Design of Improving Bus Short Circuit Residual Voltage Based on Reactive Power Regulation of Synchronous Motor

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Abstract. When a short circuit fault occurs in a power system, the short circuit current value in the short circuit increases greatly, and at the same time, it will reduce the voltage in the power network, even 60 percent to 70 percent of the original voltage, then the power of some users was destroyed. In order to make the system work properly, it is important to analyse the cause of bus voltage drop. The traditional solution is to increase reactive power by using external equipment, such as static capacitor or STATCOM device, but the cost of the above two devices is too high. And each bus bar lower end of the load is connected with synchronous motor in Xindu Chemical 110kv Substation. When a short circuit fault occurs in the system, the synchronous motor can be excited in a short time to reduce the voltage drop, which is economical and fast. In this paper, four excitation modes of synchronous machine are analysed in detail, including constant excitation current, constant reactive power excitation, constant power factor excitation and constant active power excitation. Finally, the constant active power excitation model is chosen to solve the problems encountered. Finally, the short circuit current is judged quickly, so that the short-circuit fault can be judged quickly according to the change rate of the current in the system.

Key words: Short circuit calculation; Synchronous machine excitation; Voltage drop; Reactive power regulation.

1. Introduction
The research object of this paper is Xindu Chemical 110kv Substation. The substation is divided into three sections, and each working independently. During normal operation, the bus voltage of the substation is kept near the rated value. When a short circuit fault occurs in a substation, the rapid increase of short circuit current will reduce the bus voltage to 75% or even 70% of the original voltage, which will lead to the tripping of many equipments in the substation and the failure of the system to work normally.

In this paper, the bus residual voltage of short circuit is obtained when the short circuit fault occurs. Then, the causes of bus voltage drop are analyzed. According to the calculation, the formula of voltage drop can be obtained. It can be seen from the formula that there are two factors influencing the voltage drop: reactive power Q and reactance X. In this paper, reactive Q is studied, while total reactance X remains unchanged.
The reactive power balance formula in power system is: \( Q_\Sigma = Q_l - Q_c - Q_d \). When the system is short circuited, the \( Q_l \) increases, resulting in the total reactive power \( Q_\Sigma \) increasing and the voltage drop increasing. There are a variety of solutions, such as adding reactive power to the system with additional devices, or directly using synchronous motors in substations for excitation. In terms of economy, we choose the latter approach because the use of additional equipment is not only expensive but also covers a large area. There are a variety of excitation models, this paper chooses constant active excitation. Because the load of the system does not change after the short circuit, the active power of the system remains unchanged.

Finally, a part of the content: the system short-circuit fast decision. That is to say, a numerical value can be obtained by calculation. When the rate of change of current in the system exceeds this value, it can be judged that the system is about to enter the short-circuit state. After the theoretical analysis of the solution, we should design the specific program flow chart to achieve the design of this paper.

2. Short Circuit Voltage Analysis

The formula of voltage drop in power system is as follows:

\[
\Delta U = \frac{P_1R + Q_1X}{U_1}
\]  

(1)

Where \( P_1 \) is the active power of the power system and \( Q_1 \) is the reactive power, \( R, X \) is the total resistance of the system and the total reactance, \( U_1 \) is the bus voltage. It can be seen from formula (1) that the voltage drop mainly consists of two parts: the voltage drop on the resistance and the voltage drop on the reactance in the power system. In general, the reactance of power system is much larger than that of resistance, that is, \( X >> R \), so reactive power has a great influence on voltage drop, which is the main factor of voltage drop in power system. So the formula for calculating the voltage drop can be written in another form, as follows:

\[
\Delta U \% = \frac{Q_1X}{U_1}
\]  

(2)

All reactance values remain constant in substations, and the influence of reactive power on voltage drop is mainly studied [1].

The relation of reactive power balance in power system is as follows:

\[
Q_\Sigma = Q_l - Q_c - Q_d
\]  

(3)

The \( Q_l \) is the reactive power of the circuit and resistor, \( Q_c \) is the total reactive power of the system capacitance, \( Q_d \) is the reactive power of the synchronous machine. After short circuit, \( Q_d \) and \( Q_c \) remain basically unchanged, while \( Q_l \) will rise, resulting in rapid increase of \( Q_\Sigma \). According to formula (2), the voltage drop will rise, resulting in the system bus voltage drop. So, we need to increase reactive power to reduce voltage drop after short circuit fault [2]. The traditional way is to use additional equipment to increase reactive power, such as static capacitors, static compensators or STATCOM devices. These devices can quickly replenish reactive capacity and increase the reactive power of the system, but a single set of equipment is millions of dollars higher, the cost is too high. The load at the lower end of each bus in Xindu Chemical 110kv Substation is connected with synchronous motor. When the system is short-circuiting fault, the motor can be excited in a short time to reduce the voltage drop.
3. Synchronous Machine Excitation

3.1. Role of Synchronous Motor Excitation

To provide DC power to the rotor of a synchronous motor, a DC magnetic field is induced around the rotor, which is called excitation [3].

