Characterisation of Grid Short-Circuit Faults with Energy Storage Plant

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***Abstract*—With a large number of new energy power stations connected to the grid, the power quality of the grid will be affected, in this regard, through the grid-connected energy storage power station to suppress the intermittent new energy generation characteristics such as wind power, and large-scale energy storage power station access to the grid will also have an impact on the grid short-circuit current, this paper through the study of different ways of grid-connected storage power station to obtain the short-circuit current of the output of the storage station in different ways to get with the grid type and structural grid type short-circuit current differences in the output of the storage power station. This paper investigates the different ways of grid-connected energy storage plants, obtains the output short-circuit current of energy storage plants under different control methods, gets the difference between the output short-circuit current of grid-following-type and grid-forming-type energy storage plants, and then obtains the short-circuit fault characteristics of the grid containing energy storage plants, and builds a simulation model and a short-circuit current calculation program under MATLAB/Simulink with a certain localized power grid of Shanxi Province, to verify the theoretical accuracy.**

***Keywords*—Energy storage plant, grid-following type, grid-configuration type, short-circuit current**

I. INTRODUCTION

China has clearly proposed to reach carbon peak by 2030 and strive for carbon neutrality by 2060, putting forward clear requirements for the development of renewable energy, while the ‘Fourteenth Five-Year Plan’ and the Outline of the Vision for 2035 have also put forward clear tasks for the development of renewable energy, with the aim of constructing a clean, low-carbon, safe and efficient energy system, controlling the total amount of fossil energy and focusing on improving the efficiency of its use, and implementing actions to replace renewable energy. The aim is to build a clean, low-carbon, safe and efficient energy system, control the total amount of fossil energy, focus on improving the efficiency of the use of renewable energy substitution, deepen the reform of the electric power system, and build a new type of power system with new energy as the main body. Energy storage power station has two functions of storing and releasing electric energy, which means that the energy storage power station can be used as both power supply and load power. The access of large-scale energy storage power station, on the one hand, makes the power grid from the original simple single-side power supply network into a complex dual power supply or even multiple power supply network, the size of the short-circuit current has become complex to judge, on the other hand, due to the introduction of the energy storage converter, making the transient characteristics of the system short-circuit current changes, the traditional short-circuit current discrimination is no longer applicable to the new power system.

Literature [1] analyzed the fault characteristics of IIDGs in microgrids, but the analysis results are not applicable to IIDGs directly connected to the grid.Literature [2] investigated the fault characteristics of IIDGs with constant power control and constant voltage-frequency control but the theoretical analysis is insufficient.Literature [3] studied the fault current characteristics of IIDGs operating in isolated islands. The control strategy of the grid-connected IIDG is different from that of the islanded IIDG.The control strategy of grid-connected IIDGs is different from that of islanded IIDGs, which leads to a big difference in fault current characteristics; literature [4] studied the fault current characteristics of grid-connected IIDGs, but did not fully consider the reactive power support requirements of IIDGs on the grid during the LVRT process.

In the field of power system relay protection, the measurement of short-circuit current is an important way to judge the occurrence of short-circuit faults in the circuit. Therefore, it is particularly important to reasonably analyse and calculate the impact of energy storage power plants on the system short-circuit current [5].

II. Modelling Methods for Energy Storage Plants

A typical BESS consists of an energy storage battery, converter, transformer, battery management system and monitoring system. It is shown in Figure 1.

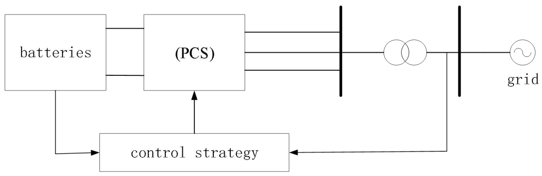


Fig. 1. Structure of grid-connected energy storage

The main components of the energy storage converter are the inverter and the filter, and there are two typical topologies of the energy storage system, the single-stage topology and the two-stage topology, and the two-stage topology is adopted in this paper. The bi-directional AC/DC converter consists of six IGBTs connected in parallel with diodes in a three-phase bridge structure, in which the LC-type filter has gradually replaced the traditional L-type filter in practical applications due to its excellent attenuation effect of high harmonics and its performance advantage at low switching frequency, Fig. 2 shows the two-stage topology of the three-phase grid-connected inverter[6].

