Design and Research of 110kv Intelligent Substation in Electrical System

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Abstract. Substation is an indispensable part of power system, responsible for the heavy task of power transmission and redistribution, and plays a pivotal role in the safe and economic operation of power grid. This design builds a 110 KV step-down substation. First of all, select the connection mode of each voltage level and choose the best flexible connection mode in terms of technology and economy. Secondly, calculate that short-circuit current. Obtain the values of the short-circuit steady-state current and the impulse current when the short-circuit occurs in the working bus of each voltage level from the three-phase short-circuit calculation. Finally, the equipment selection is made according to the rated voltage and the maximum continuous operating current of each voltage level, and then verified.

Keywords: 110kv Intelligent Substation, Design, Research

1. Introduction
Due to the use of advanced and reliable equipment, the main wiring of 110kv substation built during this period is relatively simple. In addition to the main transformer, 110KV electrical equipment is mainly in the form of indoor layout. The main transformer is the switch equipment with capacity 40MVA, which is the oil free equipment and unattended substation. These substations have a small floor area, with high degree of automation, small daily maintenance workload and high safe reliability.

2. Design Principles of Main Wiring
The design of electrical main wiring is the main body of substation design, which is closely related to the original data of power system and the reliability and economic requirements of the operation of substation. The determination of the main wiring will have a direct impact on the safety, stability, flexibility and economic operation of the power system, as well as the selection of electrical equipment in the substation and the arrangement of the distribution equipment. Therefore, the main wiring must comprehensively analyze the relevant influencing factors under the condition of power system and transformer substation, correctly handle the relationship between them, and choose the main connection mode reasonably through technical and economic comparison.
According to the different status and function of substation in the system, the performance requirements of electrical main wiring of substation have different emphases. For example, ultra-high voltage and large capacity pivotal substation in the system can cause significant losses to the system and users due to power failure, so the reliability requirements of the system are particularly high; midway substation of medium and small capacity or terminal substation in the system, cause less loss to the system and users due to power outages. The number of such substations is particularly large, so the economy of their main wiring should be paid special attention to [1].

3. Transformer Selection

3.1 Determination of the Number of Main Transformers
In order to ensure the reliability of the power supply, the substation should be equipped with two main transformers, but not more than two. When there is only one power supply, or the primary load of the substation has a standby power to ensure the power supply, one main transformer can be installed. Install two main transformers in the important substations in the area as required.

3.2 Determination of Main Transformer Capacity
When two or more main transformers are installed in the substation, the selection of each capacity shall be based on that when any one of them is shut down, that capacity can at least ensure that the primary load supply by the station is 60 to 75 percent of the total load of the substation, usually 70 % for primary substation and 60 % for secondary substation.

\[ S_{\text{max}} = 55\text{MVA} \] in summer, so the two main transformers should bear 27.5MVA respectively. When one stops, the other takes 70%, or 38.5MVA. Therefore, two main transformers with 40MVA can be selected to meet the load demand.

3.3 Determination of Phase Number of Main Transformer
Main transformer adopts three-phase or single-phase, mainly considering the transformer manufacturing conditions, reliability requirements and transportation conditions and other factors. Three-phase transformers shall be used in power plants and substations under 330kV and below when conditions of transportation are not limited. According to the above rules, the main transformer of this substation should adopt three-phase transformer.

3.4 Selection of the Number of Main Transformer Winding
Since there are only two voltage levels in the transformer, the dual winding transformer can meet the demand of power supply.

3.5 Connection Mode of Main Transformer Winding
The connection mode of the transformer must be consistent with the system voltage phase, otherwise it cannot be run in parallel. The winding connections used in the power system are only Y and \( \Delta \), in which transformer winding adopts Y connection for voltage of 110kV and above, and adopts \( \Delta \) connection for voltage of 35kV in our country. So it can be seen that Y wiring is used on 110 KV side, and \( \Delta \) wiring is used on 10 KV side in this substation.

