Study on coordinated control strategy of microgrid based on power electronic transformer

Yingzhe Huo¹, Qun Wang¹,*, Feng Li¹, Yanli Song², Chuanwu Zheng³, Zhixiong Yang³, Bangze Zeng³, Yulu Su², Jiqing Zhang³, Deli Zhao³, Gang Qin³, Linhui Xiang³

¹State Grid Liaoning Information and Communication Company, Liaoning, 110000, China
²Yunnan Provincial Hospital of traditional Chinese Medicine, Kunming, 650021, China
³Kunming Institute of Physics, Kunming 650223, China

*Corresponding author e-mail: gowork2018@126.com

Abstract. Microgrid can effectively improve the ability of power grid to absorb distributed energy. The new structure with power electronic transformer (PET) as the core of energy management is the new development direction of microgrid. A microgrid control strategy for coordinated operation of PET and energy storage is proposed. The interface converter of energy storage adopts constant voltage and constant frequency control to maintain the stability of voltage and frequency of microgrid. The low-voltage AC interface of PET connected to micro grid integrates the control of virtual synchronous generator to adjust the mechanical reference power according to the state of energy storage. Energy storage responds to the power fluctuation in microgrid rapidly, while PET maintains the stability of energy storage capacity through two-way power regulation and ensures the "flexible" exchange of power between microgrid and grid. Because energy storage and PET are controlled as voltage source interface at the same time, when one of them fails, the microgrid can still operate smoothly. Under this control strategy, microgrid operation can ensure the maximum efficiency of intermittent distributed energy utilization, and improve the stability, reliability and user friendliness of microgrid operation. Simulation and hardware in the loop hardware in the loop experiment results verify the correctness and effectiveness of the proposed control strategy.

1. Introduction

Microgrid is one of the effective ways to exert the efficiency of distributed energy resource (DER) [1]. With the deepening and development of microgrid technology, microgrid structure with power electronic transformer (PET) as the core has been proposed [2] one after another, and has been widely concerned. In this kind of microgrid, the energy storage devices such as DER and storage battery and the local load are usually connected to the main grid through the low-voltage AC interface provided by the power electronic transformer. PET transmits and manages the surplus and deficit power after the local absorption of distributed electric energy, and completes the active regulation and control of power flow,
power quality regulation and other functions [3]. This paper presents a coordinated control strategy of PET and energy storage in microgrid. PET is used as energy hub, its low voltage AC interface integrates VSG control to smooth power transmission, and energy storage SOC is adjusted based on weak communication. On the one hand, the proposed control strategy can solve the frequency fluctuation of microgrid and avoid the overcharging or over discharging of energy storage; on the other hand, when PET or energy storage fails, there is no need to switch the control strategy to ensure the stable operation of microgrid. Finally, the simulation and hardware in the loop experiment results verify the operation effect of the control strategy.

2. PET and BESS coordinated control strategy

The core of the coordinated control is to ensure the frequency stability of the microgrid, taking into account the regulation of energy storage capacity and the friendly interaction of power, and when PET or BESS fails, it can still ensure the microgrid to switch to the failure operation smoothly. The wind and PV of distributed energy use the mature MPPT algorithm [4], which will not be described in detail in this paper, and the coordinated control strategy of BESS and PET is given below.

2.1. BESS control

BESS is composed of battery, interface converter and LC filter. The output interface is connected with AC bus of microgrid. The purpose of BESS control is to provide stable voltage and frequency support for the microgrid, and output rapidly according to the fluctuating power of DER or load. Its interface converter adopts constant voltage and constant frequency (V/F) control based on voltage and current double closed-loop [5], and the control block diagram is shown in figure1.

![Figure 1. Control scheme of the BESS](image)

In Figure 1, \(i_{abc}\) is the filter inductance current, \(u_{abc}\) is the output voltage of the interface converter, and \(E_{ref}\) and \(f_{ref}\) are the given voltage amplitude and frequency reference values respectively. The phase of coordinate transformation is obtained by integrating the reference frequency \(\omega_{ref}\), the output voltage is converted by \(abc/dq\) to get the \(u_{od}\) and \(u_{oq}\) components, which are compared with the voltage reference \(E_{ref}\) and 0 respectively, and the error is PI controlled, so that the inner loop current reference signal \(i_{dref}\) and \(i_{qref}\) are obtained, and the inner loop current reference signal and the filter inductor current
components $i_{Ld}$ and $i_{Lq}$ are $PI$ controlled, current loop decoupled and $dq/abc$ transformed to get the voltage modulation signal $u_{ref}$.

