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Decentralized Frequency Control of Battery Energy Storage Systems Distributed in Isolated Microgrid

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Abstract: The penetration and integration of renewable energy sources into modern power systems has been increasing over recent years. This can lead to frequency excursion and low inertia due to renewable energy sources' intermittency and absence of rotational synchronous machines. Battery energy storage systems can play a crucial role in providing the frequency compensation because of their high ramp rate and fast response. In this paper, a decentralized frequency control system composed of three parts is proposed. The first part provides adaptive frequency droop control with its droop coefficient a function of the real-time state of charge of battery. The second part provides a fully decentralized frequency restoration. In the third part, a virtual inertia emulation improves the microgrid resilience. The presented results demonstrate that the proposed control system improves the microgrid resilience and mitigates the frequency deviation when compared with conventional ω -*P* droop control and existing control systems. The proposed control system is verified on Real-Time Digital Simulator (RTDS), with accurate microgrid model, nonlinear battery models and detailed switching models of power electronic converters.

Keywords: battery energy storage system; adaptive frequency droop control; virtual inertia; frequency restoration; state of charge

1. Introduction

In recent years, renewable energy sources (RESs) have become widely accepted due to their environmental benefits, such as zero carbon dioxide emissions. The increase in penetration of the RESs has brought about the concepts of a microgrid (MG) [1]. The microgrid consists of several types of distributed energy resources (DERs) and can seamlessly operate either in grid-connected or islanded modes [2]. Among the DERs, photovoltaic (PV) generation and wind turbines have been extensively utilized. However, owing to their natural intermittency, these sources can deteriorate the power system reliability and stability. In the islanded mode, the microgrid has very low-inertia due to lack of rotating synchronous machines. Consequently, it suffers from frequency excursion caused by the supply and demand mismatch [3]. Regulation of the frequency is more challenging in the islanded microgrid since in the grid-connected microgrid the frequency is regulated by the grid. Sufficient energy reserve and fast response are required to avoid risk of a blackout [4,5]. To regulate the frequency fluctuation in the isolated microgrid, energy storage devices such as batteries, flywheel energy storage, supercapacitors and load shedding are the key to ensure the frequency stability [6].

In an isolated microgrid, a multi-layer hierarchical control structure is typically employed. The hierarchical control structure consist of three layers. The primary control layer provides basic voltage and frequency control, and power sharing. The secondary control layer can be either centralized or distributed. It improves the voltage and frequency control, and the power sharing accuracy. The third control layer is a tertiary control responsible for economic dispatch and power optimization [7,8]. For example, in [9,10], a distributed secondary level control was employed to restore the frequency to the nominal value. However, the distributed control inherently requires a communication infrastructure, which can be detrimental to system reliability [11].

Battery energy storage systems (BESSs) are the most popular energy storage devices to maintain the power system stability and to provide ancillary services because of their fast dynamic response. Therefore, the BESSs are suitable to provide the frequency regulation in the isolated microgrids [12,13]. In general, either a centralized bulk BESS or distributed BESSs participate in the frequency control. However, the distributed BESSs are expected to play more significant role in the microgrids because they can reduce the power losses in the system [13].

BESS has been been extensively investigated for enhancing the frequency stability. In [14,15], the balancing state of charge (SOC) control of electric vehicles (EVs) was proposed to provide the primary frequency control during the vehicle-to-grid (V2G) mode in a two-area power system. The frequency droop was modified based on the current SOC of EVs. Feedback based SOC regulation was proposed in [16–19]. The SOC of the energy storage was maintained at a desired value during normal operation to prepare for the next frequency event. In [13], preserved capacity and control gain (K_i) for several BESSs participating in the frequency control were calculated. However, the SOC control of BESSs was neglected and the control system required the BESSs to be connected via a communication infrastructure. The authors in [20] presented a decentralized self-frequency recovery control for the DERs using an integral controller. In [21], a decentralized secondary frequency control was proposed using a PI controller. In [22], a decentralized frequency recovery, synthetic inertia control and conventional ω -*P* formed as a PID controller was proposed. Virtual inertia control was also proposed for strengthening the microgrid and improving the frequency regulation [3,23,24].

