

Article

Continuous Power Management of Decentralized DC Microgrid Based on Transitional Operation Modes under System Uncertainty and Sensor Failure

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Abstract: Continuous power management for a decentralized DC microgrid (DCMG) is proposed in this study to achieve power balance and voltage regulation even under system uncertainty and voltage sensor failure. The DCMG system achieves continuous power management through only the primary controller to reduce the computational burden of each power agent. To enhance the reliability and resilience of the DCMG system under DC bus voltage (DCV) sensor failure, a DCV sensor fault detection algorithm is suggested. In this algorithm, DCV sensor failure is detected by comparing the measured DCV with the estimated DCV. If power agents identify the failure of the DCV sensor, it changes the operation properly according to the proposed control mode decision algorithm to guarantee the stability of the DCMG system. When uncertain conditions like sudden grid disconnection, DCV sensor failure, electricity price change, power variation in distributed generations, and critical battery status occur, the DCMG system is changed to transitional operation modes. These transitional operation modes are employed to transmit the power agent information to other agents without digital communication links (DCLs) and to accomplish power sharing even under such uncertain conditions. In the transitional operation modes of the DCMG system, the DCV levels are temporarily shifted to an appropriate level, enabling each power agent to detect the uncertainty conditions, and subsequently to determine its operation modes based on the DCV levels. The reliability and effectiveness of the proposed control strategy are confirmed via various simulation and experimental tests under different operating conditions.

Keywords: continuous power management strategy; decentralized DC microgrid control; sensor failure; system uncertainty; transitional operation modes



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1. Introduction

Interest in sustainable and renewable energy is increasing due to environmental problems such as greenhouse gas emissions and fossil fuel depletion [1,2]. With the increasing demand for cleaner energy, the microgrid system has emerged as a promising solution to generate and distribute electrical energy. By using the microgrid, the distributed generations based on renewable energy sources, utility grid, energy storage systems (ESSs), and loads are interconnected efficiently and reliably to overcome the limitation caused by the intermittent nature of renewable energy, which provides a sustainable alternative to the conventional power grid [3–5]. By harnessing diverse renewable energy sources, microgrids contribute to reducing the carbon footprint and enhance energy resilience. Microgrid systems that are efficient and robust for the use of distributed energy sources are

usually composed of ESSs, loads, and distributed generations such as a wind turbine and photovoltaic (PV) device [6].

Depending on the type of power supplied, the microgrid configuration is divided into the DC microgrid, AC microgrid (ACMG), and hybrid AC/DC microgrid [7]. Among these structures, DCMG stands out for its simplicity and efficiency. Unlike hybrid AC/DC and AC microgrids, the DCMG minimizes unnecessary power conversion stages and reduces technical challenges such as synchronization, harmonics, and reactive power [8–11]. Furthermore, DC energy sources such as fuel cells, PV, supercapacitors, or batteries are easily interconnected in the DCMG system [12].

According to the configuration of the digital communication link (DCL), the control strategy for the DCMG system is categorized into three main types: centralized control, decentralized control, and distributed control [13–15]. The centralized control strategy uses a central controller that communicates with all power agents via DCLs to determine the operation modes of each power agent [16,17]. The distributed control strategy also uses DCL to communicate with adjacent power agents. However, in the distributed control method, power agents determine the proper operation modes with a limited DCL to adjacent power agents without relying on a central controller [18,19]. It is important to note that the transmission time delay caused by the DCL that is unavoidable in both the distributed and centralized controls might negatively impact the efficiency and stability of the DCMG system [3]. A decentralized control strategy can be employed as an alternative way to solve this weakness. In the decentralized control method, the operation modes of the DCMG system are properly determined based on only local measurements such as the DCV, without using any DCL between power agents [20]. In addition, power agents normally operate independently in the decentralized DCMG system without the use of any DCL, which significantly increases the simplicity, scalability, and flexibility of the DCMG system [21,22].

Generally, the DCV is utilized as global information for powers agent in the decentralized DCMG system [23–26]. If the DCV decreases from the nominal DCV value, it indicates that the power supply to the DC bus is less than the power demand. In contrast, if the DCV increases from the nominal DCV value, it means that there is power surplus in the DCMG system. Traditionally, the droop control strategy is employed in decentralized DCMG systems to control the DCV to the nominal value [27–31]. In the study in [29], DCMG power balance is achieved by using a voltage–current (V-I) droop controller according to the DCV level. To overcome the weakness of the DCV fluctuation in this scheme, the researchers in [31,32] proposed the use of an integral term in the secondary controller for ensuring DCV restoration to the nominal value. The secondary control strategy is used in these methods to regulate the DCV to its nominal value, while the primary control strategy is employed to maintain the power balance in the decentralized DCMG system. Although the voltage fluctuation problem caused by the droop controller is mitigated by combining the primary and secondary controls, there still exists a computational burden in the above methods. Moreover, it is desirable to consider a method to enhance system reliability even under sensor device failure.

To operate the DC microgrid efficiently, several sensors are utilized to provide feed-back signals for real-time monitoring and control systems. It is worth mentioning that the information from these sensors plays a significant role, especially in decentralized DCMG configuration, to determine the operation modes of the power agent because of the absence of the DCLs between the power agents. The sensor failure or abnormality leads to discrepancies in data interpretation among power agents, potentially resulting in suboptimal system operation, or even instability in an extreme case [33,34]. To overcome such sensor failure, the researchers in the studies in [35,36] presented fault-tolerant control via hardware redundancy. In those methods, additional sensors were equipped as redundancy hardware to deal with sensor faults. In spite of the reliability enhancement against sensor failures, these approaches obviously increase system costs. Fault detection and isolation are also proposed for the distributed DCMG system via an adaptive observer method to detect

different types of sensor failure [37]. The research in [38] proposed an H_∞ observer for DC–DC converters in order to compensate for current and voltage sensor faults. However, it is difficult to implement those control strategies for the decentralized DCMG system because the DCLs between power agents are absent in the decentralized DCMG.

Motivated by this concern, this study presents a continuous power management strategy of a decentralized DCMG system based on the transitional operation modes under system uncertainty and sensor failure to improve system reliability. To achieve both a power balance and voltage stabilization continuously under various uncertain conditions such as power variation in distributed generation, grid disconnection, and critical battery status, the transitional operation modes are employed to transmit the power agent information to others without DCLs. In these transitional operation modes of the DCMG system, the DCV levels are temporarily adjusted to a proper level. Furthermore, to minimize the electricity price, the proposed control strategy determines the operation modes of power agents by considering the electricity price conditions in the grid-connected mode (GCM). It is important to mention that the proposed control strategy uses only primary control to achieve DCV restoration, which significantly reduces the computational burden.

To monitor the abnormality of DCV sensors, all the power agents estimate the DCV by using the observer in the proposed scheme. For this aim, the proposed DCV sensor fault detection algorithm is implemented in all power agents to detect the DCV sensor fault by comparing the estimated DCV with the measured DCV. Under normal conditions without DCV sensor failure, the proposed power management strategy achieves both power balance and voltage regulation by using the estimated DCV. When the DCV sensor failure occurs in any power agent, the operation modes of the power agent are changed properly based on the proposed control mode decision algorithms to ensure a continuous power management strategy even in the presence of DCV sensor failure. The main contributions of this study are summarized as follows:

- (i) The proposed control strategy based on the decentralized DCMG configuration achieves continuous power management based on the transitional operation modes under system uncertainty and sensor failure, which greatly improves the system reliability. In addition, both voltage regulation and power sharing are accomplished by using only the primary controller to reduce the computational burden.
- (ii) Even in the presence of uncertainties such as grid disconnection, electricity price changes, power variation in the distributed generation, and critical battery status, the proposed decentralized DCMG system ensures voltage stabilization and power balance by using the transitional operation modes without DCLs. Once an uncertain condition occurs, the DCV levels are temporarily adjusted to a proper level in transitional operation modes, and then, the power agents determine their operation modes based on the DCV levels.
- (iii) The DCV sensor fault detection algorithm continuously monitors the abnormality of the DCV sensor in the proposed scheme to reinforce the DCMG system's reliability. Under normal conditions without DCV sensor failure, the proposed scheme achieves both voltage regulation and power balance. If DCV sensor failure happens in a power agent, the proposed control mode decision algorithm properly changes the power agent operation into current control mode for seamless power management. In addition, the proposed scheme can stably work even under multiple DCV sensor faults in more than one power agent at the same time if there exists a normal DCV sensor in a DCMG system.

This paper is organized as follows: In Section 2, the DCMG system configuration and decentralized control strategy are described. Section 3 explains the control strategy of power agents in normal conditions, the control strategy under DCV sensor fault, and transitional operation modes of power agents. To validate the proposed control strategies, Sections 4 and 5 show the test results of the decentralized DCMG system under various conditions by using simulation and experiments. Finally, Section 6 provides the conclusion of this study.

2. System Configuration of a DCMG and Decentralized Control Strategy

A system configuration of a decentralized DCMG is shown in Figure 1. A decentralized DCMG is composed of four power agents: a grid agent, wind turbine agent, load agent, and battery agent. The grid power agent connects the utility grid to the DC bus through a transformer and bidirectional AC–DC converter. The wind turbine power agent connects the wind turbine to the DC bus, in which the mechanical energy is converted into electrical energy via a three-phase permanent magnet synchronous generator (PMSG) and unidirectional AC–DC converter. The battery power agent connects the battery to the DC bus via the bidirectional DC–DC converter. The load agent consists of DC loads directly connected to the DC bus.

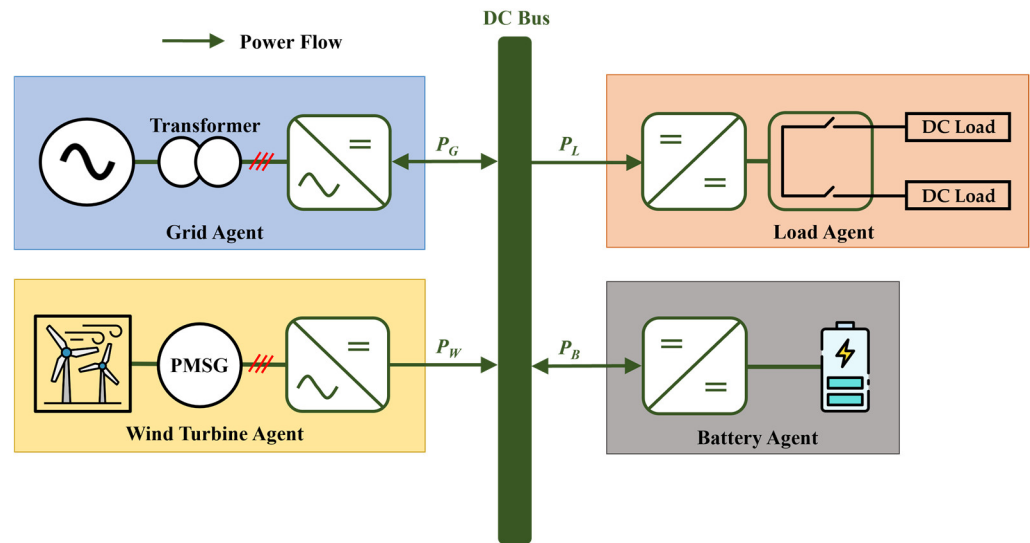


Figure 1. Configuration of a DCMG [39].

In this DCMG system, the battery and grid power agents are capable of transferring bidirectional power, by supplying the power into the DC bus, or absorbing the power from the DC bus. On the other hand, the wind turbine agent only has unidirectional power flow, supplying the power to the DC bus. As shown in Figure 1, P_L , P_W , P_G , and P_B represent the power flow of the load, wind turbine, grid, and battery agents. In this paper, positive power values (+) represent when the power agent absorbs the power from the DC bus, while negative power values (−) represent when the power agent supplies the power to the DC bus.

