Decentralized Power Management of DC Microgrid Based on Adaptive Droop Control With Constant Voltage Regulation

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ABSTRACT An adaptive droop control with constant voltage regulation is proposed for the power and voltage management of a DC microgrid (DCMG) with multiple power sources, such as a utility grid (UG), a distributed generator (DG), an energy storage system (ESS), and an electric vehicle (EV). In the proposed scheme, the droop characteristics for the UG, ESS, and EV are adaptively changed according to electricity price conditions and state-of-charge (SOC) levels in order to optimize the DCMG operation flexibility as well as electricity cost. The proposed control method not only ensures the power-sharing of DCMG reliably without the use of a communication link, but also regulates the DC bus voltage stably at the nominal value. To achieve this, the proposed scheme consists of primary control and secondary control. The primary control is used to achieve power-sharing in the decentralized DCMG, while the secondary control is used to overcome the disadvantage of conventional droop control, i.e., to remove DC bus voltage deviations. Decentralized power management is also presented to enhance the DCMG system reliability in the presence of uncertainties such as DG generation power, the ESS and EV SOC levels, the grid and EV availabilities, the load demand, and electricity price conditions. The effectiveness of the proposed scheme is demonstrated in a comprehensive simulation and experiment under various conditions. The test results clearly confirm the control flexibility and overall performance of the proposed control scheme for decentralized DCMG system.

INDEX TERMS Adaptive droop control, constant voltage regulation, DC microgrid, decentralized power management, secondary control.

ABBREVIATION

AC Alternating current
ACMG AC microgrid
B Battery unit
BDCM Battery droop control by the charging mode
BDDM Battery droop control by the discharging mode
CON UG droop control by the converter mode
DC Direct current
DCMG DC microgrid
DCLs Digital communication links
DG Distributed generation
DSP Digital signal processor
ESC Energy supporting and consumption
EDCM EV droop control by the charging mode
EDDM EV droop control by the discharging mode
ESS Energy storage system
EV Electric vehicle
IDLE Idle mode by ESS unit or EV unit
INV UG droop control by ESS unit or EV unit
LR Load reconnecting
LS Load shedding
MPPT Maximum power point tracking

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A. BATTERY

Current and current reference of battery unit

Total power and power reference of battery unit

Maximum consuming and supporting power of battery unit

Droop coefficient of battery unit

V\(_B\), V\(_B\)\(_{\text{max}}\)  Voltage and maximum voltage of battery unit

V\(_{\text{max}}\)\(_{\text{dc}}, V\(_{\text{min}}\)\(_{\text{dc}}\)  Maximum and minimum voltage deviation of battery unit

V\(_{\text{min}}, H \)\(_{\text{dc}}, V\(_{\text{min}}, L \)\(_{\text{dc}}\)  Minimum voltage level of battery unit in the highest and lowest SOC level

V\(_{\text{dc}}\)\(_{\text{ref}}\)  DC bus voltage reference of battery unit

SOC\(_B\)  Battery SOC

SOC\(_{\text{max}}, B\)  Maximum SOC of battery unit

SOC\(_{\text{min}}, B\)  Minimum SOC of battery unit

B. ELECTRIC VEHICLE (EV)

Current and current reference of EV unit

Total power and power reference of EV unit

Maximum consuming and supporting power of EV unit

Drop coefficient of EV unit

Voltage and maximum voltage of EV unit

Maximum and minimum voltage deviation of EV unit

Minimum voltage level of EV unit in the highest and lowest SOC level

Minimum voltage level of EV unit in the highest and lowest SOC level

DC bus voltage reference of EV unit

SOC\(_{\text{EV}}\)  Maximum SOC of EV unit

SOC\(_{\text{max}}, \text{EV}\)  Minimum SOC of EV unit

C. UTILITY GRID

Grid frequency

Binary state of high and low electricity price condition

q-axis current and q-axis current reference of UG unit

Total power and power reference of UG unit

Maximum consuming and supporting power of UG unit

Droop coefficient of UG unit

DC bus voltage reference of UG unit

UG voltages in synchronous reference frame

q-axis voltage of UG unit

d-axis voltage reference of UG unit

DC bus voltage reference of UG unit

Grid voltage

Maximum and minimum voltage deviation of UG unit

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NOMENCLATURE

\(k_i\)  Integrator gain

\(I_n\)  Current of the energy storage

\(I_X, I^\text{ref}_X\)  Current and current reference of the power unit

\(P_X, P^\text{ref}_X\)  Total power and power reference of the power unit

\(P^\text{C,max}_X, P^\text{S,max}_X\)  Maximum consuming and supporting power of power unit

\(Q_n\)  Nominal capacity of an energy storage

\(R_{\text{droop}, X}\)  Droop coefficient of the power unit

\(\text{SOC}_n\)  SOC of the energy storage

\(\text{SOC}_{\text{max}}, n\)  Maximum SOC of energy storage

\(\text{SOC}_{\text{min}}, n\)  Minimum SOC of energy storage

\(V_X\)  Voltage of the power unit

\(V_{\text{dc}}\)  DC bus voltage

\(V^\text{ref}\)  Auxiliary variable as the indicator to determine the operating modes of the power unit

\(V_{\text{dc}}\)\(_{\text{nom}}\)  DC bus nominal voltage

\(V^\text{max}_{\text{dc}}, V^\text{min}_{\text{dc}}\)  Maximum and minimum voltage deviation of the power unit

\(V^\text{ref}_{\text{dc}}, X\)  DC bus voltage reference of the power unit

\(\delta V_{\text{dc}}\)  DC bus voltage compensator

\(\eta_n\)  the coulombic efficiency

BATTERY

Current and current reference of battery unit

Total power and power reference of battery unit

Maximum consuming and supporting power of battery unit

Droop coefficient of battery unit

RES  Renewable energy source

PV  Photovoltaic

PWM  Pulse width modulation

PMSG  Permanent magnet synchronous generator

PSIM  Power simulation software

PLL  Phase lock loop

RTP  Real-time price

SPT  Stepwise power tariff

PCC  Point of common coupling

PI  Proportional integral

SVPWM  Space vector pulse width modulation

TOU  Time of use pricing

UG  Utility grid

VDCM  Wind turbine droop control mode

W  Wind turbine unit
The proliferation of DC power systems, such as the PV, ESS, drawn increasing amounts of attention due to its effectiveness to adopt the AC power system, the concept of the DCMG has AC microgrid (ACMG) [8]. Although existing utility grids microgrid can be classified as a DC microgrid (DCMG) or an Depending on the voltage type used on the common bus, the point of common coupling (PCC) to exchange power. connected to a single interconnected power system or to energy storages, and loads, has emerged [7]. Except, which effectively integrates several energy resources, has managed its power based on several local measurement signals to coordinate the power in the DCMG system. Generally, the current development and commercialization of electric vehicles (EVs) allow them to be used flexibly as an ESS to stabilize the system operation of RESs [5]. However, the direct interconnection of EVs, ESSs, and DGs into a utility grid (UG) involves several control issues related to different frequencies and voltages [6]. As a result, the microgrid concept, which effectively integrates several energy resources, energy storages, and loads, has emerged [7]. Essentially, the microgrid consists of several power units connected to a single interconnected power system or to the point of common coupling (PCC) to exchange power. Depending on the voltage type used on the common bus, the microgrid can be classified as a DC microgrid (DCMG) or an AC microgrid (ACMG) [8]. Although existing utility grids adopt the AC power system, the concept of the DCMG has drawn increasing amounts of attention due to its effectiveness in eliminating extra AC/DC and DC/AC conversions with the proliferation of DC power systems, such as the PV, ESS, and EV [9]. Furthermore, in terms of control strategies, the DCMG is more advantageous than the ACMG owing to the absence of frequency, phase imbalance, and reactive power issues [10]. As a result, the DCMG system has been the subject of much attention in recent MG research.

A microgrid system can operate either in grid-connected mode by being connected to the utility grid, or in islanded mode by independently operating without a connection to the utility grid. In islanded mode operation, one of the primary concerns is to achieve power balance and power-sharing among power units even in the presence of various uncertain conditions of DG and load powers as well as ESS and EV state-of-charge (SOC) levels. On the other hand, in grid-connected operation, there has been another important issue, which is to optimize the power consumption cost by adjusting power injection, or power absorption from the UG depending on the electricity pricing policies, such as time-of-use (TOU) price, real-time price (RTP), and stepwise-power-tariff (SPT) [11].