Inspired by the above discussion, this paper proposes a decentralized frequency control strategy for BESSs distributed in an isolated microgrid. The main contributions of this paper can be summarized as follows.

- The proposed frequency droop control adapts the droop coefficients based on the current battery SOC. As a result, the active power sharing is proportional to the battery SOC, and low frequency nadir and fast frequency response is achieved.
- The adaptive frequency droop control is combined with the frequency restoration and virtual inertia control. This improves the frequency control and system resilience.
- The proposed control system is fully decentralized and does not require any communication infrastructure which improves the system reliability.
- Small signal modelling and eigenvalue analysis are employed to find the parameters of the proposed control system.

The rest of the paper is organized as follows. In Section 2, the isolated microgrid is briefly described. Section 3 presents the proposed control strategy consisting of the adaptive frequency droop control, and the frequency restoration and virtual inertia controllers. Verification results are presented in Section 5. Finally, Section 6 concludes the paper.

2. Microgrid Description

Single line diagram of a four-bus isolated microgrid is shown in Figure 1. The isolated microgrid consists of four PV sources, four BESSs, four local loads and three power lines. The battery model used in this paper was adopted from [25]. PV sources and batteries are connected to the dc-links via dc-dc converters. The microgrid is interfaced with dc-links via the voltage source converters (VSCs). The PV source is operated with the maximum power point tracking (MPPT) algorithm through the dc-dc converter. Meanwhile, the voltage control loop of the battery converter maintains the dc link voltage at a pre-defined value [26]. Both the PV systems and BESSs are connected to the microgrid through step-up transformers stepping-up the rated voltage from 415 V to 4.16 kV. Since the PV sources are operated at the MPP in order to maximize the utilization of renewable energy, only the batteries participate in the frequency control. The MPP of PV sources was calculated based on the irradiance and temperature data from [27].



Figure 1. Isolated microgrid consisting of four BESSs, four PV sources, four local loads and three power lines.

3. Proposed Control Strategy

In this section, the SOC estimation, the adaptive frequency droop control, the frequency restoration control and the virtual inertia control are presented.

3.1. SOC Estimation

The battery SOC can be estimated as

$$SOC_i(t) = SOC_i(0) - \frac{1}{E_i^{batt}} \int I_{Bi} dt, i = 1, ..., N.$$
 (1)

Differentiating both sides of Equation (1) gives $SOC_i = -I_{Bi}/E_i^{batt}$. Let V_{Bi} be the output voltage of the *i*-th battery. Then, the output power of the *i*-th battery can be obtained as $P_{Bi} = V_{Bi} \cdot I_{Bi}$ and the SOC of the *i*-th battery can be defined as

$$S\dot{O}C_i = -\frac{P_{Bi}}{V_{Bi}E_i^{batt}}$$
(2)

where E_i^{batt} is the battery capacity (Ws) and P_{Bi} is the active power of the *i*-th battery. As it can be seen from Equation (2), the SOC is only a function of the battery output power if the battery voltage V_{Bi} is assumed to be constant. Hence, the frequency droop control coefficient is adapted according to the battery SOC as discussed in the following subsection.

3.2. Adaptive Frequency Droop Control

In this subsection, the adaptive frequency droop control is proposed. The droop coefficients are dynamically adapted according to the current SOC of battery. At first, the conventional droop control is introduced. The VSCs' output active and reactive powers can be calculated as

$$P_{Bi} = \frac{\omega_c}{s + \omega_c} (v_{od} i_{od} + v_{oq} i_{oq}) \tag{3}$$

$$Q_{Bi} = \frac{\omega_c}{s + \omega_c} (v_{od} i_{oq} - v_{oq} i_{od}) \tag{4}$$

where $\frac{\omega_c}{s+\omega_c}$ is the low pass filter (LPF) with the cut-off frequency of ω_c , employed to filter out the high frequency components. v_{od} , v_{oq} and i_{od} , i_{oq} are the voltages and currents in the *d*-*q* reference frame respectively.

