A novel bilayer coordinated control scheme for global autonomous economic operation of islanded hybrid AC/DC microgrids

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Abstract
This paper proposes a novel distributed bilayer coordinated control scheme (BCCS) to realize the autonomous economic operation of islanded hybrid AC/DC microgrids, which only requires a sparse communication link. In the lower layer, the optimal power reference iterative algorithm (OPRIA)-based droop control is proposed to realize the economic dispatch of each subgrid individually, while the frequency of AC subgrid and the bus voltage of DC subgrid are regulated to their rated values. Then, the upper-layer control for the interlinking converter is designed to achieve the global economic operation of the hybrid AC/DC microgrid through optimizing the exchanging power between AC and DC subgrids. The proposed BCCS has the advantage of reaching the economic operation and frequency/voltage regulation simultaneously for the hybrid AC/DC microgrid. Besides, the proposed BCCS realizes the stable and economic operation with less communication, flexible controllability, and good compatibility of renewable energy sources. Numerical simulation results based on Matlab/Simulink verify the effectiveness and excellent performance of the proposed BCCS even with the integration of renewable energy sources, and the test based on RT-LAB illustrates the good real-time performance of the proposed control scheme.

1 | INTRODUCTION

Hybrid AC/DC microgrids are considered as an effective solution for the flexible and reliable integration of various distributed generations (DGs) and AC/DC loads with minimum conversion stages [1]. Conventionally, the AC microgrids are the research mainstream for the advantage of the convenient connection with the utility grid [2]. However, with the increasing penetration of DC sources and loads, such as solar photovoltaic (PV), LED lighting, electrical vehicles, DC microgrids are gaining more and more attention recently [3]. To manage various distributed energy resources in a more efficient and flexible manner, the concept of hybrid AC/DC microgrids is proposed and explored [4].

Compared with the conventional independent AC and DC microgrids, hybrid AC/DC microgrids have the advantages of both AC and DC microgrids. As there exist numerous AC and DC DGs with different cost characteristics in the hybrid AC/DC microgrid, it is necessary to improve the economic efficiency of the hybrid AC/DC microgrid by proposing proper control schemes [5, 6].

Generally, to realize economic dispatch of islanded microgrids, centralized control schemes are commonly utilized to dispatch the output power of each DG economically. For centralized control schemes, the microgrid central controller is required to collect global information of the islanded microgrid, and then solve the optimal output power references for each DG to minimize the total generation cost (TGC) through various optimization algorithms, such as the lambda iteration [7], Lagrangian relaxation approach [8], mixed-integer programming [9], particle swarm optimization [10], memory-based genetic algorithm [11], and so on. Centralized controls necessitate global information and fast communication, which will lead to the increasing heavy communication and computation burdens with the growing scale of islanded microgrids, and is easy to suffer from a single point of failure [12].

Thus, to realize no-communication economic operation control, decentralized control schemes are investigated to resolve
the economic dispatch problem of the islanded microgrid. In [13] and [14], Nutkani et al. propose modified droop schemes to reduce generation cost by producing more power of the least costly DGs. Based on the full generation cost characteristics of DGs, two cost-prioritized droop schemes are proposed in [15] to reduce TGC of the microgrid, in which costlier DGs will operate only at higher load and can be turned OFF when the load is light. Besides, a more comprehensive economic dispatch decentralized scheme, considering DG generation costs, power ratings, and other constraints, is introduced in [16]. Later, utilizing linear droop functions, Ref. [17] presents two linear decentralized power sharing schemes to reduce the TGC of the microgrid in an easier way. However, the mentioned decentralized control methods in [13–17] are incapable of keeping the TGC remaining a minimum. To address this issue, a novel alternative cost-based droop scheme is proposed in [18] by embedding incremental costs (ICs) into the conventional droop. Even though these decentralized methods for economic dispatch of an islanded microgrid are independent of communication, the control accuracy is compromised.

Recently, with the development and application of advanced communication technology in engineering, the distributed control approaches (see [19–23] and references therein) are extensively explored to reduce communication burden and improve the control accuracy. The existing distributed methods can be classified as the consensus-based control scheme [19], multi-agent-based distributed control method [20], alternating direction method of multipliers (ADMM)-based algorithm [21], distributed event-triggered strategy [22], privacy-preserving distributed control scheme [23] and so forth. In summary, distributed controls require a sparse communication link to release the heavy communication burden compared with centralized methods, and improve the control accuracy than decentralized controls. This leads to the design and implementation of the distributed control more suitable for realizing the economic dispatch of islanded microgrids.

It is worth mentioning that the above existing economic dispatch control schemes in [7–23] are mainly conducted on independent AC and DC microgrids, which does not involve the optimal power exchanging control issues between AC and DC subgrids of the hybrid AC/DC microgrid. The economic power control between subgrids is an essential problem for realizing the economic operation of the islanded hybrid AC/DC microgrid. The economic power control between subgrids is an essential problem for realizing the economic operation of the islanded hybrid AC/DC microgrid. However, in general, the conventional controls of the interlinking converter (ILC) mainly focus on the power balance and frequency/voltage stability, in which the economic efficiency in power exchanging is not considered [24, 25].

