Study on Local Measurement Method of Bus Short Circuit Capacity in Substation

X Xu¹, P Deng² and Z Chen¹³

¹College of Electrical Engineering, Guizhou University, Guiyang, Guizhou, 550025, China
²Power Grid Planning and Research Center, Guizhou Power Grid Corporation, Guiyang, Guizhou, 550002, China

E-mail: 37495589@qq.com

Abstract. The short-circuit capacity of the bus is a key parameter required for the operation and control of the power system. Online measurement of the short-circuit capacity is crucial for the observability and controllability of the power grid. In this paper, it is proposed that the bus voltage disturbance can be caused by switching on and off the parallel capacitor. According to the voltage disturbance, the on-line measurement of the short-circuit capacity of the power grid can be performed. Based on the circuit model of the substation, using the substitution theorem and superposition principle of the linear circuit, the accurate calculation method of bus short-circuit capacity measurement is derived. It is revealed that the phase change of the voltage vector caused by the capacitor switching is the key factor affecting the measurement accuracy. It breaks through the approximate formulas of previous studies. The proposed measurement method has high accuracy; an iterative calculation method for the phase difference of the voltage vector is proposed. The method is more convenient and reliable than direct measurement. Based on MATLAB / Simulink, the substation bus and online measurement model are established. Simulation analysis of various scenarios shows that the proposed method has a measurement error of less than 1%, which is technically easy to implement and practically promote.

1. Introduction

With the changes in the scale and structure of modern power systems, short-circuit capacity, as a key parameter required for power system operation and control, has received more and more attention. Relay protection parameter setting, primary equipment selection, power quality testing, and new energy access planning must know the system short-circuit capacity as accurately as possible [1].

Reference source not found. However, as a commonly used electrical calculation, short-circuit capacity calculation has long formed a thinking inertia: the short-circuit capacity (short-circuit current, short-circuit impedance) of each node of the power grid can only be obtained by short-circuit calculation of the power system. The progress of research on short-circuit capacity acquisition methods based on field measurements is slow.

Conventional offline calculations have many inherent disadvantages: ① Short-circuit capacity calculation requires accurate grid topology, line parameters, transformer parameters, generator and regulator parameters, these parameters are huge in data volume, often change, data errors or errors are difficult to avoid, In particular, there is no error correction test method, and it is difficult to find after a
calculation error occurs. ② For on-site application technicians, short-circuit calculation is often cumbersome and difficult. Secondary and primary equipment operation and maintenance personnel can hardly complete the calculation work correctly, cannot check the rationality of the relay protection setting value, and cannot determine the short-circuit capacity of the primary equipment rationality. ③ The power generation enterprise and the power consumption enterprise do not have complete grid data, and it is difficult to calculate the short-circuit capacity (or short-circuit current). The primary and secondary equipment self-maintenance and Tuning is difficult. Therefore, grid capacity measurement technology that does not rely on complex grid parameters has a very realistic multi-party demand.

There have been some studies on the online measurement technology of short-circuit capacity, but the results are not many. References [2] use manual methods to carry out short-circuit tests or use short-circuit accidents to analyze the characteristics of short-circuit currents. Such methods have poor convenience and safety. Reference [3] adds the analysis of the system topology in the grid monitoring software, and then obtains the short-circuit capacity at each bus of the grid according to the grid model and traditional calculation methods. Its essence still belongs to the analysis based on the grid model, and still retains the disadvantages of offline calculation. And this method relies on the premise that the grid monitoring system can cover. Literature [4] gives a method for measuring short-circuit capacity by switching capacitors under the premise of no-load of the bus. This method cannot meet the requirements for normal power supply of each feeder load on the bus, nor does it consider the influence of the resistance component in the Thevenin impedance of the bus. A very ideal measurement method with little application value. Reference [5] obtains the bus short-circuit capacity according to the reactive power compensation relationship of the wind farm, the voltage value when the reactive power is zero, and at least two sets of reactive power values and corresponding voltage values. This method is only applicable to the substation bus connected to the dedicated line of the wind farm, and the method is not universal. Reference [6] calculates the short-circuit capacity based on the change in reactive power and the measurement of the voltage RMS fluctuation. The above methods are all approximate methods, and the accuracy cannot be guaranteed.