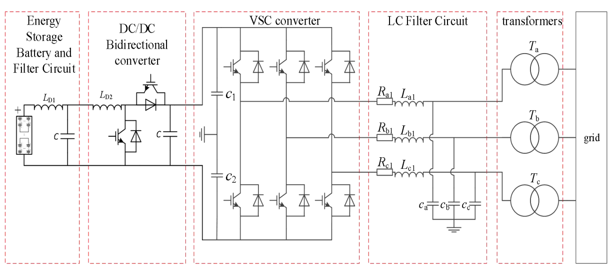


Fig. 2. Three-phase grid-connected inverter two-stage topology diagram

Using a two-stage topology DC side does not require a complex LC filter, small battery measurement ripple, higher control accuracy, and short charging and discharging conversion time. Large-capacity stand-alone design, the DC side can be implemented using multiple DC/DC, each DC/DC unit can be connected to an independent battery pack, without the need for multiple battery packs connected in series and parallel, reducing the difficulty of battery pack configuration; a single group of batteries due to failure replacement, will not degrade the performance indicators of the whole system. AC side or DC side failure, due to the existence of DC/DC circuit link, can effectively protect the battery, to avoid the battery to withstand the impact current, to extend the service life of the battery.

The energy storage system enables a bi-directional flow of energy between the three-phase grid-connected inverter and the grid.

III. Grid-connected Control Strategies for Energy Storage Plants

A. Charge/Discharge Control

The energy storage plant has three operating states, namely, discharge, charge and standby. Batteries are used as energy storage units, and the DC output during discharge operation is converted to AC by a pulse width modulation (PWM) inverter and connected to the grid. The grid-connected energy storage system adopts different control methods according to different topologies. The single-stage topology converter system consists of a bi-directional converter to realise the active and reactive power control of the system, and a double closed-loop to realise the grid-connected control of the energy storage system, with the inner loop controlling the input and output currents of the storage system, and the outer loop selecting either the constant power (P/Q) control or the constant voltage control according to the control objective. The two-stage topology grid-connected system can have the following two combinations of control modes: one is to take the output power of the AC side as the main control object, to achieve the constant power output of the AC side, the bidirectional converter adopts the P/Q control to control the input and output power of the energy storage system, and the DC/DC converter adopts the constant voltage control to control the DC bus voltage, in order to maintain the stability of the DC bus voltage; the second one is to take the voltage of the DC side as the main control object To achieve the stability of the DC side voltage, the bidirectional converter adopts constant voltage control to maintain the DC bus voltage constant, and the DC/DC converter adopts constant current control to control the charging and discharging power of the energy storage device on the DC side, so as to realise constant current charging and discharging. The charge/discharge control strategy is shown in Fig. 3.

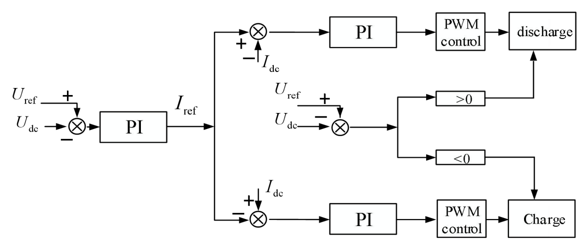


Fig. 3. Charge/discharge control block diagram

The DC/DC converter adopts constant voltage control, as shown in Fig. 3, and the difference between the DC bus reference value U_{ref} and the actual value U_{dc} is used by the PI regulator to provide the energy storage side with the current reference value I_{ref} . The energy storage system is discharged when $U_{\text{ref}} > U_{\text{dc}}$, and charged when $U_{\text{ref}} < U_{\text{dc}}$.

B. PQ Control in Concert with Low Voltage Ride-through Control

The P/Q control is based on the active and reactive power of the energy storage system as the reference command.The block diagram of the P/Q control is shown in Fig. 4. P_{ref} and Q_{ref} are the reference values of the given power, and P and Q are the measured and calculated values, respectively; i_{dref} and i_{qref} are the reference values of the dq-axis components on the AC side, respectively; i_d and i_q are the measured and calculated values of the dq-axis components on the AC side, respectively; u_d and u_q are the measured and calculated values of the dq-axis components of the inverter output voltage, respectively; u_{dl} and u_{ql} are the reference values of the dq-axis components of the inverter output voltage obtained by decoupling calculation, respectively; L is the inductance of the AC side; and θ is the phase angle of the voltage of the grid-connected system[7].

