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DISTRIBUTION NETWORK OPTIMIZATION STRATEGY AND RELIABILITY ANALYSIS CONSIDERING LARGE-CAPACITY ENERGY STORAGE SYSTEM

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Abstract: As an important distributed power source, energy storage systems are gradually being used in distribution networks. This article is based on the 10kV distribution network system taking into account the large-capacity energy storage system, which introduce the principle of the energy storage system access to the distribution network and analyze the control strategy of the energy storage system under different working modes and propose an optimization modeling method for energy storage system based on genetic algorithm. Finally, using the failure mode consequence analysis method to calculate the reliability analysis index of the distribution system, and then verifing that the application of the energy storage system can improve power supply reliability of distribution network.
Keywords: Energy storage system; Distribution network; Optimization strategy; Reliability analysis; Genetic algorithm

1 INTRODUCTION

The research and development of energy storage technologies have been highly concerned by the energy, transportation, power, and telecommunications sectors in various countries, and have been of great significance to the development of new energy industries. In a sense, the degree of application of energy storage technology will determine the level of new energy development. In the field of electricity, energy storage technology is gradually being applied to distribution networks. When distribution networks are connected to large-capacity energy storage systems, the operation and management of distribution networks will become more complicated[1-3]. Therefore, the analysis of the working mechanism and reliability of energy storage system linked distribution network is a subject worthy of study[4-6]. The connection between energy storage system and distribution network involves four typical operating modes. During the process of switching the operating mode, it is necessary to carry out transition control of the process to avoid large voltage or current impact due to voltage amplitude, frequency, phase and other factors causing the negative impact on the load. The link between energy storage system and distribution network also needs to consider how to optimize the charging and discharging strategy of the scheduling energy storage system to improve the stability of the voltage at the end node of the distribution network[7-10].

Section 1 of this paper describes the working principle of the energy storage system accessing the distribution network, analyzes the grid connection mode of the energy storage system through the PQ control strategy and the off-grid model of the V/F control strategy.Then,designing the system wiring diagram after the energy storage system is connected to the 10kV distribution network to furtherly analyze the process of switching the energy storage system off-grid to off-grid and off-grid switching to the grid. In Section 2 of this paper, based on the genetic algorithm, taking the minimum variance of the load curve as its objective function, and finding the optimal solution within the linear constraints of capacity and charge-discharge power as the optimal scheduling strategy of charge and discharge of the energy storage system for improving the stability of the voltage at the end node of distribution networks that access large-capacity energy storage systems. In section 3 of this paper, the failure mode consequence analysis method is used to calculate the failure rate before and after the energy storage system is connected to the distribution network, the time of blackout of each fault, the annual outage time and the reliability analysis index of the distribution system. The results show that the energy storage system can improve the power supply reliability of the distribution network.

2 ENERGY STORAGE SYSTEM ACCESS PRINCIPLE AND WORKING MODE CONTROL STRATEGY

1.1 Energy Storage System Access Principle

The energy storage system is a system that connects an energy conversion device with an energy storage battery pack and is connected with a power grid to store the grid energy in a battery pack or feed the battery pack energy back to the grid. The schematic diagram of the main working module of energy storage system is shown in Figure 1.

Energy conversion system (PCS) consists of DC/AC three-phase high-frequency bidirectional converter, DC/DC bidirectional buck-boost chopper, PCS control unit. The energy conversion device PCS controller receives the background control instruction through communication, and controls the converter to charge or discharge the battery according to the sign and size of the power instruction to realize the adjustment of the active power and reactive power of the power grid. The PCS controller communicates with the battery management system through the CAN interface and obtains battery pack status information, which can realize protective charge and discharge of the battery and ensure battery operation safety[11].

