Research on Control Strategy of AC DC Hybrid Power Distribution Network with Multiple Voltage Levels

Guo-Xiu Jing, *Member, IAENG*, Dong-Sheng Shuai, Bing Zhang

***Abstract*—Combining the application background and development trend of the intelligent distribution network, an AC/DC hybrid distribution network based on multiple voltage levels is designed, and the system advantages and operating characteristics of this distribution network topology are analyzed. To maintain the stability of the bus voltage in this topology modeling research, this paper adopts the proportional + quasi-proportional resonance (P+QPR) voltage and current control strategy, and verifies that the power quality of the distribution network is relatively improved through the control of the pre-unit and post-unit converters. Since the three-phase voltage and current imbalance on the AC side will cause the three-phase power imbalance, the zero-sequence voltage injection method without complicated calculations is used to achieve the phase-to-phase power balance. Based on the simulation research under the Matlab/Simulink environment, the system operation under the unbalanced voltage and harmonic voltage on the AC side of the distribution network is evaluated. The simulation results verify the feasibility of the control strategy based on this topology. The simulation shows that the process is dynamic and the response is relatively fast. The proposed control strategy can ensure the reliable operation of the distribution network system, its transient stability is relatively good, and meet the requirements of safe and reliable operation of the power system.**

***Index Terms*—AC DC hybrid distribution network, Multiple voltage level, Quasi-proportional resonance control, Zero sequence voltage**

I. INTRODUCTION

At present, energy demand and shortage have become acute problems. Energy conservation and emission reduction, large-scale use of renewable energy, and low-carbon economy have become the unanimous goals of all countries in the world. Distributed energy has begun to penetrate the power sector. The largest proportion of distributed energy is photovoltaic power generation. The intermittency in photovoltaic power generation is alleviated by battery storage, this is also a DC device. These previously discussed recent developments in DC energy and DC loads (such as DC computers, electric cars, LED lights, etc.) bring DC systems back to the power sector. However, the existing communication system will not be completely eliminated[1-5]. Therefore, in order to combine the advantages of the DC network with the advantages of the traditional AC network, the concept of an AC-DC hybrid distribution network is becoming more and more popular. With the rapid development of distributed energy technology and power electronic technology, a large number of distributed power sources and energy storage units are integrated into the distribution network to operate, and the operation of the AC/DC hybrid distribution network has attracted much attention. However, the modeling of power electronics-based converters and the optimal operation of their integration into the distribution network is a hard and critical task, which is critical to the application scenarios and operating characteristics of the AC/DC hybrid distribution network[6-11].

The currently studied AC-DC hybrid distribution network is shown in Fig.1, which is a relatively traditional topological structure diagram. The AC bus and the DC bus are connected by an AC-DC converter. Among them, the AC terminal is connected to the municipal power grid, and the DC terminal Connect the corresponding AC/DC load and distributed power supply through the converter[12-15]. As more and more DC loads are applied under various DC bus voltages, it is necessary to have a multi-voltage AC and DC hybrid distribution network[16-18]. However, connecting this new AC-DC hybrid distribution network system to a three-phase medium-voltage high-voltage grid can achieve high-power transmission and high-efficiency conversion. Most of the converters in the traditional AC-DC hybrid microgrid use three-phase PWM converters. In the submitted DC hybrid distribution network, the stability of the system is controlled based on the converter. Considering the application scenario of multiple DC voltage levels, it is necessary to connect multiple DC converters on the DC side to meet this requirement, and its cost will increase[19-25].

Aiming at the problems of the previous analysis of the hybrid distribution network, this paper designs an AC/DC hybrid distribution network based on multiple voltage levels. By setting the H-bridge converter, it can be applied to scenarios with more DC voltage levels. The distribution network meets the requirements of flexible operation. The use of DC/DC converters is reduced in the configuration of the distribution network system, which meets the requirements of economic operation of the distribution network. The front and rear converters adopt current and voltage control respectively, and the harmonic control of the

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Guo-Xiu Jing (Corresponding Author) is a graduate student at the Faculty of Electronic and Information Engineering, Xi'an Jiaotong University, Xi'an, 710049, China (e-mail: jingguoxiu512@163.com).
Dong-Sheng Shuai is a senior engineer at Jiangxi Province Coal Mine Design Institute, Nanchang, 330029, China(e-mail:520sds@163.com).
Bing Zhang is a graduate student at the Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, 710049, China (e-mail:zhangbing635@163.com).

front and rear AC bus bars does not interfere with each other, and the power quality of the distribution network is improved. In order to ensure the power balance between each phase of the system, the zero-sequence voltage injection process is adopted, so that no harmonic components need to be extracted during the whole control process, and the calculation time is saved. Finally, the simulation test proves the feasibility of the control strategy adopted in this paper and the effectiveness of the method.