Figure 2 illustrates the simplified structure of the power converter for agent i , which consists of a switch module; an inductor, L_i ; a capacitor, C_i ; virtual resistance, R_{Li} , for the grid; a wind turbine; and battery agents. In Figure 2, i denotes each agent, i.e., $i = G, B$, and W , representing the grid, battery, and wind turbine agents, respectively. From Figure 2, the power converter model is derived as follows:

$$\frac{dV_{DC,i}}{dt} = \frac{I_i^{out}}{C_i} - \frac{V_{DC,i}}{R_{Li}C_i} \quad (1)$$

where $V_{DC,i}$ and I_i^{out} denote the DCV measured from the sensor and converter output current of agent i , respectively. It should be noted that the resistance, R_{Li} , for each power agent, i , is connected in parallel to produce the total equivalent resistance, R_L , at the DC bus of the DCMG system. This yields the following relation:

$$\frac{1}{R_L} = \sum \frac{1}{R_{Li}} \quad (2)$$

where R_L is the total equivalent load.

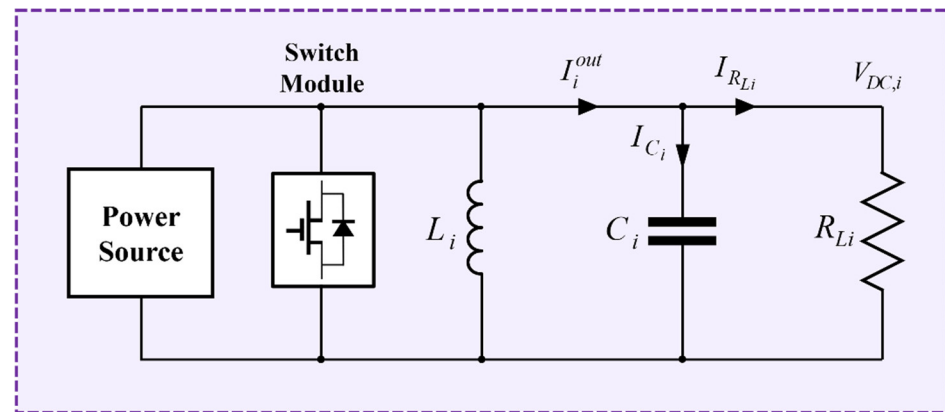


Figure 2. Simplified structure for power converter of agent i .

3. Control Strategy and Transition Operations of Power Agents under Emergency Conditions

3.1. Control Strategy of Power Agents

Figure 3 represents the control block diagram of agent i in the decentralized DCMG system. In this control block diagram, V_i^{ref} denotes the converter reference voltage and d_i denotes the converter duty ratio of power agent i . Unlike the conventional droop controllers [30,31], the proposed control strategy only utilizes the primary controller that consists of voltage and current controls to minimize computational burden. The primary controller consists of two cascaded PI controllers for voltage control and current control, as shown in Figure 3. This cascaded structure is quite common and typical in power electronic converters such as the three-phase AC–DC converter or three-phase inverter. Also, to ensure power balance even in emergency conditions, the DCV sensor fault detection algorithm is implemented in agent i , which is described in detail in Section 3.2. For this purpose, the DCV of agent i is estimated by the observer. The estimated DCV is used to detect DCV sensor fault for the purpose of guaranteeing power balance by continuously monitoring DCV sensor failures with the observer even when the DCV sensor operates normally. In addition, by using the estimated DCV value, agent i regulates the DCV using the proportional–integral (PI) controllers. By applying the conventional observer to (1) with the output error, the DCV of agent i can be estimated as follows:

$$\dot{\hat{V}}_{DC,i} = \frac{I_i^{out}}{C_i} - \frac{\hat{V}_{DC,i}}{C_i R_{Li}} + N_i(V_{DC,i} - \hat{V}_{DC,i}) \quad (3)$$

where $\hat{V}_{DC,i}$ is the estimated DCV and N_i represents observer gain. To implement the proposed control strategy in both the simulations and experiments, the sampling time was selected as 100 μ sec for all power agents to achieve current control. Considering that the current mostly has the fastest dynamics in power converters, and that the sampling time is sufficiently faster than the current dynamics, the influence of the digital control loop delays on voltage regulation and power sharing performance is not as serious as that in the studies in [32,35,38].

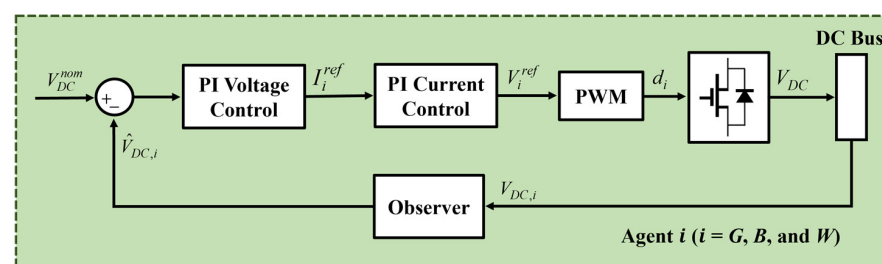


Figure 3. Control block diagram of agent i .

To ensure power balance, the decentralized DCMG controller in this study uses nine steady-state operation modes, as shown in Table 1, under normal conditions without any DCV sensor fault. In each operation, the control modes of power agent i are determined according to the criterion that only one power agent regulates the DCV at each instant. When the DCMG system is subject to a change of operation modes caused by uncertainties such as power variation, the transition operation modes are used to identify the power agent that regulates the DCV. The transition operation modes are described in detail in Section 3.3. The control modes of power agent i are separated into voltage control and current control. The voltage control mode implemented as shown in Figure 3 is used to regulate the DCV. In contrast, the current control mode is realized only by the PI current controller.

Table 1. Steady-state operation modes.

Mode	Battery Agent	Wind Turbine Agent	Grid Agent	Load Agent
NO_1	$BCCM_{dis}$	MPPT	$GVC M_{inv}$	Normal
NO_2	$BCCM_{dis}$	MPPT	$GVC M_{con}$	Normal
NO_3	$BCCM_{char}$	MPPT	$GVC M_{inv}$	Normal
NO_4	$BCCM_{char}$	MPPT	$GVC M_{con}$	Normal
NO_5	IDLE	MPPT	$GVC M_{con}$	Normal
NO_6	IDLE	MPPT	$GVC M_{inv}$	Normal
NO_7	BVCM	MPPT	Fault	Normal
NO_8	$BCCM_{char}$	VCM	Fault	Normal
NO_9	IDLE	VCM	Fault	Normal

Nine steady-state operation modes in Table 1 can be explained in detail. In $NO_1 \sim NO_9$, the load agent operates in the normal mode, which indicates that the load agent is connected to the DCMG system without load shedding [31,32,39]. In this paper, the electricity price condition is determined via the real-time pricing (RTP) method as an electricity pricing policy [30,31]. While the steady-state operation modes $NO_1 \sim NO_6$ represent the grid-connected modes, $NO_7 \sim NO_9$ represent the islanded modes when the grid agent is disconnected to the DCMG. The power balance is ensured effectively in both the grid-connected and islanded modes.

Operation NO_1 : This mode occurs with a high electricity price when the sum of the maximum discharging battery power and wind power is larger than the load. In this case, the grid agent regulates the DCV at a nominal value, V_{nom} , via $GVC M_{inv}$ (grid agent voltage control mode by inverter operation). The battery agent operates in $BCCM_{dis}$ (battery current control mode by discharging operation), and the wind turbine agent works in maximum power point tracking (MPPT) mode.

Operation NO_2 : This occurs with a high electricity price when the sum of the maximum discharging battery power and wind power is lower than the load. To guarantee power balance, the grid agent supplies power to the DC bus even with a high electricity price by regulating the DCV at V_{nom} . The grid agent works in $GVC M_{con}$ (grid agent voltage control mode by converter operation), the battery agent operates in $BCCM_{dis}$, and the wind turbine agent works in the MPPT operation.

Operation NO_3 : This occurs with a normal electricity price when the sum of the maximum charging battery power and load is less than the wind power. To ensure power balance, the grid agent absorbs power from the DC bus by regulating the DCV at V_{nom} . The grid agent works in $GVC M_{inv}$, and the battery agent operates in $BCCM_{char}$ (battery current control mode by charging operation). The wind turbine agent works in the MPPT operation.

Operation NO_4 : This occurs with a normal electricity price when the sum of the maximum charging battery power and load is higher than the wind power. The grid agent regulates the DCV at V_{nom} via $GVC M_{con}$. The battery and wind turbine agents work in the $BCCM_{char}$ and MPPT modes.

Operation NO_5 : This occurs with a normal electricity price when the battery state-of-charge (SOC) level is at the maximum and the wind power is lower than the load. Also, this mode occurs with a high electricity price when the battery SOC level is at its minimum and the wind power is lower than the load. In both situations, the grid agent regulates the DCV at V_{nom} via GVC_{con} while the battery and wind turbine agents work in the IDLE and MPPT modes.

Operation NO_6 : This occurs with a normal electricity price when the battery SOC level is at its maximum and the wind power is larger than the load. Also, this mode occurs with a high electricity price when the battery SOC level is at the minimum and the wind power is higher than the load. In both cases, the grid agent regulates the DCV via GVC_{inv} . The battery works in IDLE mode, and the wind turbine works in MPPT mode.

Operation NO_7 : This occurs in islanded mode (IM) when the wind power is less than the sum of the load and maximum charging power of the battery. The battery agent works in BVCM (battery voltage control mode) to regulate the DCV at V_{nom} while the wind turbine works in MPPT mode.

Operation NO_8 : This occurs in IM when the sum of the battery's maximum charging power and load is lower than the wind power. The wind turbine works in VCM (voltage control mode) to regulate the DCV at V_{nom} while the battery agent operates in BCC_{char} .

Operation NO_9 : This occurs in IM when the battery SOC level is at its maximum, and the wind power is higher than the load. The wind turbine agent works in VCM and the battery agent operates in IDLE mode.

3.2. Control Strategy under DCV Sensor Fault

Figure 4 represents the DCV sensor fault detection and control mode decision algorithms of agent i under DCV sensor failure. In these algorithms, e_i , ε_i , c , c_{max} , $\hat{V}_{DC,i}^{pre}$, I_i^{ref} , and $I_{i,pre}^{ref}$ represent the difference between $V_{DC,i}$ and $\hat{V}_{DC,i}$, the specified threshold value, the counter value, the specified threshold of the counter, the previous value of $\hat{V}_{DC,i}$, the reference current of agent i , and the previous value of I_i^{ref} , respectively. The variable F_{fault} denotes a fault flag, which is used to indicate the fault in the DCV sensor of agent i . When the DCV sensor has a failure, F_{fault} is set to one. Otherwise, it is reset to zero. Also, the variable F_{mode} represents a control mode flag to indicate the operation of agent i before DCV sensor fault. If the operation of agent i is in voltage control before DCV sensor fault, F_{mode} becomes one. Otherwise, it is reset to zero.

In the proposed strategy, when F_{fault} is equal to zero, the system compares e_i with ε_i to investigate the normal operation of the DCV sensor. When e_i is larger than ε_i , the counter is utilized to count this event. When counter c is less than c_{max} , counter c increases and $\hat{V}_{DC,i}$ is replaced with $\hat{V}_{DC,i}^{pre}$. However, if counter c is greater than c_{max} , the fault detection algorithm confirms DCV sensor failure in power agent i . As soon as DCV sensor fault is identified, the fault detection algorithm sets the fault flag, F_{fault} , to one. Then, the control mode decision algorithm of agent i is executed to guarantee system stability even under DCV sensor fault by determining a proper operation.

In the control mode decision algorithm, transition operations to current control mode depend on the previous operations of the power agent having DCV sensor failure. If DCV sensor failure occurs in the power agent that does not regulate the DCV, it still maintains the operation of the current control mode, with the current reference being as follows:

$$I_i^{ref} = I_{i,pre}^{ref} \quad (4)$$

On the other hand, if DCV sensor failure happens in power agent i , which regulates the DCV, the other power agent should take the role of regulating the DCV. For this purpose, the power agent operation is shifted to current control mode with the reference current change. In case DCV sensor fault occurs in the grid or battery agent that regulates the DCV,

the grid or battery agent changes its operation mode to current control mode, with the current reference being as follows:

$$I_i^{ref} = I_{i,pre}^{ref} - \delta_i \quad (5)$$

Because more power is supplied to the DC bus, the DCV level is continuously increased. As a result, by detecting this DCV transition, remaining power agents can regulate the DCV after the transition operation mode. In case DCV sensor fault occurs in the wind turbine agent that regulates the DCV, the wind turbine agent changes its operation mode to current control mode, with the current reference being as follows:

$$I_W^{ref} = I_{W,pre}^{ref} + \delta_W \quad (6)$$

Because the power supplied to the DC bus is reduced, the DCV level decreased. By detecting this DCV transition, remaining power agents can regulate the DCV after the transition operation mode.