The droop control is designed to share the active and reactive powers based on the rated capacity of distributed generation (DG) units. The droop control method can be represented as

$$\omega_i = \omega_n - m_i^p \Delta P \tag{5}$$

$$V_i = V_n - n_i^q \Delta Q, \tag{6}$$

where ω_i and ω_n are the output frequency and the rated frequency of DG unit; V_i and V_n are the output voltage and the rated voltage of DG unit. m_i^p and n_i^q are the ω -P and V-Q droop coefficients of BESS_i and can be determined as ($m_i^p = \Delta \omega / P_{max}$) and ($n_i^q = \Delta V / Q_{max}$), respectively. The active and reactive references P_{Bi}^* and Q_{Bi}^* are set to zero in this paper ($\Delta P = P_{Bi} - P_{Bi}^*$ and $\Delta Q = Q_{Bi} - Q_{Bi}^*$). The output voltage of each BESS is regulated by the conventional V-Q droop control (6) [28] in all case studies.

The ω -*P* droop control is designed to achieve equal active power sharing among the DG sources. However, this is not applicable to BESSs distributed in a microgrid since they may have different SOCs and the BESSs with lower SOCs could prematurely run out of energy. Consequently, it is important to modify the conventional droop control according to BESS's SOC. Figure 2 illustrates how the modification is achieved by adaptive frequency droop coefficient variation. For example, during the discharging mode, the slope K_i^d increases with the decrease in SOC and vice versa. As a result, each BESS provides different amount of active power according to its current SOC.



Figure 2. Adaptive frequency droop characteristic for BESS.

The adaptive active power sharing illustrated in Figure 2 can be expressed as,

$$\Delta f = \begin{cases} \frac{1}{K_i^d} P_{Bi}, P_{Bi} \ge 0\\ \frac{1}{K_i^c} P_{Bi}, P_{Bi} < 0, \end{cases}$$
(7)

where

$$K_i^d = \alpha_i \cdot K^{max} \left[1 - \left(\frac{SOC^{max} - SOC_i}{SOC^{max} - SOC^{min}} \right)^n \right], \Delta f \ge 0,$$
(8)

$$K_i^c = \alpha_i \cdot K^{max} \left[1 - \left(\frac{SOC_i - SOC^{min}}{SOC^{max} - SOC^{min}} \right)^n \right], \Delta f < 0,$$
(9)

and K^{max} is the maximum gain, n = 3, SOC^{max} and SOC^{min} are the maximum and minimum SOCs respectively.

The coefficient α_i accounts for different capacities of batteries and is given as

$$\alpha_i = \frac{E_i^{batt}}{\sum_{i=1}^{N} E_i^{batt}} \cdot N,$$
(10)

where E_i^{batt} is the *i*-th battery capacity and *N* is the total number of batteries in the microgrid. For example, if all batteries in the microgrid have the same SOC but different capacity, the battery with higher capacity will share more power.

Then, using Equations (7)–(10), the conventional ω -*P* droop control can be modified as

$$\omega_i = \omega_n - \frac{2\pi}{K_i^{c,d}} P_{Bi}.$$
(11)

The modified ω -*P* droop control given by Equation (11) can directly replace the conventional frequency droop control in an existing system.

3.3. Frequency Restoration Control

The decentralized frequency restoration control can be obtained by analyzing the active power flow from a DG unit to the AC grid as shown in Figure 3 [22].

$$Orginal C Bus = P + jQ$$

$$Orginal C Bus = P + jQ$$

Figure 3. Simplified diagram of a DG connected to the AC grid.

The active power delivered to the AC bus by the DG unit can be calculated as

$$P_{DG} = \frac{V_{DG}V_g cos(\theta - \delta) - V_g^2 cos(\theta)}{\mid R + jX \mid},$$
(12)

where V_{DG} and V_g are the DG output voltage and the grid voltage respectively, δ is the phase angle between the DG output voltage and the grid voltage, R + jX is the effective line impedance and θ is its phase angle.

Assuming that the line impedance is purely inductive, $\theta = 90^{\circ}$, and the phase angle $\delta \approx 0$, P_{DG} can be expressed as

$$P_{DG} = \frac{V_{DG} V_{g} sin(\delta)}{X},\tag{13}$$

and the frequency restoration control can be defined as

$$\Delta P_{DG} = \frac{V_{DG}V_g}{X}\Delta\delta = \frac{V_{DG}V_g}{X}\int (\omega_{DG} - \omega_g)dt.$$
(14)



If the DG unit is a BESS, Equation (14) can be rewritten as

$$\Delta P_{Bi} \approx K_i^r \int (\omega_i - \omega_n) dt, \tag{15}$$

where K_i^r is the integral gain of the frequency restoration control and is designed in Section 4.