The excitation system of synchronous motor is used to:

Providing the excitation current to the motor, that is, providing the required reactive power to the motor.

(2) When a short circuit fault occurs in the power system, the synchronous motor is excited by force to ensure the normal and stable operation of the power system.

3.2. Four Models of Synchronous Excitation

3.2.1. Constant-current Excitation. Constant excitation current regulation is also manual regulation, which is mainly to maintain the generator excitation current constant. The various losses of the motor are ignored in the process of analysis. Keep the excitation current of synchronous motor constant, so in vector diagram, the path of stator current is always on the arc line AB with the center of O as the center and the magnitude of excitation current as radius, as shown in figure 1. When corresponding to a certain active power, the corresponding size of other parameters can be obtained [4]. (There is no power factor angle in the diagram)

![Constant excitation current adjustment diagram of synchronous motor](image.png)

Fig 1. Constant excitation current adjustment diagram of synchronous motor

In the constant excitation current regulation, the imaginary straight-line P which is perpendicular to the longitudinal axis voltage intersects on the arc line AB and connects the intersection point with the origin point, that is, stator current, In figure 1 I₁, I₂, I₃. A virtual straight line perpendicular to the magnetic flux of the transverse axis, which is equivalent to the reactive power of the synchronous motor Q₁, Q₂, Q₃.
3.2.2. Constant Reactive Excitation

Fig 2. Constant reactive excitation regulation vector diagram of synchronous motor

As shown in figure 2, when the power of the synchronous motor changes, a virtual line perpendicular to the longitudinal axis intersects the dotted line, connecting the intersection point to the origin is the stator current, that is, $I_1$, $I_2$. It can be seen from figure 2 that when the synchronous motor is regulated under this condition the magnitude of the excitation current can be adjusted and the other related parameters can be adjusted.

3.2.3. Constant Power Excitation. Assuming that the power factor of the synchronous motor is ahead and invariant, the stator current is always on the ray of the leading voltage. When corresponding to a certain active power, the corresponding other parameters can be obtained.

Fig 3. Constant power factor adjustment vector illustration of synchronous motor

3.2.4. Constant Active Excitation. Constant active power is also a constant current excitation. The driving torque of the prime motor does not increase and the load does not change, so the active power of the synchronous motor will not change. The running vector diagram of the synchronous motor is shown in the following figure:
Fig 4. Constant active power regulation vector illustration of synchronous motor

It can be seen from figure 4 that the active power of synchronous motor will not change when short circuit occurs in power system. At this point, the synchronous motor will automatically increase the rated current, that is, forcing excitation. The reactive power $Q_d$ of the system is raised. According to the previous analysis, the voltage drop is reduced to maintain the stability of the bus voltage. It can be calculated that the power factor of the system has been reduced from 0.95 to 0.70, which is disadvantageous to the system. So forced excitation can only be used in a short period of time.

4. Short Circuit Calculation

The main object of this design is the 110KV 1# bus and 10KV-bus of the substation.

Only the equivalent inductance of several elements on the power supply, transformer, cable and line is calculated, while the rest is ignored. And you can use a bus bar to calculate. Don’t have to calculate the whole picture [5].

1. Selected baseline value: $S_j=100$MVA, $U_j=10$kv
2. Per-unit value of power supply: $X_e^*=0.11$ (This value is given)

Per-unit value of transformer

$$X_{u^*} = \frac{Ud\%}{100} \frac{S_j}{S_B} = \frac{17}{100} \frac{100}{50} = 0.34$$

(4)

Per-unit value of cable:

$$XL1^* = 0.08 \times 1 \times 100 / (10.5 \times 10.5) = 0.07256$$

(5)

Per-unit value of Motor start: $X_d^* = 100 / 50 = 2$

4.1. Short Circuit Calculation of Motor

When a short circuit occurs suddenly in a large motor, the equivalent impedance diagram on a single branch is shown in figure 5:
Short circuit current:

\[ I_{\text{short}} = \frac{1}{0.11 + 0.34 + 0.07256} = 0.3964 \] (6)

So, 10.5kv bus bar voltage \( U = 0.3964 \times 2.07256 = 0.8216 \). Voltage reduced to original 0.8216.