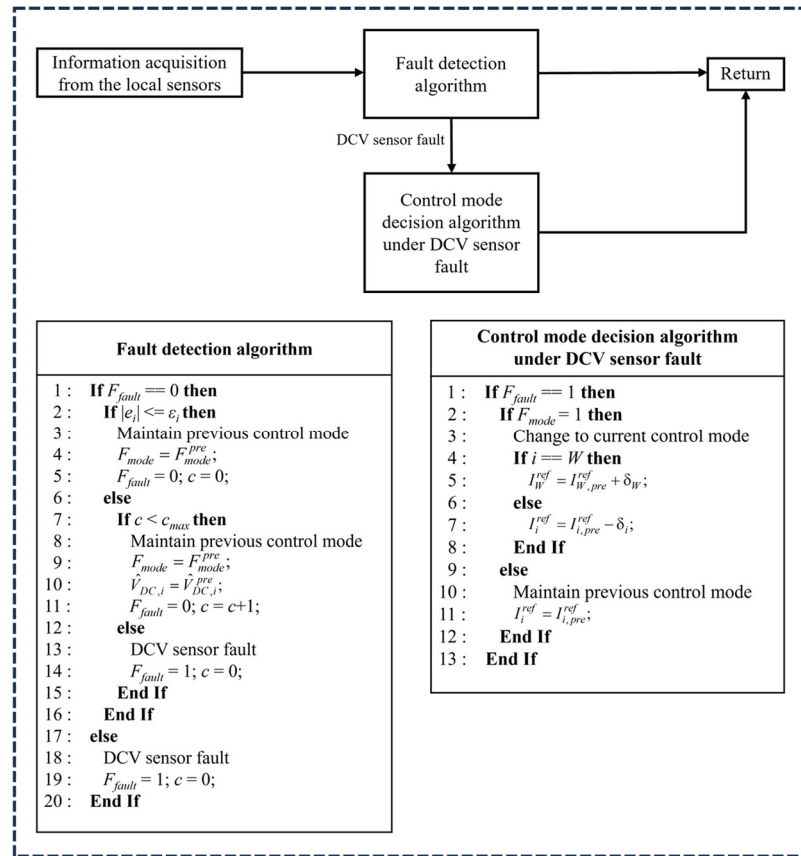


Figure 4. DCV sensor fault detection and control mode decision algorithms in agent i .

To ensure both power balance and voltage regulation under DCV sensor fault, Table 2 shows additional steady-state operation modes for a decentralized DCMG system according to the DCV sensor fault. During normal operation without any failure, the DCMG operates in one of the steady-state operation modes listed in Table 1. Under DCV sensor failure, the DCMG operation is changed to one of additional the steady-state modes in Table 2 after the transition operations, which will be explained in the next subsection.

Nine additional steady-state operation modes in Table 2 are explained in detail. The operation mode transition from the normal operation in Table 1 to the additional operation in Table 2, caused by the DCV sensor faults, will be described in Figure 5. Similarly to the fact that the DC bus voltage is always regulated by at least one power agent in steady-state

operation modes $NO_1 \sim NO_9$ in Table 1, it is also regulated by at least one power agent in $AO_1 \sim AO_9$ in Table 2.

Table 2. Additional steady-state operation modes according to DCV sensor fault.

Mode	Battery Agent	Wind Turbine Agent	Grid Agent	Load Agent
AO_1	BVCM	MPPT	$GCCM_{inv}$	Normal
AO_2	$BCCM_{dis}$	VCM	$GCCM_{inv}$	Normal
AO_3	BVCM	MPPT	$GCCM_{con}$	Normal
AO_4	$BCCM_{dis}$	VCM	$GCCM_{con}$	Normal
AO_5	$BCCM_{char}$	VCM	$GCCM_{inv}$	Normal
AO_6	$BCCM_{char}$	VCM	$GCCM_{con}$	Normal
AO_7	IDLE	VCM	$GCCM_{con}$	Normal
AO_8	IDLE	VCM	$GCCM_{inv}$	Normal
AO_9	$BCCM_{dis}$	VCM	Fault	Normal

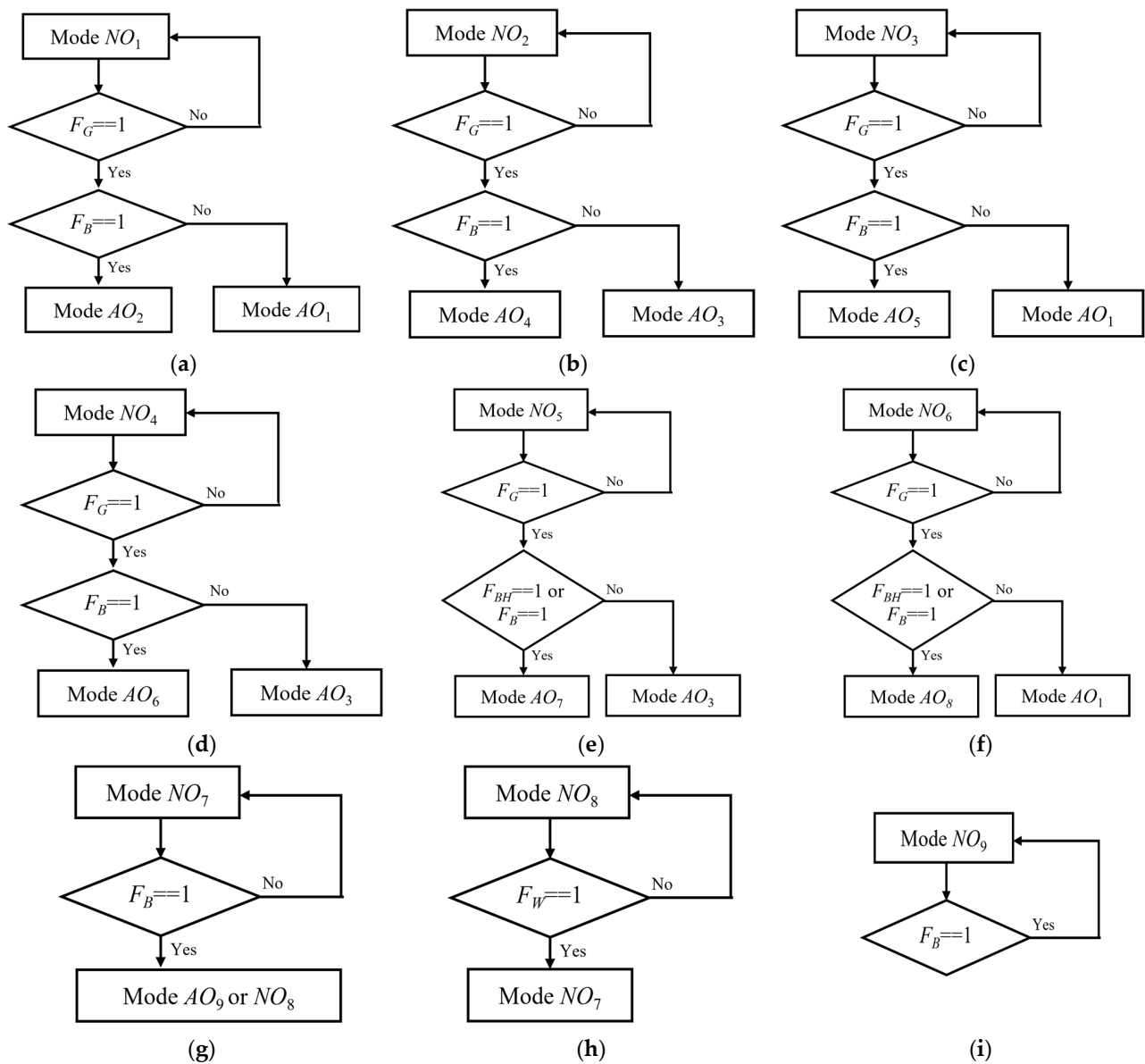


Figure 5. Operation mode transition caused by DCV sensor faults (a) from mode NO_1 ; (b) from mode NO_2 ; (c) from mode NO_3 ; (d) from mode NO_4 ; (e) from mode NO_5 ; (f) from mode NO_6 ; (g) from mode NO_7 ; (h) from mode NO_8 ; (i) from mode NO_9 .

Operation AO_1 : In this mode, because DCV sensor fault occurs in the grid, the grid operates in $GCCM_{inv}$ (grid current control mode by inverter operation), and the battery operates in $BVCM$ to regulate DCV at V_{nom} . The wind turbine operates in MPPT mode.

Operation AO_2 : In this mode, because the DCV sensor fault occurs in both the grid and battery, the battery operates in $BCCM_{dis}$ and the grid operates in $GCCM_{inv}$. The wind turbine operates in VCM to regulate the DCV at V_{nom} .

Operation AO_3 : The battery agent operates in $BVCM$ to regulate the DCV at V_{nom} . The wind operates in MPPT mode and the grid agent operates in $GCCM_{con}$ (grid current control mode by converter operation).

Operation AO_4 : The wind turbine operates in VCM to regulate the DCV at V_{nom} . The battery operates in $BCCM_{dis}$ and the grid operates in $GCCM_{con}$.

Operation AO_5 : The wind turbine operates in VCM to regulate the DCV at V_{nom} . The battery operates in $BCCM_{char}$ and the grid operates in $GCCM_{inv}$.

Operation AO_6 : The wind turbine operates in VCM to regulate the DCV at V_{nom} . The battery operates in $BCCM_{char}$ and the grid operates in $GCCM_{con}$.

Operation AO_7 : The wind turbine operates in VCM to regulate the DCV at V_{nom} . The battery operates in IDLE mode and the grid operates in $GCCM_{con}$.

Operation AO_8 : The wind turbine operates in VCM to regulate the DCV at V_{nom} . The battery operates in IDLE mode and the grid operates in $GCCM_{inv}$.

Operation AO_9 : The wind turbine operates in VCM to regulate the DCV at V_{nom} . The battery operates in $BCCM_{dis}$.

Figure 5 shows operation mode transitions caused by DCV sensor failure, in which the DCV sensor faults of the battery, wind turbine, and grid are denoted by the variables F_B , F_W , and F_G , respectively. The maximum and minimum SOC levels of the battery agent are denoted by SOC_B^H and SOC_B^L , respectively. The variables F_B , F_W , and F_G are represented as follows:

$$F_i = 1, \text{ if DCV sensor failure happens in power agent } i$$

$$F_i = 0, \text{ otherwise,}$$

$$\text{for } i = B, W, G. \quad (7)$$

Similarly, two variables to denote the battery SOC status are defined as follows:

$$F_{BH} = 1, \text{ if } SOC_B = SOC_B^H;$$

$$F_{BH} = 0, \text{ otherwise;}$$

$$(8)$$

$$F_{BL} = 1, \text{ if } SOC_B = SOC_B^L;$$

$$F_{BL} = 0, \text{ otherwise}$$

$$(9)$$

where SOC_B denotes the battery SOC.

If DCV sensor failures occur during normal operation NO_1 , the DCMG is changed to additional operation modes as represented in Figure 5a. During the operation of NO_1 , if DCV sensor failure happens in the battery ($F_B = 1$) or wind turbine ($F_W = 1$) or both the wind turbine and battery ($(F_W = 1)$ and $(F_B = 1)$), the DCMG system still maintains in NO_1 because the wind turbine and battery do not regulate the DCV before sensor fault. If the grid ($F_G = 1$) or both the grid and wind turbine ($(F_G = 1)$ and $(F_W = 1)$) have DCV sensor fault, the DCMG system is changed to mode AO_1 . The grid agent changes the control mode from $GVC_{M_{inv}}$ in NO_1 to $GCCM_{inv}$ in AO_1 according to Figure 4. In this situation, the battery operates in $BVCM$ to regulate the DCV. Finally, if both the grid and battery agents ($(F_G = 1)$ and $(F_B = 1)$) have DCV sensor fault, only the wind turbine can regulate the DCV. Therefore, the DCMG system is changed to mode AO_2 .