The grounding mode of main transformer neutral point is as follows. It is a comprehensive problem to choose neutral grounding mode in power network. It is related to voltage level, single-phase ground short-circuit current, overvoltage level, protection configuration and so on, which directly affects the insulation level of power grid, the reliability and continuity of system power supply, the operation safety of transformers and generators and the interference to communication lines. The main grounding modes are: neutral isolated, neutral grounded by Peterson coil and direct grounding. The neutral point grounding mode of power network determines that of transformer. In 35KV system, \( IC \leq 0.001KA \); In 10KV system, \( IC \leq 0.003KA \) (using neutral isolated operation). Therefore,
110kV adopts neutral point direct grounding mode, and 35KV or 10KV adopts neutral isolated mode in this design.

3.6 Voltage Regulation Mode of Main Transformer
Voltage regulation of the transformer is achieved by changing the transformer ratio by switching the transformer tap using a tap-changer.

There are two ways to switch. No live switching, called off-circuit-tap-changing, its voltage regulation range is usually within +5%; The other is with load switching, called On-Load Tap Changing, voltage regulation range can reach +30%. For transformers of 110 KV and below, it should be considered that on-load-tap-changing shall be used for transformers with at least one level of voltage [2, 3]. The main transformer of this substation adopts the on-load-tap-changing mode.

3.7 Selection of Transformer Cooling Mode
Main transformer general cooling modes are natural wind cooling, forced oil circulation air cooling, forced oil circulating water cooling and forced, guide oil circulation cooling. Small capacity transformer generally uses natural wind cooling. Large capacity transformer generally adopts forced oil circulation air cooling mode. Therefore, the main transformer in this substation adopts forced oil circulation air cooling mode.

The main transformer model in this design is SFSZ7—63000/110 power transformer, which specific technical parameters are listed in Table 1.

| Table 1. Main transformer model and main technical parameters |
|----------------|----------------|
| Model         | SFSZ7—63000/110 |
| Capacity      | 63 MVA          |
| Capacity Ratio| 63 /63 /63      |
| Impedance Voltage | High voltage 110±8×1.25% |
|               | Medium voltage 38.5±2×2.5% |
|               | Low voltage 10.5 |
| Connection symbol | YN, yn0, d11 |
| Loss          | no-load 84.7kW |
|               | load 300 kW    |
| No-load current| high-medium 1.2% |
|               | high-low 17%   |
|               | medium-low 10.5% |
| Impedance voltage | 6.5%          |

4. Calculation and Selection of Main Transformer Capacity

4.1 Load Calculation of This Station
Calculation according to preliminary design original data

35 KV side load is as shown in Eq.1.

\[
S_{35} = \sum S_p \times K_{35} = \sum \left( \frac{P}{\cos \psi} \right)_n \times K_{35}
= \left( \frac{8}{0.85} + \frac{10}{0.85} + \frac{8}{0.85} + \frac{10}{0.85} + \frac{16}{0.85} \right) \times 0.85
= 61.18(MVA)
\] (1)

10KV side load is as shown in Eq.2.
The total load

$$S_M = (S_N + S_{10}) \times K = 84.66\text{ MVA}$$

(3)

Where $K$ - the coefficient factor between 35KV load and 10KV load, the original data was given 0.85.

According to the actual needs of the average annual growth rate of power demand, consider that the main transformer capacity is generally selected based on the planning load within 5-10 years after completion, and give due consideration to the long-term load development of 10 ~ 20 years. Considering the load planning for 5 years, the final comprehensive power load of this substation is:

$$S_M = 84.66 \times 1.02 = 86.35\text{ MVA}$$

(4)

4.2 Determination of Main Transformer Capacity and Model

For substations with significant loads, when the substation is installed with two or more transformers, one fault or resection, the remaining transformer capacity shall guarantee 70% of the total load of the station, and the capacity of the single main transformer is.

$$S_N = 86.35 \times 70\% = 60.44\text{ MVA}$$

(5)

According to the calculation and selection, two models of SFSZ7-63000/110 power transformers are determined.