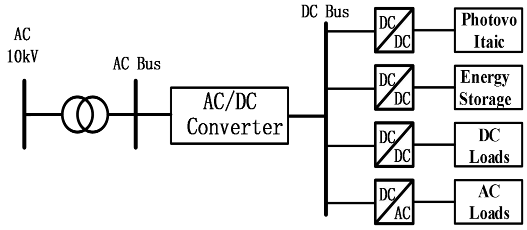

Fig. 1. Traditional AC DC hybrid power distribution network.

II. Topological structure of AC DC hybrid distribution network

Fig.2 shows the topology of the H-bridge-based AC-DC hybrid distribution network. The main components are AC power, front and rear units based on 6 H-bridge converters, DC bus and DC/DC converter. Among them, the DC/DC converter is composed of three compact converters, namely DC/DC converter1, DC/DC converter2 and DC/DC converter3. The main components of the front-end unit are: 3 H-bridges and their corresponding control units, reference value setting, power calculation and zero sequence voltage injection modules. The latter unit has one more uncontrolled rectifier unit than the previous unit, which is mainly used to generate current harmonics and an unbalanced load of three resistors.

The advantages of the hybrid distribution network based on H-bridge converters are: modular design for use and maintenance, flexible configuration and strong scalability, high system stability and high power distribution efficiency. The front and rear converter units are set on the AC side distribution bus. The DC port of each H-bridge converter canbe connected to loads of different voltage levels, which can be applied to application scenarios with relatively high power levels. As shown in Fig.3, this method can improve the operating efficiency and stability of the system, which is highly advanced and feasible.

III. Control strategy of AC DC hybrid distribution network

The AC-DC hybrid power distribution network studied in this paper adopts the H-bridge topology on the AC side. The power electronic devices in the system can withstand high voltage and operate stably, and at the same time can compensate the voltage and current harmonics in real time. The composite control based on P+QPR is used to stabilize the DC voltage and improve the power quality. In the transient process, the zero-sequence voltage injection method is used to achieve the steady-state phase-to-phase power balance.

A. Voltage and current control based on P+QPR

The AC side adopts P+QPR-based voltage and current control, and its control block diagram is shown in Fig.3. The former unit converter adopts current control based on P, and the latter converter adopts voltage control based on QPR. The latter voltage controller adopts dual-loop control, the voltage outer loop control is a quasi-proportional resonance controller, and the current inner loop control is a proportional controller to meet the requirements.

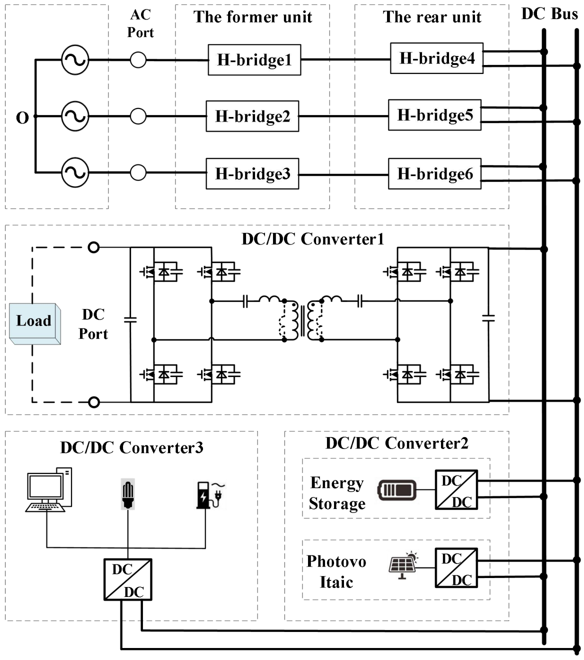

Fig.2. Topological structure diagram of AC/DC hybrid distribution network.