Figure 5b–d show the transition to additional operation modes of the DCMG when DCV sensor failure occurs during normal DCMG system operation in NO_2 , NO_3 , and NO_4 , respectively. These figures show similar behavior with that shown in Figure 5a according to the location of DCV sensor failure. However, under each DCV sensor fault, the destination of additional operation modes is quite different. In the normal operation modes NO_2 , NO_3 , and NO_4 , the grid agent regulates the DCV either in converter or inverter operation. Even

in the case of $(F_B = 1)$, $(F_W = 1)$ or $((F_B = 1) \text{ and } (F_W = 1))$, the DCMG system still maintains the previous operations, NO_2 , NO_3 , and NO_4 , respectively, as in Figure 5b–d, because the grid agent can still regulate the DCV. If DCV sensor failure happens in the grid, $(F_G = 1)$ or $((F_G = 1) \text{ and } (F_W = 1))$, DCV regulation is achieved by the battery agent, which results in a transition into additional operation modes AO_3 , AO_1 , and AO_3 , as shown in Figure 5b–d, respectively. If the failure of the DCV sensor happens in the grid and battery at the same time $((F_G = 1) \text{ and } (F_B = 1))$, only the wind turbine is able to regulate the DCV. Then, via a transition into additional operation modes AO_4 , AO_5 , and AO_6 , the wind turbine regulates DCV in VCM, and other agents operate in current control mode.

Figure 5e represents the operation mode transition from NO_5 due to DCV sensor faults. As we mentioned before, NO_5 occurs with a normal electricity price when the battery SOC level is at the maximum, and the when the wind power is lower than the load. Also, this mode occurs with a high electricity price when the battery SOC level is at the minimum, and when the wind power is lower than the load. If DCV sensor failure does not occur in the grid, the DCMG maintains mode NO_5 . In the condition $[(F_{BH} = 1) \& (F_G = 1)]$ or $[(F_G = 1) \& (F_B = 1)]$, the DCMG is changed from NO_5 to AO_7 . In the first condition, the battery operates in IDLE mode because it can not absorb charging power. In the second condition, because the battery and grid can not regulate DCV, the wind turbine operates in VCM to regulate DCV, which results in AO_7 . In the condition of $[(F_{BL} = 1) \& (F_G = 1)]$ or $[(F_G = 1) \& (F_W = 1)]$, the DCMG system is changed from NO_5 to AO_3 . This condition represents the case in which DCV sensor failure happens in the grid, or in both the grid and wind turbine agents when the battery SOC level is at the a minimum. In either case, the battery works in BVCM to regulate the DCV with charging, which results in AO_3 .

Figure 5f has a similar structure to Figure 5e. While the grid agent starts with GVC_{con} in the normal operation mode NO_5 in Figure 5e, it starts with GVC_{inv} in NO_6 in Figure 5f. Unless DCV sensor failure occurs in the grid, the DCMG maintains NO_6 . Depending on the battery's SOC condition and the DCV sensor fault locations, this normal operation mode is shifted to AO_8 or AO_1 , respectively. In AO_1 , the battery agent regulates the DCV in BVCM. If the battery is not available to regulate the DCV because of the SOC condition or DCV sensor failure, the wind turbine is used in VCM, instead.

Figure 5g shows the operation mode transition caused by the DCV sensor faults when the DCMG works in NO_7 . If the DCV sensor in the battery is operating normally regardless of whether DCV sensor failure occurs in the wind turbine or grid, the DCMG maintains NO_7 . However, when the battery has a DCV sensor failure, i.e., $(F_B = 1)$, only the wind turbine can regulate the DCV in VCM. Then, the DCMG system is changed to AO_9 or NO_8 depending on the relation of the wind power and load.

Figure 5h represents transition of the DCMG system when DCV sensor failure occurs during the normal operation NO_8 . Unless DCV sensor failure occurs in the wind turbine, the DCMG maintains NO_8 . If the wind turbine has a DCV sensor failure $(F_W = 1)$, the battery agent regulates the DCV in BVCM, which results in the change of the DCMG operation to NO_7 .

Finally, Figure 5i represents the operation transition from NO_9 caused by DCV sensor failure. Since only the wind turbine is operating in NO_9 , the DCMG maintains NO_9 , if the DCV sensor of the wind turbine does not have a fault.

3.3. Transitional Operation Modes in Power Agents

In the proposed method, all power agents in the DCMG determine the operation modes by detecting the information of the DCV level without DCLs. When certain transient conditions are introduced into the DCMG, the agents of the DCMG system temporarily shifts the DCV value to different levels during a predetermined period. During this predetermined time, all the power agents appropriately change the operation mode during the transient periods before the DCMG system returns to another steady-state operation mode.

Table 3 lists the transition operation modes that are introduced into the DCMG system due to DCMG system uncertainty. This table also shows the power agents that activate each

transition operation mode and resultant actions. In this table, V_{L1} , V_{L2} , and V_{L3} denote the first, second, and third low-level DCV, respectively, and V_{H1} , V_{H2} , and V_{H3} denote the first, second, and third high-level DCV, respectively.

Table 3. Power agents to activate each transition operation.

Mode	Grid Agent	Wind Turbine Agent	Battery Agent	Agent Action
TO_1	✓			- Grid agent activates TO_1. - Grid agent regulates DCV to V_{L1}. - If DCV level reaches V_{L1}, grid agent keeps DCV at V_{L1} for 0.5 s. - As DCV level reaches V_{L1}, and lasts for 0.1 s, other power agents identify this event, and change their operations.
TO_2	✓			- Grid agent activates TO_2. - Grid agent regulates DCV to V_{H1}. - If DCV level reaches V_{H1}, grid agent keeps DCV at V_{H1} for 0.6 s. - As DCV level reaches V_{H1}, and lasts for 0.1 s, other power agents identify this event, and change their operations.
TO_3	✓		✓	- Grid or battery agent activates TO_3. - DCV increases due to surplus power. - If DCV level reaches V_{H3}, wind turbine agent keeps DCV at V_{H3} for 0.3 s. - As DCV level reaches V_{H3}, and lasts for 0.01 s, battery agent identifies this event, and changes its operations.
TO_4	✓	✓		- Grid or wind turbine agent activates TO_4. - DCV decreases due to deficient power. - If battery agent detects that DCV level is kept lower than V_{L2} for more than 0.01 s, battery operation is changed to BVCM.
TO_5	✓			- Grid agent activates TO_5. - DCV increases due to surplus power. - If battery agent detects that DCV level is kept higher than V_{H2} for more than 0.01 s, battery operation is changed to BVCM.
TO_6	✓	✓	✓	- All power agents activate TO_6. - DCV decreases due to deficient power. - If load agent detects that DCV level is kept lower than V_{L3} for more than 0.01 s, load shedding mode is activated.

When an event occurs such as the electricity price changing from normal to high, or grid agent reconnection from a fault with a high electricity price happens, the DCMG system temporarily uses the transition operation mode TO_1 . In TO_1 , the grid agent regulates the DCV to V_{L1} to inform other power agents of this event. Figure 6 shows the detection of the transition operation modes by the power agent. In Figure 6, the horizontal axis represents the time required for transition operation detection, the vertical axis represents the DCV levels for different transition operations, and the color indicates the power agents that detect the transition operation. As the DCV level reaches V_{L1} , and lasts for 0.1 s, the other power agents such as the battery, wind turbine, and load agent identify this event, and change their operation appropriately. After 0.5 s from the instant that the DCV reaches V_{L1} , the grid regulates the DCV back to V_{nom} .

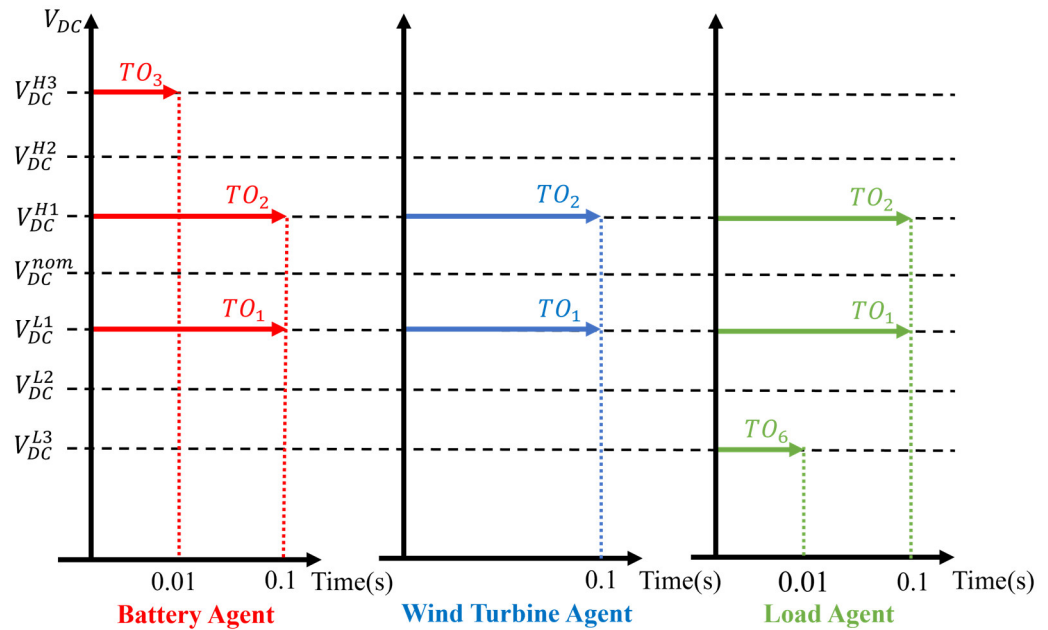


Figure 6. Transition operation detection by each agent.

When an event occurs such as a change in the electricity price from high to normal, or when the reconnection of the grid agent from a fault with a normal electricity price happens, the DCMG system temporarily uses the transition operation mode TO_2 . In TO_2 , the grid regulates the DCV to V_{H1} to inform other power agents of this event. As shown in Figure 6, as the DCV level reaches V_{H1} , and lasts for 0.1 s, the other power agents identify this event, and change their operation appropriately. After 0.6 s from the instant that the DCV reaches V_{H1} , the grid agent regulates the DCV back to V_{nom} .

In the IM of the DCMG system, if the battery is in critical condition, such as when it has a maximum battery SOC_B , the DCV increases since the battery cannot absorb power. After the DCV reaches V_{H3} , the wind turbine agent maintains the DCV at V_{H3} for 0.3 s with the transition operation mode TO_3 . After 0.01 s from the instant that the DCV reaches V_{H3} , the battery agent identifies this event to change the operation appropriately. After 0.3 s, the wind turbine agent regulates the DCV to V_{nom} again. This transition operation mode, TO_3 , is also initiated by the grid when the grid operating in $GVC M_{inv}$ is disconnected from the DCMG system, or when the grid agent has a DCV sensor fault.

The transition operation mode TO_4 is triggered by the grid when the grid operating in $GVC M_{con}$ has a fault. The transition operation mode TO_4 is also activated when the wind power is decreased in IM. In this situation, since the supply power is smaller than the load, the DCV decreases. If the battery agent detects that the DCV level is kept lower than V_{L2} for more than 0.01 s, as shown in Table 3, the battery agent acknowledges this event. Then, the battery changes operation to $BVC M$ to regulate the DCV back to V_{nom} .

When the grid agent is in emergency conditions such as a grid fault under a high electricity price or DCV sensor fault, the DCV increases due to surplus power, which triggers the transition operation mode TO_5 . As the DCV level is kept higher than V_{H2} for more than 0.01 s, the battery agent acknowledges this event, and changes operation to $BVC M$ to regulate the DCV back to V_{nom} .

When SOC_B reaches the minimum level and the wind generation power is smaller than the load demand in the islanded DCMG, the DCV is decreased to the critical value of V_{L3} . After 0.01 s from the instant the DCV reaches V_{L3} , load shedding starts.

4. Simulation Tests

In this section, the reliability and feasibility of the proposed strategy are evaluated through simulation tests by using PSIM tools. The simulations are conducted considering several uncertain operating conditions such as DCV sensor fault, grid fault, minimum or

maximum battery SOC, agent power variation, and electricity price change in the grid. System parameters of a decentralized DCMG are shown in Table 4. In this table, PMSG denotes a permanent magnet synchronous generator, and the LCL filter represents the filter composed of an inductor, capacitor, and inductor.

Table 4. DCMG parameters.

