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A fast power control method based on high-speed communication for the continuous co-phase traction power system

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ABSTRACT

Continuous co-phase traction power system is an effective method to eliminate neutral sections and provide high quality power for both the public grid and the catenary. The substations have the ability to provide cooperative support to each other to reduce capacity and improve system reliability. A fast power control method for substations is needed due to rapid load changes and low overload capability of the system. This paper proposes a fast power control method based on high-speed communication between substations, with additional transient power control to significantly improve the dynamic response of the system.

KEYWORDS

Continuous co-phase traction power system, cooperative power control, dynamic response, high-speed communication.

Continuous co-phase traction power supply technology has broad prospects for development in the field of traction power supply, which is effective to eliminate neutral sections in electrified railways, and solves power quality problems including negative sequence components, reactive power and harmonics distortion[1–3].

The basic configuration of continuous co-phase power system is shown in Figure 1. The power sources from AC utility supply power to transformers in substations. Static power converters (SPC) transmit power to the catenary through AC–DC–AC power transformation and supply power to the trains. Therefore the output voltage of substations can be totally controlled, and decoupled from the AC utility grid.

In consequence, the substations have the ability to provide cooperative support to each other. The peak power of substations can be significantly reduced, and the system becomes more reliable when fault occurs. Besides, the system can meet some optimization goals such as low catenary loss and high feedback energy utilization, through an effective system-level energy management method.

However, it puts high demands on the response speed of power control as loads of trains change rapidly and the fully power-electronized system has a weak overload capacity. According to the measured data in Beijing Daxing Airport Line, the power change rate of a train can reach up to 11 MW/s. The simultaneous acceleration or braking of multiple trains requires a high power response speed of substations. In the fault scenario, when some trains or SPCs exit from operation, the dynamic response will become more demanding.

Research on cooperative power control mainly adopts methods based on droop or inverse droop control without communication between substations[4–6]. Control strategies with communication can be found for reference in the field of microgrids, including distributed control, master-slave control, centralized control, etc. Distributed control with communication usually adopts improved droop strategies with poor dynamic characteristics, and may lead to problems such as substation output voltage drop or inaccuracy of power control[7–8]. In the master-slave control, the master unit supports the system voltage, while the slave units adopt constant power control[9]. The problem lies in slow control response, weak anti-interference ability and high capacity demand of the master unit. Centralized control is easy to optimize the system as a whole, but it has high communication requirements, low reliability and poor scalability[10]. Continuous co-phase power system has no plug-and-play requirements and is suitable for centralized control. It is easy and cheap to lay optical fiber along the railway, which provides conditions for realizing high-speed communication between substations[11]. This paper proposes a cooperative power control method based on high-speed communication between substations, with additional transient power control to significantly improve the dynamic response of power control.

1 System modeling

1.1 Steady state model

For the continuous co-phase traction power system with a given catenary impedance angle, the active and reactive power flows between the ith substation voltage $U_i\angle\theta_i$ and equivalent load voltage $U_L\angle\theta_L$ are shown in Figure 2 obey the following relationship:

$$\begin{cases} P_i = \dfrac{U_i^2 R_i - U_i U_L R_i \cos\delta_i + U_i U_L X_i \sin\delta_i}{R_i^2 + X_i^2} \\ Q_i = \dfrac{U_i^2 X_i - U_i U_L R_i \sin\delta_i + U_i U_L X_i \cos\delta_i}{R_i^2 + X_i^2} \end{cases} \tag{1}$$

where δ_i is the phase angle difference between U_i and U_L, and $Z_i\angle\theta_i = R_i + jX_i$ denotes the catenary impedance between traction substation and load.

1.2 Transient state model

According to available research, the response speed of steady state power control is in the order of 10 ms at least, limited by the filter

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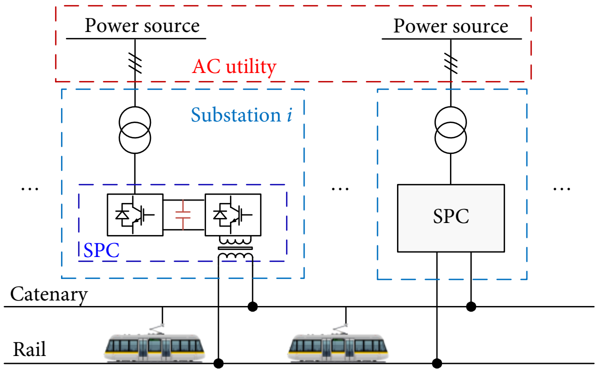

Fig. 1 Configuration of the continuous co-phase power system.

