Research on 220kV Substation Main Electrical Connection Optimization Based on Life Cycle Cost Theory

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Abstract. As a key link of power transmission, substation main wiring plays an important role in improving the reliability of power supply in the grid. At present, the design of substation main wiring mainly is made with reference to the typical design schemes. However, due to the continuous development of load and the reliability requirements, the traditional wiring scheme may not fully meet the actual operation requirements. In response to this problem, a new main wiring idea is proposed, 3/2 circuit breaker wiring is added to the conventional double bus wiring scheme to form a mixed wiring scheme. The reliability of each scheme is calculated and analyzed. A certain 220kV substation with heavy load in Chengdu is taken as an example, the loss of social output value is considered, the comprehensive economy of the whole life cycle of the substation construction is calculated and compared, and finally the conclusion is drawn that the reliability and economy of the proposed scheme are the best.

1. Introduction

If a component fails in the main electrical wiring system of the substation, the safety and reliability of the entire power system will be greatly reduced. At present, the main wiring design of the substation is mainly made with reference to the typical design schemes, which has good popularity, but it also leads to discomfort to the grid in some areas. For example, in some 220kV important substations in the urban area, there are three main transformers in operation, and the main wiring scheme is double-bus three-section wiring. When one busbar is under maintenance, the other one busbar in the remaining two busbars occurs failure, causing the two main transformers to exit operation, this may cause the substation to be out of power for areas with weak grid structure and insufficient transfer capacity. Therefore, it is necessary to strive for economic optimization while improving the reliability of the main wiring[1].

During the development of the substation, the main wiring has not changed much since the development of the 3/2 circuit breaker wiring form[2-3]. The research on the main wiring initially mainly started with reliability. In terms of components, starting from the formal introduction of the three-state model in the circuit breaker reliability research in 1971, a series of documents have carried out more in-depth research on the three-state model and the expanded fault model[4-5]. In terms of reliability calculation and evaluation, the commonly used methods mainly include analytical method, simulation method and hybrid method[6-8].
Because the utilization of smart devices in substations has increased in recent years, the power supply reliability of the grid has been greatly improved\cite{9-10}. The economic problems of the main wiring of substations are also often researched. Literature\cite{11} outlined the reliability and economic evaluation methods of main wiring; literature\cite{12-13} discussed and studied the economic issues of main wiring in multiple aspects such as main wiring operation and transformers, et.al. But the above research is based on the existing typical design schemes of main wiring.

Aiming at the problems in the main wiring of a 220kV substation in the city, a hybrid wiring form of conventional double bus wiring and 3/2 circuit breaker wiring based on a typical design scheme is proposed. The reliability of the proposed scheme is analyzed and calculated, and the comprehensive economy of various wiring schemes is calculated and compared based on the life-cycle cost analysis method. The main wiring of a 220kV substation in Chengdu is used as an example to verify and analyze, the double bus wiring adding 2 strings of 3/2 circuit breaker wiring has the best reliability and economy.

2. New scheme of main wiring for 220kv substation

2.1. Typical main wiring scheme of substation

The typical main wiring design of 220kV substation of State Grid includes 26 design schemes. Its main wiring forms mainly include double bus wiring, double bus single section wiring, line-transformer group, internal bridge or expanded internal bridge wiring. In the general main wiring schemes, according to the number of outgoing circuits, the wiring of 220kV high voltage distribution installation is mainly divided into:

(1) Wiring with busbar.
Such as single busbar, single busbar section, double busbar, double busbar section, and some important factories (substations) can also be designed as 3/2 circuit breaker wiring forms in order to meet the reliability of the power system.

(2) Wiring without busbar.
Such as the unit wiring of the transformer-line combination, bridge wiring and angle wiring.

2.2. Improved 220KV substation main wiring scheme

In some special areas, the main wiring form of a heavy-load 220 kV substation is double-bus single-segment wiring. As shown in Fig.1, when one busbar is under maintenance, the other busbar fails and exits operation. As a result, the two main transformers are forced to withdraw from operation. In severe cases, the entire station would be powered off.

![Figure 1. Double-bus single-segment wiring.](image)

According to the basic principles of electrical main wiring design and the existing problems of 220kV substation main wiring, the optimization idea of this paper is that the transformer will continue to supply power in the form of line-transformer unit after the bus exits operation. Two improved schemes are proposed:

a) The double bus is wired with a string of 3/2 circuit breakers, as shown in Fig.2;
b) The double bus is wired with two string of 3/2 circuit breakers as shown in Fig.3.
For the convenience of the following description, the three schemes shown in Fig.1 to Fig.3 are designated as scheme 1, scheme 2, and scheme 3.