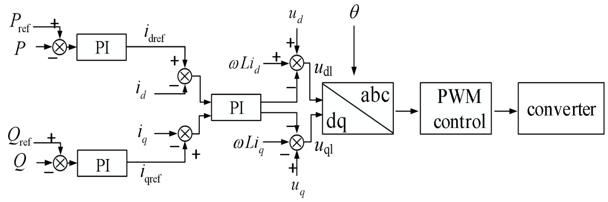
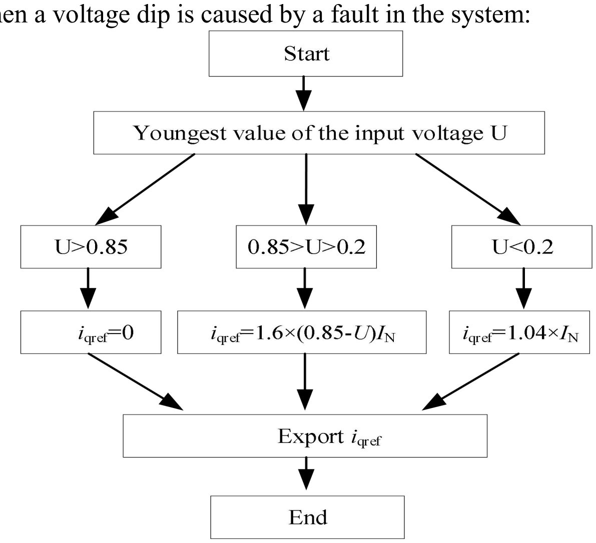


Fig. 4. PQ Control Block Diagram

In the grid-connected operation of the energy storage system, the energy storage converter is required to have a low-voltage ride-through capability, so that the energy storage system can operate continuously without disconnecting from the grid within a certain range of voltage dips and time intervals, and provide a certain amount of reactive power to the grid to support the grid voltage [8].

According to the Technical Specification for Energy Storage Converters for Electrochemical Energy Storage Systems, the dynamic reactive current i_{qref} injected into the grid by the energy storage converter of the electrochemical energy storage system shall meet the following requirements when a voltage dip is caused by a fault in the system:



Where: U for the parallel network point voltage Missing Value, I_N for the rated output current of the energy storage system.The active current reference value i_{dref} of the current inner loop control takes the smaller value of i_{dref0} and $\sqrt{I_{max}{}^2 - \left(i_{qref}\right)^2}$. i_{dref0} is the active current reference value of the energy storage inverter before the failure of the energy storage system. I_{max} is the maximum output current of the energy storage system, I_N is the rated output current of the energy storage system, and the block diagram of the LVRT control strategy is shown in Fig. 5.

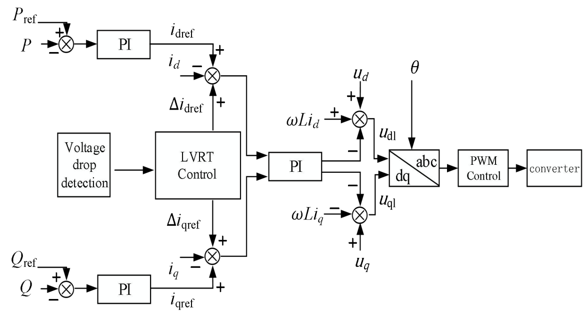


Fig. 5. LVRT control block diagram

C. Droop Control

The studies in this chapter are carried out in the case where the line impedance is inductive, and there exists X>>R, the line resistance R is negligible, i.e., R=0 . At this point, the difference in the phase angle of the voltages between the AC side of the inverter and the common point is very small, so the approximation has $\sin\varphi \approx \varphi, \cos\varphi \approx 1$,. Therefore.

$$P_i = \frac{U_{PCC} U_i}{X_i} \varphi_i \tag{1}$$

$$Q_i = \frac{U_{PCC}\left(U_i - U_{PCC}\right)}{X_i} \tag{2}$$

In general, it is necessary to ensure that the common point voltage Upcc is stable, so its value can be approximated as constant. The size of the active power output from the inverter is mainly related to φ , and the reactive power is related to the voltage magnitude U_i , and the relationship between them is linear. Therefore, by changing the phase angle and amplitude of the inverter output voltage, the active and reactive power can be changed. However, in field operation, the phase angle φ is not easy to measure, and there is an integral relationship $f = \mathrm{d}\varphi / (2\pi \cdot \mathrm{d}t)$ between f and φ . Therefore, the control of phase angle can be achieved by controlling the frequency [9].