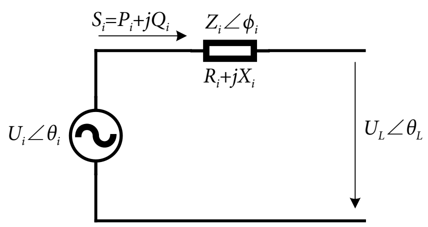

Fig. 2 Equivalent circuit of a substation and the load in steady state.

of instantaneous power calculation. This response speed can meet the normal load changes of the trains, but it is not enough to meet the requirements of the system, which may lead to SPCs overloaded and locked or even damaged when the load changes rapidly, such as faults of multiple trains or SPCs.

In the overall control, the bandwidth relationship of each loop is that the current loop is greater than the voltage loop than the power loop. Inspired by this, the output current of traction is directly controlled to get a faster response speed in the transient process. Therefore, it is necessary to model the system in order to obtain a suitable transient cooperative current control method.

In system modeling, the original system can be decomposed into an uncontrollable subsystem and a controllable subsystem. The uncontrollable subsystem reveals the natural distribution of trains' power demand, whereas the controllable subsystem embodies the effect of cooperative control. The substations and trains are assumed as voltage sources and current sources as shown in Figure 3(a), which is in a transient process that lasts about 1 ms.

The voltage of the ith substation u_i can be decomposed into two components as shown in Figure 3(b), where u_0 is the voltage under constant voltage control and Δu_i is the additional voltage of cooperative control, which can be regarded as the common mode and differential mode voltage of the substations. Based on the superposition principle, the system in Figure 3(b) is equivalent to the superposition of the natural subsystem shown in Figure 3(c) and the cooperative subsystem shown in Figure 3(d).

It can be obtained according to Figure 3(d) that:

$$u_{\mathrm{cb}i}(t)=\Delta u_i(t)-\Delta u_{i+1}(t)=R_{\mathrm{b}i}i_{\mathrm{cb}i}(t)+L_{\mathrm{b}i}\frac{\mathrm{d}i_{\mathrm{cb}i}(t)}{\mathrm{d}t} \tag{2}$$

$$u_{\mathrm{cb}(i-1)}(t)=\Delta u_{i-1}(t)-\Delta u_i(t)=R_{\mathrm{b}(i-1)}i_{\mathrm{cb}(i-1)}(t)+L_{\mathrm{b}(i-1)}\frac{\mathrm{d}i_{\mathrm{cb}(i-1)}(t)}{\mathrm{d}t} \tag{3}$$

Eq.(2) minus Eq.(3), assuming the impedances between substations are equal, the relationship between cooperative voltage and current of the ith substation can be obtained:

$$2\Delta u_i(t)-\Delta u_{i-1}(t)-\Delta u_{i+1}(t)=R_{\mathrm{b}i}i_{\mathrm{c}i}+L_{\mathrm{b}i}\frac{\mathrm{d}i_{\mathrm{c}i}(t)}{\mathrm{d}t} \tag{4}$$

2 Cooperative power control

2.1 Steady state power control

In a traction power supply system, the conventional power decoupling control method is no longer available due to the high R/X ratio of catenary impedance. The control strategy based on virtual power can decouple the power flows by rotating the power vectors with the impedance angle[12,13]. The virtual active and reactive power P' and Q' are obtained by using a transformation matrix T which is expressed in Eq. (2).

$$\begin{bmatrix} P_i' \\ Q_i' \end{bmatrix}=T\cdot\begin{bmatrix} P_i \\ Q_i \end{bmatrix}=\begin{bmatrix} \sin\phi_i & -\cos\phi_i \\ \cos\phi_i & \sin\phi_i \end{bmatrix}\cdot\begin{bmatrix} P_i \\ Q_i \end{bmatrix} \tag{5}$$

Combining Eqs. (1) and (5), the virtual power can be derived:

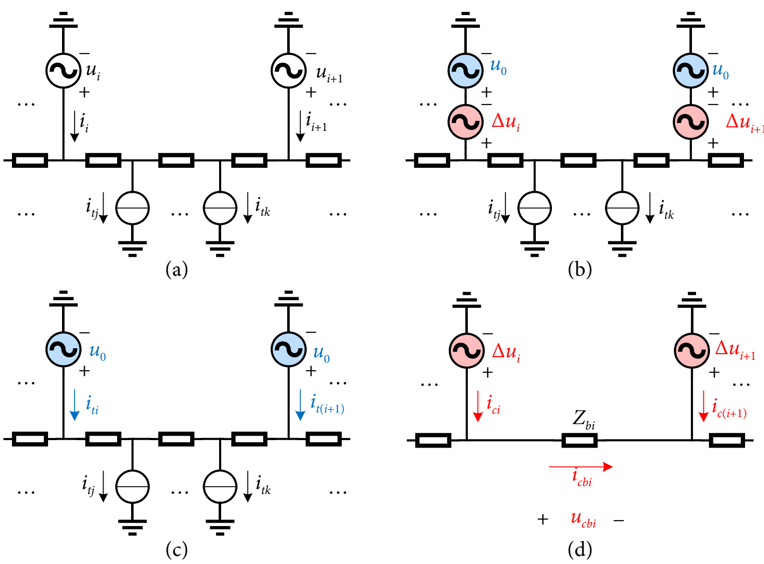

Fig. 3 Transient state system modeling based on the superposition principle. (a) Original system, **(b)** equivalent system, **(c)** natural system, and **(d)** cooperative system.

$$\begin{cases} P'_i = \dfrac{U_i U_L \delta_i}{Z_i} \\ Q'_i = \dfrac{U_i (U_i - U_L)}{Z_i} \end{cases} \tag{6}$$

which is simplified by regarding that $\sin\phi_i \approx \phi_i$ and $\cos\phi_i \approx 1$.

Then the virtual active and reactive power can be uniquely controlled by controlling the voltage phase and amplitude, which means that power decoupling in the traction power supply system is achieved. The block diagram of the virtual power decoupling control method is illustrated in Figure 4, where U_0 and θ_0 are the basic voltage amplitude and phase. PI controllers are applied to control the power accurately in the steady state.

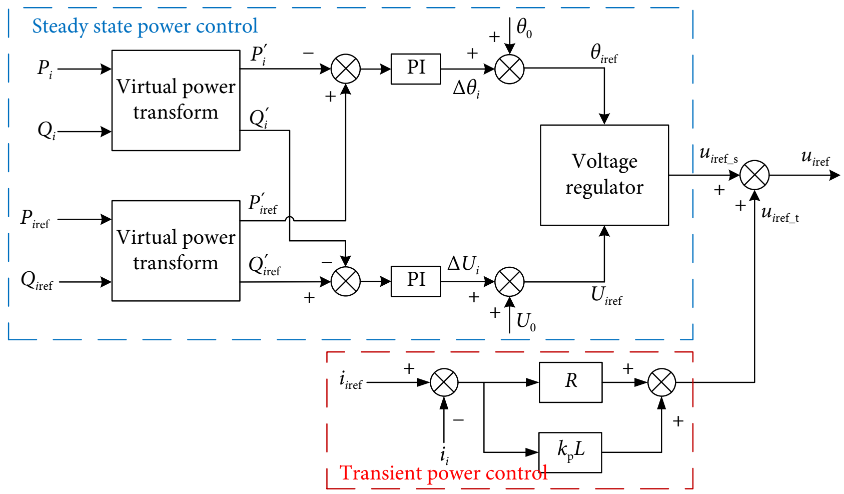

Fig. 4 Block diagram of cooperative power control.

2.2 Transient power control

The current reference value of the ith substation i_{iref} can be approximately considered to be proportional to the active power reference value P_{iref} in a transient process, as expressed in Eq. (7).

$$i_{iref}(t) = \frac{P_{iref}}{\sum_{j=1}^{N} P_{jref}} \sum_{j=1}^{N} i_j(t) \tag{7}$$

By adding two more constraints to Eq. (4), $\Delta u_1 = \Delta u_N = 0$ for example, the cooperative voltage of each substation can be obtained under a specified $\mathrm{d}i/\mathrm{d}t$. The $\mathrm{d}i/\mathrm{d}t$ is limited by SPC output voltage range, however, the response time in the order of 1 ms can be guaranteed.

