used to drive the converter switches.

At steady state, the input to the outer loop PI controller is zero which gives us:

$$a(v_{dc,ref} - v_{dc}) - b(f_{ac,ref} - f_{ac}) = 0. \tag{4}$$

From (4), the frequency–voltage droop coefficient can be defined as:

$$\frac{\Delta f_{ac}}{\Delta v_{dc}} = \frac{a}{b}. \tag{5}$$

Establishing a frequency–voltage droop coefficient for the ILC has a great significance as it linearly couples the ac and dc ends of the converter and can incorporate the relative strengths of individual subgrids in the overall system design. For instance, a large value of frequency–voltage droop coefficient is suitable for a weak dc grid as a small change in dc voltage will produce a large ac grid frequency variation and a considerable power flows from ac grid to dc grid. Similarly, a small value of droop coefficient can be used for weak ac grids. The coupled droop scheme of the hybrid microgrid is shown in Figure 4 where the dc voltage droop has been flipped for a better visualisation. The frequency and voltage droop coefficients of ac and dc grids are $m$ and $n$, respectively, while the ILC operates at droop coefficient $a/b$. In steady state, the ac microgrid is operating at $f_{ac,1}$ while the dc grid bus voltage is $v_{dc,1}$. If load increases in dc microgrid, the voltage decreases to $v_{dc,2}$ and correspondingly, dc power generation rises from $P_{dc,1}$ to $P_{dc,2}$. The frequency–voltage droop, shown in blue line, converts the voltage variation into frequency change. Thus, the ac grid frequency drops from $f_{ac,1}$ to $f_{ac,2}$ and the ac grid power generation increases to $P_{ac,2}$. This excess ac grid power is used to support dc grid.

2.2.2 ILC connecting ac subgrid and battery units

Battery storage units act as energy buffer which helps in overall power balancing of the hybrid grid. These units are linked to the ac bus through SOC-based ILC as shown in Figure 5. Similar to Figure 3, a two-level converter scheme is used where outer loop generates the current reference for inner current controller. Local measurements of battery SOC and per unit dc voltage and ac grid frequency are used in the outer control loop to generate the d-axis reference current. The coupling of SOC with ac grid frequency is facilitated by the fact that any change in loading condition within individual subgrids will impact the frequency and thus, the change in battery voltage is dictated by the amount of stored charge. The amount of power provided by the battery unit is dependent on this voltage variation. At steady state, we have:

$$f_{ac,ref} - f_{ac} = \frac{1}{\text{SOC}} \left(\frac{v_{bus}}{v_{dc,ref} - v_{dc}}\right), \tag{6}$$

where $v_{bus}$ is the dc bus voltage to which battery is connected. The battery SOC is calculated using Coulomb counting method [19]. This method incorporates battery storage with different capacities. The linear coupling between ac bus frequency and battery voltage in (6) is significant as it utilises battery charge to determine the change in battery voltage for any load variation in hybrid microgrid. In the discharge mode, a battery with higher SOC should provide more power to support the loads. Likewise, in the charging mode, a unit with lower SOC should receive increased power supply to maintain its charge at the nominal level. This is achieved via (6) as follows:
1. If the battery is operating in discharge mode and load increases in hybrid microgrid, ac frequency will reduce. According to (6), battery units with higher SOC will experience larger dc voltage deviations and thus, the battery with more charge will provide a large proportion of power to ac grid. Similarly, battery units with less amount of charge will undergo a smaller voltage deviation and contribute minimally in supporting the hybrid grid.

2. A similar analogy can be used to explain battery operation in the charging mode. If a local load connected to the battery unit is slightly increased, dc bus voltage of battery reduces. A battery unit with higher SOC will translate the voltage variation into a small change in ac bus frequency and correspondingly, the ac grid provides less power to charge the battery. Similarly, a battery with smaller SOC will produce larger ac grid frequency variation and the ac grid will transfer a larger amount of power to the battery unit.

2.2.3 DC/DC boost converter

The battery units are connected to the SOC-based ILCs through bidirectional dc/dc boost converters. The structure of the proposed boost converter is shown in Figure 6 where both dc voltage and battery power are coupled together and fed to a PI controller which produces the current reference. The difference between the reference and measured battery currents is fed to a second PI controller which generates the required modulating signals.