Until now, practical power grid bus short-circuit capacity measurement technology and devices have not yet been developed. Grid companies and other industrial companies still have to rely on conventional model-based calculations to obtain short-circuit capacity [7], which cannot meet the considerable demand of smart grids. Controllable and transparent requirements.

2. Concept description

2.1. Concept of short-circuit capacity

The short-circuit capacity of power grid refers to the short-circuit capacity of a certain bus in the power grid, so it should reflect the short-circuit capacity of bus more accurately, while the short-circuit capacity of different buses is generally different. A large short-circuit capacity at this location is called a strong system, while a weak system is the opposite. Because the accurate judgment of the strength of the system is often related to all aspects of system design, operation and control, the short-circuit capacity has become a technical parameter that must be paid attention to.

The power system includes many power plants, transmission and distribution networks at various levels, and loads. When investigating a bus alone, without loss of generality, the bus and its associated power system are expressed in Figure 1. There are several feeder loads and several capacitor groups on the 10 kV bus. For abstract description, they can be merged into a load and a group of capacitors.

![Figure 1. Power system and its electricity substation bus](image-url)
When a three-phase short-circuit occurs on the bus, all power supplies on the network provide short-circuit current, the ground current at the short-circuit point is $I_f$, and the rated voltage of the bus is $V_B$, then the short-circuit capacity is expressed by formula (1):

$$S_f = \sqrt{3}V_B I_f$$

(1)

### 2.2. Relationship between short-circuit capacity and internal resistance of the system

Equation (1) gives the definition of short-circuit capacity, indicating that the short-circuit capacity is proportional to the short-circuit current, but this formula does not reveal the circuit significance of the short-circuit capacity. In fact, the bus short-circuit capacity is determined by the Thevenin impedance that the bus looks into the system, and its circuit significance is shown in Figure 2.

![Figure 2](image)

**Figure 2.** The circuit model of bus short-circuit capacity

With reference to Figures 1 and 2, $Z_S$ is the Thevenin impedance seen from the bus to the power system, $E_S$ is the voltage when the bus is unloaded (all loads and reactive equipment exit), also known as the internal potential of the bus, and $Z_{LD}$ represents the Constant impedance, $C$ is the reactive power compensation capacitor. $Z_S$ is the structural parameter of the system, and $E_S$ is the operating parameter. It can be obtained from Figure 2 that the bus short-circuit current is only determined by $E_S$ and $Z_S$, as shown in equation (2):

$$I_f = \frac{E_S}{Z_S}$$

(2)

Since the voltage of each bus in the power system can only be operated near the rated voltage, $E_S$ can only change in a small range. If $E_S = V_B$ is assumed, both $I_f$ and $S_f$ are determined by $Z_S$ only. Therefore, the measurement of short-circuit capacity mentioned in this article is essentially the measurement of $Z_S$. It should be noted that when measuring $Z_S$, it is not necessary to assume $E_S = V_B$, but to treat $E_S$ as an unknown variable.

### 3. Principle of measurement method

#### 3.1. Circuit modeling of measurement method

It can be seen from Section 1.2 that the measurement of short-circuit capacity $S_f$ can be attributed to the measurement of $Z_S$ resistance in the system, and whether $Z_S$ has testability is the key issue of this article. It is known from Figure 2 that the circuit contains two unknown parameters $E_S$ and $Z_S$, and two unknown quantities cannot be obtained in a single circuit state, so two circuit states need to be artificially created, and each circuit state must contain two unknown quantities, you can solve it. Based on the above analysis, it is possible to find $Z_S$ by cutting or putting in capacitors to cause two circuit states.

According to the principle of circuit replacement, the capacitor is represented by a current source under stable operating conditions, the current magnitude is equal to the current of the capacitor at this time, and the capacitor element is represented by the current source $I_C$, the circuit model in Figure 2. is transformed into the circuit model in Figure 3, and $V_1$ is the bus voltage to ground.
In Figure 3, the $I_C$ is calculated by equation (3)

$$I_C = \frac{V_1}{X_C} \quad (3)$$

$X_C$ in formula (3) is the capacitive reactance of the capacitor.