In a continuous co-phase traction power system constituted of two substations, the effect of cooperative control can be further simplified. Supposing the current reference value is to be tracked in a very short time, the cooperative voltages should be

$$\Delta u_1(t) = -\Delta u_2(t) = \frac{1}{2}\left(Ri_{c1} + L\frac{\mathrm{d}i_{c1}(t)}{\mathrm{d}t}\right) \tag{8}$$

A proportional controller can be applied to achieve transient power control as shown in Figure 4. And the steady state power control is still reserved to eliminate steady state error.

Accordingly, a top-level controller is needed to realize the above-mentioned cooperative power control. The substations transmit their output power and current to the top-level controller, which calculates the reference values of output power and current and returns them to each substation. The process can be completed in tens to hundreds of microseconds through fiber optic communication.

3 Results of simulation and experiment

3.1 Simulation results

As a typical case, Beijing Daxing Airport Line is in the reconstruction stage to realize continuous co-phase traction power supply. It is constituted of two substations and each substation contains two SPCs. The system-level energy management method is to realize power equalization among SPCs. The basic parameters are shown in Table 1.

The simulation results of cooperative control enabling are shown in Figure 5. The cooperative power control enables 0.5 s. It can be seen comparing Figures 5(a) and 5(b) that the proposed transient power control significantly improved the dynamic response that the response time decreased from more than 5 ms to about 1 ms.

Figure 6 shows the waveforms of an SPC exiting from operation suddenly. SPC2, the second SPC of the first substation, exited at 0.7 s. It can be seen comparing Figures 6(a) and 6(b) that when substations face large load changes as SPC2 exiting, the proposed transient power control significantly improved the dynamic response. The transient control provides a large control voltage when the transient process occurs, then gradually decreases and the steady state control plays a leading role. The response time decreased from more than 30 ms to about 1 ms as shown in Figure 6(c).

3.2 Experiment results

A continuous co-phase traction power system prototype using MOSFET (model number IPP100N12S3-05) was built to conduct an experimental verification as shown in Figures 7. The system parameters are shown in Table 2.

Table 1 Parameters for the simulation model

Symbol	Value
U_0	27.5 kV
Rated frequency	50 Hz
Load power	62 MW
R	1.34 Ω
L	10.15 mH
kp	6000

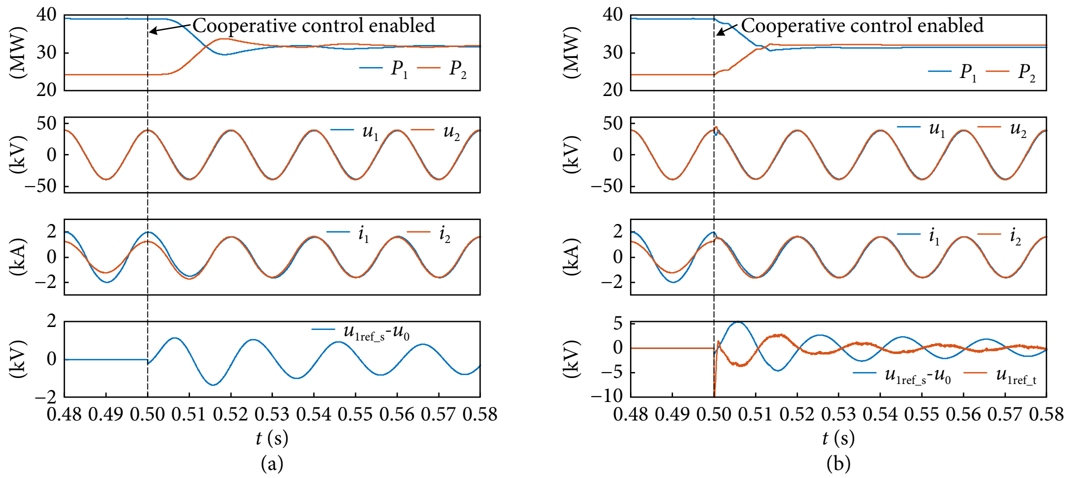

Fig. 5 Waveforms of cooperative power control enabling. **(a)** Only steady state control, **(b)** both steady state and transient control.