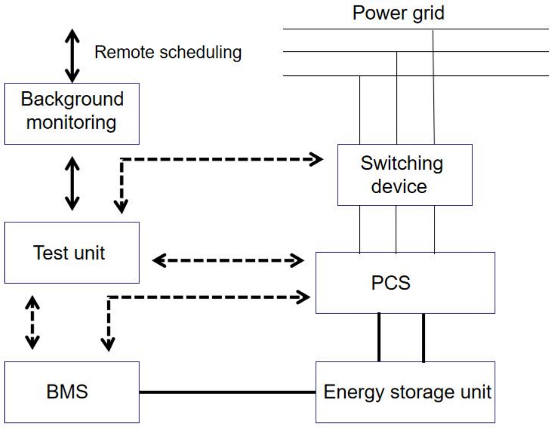

Figure 1 Schematic Diagram of Main Working Modules of Energy Storage System

1.2 Energy Storage System Working Mode Control Strategy

In grid-connected mode, according to the active and reactive power commands, PCS implements active and reactive power control through PQ control strategy. The fundamental sine variable in the stationary three-phase coordinate system is transformed into the direct current component in the synchronous rotating coordinate system through coordinate transformation to realize the decoupling control of active and reactive power in energy-storage grid-connected. When the voltage of the grid is lower than the normal voltage range, the terminal voltage of the grid system is increased by increasing the power output of the energy storage system; conversely, when the voltage is higher than the normal voltage range, the terminal voltage of the power supply system is reduced by the increase of the power absorption of the energy storage system[12-13].

Taking the 1MW/2MWh storage system grid connection as an example, the main wiring diagram of the energy storage system interconnection mode is shown in Figure 2. Both battery packs have a capacity of 1 MWh. After PCS, the DC power is reversed to AC power, then boosted to 10 kV by a step-up transformer, and finally integrated into the grid.

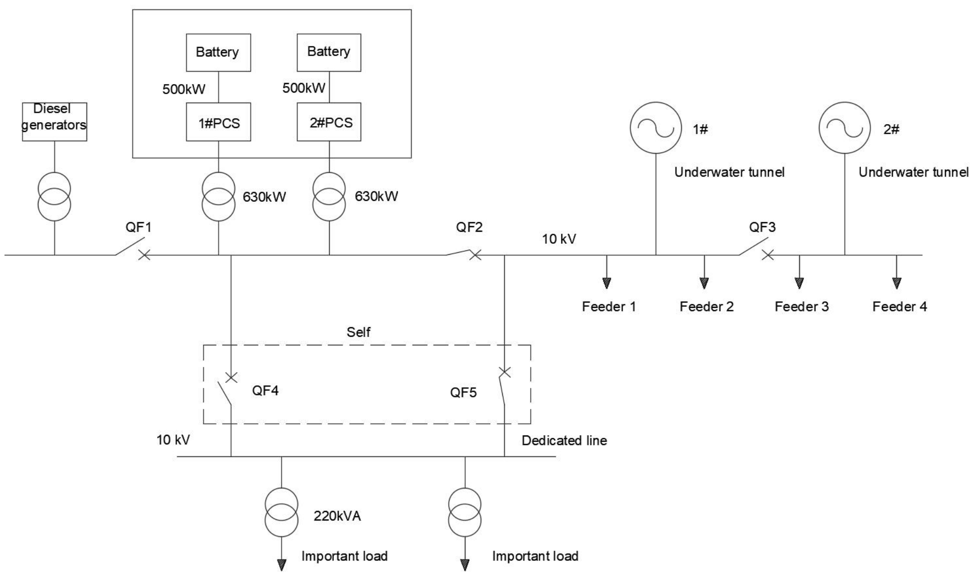

Figure 2 Main Wiring Diagram of the Energy Storage System In Grid Mode

Grid-connected working process: when the two-way power supply is normal, the QF2 and QF5 switches are closed, and the QF3 and QF4 are disconnected. The centralized monitoring system of the energy storage system controls the charge and discharge power of the energy storage system through communication instructions. The energy storage system can be charged during the low-power period. Discharge at the peak of electricity usage and provide reactive power support for distribution network to improve the power quality of the terminal distribution network. When there is a fault in one line of the cable, the energy storage system and the other cable support the load together and do not need to cut the load, which greatly improves the reliability of the power supply of the load.

In the off-grid mode, when the energy storage system operates as the main power source in the power grid or the energy storage system independently supplies power to the load, it must provide voltage (V) and frequency (F) support for the load to maintain the stability of the grid voltage and frequency(V/F control). The centralized controller provides a standard voltage phase reference signal for the PCS, which can output the same voltage phase and frequency when several PCSs are connected in parallel. At the same time, according to the collected total load current and each PCS current signal, the amplitude of each PCS output voltage is adjusted, and the current sharing control of each PCS can be realized[14].

Figure 3 shows the main wiring diagram of the 1MW/2MWh energy storage system off-grid mode under the V/F control strategy. Monitor the voltage of each node of the system. When the voltage exceeds the limit, adjust the voltage, or adjust the reactive power compensation device nearby, or adjust the energy storage output of the energy storage to restore the system voltage.