5. Lightning Protection Design

5.1 Lightning Rod Layout and Protection Range Calculation

Lightning rod is an outdoor power distribution device of substation, which is the main facilities used in electrical buildings to protect against direct lightning overvoltage in the area. The substation is realized by the protection network composed of lightning rod on the structure of outdoor distribution equipment and independent lightning rod. The lightning protection belt on the roof shall be used for lightning protection in the plant, main control room and indoor distribution room.

From the general layout of the substation, the power transformer is 100m long and 80m wide. It is advisable to set 8 lightning rods, of which 1#-8# lightning rod is set on the substation door frame, thus reducing the length of the lightning rod and enlarging the protection range.

5.2 Lightning Arrester Selection of Each Voltage Grade

Lightning arrester is the main facility of protecting lightning incoming surge in power plant and substation. It should be based on the insulation level and use conditions of the protection, to choose the type of lightning arrester, rated voltage, etc., and check the selected lightning arrester arc extinguishing voltage and power frequency discharge voltage, etc. according to the use situation [4,5].

5.3 Selection of 110KV Side Arrester
For 110 KV ultra-high voltage distribution device, Zinc oxide (En0) arresters should be selected as both lightning overvoltage protection and second line protection to limit operating overvoltage, and its protection level shall be used as the basis for insulation equipment of electrical equipment.

According to the requirements above, calculate the actual parameters of 220 KV power grid.

The effective value of the maximum operating phase voltage of the power grid is:

\[ U_{sq} = 1.1 \times 110 / \sqrt{3} = 139.72 \text{KV} \]  

(6)

The effective value of the maximum power frequency overvoltage of the power grid is:

Bus side:

\[ 1.3 \cdot U_{sq} = 1.3 \times 139.72 = 181.64 \text{KV} \]  

(7)

2 ms square wave current of power grid is estimated as follows:

\[ I_b = \frac{U_a - U_{bc}}{E} \text{(KA)} \]  

(8)

In Eq.9, \( U_c \) - Line operation overvoltage amplitude, calculated multiple of overvoltage in 220KV system according to regulations is that \( K_0 = 2.75 \).

\[ U_c = 2.75 \times 1.1 \times 110 / \sqrt{3} \times \sqrt{2} = 543.38 \text{KV} \]  

(9)

\( U_{bc} \) —the residual voltage value of the arrester corresponding to \( I_b \), make \( U_{bc} = 496 \text{KV} \).  

\( Z \) — surge impedance of a line, from reference data make that:

\[ Z = \sqrt{\frac{L_0}{C_0}} = 310 \Omega \]  

(10)

\[ I_b = \frac{543.38 - 496}{310} = 0.153KA = 153A \]

Duration of operation surge current:

\[ t = 2\tau = \frac{2L}{C} \text{(s)} \]  

(11)

L-line length (km), take L=240km; C-electromagnetic wave length, \( C = 3 \times 10^8 \text{km/s} \).

\[ t = \frac{2 \times 240}{3 \times 10^5} = 0.0016s = 1.6\text{ms} \]  

(12)

Because the length of the line L is an estimate of the system, the actual length will increase, so take \( t=2\text{ms} \).

\[ I_b = 0.153KA \]  

(13)

According to the actual calculation of the power grid, the characteristics of the selected arresters are compared, as shown in the following table.
### Table 2. Technical parameter selection of zinc oxide arrester

| Lightning arrester installation position | BUS side |
|----------------------------------------|---------|
| Grid parameter                         |         |
| Effective value of maximum operating phase voltage | 139.72KV |
| 2 ms square wave current value          | 0.153KA |
| Characteristics of the selected arrester |         |
| Effective values for maximum continuous operating voltage | 146KV |
| Effective value of rated voltage        | 200KV   |
| 20 times 2ms square wave surge absorption capability | 1KA |

The zinc oxide arrester adopts the Y10W2 series zinc oxide arrester of Shanghai Electric Porcelain Works, and its technical parameters are shown in Table 3.