In the proposed scheme, the coupling of dc voltage and battery power realises dc voltage droop as:

\[ \Delta v_{dc}^{bat} = 0.001 \Delta P_{dc}^{bat}, \]  

where 0.001 is a power conversion factor between watt and kilowatt and \( P_{dc,ref}^{bat} \) is the reference battery power. This reference power is defined as the product of battery reference voltage and current. If load changes in hybrid microgrid, ac grid frequency changes and based on the individual unit’s SOC, the ILC converts the frequency change into a dc voltage variation. Correspondingly, the dc/dc boost controller uses the voltage droop to generate output power.

3 | STATE-SPACE MODELLING

To analyse the impact of scaling factors \( a \) and \( b \), a small-signal model of single standalone hybrid microgrid is derived. Since the focus is on the converter control and dynamics, the dc and ac grids are modelled by ideal, balanced sources. The system parameters and initial conditions are given in Table 2.

### Table 2: System parameters and initial conditions

| Parameter | Value | Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|-----------|-------|
| \( \omega_{PLL} \) | 200 | \( v_{qf} \) | 0.7 V | \( K_{b,PLL} \) | 10 |
| \( K_{a,PLL} \) | 100 | \( \omega_{d} \) | 20 | \( K_{v,PLL} \) | 321.5 A |
| \( r_{ref} \) | 456.3 V | \( i_{d} \) | 4.4 A | \( a \) | 0.5 |
| \( b \) | 20 | \( r_{dc,ref} \) | 800 V | \( \omega_{v,PLL} \) | 793.87 V |
| \( \omega_{ac,PLL} \) | 314.16 | \( \omega_{ac} \) | 300 | \( K_{v} \) | 1 |
| \( K_{p} \) | 1000 | \( i_{d} \) | 1 A | \( i_{q} \) | 0.01 A |
| \( K_{i} \) | 10 | \( K_{v} \) | 1000 | \( L_f \) | 4.2 mH |
| \( r_{ac} \) | 275 V | \( r_{q} \) | 0.1 V | \( R_f \) | 0.5 \( \Omega \) |
| \( R_c \) | 0.09 \( \Omega \) | \( L_f \) | 0.5 mH | \( C_f \) | 50 \( \mu F \) |
| \( R_f \) | 2 \( \Omega \) | \( C_{dc} \) | 2 mF | \( \frac{load_{ac,Q}}{load_{ac,Q}} \) | \( \frac{load_{ac,D}}{load_{ac,D}} \) | \( -43 \) A |
| \( K_{dc} \) | 3.63 \( \Omega \) | \( F_{ac} \) | 3.75 mH | \( \frac{load_{ac,Q}}{load_{ac,Q}} \) | \( \frac{load_{ac,D}}{load_{ac,D}} \) | 111 A |

3.1 Mathematical model

In order to synchronise the converter to the grid, a PLL is utilised which aligns the terminal voltage with the d-axis. The PLL can be described as [27]:

\[ v_{qf} = \omega_{PLL} (v_{qf} - v_{qf}), \]  

\[ \phi_{PLL} = v_{qf}, \]  

\[ \delta = \omega_{ PLL} = \left( K_{b,PLL} + \frac{K_{a,PLL}}{s} \right) \phi_{PLL} + 314.16, \]

where \( \gamma \) is derivative of \( \gamma \) with respect to time, \( \omega_{PLL} \) measured grid frequency and \( K_{b,PLL}, K_{a,PLL} \) are the integral and proportional gains of PLL, respectively. The oscillatory components in instantaneous reactive and active powers are removed by low pass filters and the dynamics can be described as:

\[ P = -P_{PLL} + 1.5 \omega_{PLL} (v_{qf}i_{qf} + v_{ref}i_{d}), \]  

\[ Q = -Q_{PLL} + 1.5 \omega_{PLL} (-v_{ref}i_{qf} + v_{qf}i_{d}). \]
controller as:

$$\dot{v}_d = \phi_d = a(v_{dc,ref} - v_{dc}) - \frac{b}{2\pi}(\omega_{ac,ref} - \omega_{ac}), \quad (13)$$

$$\dot{i}_{d,ref} = \left(K_{pr} + \frac{K_{ic}}{s}\right)\phi_d. \quad (14)$$

The current controller minimizes the error between the measured filter current and reference generated by outer controller. Since reactive power is absent in dc grid, the q-axis reference current is set to zero. The current controller is described as:

$$\dot{v}_d = i_{d,ref} - i_{id}, \quad (15)$$

$$\dot{v}_q = -i_{iq}. \quad (16)$$

$$v_{id} = v_{ad} + 314.16L_s i_{d,ref} - \left(K_{pr} + \frac{K_{ic}}{s}\right)v_d, \quad (17)$$

$$v_{iq} = v_{ag} - 314.16L_s i_{q,ref} - \left(K_{pr} + \frac{K_{ic}}{s}\right)v_q. \quad (18)$$