Based on the output characteristics of the inverter the droop characteristic equation can be obtained as

$$\begin{cases} f = f_0 - m\left(P - P_0\right) \\ U = U_0 - n\left(Q - Q_0\right) \end{cases} \tag{3}$$

Where f and U denote the frequency and amplitude of the output voltage of the inverter; P and Q denote the active and reactive power output from the inverter; f_0 and U_0 denote the reference values of frequency and amplitude; P_0 and Q_0 denote the reference values of active and reactive power; and m and n denote the droop coefficients of the active and reactive power, respectively.

$$\begin{cases} m = \dfrac{f_0 - f_{\min}}{P_{\max} - P_0} \\ n = \dfrac{U_0 - U_{\min}}{Q_{\max} - Q_0} \end{cases} \tag{4}$$

The droop control module firstly calculates P and Q according to the power measurement part, and then generates the voltage frequency ω and amplitude U with the help of the droop characteristic curve, and then according to the relationship between the frequency and the phase angle, it can get the input reference voltage of the voltage-current double closed-loop control module. The schematic diagram of the droop control module is shown in Fig. 6.

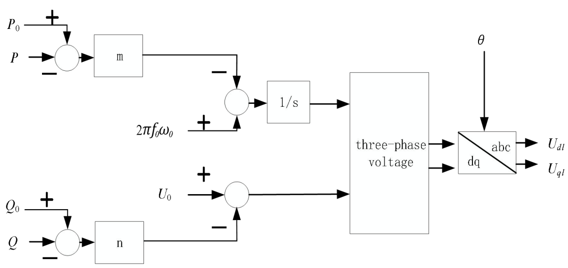


Fig. 6. Droop control block diagram

D. VF Control

The voltage-current double closed-loop control takes the output voltage as the outer-loop control and the filter inductor current as the inner-loop control, as shown in Fig. 7. In the figure, u_{ref} is the reference value of the given voltage; u_{dref} and u_{qref} are the dq component of the voltage reference value; i_{dref} and i_{qref} are the reference value of the dq axis component of the AC side current; i_d and i_q are the actual value of the dq axis current of the AC side current; v_d and v_q are the actual value of the dq axis component of the output voltage of the inverter; v_{sd} and v_{sq} are the reference value of L_s is the coupled inductance of the AC side; f is the the given frequency command; ω is the initial electrical angle of the voltage; θ is the phase angle of the voltage [10].

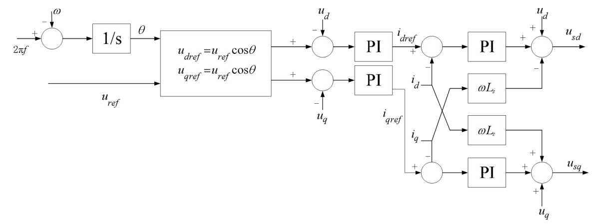


Fig. 7. VF control block diagram

This control strategy, on the basis of the voltage closed-loop, adds the current inner-loop, which realises the control of both the output voltage RMS and the waveform of the output current. The voltage outer-loop control provides voltage support for the AC side, and the inductor current inner-loop control can quickly track load changes and improve dynamic response speed.The simulation analysis of V/f control characteristics is shown in Fig. Under off-grid condition, the voltage and frequency of the parallel network point under V/f control, etc. When the load input changes, the voltage remains unchanged, and the current changes with the change of load power, the main role of V/f control is to keep the voltage and frequency of the parallel network point unchanged [11].

IV. SHORT-CIRCUIT CURRENT CHARACTERISTICS OF ENERGY STORAGE PLANT

When the energy storage power station is connected to the grid, when a three-phase short-circuit occurs at a certain point in the grid, the voltage at the point of the grid drops by 50%, switching between different control modes, the short-circuit current output from the energy storage power station is as follows

A. PQ Control in Concert with Low Voltage Ride-through Control

The figure 8,9 and 10 shows the power, voltage and current output of the energy storage plant when a three-phase short-circuit occurs somewhere in the grid under the grid-connected condition of the PQ-controlled energy storage plant.