### Table 3. 110KV zinc oxide arrester technical parameters

| Arrester model | Y10W2 – 200 / 520 | Y10W2 – 200 / 496 | Y10W2 – 200 / 580 |
|----------------|-------------------|-------------------|-------------------|
| System voltage [KV](effective value) | 110 | 110 | 110 |
| System maximum voltage effective value [KV] | 121 | 121 | 121 |
| Effective value of arrester rated voltage [KV] | 110 | 110 | 110 |
| Reference voltage [KV] | 200 | 200 | 200 |
| Continuous operating voltage effective value [KV] | 146 | 146 | 146 |
| Operating residual voltage at 30/60us (2KV) [KV](peak) | 442 | 422 | 494 |
| 8/20us Lightning impulse residual voltage [KV] | 520 | 496 | 580 |
| Operating impulse current withstand capacity, 20 times of 2ms and 20ms square wave [KA](peak) | 100 | 100 | 100 |

Line side, zinc oxide arrester Y10W2 – 200 / 496:

Voltage ratio = \[ \frac{496}{290} = 1.71 \]

Electric load rate = \[ \frac{\sqrt{2} \times 146}{290} \times 100\% = 71.2\% \]

Protection ratio = \[ \frac{1.71}{0.71} = 2.41 \]

The bus side also selects zinc oxide arrester Y10W2 – 200 / 496. It can be seen that the selected zinc oxide arrester has superior protection performance.

#### 5.4 Selection and Verification of 35KV Side Lightning Arrester

Select FCZ-110J magnetic blow arrester for 35KV Bus, and check the technical parameters:

\[ U_{mh} = 100V; U_{gf} = 170 \sim 195KV; U_{ch} = U_{c(5)} = 260KV \]

Check out extinction voltage:

\[ U_{mh} \geq 1.15 \sqrt{3} U_{sq} \cdot 80\% = 1.15 \times 35 \times 80\% = 101KV \]

Power-frequency discharge voltage:
\[ U_{gf} \geq \sqrt{3} U_{xq} = 3 \times \frac{35}{\sqrt{3}} = 190KV \]

And
\[ U_{gf} \geq 1.8 U_{mh} = 1.8 \times 100 = 180KV \]

The selected FCZ-110J lightning arrester meets the requirements.

### 5.5 Selection and Verification of 10KV Side Lightning Arrester

The 10KV side arrester of the substation adopts the normal valve arrester, its model FS-10, and the technical parameters are:

\[ U_{mh} = 12.7KV; U_{gf} = 26 ~ 31KV; U_{ch} = 45KV; U_{c(5)} = 45KV \]

Check extinction voltage \( U_{mh} \) meeting requirements.
\[ U_{mh} \geq 1.0 \times \frac{1.15 U_{c(5)}}{\sqrt{3}} = 6.64KV \]

Check power-frequency discharge voltage:
\[ U_{gf} \geq 3.5 \times \frac{1.15 \times 10}{\sqrt{3}} = 23.24KV \]

And
\[ U_{gf} \geq 1.8 \times U_{mh} = 1.8 \times 12.7 = 22.86KV \]

The selected FS-10 lightning arrester meets the requirements.

| Model | \( Y_{10} W_{2} = 200 / 496 \) | FCZ-110J | FS-10 |
|-------|-------------------------------|----------|-------|
| Extinction voltage | \( U_{mh} \) | 100V | 12.7KV |
| Power-frequency discharge voltage | \( U_{gf} \) | 170~195KV | 26~31KV |
| Impulse flash over voltage | \( U_{ch} \) | 260KV | 45KV |
| Residual voltage | \( U_{c} \) | 496KV | 260KV | 45KV |
| Quantity | 1 | 2 | 2 |
| Installation site | 220KV Bus | 110KV Bus | 10KV Bus |

### 5.6 The Maximum Electrical Distance between the Bus Arrester and the Transformer

The second measure to protect the substation from lightning incoming surge overvoltage is to set the lead-in line protection section. Namely in the 1-2 km incoming lines of the substation, set up the Lightning Shield Line, prevent or reducing lightning flashover in that near area, reducing the steepness of the lightning intrusion wave, limiting the magnitude of the lightning current, and ensure the safe operation of substation [6-8].