![Diagram of scheme 1]

Figure 2. The double bus is wired with a string of 3/2 circuit breakers.

![Diagram of scheme 2]

Figure 3. The double bus is wired with two string of 3/2 circuit breakers.

3. Reliability analysis

3.1. Qualitative analysis of reliability

In normal operation, all circuit breakers of the three schemes are closed, and all bus bars and transformers are put into operation.

When one busbar is under maintenance, the schemes 1-3 can guarantee that the two main transformers will not lose power, and the power supply of the third main transformer will be restored in a short period of time, and the load will not be lost for a long time.

When one busbar is under maintenance and the other one busbar occurs failure and exits operation, scheme 1 may cause two main transformers to be forced out of operation in severe case, leaving only one transformer to operate. In the worst case, the third transformer will be shut down due to overload, and the whole station will be out of power at this time; similarly, 2 main transformers are forced to shut down in scheme 2, leaving only one main transformer; only 1 main transformer is forced to withdraw from operation in scheme 3, the remaining 2 main transformers can continue to supply power as the form of line-transformer unit.
3.2. Reliability quantitative analysis

3.2.1. Failure rate. In the main wiring, even if the circuit breaker is same type, the failure rate of the circuit breaker will be different because of the different location, and it would be calculated separately. The fault rate of the feeder circuit breaker from the busbar is shown in equation (1).

\[ \lambda_{Qf} = \lambda_Q + \lambda_L \frac{L}{100} + \lambda \]  

(1)

Where \( L \) is the line length; \( \lambda \) is the failure rate affected by the busbar failure, its general value is 0.002–0.004f/a. For intermediate circuit breakers and bus tie circuit breakers in double busbars, the value of \( \lambda_Q \) in formula (1) can be adjusted to 2\( \lambda_Q \), and the value of \( \lambda \) can be adjusted if necessary.

The breaker failure shutdown coefficient and planned maintenance shutdown coefficient are shown in equations (2) and (3) respectively:

\[ K_{Qf} = \frac{\lambda_{Qf} T_{Qf}}{8760} \times 100\% \]  

(2)

\[ K_{Qr} = \frac{\mu_Q T_{Qr}}{8760} \times 100\% \]  

(3)

Where \( T_{Qf} \) is the outage time of circuit breaker failure; \( T_{Qr} \) is the average time required for each minor repair of each circuit breaker; \( \mu_Q \) is the number of minor repairs per year for each circuit breaker.

The busbar fault outage coefficient and planned maintenance outage coefficient are shown in equations (4) and (5) respectively:

\[ K_{Wf} = \frac{\lambda_W T_{Wf}}{8760} \times 100\% \]  

(4)

\[ K_{Wr} = \frac{\mu_W T_{Wr}}{8760} \times 100\% \]  

(5)

Where \( \lambda_W \) is the bus failure rate; \( T_{Wf} \) is the average time of each bus outage due to failure; \( \mu_W \) is the average number of maintenance of the bus per year; \( T_{Wr} \) is the average time of each bus maintenance.

The percentage of the time that each equipment component of the main wiring is in a perfect operating state in a year to the entire year is the normal operating coefficient \( K_0 \), which is:

\[ K_0 = 1 - \sum_{i=1}^{N} K_{Qi} - \sum_{i=1}^{M} K_{Wi} - \sum_{i=1}^{M} K_{Wi} \]  

(6)

Where \( N \) is the number of circuit breakers in the main wiring; \( M \) is the number of bus bars in the main wiring.

3.2.2. Outage time. When the equipment connected to the disconnector occurs failure, it takes a certain amount of time from the identification of the cause of the failure to the completion of the switching operation to restore the power supply to the line. It consists of two parts:

\[ T = T_0 + T_c \]  

(7)

Where \( T_0 \) is the fault finding time; \( T_c \) is the disconnector closing time; \( T \) is the disconnector switching operation time.

Two situations need to be considered when a double fault occurs, which are:

i. During maintenance of one circuit breaker, the other component occurs failure;
ii. During maintenance of one busbar, the other component occurs failure.

In the first situation, when the corresponding line is forced to withdraw from operation, the outage time \( T_{112} \) can be obtained by the following formula:
Where $T_{r1}$ is the outage time of the maintenance component; $T_{f2}$ is the outage time of the faulty component.

The time when the corresponding line is forced to withdraw from operation in the second situation, which is:

$$T_{wr1f2} = \begin{cases} \frac{1}{2}T_{r1}, & T_{r1} \leq T_{f2} \\ T_{f2} - \frac{T_{r1}^2}{2T_{r1}}, & T_{r1} > T_{f2} \end{cases}$$

(8)

Where $T_{r1}$ is the outage time of the maintenance component; $T_{f2}$ is the outage time of the faulty component.