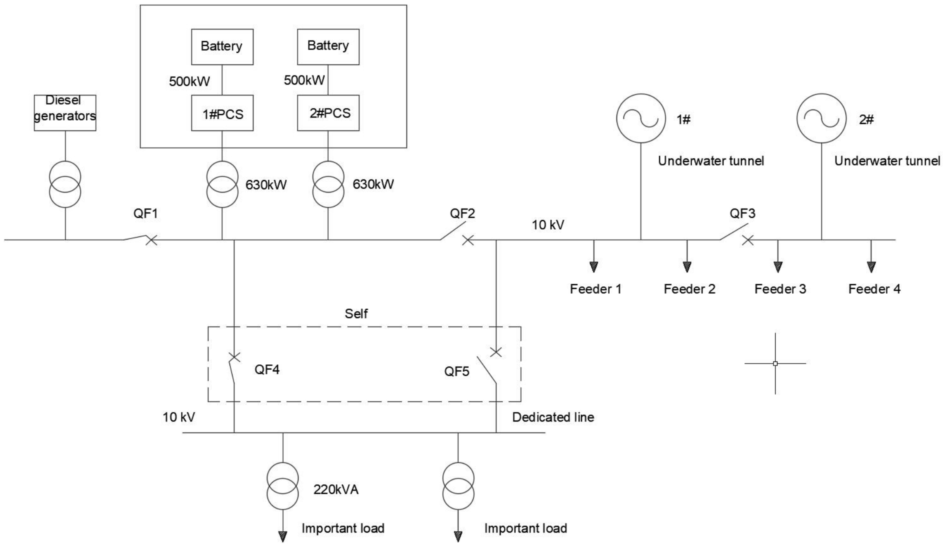

Figure 3 Main Wiring Diagram of the Off-Grid Mode of the Energy Storage System

Off-grid mode working process: When the two cables enter the line fault occurs, the distribution network loses the main power. The centralized monitoring system first controls the QF2 and QF5 switches to open, and issues a command to close the QF4 switch. At the same time, the energy storage system is started in V/F mode through communication instructions. At this time, the energy storage system becomes an off-network working mode, providing power support for important users.

During the main power supply of the PCS, the main power source should be converted to a diesel generator before the PCS discharges to the minimum limit allowed by the remaining capacity (SOC) as the power consumption of the important users increases. The centralized monitoring system of the energy storage system monitors the SOC of the two energy storage battery packs in real time. When the SOC approaches the lower limit value, the QF1 switch is closed, and the diesel generator can charge the energy storage system. This will ensure the reliability of power supply for important loads to the utmost extent.

When the energy storage system is connected to the network, if there is an external fault in the system and the power grid cannot be used as the main power source to provide power to the user, the energy storage system will be converted into the off-network mode and continue to supply power to the important load. This process is called on-grid to off-gird mode.

When the energy storage system is running off-grid, if the external power grid has been repaired and can be used as the main power supply to provide power support for the load, the energy storage system will be changed from the off-grid mode to the grid-connected mode. This process is called off-grid to on-gird mode[15].

Figure 4 shows a schematic diagram of two mode conversion.

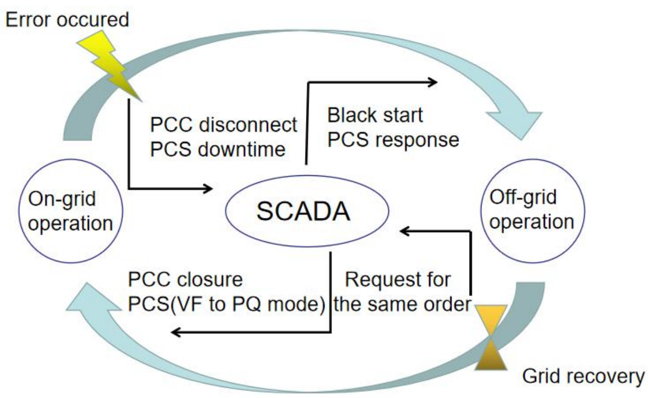

Figure 4 A Schematic Diagram of Two Mode Conversion

3 OPTIMIZATION STRATEGY OF ENERGY STORAGE SYSTEM BASED ON GENETIC ALGORITHM

2.1 Establish an Energy Storage System Optimization Model

The goal of the distribution network is to make the load curve as flat as possible. If the original load of the grid and the output power of the energy storage system are taken as a whole, as the new load of the grid, the goal of the energy storage system modeling is to make the new load curve as flat as possible without large peaks and troughs.
The variance can reflect the extent to which the load curve connected by a series of points deviates from its average. Therefore, the variance of the load curve is selected to establish the optimization model of the energy storage system.
The objective function of the energy storage system optimization model is