The constant frequency of microgrid is generated by BESS interface converter, and the control accuracy is improved by voltage and current double closed-loop, which further enhances the anti-disturbance ability of microgrid frequency.

2.2. PET control

The input stage and isolation stage of PET adopt the double loop control and phase-shift angle control of traditional outer loop voltage and inner loop current respectively. The external loop voltage control of the input stage stabilizes the total voltage of all capacitors according to the measured capacitance voltage of the high voltage side, and the internal loop current control realizes the direct control of the grid connected current at the AC side of the input stage. The isolation stage controls the constant voltage of the low-voltage side capacitor through PI regulation, and then controls the phase-shifting angle to realize the bidirectional power flow.

The output stage of PET adopts VSG control as shown in Figure 2 [6], which aims to equivalent its external characteristics to synchronous generator, simulate the transmission of virtual inertia smooth fluctuating power, and provide voltage and frequency support of microgrid in case of BESS failure. Referring to the PET output stage structure in Figure 2b and the mechanical motion equation of synchronous generator, the virtual inertia is introduced into the output stage control to simulate the inertia and active frequency regulation characteristics of synchronous motor rotor. The active frequency control equation of VSG can be obtained as follows:

$$\begin{align*}
J \frac{d\omega}{dt} &= T_m - T_e + D_p (\omega_n - \omega) \\
P_{ref} &= T_m \omega \approx T_m \omega_n \\
P_e &= T_e \omega \approx T_e \omega_n
\end{align*}$$

Where, $J$ is the virtual moment of inertia; $D_p$ is the frequency droop coefficient; $\omega$, $\omega_n$ is the actual value and rated value of angular speed; $T_m$ and $T_e$ are the mechanical torque and electromagnetic torque; $P_{ref}$ is the mechanical reference power; $P_e$ is the active output power.

![Figure 2. Control scheme of VSG for the output stage of PET](image-url)
Similarly, based on the principle of synchronous motor regulating excitation to control its reactive output and induced electromotive force, the reactive voltage control equation can be obtained as follows

$$E = \frac{1}{K_s} \left[ Q_{ref} - Q_e + D_q (U_n - U_o) \right]$$

(2)

Where, $E$ is the effective value of voltage command; $D_q$ is the voltage droop coefficient; $U_o$ and $U_e$ are the effective values of voltage reference value and actual output value; $K$ is the voltage regulation coefficient; $Q_e$ is the reactive output power. The additional reactive power provided by PET to microgrid is not considered in this paper, and the reactive reference value $Q_{ref}$ is set to zero.

The frequency and voltage amplitude generated by active power frequency control and reactive power voltage control are sinusoidized to form the output voltage reference value $e$. according to the electrical equation of virtual synchronous motor, the output current command $i_{ref}$ is obtained.

$$i_{ref}(s) = \frac{1}{sL} \left( e(s) - u_0(s) \right)$$

(3)

Where, $L$ is the interface filter inductance and $u_0$ is the instantaneous value of output voltage. $i$ quasi proportional resonance (PR) controller is used to track the instantaneous value of output current $I$ to the current instruction $i_{ref}$ accurately, and the three-phase modulation wave $e_m$ of SPWM is obtained.

$$e_m = G_{PR}(S) \left( i(s) - i_{ref}(s) \right)$$

(4)

Where, $G_{PR}(s)$ is the transfer function of the quasi PR controller, and the expression is

$$G_{PR}(S) = K_p + \frac{2K_r \omega_s}{s^2 + 2\omega_c s + \omega_0^2}$$

(5)

Where $K_p$ is the proportional coefficient, $Kr$ is the resonance coefficient, $\omega_c$ is the fundamental angular frequency, and $\omega_0$ is the cut-off frequency.

2.3. PET and BESS coordinated control

Based on VSG control, the coordinated operation of PET and BESS is realized through the design of mechanical reference power. The specific control block diagram is shown in Figure 3. In Figure 3, when BESS is in normal operation, the switch is connected to point A, because the frequency of microgrid is clamped by BESS, the active power frequency regulation characteristic of VSG fails. PET adjusts the energy storage capacity according to the output power of mechanical reference power $p_{ref}$, then the expression of $p_{ref}$ is

$$p_{ref} = P_o + \Delta P$$

(6)

In the formula, $P_o$ is the base point operation power command, which is estimated by the difference between the predicted average output of DER and the load; $\Delta P$ is the regulating power that PET needs to output to maintain the stability of energy storage capacity. Since SOC can represent the remaining charge of the battery, if the instantaneous value of the state of charge of the battery can track the reference value of $SOC_{ref}$, the stability of BESS capacity can be achieved. Therefore, closed-loop control is applied to SOC, the instantaneous value of SOC collected is transmitted to PET controller, and the
difference between SOC and $SOC_{ref}$ after closed-loop feedback is controlled by PI to obtain the regulated power $\Delta P$.

$$\Delta P = \left( K_p + \frac{K_i}{s} \right) \left( SOC_{ref} - SOC \right)$$  \hspace{1cm} (7)$$

Where $K_p$ and $K_i$ are the proportional and integral coefficients of PI controller respectively.

