Transformer Short Circuit Current Calculation and Solutions

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Bachelor's Thesis

Electrical Engineering

Vaasa 2013

BACHELOR'S THESIS

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Specialization:	Electrical Power
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Title:

Transformer Short Circuit Current Calculation and Solutions

Date	Number of pages	Appendices
14 June 2013	31 pages	0 page

Summary

There are three goals for the thesis. The first one is to introduce types of short-circuits. The second one is to introduce the transformer short-circuit current calculations. And the last one is to find suitable reinforcement methods for the transformers which are running now. Using a comparative approach to analytic research, the advantages and disadvantages of different reinforcement methods can be analyzed. The result shows that the neutral reactor is the best choice to reinforce the S/C withstand capability: low cost, easy maintenance, high technique maturity and so on.

Language: English

Key words: short-circuit, transformer calculation methods, short-circuit withstand capability

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ABBREVIATIONS

S/C	short circuit
AC	alternating current
DC	direct current
Emf	electromotive force
HV	high voltage
LV	low voltage
MV	medium voltage
SGCC	State Grid Corporation of China

1 Background

1.1 Introduction to the short circuit phenomenon

A short circuit (S/C) in an electrical circuit is a part of the circuit that for some reasons has become “shorter” than it should be. The current in an electrical circuit flows the easiest way and if two points in a circuit with different potentials are connected with low electrical impedance the current is taking a shortcut between the two points. The consequences of an S/C can be everything from just a minor malfunction to a disaster. The consequences are dependent of the system´s capacity for driving current in an S/C situation and how long time the S/C current is allowed to flow. In almost every electric circuit there has to be some kind of protection against S/C currents.

When circuits are analyzed mathematically, an S/C is usually described by zero impedance between two nodes in the circuit. In reality it is impossible that the impedance should be zero and therefore the calculations will not give the “real” value but in most cases the highest possible value. To get right results of a calculation it is also important to know all parameters of the circuit. Especially in S/C situations the behavior of the circuits are “strange” and there is no linearity between the voltage of the system and the current flowing.

A short circuit may lead to an electric arc if the current driving capacity of the system is “enough” and protecting devices don´t disconnect the circuit. The arc is a channel of hot ionized plasma that is highly conductive. Even short arcs can remove significant amount of materials from the contacting points. The temperature of the electrical arc is very high causing the metal on the contact surfaces to melt. /1/

Even in circuits where no visible arcs appear the S/C current often causes excessive heating of some part of the circuit. Short circuits can produce very high temperatures due to the high power dissipation in the circuit.

A practical example of heating due to a short circuit is arc welding. The power supply for an arc welder can supply very high currents that flow through the welding rod and the metal pieces being welded. The point of contact between the rod and the metal surfaces gets heated to the melting point, fusing a part of the rod and both surfaces into a single piece. /2/

1.2 Needs of transformer short-circuit current calculation

Today more than ever before, the electricity grid is developing so quickly — the power plant capacity, the substation capacity and electricity loads, as well as load density, sustainably grow. Take China as an example. The number of 500 kV substations in the North China power grid is almost 2 times higher than in the past decade. The number has grown from 48 to 97; the substation capacity has increased from 52,069,000 kVA to 157,960,000 kVA. /3/

As a result, the short-circuit currents in the power grid increase year by year. Based on the statistical analysis of the State Grid Corporation of China (SGCC) /4/, /5/, the S/C current accidents of power transformers (Size ≥ 110 kV) happened 125 times. The total power capacity influenced by the S/C accidents is 7,996 MVA in 1995~1999. The number represents 37.5% of all power accidents and 44% of the transformers accidents. The details are shown in Table 1 and Table 2.