In order to properly achieve an effective power-sharing and power management system among different sources and storages in the DCMG under a variety of uncertain conditions such as electricity price, grid connection, DG power, load power, EV availability, and ESS SOC, a coordinated control is required. The coordinated control strategy for a DCMG can be formulated in three different ways: centralized control, distributed control, and decentralized control [12]. With centralized control, several power units transfer data to a central controller through the digital communication links (DCLs) and receive command signals from the central controller. Several studies have demonstrated the effectiveness of this control strategy when combined with an optimization method to reduce electricity costs while improving the stability and reliability of the DCMG system under several conditions [13], [14], [15]. In contrast, with distributed control, each power unit transmits data through DCLs to other power units, making independent decisions based on the data received from the other power units. With distributed control, the coordination problem caused by the use of a single controller can be avoided. Therefore, the DCMG system is more reliable and can still achieve optimal power management, as demonstrated in earlier works [16], [17], [18]. However, the use of a DCL in a large-scale system may not be economical and practical, as it can yield certain communication delays or failures [19]. The decentralized control scheme is presented as a solution to overcome the problems that arise when using DCLs in a DCMG system [20], [21].

With decentralized control, each power unit independently manages its power based on several local measurement signals to coordinate the power in the DCMG system. Generally, the droop method is adopted to realize decentralized control [22]. This method utilizes the behavior of the DC bus voltage \(V_{dc}\) as an indicator to control the power of each power unit \(P_{dc}\). For instance, an increase in \(V_{dc}\) indicates surplus power within a DCMG, a decrease in \(V_{dc}\) indicates a deficit of power, and a constant \(V_{dc}\) indicates a power balance. These behaviors

\[
\begin{align*}
V_{\text{max}, \text{dc}, \text{EV}} & \quad, V_{\text{max}, \text{L}, \text{dc}, \text{EV}} \\
V_{\text{min}, \text{dc}, \text{EV}} & \quad, V_{\text{min}, \text{L}, \text{dc}, \text{EV}} \\
I_{q, W}, I'_{q, W} & \quad \text{q-axis current and q-axis current reference of wind turbine unit} \\
J & \quad \text{PMSG inertia} \\
p & \quad \text{PMSG number of poles} \\
P_W, P'_{W} & \quad \text{Total power and power reference of wind turbine unit} \\
p_{W}^{\text{C, max}}, p_{W}^{\text{S, max}} & \quad \text{Maximum consuming and supporting power of wind turbine unit} \\
R_{\text{droop}, W} & \quad \text{Droop coefficient of wind power unit} \\
V_{\text{abc}, W} & \quad \text{Wind turbine voltages in synchronous reference frame} \\
V_{q, W}, V'_{q, W} & \quad \text{q-axis voltage of wind turbine unit} \\
V_{d, W}, V'^{\text{ref}}_{d, W} & \quad \text{d-axis voltage reference of wind turbine unit} \\
V_{dc, W} & \quad \text{DC bus voltage reference of wind turbine unit} \\
V_{\text{max, dc}, W}, V_{\text{min, dc}, W} & \quad \text{Maximum and minimum voltage deviation of wind turbine unit} \\
\psi & \quad \text{PMSG flux linkage} \\
\end{align*}
\]

I. INTRODUCTION
The growth of electric devices has had the impact of increasing the demand for electric power [1]. In recent years, accelerated efforts to build power plants have been realized by developing distributed generators (DG) based on renewable energy sources (RESs) such as wind energy and photovoltaic (PV) sources [2]. DGs are more efficient and flexible to develop as compared to traditional power sources, such as centralized generators [3]. In order to optimize the use of RES-based DGs, the installation of an energy storage system (ESS) is required to reduce RES power fluctuations [4]. Moreover, the current development and commercialization of electric vehicles (EVs) allow them to be used flexibly as an ESS to stabilize the system operation of RESs [5]. However, the direct interconnection of EVs, ESSs, and DGs into a utility grid (UG) involves several control issues related to different frequencies and voltages [6]. As a result, the microgrid concept, which effectively integrates several energy resources, energy storages, and loads, has emerged [7]. Essentially, the microgrid consists of several power units connected to a single interconnected power system or to the point of common coupling (PCC) to exchange power. Depending on the voltage type used on the common bus, the microgrid can be classified as a DC microgrid (DCMG) or an AC microgrid (ACMG) [8]. Although existing utility grids adopt the AC power system, the concept of the DCMG has drawn increasing amounts of attention due to its effectiveness in eliminating extra AC/DC and DC/AC conversions with the proliferation of DC power systems, such as the PV, ESS, and EV [9]. Furthermore, in terms of control strategies, the DCMG is more advantageous than the ACMG owing to the absence of frequency, phase imbalance, and reactive power issues [10]. As a result, the DCMG system has been the subject of much attention in recent MG research.
of $V_{dc}$ are utilized in the droop method to raise the power within a DCMG when $V_{dc}$ decreases, to reduce the power when $V_{dc}$ increases, and to keep the power constant when $V_{dc}$ remains constant.

In the conventional droop control scheme, an increase or a decrease of $V_{dc}$ causes $V_{dc}$ to deviate, which is the main disadvantage of this control scheme [24], [25], [26]. The significant variation of $V_{dc}$ affects the amount of power delivered to the load and the accuracy of power-sharing. To mitigate this, secondary control is implemented in the controller to restore $V_{dc}$ to its nominal value. However, in several studies, the implementation of a secondary control scheme in a DCMG system was shown to require additional DCLs [27], [28], which is less economical and reduces the degree of flexibility. To overcome such a limitation, this study utilizes a decentralized secondary control to remove the deviation of $V_{dc}$. In addition, for the purpose of improving the flexibility and reliability of the DCMG system, an adaptive droop control method that adaptively adjusts the droop characteristics according to the status of power units is proposed.

This paper presents a power management of a decentralized DCMG system based on the adaptive droop control to achieve reliable power-sharing with constant voltage regulation. In this study, the DCMG system consists of the UG, ESS, EV and DG components along with load units. By using the decentralized structure approach, each power unit effectively determines its operating mode to achieve power-sharing and a power balance without using DCLs, as in the centralized and distributed control schemes, which leads to a more economic and flexible DCMG system. By using the proposed adaptive droop control, the DCMG system can flexibly manage the power flow of each power unit even under uncertainties of DG generation power, the ESS and EV SOC levels, the grid and EV availability, the load demand, and electricity price conditions. Moreover, even during the power exchange process, the DCMG system keeps regulating $V_{dc}$ to its nominal value, which overcomes the disadvantages of conventional droop control producing deviations of $V_{dc}$. As a result, the DCMG system is more economic and flexible. Furthermore, the proposed scheme can realize a scalable DCMG system as a DCL is not needed, and the accuracy of power-sharing and the power balance increases because $V_{dc}$ is regulated to its nominal value. In addition, to optimize the power-sharing of the system under various conditions, power management based on the proposed control is developed. The operating modes of all power units are autonomously determined according to the condition of $V_{dc}$.

Compared to previous studies, the main contributions of this paper are summarized as follows:

1) A fully decentralized architecture is proposed in this study to achieve power-sharing and constant voltage regulation in the DCMG system without using DCLs and complex hierarchical control structure as in [13], [14], [15], [16], [17], and [18]. With the proposed method, each power unit independently determines its operation based on only several local measurements to coordinate the power in the DCMG system. Also, the DCMG system can regulate the $V_{dc}$ to the nominal value in various conditions.

2) The power management is proposed to ensure the effectiveness of decentralized DCMG architecture based on the proposed adaptive droop control method that adaptively changes the droop characteristics for the UG, ESS, and EV according to electricity price and SOC levels with the aim of optimizing the DCMG operation and electricity cost. As a result, the proposed power management enhances the DCMG system reliability in the presence of uncertainties such as the DG power, ESS and EV SOC levels, load demand, and grid availability conditions.

3) The proposed adaptive droop control algorithm is simply and flexibly implemented in practical power units to integrate various power sources in the DCMG system easily. The simulation and experimental results are provided to prove the flexibility of the proposed control which is implemented in real power sources.

The remainder of this paper is organized as follows. Section II introduces the configuration of the DCMG system considered in this study. Section III presents the proposed decentralized control strategy of the DCMG, including the explanation of the proposed adaptive droop control with constant voltage regulation, the power management for operating mode decisions in the DCMG system, and the control scheme of a power converter in each power unit. In order to verify the proposed control scheme, simulation and experimental results are demonstrated under various operating conditions in Section IV and Section V. Finally, the conclusion of the paper is given in Section VI.

II. SYSTEM CONFIGURATION

Fig. 1 depicts the configuration of the decentralized DCMG studied in this paper, which is composed of five main power units: a wind turbine unit for DG, a battery unit for ESS, an EV unit, a UG unit, and a load unit. In the wind turbine unit, a permanent magnet synchronous generator (PMSG) is installed to convert the mechanical output power into electrical power, which is delivered to the DC bus through an AC-DC converter. In the battery and EV units, the interleaved DC-DC converter is employed to connect those systems with the DC bus. In the UG unit, the main grid is connected to the DC bus using a transformer and an AC-DC converter. Then, in the load unit, electronic switches are installed to implement load shedding or reconnection between the resistive load and the DC bus. Power units are connected in parallel to the DC bus as the bus-bar of the DCMG through the different converter topologies of the power units. The power flow of each power unit is denoted by an arrow between the converter and the DC bus, in which the UG unit, EV unit, and battery unit operate via a bidirectional power exchange to support power into or absorb power from the DC bus.
the wind turbine unit and load unit operate only under a unidirectional power exchange scheme; the wind turbine unit only injects power into the DC bus and the load unit only absorbs power from the DC bus.