Figure 3. Coordinated control scheme

In order to avoid the transmission power of PET exceeding the rated range in extreme cases, $SOC_{ref}$ is a reference value that can be adjusted dynamically. By changing $SOC_{ref}$, PET can control the active output of BESS. For example, when the wind, light and other output increase substantially, the surplus power transmitted from PET to the main grid exceeds its rated range, at this time, by increasing $SOC_{ref}$, BESS can absorb part of the electric energy and share the power transmitted by PET. According to the relationship between the outputs active power of the battery and its state of charge, there are

$$SOC = SOC_{ref} - \int \frac{I_{dc}}{Q} dt$$  \hspace{1cm} (8)$$

$$I_{dc} = \frac{P_{BESS}}{V_{dc}}$$  \hspace{1cm} (9)$$

$$Q = \frac{I_{dc, rate} C_{BESS, rate}}{P_{BESS, rate}}$$  \hspace{1cm} (10)$$

Where, $SOC_i$ is the initial value of the state of charge; $I_{dc}$ is the output current of BESS DC side; $V_{dc}$ is the voltage of BESS DC side; $P_{BESS}$ is the output active power of BESS; $I_{dc, rate}$ is the output DC current rating; $C_{BESS, rate}$ is the rated capacity of BESS; $P_{BESS, rate}$ is the rated active power of BESS. Substituting formula (8) and formula (9) into formula (10)

$$SOC = SOC_i - \int \frac{P_{BESS, rate} P_{BESS}}{V_{dc} I_{dc, rate} C_{BESS, rate}} dt$$  \hspace{1cm} (11)$$

Differential equation (11) on both sides at the same time, get
\[
\frac{d\text{SOC}}{dt} = -K_c P_{\text{BESS}}
\]

Where, \( K_c = P_{\text{BESS, rate}} / (V_{dc, rate} C_{\text{BESS, rate}}) \). Since \( V_{dc} \) is approximately constant, \( KC \) can be equivalent to a constant value. It is not difficult to find from equation (13) that the active output value \( P_{\text{BESS}} \) of BESS can be controlled by changing the slope \( d\text{SOC}/dt \), corresponding to the control in Figure 3. \( P_{\text{BESS}} \) and \( \text{ref} \) are the active power that PET wants BESS to share. By setting \( P_{\text{BESS, ref}} \), to change the slope of \( \text{SOC}_{\text{ref}} \), and then dynamically change the value of \( \text{SOC}_{\text{ref}} \), so as to adjust the active output of PET, so as to control BESS to share the expected active power \( P_{\text{BESS, ref}} \).

When BESS fails and stops working, the switch is connected with point B and the regulating power is zero. At this time, VSG active frequency regulation plays a role. PET adjusts the frequency of microgrid according to the droop characteristics, and bears the active difference between der and load. From the active frequency control loop in Figure 4, it can be determined that the frequency droop coefficient \( D_p \) is

\[
D_p = \frac{\Delta T}{\Delta \omega} = \frac{\Delta P}{2\pi \omega_0 \Delta f}
\]

Where, \( \Delta f \) is the variation range of frequency offset of microgrid; \( \Delta P \) is the variation of active power output corresponding to PET.

3. Simulation and experiment

3.1. Simulation analysis

In order to verify the correctness and effectiveness of the proposed control strategy, based on the system structure shown in Figure 1, a microgrid simulation model is built on the MATLAB / Simulink platform, and different conditions are set up for simulation. The distributed energy in the model includes wind turbine and photovoltaic, and lead-acid battery is widely used for energy storage. The cascade number of PET input stage is 3, and the single-phase AC main power grid with effective value of 10kV is connected. The capacitance voltage at the low-voltage side is maintained at 800V. The main parameters of simulation are shown in Table 1.