Therefore, to realize the global autonomous economic operation of the islanded hybrid AC/DC microgrid, some recent researches containing the optimal power control of ILC are reported in [26–29]. Specifically, Ref. [26] proposes a fully decentralized economic power sharing control scheme for hybrid AC/DC microgrids, in which the global information of all DGs is required and the frequency and voltage are selected as the global state indicators in AC and DC subgrids, respectively. In [27], a decentralized economic dispatch control is proposed to realize the DG economic dispatch and minimize the TGC, which is analysed and categorized into various modes based on the load conditions. However, for the hybrid AC/DC microgrid, decentralized economic dispatch control schemes only require local information, which makes the control schemes more complicated for the optimal power control of ILC based on the limited information compared with distributed controls. In addition, the mentioned works in [26, 27] does not involve the frequency/voltage regulation. In [28], the authors propose a two-level hierarchical optimization control scheme for the islanded hybrid AC/DC microgrid, in which a centralized ILC coordination is embedded to regulate the power interaction between AC and DC subgrids in the upper-layer. However, the proposed method in [28] requires droop parameters and cost function coefficients of all DGs in advance for the control parameters setting of the lower-layer control scheme. Besides, to realize the economic operation of the islanded hybrid AC/DC microgrid in a distributed manner, Ref. [29] proposed a distributed architecture consisting of the IC-based droop control scheme and the proposed distributed control canonical form, unfortunately, in which the performance of the proposed control scheme in [29] with the stochastic output of renewable energy sources (RESs) is not introduced.

Motivated by the existing works, this paper proposes a novel bilayer coordinated control scheme (BCCS) for the global autonomous economic operation of islanded hybrid AC/DC microgrids, which is implemented in a fully distributed manner. In the proposed BCCS, the lower-layer control is utilized to realize the local economic dispatch in the AC and DC subgrids individually, and the global economic operation of the hybrid AC/DC microgrid is further achieved by the upper-layer control through optimizing the power exchanging between the AC and DC subgrids. The comparison of the proposed control scheme with the existing control methods is shown in Table 1, and the contributions of this paper can be summarized as follows.

1. The proposed BCCS, consisting of the optimal power reference iterative algorithm (OPRIA)-based droop control in the lower layer and optimal ILC control in the upper layer, is implemented in a fully distributed manner, in which the communication and computation burdens are reduced by sharing among local DG controllers.
2. The proposed OPRIA-based \( f-P/U-P \) droop control schemes with the designed frequency/voltage secondary controls can ensure the stable and economic operation of the hybrid microgrid, while the frequency/voltage regulation is not considered in [26] and [27]. Besides, the proposed BCCS can realize the economic operation of both individual AC and DC subgrids and the global hybrid AC/DC microgrid by properly turning off/on the upper-layer control. Further, the upper-layer control for ILC is simpler and easier to be implemented compared with [28] and [29].
3. The proposed BCCS has a good performance for realizing economic operation with the integration of RESs and can realize the maximum utilization of renewable energy sources for the hybrid AC/DC microgrid, which is verified by the simulation results.
TABLE 1 Comparison of control schemes

| Control scheme | Economic dispatch control for DGs within AC and DC subgrids | ILC control scheme | Economic dispatch for AC subgrid | Economic dispatch for DC subgrid |
|----------------|-------------------------------------------------------------|--------------------|----------------------------------|----------------------------------|
|                | Require global information of all DGs                      | Require communication | Require leader DG                | Require leader DG                |
|                | ×                              | × × × × × ×          | ×                               | ×                               |
|                | ×                              | × × × × × ×          | ×                               | ×                               |
|                | ×                              | × × × × × ×          | ×                               | ×                               |
|                | ×                              | × × × × × ×          | ×                               | ×                               |
|                | ×                              | × × × × × ×          | ×                               | ×                               |
|                | ×                              | × × × × × ×          | ×                               | ×                               |

FIGURE 1 Typical topology of the hybrid AC/DC microgrid

The rest of this paper is organized as follows. In Section 2, some preliminaries about the studied hybrid AC/DC microgrid and economic dispatch issues are presented. Sections 3 and 4 introduce the specific lower-layer and upper-layer control schemes, respectively. Some case studies are discussed in Section 5 and Section 6 concludes this paper.

2 | PRELIMINARIES

2.1 | System configuration

The configuration of a typical hybrid AC/DC microgrid is shown in Figure 1. As can be seen, various RESs, DGs, energy storages (ESs), and loads are gathered to the common AC and DC buses, respectively. The AC subgrid and DC subgrid are connected by one ILC for power exchange between AC and DC subgrids, and the hybrid AC/DC microgrid can be connected to the utility grid through the point of common coupling (PCC) in the AC subgrid. Each DG is connected to the common AC bus through a voltage source inverter in the AC subgrid, while DGs in the DC subgrid are connected to the common DC bus via DC/DC converters. RESs, such as wind turbines (WTs) and PV panels, are operated in maximum power point tracking modes to fully utilize renewable energy. Various DGs with different cost characteristics will inherently induce generation cost, which naturally constitutes the operation cost of the islanded hybrid AC/DC microgrid.

2.2 | Economic dispatch problem in an islanded hybrid AC/DC microgrid

The economic dispatch problem in an islanded hybrid AC/DC microgrid is solved to optimize the operation cost generated
by active power while the operational constraints are satisfied. Accordingly, the economic dispatch model can be formulated as below:

$$\min \sum_{i=1}^{N_a} C_i(P_{ac,i}) + \sum_{j=1}^{N_d} C_j(P_{dc,j})$$

(1)

with the following two operational constraints:

1. supply-demand balance constraint

$$\sum_{i=1}^{N_a} P_{ac,i} + \sum_{j=1}^{N_d} P_{dc,j} = P_{ac}^{\text{ref}} + P_{dc}^{\text{ref}} = P_{g}$$

(2)

2. DG capacity constraint

$$P_{ac,i}^{\text{min}} \leq P_{ac,i} \leq P_{ac,i}^{\text{max}}$$

(3)

$$P_{dc,j}^{\text{min}} \leq P_{dc,j} \leq P_{dc,j}^{\text{max}}$$

(4)

where $C_i(P_i) = \alpha_i P_i^2 + \beta_i P_i + \gamma_i$ is the cost function of DG $i$. $\alpha_i, \beta_i, \gamma_i$ are the coefficients of the cost function of DG $i$.