There are two power supplies in Figure 3, which are the internal potential $E_S$ and the equivalent current source $I_C$, so the circuit model under the separate action of each power supply can be considered separately. The model of $E_S$ alone is shown in Figure 4 (a), which is equivalent to the capacitor cut-off state, and the bus voltage is $V_2$; the model of $I_C$ alone is shown in Figure 4 (b). This model has only circuit analysis significance and no actual scene. Meaning, but the model has only one unknown quantity $Z_S$, and the measurement equation can be listed accordingly, such as equation (4).

$$\Delta V = \frac{\Delta V}{Z_{LO}} + \frac{\Delta V}{Z_S} = I_C \quad (4)$$

It can be known from equation (4) that if $\Delta V$ can be measured and the resistance-to-inductance ratio $k$ of $Z_S$ is known, $Z_S$ can be solved. However, the measurement of $\Delta V$ is a difficult point. It is known from Figure 4 (b) that $\Delta V$ is the voltage caused at the busbar when the $I_C$ acts alone, and only the meaning of circuit analysis cannot directly measure its value.

According to the analysis of Figure 3 and Figure 4, the bus voltages $V_1$, $V_2$ and $\Delta V$ before and after the capacitor switching just have a vector synthesis relationship, that is, the vector sum of $V_2$ and $\Delta V$ is equal to $V_1$, as shown in Figure 5.
Figure 5. Vectors of voltage before and after capacitor switching

It can be seen that \( \Delta V \) has another meaning: that is, the vector difference between the voltage vector before the capacitor is cut off and the voltage vector after the capacitor is cut off. This meaning is different from the voltage amplitude difference described in reference [8], which is also the root cause of the low measurement accuracy in the previous literature. The resistance and reactance of load impedance and internal impedance in Figure 4 (b) are converted into parallel form, as shown in Figure (6). \( R_{LO} \) corresponds to the active power of the load, \( X_{LO} \) corresponds to the reactive power of the load and the reactive compensation capacity of the bus; \( X_S \) and \( R_S \) correspond to the reactive and active components of the short-circuit capacity respectively, such as equation (5).

\[
R_S = kX_S
\]  
(5)

Figure 6. Parallel form of Load impedance and Internal impedance

The first step, as can be seen from Figure 6, \( X_{LO} \) and \( X_S \) can be merged in this circuit, after the merger is equivalent to change \( X_S \), but this change can be corrected in the second step. Therefore, \( X_{LO} \) is not considered temporarily, and the following equation can be listed:

\[
\left( \frac{\Delta V}{R_{LO}} + \frac{\Delta V}{kX_S} \right)^2 + \left( \frac{\Delta V}{X_S} \right)^2 = I_C^2
\]  
(6)

The finishing formula is:

\[
\left( \frac{1}{R_{LO}^2} - \left( \frac{I_C}{\Delta V} \right)^2 \right) X_S^2 + \frac{2X_S}{kR_{LO}} + \left( 1 + \frac{1}{k^2} \right) = 0
\]  
(7)

If \( \Delta V \) is measurable, it is a known quantity. \( X_S \) can be obtained by solving the quadratic equation of one variable shown in formula (7), \( R_S \) and \( Z_S \) can be obtained according to \( X_S \), and the short-circuit capacity \( S_f \) can be further obtained.

In the second step, when \( X_{LO} \) is considered, the equivalent treatment is as follows: the \( \Delta V \) caused by \( I_C \) acting on \( X_{LO} \) as load is completely equivalent to the \( \Delta V \) caused by \( I_C \) acting on \( X_{LO} \) as internal reactance parallel branch. Therefore, when considering the calculation of \( S_f \) by \( X_{LO} \), it is only necessary to add the short-circuit capacity corresponding to \( X_{LO} \) to the calculation results in the
first step, that is, to add the parallel reactive capacity and load reactive capacity.