The time when the corresponding line is forced to withdraw from operation in the second situation, which is:

$$T_{wr1f2} = \frac{1}{2}T_{wr}$$

(9)

Where $T_{wr}$ is busbar maintenance shutdown time.

3.2.3. Reliability calculation. According to the aforementioned basic parameters for reliability calculation, a logic table can be compiled, and the main wiring reliability indexes can be calculated in the table. Now take a substation in Chengdu as an example to calculate the reliability of three schemes, and the parameters of each component are shown in Tab.1-3.

| Table 1. Parameters of circuit breaker. | Parameter | Value |
|----------------------------------------|-----------|-------|
| Minor repair period                    | 1 year    |
| Minor repair time                      | 1 h/time  |
| Fault repair time                      | 1 h/time  |
| Fault finding time                     | 0.3 h     |
| Planned outage rate                    | 7.22 time/100 units/year |
| Unplanned outage rate                  | 0.087 time/100 units/year |

| Table 2. Parameters of bus. | Parameter | Value |
|-----------------------------|-----------|-------|
| Average time to repair      | 10 h      |
| Planned outage rate         | 4.505 time/year |
| Unplanned outage rate       | 0.961 time/year |

| Table 3. Parameters of transformer. | Parameter | Value |
|------------------------------------|-----------|-------|
| Average time to repair             | 90 h      |
| Time of disconnecting switch once  | 0.1 h     |
| Nominal capacity                   | 240 MVA   |
| Power factor                       | 0.9       |

This paper mainly studies the influence of the main wiring form on the outage of the transformer, so the maintenance and fault conditions of the transformer itself are not considered. According to the aforementioned calculation method, the failure rate of each transformer is obtained, as shown in Tab.4, it shows the total probability of the circuit outage under various working conditions (operation and maintenance), and its value is the sum of various probabilities of the circuit outage. The failure rate, outage time and the number of outage transformers are shown in Tab.5.
Table 4. A comparison table of the failure rates and power outage times for each circuit of the transformer.

| Wiring form | Scheme 1 | Scheme 2 | Scheme 3 |
|-------------|----------|----------|----------|
| Transformer 1 | 0.265 0.788 | 0.264 0.788 | 0.264 0.799 |
| Transformer 2 | 0.265 0.788 | 0.002 0.0017 | 0.0008 0.001 |
| Transformer 3 | 0.265 0.788 | 0.264 0.788 | 0.0008 0.001 |
| Sum | 0.682 2.365 | 0.417 1.578 | 0.266 0.801 |

Table 5. Comparison table of failure rates and downtime for different transformer circuits.

| Wiring form | Scheme 1 | Scheme 2 | Scheme 3 |
|-------------|----------|----------|----------|
| One | 0.569 1.236 | 0.304 0.449 | 0.266 0.801 |
| Two | 0.113 0.564 | 0.113 0.564 | 0 0 |
| Three | 0 0 | 0 0 | 0 0 |
| Sum | 0.681 1.801 | 0.417 1.0135 | 0.266 0.801 |

Tab.4 and Tab.5 show that the transformer circuit failure rate of the double busbar with 2 strings 3/2 circuit breaker wiring scheme is the lowest, and the failure rate that causes the two main transformers to withdraw from operation is also the smallest.

4. Calculation and analysis of life cycle cost

In this paper, the annual cost comparison method is adopted to compare the total cost of the static total investment and the power outage loss cost converted to the annual value in the life cycle of all the schemes.

There are certain differences in the number of equipment, unit price and comprehensive interval of each scheme, and the annual value of investment can be calculated according to formula (10).

\[
Z_{TZ} = C_{Q,TZ} \frac{i(1+i)^n}{(1+i)^n-1} + C_{Y,TZ} \frac{i}{(1+i)^n-1}
\]  

(10)

Where \( Z_{TZ} \) is the investment equivalent annual value; \( C_{Q,TZ} \) and \( C_{Y,TZ} \) are the initial investment and the long-term investment respectively; \( i \) is the discount rate or benchmark rate of return; \( n \) is the calculation period.

In addition to calculating the investment cost, it is also necessary to calculate the power loss cost of each scheme according to formula (11).

\[
Z_{TD} = \rho \times T \times P
\]  

(11)

Where \( Z_{TD} \) is the loss of outage; \( \rho \) is the cost, the unit is ¥/kWh, when \( \rho \) is the ratio of output value to unit electric energy consumption(usually the ratio of the total local GDP to the total electricity consumption at the time), \( Z_{TD} \) represents the loss of social output value, and when \( \rho \) is electricity price, \( Z_{TD} \) represents the loss of the electricity cost of the substation; \( T \) is the annual failure time of the power outage; \( P \) is the lack of power delivered due to the failure, it is equal to the power of the transformer when the transformer is out of operation.