To solve (1) in a viable way, the economic dispatch problem in an islanded hybrid AC/DC microgrid can be addressed as two subproblems in AC and DC subgrids with a coupling of optimal power exchange between AC and DC subgrids [28]. The equivalent economic dispatch model of (1) is shown as follows:

$$\min \sum_{i=1}^{N_a} C_i(P_{ac,i})$$

s.t. $\sum_{i=1}^{N_a} P_{ac,i}^{\text{ref}} = P_{ac}^{\text{ref}} - P_{dc}^{\text{ref}}$  

$$P_{ac,i}^{\text{min}} \leq P_{ac,i} \leq P_{ac,i}^{\text{max}}$$

(5)

and

$$\min \sum_{j=1}^{N_d} C_j(P_{dc,j})$$

s.t. $\sum_{j=1}^{N_d} P_{dc,j}^{\text{ref}} = P_{dc}^{\text{ref}} - P_{ac}^{\text{ref}}$  

$$P_{dc,j}^{\text{min}} \leq P_{dc,j} \leq P_{dc,j}^{\text{max}}$$

(6)

Accordingly, the economic dispatch problem in an islanded hybrid AC/DC microgrid can be solved by two stages. The first stage is utilized to minimize the operation cost for AC and DC subgrids, corresponding to the proposed lower-layer control scheme in Section 3. The second stage aims to realize the optimal power exchanging between AC and DC subgrids for the purpose of realizing the economic operation of the global hybrid AC/DC microgrid, corresponding to the proposed upper-layer control scheme in Section 4.

### 2.3 Equal incremental cost criterion

The equal incremental cost criterion (EICC) is renowned that the operation cost of a power system can be minimized when the incremental costs of all DGs in the power system are equal [18]. The EICC can be described as

$$IC_i = \frac{\delta C_i(P)}{\delta P_i} = \lambda^*$$

for $P_i^{\text{min}} \leq P_i \leq P_i^{\text{max}}$  

(7)

where $\lambda^*$ is the optimal incremental cost.

It is worth noting that once the output power of DG $i$ reaches the lower capacity limit, the $P_i$ will remain at the bound value, and the generated power by the rest DGs continue to be dispatched according to the EICC. In detail, when DG $i$ reaches the lower capacity limit, that is $P_i = P_i^{\text{min}}$, there has $IC_i = \frac{\delta C_i(P)_{\text{opt}}}{\delta P_i} \geq \lambda^*$; when DG $i$ reaches the upper capacity limit, that is $P_i = P_i^{\text{max}}$, there exists $IC_i = \frac{\delta C_i(P)_{\text{opt}}}{\delta P_i} \leq \lambda^*$.

### 3 LOWER-LAYER CONTROL SCHEME: OPTIMAL POWER SHARING FOR THE AC AND DC SUBGRIDS

The lower-layer control, consisting of the proposed OPRIA-based droop and the designed secondary control, is proposed to realize economic and stable operation of the islanded AC and DC subgrids. First, the optimal power reference iterative algorithm is proposed, based on which the OPRIA-based droop control is further given. Then, to ensure the stable and economic operation can be achieved simultaneously, the secondary control for OPRIA-based droop is designed and introduced. Finally, the effectiveness of the proposed lower-layer control schemes in AC and DC subgrids are demonstrated theoretically.

### 3.1 Optimal power reference iterative algorithm

#### 3.1.1 Graph theory

For a directed communication topology of a given islanded microgrid with $N$ DGs, the directed graph $G = (V, E)$ is modelled, where $V = \{1, 2, \ldots, N\}$ is the node set consisting of nodes and $E \subseteq V \times V$ is a set of ordered pairs of different nodes called edges. The set $N_i = \{j \in V \mid (i, j) \in E\}$ is the set of neighbours of the $i$th node. The adjacency matrix $A = [a_{ij}] \in \mathbb{R}^{N \times N}$ consists of elements $a_{ij} = 1$ if $j \in N_i$, otherwise, $a_{ij} = 0$. This shows that if node $j$ belongs to the neighbours of the node $i$, then node $i$ can acquire information from node $j$. The degree matrix $D = \text{diag}\{d_i\} \in \mathbb{R}^{N \times N}$ is a diagonal matrix and has elements $d_i = \sum a_{ij}$ if $j \in N_i$. Then, the Laplacian matrix of the directed graph $G$ can be defined as $L = D - A$. 

3.1.2 Proposed distributed optimal power reference iterative algorithm

When all DGs are within capacity limits, the optimal output power of DG \( i \) can be solved as (8) by the Lagrange function [30].

\[
p_i^* = P_{sg} + \frac{\sum_{j=1}^{n} \beta_j}{2\alpha_i} - \frac{\beta_i}{2\alpha_i}
\]

where \( P_i^* \) is the optimal output power of DG \( i \).

To reflect the power supply capability of DG \( i \) in economic operation mode, the factor \( \eta_i \) is defined as follows.

\[
\eta_i = \frac{P_i^*}{P_i^N}
\]

where \( P_i^N \) is the nominal capacity of the \( i \)th DG.

From Equation (9), it can be concluded that different DGs correspond to different power supply capability \( \eta_i \), and the smaller of \( \eta_i \), the stronger power supply capability of DG \( i \). Moreover, the DG with the strongest power supply capability will be selected as the leader DG.

If DGs are numbered by their power supply capability in economic operation mode, that is

\[
\eta_1 \leq \eta_2 \leq \cdots \leq \eta_n
\]

Then, the optimal power reference iterative algorithm can be designed as

\[
\mathbf{P}_i^{op} = (2\mathbf{a})^{-1}(2\mathbf{A} \mathbf{P} - \mathbf{L} \mathbf{1}_n)
\]

where \( \mathbf{a} = \text{diag}\{\alpha_1, \alpha_2, \ldots, \alpha_n\}, \mathbf{b} = \text{diag}\{\beta_1, \beta_2, \ldots, \beta_n\}, \mathbf{P} = [P_1, P_2, \ldots, P_n]^T, \mathbf{P}_i^{op} = [P_1^{op}, P_2^{op}, \ldots, P_n^{op}]^T, \mathbf{1}_n \) is an \( n \times 1 \) column matrix with all elements of 1. \( \mathbf{A} \) and \( \mathbf{L} \) are the adjacency matrix and the Laplacian matrix of the communication topology shown in Figure 2, respectively.