| parameter | numerical value |
|-----------|----------------|
| Maximum fluctuation power of fan / kw | 83 |
| Maximum fluctuation power of photovoltaic / kw | 33 |
| Bess rated capacity (A h) | 4 |
| Pet rated power / kw | 100 |
| Controllable load / kw | 0~100 |
| SOC reference value \( \text{SOC}_{\text{ref}} \) | 0.5 |
| Base point operating power command / kw | 10 |
| Average output of fan / kw | 65 |
| PV average output / kw | 25 |
| Frequency droop coefficient / (Nm · s / rad) | 50.6 |
| Line voltage rating / V | 380 |
| Frequency rating / Hz | 50 |
| PI control scale factor | 120 |
| PI control integral coefficient | 200 |
3.1.1. **Condition 1: random fluctuation of wind power output.** The actual output of wind and solar power is shown in Figure 4A. The fluctuation range of fan output is 47.5-83kw, and that of photovoltaic output is 18-33kw. The total load demand is 100kW. Figure 6B to figure 6D show the waveforms of active power and SOC output by BESS and PET respectively. It can be seen that BESS can quickly respond to the unbalanced power of wind and load when the wind and power output fluctuates, so as to ensure the balance of internal load supply and demand of microgrid; while PET reflects virtual inertia, slowly adjust the output power according to SOC, support the operation of BESS, and maintain the stability of SOC. In this simulation, SOC Figure 6 simulation waveform of wind power output fluctuation

There are fluctuations near the reference value, one is because of the inertia controlled by the virtual synchronous motor, PET output is slow, and the other is because of the fluctuation of wind power output. When there is no power fluctuation in the microgrid in condition 2, SOC can fit the reference value well. As can be seen from figure 4e, the frequency of microgrid is well stable at 50Hz, and it is hardly affected by the wind and rain fluctuation.

3.2. **Experimental analysis**

To verify the correctness of the theoretical analysis, a hardware in the loop hardware in the loop experimental device based on RT-LAB is built. The main controller and op5600 real-time emulator are used to model the wind, BESS and PET modules. The sampling period of the control system is 6.4 kHz. DSP2812 is selected for PET and BESS controllers, which are respectively connected with RT-LAB's signal acquisition and output board card through signal conversion module. The experimental parameters are consistent with the simulation parameters. In the same condition, the random fluctuation of wind and solar power and the hardware in the loop experiment of PET failure were carried out.

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**Figure 4.** Simulation waveforms under wind and PV power fluctuation
Figure 5. HIL waveforms under wind and PV power fluctuation

Figure 5 shows the experimental waveform of hardware in the loop when the wind power output fluctuates. It can be seen that the experimental results are consistent with the simulation results. When the wind power fluctuates, BESS can quickly respond to the fluctuating power. PET also reflects the virtual inertia characteristic and slowly adjusts the energy storage capacity. From the charging and discharging power of BESS and the corresponding time, it can be roughly seen that the power of energy storage release and energy absorption is the same, and the SOC can be maintained near the reference value. At the same time, the frequency of microgrid is stable, the fluctuation value is minimal, the voltage and current of AC bus is smooth, the voltage amplitude is stable, and the overall operation performance of microgrid is good.

Figure 6. HIL waveforms under PET fault

Figure 6 shows the hardware in the loop experimental waveform of energy storage independent support microgrid operation in case of PET failure. As the result of simulation analysis, BESS can respond to the unbalanced power of wind and load after PET failure, and the frequency of microgrid is stable. During the fault switching, the voltage of microgrid has almost no distortion and the amplitude is stable, and the frequency is within the allowable range. It can generate small jitter and realize smooth switching at PET fault time. Similar conclusions can also be drawn from the experiment of BESS failure, which are limited to space and will not be given any more.
4. Conclusion

In this paper, a coordinated control strategy of PET and BESS is proposed for the microgrid structure based on power electronic transformer. The principle of PET and BESS coordinated operation under the microgrid system structure is described and analyzed, and the specific coordinated control method of PET and BESS is given. The simulation and hardware in the loop hardware in the loop experiment are carried out, and the following conclusions are obtained:

1) BESS adopts constant voltage and constant frequency control to stabilize the frequency at the rated value, and can quickly respond to power fluctuation to ensure the active power balance of microgrid.

2) PET maintains the stability of energy storage capacity, and realizes the control of BESS output power by adjusting $SOC_{ref}$. The virtual synchronous motor control makes PET interface have the virtual inertia of synchronous motor, and ensures the "flexible" exchange of power between microgrid and grid.

3) When PET or BESS fails, microgrid can switch to failure operation smoothly, which improves the reliability of system operation.

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