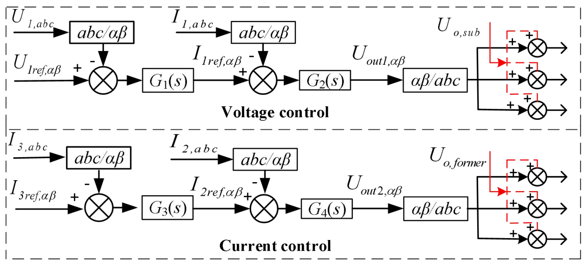

Fig.3. Voltage and current control block diagram.

The outer loop quasi-proportional resonance controller is as follows:

$$G_1(s)=k_{p1}+\sum_{h=1,3,5,7}\frac{2k_{i1,h}\omega_c s}{s^2+2\omega_c s+(h\cdot\omega_o)^2} \tag{1}$$

The output of the outer loop voltage loop is:

$$I_{1ref,\alpha\beta}=G_1(s)\cdot(U_{1ref,\alpha\beta}-U_{c1,\alpha\beta}) \tag{2}$$

The inner loop proportional controller is as follows:

$$U_{out1,\alpha\beta}=G_2(s)\cdot(I_{1ref\alpha\beta}-I_{1,\alpha\beta}) \tag{3}$$

In order to maintain the sine of the current and voltage of the AC side front-stage unit, the controller adjusts the parameters in the static coordinate system:

$$I_{2ref,\alpha\beta}=G_3(s)\cdot(I_{3ref,\alpha\beta}-I_{3,\alpha\beta}) \tag{4}$$

$$U_{out2,\alpha\beta} = G_4(s)\cdot(I_{2ref,\alpha\beta} - I_{2,\alpha\beta}) \tag{5}$$

The latter unit adopts a voltage controller, and for the effect of harmonics after the load is connected, an LC filter module is added:

$$z_{c1}(s)\cdot(I_1 - I_{sub}) = (1/sC_1)\cdot(I_1 - I_{sub}) = V_{c1} \tag{6}$$

Where: I_{sub} is the output current of the rear power unit after the LC filter.

$$V_{out1} - V_{c1} = Z_1(s)\cdot I_1 = (sL_1 + R_1)I_1 \tag{7}$$

$$V_{c1} = G_V(s)\cdot V_{1ref} - Z_{eq}V(s)\cdot I_{sub} \tag{8}$$

The closed loop response of the filter capacitor voltage: $G_V(s)$ is the gain of the controlled voltage source.

The front-end unit uses a proportional controller, and the response of the added LCL filter is:

$$z_{c2}(s)\cdot(I_2 - I_3) = (1/sC_2)\cdot(I_2 - I_3) = V_{c2} \tag{9}$$

$$V_{c1} + V_{out2} - V_{c2} = z_2(s)\cdot I_2 = (sL_2 + R_2)I_2 \tag{10}$$

$$V_{c2} - V_g = z_3(s)\cdot I_3 = (sL_3 + R_3)I_3 \tag{11}$$

The closed-loop response of the AC side current is as follows:

$$I_3 = G_I(s)\cdot I_{3ref} - \frac{1}{Z_{eq,I}(s)}\cdot(V_g - V_{c1}) \tag{12}$$

Where: $G_I(s)$ is the gain of the controlled current source, and $Z_{eq},I(s)$ is the parallel impedance of the Norton equivalent circuit.

B. Transient control based on zero sequence voltage injection

When the current of the front-level unit of the AC side grid and the voltage of the back-level unit track the reference value, considering the impact of the grid voltage imbalance on the local load and the requirement for the DC bus voltage to remain stable, there will be significant interphase power flow between the front and rear level units. However, the current and supply voltage of the three-phase power grid always need to be balanced and maintain a good sine. In order to resolve this conflict, the zero-sequence voltage injection method is applied to the front and rear units of the system. Through this control, the output power of each unit can be adjusted, but the line supply voltage and grid current are not affected. In order to equal the output power of the three phases, PI control is used, and the error of each phase is used as the feedback amount. The target of PI control is $P_z = 0$. After zero sequence voltage injection, the three-phase power is finally balanced.

$$\begin{cases} \Delta P_a = \dfrac{P_a - \overline{P}}{P_a + P_b + P_c} \\ \Delta P_b = \dfrac{P_b - \overline{P}}{P_a + P_b + P_c} \\ \Delta P_c = \dfrac{P_c - \overline{P}}{P_a + P_b + P_c} \end{cases} \tag{13}$$

Where: ΔP is the difference between single-phase active power and average power, and $\overline{P}$ is the average power of three-phase.