Figure 2 shows the principle of OPRIA including both transmitting information and communication topology, and Figure 3 displays the flow chart of the proposed OPRIA. As can be seen, each DG only requires the information of its neighbour's output power, and sends its own output power information to its follower neighbour node through the communication link. It is obvious for the OPRIA that when the entire system reaches the steady state, there exists \( P_i^{op} = P_i \) as \( i \to \infty \), for \( i = 1, 2, \ldots \),
improved \( f^P \) droop control based on OPRIA is designed as

\[
f_i = f^* - m_{ac,i}(P_{ac,i} - P_{ac,i}^p) \tag{16}
\]

where \( P_{ac,i}^p \) is the optimal power reference for the \( i \)th AC DG and solved by (11).

Under the control scheme in (16), it can be obtained that if \( f_i \to f^* \) as \( t \to \infty \), there must exist \( P_{ac,i} \to P_{ac,i}^p \) as \( t \to \infty \). According to (13), it can be further concluded that ICs are the same for all DGs in the AC microgrids and the economic dispatch is achieved. However, it is renowned that droop control cannot realize the accurate power dispatch, and will generate the frequency/voltage deviations inevitably. Therefore, for droop-based schemes, the secondary control is commonly utilized to regulate the frequency/voltage to the nominal values and improve the operation stability of the microgrid. Form (16), it can be known that, to ensure \( f_i \to f^* \) and \( P_{ac,i} \to P_{ac,i}^p \) as \( t \to \infty \) being achieved simultaneously, the compensated value of secondary control of DG \( i \) should be zero in steady state. Therefore, to achieve this goal, the secondary control (SC) for OPRIA-based \( f^P \) droop control is proposed as follows

\[
\begin{align*}
\Delta f_i &= k_{p,i} e_i + k_{u,i} \int e_i \, dt \\
e_i &= g_i (\Delta f_i - \Delta f^\ast) + p_i (f^* - f_i)
\end{align*} \tag{17}
\]

where \( j \in N_i \) is the neighbour of the \( i \)th node. \( k_{p,i} \) and \( k_{u,i} \) are the proportional and integral gains of PI controller of secondary control, respectively. \( g_i, p_i \) are the proportional gains of the secondary control.

Figure 4 shows the control scheme of the proposed OPRIA-based \( f^P \) droop control and secondary control for AC subgrid. It can be seen that OPRIA-based \( f^P \) droop control realizes the optimal power sharing by updating the power reference values solved by the OPRIA. Moreover, the proposed secondary control in (17) is utilized to eliminate the frequency deviations and ensure the output power of the \( i \)th DG to stabilize at the optimal power value of \( P_{ac,i}^p \).

To verify the effectiveness of the proposed OPRIA-based \( f^P \) droop control integrated with the secondary control for economic dispatch in the islanded AC subgrid, the following deduction are conducted.

Combining frequency compensating value of (17) with (16), the OPRIA-based \( f^P \) droop control is rewritten as

\[
f_i = f^* - m_{ac,i}(P_{ac,i} - P_{ac,i}^p) + \Delta f_i \tag{18}
\]

which can be written in the compact form as follows.

\[
f = f^* - M(P_{ac} - P_{ac}^p) + \mathbf{F} \tag{19}
\]

where \( f = [f_1, f_2, \ldots, f_n]^T \), \( f^* = f^* \mathbf{1}_n \), \( M = \text{diag} \{m_{ac,1}, m_{ac,2}, \ldots, m_{ac,n}\} \), \( P_{ac}^p = [P_{ac,1}^p, P_{ac,2}^p, \ldots, P_{ac,n}^p]^T \), \( P_{ac} = [P_{ac,1}, P_{ac,2}, \ldots, P_{ac,n}]^T \), and \( \mathbf{F} = [\Delta f_1, \Delta f_2, \ldots, \Delta f_n]^T \).

According to (11) and (19), the following equation is obtained.

\[
f = f^* - M(P_{ac} - P_{ac}^p) + 2\alpha \mathbf{1}_n - (2\alpha \mathbf{1}_n)^T \mathbf{L} \left( \mathbf{F}^T \mathbf{F} \right)
\]

which can be further simplified as

\[
L(2\alpha P_{ac} + \mathbf{1}_n) = 2\alpha \cdot M^{-1}(f^* - f + \mathbf{F}) \tag{20}
\]

Since \( IC_{ac,i} = 2\alpha P_{ac,i}^p + \beta_{ac,i} \), (21) can be expanded as

\[
\begin{align*}
IC_{ac,1} - IC_{ac,2} &= 2\alpha_m \left( f^* - f_1 + \Delta f_1 \right) \\
IC_{ac,2} - IC_{ac,1} &= 2\alpha_m \left( f^* - f_2 + \Delta f_2 \right) \\
IC_{ac,3} - IC_{ac,2} &= 2\alpha_m \left( f^* - f_3 + \Delta f_3 \right) \\
&\quad \vdots \\
IC_{ac,n} - IC_{ac,n-1} &= 2\alpha_m \left( f^* - f_n + \Delta f_n \right)
\end{align*} \tag{22}
\]

Under the secondary control described in (17), there exists \( f_i \to f^* \) for \( i = 1, 2, \ldots, n \) in steady state, that is \( |f_i-f^*| \to 0 \) as \( t \to \infty \). Therefore, the following equation can be obtained by (22) in steady state.

\[
IC_{ac,i} - IC_{ac,j} = \xi_i \Delta f_i \text{ for } i \in V_{ac} \land j \in N_i \tag{23}
\]

where \( \xi_i = 2\alpha_m / m_{ac,i} \) and \( V_{ac} = \{1, 2, \ldots, n\} \).