The dynamics of output LCL filter are given as:

$$\dot{i}_{idq} = -\frac{R_s}{L_f}i_{idq} - \frac{1}{L_f}v_{idq} + \frac{1}{L_f}v_{adq} + Xi_{idq}. \quad (19)$$

$$\dot{i}_{adq} = -\frac{R_s}{L_c}i_{adq} - \frac{1}{L_c}v_{adq} + \frac{1}{L_c}v_{agq} + Xi_{adq}. \quad (20)$$

$$\dot{v}_{adq} = -\frac{1}{C_f}i_{idq} + \frac{1}{C_f}i_{idq} + Xi_{adq} - R_d i_{idq} + R_d i_{adq}. \quad (21)$$

where $X = \begin{bmatrix} 0 & \omega_{PLL} \\ -\omega_{PLL} & 0 \end{bmatrix}$. Assuming negligible losses, the input and output power at ac and dc ends of the converter are same which relates the dc voltage as:

$$v_{dc} = \frac{1}{C_{dc}} \left(i_{dc,line} - \frac{i_{id}}{v_{dc}} \right). \quad (22)$$

The local load attached to ac grid is described as:

$$i_{ac,dq} = \frac{1}{f_{ac}} v_{idq} - \frac{\delta}{f_{ac}} v_{load ac,dq} + X_{load ac,dq}. \quad (23)$$

By combining Equations (8) to (23), the small-signal model of the hybrid microgrid can be expressed in the form $\dot{x} = Ax + Bu$ where the state vector $x = \begin{bmatrix} v_{adq} \phi_{PLL} \delta P Q \phi_d \gamma_{dq} i_{dq} i_{dq} v_{adq} v_{dc} \end{bmatrix}^T$. The system stability can be analysed via matrix $A$.

3.2 Eigenvalue analysis

The system represented by (8) to (23) is linearised around a stable operating point which is extracted from PSCAD/EMTDC simulation and is given in Table 2. The system eigenvalues are shown in Figure 7. It can be observed that the system is stable as all the eigenvalues are placed on the left half of the plane. The dynamic performance and damping of system is determined by the eigenvalues in close vicinity of real axis. Participation analysis reveals that the inner current controller and PLL dynamics lead to eigenvalues at $-20, -5$ and $-6$, thereby increasing the damping of the system. As we move towards the negative real axis, the imaginary value of the eigenvalue pairs increases which reflects higher oscillations. The natural frequencies of the complex pairs at $(-2261 \pm 6400j)$ and $(-1914 \pm 5526j)$ are 1080 and 931 Hz while the damping ratios are 33.3% and 32.7%, respectively. The LCL filter is the major participant in these high frequency oscillatory modes.

Parameters $a$ and $b$ define the frequency–voltage droop of converter by coupling the dc voltage and ac frequency in the outer loop. The system stability is influenced by these factors and it is worthwhile investigating this effect. The time-domain simulation helps establish the base point values of $a$ and $b$ at which the system is stable. It is observed that the system is stable for $a = 0.5$ and $b = 20$. In order to study the impact of $a$ on system stability, the value of $b$ is kept at 20 while $a$ is increased from zero to 10. The eigenvalue variation of dominant modes is shown in Figure 8a. As $a$ increases, the eigenvalues at $(-33.8 \pm 104.4j)$ start moving towards the real axis which reduces the oscillations and improves damping ratio. However, the dynamics of the inner current controller are affected as the eigenvalues move from -20 towards the imaginary axis. As $a$ increases above 4.5, these eigenvalues cross over into the right half plane which results in an unstable system. Thus, the value of $a$ should be less than 4.5.