The above frequency restoration control system is fully decentralized, hence no communication links for the secondary frequency control are required. The control system injects additional power from the BESS to restore frequency to the nominal value.

3.4. Virtual Inertia Control

The idea of introducing the virtual inertia into a microgrid with high penetration of renewable sources has been widely adopted [22–24]. In a conventional power system, the system inertia can be determined by the classical swing equation [29]

$$M\frac{d^2\delta_m}{dt^2} = M\frac{d}{dt}(\Delta\omega) = P_m - P_e,$$
(16)

where *M* is the inertia constant, δ_m is the mechanical power angle, $\Delta \omega$ is the change in angular frequency, P_m and P_e are the mechanical and electrical powers respectively.

Based on Equation (16), the virtual inertia can be emulated by requiring additional power ΔP_{Bi} from a BESS as

$$-M\frac{d}{dt}(\Delta\omega) \approx \Delta P_{Bi} = K_i^{iner} \frac{d}{dt}(\omega_i - \omega_n),$$
(17)

where K_i^{iner} is the derivative control gain. By proper selection of K_i^{iner} , the dynamic performance of the frequency response can be enhanced.

The proposed decentralized frequency control in the isolated microgrid is then defined by combining Equations (11), (15) and (17) as

$$\omega_i = \omega_n - \frac{2\pi}{K_i^{c,d}} \cdot \left[P_{Bi} + K_i^r \int (\omega_i - \omega_n) + K_i^{iner} \frac{d}{dt} (\omega_i - \omega_n) \right].$$
(18)

In [22], the conventional ω -*P* droop control, synthetic inertia control and frequency recovery control were formed as a PID controller in order to adjust the active power according to the frequency deviation. However, in the control system proposed in this paper, the frequency restoration and the virtual inertia controllers are designed as an input of the the adaptive frequency droop control. As an additional advantage, the battery active power is shared as a function of the current SOC.

The overall block diagram of the proposed control system is illustrated in Figure 4. The red-dashed rectangle indicates the frequency restoration and virtual inertia controllers. The adaptive frequency droop gain is indicated by the yellow triangle. The magenta-dashed and green-dashed rectangles indicate the voltage and current controllers in the d-q reference frame respectively. The outputs from the current controllers generate the references for the VSC's pulse width modulation (PWM) generator.



Figure 4. BESS and proposed control strategy.

4. Small Signal Stability Analysis

To study the dynamic response of the proposed control strategy, the small signal stability based parameter sensitivity of the isolated microgrid is presented. Note that the small signal model is derived for the proposed control system only. The voltage and current control loops are neglected [7,30]. The active power flow in Equation (13) and the proposed control system in Equation (18) are linearized around operating points and expressed as

$$\Delta P_{DG0} = H_{LPF}(s)G_0\Delta\delta,\tag{19}$$

$$\Delta\omega = \Delta\omega_n - \frac{2\pi}{K_i^{c,d}} \left[\Delta P + \frac{K_i^r}{s} \Delta\omega + sK_i^{iner} \Delta\omega \right],$$
(20)

where $H_{LPF}(s) = \frac{\omega_c}{s + \omega_c}$ is the transfer function of low pass filter and G_0 is

$$G_0 = \frac{V_{DG0}V_{g0}}{X}\cos\delta_0,\tag{21}$$

where V_{DG0} , V_{g0} and δ_0 are the operating points and X is the equivalent impedance of transformers.