The power of each power unit is denoted by \( P_X \) for the power in the battery unit, \( P_{EV} \) for the power in the EV unit, \( P_{UG} \) for the power in the UG unit, \( P_W \) for the power in the wind turbine unit, and \( P_L \) for the power in the load unit. The reference direction of the current and the power flow in this paper are denoted by the minus sign (−) for the supported current and power into the DC bus, and the plus sign (+) for the consumed current and power from the DC bus. In order to achieve proper power-sharing and a power balance without an additional communication link, the same control method with different parameters is employed in each power unit, as shown in Fig. 1, in which W, B, EV, and UG denote the wind turbine unit, battery unit, EV unit, and UG unit, respectively. The detailed control methods and operations of the converters are described in the subsequent sections.

III. PROPOSED CONTROL SCHEME

A. POWER-SHARING AND CONSTANT VOLTAGE REGULATION

Fig. 2 shows a control block diagram of the proposed adaptive droop control which can maintain the power balance in the DCMG system and regulate \( V_{dc} \) in the nominal value. The proposed control method is divided into two parts: primary control and secondary control. Even though the primary control to maintain the power balance in the DCMG system is based on the same droop control used in earlier work [23], the droop characteristics for the UG, ESS, and EV are adaptively changed in this study according to electricity price condition and SOC levels of ESS and EV to optimize the DCMG operation and electricity cost. The secondary control uses an integrator to compensate for the deviation of \( V_{dc} \), which is caused by the existing primary control process. Because \( V_{dc} \) is always maintained constant when implementing the proposed adaptive droop control with secondary control, an auxiliary variable \( V_{dc}^* \) is introduced as the indicator to determine the operating modes of each power unit. In Fig. 2, an auxiliary variable \( V_{dc}^* \) can be calculated as below:

\[
V_{dc}^* = V_{dc} + \delta V_{dc}
\]  

(1)

where \( \delta V_{dc} \) is the DC bus voltage compensator. By using the integral control, \( \delta V_{dc} \) can be determined as follows:

\[
\delta V_{dc} = -\frac{k_i}{s} (V_{dc}^{nom} - V_{dc})
\]

(2)

where \( V_{dc}^{nom} \) is the DC bus nominal voltage for secondary control and \( k_i \) is the integrator gain. An auxiliary variable \( V_{dc}^* \) is employed in primary control to determine the operating modes of each power unit as follows:

\[
V_{dc}^* = V_{dc}^{ref} + R_{droop, X} P_{X}^{ref}, \text{ for } X = W, B, EV, UG
\]

(3)

where \( V_{dc}^{ref}, R_{droop, X}, \) and \( P_{X}^{ref} \) are the DC bus voltage reference, the droop coefficient, and the total power of each power unit, respectively. The power reference \( P_{X}^{ref} \) of each power unit in Fig. 2 can be determined based on the constraint and selection of \( V_{dc}^{ref} \) and the droop coefficient \( R_{droop, X} \) as follows:

\[
P_{X, max}^D < P_{X}^{ref} < P_{X, max}
\]

(4)

\[
V_{dc}^{ref} = V_{dc,X, max}^{ref} - R_{droop, X} P_{X, max}^{C}, \text{ or}
\]

\[
V_{dc}^{ref} = V_{dc,X, min}^{ref} - R_{droop, X} P_{X, max}^{S}
\]

(5)

\[
R_{droop, X} = \frac{\Delta V_{dc,X}}{\Delta P_{X}} = \frac{V_{dc,X, max} - V_{dc,X, min}}{P_{X, max}^C - P_{X, min}^S}
\]

(6)

where \( V_{min, X}^{dc} \) is the minimum voltage deviation of a power unit, \( V_{max, X}^{dc} \) is the maximum voltage deviation of a power unit, \( P_{X, max}^C \) is the maximum consuming power of a DCMG in power unit, and \( P_{X, max}^S \) is the maximum supporting power of a DCMG in power unit, respectively. In addition, constraints of the SOC for energy storage units such as the battery and EV are expressed as follows [29] and [30]:

\[
SOC_n(t) = SOC_n(t_0) + \int_{t_0}^{t} I_n(t) \times \eta_{in} \frac{C_{e,n}}{dt}
\]

(7)

\[
SOC_{min, n} < SOC_n < SOC_{max, n}
\]

(8)

where \( SOC_n \) is SOC of an energy storage, \( I_n \) is current of an energy storage, \( \eta_{in} \) is the coulombic efficiency, \( Q_n \) is the nominal capacity of an energy storage, \( SOC_{min, n} \) is minimum SOC of energy storage, and \( SOC_{max, n} \) is maximum SOC of energy storage.

According to (2), (5), and (6), the values of \( V_{dc}^{nom}, k_i, V_{min, X}^{dc}, V_{max, X}^{dc}, P_{X, max}^C, \) and \( P_{X, max}^S \) should initially be established. In secondary control, the main control objective is to regulate the DC bus voltage to its nominal value. To do this,
an integrator is employed in the secondary control for the purpose of eliminating the DC bus voltage error by continually summing the voltage error over time. To realize the decentralized DCMG system without any DCL, the value of the auxiliary variable \( V^*_\text{ref,dc} \) as an indicator of droop control should be identical for all power units. For this purpose, the values of \( V^\text{nom,dc} \) and \( k_i \) in the secondary control should be identical in each power unit, as indicated by the variables in blue in Fig. 2.

The auxiliary variable \( V^*_\text{ref,dc} \) generated by the secondary control is utilized in primary control of each power unit to determine the operating mode and exchange power. As indicated by (3), because the \( V^*_\text{ref,dc} \) values of the power units are identical, the operating mode and exchange power of each power unit can be determined based on \( V^\text{ref,dc, x} \), with \( R^\text{droop, x} \) in each power unit. Since \( V^\text{ref,dc, x} \) and \( R^\text{droop, x} \) can be defined by setting the values of \( V^\text{min,dc, x} \), \( V^\text{max,dc, x} \), \( P^\text{max,dc, x} \), and \( P^\text{dc, max} \), those values should be selected based on power management planning in order to achieve the optimal power-sharing scheme in the DCMG, as will be discussed in the subsequent sections.

**B. POWER MANAGEMENT BASED ON ADAPTIVE DROOP CONTROL SCHEME**

The control method in this study has two objectives: to regulate \( V_{\text{dc}} \) to its nominal value and to achieve optimal power-sharing and power management by adaptively changing the droop characteristics for the UG, battery, and EV units according to electricity price conditions and SOC levels. To realize both objectives, the control scheme requires two reference voltages as the input: the DC bus voltage reference \( V^\text{ref,dc, x} \), which is used to coordinate the power-sharing, and the DC bus nominal voltage of the DCMG \( V^\text{nom,dc} \), which is used to regulate the DC bus voltage. Because the load unit in the system configuration in this study only consists of resistive loads without a converter, the value \( V^\text{nom,dc} \) should be set such that it matches the voltage needed in the load unit. On the other hand, \( V^\text{ref,dc, x} \) can be determined according to the energy supporting and consumption (ESC) priority [22]. In this study, the priority order of the power units for energy support is selected as follows: the wind turbine unit, UG unit, battery unit, and EV unit. It means that the voltage reference values of each power unit are arranged in the order of magnitude as \( V^\text{ref,dc, W} \), \( V^\text{ref,dc, UG} \), \( V^\text{ref,dc, B} \), and \( V^\text{ref,dc, EV} \) from the highest to the lowest voltage levels. On the contrary, the priority order for energy consumption is given as EV unit, battery unit, and UG unit.

Based on the priority order of the power units for energy support and consumption, the proposed adaptive droop control method for a decentralized DCMG system is designed as shown in Fig. 3, which shows the operating mode decisions of power units according to the relationship between \( V^*_\text{dc} \) and the power of each power source. The auxiliary variable \( V^*_\text{dc} \) is obtained through the integral control as in Fig. 2. In order to optimize the power management of the DCMG system, the droop characteristic of the UG unit is adaptively adjusted between \( \text{①} \) and \( \text{②} \) in Fig. 3. In this study, it is assumed that the electricity price condition is only known to the UG unit, and TOU pricing method which divides the electricity price into two conditions, high and low is considered [11]. When the electricity price is low condition, the droop characteristic of UG unit is placed at a higher voltage level in order to use the power from the UG to support the DCMG system. On the other hand, if the electricity price is changed to high, the UG droop characteristic becomes lower in order to reduce the power from the UG, or to inject more power into the UG.