According to (23), we have \( IC_{ac,1} - IC_{ac,2} = \xi_1 \Delta f_1 \) and \( IC_{ac,2} - IC_{ac,1} = \xi_2 \Delta f_2 \), as \( t \to \infty \). By (17), it can be obtained that \( \Delta f_i = \Delta f_2 = \cdots = \Delta f_n \) in steady state. Therefore, in steady state, there exists \( \Delta f_i \to \Delta f_2 \) and \( \xi_i, \xi_2 > 0 \). Hence, based on the above discussion, it can be further concluded that \( |\Delta f_i| \to 0 \) as \( t \to \infty \) for all \( i \in V_{ac} \). This means that the islanded AC subgrid controlled by the proposed control scheme in (18) can achieve regulating the frequency to its nominal value and realizing the accurate power dispatch of DG \( i \) to its optimal power reference value of \( P_{ac,i}^p \). Combining with (11)-(13), the conclusion can be
further obtained that the proposed control scheme in (18) is able to realize economic operation for the AC subgrid and restore the frequency to the rated value at the same time.

3.3 Distributed OPRIA-based droop control and secondary control in DC subgrid

For an islanded DC microgrid, the traditional U-P droop control can be given as follows

$$U_i = U^* - n_{dc,i}(P_{dc,i} - P_{dc,i}^p)$$

(24)

where \( n_{dc,i} \) is the U-P droop coefficient for the \( i \)th DC DG.

Similar to the proposed OPRIA-based \( p-P \) droop for the AC subgrid, the proposed control scheme for the islanded DC subgrid is described as (25), which includes the OPRIA-based U-P droop control and the designed secondary control.

$$U_i = U^* - n_{dc,i}(P_{dc,i} - P_{dc,i}^p) + \Delta U_i$$

(25)

where \( P_{dc,i}^p \) is the optimal power reference generated by (11) for the \( i \)th DC DG. \( \Delta U_i = k_p(e_{dc,i}) + k_i \int (e_{dc,i})dt. \) Besides, \( e_{dc,i} = \frac{1}{\epsilon} (U_i - \epsilon U_i^*) \).

Figure 5 displays the diagram of the proposed lower-layer control scheme for the DC subgrid. Similar to the case in the AC subgrid, it can be known from Figure 5 that, for the DC subgrid, the OPRIA is utilized to update the optimal power reference automatically based on the transmitted neighbours’ output power information, while the designed secondary control is responsible for eliminating voltage deviations and ensuring the accurate power dispatch to be the same with the optimal power reference value generated by the OPRIA.

The effectiveness of the proposed control scheme for the islanded DC subgrid in (25) is demonstrated theoretically in the following context.

The equation of (25) can be written in matrix form as

$$U = U^* - N(P_{dc} - P_{dc}^p) + \Phi$$

(26)

where \( U = [U_1, U_2, \ldots, U_m]^T \), \( U^* = U^* 1_m, N = \text{diag}(n_{dc,1}, n_{dc,2}, \ldots, n_{dc,m}) \), \( P_{dc}^p = [P_{dc,1}^p, P_{dc,2}^p, \ldots, P_{dc,m}^p]^T \), \( P_{dc} = [P_{dc,1}, P_{dc,2}, \ldots, P_{dc,m}]^T \), and \( \Phi = [\Delta U_1, \Delta U_2, \ldots, \Delta U_m]^T. 1_m \) is an \( m \times 1 \) column matrix with all elements of 1.

Submitting \( P_{dc}^p = (2\alpha)^{-1}(2\alpha P_{dc} - I_1 1_m) \) into (26) yields

$$L(2\alpha P_{dc} + \beta 1_m) = 2\alpha \cdot M^{-1}(U^* - U + \Phi)$$

(27)

which can be transformed as

$$IC_{dc,1} - IC_{dc,2} = \frac{2\alpha_1}{n_{dc,1}}(U^* - U_1 + \Delta U_1)$$

$$IC_{dc,2} - IC_{dc,1} = \frac{2\alpha_2}{n_{dc,2}}(U^* - U_2 + \Delta U_2)$$

$$IC_{dc,3} - IC_{dc,2} = \frac{2\alpha_3}{n_{dc,3}}(U^* - U_3 + \Delta U_3)$$

$$\ldots$$

$$IC_{dc,\text{m}} - IC_{dc,\text{m-1}} = \frac{2\alpha_m}{n_{dc,m}}(U^* - U_m + \Delta U_m)$$

(28)

where \( IC_{dc,i} = 2\alpha_i P_{dc,i} + \beta_i \) and the following equation can be further obtained as

$$IC_{dc,i} - IC_{dc,j} = \xi_i(U^* - U_i + \Delta U_i)$$

(29)

for \( i \in V_{dc} \) and \( j \in N_i \).

Due to the PI function of secondary control, the voltage can be regulated the nominal value in steady state, that is \( |U_i - U_i^*| \rightarrow 0 \) as \( t \rightarrow \infty \). Combined with (29), it can be obtained that \( IC_{dc,i} \rightarrow IC_{dc,j} \rightarrow \xi \Delta U_i \) as \( t \rightarrow \infty \), for \( i \in V_{dc} \) and \( j \in N_i \). Besides, under the control of proposed secondary control, there is \( \Delta U_1 = \Delta U_2 = \ldots = \Delta U_m \). Moreover, there exists \( \xi > 0 \). Therefore, according to \( IC_{dc,i} - IC_{dc,j} \rightarrow \xi \Delta U_i \), it can be concluded that \( \Delta U_i \rightarrow 0 \) as \( t \rightarrow \infty \), for \( i \in V_{dc} \). Hence, the conclusion is drawn that the proposed control scheme in (25) can restore the voltage to its rated value while guaranteeing accurate power sharing according to the power reference generated by the OPRIA. This means that the proposed control scheme in (25) is able to ensure the stable and economic operation for the islanded DC subgrid simultaneously.