By integrating the angular frequency change ($\Delta \omega$), the small disturbance of the phase angle (δ) around the operating point can be obtained as

$$\Delta \delta = \int \Delta \omega dt. \tag{22}$$

Consequently, the small signal model of the proposed control system is

$$\Delta P = \frac{As^3 + Bs^2 + Cs + D}{s^3 + Es^2 + Fs + G} \Delta \omega_n,$$
(23)

where the coefficients A, B, C, D, E, F and G in Equation (23) are given as

$$A = \frac{K_i^{c,d}}{2\pi}$$

$$B = \frac{\omega_c K_i^{c,d}}{2\pi}$$

$$C = \frac{K_i^r K_i^{c,d}}{2\pi K_i^{iner}}$$

$$D = \frac{\omega_c K_i^{c,d}}{2\pi} \left[\frac{G_0 + K_i^r}{K_i^{iner}} \right]$$

$$E = \frac{K_i^{c,d} + 2\pi\omega_c K_i^{iner}}{2\pi K_i^{iner}}$$

$$F = \frac{\omega_c K_i^{c,d} + 2\pi K_i^r}{2\pi K_i^{iner}}$$

$$G = \omega_c \left[\frac{G_0 + K_i^r}{K_i^{iner}} \right].$$
(24)

Figure 5 shows the block diagram of the small signal model of the proposed controller. The time response of the transfer function in Equation (23) can be adjusted by varying K_i^r and K_i^{iner} .



Figure 5. Small signal model of the proposed control system.

Next, the eigenvalue based analysis to properly tune the control parameters is presented. The initial conditions for Equation (23) are given in Table 1.

Parameter	Value		
V_{DG0}	414.7 V		
V_{g0}	414.5 V		
δ_0	0.05388 rad		
X	1.35Ω		
п	3		
$SOC_{50\%}$	50%		
K_i^r	[1000, 30,000]		
K ^{iner}	[10, 300]		

Table 1. Initial Conditions.

It is important to note that K_i^r and K_i^{iner} parameters affect the BESS' active power sharing. Since the value of $K_i^{c,d}$ is adaptively changing as a function of the current SOC, the K_i^r and K_i^{iner} values should also vary accordingly. First, K_i^r and K_i^{iner} are chosen based on the eigenvalue analysis, assuming the

initial SOC of 50%, and are denoted as $K_{i_{50\%}}^r$ and $K_{i_{50\%}}^{iner}$. Then, K_i^r and K_i^{iner} are varied as a function of the current SOC_i as

$$K_{i}^{r} = K_{i_50\%}^{r} \left[1 - \frac{SOC_{50\%} - SOC_{i}}{SOC^{max} - SOC^{min}} \right]^{n},$$
(25)

$$K_{i}^{iner} = K_{i_50\%}^{iner} \left[1 - \frac{SOC_{50\%} - SOC_{i}}{SOC^{max} - SOC^{min}} \right]^{n},$$
(26)

where $SOC_{50\%}$ is the selected initial SOC for tuning the control parameters and *n* is the same variable as in Equations (8) and (9). Note that the stability has to be ensured for all values of K_i^r and K_i^{iner} which are varying as a function of SOC_i .

The eigenvalues trajectories corresponding to the parameters in Table 1 and 85%, 50% and 15% SOCs are shown in Figures 6 and 7. Figure 6 shows the eigenvalues trajectories for both K_i^r and K_i^{iner} decreasing from 30,000 to 1000 and 300 to 10 respectively. Figure 7 depicts the eigenvalues trajectories for decreasing K_i^{iner} and increasing K_i^r . It can be observed that the proposed controller is more stable for both K_i^r and K_i^{iner} decrease. Moreover, for the same SOC, decrease in K_i^{iner} can enhance the stability. On the other hand, the complex eigenvalues can be unstable for high values of K_i^{iner} , low values of K_i^r and low SOC. This can be observed for 15% SOC in the zoomed-in graph in Figure 7.

To ensure the stability for all values of K_i^r and K_i^{iner} in Equations (25) and (26), first K_i^r and K_i^{iner} at 50% of SOC are selected as $K_{i_{50\%}}^r = 8500$ and $K_{i_{50\%}}^{iner} = 85$ respectively. For both values all eigenvalues are stable. Then, using Equations (25) and (26), the values of K_i^r and K_i^{iner} at 85% and 15% SOC can be found as 25,490, 252.489 and 1512.82, 15.1282 respectively. For all these values, the eigenvalues lie in the left-hand side of the complex plane, which ensures that the control system is stable within the given SOC range.



Figure 6. Eigenvalues trajectories of the third-order small-signal model of the proposed control system with decrease in both K_i^r and K_i^{iner} from 30,000 to 1000 and 300 to 10 respectively.