Moreover, the droop characteristics of battery and EV units are also adaptively changed according to their SOC levels to use the power of the DCMG system optimally. In the proposed adaptive droop control, the SOC of battery directly influences on determination of the power reference. As seen in Fig. 3, the droop characteristic of the battery unit is continuously changed according to the \( \text{SOC}_B \) level in the region between \( \text{③} \) and \( \text{④} \). As the SOC of battery is higher, the droop characteristic of the battery approaches \( \text{③} \). On the contrary, as the SOC of battery is lower, it approaches \( \text{④} \). To realize adaptive droop control, the minimum voltage level of the battery unit is modified. This value is used in (5) and (6) to determine the droop coefficient of the battery. Finally, the obtained droop coefficient of the battery is used to generate the power reference of the battery by (1)-(3) according to the constraint in (4), (7), and (8). In case of the EV unit, the droop characteristic which is placed lower than that of the battery unit, is also continuously changed according to the SOC level in the region between \( \text{⑥} \) and \( \text{⑦} \) in Fig. 3. Similarly,
as the $SOC_{EV}$ level is increased by charging operation, the droop characteristic is continuously moved toward the region $\textcircled{5}$. On the other hand, as the $SOC_{EV}$ level is decreased by discharging operation, it is moved toward the region $\textcircled{6}$."

According to the proposed adaptive droop control strategy, the variables $V_{\text{dc}, \text{X}}^\text{min}$ and $V_{\text{dc}, \text{X}}^\text{max}$ used in (5) and (6) to design the primary control are modified. Whereas the wind turbine unit has only one maximum and minimum value, i.e., $V_{\text{dc}, \text{W}}^\text{min}$ and $V_{\text{dc}, \text{W}}^\text{max}$, the UG, battery, and EV units have several maximum and minimum values in the proposed scheme which are defined in Table 1. By using the voltage levels defined in Table 1, $V_{\text{dc}, \text{X}}^\text{min}$ and $V_{\text{dc}, \text{X}}^\text{max}$ used in (5) and (6) to design the primary control should be modified for the UG, battery, and EV units in the proposed scheme to adaptively change the droop control by considering electricity price conditions and SOC levels. First, the voltage levels of the UG unit are obtained as follows:

$$V_{\text{dc}, \text{UG}}^\text{min} = (E_H) V_{\text{dc}, \text{UG}}^\text{min} + (E_L) V_{\text{dc}, \text{UG}}^\text{min} \quad (9)$$

$$V_{\text{dc}, \text{UG}}^\text{max} = (E_H) V_{\text{dc}, \text{UG}}^\text{max} + (E_L) V_{\text{dc}, \text{UG}}^\text{max} \quad (10)$$

where $E_H$ and $E_L$ are binary state variables determined by electricity price conditions. Variables $E_H$ and $E_L$ are introduced to simply select the values of $V_{\text{dc}, \text{UG}}^\text{min}$ and $V_{\text{dc}, \text{UG}}^\text{max}$ according to electricity price condition. If the electricity price condition is high, $E_H = 1$ and $E_L = 0$, and vice versa. The voltage levels given in (9) and (10) are employed in (5) and (6) to constitute the primary droop control of the UG.

The voltage levels of the battery and EV units are obtained as follows:

$$V_{\text{dc}, \text{B}}^\text{min} = (SOC_B - SOC_{\text{min}, B}) \times \left( \frac{V_{\text{dc}, B}^\text{min} - V_{\text{dc}, B}^\text{min}}{SOC_{\text{max}, B} - SOC_{\text{min}, B}} \right) + V_{\text{dc}, B}^\text{min} \quad (11)$$

$$V_{\text{dc}, \text{EV}}^\text{max} = \left( SOC_{\text{EV}} - SOC_{\text{min}, \text{EV}} \right) \times \left( \frac{V_{\text{dc}, \text{EV}}^\text{min} - V_{\text{dc}, \text{EV}}^\text{min}}{SOC_{\text{max}, \text{EV}} - SOC_{\text{min}, \text{EV}}} \right) + V_{\text{dc}, \text{EV}}^\text{min} \quad (12)$$

$$V_{\text{dc}, \text{EV}}^\text{max} = \left( SOC_{\text{EV}} - SOC_{\text{min}, \text{EV}} \right) \times \left( \frac{V_{\text{dc}, \text{EV}}^\text{max} - V_{\text{dc}, \text{EV}}^\text{max}}{SOC_{\text{max}, \text{EV}} - SOC_{\text{min}, \text{EV}}} \right) + V_{\text{dc}, \text{EV}}^\text{max} \quad (13)$$

where $SOC_{\text{min}, B}$ and $SOC_{\text{max}, B}$ are the minimum and maximum SOC of the battery, respectively, and $SOC_{\text{min}, \text{EV}}$ and $SOC_{\text{max}, \text{EV}}$ are the minimum and maximum SOC of the EV, respectively.

Similarly, the voltage levels given in (11)-(13) are employed in (5) and (6) to constitute the primary droop control of the battery and EV units.

Table 2 presents detailed descriptions of the operating modes for each power unit in the proposed decentralized DCMG system. In the proposed control scheme, $V_{\text{dc}}$ is regulated either by the wind turbine unit, UG unit, battery unit, or EV unit using the adaptive droop control method according to the deviation of $V_{\text{dc}}^\text{L}$ to determine the operating modes of each unit. The description of control operation in each power unit is explained in next subsection.

1) CASE 1 ($V_{\text{dc}, \text{W}}^\text{min} < V_{\text{dc}} < V_{\text{dc}, \text{W}}^\text{max}$)

During this voltage interval, the DCMG system works in an islanded mode and the wind turbine unit produces the power between $P_{\text{W}}^\text{min}$ and $P_{\text{W}}^\text{max}$. During this voltage interval, since the wind power generation exceeds the sum of the power needed for $P_{\text{B}}^\text{min}$, $P_{\text{B}}^\text{max}$, and $P_{\text{EV}}^\text{max}$, the DCMG system has surplus power, which causes $V_{\text{dc}}$ to increase beyond $V_{\text{dc}, \text{W}}^\text{min}$. In order to prevent the DCMG system from overvoltage caused by surplus power, the wind turbine unit operates in VDCM to regulate $V_{\text{dc}}$ by adjusting its power generation. Meanwhile,

| Power Unit | Variable | Description |
|------------|----------|-------------|
| UG Unit    | $V_{\text{dc}, \text{UG}}^\text{min}$ | Maximum voltage level of UG unit in low electricity price condition |
|            | $V_{\text{dc}, \text{UG}}^\text{max}$ | Minimum voltage level of UG unit in low electricity price condition |
|            | $V_{\text{dc}, \text{UG}}^\text{min}$ | Maximum voltage level of UG unit in high electricity price condition |
|            | $V_{\text{dc}, \text{UG}}^\text{max}$ | Minimum voltage level of UG unit in high electricity price condition |
| Battery Unit | $V_{\text{dc}, \text{B}}^\text{min}$ | Minimum voltage level of battery unit in the lowest SOC level |
|            | $V_{\text{dc}, \text{B}}^\text{max}$ | Minimum voltage level of battery unit in the highest SOC level |
| EV Unit    | $V_{\text{dc}, \text{EV}}^\text{min}$ | Maximum voltage level of EV unit in the lowest SOC level |
|            | $V_{\text{dc}, \text{EV}}^\text{max}$ | Minimum voltage level of EV unit in the highest SOC level |
|            | $V_{\text{dc}, \text{EV}}^\text{min}$ | Minimum voltage level of EV unit in the highest SOC level |

| Power unit | Description | Operating modes |
|------------|-------------|-----------------|
| UG unit    | UG unit is disconnected due to a fault |
|            | UG droop control by the inverter mode |
|            | UG droop control by the converter mode |
| Battery unit | Idle mode | IDLE |
|            | Battery droop control by the discharging mode | BDDM |
|            | Battery droop control by the charging mode | BDCM |
| EV unit    | EV droop control by the discharging mode |
|            | EV droop control by the charging mode |
| Wind turbine unit | Maximum power point tracking mode | MPPT |
| Load unit  | Load shedding |
|            | Load reconnecting |
|            | Load under a normal condition |

$$V_{\text{dc}, \text{EV}} = (SOC_{\text{EV}} - SOC_{\text{min}, \text{EV}}) \times \left( \frac{V_{\text{dc}, B}^\text{min} - V_{\text{dc}, B}^\text{min}}{SOC_{\text{max}, B} - SOC_{\text{min}, B}} \right) + V_{\text{dc}, B}^\text{min} \quad (11)$$

$$V_{\text{dc}, \text{EV}} = (SOC_{\text{EV}} - SOC_{\text{min}, \text{EV}}) \times \left( \frac{V_{\text{dc}, \text{EV}}^\text{max} - V_{\text{dc}, \text{EV}}^\text{max}}{SOC_{\text{max}, \text{EV}} - SOC_{\text{min}, \text{EV}}} \right) + V_{\text{dc}, \text{EV}}^\text{max} \quad (12)$$

$$V_{\text{dc}, \text{EV}} = (SOC_{\text{EV}} - SOC_{\text{min}, \text{EV}}) \times \left( \frac{V_{\text{dc}, \text{EV}}^\text{max} - V_{\text{dc}, \text{EV}}^\text{max}}{SOC_{\text{max}, \text{EV}} - SOC_{\text{min}, \text{EV}}} \right) + V_{\text{dc}, \text{EV}}^\text{max} \quad (13)$$
the battery unit operates in BDCM with \( P_{B}^{C, \text{max}} \), and the EV unit operates in EDCM with \( P_{EV}^{C, \text{max}} \) as indicated in Table 2.