4.1. Transition in the construction of each scheme

It is now assumed that two main transformers are put into operation at the initial stage of construction of a substation in Chengdu. After 5 years, the long-term construction is completed and all three main
transformers will be put into operation. The specific conditions are shown in Tab.6. Tab.7 shows the quantity of equipment that needs to be installed in the initial construction and the long-term construction of each scheme.

Table 6. Early stage and long-term construction of each scheme.

| Scheme | Initial stage | Long-term |
|--------|---------------|------------|
| 1      | Transformer #1, #2, busbar I, II | Transformer #3, busbar III |
| 2      | Transformer #1, #2, busbar I, II | Transformer #3 |
| 3      | Transformer #1, #2, busbar I, II | Transformer #3 |

Table 7. The number of equipment installed in the initial stage and in the future.

| Equipment                          | Initial stage | Long-term |
|------------------------------------|---------------|-----------|
|                                    | Scheme 1   | Scheme 2 | Scheme 3 | Scheme 1 | Scheme 2 | Scheme 3 |
| Main transformer interval          | 2          | 1        | 1        | 1        | 1        | 0        |
| 3/2 wiring main transformer interval| 0          | 1        | 1        | 0        | 0        | 1        |
| Line interval                      | 4          | 3        | 3        | 4        | 4        | 3        |
| 3/2 wiring line interval           | 0          | 1        | 1        | 0        | 0        | 1        |
| Bus coupler interval               | 1          | 1        | 1        | 1        | 0        | 0        |
| Segment interval                   | 0          | 0        | 0        | 1        | 0        | 0        |
| 3/2 wiring busbar                  | 0          | 1        | 1        | 0        | 0        | 1        |
| busbar                            | 2          | 2        | 2        | 1        | 0        | 0        |

4.2. Life cycle cost

The cost of various intervals is shown in Tab.8. The electricity price is 0.4 ¥/kWh, the discount rate is 8%, and the ratio of output value to unit electric energy consumption is calculated based on the data of Chengdu in 2018. The calculation period is 25 years.

The equipment investment cost of each scheme is shown in Tab.9. The annual value of investment, the loss of substation electricity fee (loss 1), and the loss of social output value (loss 2) are shown in Tab.10. Considering the different loss costs, the overall life cycle cost of each scheme is shown in Tab.11. Combining Table 10 and Table 11, it shows that only considering the investment cost, the double-busbar single-segment cost is the least, but the power supply reliability is the worst. But considering the social output value loss, the overall economy of the scheme 3 wiring is the best.

Table 8. Costs of various equipments(unit: thousand yuan).

| Equipment                                      | Cost |
|-----------------------------------------------|------|
| Main transformer interval                      | 1240 |
| 3/2 wiring main transformer interval           | 1450 |
| Line interval                                  | 1380 |
| 3/2 wiring line interval                       | 1470 |
| Bus coupler interval                           | 1040 |
| Segment interval                               | 1190 |
| 3/2 wiring interval                            | 1325 |
| Busbar of double busbar single section wiring  | 156  |
| Busbar of 3/2 wiring                           | 640  |
Table 9. Investment cost of each scheme (unit: thousand yuan).

| Scheme | Initial stage | Long-term |
|--------|---------------|-----------|
| 1      | 9352          | 9146      |
| 2      | 11945         | 6760      |
| 3      | 11945         | 8385      |

Table 10. Computed result of the three schemes (unit: thousand yuan).

| Scheme | 1   | 2   | 3   |
|--------|-----|-----|-----|
| Annual value of investment | 1001 | 1211 | 1234 |
| Loss 1 | 109  | 62  | 49  |
| Loss 2 | 4105 | 2311 | 1827 |

Table 11. The economy of the schemes considering different losses (unit: thousand yuan).

| Scheme | Considering loss 1 | 2   | 3   |
|--------|--------------------|-----|-----|
|        | 1110               | 1273 | 1283 |
|        | 5106               | 3522 | 3061 |

5. Conclusions

Based on the typical design schemes of 220kV main wiring, this paper proposed a conventional double bus wiring adding 3/2 circuit breaker wiring, and the reliability and economy of proposed scheme and double busbar single-segment wiring scheme is compared and analyzed based on the life cycle cost analysis method, and finally it is concluded that the double busbar with 2 strings 3/2 circuit breaker wiring form is the optimal scheme.

The new main wiring scheme proposed in this paper is different from the typical design schemes. The installation scheme of the secondary equipment may become more complicated, so further research is needed.

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