Power Agents	Parameters	Values
Battery	Minimum SOC (SOC_B^L)	20%
	Maximum SOC (SOC_B^H)	90%
	Maximum discharging power	−540 W
	Maximum charging power	540 W
	Maximum voltage	180 V
	Rated capacity	25 Ah
	Converter filter inductance, L	7 mH
Grid	Transformer, Y/ Δ	380/220 V
	Grid frequency	60 Hz
	Grid voltage	220 V
	LCL filter	1.7 mH/4.5 μ F/1.7 mH
Wind turbine	PMSG number of poles	6
	PMSG inertia	0.111 kgm ²
	PMSG stator resistance	0.64 Ω
	PMSG dq-axis inductance	0.82 mH
	PMSG flux linkage	0.18 Wb
	Converter filter inductance	7 mH
Load	Load 1	200 W
	Load 2	200 W
	Load 3	200 W
	Priority: load 1 > load 2 > load 3	-
DC bus	Nominal DCV (V_{nom})	400 V
	First level of high DCV (V_{H1})	405 V
	Second level of high DCV (V_{H2})	410 V
	Third level of high DCV (V_{H3})	415 V
	First level of low DCV (V_{L1})	390 V
	Second level of low DCV (V_{L2})	380 V
	Third level of low DCV (V_{L3})	370 V
	Capacitance	4 mF

4.1. Transition from Grid-Connected Mode to IM under DCV Sensor Fault

Figure 7 represents simulation test results for when the DCMG undergoes a transition from grid-connected mode to IM, and the battery has DCV sensor failure. In Figure 7, $\hat{V}_{DC,i}$ (for $i = G, W$, and B) is the estimated DCV value in the power agent, $V_{DC,i}^{sensor}$ is the DCV measured by the sensor in the power agent, and V_{DC}^{real} is the actual DCV value. In this simulation test, the DCMG starts in NO_4 , which is one of the GCMs. In this mode, the grid operates in $GVCM_{con}$ to regulate the DCV at V_{nom} , the battery operates in $BCCM_{char}$, and the wind turbine agent operates in MPPT mode. At $t = 0.5$ s, grid fault occurs, which causes the change of the DCMG system operation from GCM NO_4 to IM TO_4 . Since the supplied power is smaller than the load, the DCV is reduced. If the battery agent detects that the DCV level is kept lower than V_{L2} for more than 0.01 s, as shown in Table 3, the battery acknowledges grid disconnection from the DCMG. Then, the battery changes operation from $BCCM_{char}$ to $BVCM$ to regulate the DCV back to V_{nom} , and the entire DCMG system operation is changed from TO_4 to NO_7 .

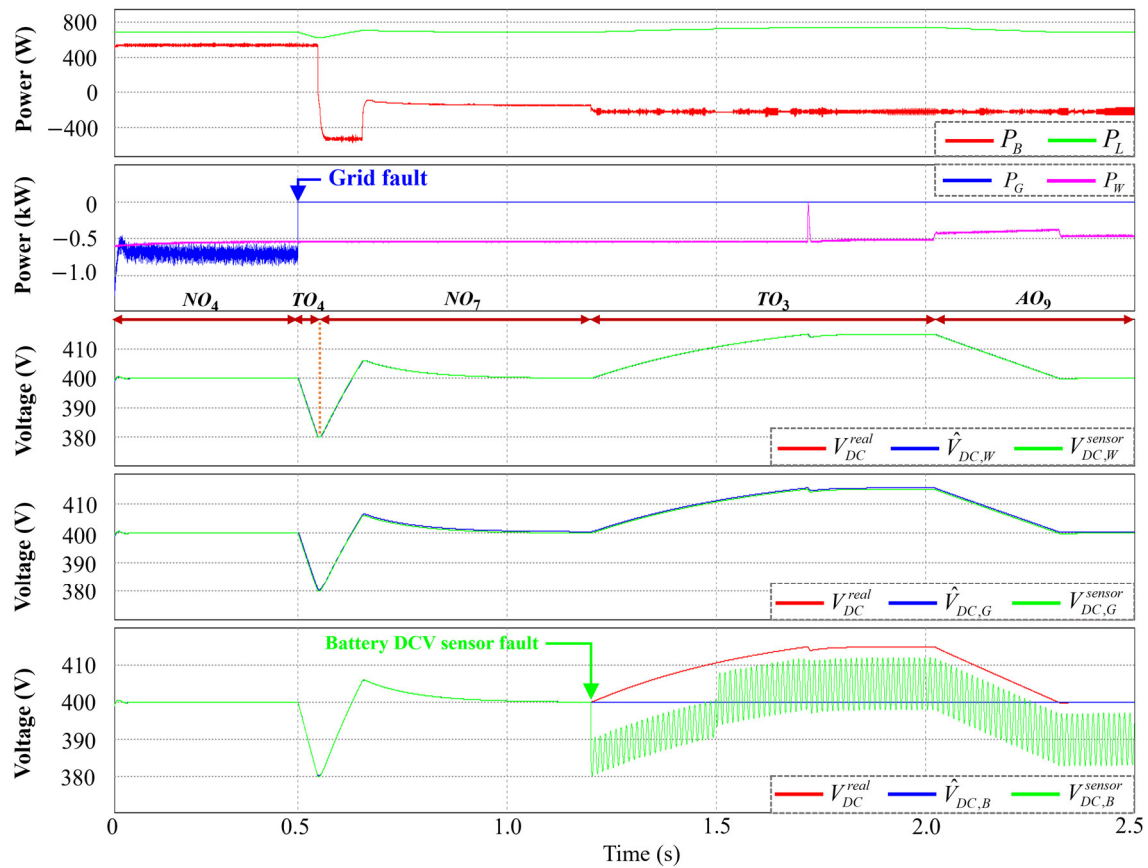


Figure 7. Simulation tests in case of transition from grid-connected mode to IM under battery DCV sensor fault.

At $t = 1.2$ s, when the DCV is regulated by the battery, battery DCV sensor fault occurs. As soon as the battery agent identifies DCV sensor failure, it is shifted to current control mode by the proposed fault detection and control mode decision algorithms shown in Figure 4. By using the proposed strategy, the battery agent increases the DCV by supplying more power to the DC bus. If the DCV level reaches V_{H3} , the wind turbine agent maintains the DCV to V_{H3} for 0.3 s. Eventually, the DCMG is changed from NO_7 to TO_3 . After 0.3 s from the instant that the DCV reaches V_{H3} , the wind turbine agent regulates the DCV back to V_{nom} and subsequently the DCMG system operation is changed from TO_3 to AO_9 .

This simulation test confirms that the battery agent can still supply power to the DC bus in current control mode even if the battery has a DCV sensor failure, which clearly demonstrates that the proposed control strategy ensures power sharing and seamless power management even in abnormal system conditions.

4.2. Transition from Normal to High Electricity Price Conditions under DCV Sensor Fault

Figure 8 represents simulation test results for when the electricity price changes from normal to high under grid DCV sensor failure. The DCMG initially works in NO_4 with a normal electricity price. In this mode, the grid operates in $GVCM_{con}$ to regulate the DCV at V_{nom} , the battery operates in $BCCM_{char}$, and the wind turbine operates in MPPT mode. At $t = 0.3$ s, when the electricity price is changed from normal to high, the grid agent regulates the DCV to V_{L1} in order for the other agents to recognize the electricity price change. Then, the DCMG is changed from NO_4 to TO_1 . After 0.1 s from the instant that the DCV reaches V_{L1} , the wind turbine and battery detect this event. Then, the battery changes operation from $BCCM_{char}$ to $BCCM_{dis}$ to inject power to the DC bus, which causes the grid to change from $GVCM_{con}$ to $GVCM_{inv}$. After 0.5 s from the instant that the DCV reaches V_{L1} , the

grid regulates the DCV back to V_{nom} , and the entire DCMG operation is changed from TO_1 to NO_1 .

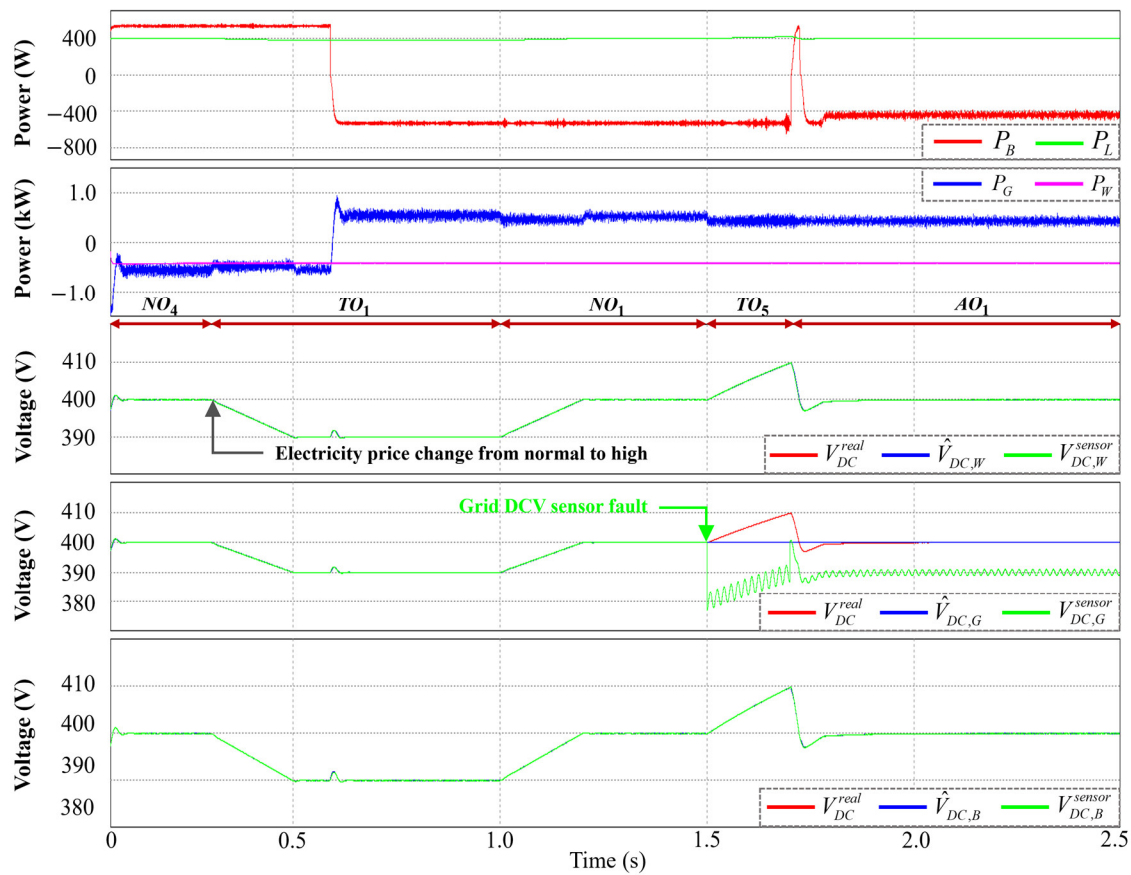


Figure 8. Simulation tests in case electricity price changes from normal to high under grid DCV sensor fault.

At $t = 1.5$ s, when grid DCV sensor fault occurs, the grid operation is changed to current control mode as soon as DCV sensor failure is detected, as shown in Figure 4. After that, the DCMG system is changed from NO_1 to TO_5 . According to the proposed fault detection and control mode decision algorithms, the grid agent increases the DCV by injecting more power to the DC bus. When the battery detects that the DCV level is kept higher than V_{H2} for more than 0.01 s, the battery recognizes the DCV sensor fault in the grid. Then, the battery changes operation from $BCCM_{dis}$ to BVCM to regulate the DCV back to V_{nom} , and the DCMG is changed from TO_5 to AO_1 . This simulation test result also validates continuous power sharing in the presence of failure in the grid DCV sensor.

4.3. Grid Recovery with High Electricity Price Condition under DCV Sensor Fault

Figure 9 represents the simulation test results in the case of grid reconnection at a high electricity price under wind DCV sensor failure. The DCMG is assumed to start in NO_7 , which is one of the IMs. In this mode, the battery works in BVCM to regulate the DCV at V_{nom} , and the wind turbine operates in MPPT mode. At $t = 0.5$ s, DCV sensor failure occurs in the wind turbine. However, the DCMG system maintains mode NO_7 since the wind turbine does not regulate the DCV. In this circumstance, the wind turbine continues operating in MPPT mode with $I_W^{ref} = I_{W,pre}^{ref}$, as explained in Figure 4.