2) CASE 2 \( (V_{dc, \text{U}}^{\text{min, L}} < V_{dc} < V_{dc}^{\text{max, L}}) \)

During this voltage interval, the DCMG system works in the grid-connected mode in low electricity price conditions, and the operating modes of the battery and EV units are identical to those in Case 1. Because the UG unit has the largest power range compared to the other unit powers, the wind turbine unit can produce \( P_{W}^{S, \text{max}} \) by operating in MPPT mode without an overvoltage situation arising. In contrast, the operating mode of the UG unit is determined based on the \( P_{W}^{\text{max}} \) value. If the wind turbine unit produces more power than the sum of the power needed for \( P_{L} \), \( P_{B}^{C, \text{max}} \), and \( P_{EV}^{C, \text{max}} \), the remaining power from the wind turbine unit is absorbed by the UG unit by regulating \( V_{dc} \). This operating mode is expressed in Table 2 as INV. Otherwise, if the wind turbine unit produces less power than the sum of the power demand for \( P_{L} \), \( P_{B}^{C, \text{max}} \), and \( P_{EV}^{C, \text{max}} \), the deficit power is supported by the UG unit, which operates with CON operation. If the grid unit has a fault suddenly, the UG unit is immediately disconnected. In this condition, the DCMG system cannot operate in this voltage interval. Depending on the wind power generation, load demand, and battery and EV status, \( V_{dc} \) will increase or decrease, resulting in \( V_{dc} \) regulation by the other power units.

3) CASE 3 \( (V_{dc, \text{B}}^{\text{min, H}} < V_{dc} < V_{dc, \text{B}}^{\text{max, H}}) \)

In this voltage range, the DCMG system works in islanded mode, and the wind turbine unit operates in the MPPT mode to draw the maximum power \( P_{W}^{S, \text{max}} \). However, it is still less than the sum of the power needed for \( P_{L} \), \( P_{B}^{C, \text{max}} \), and \( P_{EV}^{C, \text{max}} \). In this case, the \( V_{dc} \) is regulated by the battery unit depending on the value between \( P_{W}^{S, \text{max}} \) and the sum power of \( P_{L} \) and \( P_{B}^{C, \text{max}} \). If the wind turbine unit can provide more power than the sum power of \( P_{L} \) and \( P_{B}^{C, \text{max}} \), the battery unit regulates \( V_{dc} \) by absorbing the remaining power via BDCM operation. Otherwise, if the wind turbine unit produces less power than the sum power of \( P_{L} \) and \( P_{B}^{C, \text{max}} \), the battery unit regulates \( V_{dc} \) by supplying more power to the DC bus via BDDM. However, the battery has a limitation to supply and consume the power depending on the SOC level. Thus, the battery unit automatically changes its operation into IDLE if the battery SOC is less than \( SOC_{\text{min, B}} \) or more than the maximum \( SOC_{\text{max, B}} \). Also, it is worth to mention that the droop characteristic of the battery unit is lower as the battery SOC level reduces as explained in (11) and Fig. 3.

4) CASE 4 \( (V_{dc, \text{U}}^{\text{min, L}} < V_{dc} < V_{dc, \text{U}}^{\text{max, L}}) \)

In this voltage range, the DCMG system and the wind turbine unit operate identically to how they operate in Case 3. Here, \( V_{dc} \) is regulated by the EV unit depending on the sum power of \( P_{W}^{S, \text{max}} \) and \( P_{B}^{C, \text{max}} \). If the sum power of \( P_{W}^{S, \text{max}} \) and \( P_{B}^{S, \text{max}} \) exceeds \( P_{L} \), and the remaining power is less than \( P_{EV}^{C, \text{max}} \), the EV unit regulates \( V_{dc} \) by absorbing the remaining power in EDCM. Otherwise, if the sum of power \( P_{W}^{S, \text{max}} \) and \( P_{B}^{S, \text{max}} \) produces less power than \( P_{L} \), the EV unit regulates \( V_{dc} \) by supplying more power to the DC bus with EDDM operation. Similar to the battery unit operation, the EV unit also changes its operation immediately to idle mode (IDLE) if the EV SOC is less than \( SOC_{\text{min, EV}} \) or more than \( SOC_{\text{max, EV}} \). In addition, the droop characteristic of the EV unit also moves lower as the EV SOC level reduces as explained in (12), (13), and Fig. 3.

5) CASE 5 \( (V_{dc, \text{dc}}^{\text{shed}} < V_{dc} < V_{dc, \text{dc}}^{\text{min, L}}) \)

In this voltage range, the DCMG system works in the grid-connected mode in high electricity price conditions. During this period, the droop characteristic of the UG unit is placed at the lowest position. As a result, the CON operation of the UG unit is carried out at the lowest voltage level to save electricity costs by reducing the power supplied in the UG. The battery and EV units operate in BDDM and EDDM, respectively, to supply the power to the DC bus by discharging.

6) CASE 6 \( (V_{dc}^{\text{nom}} < V_{dc} < V_{dc, dc}^{\text{min, L}}) \)

If \( V_{dc}^{\text{nom}} \) is reduced further below \( V_{dc}^{\text{shed}} \), a load shedding (LS) algorithm should be used by the load management system as a final solution to prevent the DCMG system from collapsing in this critical situation. The LS algorithm is automatically activated when \( V_{dc} \) reaches \( V_{dc}^{\text{shed}} \) depending on the load priority according to earlier work [10]. On the other hand, when the system returns back to normal operation, a load reconnecting (LR) algorithm is executed to connect the disconnected load, which improves the reliability of the DCMG system. In this paper, the LR algorithm automatically starts when \( V_{dc}^{\text{nom}} \) is recovered to \( V_{dc} \) according to the load priority in the literature [10].

C. CONTROL SCHEME OF POWER CONVERTER

The overall power and voltage management for the proposed decentralized DCMG system are achieved by the control of power converters in each power unit. Fig. 4 shows the details of the converter control design in each power unit. In this study, to generate power reference, power units work based on the adaptive droop control method as in Fig. 2, with the different droop characteristics denoted by the same color for each power unit in Fig. 2. The current references of each power unit are generated from the power references. Then, depending on the power converter types, the current controllers for each power unit are designed by using the proportional-integral (PI) controllers, phase-locked loop (PLL) block, and space vector pulse width modulation (SVPWM) to realize the operating modes of each power unit.

D. SYSTEM STABILITY

In this section, the system stability of the proposed control scheme is analyzed. To investigate the system stability, the control block diagram of the proposed adaptive droop control is presented in Fig. 5. This control block diagram consists of the proposed droop control in Fig. 2 with an additional current
controller block and DC-link capacitor with the resistive load. The closed-loop current control transfer function is modeled as high-bandwidth first order system as follows:

$$I_{X}(s) = \frac{1}{1 + \tau s} \tag{14}$$

where $\tau = \frac{1}{\omega_c}$ and $\omega_c$ is the cut-off frequency. The relation between the converter output current and DC-link is represented as follows [31]:

$$C \frac{dV_{dc}}{dt} = I_o - \frac{V_{dc}}{R_L} \tag{15}$$

where $C$ is the DC-link capacitance, $I_o = -I_X$ is the converter output current, and $R_L$ is the resistive load in the DC-link. From Fig. 5, the closed-loop transfer function of the proposed control is represented as third order system as follows:

$$V_{dc} \frac{V_{nom}}{V_{dc}} = \frac{R_L k_i}{\alpha s^3 + \beta s^2 + \gamma s + R_L k_i} \tag{16}$$

From (16), the stability of the closed-loop system can be tested for the proposed control by investigating the location of the closed-loop poles. Fig. 6 shows the closed-loop eigenvalues of each power unit in the DCMG system for the proposed control scheme when the secondary control gain $k_i$ varies from 1 to 8.5. As shown in Fig. 6, all the closed-loop eigenvalues of each power unit lie in the stable region for this variation of $k_i$, which ensures the system stability of the proposed control scheme. However, since (16) is third order system, the asymptote angle of the root locus is given as $60^\circ$, $180^\circ$, $300^\circ$. As a result, as $k_i$ increases, one pole moves toward the left side of the s-plane, and the other two poles move toward the right side of the s-plane along asymptote angle $60^\circ$ and $300^\circ$. This indicates that the closed-loop system become unstable for a large value of $k_i$.