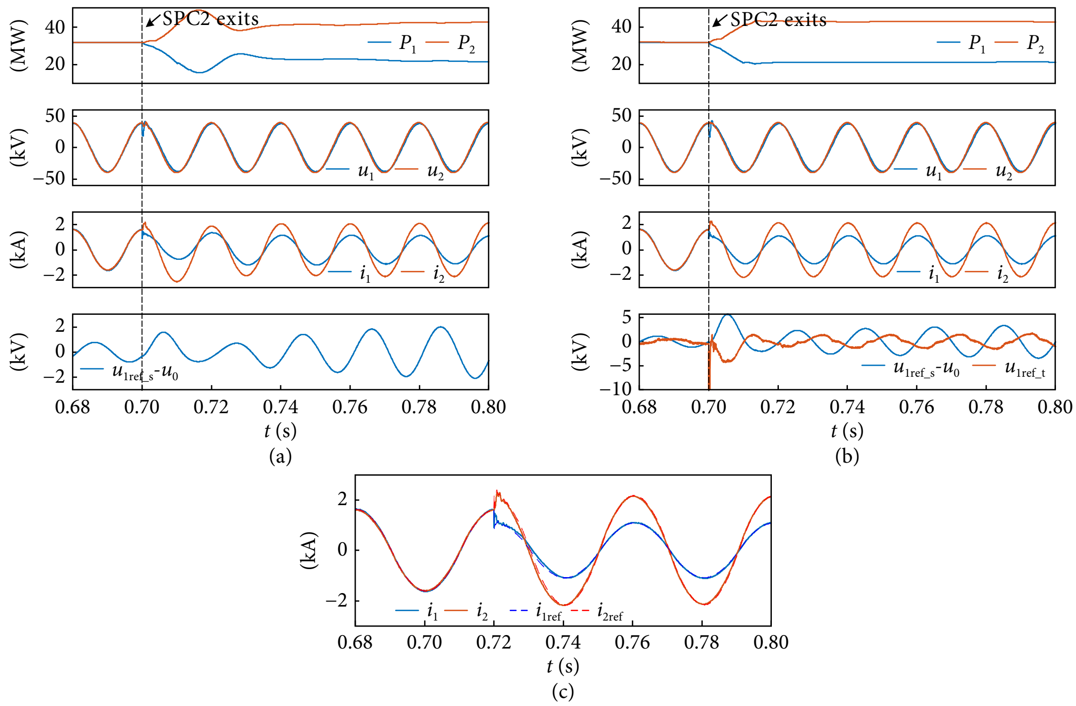

Fig. 6 Waveforms of SPC2 exiting. **(a)** Only steady state control, **(b)** both steady state and transient control, and **(c)** response speed of transient power control.

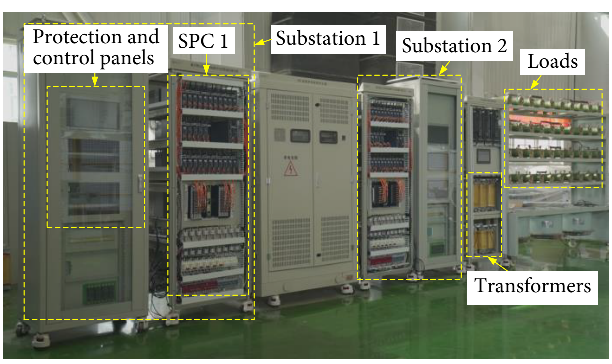

Fig. 7 Hardware picture of the built laboratory prototype.

A 15.2 kW resistive load is set at the output port of substation 2. The load is connected to the circuit at a certain moment, and a load step occurs. The results are shown in Figure 8, and it can be seen the transient power control improved the dynamic performance significantly.

And the waveforms of SPC3 exiting are shown in Figure 9. The results are basically consistent with the simulation results in Figure 6. The proposed transient power control can speed up the system response when SPC exits on fault.

Table 2 Parameters for the prototype

Symbol	Value
U_0	380 V
Rated frequency	50 Hz
Load power	15.2 kW
R	0.4 Ω
L	5 mH
kp	6000

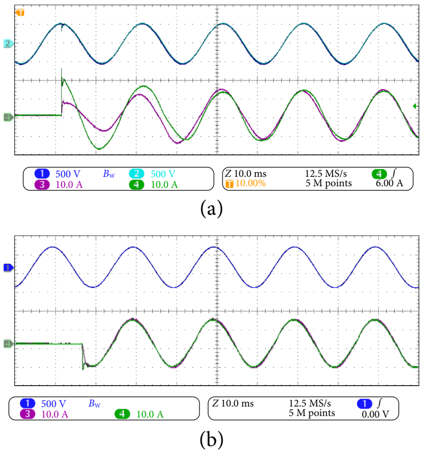

Fig. 8 **Waveforms of step load. (a)** Only steady state control, and **(b)** both steady state and transient control.