$$\min f(\mathrm{P}) = \frac{1}{n}\sum_{i=1}^{n}[F(i)+P(i)-\frac{1}{n}\sum_{i=1}^{n}(F(i)+P(i))]^{2} \tag{1}$$

Among them, $F(i)+P(i)$ Is the new load value of the grid, $\sum_{i=1}^{n}(F(i)+P(i))$ is the load average , n represents the number of load data in a day, $F(i)$ is the load value at time i, $P(i)$ is the output power of the energy storage system at time i, $P(i)$ is the output power of the energy storage system at time i. When the energy storage system is charged, $P(i)$ is positive. When the energy storage system is discharged, $P(i)$ is negative.
The linear constraints of the energy storage system optimization model include:
① Power constraints of energy storage systems satisfy

$$-P_{\max} \le P(i) \le P_{\max}, i = 1,2,\cdots n \tag{2}$$

② Capacity constraints of energy storage systems satisfy

$$S_{\min} < S(i) < S_{\max}, i = 1,2,\cdots n \tag{3}$$

2.2 An Algorithm for Solving Energy Storage System Optimization Model Based on Genetic Algorithm

Set the capacity of the energy storage system to 500kW/1MWh and 1MW/2MWh, and find the optimal solution of the optimal model for the energy storage system under different capacity sizes. Figure 5 shows the hourly load data of the distribution network 24 hours a day.

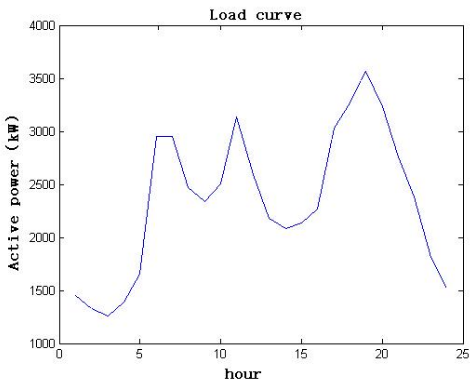

Figure 5 The Hourly Load Data of the Distribution Network 24 Hours a Day

Using genetic algorithm to solve the energy storage system optimization model:

$$\begin{aligned}\min f(P) = &(\frac{1}{n}-\frac{1}{n^2})\sum_{i=1}^{n}(P(i))^2 - \frac{1}{n^2}[2p(1)p(2)+2p(1)p(3)+\cdots+2p(n-1)\\ &p(n)]+\{[\frac{2}{n}F(1)-\frac{2}{n^2}\sum_{i=1}^{n}(F(i)]p(1)+[\frac{2}{n}F(2)-\frac{2}{n^2}\sum_{i=1}^{n}(F(i)]p(2)\\ &+\cdots+[\frac{2}{n}F(n)-\frac{2}{n^2}\sum_{i=1}^{n}(F(i)]p(n)\}+4.4728\times10^5\end{aligned} \tag{4}$$

Where, 4.4728×10^5 is the calculated value of the constant term;
the capacity constraint of the energy storage system of the energy storage system is $5\%S \le S(i) \le 95\%S$;
The charge and discharge power constraints of the energy storage system are $-500kW \le P(i) \le 500kW$;
The initial and final charge of the energy storage system are $S_0 = 10\%S$ and $S_1 = 80\%S$ respectively.