Table 1. Transformer S/C accidents in China (1995-1999)

year	1995	1996	1997	1998	1999	Total
Accident times	59	58	55	63	49	284
S/C accident times	29	29	21	26	20	125
The rate	49.2%	50%	38.2%	41.3%	40.8%	44%

Table 2. Transformer S/C accidents in China (2001-2005)

year	2001	2002	2003	2004	2005[a]	Total
Accident times	63	28	32	53	18	194
S/C accident times	21	9	12	21	8	71
The rate (%)	33.3%	32.1%	37.5%	39.6%	44.4%	36.6%
a) The total number of transformers decreased in 2005 because of the reshuffle of the electrical enterprises. Some transformers weren't calculated in this table						

There are some examples of the transformer S/C accidents. The first one happened in Stone Road Substation in Hubei Province. The results are electricity power losses of 550000 kWh and direct economic losses of about 140,000 euros. /6/ A second accident happened in Riverside Substation in Kaifeng City, Henan Province in1998. The transformer in the S/C accident was 110 kV, S_N =31500 kVA. The S/C current which it encountered was 1288 A, about 1.3 kA /7/.

Not only in China, but also in other countries, the percentage of S/C accidents is high. The transformers whose capacities are greater or equal to 2500k VA encounter 199 S/C accidents in the total 898 tests in high power laboratories in Korea, Sweden, Great Britain, Italy, Poland, Holland, Brazil, India, Rumania, South Africa, Russia, Mexico, the Czech Republic and Germany. The fail rate is 22%. In Canada, the rate of S/C accidents is 33％ of transformers whose capacities are 2501~4000 kVA, the fail rate for transformers which are greater than 4000 kVA is 25％. /8/

The S/C current is an important specification and standard for equipment and conductors in the power industry, and S/C current withstand capability of the main devices decides whether the grid could run more safely or not. So it's significant to calculate the S/C current and offer some possible solutions. The calculation can help us to

1) specify fault ratings for electrical equipment (e.g. short circuit withstand ratings)
2) help identify potential problems and weaknesses in the system and assist in system planning
3) form the basis for protection coordination studies /9/

So, it is not only the S/C calculation methods that are necessary but also the power transmission and the transformation devices should be equipped with better withstand ability for the higher S/C currents.

1.3 Symmetrical components

In the practical work, engineers often use “symmetrical components” to analyze the three-phase power system.

It was invented by a Canadian electrical engineer Charles L.Fortescue in 1913. Mr Fortescue’s original purpose was to analyze the operation of the electrical motors. The theory was not used for the power system until 1937. The analytical technique was adopted and advanced by engineers at General Electric and Westinghouse and after World War II it was an accepted method for asymmetric fault analysis. Now it’s a common tool used to analyze the faults of three-phase power system. /10/

The basic setting for the theory is that any unbalanced system quantities (current or voltage) could be decomposed into 3 symmetrical sets of balanced vectors: positive sequence components, negative sequence components and zero sequence components.

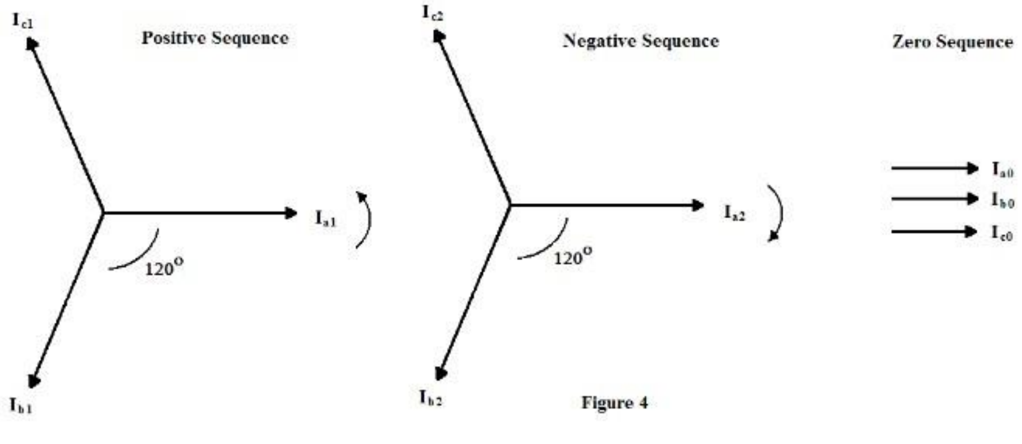

Figure 1. Sequence components to represent the three-phase electrical system /11/

The positive sequence component of the current shown in Figure 1 is balanced in magnitude with a 120 degree phase separation and counter-clockwise rotation, just like the original balanced system. The negative sequence component of the current is balanced in magnitude with a 120 degree phase separation, but has the opposite rotation, in this case, clockwise. The zero sequence components have equal magnitudes, but zero phase separation. Here, we denote the positive sequence with the subscript “1”. Likewise, the negative sequence is denoted with the subscript “2” and the zero sequence is denoted with the subscript “0”.