It can be seen that the problem is transformed into the measurement of $\Delta V$. It can be seen from Figure 5 that $\Delta V$ can be obtained according to the cosine theorem under the conditions that $V_1$, $V_2$, and $\theta$ are known. Therefore, the measurement of $\theta$ becomes the key. However, $\theta$ is not the phase difference between two nodes in the circuit analysis, but the phase difference of the same node in different times relative to the grid synchronous rotation phasor. The actual measurement is difficult, and there is no measurement example in the power field. For this reason, an iterative method for calculating the diagonal difference $\theta$ is proposed.

4. Iterative calculation of angular difference $\theta$

The accurate acquisition of angle difference $\theta$ is the decisive factor for the success or failure of the technology. In the actual power grid scenario, the variation range of $\theta$ is between $0^\circ$ and $10^\circ$. In this range, there are three features as follows. Feature ①: $\theta$ and $\Delta V$ have a nearly linear monotonic correspondence, that is, after the amplitude measurement values of $V_1$ and $V_2$ are obtained, according to the vector relationship in Figure 5, the larger $\theta$ must correspond to the larger $\Delta V$. Feature ②: $\Delta V$ and $X_S$ have nearly linear monotonic correspondence, that is to say, according to Formula (5), a larger $\Delta V$ must solve a larger $X_S$. Feature ③: $X_S$ and $\theta$ have a monotonic correspondence, that is, determined by the circuit in Figure (2), the larger $X_S$ must correspond to the larger $\theta$. The above characteristics determine the feasibility of $\theta$ iteration.

Basic principle: first assume the initial value of $\theta$ $\theta(1)=0$, that is, the difference between the amplitudes of $V_1$ and $V_2$ is used as the first estimate of $\Delta V$ $\Delta V(1)$, and calculate the first estimate of $X_S X_S(1)$ ① and characteristics ② there must be $\Delta V(1)<\Delta V$, $X_S(1)<X_S$. Then, based on $X_S(1)$ and according to Figure (2), the first iteration value $\theta(2)$ of $\theta$ is calculated. According to the characteristics ③, there must exist $\theta(1)<\theta(2)<\theta$.

Then $\theta(2)$ can be used to obtain $\Delta V(2)$, $X_S(2)$ and $\theta(3)$ according to the previous iteration sequence, and there must be $\theta(1)<\theta(2)<\theta(3)<\theta$. According to these iterations, each iteration can approach the true value monotonically, neither falling into the local optimum nor diverging. According to the basic principle, the flow chart of angle difference iteration is obtained, as shown in Figure 7.

![Figure 7. Iterative calculation flow chart of phase-angle differences $\theta$](image-url)
5. Example analysis

In order to verify the measurement principle and method in this paper, the simulation model is established based on MATLAB / Simulink software platform. The tested object is 35kV bus of substation. No matter the 35kV bus is located in 500kV, 220kV or 110kV substation, and no matter how complex the network behind it is, for the study of short-circuit capacity, it can be strictly equivalent to the voltage source short-circuit impedance model. Then the reactive compensation model and load model can be established. The short-circuit capacity meter is connected to the secondary circuit, and the overall simulation model and main parameters are shown in Figure 8.

![Figure 8. The model of substation and bus bar short-circuit capacity measurement apparatus](image)

5.1. Selection of capacitance removal

In practice, the compensation capacitors on the medium-voltage bus (35 kV or 10 kV) of the substation have multiple sets of configurations with different sizes. Before removing the capacitance, the amount of capacitance removal should be estimated to determine which group to remove. In order to reduce the influence as much as possible, it is desirable that the voltage drop after removing the capacitor falls within 2% to 5% of the rated voltage. Accordingly, the estimated formula for the cut-off capacitance $S_C$ is:

$$S_C = (2\% - 5\%)S_f$$  \hspace{1cm} (6)