To analyse the impact of factor $b$ on the system stability, $a$ is kept at 0.5 while $b$ is increased from zero to 40. The results are
shown in Figure 8b. As $b$ increases, the complex eigenvalue pair moves away from the real axis which affects the system dynamic performance. Due to increase in the imaginary values of this complex pair, the oscillations increase and damping decreases. The PLL dynamics are mostly affected by $b$ which is highlighted by the movement of eigenvalues -5 and -6 towards the imaginary axis. As $b$ increases above 32.3, the system becomes unstable. This helps define a stable range of operation for $a$ and $b$.

Neglecting the dc side dynamics and representing the battery as a controlled voltage source, the impact of battery SOC, used in converter linking the storage to ac grid, can be studied. Comparing (6) with (4), it can be seen that the SOC is essentially the ratio of $b$ and $a$ and a stable system operation can be achieved by appropriately adjusting the values of these factors. Of course, a more comprehensible understanding can be developed by actually measuring the SOC of battery and relating with the system stability but this is beyond the scope of this paper. In this section, $a$ is chosen as 0.2 and $b$ is varied from 1 to 20. These values are well within the defined stable limits and produce an SOC variation from 5% to 100%. The eigenvalue variation of the dominant modes is shown in Figure 9. The system stability is evident as the eigenvalues are on the left half plane. It can be observed that as the SOC increases, the damping of the system improves. This is expected since a higher SOC battery can provide system support through active power and minimises fluctuations. The results show that the defined range of $a$ and $b$ can help specify the SOC in a stable hybrid system.

4 | SIMULATION RESULTS

To verify the effectiveness of the proposed scheme, an interconnected hybrid microgrid is constructed in PSCAD/EMTDC where a dc grid is linked to ac grid via a frequency–voltage converter. Two battery units are also linked to the ac bus through SOC-based converters. The ac grid is modelled as frequency-droop converter operating at 50 Hz with a nominal voltage of 320 V while dc grid consists of voltage-droop converter with a nominal voltage of 800 V. Both the battery units are also operating at a reference voltage of 800 V. For convenience, the battery units are designated as ‘A’ and ‘B’ which are connected to the ac bus via converters ‘B’ and ‘C’, respectively. Similarly, converter ‘A’ connects the dc grid to the ac grid. The frequency–voltage droop for converter ‘A’ is set at 0.05 such that a 1 V dc voltage variation will change the ac grid frequency by 20 Hz. The reference direction of power flow through all three converters is taken negative in inverter mode and positive in rectifier mode of operation. It is assumed that battery units ‘A’ and ‘B’ are operating at a SOC 56.7% and 20%, respectively. The minimum and maximum SOC limits of batteries are 5% and 100%. The system parameters and droop coefficients are given in Tables 2 and 3, respectively.
4.1 | Load variations in subgrids

The initial steady state of the system is shown in Figure 10. The ac grid is generating 57.4 kW and a load of 64 kW is attached to the ac bus. Battery unit ‘A’ is providing 37.17 kW to the ac bus through converter ‘B’. A critical dc load of 39.87 kW is attached to the battery ‘B’ which is satisfied by 32.64 kW power generated by the battery unit and 7.23 kW power support through converter ‘C’. The ac grid is producing 55.17 kW which, along with 23.34 kW power through the converter, meets the local demand of 78.5 kW. The system undergoes different load variations as follows:

1. At \( t = 2 \) s, the load in ac grid is increased by 21 kW while the loading condition in dc grid is kept constant.
2. A dc load of 17 kW is switched off at \( t = 3 \) s while the load in ac grid undergoes no change.
3. At \( t = 4 \) s, the loads in dc and ac grids are changed simultaneously. The ac load is increased by 6 kW while the dc load is raised by 16.8 kW.

4.1.1 | AC grid load variation

The load connected to the ac bus is increased by 21 kW at \( t = 2 \) s. The sudden load change decreases the ac grid frequency from 49.85 to 49.73 Hz and according to (1), the power generation of this grid rises to 63.68 kW. The frequency–voltage droop of converter ‘A’ translates the 0.125 Hz frequency change to 2.5 V bus voltage variation for dc grid and correspondingly, the power production in this grid increases from 55.17 to 60.17 kW. Since the load in dc grid is constant at this instant, the power flow through converter ‘A’ decreases by 5 kW which shows that the dc grid is supporting the ac grid. From (5), the frequency change of ac grid reduces the dc voltage of battery unit ‘A’ by 7.08 V. This voltage change raises the battery power supply from 37.46 to 44.54 kW which is also reflected in the power change of converter ‘B’ as shown in Figure 11. Similarly, from (7), the dc voltage of battery unit ‘B’ decreases by 2.5 V and the battery controller raises its power supply by 2.5 kW. Thus, the power through converter ‘C’ drops by 2.5 kW which shows that this battery unit is supplying power to the ac grid to satisfy the load requirement. Based on the SOC, it can be observed that the battery ‘A’ with 56.7% charge raises its power generation by 7.08 kW while the battery unit ‘B’ with 20% charge increases its power production by 2.5 kW to satisfy the new load requirement. Thus, the battery with higher SOC contributes more in power sharing as expected. All these results are in harmony with the simulations given in Figure 11.