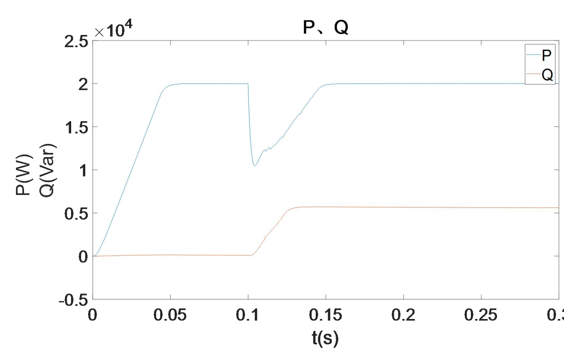


Fig. 8. Active and reactive power under faults

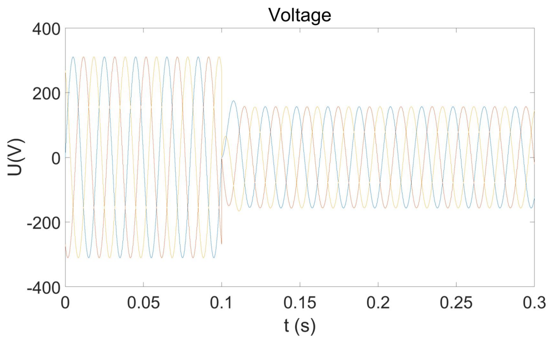


Fig. 9. Short-circuit voltage

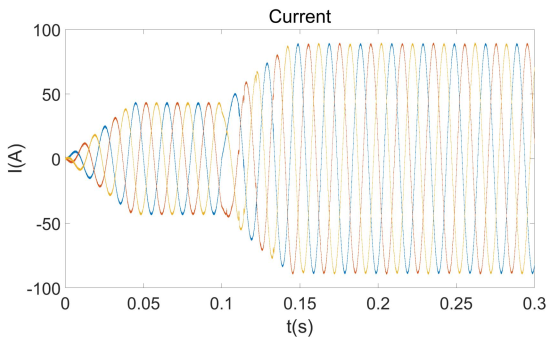


Fig. 10. Short-circuit current

B. *Droop Control*

The figure 11,12 and 13 shows the power, voltage and current output of the energy storage plant when a three-phase short-circuit occurs somewhere in the grid under the grid-connected condition of the droop control energy storage plant.

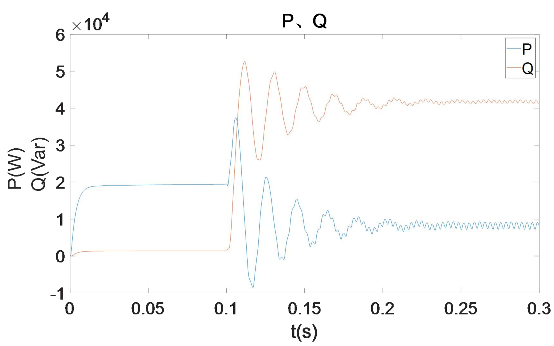


Fig. 11. Active and reactive power under faults

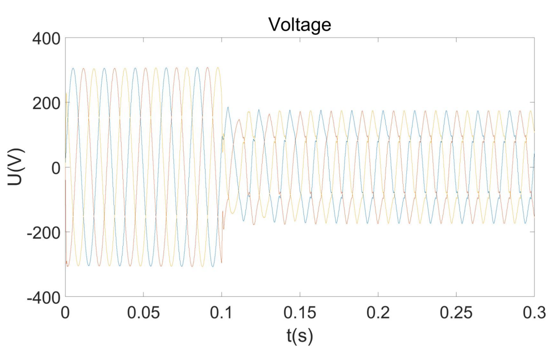


Fig. 12. Short-circuit voltage

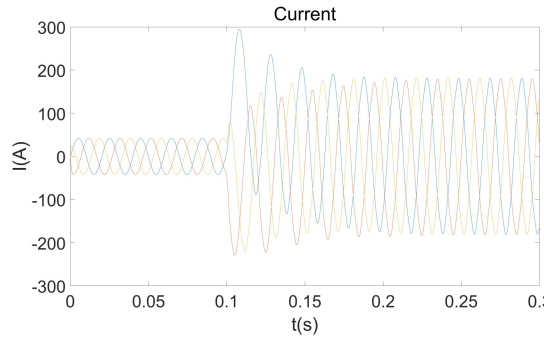


Fig. 13. Short-circuit current

C. *VF Control*

The figure 14,15 and 16 shows the power, voltage and current output of the energy storage plant when a three-phase short-circuit occurs somewhere in the grid under the grid-connected condition of the VF control energy storage plant.