**IV. SIMULATION RESULTS**

The objective of this simulation is to validate the control performance of the proposed adaptive droop control method and power management of a prototype DCMG system. The simulation results are obtained based on PSIM software. In the simulation, the transient and steady-state performances of the proposed decentralized DCMG system are evaluated under several uncertainties of the ESS and EV SOC levels, wind and load power variations, uncertain conditions of UG availability, and the change of electricity price. Table 3 shows the specifications and parameters of the DCMG system used in the simulation. This study presents four simulation cases:
TABLE 3. Specifications and parameters of the DCMG system.

| Power unit | Parameters | Symbol | Value |
|------------|------------|--------|-------|
| UG unit    | Grid voltage | \( V_{\text{nom}}^{\text{UG}} \) | 220 V |
|            | Grid frequency | \( f_{\text{UG}} \) | 60 Hz |
|            | Maximum consuming power | \( P_{\text{max}}^{\text{UG}} \) | 2000 W |
|            | Maximum supporting power | \( P_{\text{max}}^{\text{UG}} \) | 1200 W |
|            | Maximum voltage level in low electricity price | \( V_{\text{min}, \text{L}}^{\text{dc,UG}} \) | 420 V |
|            | Minimum voltage level in low electricity price | \( V_{\text{max}, \text{L}}^{\text{dc,UG}} \) | 400 V |
|            | Maximum voltage level in high electricity price | \( V_{\text{min}, \text{H}}^{\text{dc,UG}} \) | 390 V |
|            | Minimum voltage level in high electricity price | \( V_{\text{max}, \text{H}}^{\text{dc,UG}} \) | 380 V |
| Wind turbine unit | PMSG number of poles | \( p \) | 6 |
|            | PMSG inertia | \( J \) | 0.111 kgm² |
|            | PMSG flux linkage | \( \psi \) | 0.18 Wb |
|            | Maximum supporting power | \( P_{\text{max}}^{\text{turb}} \) | -1500 W |
|            | Maximum voltage level | \( V_{\text{max}}^{\text{turb}} \) | 430 V |
|            | Minimum voltage level | \( V_{\min}^{\text{turb}} \) | 420 V |
| EV unit    | SOC | \( SOC_{\text{max}, EV} \) | 90 % |
|            | Minimum SOC | \( SOC_{\text{min}, EV} \) | 20 % |
|            | Maximum EV voltage | \( V_{\text{max}}^{\text{EV}} \) | 180 V |
|            | Maximum consuming power | \( P_{\text{max}}^{\text{EV}} \) | 360 W |
|            | Maximum supporting power | \( P_{\text{max}}^{\text{supp}} \) | -360 W |
|            | Maximum voltage level in the highest SOC | \( V_{\text{max}, \text{H}}^{\text{turb}} \) | 390 V |
|            | Minimum voltage level in the highest SOC | \( V_{\text{min}, \text{H}}^{\text{turb}} \) | 385 W |
|            | Maximum voltage level in the lowest SOC | \( V_{\text{max}, \text{L}}^{\text{turb}} \) | 380 V |
|            | Minimum voltage level in the lowest SOC | \( V_{\text{min}, \text{L}}^{\text{turb}} \) | 375 V |
| Battery unit | Maximum SOC | \( SOC_{\text{max}, \text{B}} \) | 90 % |
|            | Minimum SOC | \( SOC_{\text{min}, \text{B}} \) | 20 % |
|            | Maximum battery voltage | \( V_{\text{max}}^{\text{B}} \) | 180 V |
|            | Maximum consuming power | \( P_{\text{max}}^{\text{B}} \) | 450 W |
|            | Maximum supporting power | \( P_{\text{max}}^{\text{supp}} \) | -450 W |
|            | Maximum voltage level | \( V_{\text{max}, \text{B}}^{\text{turb}} \) | 400 V |
|            | Minimum voltage level | \( V_{\min}^{\text{turb}} \) | 390 V |
| Load unit  | Load 1 | \( R_{11} \) | 800 Ω |
|            | Load 2 | \( R_{12} \) | 800 Ω |
|            | Load 3 | \( R_{13} \) | 800 Ω |
|            | Priority level: load 1 > load 2 > load 3 | - | - |
| DC bus     | Load shedding voltage level | \( V_{\text{shed}}^{\text{dc}} \) | 370 V |
|            | Nominal voltage | \( V_{\text{nom}}^{\text{dc}} \) | 400 V |

The system starts at \( t = 0.05 \) s in islanded mode and the wind turbine unit produces less power than the load demand. As a result, \( V_{\text{dc}}^{\text{nom}} \) decreases and triggers the battery and EV units to supply power to the DCMG by operating in BDDM and EDDM, respectively. In this condition, the system power balance is guaranteed by the EV unit. Then, at \( t = 0.5 \), the battery SOC reaches \( SOC_{\text{min}, B} \), which causes the battery unit to stop discharging by changing the operation from BDDM to IDLE. Due to the power deficit in the DCMG, \( V_{\text{dc}}^{\text{nom}} \) gradually decreases, causing the EV unit to increase supply power to the DC bus. However, despite the fact that an EV unit supplies the power in \( P_{\text{EV}}^{\text{max}} \), \( V_{\text{dc}}^{\text{nom}} \) still decreases, which indicates that the total power from the EV and wind turbine units is not sufficient to meet the load demand. Then, \( V_{\text{dc}}^{\text{nom}} \) falls below \( V_{\text{shed}}^{\text{dc}} \), which triggers the LS process in the load unit. As a result of the LS process, \( V_{\text{dc}}^{\text{nom}} \) increases. When \( V_{\text{dc}}^{\text{nom}} \) increases beyond \( V_{\text{ref}}^{\text{dc}} \), the EV unit operates in EDCM to regulate \( V_{\text{dc}}^{\text{nom}} \) by charging EV until the end of the simulation as in the diagram of Fig. 3. From the entire simulation in Fig. 7, even with the variation of wind power generation as well as the ESS and EV status uncertainties, the DC bus \( V_{\text{dc}}^{\text{nom}} \) remains constant at \( V_{\text{nom}}^{\text{dc}} \) and the EV unit automatically reduces the output power based on the \( V_{\text{dc}}^{\text{nom}} \) value.

A. ISLANDED MODE WITH LOW DG POWER UNDER DG POWER VARIATIONS

Fig. 7 shows the simulation results when the DCMG system is in islanded mode with low DG power conditions.
B. ISLANDED MODE WITH VARIATIONS OF THE DG POWER AND LOAD DEMAND

Fig. 8 shows the simulation results of the proposed decentralized DCMG control scheme with the variations of load demand and DG power in the islanded mode. Initially, the DCMG system starts in islanded mode at $t = 0.05$ s, where the wind turbine unit operates in VDCM because it produces power more than the sum of $P_L$, $P_{B_{\text{C, max}}}$, and $P_{C_{\text{EV, max}}}$. When the battery SOC reaches $SOC_{\text{max,B}}$ at $t = 0.58$ s, the operating mode of the battery unit automatically changes from BDCM to IDLE to prevent the battery from overcharging. As a result, $V_{dc}$ increases and causes the wind power to decrease its output. At $t = 1.2$ s, the EV SOC reaches $SOC_{\text{max,EV}}$ and the load increases at nearly the same time. As a response to the EV SOC condition, the operating mode of the EV unit changes from EDCM to IDLE. Also, the wind turbine unit still regulates $V_{dc}$ by operating in VDCM since $V_{dc}$ is increasing as a result of the surplus power into the DCMG. Even though two transition conditions such as the load increase and EV $SOC_{\text{max,EV}}$ are introduced in the DCMG at $t = 1.2$ s, the DCMG system not only switches the operating mode for power-sharing reliably, but also regulates $V_{dc}$ at $V_{dc}^{\text{nom}}$ effectively.

At $t = 1.8$ s, the wind power drops until it is less than the load demand. In order to offset the deficit of power, the battery unit is triggered by $V_{dc}$ to change its operating mode from IDLE to BDDM. At $t = 2.5$ s, the wind turbine unit increases more than the load demand, as indicated by the $V_{dc}^{\text{ref}}$ value. Because $V_{dc}^{\text{ref}}$ is at a constant value between $V_{dc}^{\text{nom}}$ and $V_{dc}^{\text{ref,B}}$, the operating mode of the battery unit changes from BDDM to VDCM. It is also confirmed from Fig. 8 that the proposed control scheme can ensure regulation of the DC bus voltage to the nominal value even with variations of the DG power and the load demand condition.

C. TRANSITION BETWEEN GRID-CONNECTED MODE AND ISLANDED MODE UNDER DG POWER VARIATIONS

Fig. 9 shows the simulation results of the proposed decentralized DCMG control during a transition between the islanded mode and grid-connected mode with the variations of the DG power. Initially, the DCMG system starts its operation at $t = 0.05$ s in islanded mode with wind power less than the load demand, and the battery unit is in the IDLE mode. Under this condition, the EV releases power into the DC bus by operating in the EDDM to offset the deficit of power in the DCMG system. As the EV SOC value reaches $SOC_{\text{max,EV}}$ at $t = 0.7$ s, the operating mode of the EV unit changes to IDLE. Due to the power deficit in the DCMG, $V_{dc}$ gradually decreases to the $V_{dc}^{\text{shed}}$ level and triggers the activation of the LS algorithm. As a result of the LS process, it is shown that $V_{dc}$ increases, which indicates that $P_W$ exceeds $P_L$.