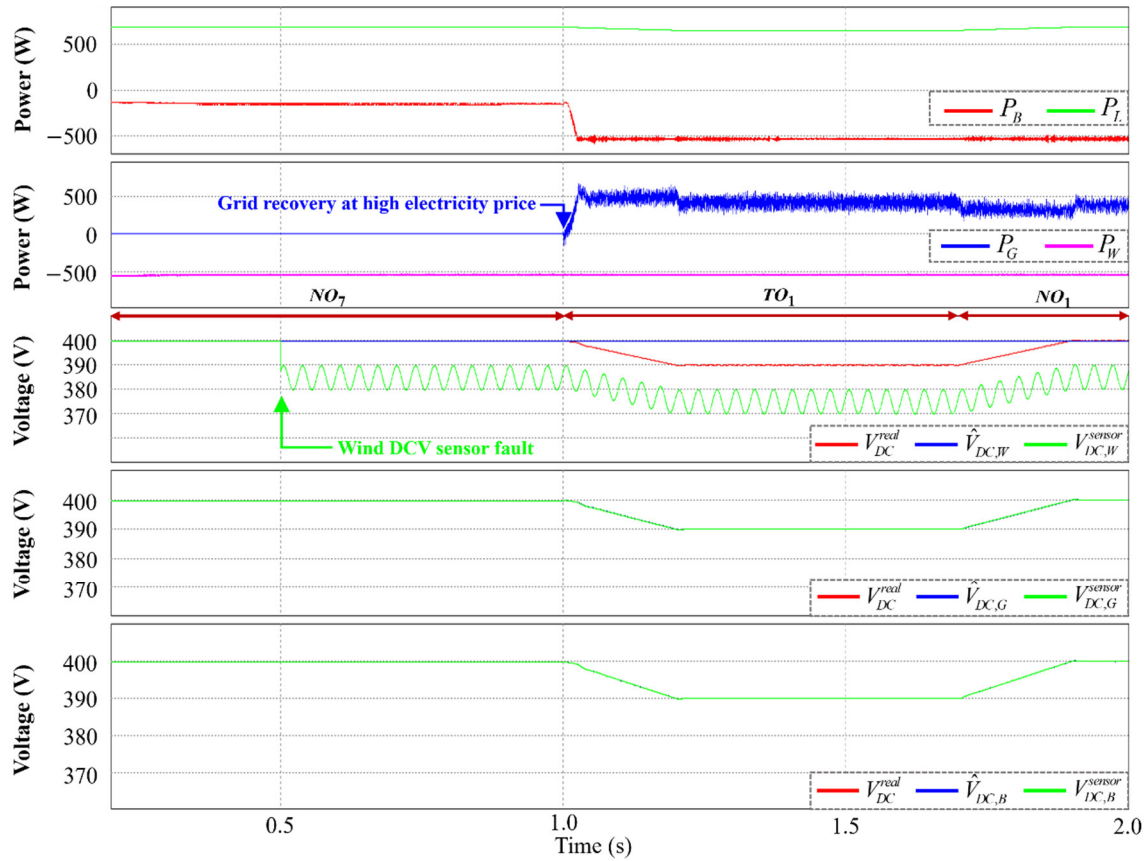


Figure 9. Simulation tests in case of grid reconnection with high electricity price under wind DCV sensor fault.

At $t = 1.0$ s, when the grid agent reconnects at a high electricity price, the grid works in GVC_{inv} to regulate the DCV to V_{L1} , and the DCMG is changed from NO_7 to TO_1 . After 0.1 s from the instant that the DCV reaches V_{L1} , the wind turbine and battery detect grid reconnection at a high electricity price. Then, the battery changes operation from BVC_{M} to $BCC_{M_{dis}}$ to supply the power to the DC bus. After 0.5 s from the instant that the DCV reaches V_{L1} , the grid regulates the DCV back to V_{nom} , and the entire DCMG operation is changed from TO_1 to NO_1 . This simulation result also proves the occurrence of continuous power sharing under DCV sensor failure in the wind turbine.

4.4. Transition of Electricity Price Condition from High to Normal under DCV Sensor Fault

Figure 10 represents simulation test results for when the electricity price changes from high to normal under battery and grid DCV sensor faults. In this simulation, the DCMG initially operates at NO_1 with a high electricity price. The grid agent operates in GVC_{inv} to regulate the DCV at V_{nom} , the battery agent operates in $BCC_{M_{dis}}$, and the wind turbine operates in MPPT mode.

At $t = 0.3$ s, when the electricity price changes from high to normal, the grid agent regulates the DCV to V_{H1} , and the DCMG system is changed from NO_1 to TO_2 . After 0.1 s from the instant that the DCV reaches V_{H1} , the wind turbine and battery detect the change in electricity price. Then, the battery agent changes operation from $BCC_{M_{dis}}$ to $BCC_{M_{char}}$ to absorb power from the DC bus, which causes the grid to change operation from GVC_{inv} to GVC_{con} . After 0.6 s from that instant the DCV reaches V_{H1} , the grid regulates the DCV back to V_{nom} , and the DCMG is changed from TO_2 to NO_4 .

At $t = 1.4$ s, DCV sensor failure occurs in the battery. The DCMG maintains NO_4 because the battery does not regulate DCV. In this case, the battery agent maintains the previous operation $BCC_{M_{char}}$ with $I_B^{ref} = I_{B,pre}^{ref}$ as shown in Figure 4.

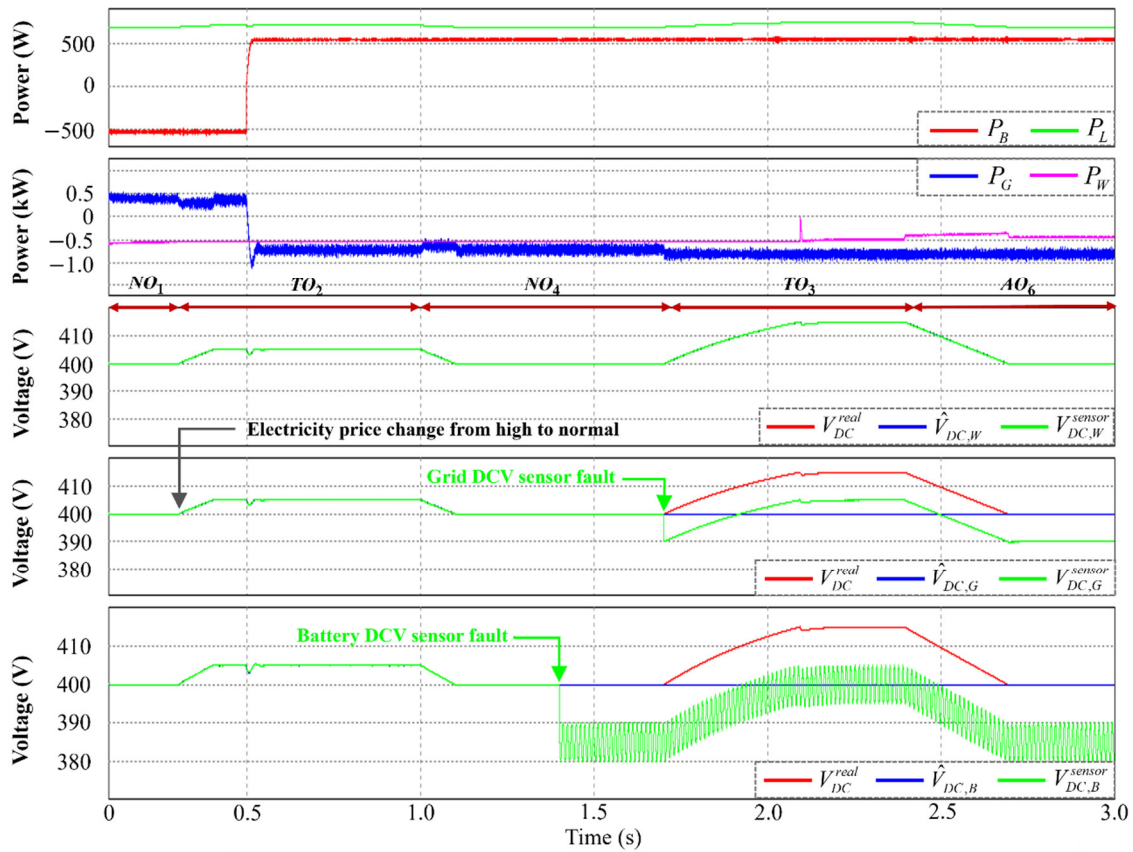


Figure 10. Simulation tests for when electricity price changes from high to normal under multiple DCV sensor failures in grid and battery.

At $t = 1.7$ s, DCV sensor failure happens in the grid that is regulating the DCV to V_{nom} . When the grid agent detects DCV sensor failure, the grid operation is instantly shifted to current control mode by the proposed scheme, which changes the DCMG operation from NO_4 to TO_3 . The grid agent increases the DCV by injecting larger power into the DC bus. If the battery agent detects that the DCV level is kept higher than V_{H2} for more than 0.01 s, the battery agent acknowledges the grid DCV sensor fault. However, the battery cannot regulate the DCV due to DCV sensor failure. In this case, the DCV level further increases to more than V_{H2} . As the DCV reaches V_{H3} , the wind turbine instantly maintains the DCV at V_{H3} for 0.3 s. After 0.3 s from the instant that the DCV reaches V_{H3} , the wind turbine regulates the DCV back to V_{nom} , and the entire DCMG operation is changed from TO_3 to AO_6 . This simulation test shows that the proposed scheme ensures uninterrupted power management even in circumstances of multiple failures in a DCV sensor.

4.5. Case of Minimum Battery SOC Level

Figure 11 represents simulation test results for load shedding when the battery SOC level reaches the minimum. The DCMG starts in NO_7 , which is one of the IMs. In this mode, the wind power is smaller than the load, which causes the battery to operate in BVCM by discharging to maintain the DCV at V_{nom} .

At $t = 0.6$ s, when the battery SOC level drops to the minimum value, the battery changes operation from BVCM to IDLE mode, and the DCMG is changed from NO_7 to TO_6 . Since the power supply is smaller than the load, the DCV drops rapidly. If the load agent detects that the DCV level is kept lower than V_{L3} for more than 0.01 s, as shown in Table 3, the load agent recognizes that the supplied power is less than the load. Consequently, load shedding is activated to prevent DCMG system collapse in these emergency conditions. When the DCV becomes higher than V_{nom} because of load shedding, the battery operation

is changed from IDLE mode to BVCM to regulate the DCV back to V_{nom} , which changes the DCMG operation from TO_6 to NO_7 .

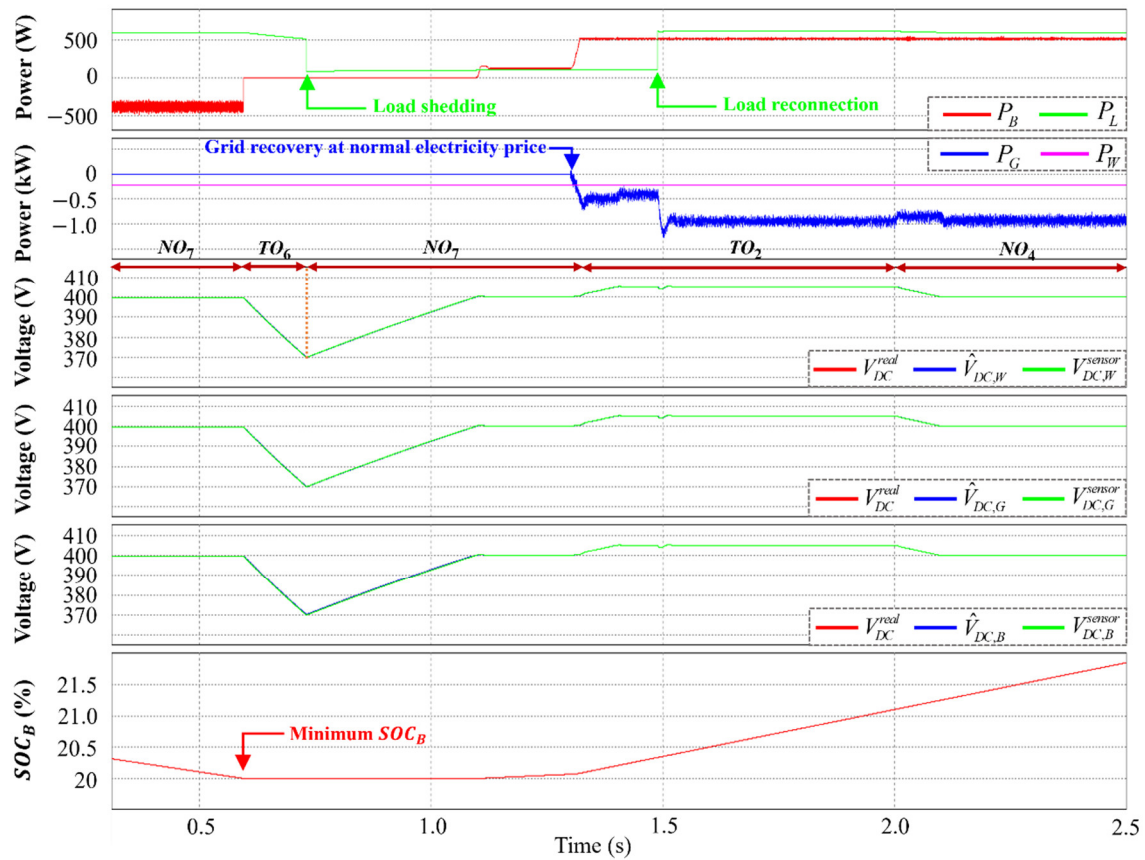


Figure 11. Simulation tests for load shedding when the battery SOC level reaches the minimum.