4 UPPER-LAYER CONTROL SCHEME: OPTIMAL POWER EXCHANGING CONTROL FOR ILC

In a given hybrid AC/DC microgrid, the exchanging power between AC and DC subgrids is coordinated via ILC. The exchanging power plays an important role in keeping the frequency and voltage stabilizing in acceptable ranges for AC and
DC subgrids, respectively, as well as reaching the global economic dispatch for the hybrid AC/DC microgrid.

For the AC and DC subgrids in a hybrid microgrid, the frequency and voltage fluctuating situations imply the loading condition changes, respectively. Hence, the ILC is commonly controlled based on the AC frequency and DC voltage to regulate the power exchange autonomously [21]. However, due to the function of the proposed secondary control in the lower-layer control scheme, the AC frequency and DC voltage will be stabilized at their rated values strictly. As a result, under the proposed lower-layer control scheme, the loading conditions of AC and DC subgrids cannot be reflected by frequency and voltage fluctuations. Since that lower-layer control scheme is responsible for AC frequency and DC voltage regulations, the upper-layer control scheme for ILC should schedule the optimal power exchange between AC and DC subgrids to realize the global economic operation for a hybrid AC/DC microgrid.

Even though the economic dispatch is achieved in AC and DC subgrids respectively, the global economic operation may not be realized well and there still exists a difference between ICs of AC and DC subgrids. Therefore, the optimal exchanging power of ILC should be scheduled to make the ICs of two subgrids be the same in real time. As a result, the global economic operation of the islanded hybrid AC/DC microgrid will be achieved. Hence, Equation (30) is designed and utilized to schedule the optimal power exchange for ILC.

\[
\Delta I = k_{PLC}^H (I_{IC} - I_{IC}) + k_{ILC}^H \int (I_{IC} - I_{IC}) dt \quad (30)
\]

where \(k_{PLC}^H\) and \(k_{ILC}^H\) are the proportional and integral gains of PI controller within the upper-layer control.

Figure 6 shows the specific control diagram of the ILC in the upper layer. As can be observed in Figure 6, the difference between \(I_{IC} - I_{IC}\) is generated by a PI controller, which further provides the optimal active power reference for ILC. If \(I_{IC} > I_{IC}\), it means that a more economic power supply in the DC subgrid than AC subgrid and the DC subgrid should supply more load comparing with the AC subgrid, then ILC drives the power exchanging from the DC subgrid to the AC subgrid for achieving \(I_{IC} = I_{IC}\). On the contrary, in the case of \(I_{IC} < I_{IC}\) the power flow will be scheduled from the AC subgrid to the DC one by ILC under the upper-layer control scheme. In the steady state, due to the PI regulation, the difference of the two ICs of the AC and DC subgrids will be eliminated totally, that is \(|I_{IC} - I_{IC}| \to 0\) as \(t \to \infty\). Combined with the proposed lower-layer control in Section 3, there is \(I_{IC} = I_{IC}\) as \(t \to \infty\), for \(i \in \{V_s, \Omega, \phi\}\) which illustrates the realizing of economic operation of the global hybrid AC/DC microgrid.

### 5.1 CASE STUDIES

In this section, to verify the effectiveness of the proposed BCCS, a simulation platform for the studied hybrid AC/DC microgrid shown in Figure 1 is conducted in Matlab/Simulink. Besides, a real-time test is conducted based on RT-LAB to demonstrate the real-time performance of the proposed control scheme. In the studied islanded hybrid AC/DC microgrid, the nominal frequency and voltage magnitude of AC subgrid is set as 50 Hz and 311 V, respectively. Besides, for the DC subgrid, the DC bus voltage is set as 700 V. Coefficients of the different DGs are shown in Table 2.

#### 5.1.1 Case study 1: Comparison between conventional droop-based control scheme and the proposed BCCS

In this case study, AC and DC subgrids are operated independently until 4s. Then the following scenarios will occur in this hybrid AC/DC microgrid successively: (1) At \(t = 4s\), AC and DC subgrids are connected via ILC and the power exchange is regulated by the proposed ILC control scheme in (30); (2) At \(t = 8s\), the load reduction in AC subgrid, represented by a constant-resistance load of 10Ω, is removed from the AC subgrid; (3) At \(t = 12s\), the increasing load in DC subgrid, represented by a constant-resistance load of 20Ω, is added into the DC subgrid; (4) At \(t = 16s\), the load demand in AC subgrid, represented by a constant-resistance load of 10Ω, is added into the AC subgrid. First, the conversion \(f-P\) droop control in (14) and \(U-P\) droop control in (24) are implemented for the AC and DC subgrids, respectively. The conventional ILC control scheme is utilized to regulate DC bus voltage and AC subgrid frequency. Next, the proposed BCCS is employed for realizing autonomous economic operation in the studied hybrid AC/DC microgrid. The main simulation parameters are shown in Table 3.
TABLE 3  Main simulation parameters

| Subgrids   | Parameters | Symbol | Value          |
|-----------|------------|--------|----------------|
| DC subgrids | Nominal voltage | $U^*$ | 700 V          |
|           | $U/P$ droop gains | $n_{dc}$ | $1.3 \times 10^{-3}$ V/W |
|           | Line resistance | $R_{line}$ | 1 Ω          |
|           | DC DG capacity  | $P_{dc, \max}$ | 15 kW        |
| AC subgrids | Nominal frequency | $f$ | 50 Hz          |
|           | $f/P$ droop gains | $n_{ac}$ | $8 \times 10^{-4}$ Hz/W |
|           | Line impedance  | $R_{line, L}$ | 0.5 Ω, 1.5 mH |
|           | AC DG capacity  | $P_{ac, \max}$ | 15 kW        |