4.1.2 | DC grid load variation

At \( t = 3 \) s, the load in dc grid is decreased by 17 kW which raises the voltage of this grid from 794.9 to 797.19 V. From the voltage droop of (3), the power generation in the grid reduces by 4.28 kW. The frequency–voltage droop of converter ‘A’ translates this voltage change into an ac grid frequency variation of 0.107 Hz. This activates the ac grid droop control which reduces the power generation from 63.68 to 58.3 kW. These results are expected as any load reduction within the dc grid will also lead to a decrease in power produced by the ac grid.

The SOC-based droop control of converter ‘B’ produces a voltage increase of 6.06 V for battery unit ‘A’ and thus, the power produced by this battery is reduced by 6.06 kW. In a similar manner, the SOC droop of converter ‘C’ leads to an increase in dc voltage of 2.14 V for battery unit ‘B’ and this reduces the power produced by this battery from 35.14 to 33 kW. It can be seen that the battery with the higher SOC reduces its power to a larger extent as compared to a battery with lesser SOC. The coherency between the simulation results and mathematical model of the system is apparent.

4.1.3 | Simultaneous load variations in ac and dc grid

Hybrid microgrids can also experience simultaneous variations in load and this aspect is analysed in the simulation at \( t = 4 \) s. The load in ac grid is increased by 6 kW which decreases the frequency from 49.83 to 49.69 Hz. Similarly, the load in dc grid is raised by 16.8 kW which drops the dc grid voltage from 797.2 to 794.38 V. Due to these load changes, the frequency droop and voltage droop of ac and dc grids is activated which raises the power production level by 6.8 kW in ac grid and 5.6 kW in dc grid, respectively.
From (5), converter ‘B’ changes the 0.136 Hz frequency change into a 7.7 V voltage drop at battery unit ‘A’ while converter ‘C’ translates this frequency variation to 2.72 V change for battery unit ‘B’. Thus, the local controllers of battery ‘A’ and ‘B’ increase power by 7.7 and 2.72 kW, respectively. This increase in power supplied by the two battery units is also reflected in converter power variations. It can be seen that the sum of power supplied by the sources is always equal to the sum of power consumed by the loads. Battery unit ‘A’ supplies more power than unit ‘B’ due to its higher SOC. These results are in coherence with the proposed scheme.

Depending on the SOC, a battery might require switching from charging mode to discharging mode and vice versa. This scenario is studied at $t = 5 \text{ s}$ when the SOC of battery ‘B’ is increased from 20% to 60%. This is achieved by changing factor $a$ from 0.5 to 0.1 while $b$ is varied from 10 to 6. The total system load is kept constant. The results are shown in Figure 11. It can be observed that the direction of power flow through ILC ‘C’ changes from positive to negative which shows battery switching from charging mode to discharging mode. Correspondingly, the power supplied by battery ‘A’, dc grid and ac grid is adjusted so as to maintain supply–demand balance. Thus, under this control strategy, battery units can successfully supply and absorb power to support the hybrid microgrid. These results are summarised in Table 4.

### 4.2 Impact of battery storage

The impact of battery storage on the performance of hybrid microgrid can be analyzed from two perspectives: (a) the number of battery units connected to ac bus, and (b) the battery SOC. To analyse the first aspect, the critical load of battery ‘B’ is removed so that all the available power is used to support the hybrid grid. The factors $a$ and $b$ for SOC-based ILCs are selected as 0.5 and 20, respectively, so each battery unit has the same amount of charge. Simulations are performed in two stages and the results are shown in Figure 12. In the first stage, battery ‘A’ is connected to ac bus while battery ‘B’ is removed. The load variations at $t = 2 \text{ s}$ and $t = 3 \text{ s}$ are the same as in the previous case. A single battery unit can supply limited power to support hybrid microgrid and thus, any load variation will produce a relatively large change in ac grid frequency and dc grid voltage. This is apparent in Figure 12a where the frequency changes are -0.17 and 0.13 Hz and voltage variations are -3.18 and 2.73 V for ac and dc load variations, respectively. The peak time $T_p$ and set-
TABLE 4 Summary of results