110 KV overhead transmission line, is equipped with lightning arrester along the whole line. Within the scope of 2 km into the lead-in line protection section of the tower, the lightning withstand level should be 140 KA or more, protection angle is not more than \( 20^\circ \), and lightning protection wire grounding resistance is less than 10Ω. The 10KV and 35KV overhead lines with lightning protection wire not along the whole line, should be equipped with lightning protection wire.
within 1-2 km to incoming lines of the substation. Its lightning withstand level should be not less than 8 KA and 75KA respectively, with protection angle within the scope of 25° to 30° and the impulse grounding resistance around 10Ω.

After setting the lead-in line protection section, the steepness of the lightning intrusion wave of the substation is calculated according to Eq.14:

\[
a = \frac{1}{(\frac{150}{U_e} + \frac{2.4}{h_d})L_0} (KV/m)
\]

For 110 KV outgoing line of the substation: Lightning arrester, \(U_e^{(10)} = 496KV\), the average height of the tower \(h_d = 20m\).

\[
a = \frac{1}{(\frac{150}{496} + \frac{2.4}{20}) \times 2} = \frac{1}{(0.302 + 0.12) \times 2} = \frac{1}{0.844} = 1.18(KV/m)
\]

For 35KV outgoing line of the substation: Lightning arrester, \(U_e^{(35)} = 260KV\), and the average height of the tower \(h_d = 10m\).

\[
a = \frac{1}{(\frac{150}{260} + \frac{2.4}{10}) \times 2} = \frac{1}{(0.58 + 0.24) \times 2} = 0.61(KV/m)
\]

For 10KV outgoing line of the substation: Lightning arrester, \(U_e^{(35)} = 45KV\), the average height of the tower \(h_d = 5m\).

\[
a = \frac{1}{(\frac{150}{45} + \frac{2.4}{5}) \times 2} = \frac{1}{(3.33 + 0.48) \times 2} = 0.13(KV/m)
\]

Calculate maximum electrical distance between bus arrester and transformer according to the Eq.18.

\[
L_m \leq \frac{U_j - U_c - K}{2a}
\]

It is required to meet the maximum protection distance between the transformer and lightning arrester to prevent the danger of counterattack when the lightning arrester operates. Also, the distance between the lightning rod and protection equipment should meet such requirements: air distance \(Sk \geq 5m\); the ground distance \(Sd \geq 3m\).

5.7 Grounding for Lightening

According to the soil resistivity of the substation 500Ω/M, the resistivity is not too high, so the ring compound grounding device is adopted. That is, a steel pipe with a diameter of 50mm and a length of 250cm used as a vertical grounding electrode, and a flat steel pipe of 40×4mm with a buried depth of 0.8m used as a horizontal grounding electrode, welding into mesh shape, ensure that the grounding resistance is less than 4Ω, step voltage and touch voltage within the allowable range [9-12].
6. Summary
Through investigation and understanding, appropriate technologies are selected for application in substation design to form a preliminary design scheme of intelligent substation. However, it should not be ignored that intelligent substation technology is still in the process of rapid development. Some existing technologies and equipment are still immature and lack the test of long-term operation, which still need to be improved continuously. In this paper, only at the current level of technology and equipment development, the existing technology and equipment are analyzed and studied according to an arrangement mode of substation, which has certain limitations. In the future work and study, more in-depth research and practice will continue on the subject of intelligent substation design.

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