Figure 7 shows the frequency of AC subgrid and bus voltage of DC subgrid in the studied hybrid AC/DC microgrid. It is observed that the proposed BCCS has a better performance than the conventional droop control in frequency and voltage regulations. Figures 8 and 9 present the corresponding IC and power sharing of each DG under the control of conventional droop and the BCCS, respectively. As can be seen in Figure 8, under the conventional droop control, power is shared equally in each subgrid in steady state while ICs of DGs are various, which illustrates that the hybrid AC/DC microgrid is not operated at the optimal point. On the contrary, Figure 9 demonstrates that before AC and DC subgrids are connected, DGs in each subgrid have the same IC values of 0.7031$/kWh$ and 0.5294$/kWh$, respectively. When AC and DC subgrids are connected, ICs of all the DGs are stabilized to 0.6144$/kWh$, 0.4561$/kWh$, 0.7263$/kWh$, and 0.8777$/kWh$ in steady state, respectively. This means the optimal operation of the hybrid AC/DC microgrid is achieved by the proposed BCCS effectively.

Figures 10a and 10b compare the active power transmitted from AC to DC subgrid and total operating costs of the studied hybrid AC/DC microgrid under the control of conventional droop control and the BCCS, respectively. From Figure 10a, it can be seen that, under the conventional droop control, the AC subgrid does not transmit any power to DC subgrid before 12s, and transmits active power to DC subgrid 6.944kW during 12–16s and 6.880kW during 16–20s, respectively. On the contrary, under the control of the proposed BCCS, after AC and DC subgrids are connected, DC subgrid transmits about 4.085kW to AC subgrid during 4–8s, and AC subgrid transmits 3.585kW, 15.402kW, and 7.830kW to DC subgrid during 8–12s, 12–16s, and 16–20s in steady state, respectively.

According to Figure 10b, when subgrids are not connected, compared with the conventional droop control, the total operating costs of both AC and DC subgrids are reduced to 20.4361$/h$ from 21.0182$/h$ by the proposed BCCS, which is reduced by 2.77%. After the AC and DC subgrids are connected, the total costs of the system are 21.0184$/h$, 12.5547$/h$, 29.0024$/h$, and 39.9088$/h$ at the four equilibrium points with the implementation of conventional droop control; and 20.1796$/h$, 12.0803$/h$, 27.3738$/h$, and 38.9706$/h$ in steady state under the control of proposed BCCS.
BCCS. Compared with conventional droop control, the proposed BCCS is able to reduce the total costs by 3.99%, 3.78%, 5.62%, and 2.35%, respectively. Based on the above results and analysis, the effectiveness of the proposed BCCS is validated.

5.2 Case study 2: Performance with some DGs reaching its capacity constraints

The performance of the proposed BCCS with some DGs operated at its capacity limits are tested in Case Study 2. In this case study, the lower and upper limits of DG_4 and DG_8 are set to 6 and 10kW, while the other DG capacity limits remain the same as Case Study 1. Besides, the other control parameters and operation scenarios are set the same as that in Case Study 1.
The BCCS can effectively maintain the stable operation of the studied hybrid AC/DC microgrid with some DGs operated at their capacity limits.

Figure 12 shows the IC curves of all DGs and the active power generated by different DGs. Moreover, the detailed output power of DG4 and DG8 is shown in Figure 13. From Figures 12 and 13, it can be observed that when the AC and DC subgrids operate independently, the IC values of AC DGs and DC DGs are converged to the same level respectively; when AC and DC subgrids are connected, DG4 and DG8 reach the capacity limits in the steady state during 8–12s and 16–20s while ICs of the remained DGs are the same. Besides, in the steady state of 4–8s and 12–16s, the ICs of all DGs converged to the same value. These simulation results verify that the proposed BCCS can effectively realize the stable and economic operation of the hybrid AC/DC microgrid with some DGs operating at their capacity limits.

5.3 Case study 3: Performance of the proposed BCCS considering stochastic characteristics of RESs

In Case Study 3, the performance of the proposed BCCS considering the stochastic characteristics of RESs is validated. Based on the studied hybrid AC/DC microgrid architecture shown in Figure 1, a PV operating at maximum power point is connected to the common bus in the DC subgrid through DC/DC boost converter, and the varying output power of the PV is shown in Figure 14. The load power is set at 49kW in the DC subgrid and 14.52kW in the AC subgrid. Besides, AC and DC subgrids are operated independently until 4s, and the other control parameters are set the same as that in Case Study 1.

Figures 15 and 16 show the simulation results of the hybrid AC/DC microgrid with the stochastic PV output power. It can be observed from Figure 15 that the frequency of the AC subgrid and the bus voltage of the DC subgrid can maintain the nominal values with negligible fluctuations even when the RESs are connected. Figures 16a and 16b display the IC values and output power of each DG, respectively. As can be seen, the ICs of DGs in each subgrid are converged to the same values before the AC and DC subgrids are connected, while ICs of all DGs are driven to the same level after the two sub grids are connected. This demonstrates that the proposed BCCS has an excellent performance of both maintaining the stable operation and realizing global economic operation with the integration of RESs. Besides, Figure 16c compares the total operating cost with/without a PV connection, which shows that RESs play an important role in improving the economic efficiency of the hybrid AC/DC microgrid. The above simulation results verify that the proposed BCCS shows a good integration performance with RESs and is able to realize the economic operation of the islanded hybrid AC/DC microgrid even when the stochastic characteristics of RESs being considered.