At $t = 1.3$ s, as the grid agent is reconnected to the DCMG system with a normal electricity price, the grid operates in $GVCM_{con}$ to regulate the DCV to V_{H1} , and the DCMG operation is changed from NO_7 to TO_2 . After 0.1 s from the instant that the DCV reaches V_{H1} , the wind turbine, load, and battery recognize grid reconnection with a normal electricity price. Consequently, the battery changes operation from BVCM to $BCCM_{char}$ and load reconnection starts. After 0.6 s from the instant that the DCV reaches V_{H1} , the grid regulates the DCV back to V_{nom} , and the entire DCMG operation is changed from TO_2 to NO_4 .

5. Experimental Results

An experimental hardware setup of the decentralized DCMG that is depicted in Figure 12 is utilized to confirm the feasibility and reliability of the proposed strategy. To construct a decentralized DCMG, four power agents, which are the wind turbine, grid, battery, and load agents, are used with the system parameters in Table 4. The wind turbine agent is constructed with a unidirectional AC–DC converter and wind turbine emulator that is composed of a PMSG, a mechanically coupled induction motor, and an AC motor control panel. The battery agent employs an interleaved bidirectional DC–DC converter to connect the battery with the DC bus. The grid agent is composed of a bidirectional AC–DC converter, main grid, and a Y–Δ transformer. A digital signal processor, TMS320F28335, is used to realize the proposed strategy. The experimental tests are conducted under five different conditions: change in electricity price from normal to high, DCV sensor failure in GCM, transition from grid-connected mode to IM, minimum SOC_B level in IM, and DCV sensor fault in IM.

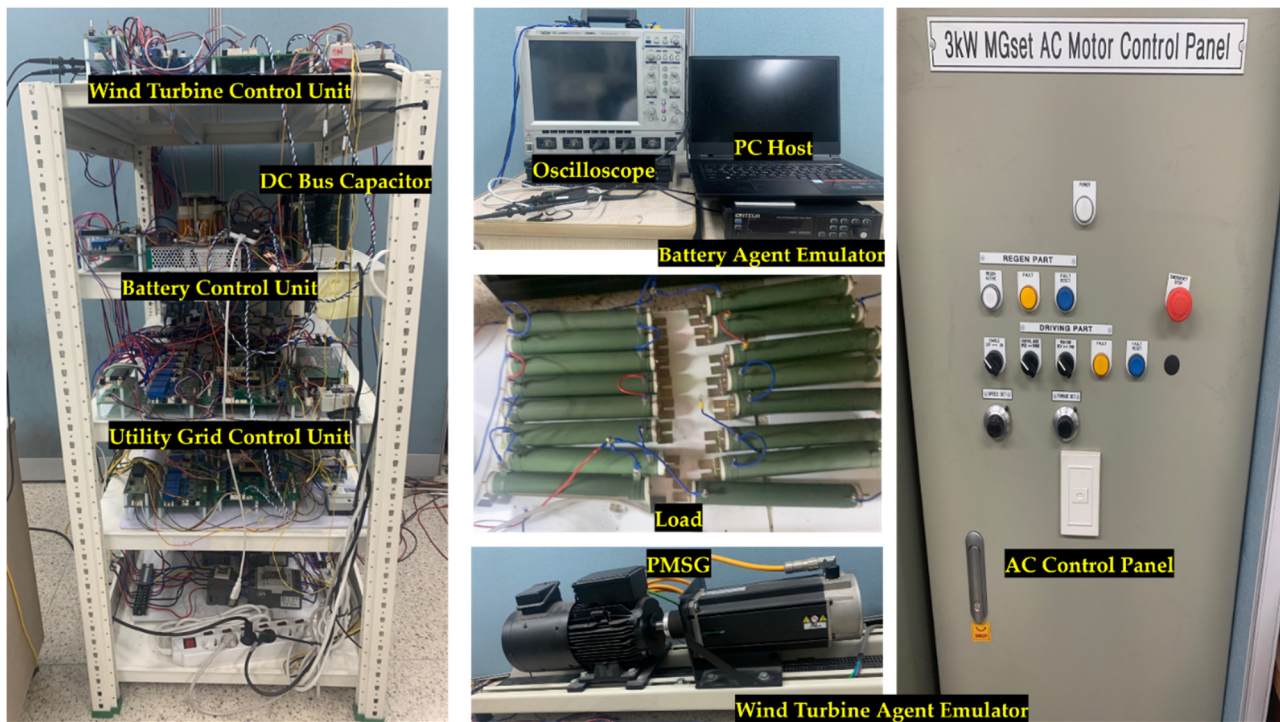


Figure 12. Experimental hardware setup for a decentralized DCMG.

5.1. Transition of Electricity Price from Normal to High in GCM

Figure 13 represents the experimental tests in the case that the electricity price changes from high to normal in GCM. The DCMG system starts in NO_5 , which is one of the GCMs, and SOC_B is at the maximum level. The grid operates in GVC_{con} to regulate the DCV to V_{nom} , the wind turbine works in MPPT mode, and the battery works in IDLE mode.

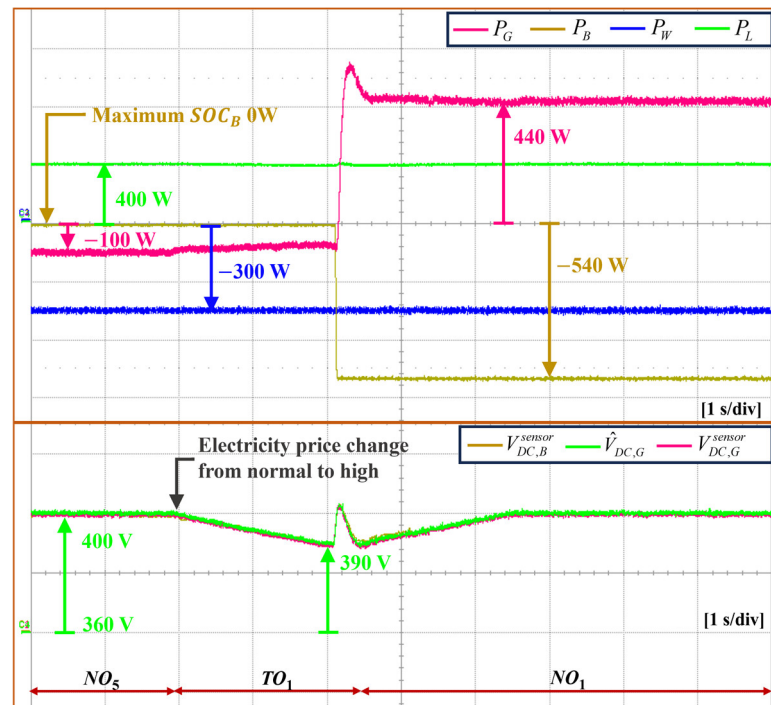


Figure 13. Experimental test for transition of electricity price condition from normal to high in GCM.

When the electricity price changes from normal to high, the grid regulates the DCV to V_{L1} in order for the other agents to recognize the change in electricity price. Consequently, the DCMG operation is changed from NO_5 to TO_1 . After 0.1 s from the instant that the DCV reaches V_{L1} , the wind turbine and battery detect the change in electricity. Then, the battery changes the operation from IDLE mode to $BCCM_{dis}$ to supply power to the DC bus, which makes the grid change operation from $GVC M_{con}$ to $GVC M_{inv}$. After 0.5 s from the instant the DCV reaches V_{L1} , the grid regulates the DCV back to V_{nom} , and the entire DCMG operation is changed from TO_1 to NO_1 . This experimental result clearly shows voltage stabilization and good power balance using the decentralized control method without any DCLs.

5.2. GCM under DCV Sensor Fault

Figure 14 represents the experimental test for GCM under grid and battery DCV sensor faults. In this test, the DCMG system initially operates in NO_4 with a normal electricity price. In this mode, the grid operates in $GVC M_{con}$ to regulate the DCV at V_{nom} , while the battery and wind turbine operate in $BCCM_{char}$ and MPPT mode.

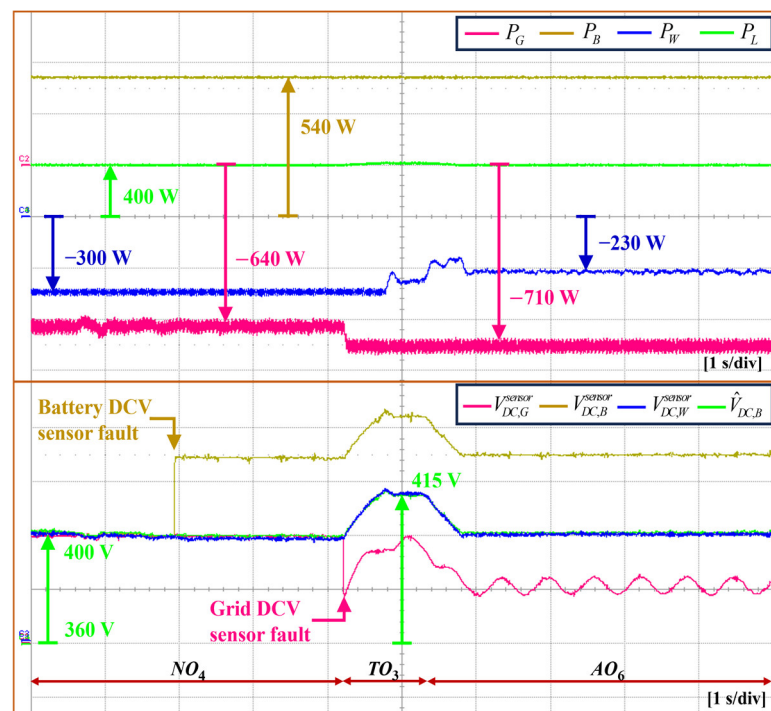


Figure 14. Experimental test for GCM under grid and battery DCV sensor faults.

When a DCV sensor fault happens in a battery, the DCMG system stays in NO_4 because the battery does not regulate the DCV. In this situation, the battery operation is still $BCCM_{char}$ with $I_B^{ref} = I_{B,pre}^{ref}$, as shown in Figure 4. When the grid agent that is regulating the DC bus has a sensor failure, the grid operation mode is changed to $GCCM_{con}$, and the DCMG system operation is changed from NO_4 to TO_3 . Similar to what is shown in Figure 10, the DCV increases rapidly in this case since the grid supplies larger power to the DC bus. If the battery agent detects that the DCV level is kept higher than V_{H2} for more than 0.01 s, the battery agent acknowledges grid DCV sensor fault. However, the battery cannot regulate the DCV due to DCV sensor failure. In this case, the DCV level further increases to more than V_{H2} . As the DCV reaches V_{H3} , the wind turbine instantly operates in VCM to maintain the DCV at V_{H3} . After 0.3 s from the instant that the DCV reaches V_{H3} , the wind turbine regulates the DCV back to V_{nom} , and the DCMG operation is changed from TO_3 to AO_6 . This experimental test shows the same behaviors as those in the

simulation in Figure 10, which verifies that the proposed control strategy achieves both voltage stabilization and power balance even under multiple failures in DCV sensors.