The closed-loop response of the AC side current is as follows:

$$u_z = \Delta P_a + \Delta P_b + \Delta P_c \tag{14}$$

The reference voltage is injected through the above zero-sequence voltage, and the following can be obtained:

$$\begin{cases} u_a = \sqrt{2}u_p\sin(\omega t) + \sqrt{2}u_z\sin(\omega t + \theta_z) \\ u_b = \sqrt{2}u_p\sin(\omega t - \dfrac{2\pi}{3}) + \sqrt{2}u_z\sin(\omega t + \theta_z) \\ u_c = \sqrt{2}u_p\sin(\omega t + \dfrac{2\pi}{3}) + \sqrt{2}u_z\sin(\omega t + \theta_z) \end{cases} \tag{15}$$

$$\begin{cases} i_a = \sqrt{2}i_p\sin(\omega t + \varphi) \\ i_b = \sqrt{2}i_p\sin(\omega t + \varphi - \dfrac{2\pi}{3}) \\ i_c = \sqrt{2}i_p\sin(\omega t + \varphi + \dfrac{2\pi}{3}) \end{cases} \tag{16}$$

In the formula: u_p represents the effective value of the positive sequence voltage of the power grid, i_p represents the effective value of the positive sequence current flowing in, φ represents the phase angle of the positive sequence current flowing in, u_z represents the effective value of the zero sequence voltage, and θ_z represents the phase angle of the zero sequence voltage.

$$\begin{cases} P_a = u_p i_p\cos\varphi + u_z i_p\cos(\theta_z - \varphi) \\ P_b = u_p i_p\cos\varphi + u_z i_p\cos(\theta_z - \varphi - \dfrac{2\pi}{3}) \\ P_c = u_p i_p\cos\varphi + u_z i_p\cos(\theta_z - \varphi + \dfrac{2\pi}{3}) \\ P_z = u_z i_p\cos(\theta_z - \varphi) + u_z i_p\cos(\theta_z - \varphi - \dfrac{2\pi}{3}) \\ + u_z i_p\cos(\theta_z - \varphi + \dfrac{2\pi}{3}) = 0 \end{cases} \tag{17}$$

Where: P_z represents the power change caused by the injected zero sequence voltage.

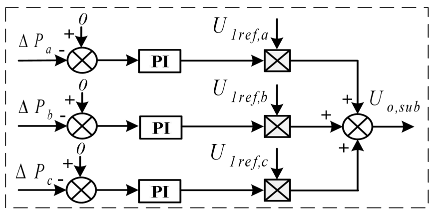

Fig.4. Zero sequence voltage calculation process.

The calculation process of the zero-sequence voltage of the latter unit is shown in Fig.4. The error between the single-phase active power and the average power is used as the feedback input. After PI control, the zero-sequence voltage injection method is used to modulate the reference voltage of each phase. Since the system adopts three-phase three-wire connection, the reference line voltage is not affected, and the three-phase power balance is finally realized. At the same time, the line-to-line reference voltage adjusts the current harmonic suppression of the previous unit and the harmonic voltage suppression of the subsequent unit. This adjustment and the zero-sequence voltage injection method complete the decoupling control.