5.2. Iterative process analysis

Based on the simulation overall model in Figure 8, the parameters such as load and reactive power compensation device are set according to the 10 kV voltage level. The key parameters are set as follows: the bus to be tested is 10 kV voltage level, the system frequency is equal to 50Hz, no frequency offset, and the three-phase short-circuit capacity is set to 600 MVA, the load of the substation is (50+j30) MW, the fixed reactive power compensation of the line is 40 MVar, and the reactive power compensation capacitor that performs the cut-off operation is 20 MVar. Cut off the capacitor at $t=1$ and observe the change of its bus voltage.
Figure 9. The waveform of phase voltage during capacitor cutting

It can be seen from Figure 9 that the capacitor is cut off at t=1s, the bus phase voltage drops slightly, and the steady-state voltage before and after t=1s is recorded by the short-circuit capacity measuring instrument in Figure 7. Based on this waveform and the algorithm in this paper, the short-circuit capacity at the bus can be obtained. Place a three-phase short-circuit fault at the point to be measured, and the short-circuit capacity corresponding to the measured three-phase short-circuit current is taken as the theoretical value of the short-circuit capacity at that point. During the iteration process, record the angular difference θ, voltage vector difference ΔV, the reactance component Xₜ of the internal impedance and the corresponding short-circuit capacity measurement value Sₜ after each iteration. The changes in each quantity are recorded in Table 1.

Table 1. The trends of variables in the iterative process

| Number of iteration | θ (°) | ΔV(kV) | Xₜ(Ω) | Sₜ(MVA) |
|---------------------|------|--------|------|--------|
| 0                   | 0    | 0.312  | 0.165| 630.012|
| 1                   | 4276 | 0.348  | 0.168| 601.083|
| 2                   | 4428 | 0.349  | 0.168| 600.033|
| 3                   | 4439 | 0.349  | 0.168| 599.956|
| 4                   | 4439 | 0.349  | 0.168| 599.951|
| 5                   | 4440 | 0.349  | 0.168| 599.950|
| 6                   | 4441 | 0.349  | 0.168| 599.950|

It can be seen from Table 1. that before the iteration, the voltage vector phase difference θ is 0 degrees, which is equivalent to the method used in the previous literature. The calculated short-circuit capacity value at this time is 632.012 MVA, which is very different from the theoretical value of 600 MVA, and the error It has reached 5.06%, which is no longer acceptable. After starting the iteration, θ approaches the stable value of 0.4441 with the increase of the number of iterations; ΔV approaches 0.349 kV from 0.312 kV; the reactance component Xₜ of the internal impedance approaches 0.165Ω from 0.165Ω to 0.168Ω; the measured value of the short-circuit capacity is 630.012 MVA. It is close to 599.950 MVA, very close to the theoretical value of 600 MVA, and the error is only 0.008%.

5.3. Measurement of different short-circuit capacity levels

In order to verify the effectiveness of the method in this paper when the short-circuit capacity changes widely, consider a variety of system scenarios and set the system to various short-circuit capacities for simulation measurement. For the 10 kV voltage level, the load is (20+j10) MW, the reactive power compensation is 20 MVar, and the short circuit capacity of the 10MVar system with the cut-off
capacitor is in the range of 200 MVA to 300 MVA is reasonable. Based on the method in this paper, the in-situ measurement is performed. Record the voltage U1 before switching and the voltage U2 after switching, the angle difference θ, the short-circuit capacity measurement value Sr, the short-circuit capacity measurement error h under different short-circuit capacities S. Table 2 gives the measurement results within this range.

| S(MVA) | U1 (kV) | U2 (kV) | θ(°) | Sr(MVA) | h(%) |
|--------|---------|---------|------|---------|------|
| 200    | 11.10   | 10.56   | 0.7438 | 198.1   | -0.95|
| 210    | 11.08   | 10.56   | 0.6927 | 208.0   | -0.95|
| 220    | 11.05   | 10.56   | 0.6476 | 217.9   | -0.95|
| 230    | 11.03   | 10.56   | 0.6076 | 227.8   | -0.96|
| 240    | 11.01   | 10.55   | 0.5719 | 237.7   | -0.96|
| 250    | 10.99   | 10.55   | 0.5399 | 247.6   | -0.96|
| 260    | 10.97   | 10.55   | 0.5111 | 257.5   | -0.96|
| 270    | 10.95   | 10.55   | 0.4849 | 267.4   | -0.96|
| 280    | 10.94   | 10.55   | 0.4611 | 277.3   | -0.96|
| 290    | 10.92   | 10.55   | 0.4395 | 287.2   | -0.97|
| 300    | 10.91   | 10.55   | 0.4196 | 297.1   | -0.97|