2.2.1 Optimization model of energy storage system with capacity of 500kW/1MWh

Set the number of terminations R=100. After 100 iterations, the best fitness curve, average fitness curve and optimal adaptation are shown in Figure 6. The best fitness at this time is best fitness=284690.7948. That is, the minimum value of the energy storage system optimization model is: $\min f(P) = 2.8649 \times 10^5$

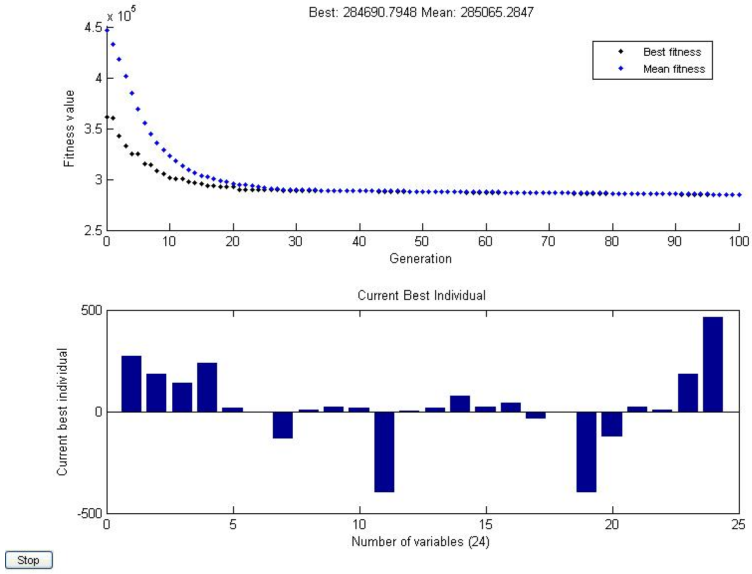

Figure 6 Best Fitness, Average Fitness, Best Individual Curve

After 30 iterations, the optimal fitness curve and the average fitness curve tend to be stable. After 100 iterations, the optimization results are shown in the power curve of the energy storage system in Figure 7.

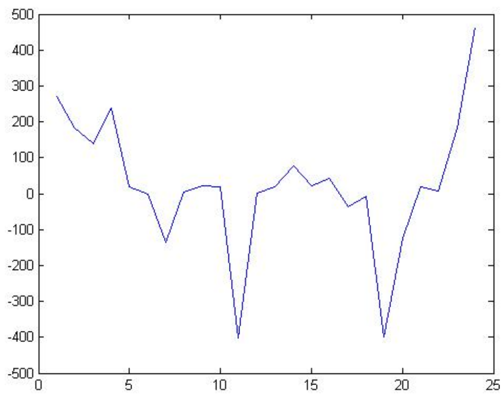

Figure 7 Energy Storage System Power Curve

The comparison of the original load curve and the load curve after the peak-filling of the energy storage system is shown in Figure 8.

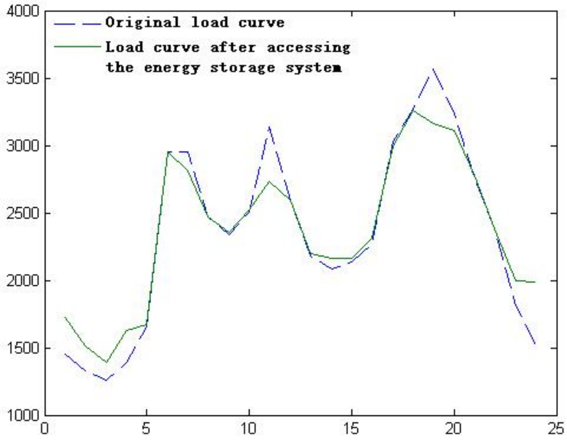

Figure 8 Comparison of Load Comparison Curves before and after Peak Filling

After the charge and discharge of the energy storage system, the maximum load curve max(P)=3260.9 kW, and the minimum value min(P)=1394.6 kW.

2.2.2 Optimization model of energy storage system with capacity of 1MW/2MWh

Set the number of terminations R=100. After 100 iterations, the best fitness curve, average fitness curve and optimal adaptation are shown in Figure 9. The best fitness at this time is best fitness=175300.1481. That is, the minimum value of the energy storage system optimization model is: $\min f(P) = 1.7530 \times 10^5$