4.2. Short Circuit Calculation

When the cable is short circuited, the short-circuit current is:

\[ I_{\text{short}} = \frac{1}{0.11 + 0.34 + 0.07256} = 1.9137 \] (7)

So, 10.5kv bus bar voltage \( U = 1.9134 \times 0.07256 = 0.1389 \), down to 0.1389. The lowest residual bus voltage at any point in the system can be reduced to 0.75.

4.3. Calculation of Transformer Short Circuit

When a short circuit occurs at the back of the transformer, the workshop transformer

\[ X_\text{B} = \frac{U_k}{100} \times \frac{S_j}{S_{x3}} = \frac{45}{100} \times 1.6 = 2.8125 \] (8)

The short-circuit current is:

\[ I_{\text{short}} = \frac{1}{0.11 + 0.34 + 0.07256 + 2.8125} = 0.2998 \] (9)

So, 10.5kv bus bar voltage \( U = 0.2998 \times 2.88506 = 0.8647 \), down to 0.8647.

5. System Realization

5.1. Theoretical Calculation of System Implementation

When the system is short circuited, we can make strong excitation to the synchronous motor in a short time. Select constant active mode, and synchronous motor selection capacity of 5300kw motor. The vector graph is shown in figure 4.
The reactance standard for short circuit is:

\[ X_\Sigma^* = 0.11 + 0.34 + 0.0726 = 0.52 \]  

(10)

In the power system,

\[ X_j = \frac{U_j^2}{S_j} = \frac{10^2}{100} = 1 \]  

(11)

So, the actual value of reactance in short circuit is:

\[ X_\Sigma = X_\Sigma^* \times X_j = 0.52 \times 1 = 0.52 \]  

(12)

The voltage drop of short circuit is 0.25, according to formula (2).

\[ \Delta U\% = \frac{Q_e \times X_\Sigma}{U^2} = \frac{0.52 \times Q_e}{10^2} = 0.25 \]  

(13)

The reactive power of the system with short circuit is calculated to be 48MVar. When the power factor of the motor is 0.98, the working current of the motor is 0.98.

\[ I_1 = \frac{P \times \lambda}{\sqrt{3}U_e} = \frac{5300 \times 0.9}{\sqrt{3} \times 10} = 275 \, A \]  

(14)

This moment

\[ I_p = I_1 \times \cos \psi = 0.98 \times I_1 = 270 \, A \]  

(15)

\[ I_{Q1} = \sqrt{I_1^2 - I_p^2} = \sqrt{275^2 - 270^2} = 52 \, A \]  

(16)

A strong excitation for a synchronous motor is the process of increasing its rated current. At this point, the maximum rated current can be increased to 2 times of the original current, so the stator current after strong excitation of the synchronous motor increases to 550 A. Then calculate:

\[ I_{Q2} = \sqrt{I_2^2 - I_p^2} = \sqrt{550^2 - 270^2} = 480 \, A \]  

(17)

So, the increase in reactive power is:

\[ \Delta Q_a = (480 \times 52) \times \sqrt{3} \times 10 = 7413 \, KVar = 7.4 \, MVar \]  

(18)

There are four synchronous motors, so

\[ 7.4 \times 4 = 29.6 \, MVar \]  

(19)
After synchronous motor excitation,
\[ \Delta Q' = 48 - 29.6 = 18.4 \text{MV ar} \]  
(20)

Then according to formula (2)
\[ \Delta U = \frac{Q}{U^2} = \frac{18.4 \times 0.52}{10^2} = 0.096 = 0.1 \]  
(21)

Through calculation, it can be seen that the voltage drop is reduced from 0.25 to 0.1, and the residual voltage of the system short-circuit bus is increased by 0.15, so that the bus can return to normal working condition. When short-circuit occurs, the short-circuit residual voltage of the bus can be increased by forcing excitation on the synchronous motor in a short time. Once the time is too long, the relay protection device will automatically and quickly remove the short-circuit fault. \( U_M \) is the bus voltage, \( Q \) is the reactive power of the system, \( Q' \) is the excitation, the reactive power \( I_{\text{max}} \) is the recovery current and \( I_t \) is the current of the current state bus. As shown in figure 6. At \( t_{a1} \), the short circuit fault occurs, the current of the system increases rapidly, the reactive power increases, and the voltage decreases. At \( t_{a2} \) time, the current and reactive power decrease slowly, and the bus voltage slowly returns to normal level, and all of them return to normal level at \( t_a \) time. It can be seen from the diagram that the reactive power of the system is reduced after the excitation of the synchronous machine. And it is clear that the voltage drop on the bus has decreased, and the decrease is the 0.15 calculated above[6].