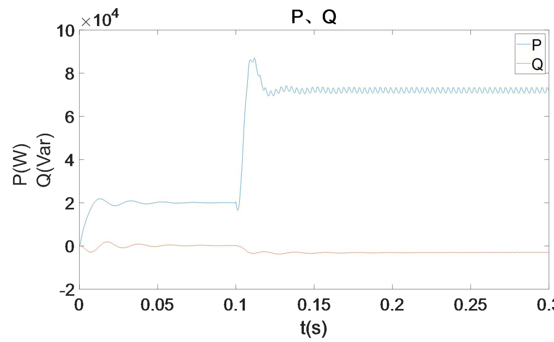


Fig. 14. Active and reactive power under faults

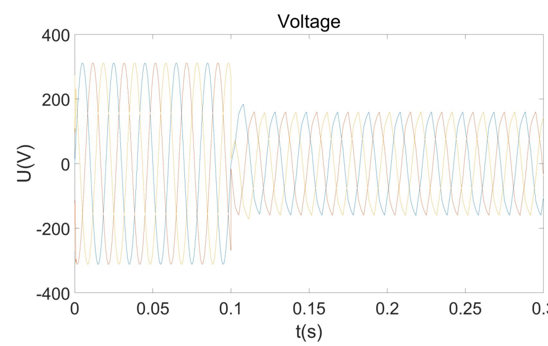


Fig. 15. Short-circuit voltage

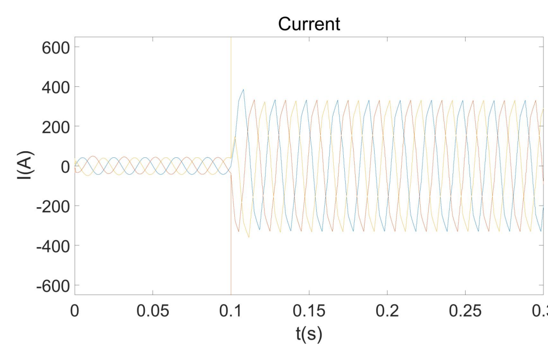


Fig. 16. Short-circuit current

V. Differences between Grid-following and Grid-forming Converters

The output short-circuit current of the energy storage plant varies greatly under the three control modes, in which the PQ control belongs to the grid-following type converter, and the droop control belongs to the grid-conforming type converter, which can be equated to a controlled current source connected in parallel with an impedance, and usually adopts a phase-locked loop to trace the phase angle of the grid to ensure that the converter is synchronised with the grid and the measured phase angle is used as the current control. A grid-type storage converter is equivalent to a controlled voltage source connected in series with an impedance, which is self-synchronised with the grid by the principle of power synchronisation of a conventional generator and does not require a phase-locked loop to measure the grid phase angle. The GFM has a faster power response to improve the frequency stability of the system compared to a conventional generator that improves the grid frequency stability by releasing the kinetic energy stored in the rotating rotor.

1. GFM

The main characteristic of a grid-constructing converter is its ability to autonomously form a grid and independently regulate voltage and frequency. Its control strategy is usually similar to that of a synchronous generator, so that it is able to provide higher short-circuit currents in the face of short-circuit faults. The main impacts include: higher short-circuit current contribution: the grid-type converter is able to mimic the behaviour of a synchronous generator by actively regulating the output voltage and current to provide a certain amount of short-circuit current support in the event of a fault. This allows the system to have relatively high current levels during a short-circuit, especially in microgrid or islanding operation scenarios, where the GFM converter can respond to a short-circuit event like a conventional generator. Strong voltage support: Because it can actively regulate the system voltage, it can still support the voltage near the point of fault even during a short-circuit, helping to quickly restore system stability.

2. GFL

A grid-following converter, on the other hand, relies on external grid signals (usually voltage and frequency) to synchronise and adjust its own output. It therefore has a more passive behaviour in the face of short-circuit faults and its contribution to short-circuit current is relatively low. Specific effects include:

Lower short-circuit current contribution: The current output of a grid-following converter is usually limited by its internal control strategy, especially when the voltage of the external grid drops significantly. As a result, the GFL converter's contribution to the short-circuit current in the event of a short-circuit fault is relatively low and will not provide as large a short-circuit current as a synchronous generator.