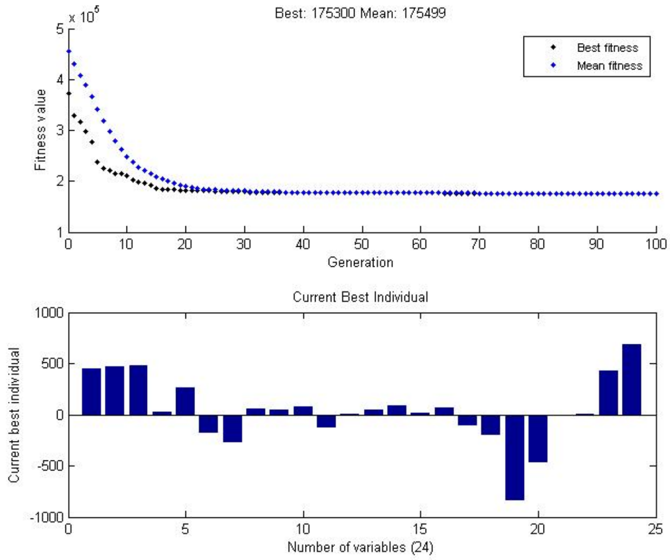

Figure 9 Best Fitness, Average Fitness, Best Individual Curve

After 30 iterations, the fitness curve gradually stabilized. After 100 iterations, the optimization results are shown in Figure 10.

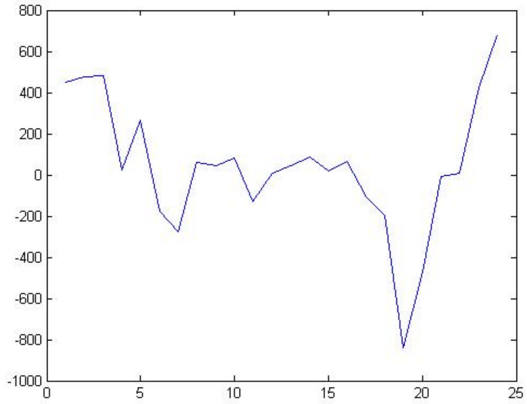

Figure 10 Energy Storage System Power Curve

The comparison of the original load curve and the load curve after the peak-filling of the energy storage system is shown in Figure 11.

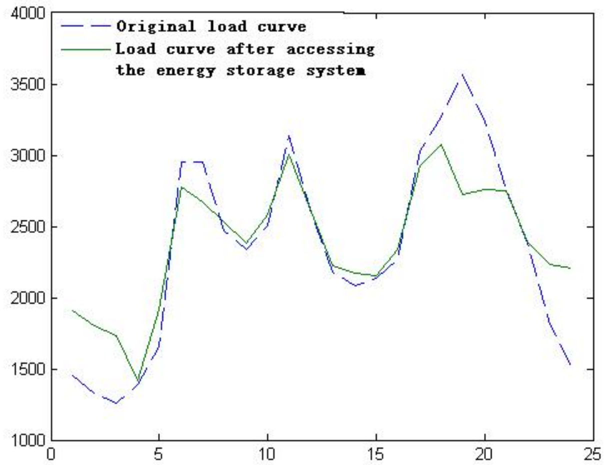

Figure 11 Comparison of Load Comparison Curves before and after Peak Filling

After the charge and discharge of the energy storage system, the maximum load curve max(P)=3071kW, and the minimum value min(P)=1414.9kW.

2.3 Optimization Strategy Effect Analysis

The optimal solution of the energy storage system optimization model based on genetic algorithm plays a role in peak clipping and filling. The optimal fitness value corresponding to the best individual obtained by genetic algorithm has a great relationship with the capacity of the energy storage system. The larger the capacity, the smaller the variance of the load curve and the flatter the load curve.

4 DISTRIBUTION SYSTEM RELIABILITY ANALYSIS

The medium voltage distribution system is mostly a ring network with open loop operation, which can be treated as a radial system. The reliability analysis method adopted is the failure mode consequence analysis method($FMEA$).
For a series system, the following formula is used

$$\lambda_s = \sum_{i=1}^{n} \lambda_i \tag{5}$$

$$r_s = \frac{\sum_{i=1}^{n} \lambda_i r_i}{\sum_{i=1}^{n} \lambda_i} = \frac{U_s}{\lambda_s} \tag{6}$$

$$U_s = \sum_{i=1}^{n} \lambda_i r_i = \lambda_s r_s \tag{7}$$

Where, λ_s is the average failure rate of the system load point (time / year), λ_i is component failure rate (time / year), r_i is the component repair time (hours/times), r_s is the equivalent repair time (hours/times) for each faulty system load point, U_s is the system unavailability rate, that is, the annual power outage time of the load point (hour/year).
For parallel systems, the following formula is used