| Time (s) | Δf_{ac} (Hz) | ΔP_{ac}^{grid} (kW) | Δv_{grid} (V) | ΔP_{ac}^{grid} (kW) | ΔP_{ac}^{batA} (kW) | ΔP_{ac}^{batB} (kW) | Δf_{dc} (Hz) | ΔP_{dc}^{batA} (kW) | ΔP_{dc}^{batB} (kW) | Δv_{batA} (V) | ΔP_{ILC} (kW) | ΔP_{ILC} (kW) | ΔP_{ILC} (kW) |
|----------|----------------|---------------------|----------------|---------------------|---------------------|---------------------|----------------|---------------------|---------------------|----------------|---------------|---------------|---------------|
| t = 2 s  | -0.125         | 6.28                | -2.5           | 5                   | -7.08               | 7.08                |                 | -2.5               | 2.5                | -7.08          | 7.08          | -7.08         | -7.08         |
| t = 3 s  | 0.107          | -5.38               | 2.29           | -4.28               | 6.06                | -6.06               |                 | 2.14               | -2.14              | -12.5          | 6.06          | 2.14          | -2.14         |
| t = 4 s  | -0.14          | 6.8                 | -2.82          | 5.64                | -7.7                | 7.7                  |                 | -2.72              | 2.72               | -10.7          | -7.7         | -3            | -3            |
| t = 5 s  | 0.06           | -3.1                | 1.16           | -2.4                | 3.45                | -3.45               |                 | -8.35              | 8.35               | 2.6            | 3.38          | -9.14         | -9.14         |

FIGURE 12 AC frequency and dc voltage variation with (a) one battery unit, and (b) two battery units

FIGURE 13 AC bus voltage with battery SOC as (a) 20%, and (b) 80%

The results in Figure 12b are obtained when both batteries ‘A’ and ‘B’ are connected to the hybrid microgrid. In this scenario, the power support to ac grid from the storage units is larger which reduces the voltage and frequency variations due to load change. At the ac end, \( T_{p} \) is reduced from 2.11 to 2.08 s and \( T_{s} \) drops from 2.34 to 2.26 s while the improvement in \( T_{s} \) at the dc end is 0.17 s for ac load change. Similarly, for the dc load variation, \( T_{s} \) changes by 0.04 and 0.06 s for frequency and voltage, respectively. This highlights the improved transient performance of the system as the number of battery units increase.

In order to study the impact of battery SOC on the system response, only battery ‘A’ is connected to ac bus and the factors \( a \) and \( b \) of ILC ‘B’ are changed to represent a variation in SOC. The value of \( a \) is fixed at 0.2 while \( b \) is changed from 4 to 16 which signifies increase in SOC from 20% to 80%. The three-phase ac bus voltage waveform is shown in Figure 13. It can be see that the ac voltage experiences oscillations at lower SOC while the transient response improves at higher battery charge.
The system is stable at both SOCs since the ac grid and dc grid support each other through ILCs. However, a higher SOC battery can help reduce oscillations by rapidly responding to load variations and supplying better power quality. These results are consistent with the frequency-domain analysis.

### 4.3 Comparison with normalised SOC scheme

Further insight into the performance of the proposed control is developed by comparing it with normalised SOC scheme of [20] which has been widely adopted in autonomous hybrid microgrid control. This comparison is facilitated by the following aspects: (1) the distributed system architecture adopted in this literature is similar to the proposed configuration, and (2) battery SOC is utilised in the ILC droop control linking battery storage to hybrid microgrid which will help analyse transient response in both schemes.