Dependence on external grid voltage support: The GFL converter relies on the voltage and frequency signals provided by the grid for its operation, and is therefore weakly supported by the voltage during a short circuit. If the grid voltage collapses, the GFL converter may not be able to provide effective power support.

The GFM converter is able to provide higher short-circuit currents during short-circuits, and has strong support for grid voltage and frequency, which makes it particularly suitable for islanded operation or microgrid scenarios.

The GFL converter has a lower current contribution during short-circuit and relies on grid signals for its operation, and therefore exhibits weaker voltage support during grid faults.

As shown in Fig. 17 is the comparison of RMS values of short-circuit currents under the three control modes. the VF control output short-circuit current is the largest, followed by the droop control, and the PQ control short-circuit current is the smallest.

Since PQ control is constant power control, when the grid voltage dips, its output current increases compared to normal, but the power remains constant; with sag control, the converter reactive power command increases due to the voltage drop of 50% at the PCC point, which sends out reactive power to support the voltage, thus increasing its total apparent power, which in turn makes the output current increase more.The grid-type converter mostly uses sag control, and its effect on short-circuit current will be even greater. In some field test conditions, the converter is required to have an overcurrent capacity of 3 times under such conditions, the short-circuit current provided by the converter at this overcurrent multiplier will rise sharply to 1.3-3 times the rated current, and its impact on the grid short-circuit current will be further increased.

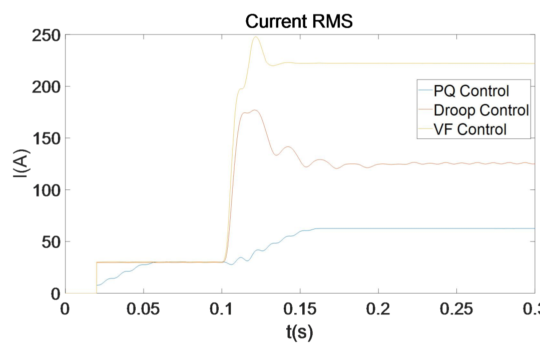


Fig. 17. RMS short-circuit current

Comparison of short-circuit currents at the output of an energy storage plant under three control methods.

TABLE I. Short-circuit Current

Short-circuit current supplied by energy storage plant	
control method	Three-phase short circuit/A
PQ Control	62.6
Droop Control	125.1
VF Control	221.2

VI. Calculus Analysis

Selecting a local power grid in Shanxi Province and building a simulation model in MATLAB/Simulink

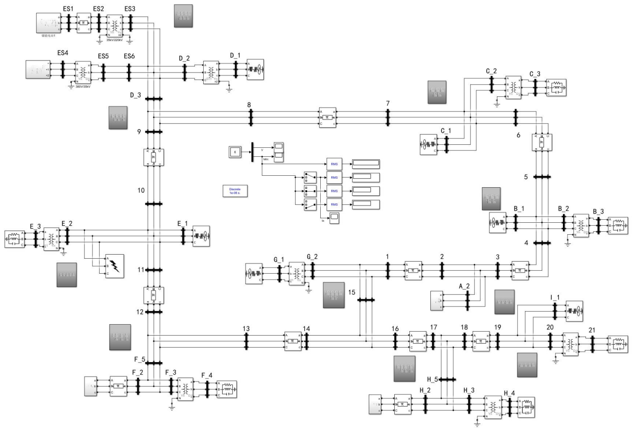


Fig. 18. Grid Simulation Models

In the event of a three-phase short-circuit fault at different locations on the grid, the circuit currents output from the energy storage plant are shown in Table 2

TABLE II. SHORT-CIRCUIT CURRENT

Short-circuit current supplied by energy storage plant (220kV side)	
Parallel Point Voltage	Three-phase short circuit/kA
$0.7U_N$	0.351
$0.5U_N$	0.513
$0.3U_N$	0.826

VII. CONCLUSION

When a short-circuit occurs in the grid containing an energy storage plant, its short-circuit current characteristics mainly depend on its converter control method, when PQ control is used, its short-circuit current is limited to the maximum output power, so the output current is smaller, when droop control is used, it mimics the behaviour of synchronous machines, with strong voltage support capability, more output power and greater output short-circuit current.

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