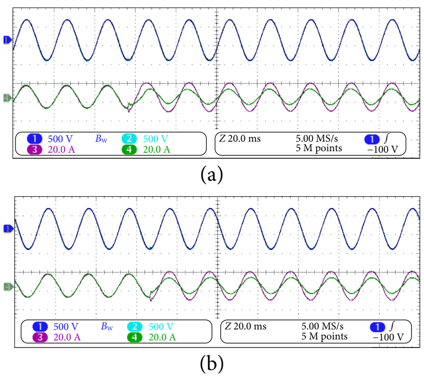

Fig. 9 **Waveforms of SPC3 exiting. (a)** Only steady state control, and **(b)** both steady state and transient control.

4 Conclusions

This paper proposes a cooperative power control method based on communication between substations, which has both steady state accuracy and high dynamic response. The system is modeled in both a steady and transient state. Transient power control is applied to significantly improve the dynamic response of power control. The method has been proven to be effective by simulation and experiment.

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Additional information

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

References

[1] Krastev, I., Tricoli, P., Hillmansen, S., Chen, M. W. (2016). Future of electric railways: Advanced electrification systems with static converters for ac railways. *IEEE Electrification Magazine*, 4: 6–14.

[2] Li, Q. Z., Zhang, J. S., He, W. J. (1988). Study of a new power supply system for heavy haul electric traction. *Journal of the China Railway Society*, 10: 23–31. (in Chinese)

[3] Wu, Q., Jiang, Q. R., Wei, Y. D. (2011). Study on railway unified power quality controller based on STATCOM technology. In: Proceedings of the 2011 5th International Power Engineering and Optimization Conference, Shah Alam, Selangor.

[4] Lee, C. T., Chu, C. C., Cheng, P. T. (2013). A new droop control method for the autonomous operation of distributed energy resource interface converters. *IEEE Transactions on Power Electronics*, 28: 1980–1993.

[5] Katiraei, F., Iravani, M. R. (2006). Power management strategies for a microgrid with multiple distributed generation units. *IEEE Transactions on Power Systems*, 21: 1821–1831.

[6] Sharifi, D., Tricoli, P., Hillmansen, S. (2016). A new control technique enabling dual-feeding of 50 Hz AC railways with static converter feeder stations. In: Proceedings of the 8th IET International Conference on Power Electronics, Machines and Drives, Glasgow, UK.

[7] Shi, H. X., Sun, K., Hou, X. C., Li, Y. W., Jiang, H. H. (2022). Equilibrium mechanism between dc voltage and ac frequency for ac-dc interlinking converters. *iEnergy*, 1: 279–284.

[8] De Brabandere, K., Bolsens, B., Van den Keybus, J., Woyte, A., Driesen, J., Belmans, R., Leuven, K. U. (2005). A voltage and frequency droop control method for parallel inverters. In: Proceedings of the 2004 IEEE 35th Annual Power Electronics Specialists Conference, Aachen, Germany.

[9] Caldognetto, T., Tenti, P. (2014). Microgrids operation based on master–slave cooperative control.. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 2: 1081–1088.

[10] Mehdi, M., Kim, C. H., Saad, M. (2020). Robust centralized control for DC islanded microgrid considering communication network delay. *IEEE Access*, 8: 77765–77778.

[11] Song, J., He, G. N., Wang, J. X., Zhang, P. W. (2022). Shaping future low-carbon energy and transportation systems: Digital technologies and applications. *iEnergy*, 1: 285–305.

[12] Rowe, C. N., Summers, T. J., Betz, R. E., Cornforth, D. J., Moore, T. G. (2013). Arctan power–frequency droop for improved microgrid stability. *IEEE Transactions on Power Electronics*, 28: 3747–3759.

[13] Wu, T., Liu, Z., Liu, J. J., Wang, S. K., You, Z. Y. (2016). A unified virtual power decoupling method for droop-controlled parallel inverters in microgrids. *IEEE Transactions on Power Electronics*, 1: 5587–5603.