As shown in Table 1, one of the major advantages of proposed scheme is that it allows linking of ac and dc grids with different capacities by defining a linearised frequency–voltage droop coefficient. In normalised SOC scheme of [20], the ILC control between ac and dc grids is achieved by two cascaded converters which raises the system cost and is undesirable for large-scale interconnected hybrid grids. Moreover, the normalised SOC control links the battery charge to voltage and frequency as:

\[
\frac{f_{\text{nomac}}}{2} + \frac{v_{\text{nomdc}}}{2} = \left( \frac{\text{SOC}}{\text{SOCref}} \right) \left( \frac{P_{\text{bat}}}{P_{\text{bat}}^\text{ref}} \right),
\]

where \( P_{\text{bat}} \) is output battery power and \( f_{\text{nomac}} \), \( v_{\text{nomdc}} \) are the normalised frequency and voltage, respectively. According to this strategy, any change in either of these three variables will impact the other variables and the power flow among grids will be decided accordingly. For instance, if ac load changes, the frequency will vary which will impact the dc voltage and battery power. However, the scheme fails to dictate the amount of change in voltage or power. This is another drawback of the scheme which can be compensated by defining the frequency–voltage droop coefficient with the control given in (6). Thus, the proposed scheme offers greater level of control and flexibility.

Unlike the normalised SOC-based droop, the relative strengths of individual subgrids can also be considered while defining the frequency–voltage droop coefficient. This is shown in Figure 14 where the ac grid frequency, dc grid voltage and battery voltage are compared. In this scenario, the ac grid has a limited power generation capacity and requires support from dc grid and battery storage. Thus, the value of frequency–voltage droop for converters is kept small as any load variation in hybrid microgrid produces a relatively small variation in frequency and ac grid power generation does not undergo a large change. Correspondingly, the change in dc voltage is large and the bulk of power is supplied by dc grid to satisfy the demand. While comparing the two schemes in Figure 14, the battery SOC and frequency and voltage droop coefficients inside ac and dc grids are kept the same. It can be observed that as compared to normalised SOC-based control, for the same ac and dc load changes at \( t = 2 \) s and \( t = 3 \) s, the proposed scheme has smaller variation in battery voltage and ac frequency which is desirable for large-scale systems. Relative strengths of individual grids are incorporated and the system transient response is improved.

### 5 CONCLUSION AND FUTURE WORK

Autonomous power sharing control in battery-dominated stand-alone hybrid microgrids is analysed. In the proposed topology, multiple battery units are connected to the ac bus for power support. A frequency–voltage control scheme is adopted for ILCs linking ac and dc grids where ac frequency and dc voltage are coupled in outer controller loop via two scaling factors, the ratio of which define the frequency–voltage droop coefficient. A SOC-based strategy is used for ILCs linking battery units to ac bus and voltage droop is adopted for dc/dc boost converter. The system performance is analysed by considering the number of battery storage units and SOC of an individual battery. Furthermore, the feasibility of the scheme is discussed by...
comparing it with normalised SOC-based droop. The proposed control is autonomous and converter actions are performed based on local information. The simulation results lead to the following conclusions.

1. The frequency–voltage ILC scheme provides a linear linkage between ac grid and dc grid by relating ac frequency to dc voltage. The droop coefficient of the ILC is defined by scaling factors and helps manage bidirectional power flow between the grids.

2. Small-signal analysis can be used to determine the range of scaling factors for a stable system operation. The dynamics of inner current controller are mostly affected by $a$ while $b$ dictates the PLL dynamics. Eigenvalue analysis reveals that a higher SOC battery improves the system damping as it minimises oscillations.

3. The SOC-based ILCs connecting battery units to ac bus utilise the battery charge to determine the amount of power supply. In discharging mode, a battery unit with higher SOC supplies more power to ac grid while in charging mode, a high SOC implies that the battery will absorb less power. This helps maintain a charge balance among the battery units.

4. The voltage and frequency deviations in the hybrid microgrid can be reduced by increasing the number of battery units since a larger proportion of power is available for support. Likewise, a higher SOC battery can help reduce oscillations by rapidly responding to load variations and supplying better power quality.

Compared to the normalised SOC droop scheme which couples frequency, voltage and battery power in one equation, the proposed strategy offers greater level of control and flexibility as it defines frequency–voltage droop coefficient which can facilitate the linkage of ac and dc grids with different power generation capacities. The droop coefficient helps reduce voltage and frequency deviations which is a favourable aspect for future power systems.

For future work, system uncertainty can be analysed with focus on battery SOC and increased penetration of renewable sources. Furthermore, loss of battery storage unit will impact supply–demand balance in the system and this requires further study. The transmission line models can be incorporated into the system design to study the rate of current and power. The performance of the control scheme under unbalanced sources with converter switching losses, along with experimental verification will help researchers in designing an efficient and reliable hybrid microgrid.

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