As the UG is recovered and $P_W$ increases at $t = 1.5$ s, the DCMG system returns to the grid-connected mode and the UG unit immediately starts to regulate the DC bus by operating in the CON mode as defined in Table 2. As soon as $V_{dc}$ approaches $V_{dc}^{\text{nom}}$, the LR algorithm is triggered to reconnect the load, which has been disconnected. At the same time, the battery and EV are charged with BDCM and EDCM, respectively. As the wind power increases significantly to more than the sum of $P_L$, $P_{B_{\text{C, max}}}$, and $P_{C_{\text{EV, max}}}$ at $t = 2.5$ s, the operating mode of the UG unit changes from CON to INV mode to inject the surplus power into the UG. It is assumed that the system returns to the islanded mode due to a UG fault at $t = 3.5$ s. At this instant, because the wind power exceeds the sum of $P_L$, $P_{B_{\text{C, max}}}$, and $P_{C_{\text{EV, max}}}$, the wind turbine unit automatically regulates $V_{dc}$ by changing its operation from MPPT to VDCM. Given the overall performance shown in Fig. 9, the proposed adaptive droop control and power management scheme of DCMG system effectively achieve a power balance and regulate $V_{dc}$ to its nominal value even when the DCMG system has a transition between grid-connected mode and islanded mode.

D. GRID-CONNECTED MODE WITH ELECTRICITY PRICE CONDITION CHANGE

Fig. 10 shows the simulation results of the proposed decentralized DCMG control in grid-connected mode under...
electricity price condition change. Initially, the DCMG system starts its operation at \( t = 0.05 \) s in grid-connected mode with low electricity price conditions, in which the UG unit supplies the power to DCMG with CON operation. The battery and EV units operate in BDCM and EDCM to charge them with the maximum powers \( P_{B}^{c, max} \) and \( P_{E}^{c, max} \), respectively. The wind turbine unit operates in MPPT mode with \( P_{W}^{max} \). Then, as the battery SOC reaches \( S_{max,B} \) at \( t = 0.92 \) s, the battery unit stops charging by changing the operation from BDCM to IDLE. As a result, \( V_{dc}^{ref} \) increases, which reduces the power supplied from the UG into the DCMG system. However, the UG increases the power supplied into the DCMG system again as the wind power drops at \( t = 1.5 \) s.

When the electricity price is changed to high at \( t = 2.0 \) s, the UG unit changes the \( V_{dc,UG}^{ref} \) value from 1 to 2 in Fig. 3 based on the proposed adaptive droop control. As a result, the UG unit changes operation from CON into INV mode to inject power from DC bus to the UG. Hence, \( V_{dc}^{ref} \) and \( V_{dc}^{ref} \) gradually decrease, which triggers the battery unit to change the operation from IDLE into BDCM with \( P_{B}^{max} \). The sum of \( P_{W}^{max} \) and \( P_{L}^{max} \), the UG unit decreases the absorbed power to maintain \( V_{dc} \) at \( V_{nom}^{ref} \). At the same time, since the EV SOC level is low, the power absorbed by the UG unit is divided with the EV unit after \( V_{dc}^{ref} \) exceeds \( V_{dc, EV}^{ref} \) according to the droop characteristic of each power unit. At \( t = 3.0 \) s, the wind power increases significantly, which causes \( V_{dc}^{ref} \) to increase. As a result, the EV and UG units increase the power absorption according to the level of \( V_{dc}^{ref} \) and droop characteristics. The simulation results in Fig. 10 clearly demonstrate that the proposed adaptive droop control method can effectively regulate \( V_{dc} \) to its nominal value and optimize the power-sharing performance even under the uncertainties of electricity price conditions and SOC levels.

V. EXPERIMENTAL VALIDATIONS
For a practical verification of the overall control performance and effectiveness of the proposed adaptive droop control for a decentralized DCMG system, experiments were conducted using the same configuration shown in Fig. 1. Fig. 11 shows the configuration of a prototype DCMG testbed used in the experiment. In the experiments, power units are connected to a DC-link capacitor as the PCC to exchange power within the DCMG. The wind turbine is realized using an AC motor control panel and an induction motor mechanically coupled to a PMSG. Bidirectional DC power sources are used as the ESS and EV, respectively. The UG unit is connected to a three-phase grid through a Y-Δ transformer, and the load unit consists of resistors equipped with magnetic contactors for the implementation of the LS and LR algorithms. A digital signal processor (DSP) TMS320F28335 control set is employed in each power unit to execute the proposed control algorithm. In order to represent the effectiveness of the proposed control in each power unit, experiments are carried out for five cases: in islanded mode with low DG power, in islanded mode under variation of the DG power, in grid-connected mode under variation of the DG power, during a transition from the grid-connected mode to the islanded mode, and in grid-connected mode with electricity price condition change.

A. ISLANDED MODE WITH LOW DG POWER
Fig. 12 shows the experimental results of the proposed adaptive droop control for the islanded-mode decentralized DCMG when the DG supplies less power than the load demand. Initially, the DCMG system is in islanded mode and the wind turbine unit operates in the MPPT mode, generating \( P_{W}^{max} \) less than \( P_{L} \). Because the battery is in the IDLE mode due to the minimum SOC, the EV unit supplies additional power to the DC bus to overcome the deficit of power in the DCMG system. In this condition, the EV unit operates in EDDM, and all loads are fed.

It is assumed that the EV SOC reaches \( S_{min,EV} \), which causes the EV unit operation to change from EDDM to IDLE mode. Because the DCMG system has a deficit of power, \( V_{dc} \) gradually decreases, which causes \( V_{dc}^{up} \) to also decrease at the same time. As soon as \( V_{dc}^{up} \) reaches \( V_{dc,shed} \), the LS algorithm is started to disconnect the load with the lowest priority. The LS process can be observed by the reduction of \( P_{L} \) in Fig. 12, which causes \( V_{dc} \) to gradually increase. When \( V_{dc}^{up} \) increases and exceeds the voltage level.
V\text{ref}_{dc, EV}$, the second DCMG mode transition occurs. In this case, the EV unit works in EDCM to use the remaining power to charge the EV. Although the fluctuation of $V^*_{dc}$ causes the transition of the operating mode, the proposed control scheme can effectively regulate $V_{dc}$ to its nominal value except for only the critical power deficit case, and the proposed adaptive droop control and power management reliably achieve a proper power balance in a decentralized DCMG system.

**B. ISLANDED MODE UNDER DG POWER VARIATION**

Fig. 13 shows the experimental results of the proposed adaptive droop control and power management when the DCMG system is in islanded mode with DG power variations. In this test, the DCMG system initially operates in a steady-state, where the EV unit is in IDLE mode and the wind power is less than the load demand, which causes $V^*_{dc}$ to be less than $V^\text{nom}_{dc}$. Because $V^*_{dc}$ is constantly regulated between $V^\text{ref}_{dc, B}$ and $V^\text{nom}_{dc}$, the battery unit has the responsibility to supply additional power to the DCMG and maintain $V_{dc}$ by operating in BDDM.

Suddenly, the wind power increases and exceeds the load demand, which causes surplus power within the DCMG system. As a result, $V^*_{dc}$ increases and then is constantly regulated between $V^\text{ref}_{dc, B}$ and $V^\text{max}_{dc, B}$. In this case, the battery unit absorbs the surplus power from the DCMG by operating in BDCM. It is also confirmed in Fig. 13 that despite the power variation of the DG into the DCMG, the proposed control scheme with constant voltage regulation capability stably holds $V_{dc}$ at the nominal value and effectively maintains power-sharing within the DCMG system.

**C. GRID-CONNECTED MODE WITH DG POWER VARIATION**

Fig. 14 shows the experimental results of the proposed adaptive droop control when the DCMG system is in the grid-connected mode under variations of the DG power. In this case, the electricity price is in low condition and the UG unit maintains the power balance and regulation of $V_{dc}$ at all times. Initially, the DCMG system starts in grid-connected mode with wind power less than the load demand. In order to support power deficit to the load, the UG supports additional power into the DCMG by operating in the CON mode. Furthermore, the EV and battery units operate in the IDLE mode, which indicates that the battery and EV SOC levels are in the maximum. However, as the wind power increases and exceeds the load demand instantly, it causes surplus power within the DCMG. As a result, the operating mode of the UG unit changes from CON to INV mode, and it then absorbs the surplus power from the DCMG into the UG. Despite the variation of the DG power within the DCMG in the grid-connected mode, the proposed power management scheme effectively determines the operating mode of each power unit to achieve a power balance properly.