For the 10 kV voltage level, the load is (50+j30) MW, the reactive power compensation is 40 MVar, the switching capacitor is 20MVar, and the system short-circuit capacity is reasonable in the range of 600 MVA to 700 MVA. The in-situ measurements were carried out based on the method in this paper. Record the voltage U1 before switching and the voltage U2 after switching, the angle difference θ, the short-circuit capacity measurement value Sr, the short-circuit capacity measurement error h under different short-circuit capacities S. Table 3 gives the measurement results in this range.

| S(MVA) | U1 (kV) | U2 (kV) | θ(°) | Sr(MVA) | h(%) |
|--------|---------|---------|------|---------|------|
| 600    | 10.87   | 10.51   | 0.4499 | 594.3   | -0.95|
| 610    | 10.86   | 10.51   | 0.4396 | 604.2   | -0.95|
| 620    | 10.86   | 10.51   | 0.4298 | 614.1   | -0.95|
| 630    | 10.85   | 10.51   | 0.4203 | 624.0   | -0.95|
| 640    | 10.85   | 10.51   | 0.4133 | 633.9   | -0.95|
| 650    | 10.84   | 10.51   | 0.4025 | 643.7   | -0.97|
| 660    | 10.84   | 10.51   | 0.3942 | 653.6   | -0.97|
| 670    | 10.83   | 10.51   | 0.3861 | 663.5   | -0.97|
| 680    | 10.83   | 10.51   | 0.3783 | 673.4   | -0.97|
| 690    | 10.82   | 10.51   | 0.3708 | 683.3   | -0.97|
| 700    | 10.82   | 10.51   | 0.3636 | 693.2   | -0.97|

As can be seen from Table 2 and Table 3, under each setting, the measured value and the theoretical value are very close, and the measurement error does not exceed 1%. The voltage drop caused by the removal of the capacitor falls between 2.1% and 2.4% of the rated phase voltage. Such a voltage change is safe for the system. In particular, although the value of θ is generally small, if you ignore this value, as in the practice of [8], it will bring a lot of errors. Taking the theoretical value of the short-circuit capacity 700 MVA as an example, the corresponding θ value of this scenario is only 0.3636 degrees. If this value is ignored and considered to be 0, it will result in a short-circuit capacity measurement value of 729. It can be seen that the accurate acquisition of θ value is very important. In fact, even if the direct measurement method is adopted, it is difficult to ensure the measurement accuracy for the case where the value of θ is 0.3636 degrees. The iterative method proposed in this paper solves this problem well.
6. Conclusion
In this paper, through the mechanism modeling, algorithm deduction and multi scene simulation research of on-line short-circuit capacity measurement, the following conclusions are drawn:

(1). It is revealed for the first time that the change of voltage vector phase caused by capacitor switching is the key factor affecting the measurement accuracy, breaking through the previous approximate formula, and the proposed measurement method has high accuracy.

(2). The iterative solution of voltage vector phase difference can ensure convergence and accuracy, which is more reliable and convenient than direct measurement.

(3). The non-fault disturbance method is adopted to measure the short-circuit capacity of the power grid, which allows operation with load, does not need to be carried out under no-load conditions, does not affect the safety of the power grid, and does not limit the specific operation mode of the grid.

(4). The proposed method does not require complete grid parameters, and is safe, convenient and timely, which effectively makes up for the limitation of short-circuit capacity calculation.

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Authors
Xiao Xu is a postgraduate student. Her research direction is Microgrid energy management.
Zhuo Chen is the correspondence author. She received Ph. D degree in 2014 in electrical engineering from Guizhou University, Guiyang, China. At present she is a Professor with the Electrical Engineering Department at Guizhou University.

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