Figure 7. Eigenvalues trajectories of the third-order small-signal model of the proposed control system with increase in K_i^r and decrease in K_i^{iner} .

5. Simulation Results and Discussion

Real-time digital simulator (RTDS) was used to verify the proposed control system on an isolated microgrid shown in Figure 1. The RTDS setup is depicted in Figure 8. Nonlinear battery models and detailed switching converter models are implemented for the microgrid. The electrical and control parameters are given in Tables 2 and 3 respectively. The verification results are divided into three scenarios. The first scenario investigates performance of the adaptive frequency droop control. The second scenario examines the dynamic performance of the entire proposed frequency control system with purely resistive and RL loads. In the third scenario, the complete control system with variable PV generation is verified over long time period. Note, that in all three scenarios, the conventional V-Q droop control coefficient in Table 3 is same for all BESSs.

The RTDS model is run with two different time-steps. All power electronic systems and sources (dc-dc converters, voltage source converters, PV sources and BESSs) are executed as a sub-network with a time-step of 1.5 μ s to 2.5 μ s. The remaining parts of the system (power system circuits, power lines and loads) are solved as a main network with a time-step of 50 μ s. Therefore, the verification is performed in real-time, including nonlinear battery models and high-frequency switching dynamics of all power electronic converters.

Parameter	Value	Parameter	Value
V_{VSC}	415 V	V_{MG}	4.16 kV
C_{f}	68 µF	r _f	0.01 Ω
L_{f}	5 mH	Ĺ _c	4 mH
r_c	0.01 Ω	C_{link}	3.4 µF
V _{DClink}	700 V	$Z_{12} = Z_{23} = Z_{34}$	$0.0035 + j1.837 \ \Omega$
$R_1 = R_2 = R_3 = R_4$	$3.5 k\Omega$	$E_1^{batt} = E_2^{batt}$ and $E_3^{batt} = E_4^{batt}$	25 kWh and 20 kWh (lead acid)

Tal	ble	2.	Elect	rical	Pai	ramet	ers.
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Parameter	Value	Parameter	Value
k_{pi}	10	k _{ii}	0.2
k'_{pv}	3000	k_{iv}	10
$\dot{\omega}_c$	5 rad/s	ω_n	314 rad/s

Parameter	Value	Parameter	Value
m_i^p	$2.1 imes 10^{-5} \text{ rad/W}{\cdot}\text{s}$	n_i^q	$2.5 imes 10^{-4} \text{ V/VAr}$
K ^{max}	150 kW/Hz	fvsc	2 kHz
$[SOC^{min}, SOC^{max}]$	[10%, 90%]	f _{dcdc}	1 kHz

Table 3. Cont.



Figure 8. RTDS setup for verification of the proposed decentralized frequency control strategy on an isolated microgrid. Racks 1 implements the isolated microgrid, control systems for both BESSs and PV sources as well as the proposed control system.

5.1. Scenario 1: Adaptive Droop Control

In this scenario, the performance of the adaptive droop control is investigated. A 0.55 k Ω resistive load is suddenly connected at t = 15 s at bus 2. The initial batteries SOCs are set as 70%, 60%, 50% and 40% for BESS1, BESS2, BESS3 and BESS4 respectively. As shown in Figures 9 and 10, the adaptive droop controllers adjust the BESSs' active power outputs according to the current SOCs. This results in frequency decrease in accordance with the droop characteristic shown in Figure 2. The BESS1 with the highest SOC shares most active power whereas the BESS4 with the lowest SOC shares least active power. The proportion of the BESS' active power sharing is defined by Equation (8). Hence, the proposed adaptive frequency controller both improves the system frequency regulation and achieves proportional BESSs' active power sharing. This is unlike the conventional frequency droop control in which the active powers of the DG units are equally shared. If the conventional ω -*P* droop control is applied to BESSs, the BESSs with lower SOCs may prematurely run out of energy and are not anymore able to contribute to the frequency regulation.





Figure 11 compares performance of the proposed adaptive frequency droop control with the conventional frequency droop control and similar control systems from [15,31]. Note that in the comparison, the initial SOCs of the BESSs were set to 50%. The results clearly demonstrate that the frequency deviation from the nominal value of 50 Hz, both before and after the load change, is improved for the proposed adaptive frequency droop controller.