$$\lambda_p = \lambda_1 \lambda_2 (r_1 + r_2) \tag{8}$$

$$r_p = \frac{r_1 r_2}{r_1 + r_2} \tag{9}$$

$$U_p = \lambda_p r_p = \lambda_1 \lambda_2 r_1 r_2 \tag{10}$$

when two components are connected in parallel

$$\lambda_p = \lambda_1 \lambda_2 \lambda_3 (r_1 r_2 + r_1 r_3 + r_2 r_3) \tag{11}$$

$$r_p = \frac{r_1 r_2 r_3}{r_1 r_2 + r_1 r_3 + r_2 r_3} \tag{12}$$

$$U_p = \lambda_p r_p = \lambda_1 \lambda_2 \lambda_3 r_1 r_2 r_3 \tag{13}$$

Where, λ_1、λ_2、λ_3 are the failure rate of components 1, 2, 3 (time / year), r_1、r_2、r_3 a, b, c are the fault repair time of components 1, 2, 3 (hours / times), λ_p is the average failure rate of the system load point (times / year), r_p is the equivalent repair time for each faulty system load point, U_p is the system unavailability rate, that is, the annual power outage time (hour/year) of the load point.
Distribution system reliability analysis indicators related to users:
System average interruption frequency index($SAIFI$)

$$SAIFI = \frac{\text{Total number of user power outages}}{\text{Total number of users}} = \frac{\sum \lambda_i N_i}{\sum N_i} \tag{14}$$

Where, the unit of $SAIFI$ is: times / (user · year), λ_i is the failure rate, N_i is the number of users of load point i.
Customer average interruption frequency index($CAIFI$)

$$CAIFI = \frac{\text{Total number of user power outages}}{\text{Total number of users affected by power outages}} \tag{15}$$

Where, the unit of $CAIFI$ is: times / (blackout user · year).。
System average interruption duration index($SAIDI$)

$$SAIDI = \frac{\text{Total user power outage time}}{\text{Total number of users}} = \frac{\sum U_i N_i}{\sum N_i} \tag{16}$$

Where, the unit of $SAIDI$ is: h/(user· year), U_i is the annual power outage time, N_i is the number of users of load point i.
Customer average interruption duration index($CAIDI$)

$$CAIDI = \frac{\text{Total user power outage time}}{\text{Total number of user power outages}} = \frac{\sum U_i N_i}{\sum \lambda_i N_i} \tag{17}$$

Where, the unit of $CAIDI$ is: h/(blackout user·year), λ_i is the failure rate, U_i is the annual power outage time, N_i is the number of users of load i.
Average serviceav ailability index($ASAI$)

$$ASAI = \frac{\text{Total user power supply hours}}{\text{Total number of hours the user requests power}} = \frac{\sum N_i \times 8760 - \sum U_i N_i}{\sum N_i \times 8760} \tag{18}$$

In the formula, 8760 is the number of hours in a year.
Average service unavailability index($ASUI$)

$$ASUI = 1\text{-}ASAI = \frac{\sum U_i N_i}{\sum N_i \times 8760} \tag{19}$$

3.1 Reliability Calculation

Assume that the circuit breaker bus and power supply mains breakers in the distribution network system are completely reliable. When a certain part of the system fails, just disconnect the isolation switch of its branch to disconnect the fault area and restore the system.

(1)Reliability calculation of distribution network system before energy storage system is connected,as shown in Figure 12.

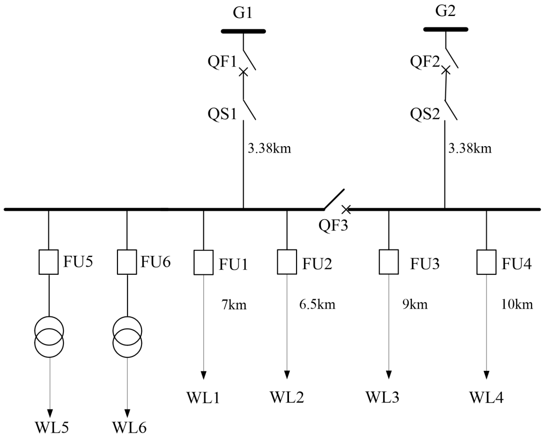

Figure 12 Wiring Diagram of the Distribution System before the Energy Storage System is Connected

Through the failure mode consequence analysis method, the reliability analysis index of the distribution network system before the energy storage system is accessed can be obtained, as shown in Table 1:

Table 1 Reliability Analysis Indicators of the Distribution Network System before the Energy Storage System is Connected

Reliability index	SAIFI	CAIFI	SAIDI	CAIDI	ASAI	ASUI	ACCI
Unit	Time/(user·year)	Times / (blackout users · years)	h/(user·year)	h/(blackout user·year)			kWh
value	1.489	1.489	9.8316	6.6026	0.998878	0.001122	3.9049

(2) Reliability calculation of distribution network system after energy storage system is connected,as shown in Figure 13.