5.3. Transition between GCM and IM

Figure 15 shows the experimental test for the transition from GCM to IM. The DCMG operates in NO_4 , which is one of the GCMs. The grid operates in GVC_{con} to regulate the DCV to V_{nom} , while the battery and wind turbine operate in $BCCM_{char}$ and MPPT mode.

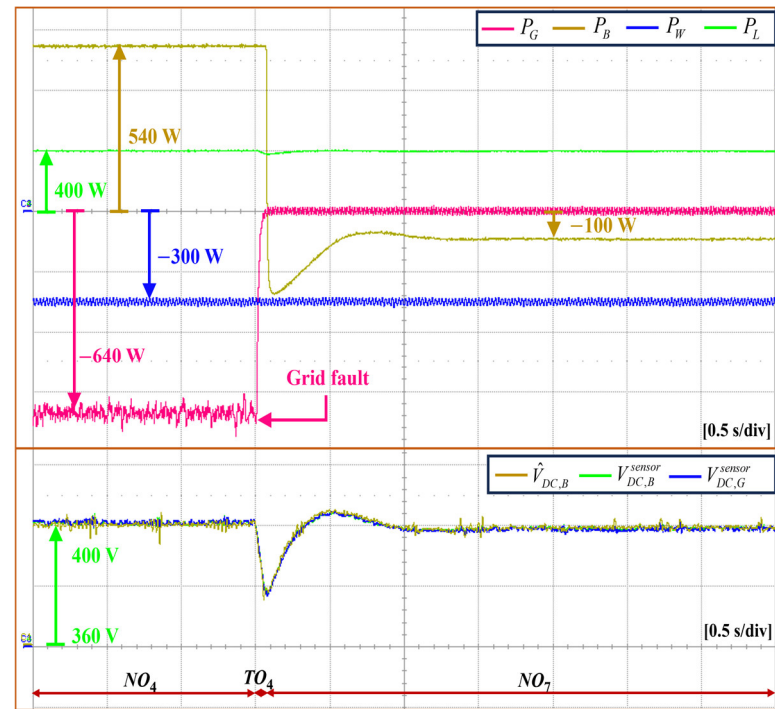


Figure 15. Experimental test for transition from GCM to IM.

When the grid is disconnected from DCMG, it causes a change of DCMG operations from GCM NO_4 to IM TO_4 . The DCV decreases rapidly since the power supply is smaller than the power demand. If the battery detects that the DCV level is kept lower than V_{L2} for more than 0.01 s, the battery acknowledges grid disconnection from the DCMG system. Then, the battery changes operation from $BCCM_{char}$ to $BVCM$ to regulate the DCV back to V_{nom} , and the entire DCMG system operation is changed from TO_4 to NO_7 .

5.4. Test with IM under Minimum Battery SOC Level

Figure 16 shows the experimental test for load shedding when the battery SOC level reaches the minimum value. The DCMG starts in NO_7 , which is one of the IMs. In this mode, the battery supplies power to the DC bus to regulate the DCV in $BVCM$ since the wind power is smaller than the load. When the battery SOC level reaches the minimum value, the battery changes the operation from $BVCM$ to $IDLE$ mode, and the DCMG is changed from NO_7 to TO_6 . The DCV is decreased rapidly because the power supply is smaller than the power demand. After 0.01 s from the instant that the DCV is lower than V_{L3} , the load agent detects that the power supply is smaller than the demand, and then load shedding is activated to prevent DCMG system collapse for such an emergency condition. When the DCV becomes higher than V_{nom} , because the power supply is higher than the demand, the battery operation is changed from $IDLE$ mode to $BVCM$ to regulate the DCV back to V_{nom} , which changes the DCMG system from TO_6 to NO_7 .

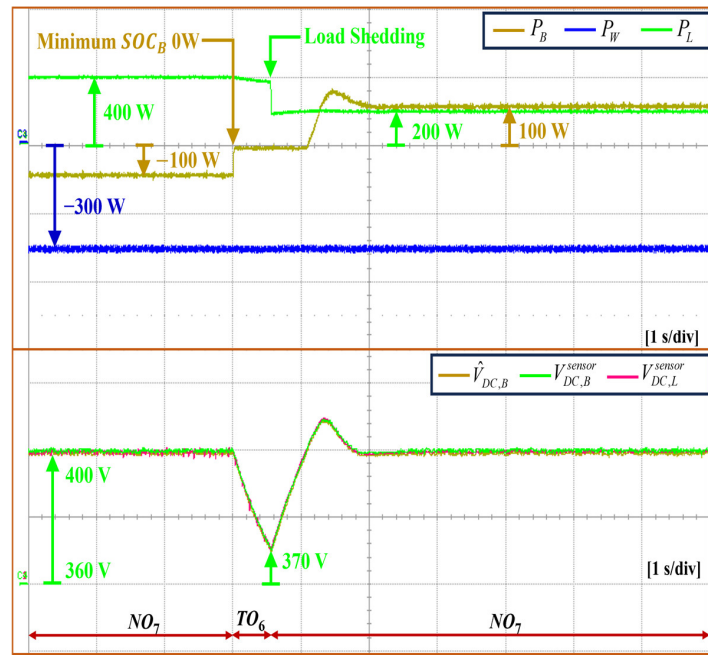


Figure 16. Experimental test for IM when the battery SOC reaches the minimum value.

5.5. Test with IM under DCV Sensor Fault

Figure 17 shows the experimental test for the IM under battery DCV sensor failure. Initially, the DCMG system starts in NO_7 , which is one of the IMs. In this mode, the battery supplies power to the DC bus to regulate the DCV in BVCM since the wind power is smaller than the load. When battery DCV sensor fault occurs, the battery identifies DCV sensor failure. Then, the battery changes the operation to current control mode. By using the proposed scheme, the battery increases the DCV, and the DCMG is changed from NO_7 to TO_3 . When the DCV reaches V_{H3} , the wind turbine regulates the DCV to V_{H3} in VCM. After 0.3 s from the instant that the DCV reaches V_{H3} , the wind turbine regulates the DCV back to V_{nom} , and the DCMG operation is changed from TO_3 to AO_9 .

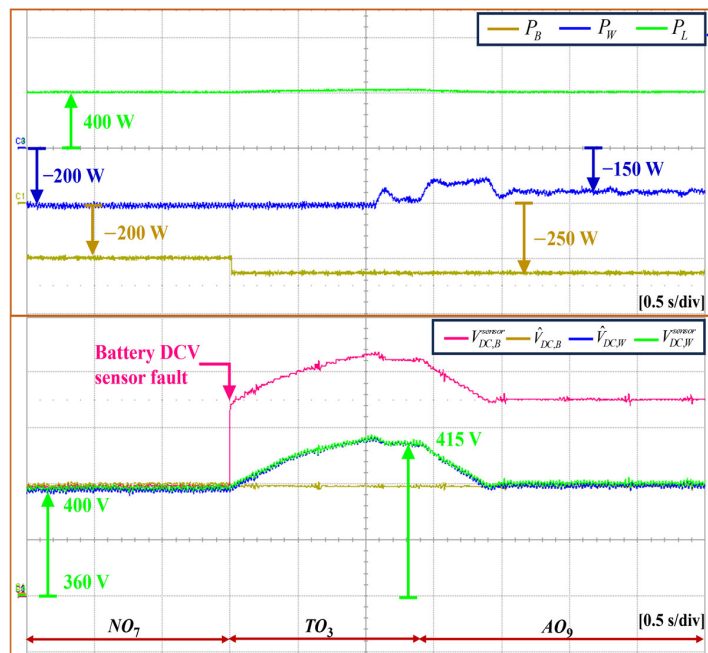


Figure 17. Experimental test for IM under battery DCV sensor failure.

6. Conclusions

This study proposed a continuous power management strategy for a decentralized DCMG based on transitional operation modes under system uncertainty and sensor failure. The power agents connected in the decentralized DCMG utilize only a primary controller to achieve both voltage regulation and power sharing with reduced computational burden. To improve the reliability of DCMG operation, the abnormality of the DCV sensor is monitored by the proposed DCV sensor fault detection algorithm, in which all the power agents estimate the DCV by using the observer and compare the estimated DCV with the measured DCV. If a power agent detects the failure of the DCV sensor, it modifies the operational mode appropriately to ensure the stability of the DCMG in accordance with the proposed control mode decision algorithm under the DCV sensor fault. The proposed algorithms can maintain the operation of the DCMG system without system collapse even with multiple sensor failures, if only one sensor operates normally.

To achieve continuous power balance as well as voltage stabilization even under several uncertainty conditions such as power variation in distributed generation, sudden grid disconnection, and critical battery status, the DCMG system uses the transitional operation modes to transmit the proper information to other power agents without using DCLs in this study. In the transitional operation modes, the DCV levels are temporarily shifted to an appropriate level during the predetermined period. Based on the DCV levels, each power agent determines its operation mode after detecting the uncertain conditions. The effectiveness and reliability of the proposed control strategy were demonstrated via various simulation and experimental tests under several test conditions. In summary, the experimental tests clearly demonstrated that DCV regulation could be achieved rapidly even under uncertain conditions. In the experimental tests, when multiple DCV sensor faults occurred, the transition time to restore the DCV to its nominal value was 1.6 s under the proposed strategy. In the grid fault condition, the DCV was restored in 1.0 s. In addition, when the battery reached the minimum SOC level, the transition time to restore the DCV to its nominal value was 1.8 s. In the case of DCV sensor failure in islanded mode, the transition time was 1.9 s.

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Abbreviations

ACMG	AC microgrid
$BCCM_{char}$	Battery current control mode by charging operation
$BCCM_{dis}$	Battery current control mode by discharging operation
BVCM	Battery voltage control mode
DCMG	DC microgrid
DCL	Digital communication line
DCV	DC bus voltage

ESS	Energy storage system
$GCCM_{con}$	Grid agent current control mode by converter operation
$GCCM_{inv}$	Grid agent current control mode by inverter operation
IM	islanded mode
LCL	Inductive–Capacitive–Inductive
MPPT	Permanent magnet synchronous generator
PI	Proportional–integral
PMSG	Permanent magnet synchronous generator
PV	Photovoltaic
SOC	State of charge
VCM	Voltage control mode of wind turbine
AO_m	Additional steady-state operation mode, $m = 1, 2, 3, \dots, 9$
c	Counter
C_i	Capacitor of agent i
c_{max}	Specified threshold of the counter
δ_i	Small positive value of agent i
e_i	Difference between $V_{DC,i}$ and $\hat{V}_{DC,i}$
ε_i	Specified threshold value
F_B	Flag variable to denote the DCV sensor failure in battery agent
F_W	Flag variable to denote the DCV sensor failure in wind turbine agent
F_G	Flag variable to denote the DCV sensor failure in grid agent
F_{mode}	Control mode flag
F_{fault}	Fault flag
I_i^{out}	Converter output current of agent i
I_i^{ref}	Reference current of agent i
$I_{i,pre}^{ref}$	Previous value of I_i^{ref}
L_i	Inductor of agent i
NO_m	Normal operation mode, $m = 1, 2, 3, \dots, 9$
N_i	Observer gain
P_B	Power flow of the battery agent
P_G	Power flow of the grid agent
P_L	Power flow of the load agent
P_W	Power flow of the wind turbine agent
R_L	Total equivalent resistance
R_{Li}	Virtual resistance of agent i
SOC_B	State of charge of the battery
SOC_B^H	Maximum SOC level of the battery
SOC_B^L	Minimum SOC level of the battery
TO_m	Transition operation mode, $m = 1, 2, 3, \dots, 6$
$V_{dc,i}$	DCV measured from the sensor of agent i
$\hat{V}_{DC,i}$	DCV estimated from the observer of agent i
$\hat{V}_{DC,i}^{pre}$	Previous value of $\hat{V}_{DC,i}$
V_{nom}	Nominal DCV
V_{H1}	First level of high DCV
V_{H2}	Second level of high DCV
V_{H3}	Third level of high DCV
V_{L1}	First level of low DCV
V_{L2}	Second level of low DCV
V_{L3}	Third level of low DCV

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