**D. TRANSITION BETWEEN GRID-CONNECTED MODE AND ISLANDED MODE**

Fig. 15 shows the experimental results of the proposed adaptive droop control when the DCMG system is in a transition from the grid-connected mode to the islanded mode. Initially, the DCMG system is in grid-connected mode, the battery unit is in the IDLE mode, and the wind turbine unit is in the MPPT mode, with $P^\text{S,max}_W$ more than meeting the supply to $P_L$ and $P^\text{C,max}_{EV}$ for EV in EDCM. As a result, the surplus power in the
DCMG system is absorbed by the UG unit, which operates in INV mode.

When a UG fault occurs, $V_{dc}$ immediately increases because the DCMG system has surplus power. After $V_{dc}$ reaches its peak value, the wind turbine unit triggers VDCM operation to maintain $V_{dc}$ in the DCMG system, which causes $V_{dc}$ slowly to decrease until it is constant in $V_{dc}^{nom}$. Despite the fact that $V_{dc}$ increases significantly during the transition, the $V_{dc}$ interval is acceptable, and the system still can maintain power-sharing within the DCMG system, which confirms the effectiveness of the proposed control method.

### E. Grid-Connected Mode with Electricity Price Condition Change

Fig. 16 shows the experimental results of the proposed control method during a transition from the grid-connected mode to the islanded mode operation. In this simulation, it is assumed that the EV SOC level is very short time because the sum of $P_{dc}, UG$ and $P_{dc}, EV$ in Fig. 3. Although the DC bus voltage $V_{dc}$ temporarily fluctuates due to sudden UG electricity price conditions, the proposed control scheme can effectively regulate $V_{dc}$ to its nominal value and optimize the power management according to the electricity price condition and EV SOC level.

![FIGURE 15. Experimental results during a transition from the grid-connected mode to the islanded mode operation.](image1)

![FIGURE 16. Experimental results in the grid-connected mode with electricity price condition change.](image2)

**VI. CONCLUSION**

To ensure an effective power and voltage management of a decentralized DCMG system with multiple power sources, such as a UG, a DG, an ESS, and an EV, this paper has presented an adaptive droop control scheme with constant voltage regulation. In the proposed scheme, the droop characteristics for the UG, ESS, and EV are adaptively changed according to electricity price conditions and SOC levels in order to optimize the DCMG operation flexibility as well as electricity cost. The proposed control scheme is mainly achieved by combining droop control as a primary control method and secondary control. Secondary control is used to regulate effectively the DC bus voltage to its nominal value while droop control serves to maintain power-sharing and the power balance within the DCMG system without any DCL. Additionally, power management is presented in this study to guarantee power-sharing to enhance the reliability of the DCMG system in the presence of uncertainties such as UG availability, EV and ESS SOC levels, variations of the DG power, load demand, and electricity price conditions. The proposed power management for a decentralized DCMG system has been validated by both simulations based on PSIM software and experiments based on a laboratory DCMG testbed. Comprehensive simulation and experimental results under various test conditions demonstrate the effectiveness and usefulness of the proposed control method. In addition to constant DC bus voltage regulation, the proposed adaptive droop control scheme significantly enhances the flexibility of the DCMG system.
REFERENCES

[1] C. W. Geiling, M. Samotyj, and B. Howe, “The future’s power delivery system,” IEEE Power Energy Mag., vol. 2, no. 5, pp. 40–48, Oct. 2004.

[2] P. C. Loh, D. Y. K. Chai, and F. Blaabjerg, “Autonomous operation of hybrid microgrid with AC and DC subgrids,” IEEE Trans. Power Electron., vol. 28, no. 5, pp. 2214–2223, May 2013.

[3] B. Zakeri, G. C. Gissey, P. E. Dodds, and D. Subbhanakulova, “Centralized vs. distributed energy storage—Benefits for residential users,” Energy, vol. 237, pp. 118–127, 2014.

[4] J. Ospina, N. Gupta, A. Newaz, M. Harper, M. O. Faruque, E. G. Collins, R. Meeker, and G. Lofman, “Sampling-based model predictive control of PV-integrated energy storage system considering power generation forecast and real-time price,” IEEE Power Energy Technol. Syst. J., vol. 6, no. 4, pp. 195–207, Dec. 2019.

[5] J. Wang, W. Wang, H. Wang, and H. Zuo, “Dynamic reconfiguration of multi-objective distribution networks considering DG and EVs based on a novel LDBAS algorithm.” IEEE Access, vol. 8, pp. 216873–216893, 2020.

[6] M. F. Zia, E. Elbouchikhi, and M. Benbenzid, “Microgrids energy management systems: A critical review on methods, solutions, and prospects,” Appl. Energy, vol. 222, pp. 1033–1055, Jul. 2018.

[7] M. Farrokhhabadi et al., “Microgrid stability definitions, analysis, and examples,” IEEE Trans. Power Syst., vol. 35, no. 1, pp. 13–29, Jan. 2020.

[8] M. A. Mahmud, T. K. Roy, S. Saha, M. E. Haque, and H. R. Pota, “Resilience-oriented multistage scheduling for power grids considering nonanticipativity under tropical cyclones,” IEEE Trans. Power Syst., early access, Aug. 31, 2022, doi: 10.1109/TPWRS.2022.3203066.

[9] H. Qiu, W. Gu, W. Sheng, L. Wang, Q. Sun, and Z. Wu, “Resilience-oriented multistage scheduling for power grids considering nonanticipativity under tropical cyclones,” IEEE Trans. Power Syst., vol. 31, no. 10, pp. 7369–7383, Oct. 2016.

[10] M. Chen, X. Xiao, and J. M. Guerrero, “Secondary restoration control of islanded microgrids with a decentralized event-triggered strategy,” IEEE Trans. Ind. Informat., vol. 14, no. 9, pp. 3870–3880, Sep. 2018.

[11] D. Li, Y. K. Chai, and F. Blaabjerg, “Autonomous operation of DC microgrids,” IEEE Trans. Ind. Appl., vol. 29, no. 4, pp. 793–801, Dec. 2014.

[12] M. A. Mahmud, T. K. Roy, S. Saha, M. E. Haque, and H. R. Pota, “Robust nonlinear adaptive feedback linearizing decentralized controller design for islanded microgrids,” IEEE Trans. Ind. Appl., vol. 55, no. 5, pp. 5343–5352, Sep. 2019.

[13] A. Khorsandi, M. Ashourloo, and H. Mokhtari, “A decentralized control method for a low-voltage DC microgrid,” IEEE Trans. Energy Convers., vol. 29, no. 4, pp. 793–801, Dec. 2014.

[14] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. de Vicuna, and M. Castilla, “Hierarchical control of droop-controlled AC and DC microgrids—A general approach toward standardization,” IEEE Trans. Ind. Electron., vol. 58, no. 1, pp. 158–172, Jan. 2011.

[15] A. Azizi, S. Peyghami, H. Mokhtari, and F. Blaabjerg, “Autonomous and decentralized load sharing and energy management approach for DC microgrids,” Electr. Power Syst. Res., vol. 177, Dec. 2019, Art. no. 106009.

[16] A. F. Habibullah, F. A. Padhilah, and K.-H. Kim, “Decentralized control of DC microgrid based on droop and voltage controls with electricity price consideration,” Sustainability, vol. 13, no. 20, p. 11398, Oct. 2021.

[17] E. Mojica-Nava, J. M. Rey, J. Torres-Martinez, and M. Castilla, “Decentralized switched current control for DC microgrids,” IEEE Trans. Ind. Electron., vol. 66, no. 2, pp. 1182–1191, May 2019.

[18] I. U. Nutkani, P. C. Loh, P. Wang, and F. Blaabjerg, “Decentralized economic dispatch scheme with online power reserve for microgrids,” IEEE Trans. Smart Grid, vol. 8, no. 1, pp. 139–148, Jan. 2017.

[19] F. Gao, S. Bozhko, G. Asher, P. Wheeler, and C. Patel, “An improved voltage compensation approach in a droop-controlled DC power system for the more electric aircraft,” IEEE Trans. Power Electron., vol. 31, no. 10, pp. 7369–7383, Oct. 2016.

[20] M. Chen, X. Xiao, and J. M. Guerrero, “Secondary restoration control of islanded microgrids with a decentralized event-triggered strategy,” IEEE Trans. Ind. Informat., vol. 14, no. 9, pp. 3870–3880, Sep. 2018.

[21] H. Qiu, W. Gu, W. Sheng, L. Wang, Q. Sun, and Z. Wu, “Resilience-oriented multistage scheduling for power grids considering nonanticipativity under tropical cyclones,” IEEE Trans. Power Syst., early access, Aug. 31, 2022, doi: 10.1109/TPWRS.2022.3203066.

[22] X. Hu, F. Feng, K. Liu, L. Zhang, J. Xie, and B. Liu, “State estimation for advanced battery management: Key challenges and future trends,” Renew. Sustain. Energy Rev., vol. 114, Oct. 2019, Art. no. 109334.

[23] A. Al Faris Habibullah, K.-H. Kim, “Hierarchical control for multiple DC-microgrids clusters,” IEEE Trans. Energy Convers., vol. 29, no. 4, pp. 922–933, Dec. 2014.