5.4 Case study 4: Real-time performance test based on RT-LAB

To validate the real-time performance of the proposed control scheme for global economic operation within the hybrid AC/DC microgrid, the real-time test is carried out based the RT-LAB platform, as shown in Figure 17. The real-time testing platform is mainly comprised of a RT-LAB OP5700 simulator, a computer host, and two scopes. The studied hybrid AC/DC microgrid with 2 AC DGs and 2 DC DGs is established and tested. In this test, the DC voltage ($U_{dc}$) and AC frequency ($f_{ac}$) of the studied hybrid microgrid are set as 700V and 50Hz, and the test is divided into five stages as: (1) During 0–4s, the AC and DC subgrids are operated individually with local loads; (2) At $t=4s$, the AC and DC subgrids are integrated to work together; (3) At $t=8s$, the load demands are decreased within the AC subgrid; (4) At $t=12s$, the load demands are increased within the DC subgrid; (5) Finally, the load demands are increased within the AC subgrid at 16s.

The test results are shown in Figure 18. As can be observed in Figure 18a, in the beginning, each subgrid operates at its individual optimal operating point, as DG ICs within each subgrid are driven to the same level by the proposed control scheme respectively. After 4s, the subgrids are connected and all the DG ICs are matched in different test stages, which implies the
FIGURE 16 Simulation results for Case Study 3. (a) IC curves of different DGs, (b) Active power of different DGs, (c) Total operation costs of the studied hybrid AC/DC microgrid

FIGURE 17 Real-time testing platform

FIGURE 18 Real-time test results of the proposed BCCS, (a) ICs of different DGs, (b) Active power generated by different DGs, (c) DC Voltage, AC frequency, and the total cost of the hybrid AC/DC microgrid

global economic operation of the hybrid AC/DC microgrid is achieved under various loading conditions. Besides, Figure 18b shows the active power sharing of different DGs in every test stage, and Figure 18c displays the DC voltage, AC frequency, and total cost of the studied hybrid AC/DC microgrid. As can be seen, the voltage of DC subgrid and the frequency of the AC subgrid are stabilized at 700V and 50Hz, respectively. When the AC and DC subgrids are connected at 4s, it is obvious that the total cost is further minimized, which verifies the effectiveness of the optimal power exchanging control for ILC in the upper layer. The test results shown in Figure 18 effectively validate that the proposed BCCS has a good real-time performance with various loading conditions.

6 | CONCLUSION

This paper proposes a novel bilayer coordinated control scheme to realize the global autonomous economic operation of the islanded hybrid AC/DC microgrid in a fully distributed manner. In the lower layer, the proposed OPRIA-based $f$-$P$/$U$-$P$ droop control schemes with the designed corresponding secondary control for the frequency/voltage regulations are implemented in the AC and DC subgrids, respectively. In the upper layer, the optimal power control of ILC is further proposed and implemented. The proposed BCCS can realize the global economic dispatch and the frequency/voltage regulation at the same time, with less communication burden and good compatibility of RESs. Simulations results conducted in Matlab/Simulink validate the effectiveness of the proposed BCCS realizing the economic operation of the islanded hybrid AC/DC microgrid, and the test results based on RT-LAB platform verify the good real-time performance of the proposed control scheme.

Interesting extensions of this work include the application of the proposed control scheme to the AC microgrid clusters and DC microgrid clusters. Also, in the future research, the optimal voltage/reactive power control and optimal ESs control will be considered.
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NOMENCLATURE

\[ P_{ac,i} \] Active power generated by the \( i \)th AC DG.
\[ P_{dc,i} \] Active power generated by the \( i \)th DC DG.
\[ N_{ac} \] Number of AC DGs.
\[ N_{dc} \] Number of DC DGs.
\[ P^c_{ac,i} \] Load demand value of the AC subgrid.
\[ P^c_{dc,i} \] Load demand value of the DC subgrid.
\[ P_g \] Total load demand value.
\[ P_{ac,i}^{min} \] Lower limit of the \( i \)th AC DG capacity.
\[ P_{ac,i}^{max} \] Upper limit of the \( i \)th AC DG capacity.
\[ P_{dc,i}^{min} \] Lower limit of the \( i \)th DC DG capacity.
\[ P_{dc,i}^{max} \] Upper limit of the \( i \)th DC DG capacity.
\[ P_{ll,c} \] Active power transmitted from DC to AC subgrid.
\[ P_i \] Active power of DG \( i \).
\[ I_{ci} \] Incremental cost of DG \( i \).
\[ f_i \] Operating frequency of the \( i \)th AC DG.
\[ V_i \] Operating voltage of the \( i \)th AC DG.
\[ f^* \] Nominal frequency of the AC subgrid.
\[ V^* \] Nominal voltage of the AC subgrid.
\[ Q_{ac,i} \] Reactive power generated by the \( i \)th AC DG.
\[ P_{ac,i}^* \] Active power reference for the \( i \)th AC DG.
\[ Q_{ac,i}^* \] Reactive power reference for the \( i \)th AC DG.
\[ P_{ac,i}^o \] Optimal power reference for the \( i \)th AC DG.
\[ \Delta f_i \] Compensated frequency value for the \( i \)th AC DG.
\[ U_i \] Operating voltage of the \( i \)th DC DG.
\[ U^* \] Nominal voltage of the DC subgrid.
\[ P_{dc,i} \] Active power reference for the \( i \)th DC DG.
\[ P_{dc,i}^o \] Optimal power reference for the \( i \)th DC DG.
\[ \Delta U_i \] Compensated voltage value for the \( i \)th DC DG.
\[ IC_{ac} \] Leader DG IC in the AC subgrid.
\[ IC_{dc} \] Leader DG IC in the DC subgrid.

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