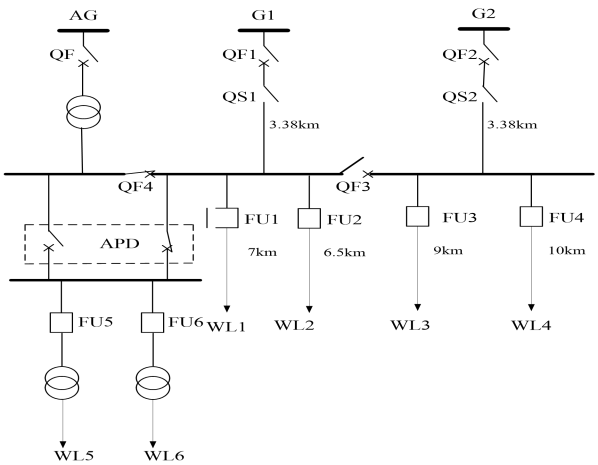

Figure 13 Wiring Diagram of the Distribution System after the Energy Storage System is Connected

Through the failure mode consequence analysis method, the reliability analysis index of the distribution network system after the energy storage system is connected can be obtained, as shown in Table 2 and Table 3:

Table 2 Reliability Analysis Indicators of Distribution Network System after Energy Storage System Access

Reliability index	SAIFI	CAIFI	SAIDI	CAIDI	ASAI	ASUI	ACCI
Unit	Time/(user·year)	Times / (blackout users · years)	h/(user·year)	h/(blackout user·year)			kWh
value	1.467	1.467	9.5012	6.4734	0.998915	0.001085	3.7618

Table 3 Critical Load Reliability Analysis Table

index	failure rate(λ)	Power failure time each time(r)	Annual blackout time(u)
Original system	0.2707	3.4034	0.9213
After the energy storage system is connected	0.2531	2.5942	0.6566

3.2 Reliability Conclusion Analysis

After the energy storage system is connected to the power distribution system, the failure rate of the important load, the average time per failure, and the annual power outage time on the two feeders of WL5 and WL6 are significantly reduced. The failure rate of important loads decreased from 0.2707 to 0.2531, and the average time per failure was reduced from 3.4034 hours to 2.5942 hours. The annual average power outage time was reduced from 0.9213 hours to 0.6566 hours. The energy storage system has an obvious effect on improving the reliability of power supply for important loads.

Calculate the reliability index based on all the load of the power distribution system, and compare the data before and after the energy storage system is connected to the power distribution system. The results show that the total number of power outages of users decreased from 17198.35 times to 16952.23 times, and the total duration of power outages decreased from 113,554.67 to 109,739.37. The average number of power outages decreased from 1.489 to 1.467 and the average user power outage duration was reduced from 6.6026 to 6.4734 times. The number of power outages and power outages were significantly reduced.

Finally, compare them with the average power availability indicator. Before the energy storage system is connected, the average power supply availability of the power distribution system is 0.998878. After the energy storage system is connected, the average power supply availability of the power distribution system is 0.998915, and the reliability is effectively improved.

5 CONCLUSION

Insufficient power supply capacity at the end of the distribution network has always been a major concern in power grid operation. As an important distributed power source, energy storage system plays an active role in power grid peak-filling, new energy access, power quality improvement and emergency power supply. Based on the 10kV distribution network system considering large-capacity energy storage system, this paper proposed the optimal control strategy for charge and discharge of energy storage system based on analyzing the principle that the energy storage system is connected to the distribution network and the control strategy of the energy storage system under different working modes and genetic algorithm. It is concluded that the larger the capacity of the stored energy storage system, the smaller the variance of the load curve and the flatter the load curve. Finally, the failure mode consequence analysis method is used to calculate the reliability analysis index of the distribution system. The calculation results show that after the energy storage system is connected, the failure rate of the load, the average time of each failure, and the annual power outage time are significantly reduced, and the average power supply availability rate is improved. It is verified that the application of the energy storage system can improve the reliability of the power supply of the distribution network.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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