Convert the voltage in the αβ static coordinate system to the voltage in the abc coordinate system, and at the same time inject the zero sequence voltage into the phase-to-phase power flow control of the subsequent unit. The previous control unit is the same as the subsequent control unit, as shown below:

$$\begin{bmatrix} U_{out1,a} \\ U_{out1,b} \\ U_{out1,c} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} U_{out1,\alpha} \\ U_{out1,\beta} \end{bmatrix} + \begin{bmatrix} U_{0,sub} \\ U_{0,sub} \\ U_{0,sub} \end{bmatrix} \tag{18}$$

$$\begin{bmatrix} U_{out2,a} \\ U_{out2,b} \\ U_{out2,c} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} U_{out2,\alpha} \\ U_{out2,\beta} \end{bmatrix} + \begin{bmatrix} U_{0,former} \\ U_{0,former} \\ U_{0,former} \end{bmatrix} \tag{19}$$

IV. SIMULATION VERIFICATION

A. Simulation Settings

In order to verify the reliability of the operation of the DC hybrid distribution network system and the effectiveness of its control strategy, a simulation model was built on the Matlab/Simulink platform. The main simulation parameters are shown in Table 1.

TABLE I
MAIN PARAMETERS OF THE SIMULATION SYSTEM

Parameter	Value
Voltage of the front AC bus	690 V
Voltage of the subsequent AC bus	400 V
Grid frequency	50 Hz
Switching frequency	8 kHz
Impedance of AC side grid	1mH, 0.3mΩ
DC bus voltage	1200V

B. Comparative analysis

In order to verify the operating characteristics of the system under voltage imbalance and harmonic voltage, in the simulation process, the harmonic voltage is injected at 0.2s, the unbalanced load is connected at 0.3s, and the zero sequence voltage is injected at 0.5s. The latter unit adopts the controller voltage control, the outer loop adopts the PR controller to track the given reference sinusoidal voltage value, the inner loop adopts proportional control. After double-loop adjustment, the reference wave is given to the PWM generator. The PWM generator function compares the reference wave with the triangular carrier, and then determines the duty cycle of the output PWM wave. Fig.5 shows the comparison between the input reference voltage and the actual voltage in the voltage control PR link. It can be seen that when the reference voltage changes, the PR control can track the reference value in a short time and has a fast dynamic response.

In order to verify the effectiveness of the proposed control method under complex working conditions, in the experiment, before 0.5s, the grid impedance was relatively large, and the voltage of phase A was higher than the voltage of phase B and phase C. Fig.6 shows the grid voltage waveform diagram under three-phase unbalance. The zero-sequence voltage injection is started at 0.5s. Fig.7 shows the waveform after the zero-sequence voltage injection. It can be seen that after the zero-sequence voltage has been injected for a period of time, the power between the three phases gradually balances and tends to be consistent after steady state. At the same time, the zero sequence reference voltage returns to zero. When three-phase power imbalance occurs in the control system, the zero-sequence voltage injection method is started in real time. When the three-phase power is balanced, that is, when the system is stable, the zero-sequence voltage injection amplitude is zero, which can dynamically respond in real time and improve the stability of the distribution network.

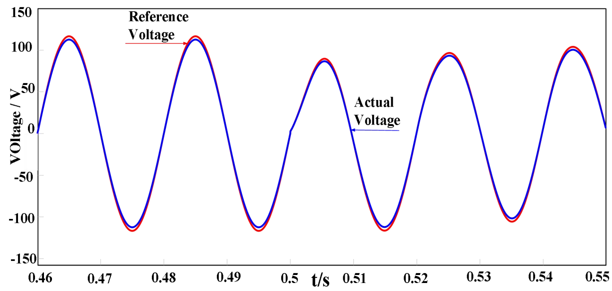

Fig.5. Voltage control waveform.

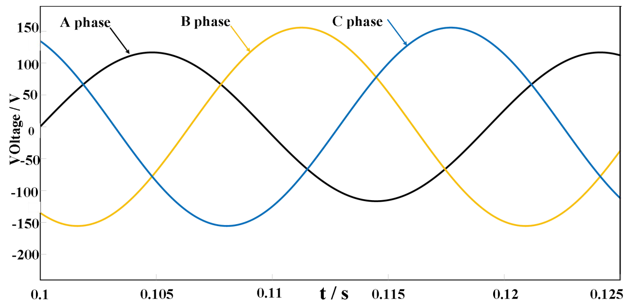

Fig.6. Grid voltage waveform diagram under three-phase unbalance.