![Fig 6. Compensation chart of high-voltage bus short-circuit to join the synchronous motor](image)

**5.2. Implementation of the System**

**5.2.1. Short Circuit Fast Judge of system.** The calculation of the short-circuit current impact coefficient is as follows:
\[ K_H = 1 + e^{\frac{0.01}{\tau}} \]  
(22)
Here $\tau$ is the decay time constant of the own component of short circuit current. In practical calculation, the value of $K_M$ is generally 1.8-1.9. According to formula (22), the value of $\tau$ can be obtained. When the short circuit fault occurs in the power system, the short circuit current has basically risen to the maximum value in the time of 3-4 $\tau$. Here we take 4$\tau$. In this way, we can calculate the change ratio of short-circuit current.

$$\frac{di}{dt} = \frac{\Delta I}{4\tau} \quad (23)$$

The current flowing through the power system during normal operation is about the rated $I_e$. When a short circuit fault occurs in the power system, the current value increases instantly. At this point, the maximum effective value of short-circuit current $I_d$ in the time of 4$\tau$ can be calculated, and then the difference $\Delta I$ can be obtained. Thus, according to formula (23), the rate of variation of short-circuit current can be calculated [7].

The reference value of the current of the power system before the short circuit of the line:

$$I_j = 100 \sqrt{3} \times 10.5 = 5.5 \text{ KA} \quad (24)$$

When a short circuit occurs suddenly on a power line, the steady effective value of the short circuit current in the power system is as follows:

$$I_d = I_d^* \times I_e = 1.9137 \times 5.5 = 10.53 \text{ KA} \quad (25)$$

So, the variation of short circuit current in power system is as follows:

$$\Delta I = I_d - I_e = 10.53 - 0.28 = 10.25 \text{ KA} \quad (26)$$

When the short circuit fault occurs on the synchronous motor, the $K_M$ value is 1.8, according to formula (22), $\tau$ is 0.0448. Finally, according to formula (23), the change rate of the current in the system when the short circuit of the large motor suddenly occurs is as follows:

$$\frac{di}{dt} = \frac{\Delta I}{4\tau} = \frac{10.25}{0.0448} = 57.2 \text{ KA/s} \quad (27)$$

The safety factor is 0.5, when the current change rate is greater than 0.5 times of this value, it can be concluded that the short-circuit fault of the system has occurred. Therefore, through the above calculation, we can take a discriminant condition, that is,

$$\frac{di}{dt} \geq 25 \text{ KA/s} \quad (28)$$

When the current in the power system satisfies the formula (28), the short circuit of the power system can be considered.

5.2.2. Flow Chart of Program Implementation. When the short circuit fault occurs in the power system of Xindu Chemical 110kv Substation, the synchronous motor is forced to be excited when the above conditions are satisfied, so as to reduce the voltage drop on the bus bar and make the bus voltage close to the normal operating level. The specific program flow chart is as follows [8]:

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The program flow chart includes a short circuit current determination device, a recovery device, an excitation voltage setting device, an excitation voltage feedback device and a given signal device. When the short circuit current judge device judges the short circuit fault in the power system, the bus voltage will decrease from 0 to 1, that is to say, the synchronous motor will be forced to excite, and the stator current will increase twice as much as the original one. At this time, the excitation voltage will slowly rise, we can compare the voltage rise through the excitation voltage feedback device. When the bus voltage rises to the normal working value, the recovery device begins to function from 1 to 0, and the stator current of the synchronous motor recovers the rated current of the original normal operation, and the system returns to normal operation.

6. Conclusion
This paper uses the synchronous motor of Xindu Chemical to force excitation. The model chooses constant active excitation, which can be calculated by theory. The residual voltage of short circuit bus is raising from 0.75 to 0.9, and designed a specific program flow chart so that the design can be realized. In actual life, when the short circuit fault occurs in Xindu Chemical 110kv Substation, the bus residual voltage has been raised from 0.75 to more than 0.85 by using synchronous excitation method, the equipment has not tripped and the system is back to normal operation. The actual operation is possible. So, this graduation project from theory to practice has proved feasible. Finally, add a part of the content: short circuit fast judgment of system. We can get a numerical value by calculation. When the rate of change of current in the system exceeds this value, we can judge that the system is about to enter the short circuit state, which greatly improves the working efficiency.

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