Figure 11. Comparison of the frequency deviation of the proposed control system with existing control systems.

5.2. Scenario 2: Adaptive Droop Control with Virtual Inertia and Frequency Restoration Control

The complete control system is examined and discussed in this scenario. In this scenario, a 0.90 k Ω resistive load is connected at t = 15 s at bus 2. As a result, additional active power is required for the restoration of frequency to the nominal value and virtual inertia emulation. The initial SOCs of BESSs are same as in Scenario 1. The gains of K_i^r and K_i^{iner} are found from Equations (25) and (26) as 16,602 and 166.2, 12,103 and 121.03, 8500 and 85, 5694 and 56.94 for BESS1, BESS2, BESS3, BESS4 respectively.

Figures 12 and 13 show the frequency and the BESSs' active powers before and after the load change. Before the load change, the frequency was regulated at 50 Hz. After the sudden load change the frequency is recovered to the nominal value while the BESSs provide the active power proportionally to their SOC levels. This demonstrates that the proposed control system can improve frequency excursion and recover the frequency to the nominal value in a decentralized manner, without requiring any

recovery time.

communication links. This is of significant advantage for microgrids in remote or rural areas since without the communications links reliability is enhanced and cost is reduced.



To compare the frequency recovery and frequency nadir performance, the proposed control system is compared with the same existing control strategies as in Scenario 1. The initial SOCs of all BESSs are set to 50% for all control strategies. As it can be seen from Figure 14, both the frequency drop, called frequency nadir, and the frequency recovery are improved for the proposed control system as compared with the existing control strategies. Among all control strategies, performance

Moreover, in this scenario, the proposed control system is verified with RL loads. The purely resistive loads of 3.5 k Ω are all replaced by RL loads of 4.0 + *j*0.75 k Ω . Similarly, at *t* = 15 s, an RL load of 0.9 + *j*0.47 k Ω is suddenly connected to the microgrid at bus 2.

of the conventional frequency droop control is worst in both the frequency nadir and the frequency

Figures 15–17 illustrate the dynamic responses of frequency, active power and reactive power respectively before and after the load change. BESSs' frequencies were recovered to the nominal value and the active powers were shared proportionally to the BESSs' SOCs.



Figure 14. Comparison of the frequency recovery and frequency nadir performance of the proposed control system with existing control systems.





5.3. Scenario 3: Complete Control System with PV Generation

In this scenario, the proposed control system is verified considering PV generation variation over longer period of time. Compared with Scenarios 1 and 2, the parameter K_i^{iner} is reduced by 10% while the parameter K_i^r remains same. Both parameters guarantee the system stability as analyzed in Section 4. In Scenarios 1 and 2, the parameter K_i^{iner} was tuned for fair comparison with the existing control strategies. It is assumed that both the BESSs and PV sources are optimally sized to ensure the SOC recovery during daytime considering anticipated frequency support and loads. Alternatively, load shedding or a dispatchable backup source such as a generator may be used to recover the SOC.

The PV sources are operated at MPP and the VSCs are controlled to work in the grid feeding mode. Hence, the PV sources do not participate in the frequency control. The PV sources intermittent output powers over one hour period are illustrated in Figure 18. The BESSs level out the PV sources power fluctuations and regulate the frequency deviation.



Figure 18. PV sources output powers.

Figures 19–21 show BESSs' frequencies, active powers and SOCs respectively. The proposed control system maintains the frequency at the nominal value and BESSs share loads proportionally to their SOC levels. The differences between the BESSs' SOCs are getting smaller over time. BESSs with lower SOCs share the loads by supplying less active power and hence will run out of energy slower.



6. Conclusions

This paper presented a decentralized frequency control strategy for BESSs distributed in an isolated microgrid. The proposed control strategy comprised three components: the adaptive frequency

powers in proportion to their current SOCs, (ii) fast frequency recovery to the nominal value and (iii) improved frequency nadir. The proposed control strategy was verified using the real-time digital simulator (RTDS) with accurate microgrid model, non-linear battery models and detailed switching models of power electronic converters. The presented results demonstrated superior performance when compared with existing control strategies.

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