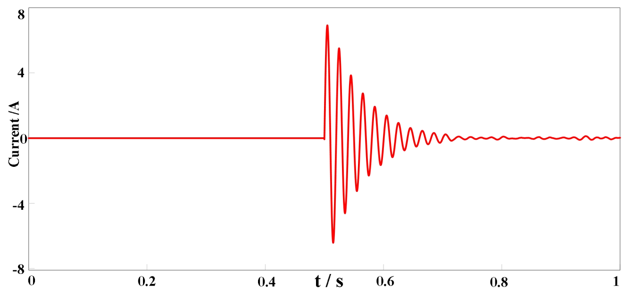

Fig.7. Waveform diagram of zero sequence voltage injection.

The power response of the front and rear converter units is shown in Fig.8 and Fig.9. It can be seen that before 0.5s, due to the voltage imbalance and harmonic voltage of the AC side grid, the three-phase output power difference is relatively large. When the zero-sequence voltage injection method is adopted after 0.5s, the output power of the three-phase unit is the same. Due to the small calculation amount of this method, the dynamic response of the system is fast, and the reliability of the power distribution system is improved.

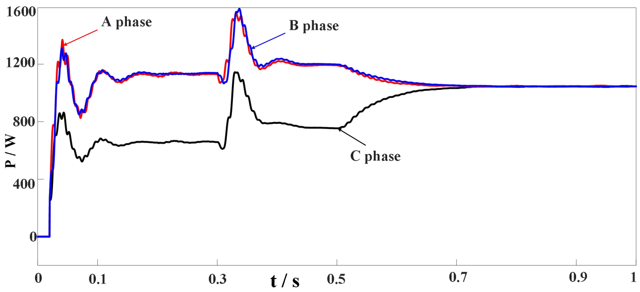

Fig.8. Three-phase power of the front unit.

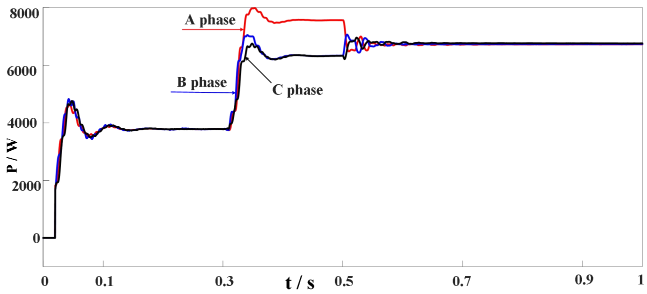

Fig.9. Three-phase power of the subsequent unit.

V. Conclusion

Considering the application scenarios of multiple voltage levels in the AC DC hybrid distribution network, while taking into account the control requirements of the stable operation of the distribution network system, an easy-to-implement voltage and current control strategy is adopted. The control adopted by this method does not require any detection of harmonic components, and can compensate low-voltage harmonics and high-voltage current harmonics at the same time, and does not require phase-locked loops and harmonic current extraction links during the entire simulation experiment. The problem of power imbalance between three phases in the distribution network is solved by the zero sequence voltage injection method. These methods can also improve power quality. The simulation experiments show that the control strategy adopted in this paper has good effectiveness and feasibility, and the method makes the power grid have good steady-state and transient characteristics. The proposed control strategy of distribution network is suitable for high power AC/DC hybrid topology and high voltage scenarios.

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Guo-Xiu Jing (Student Member, IEEE) was born in Shaanxi, China, in 1986. She received the B.S. degree in electrical engineering and the M.S.degree in control engineering from Nanchang University, Nanchang, China, in 2009 and 2013, respectively. She is a graduate student at the Faculty of Electronic and Information Engineering of Xi 'an Jiaotong University. Her current research interests include ac/dc hybrid distribution network in the controland protection, high performance ac drives, and multiphase motor drive.

Dong-Sheng Shuai was born in Jiangxi, China, in 1977. He received the B.S. degree in electrical engineering from Nanchang University, Nanchang, China, in 2001. He obtained senior Electrical Engineer, in 2013. He has obtained the national Registered Electrical Engineer certificate. He is a senior engineer at Jiangxi Province Coal Mine Design Institute. His current research interests include smart grid operation and control, distribution network automation technology.

Bing Zhang was born in Shaanxi, China, in 1983. He received the B.S. degree in transportation from Gansu Agricultural University, Gansu, China, in 2008. He is studying for a master's degree in energy and power engineering from Xi 'an Jiaotong University, Xian, China. His current interests include electronic generator control technology and new energy generation.