Under a no fault condition, the power system is considered to be essentially a symmetrical system and therefore only positive sequence currents and voltages exist. At the time of a fault, positive, negative and possibly zero sequence currents and voltages exist. Using real world phase voltages and currents along with Fortescue’s formulas, all positive, negative and zero sequence currents can be calculated. Protective relays use these sequence components along with phase current and/or voltage data as the input to protective elements. /12/

2 Different kinds of short circuits

2.1 DC circuits

What circuit information is needed to do an S/C calculation for a DC circuit? In an electrical circuit the current is dependent of the electromotive force (emf), the electromagnetic field, and the total impedance of the circuit. In a battery the emf-value is dependent of the charge of the battery. The internal impedance of the battery is also a changing parameter and dependent of the charge, the temperature, and the age of the battery and so on. In a DC circuit the resistance is the current limiting factor together with the emf in steady-state which means “after a while”. In the beginning of a transient, like an S/C situation, also the inductance of the circuit is limiting. Any inductance in the circuit will smooth up the rise of the current. The current is increasing exponentially due to the relation between the inductance and the resistance of the circuit.

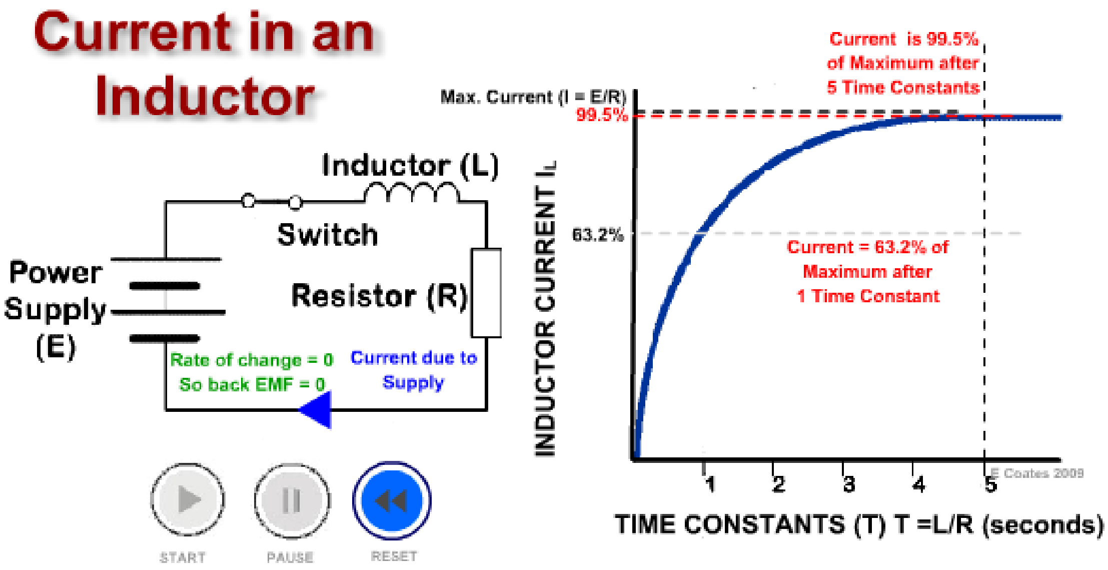

Figure 2. The current in an inductor /13/

Direct current causes different problems from AC when trying to interrupt high value currents since the arc extinction is more difficult. AC passes through zero every half period thus helping the breaking of current. A circuit breaker for a certain AC current is usually not able to break the same magnitude of DC current. The difficulties of breaking a DC circuit increases with the ratio of inductance versus resistance in the circuit. Inductances are always in opposition to changes of current.

2.2 AC circuits

Alternating current circuits (AC) are more complex to solve than direct current circuits (DC). There are more parameters affecting the results and in fast changing situations the first values of current are strongly dependent of the phase of the active voltage source.

2.2.1 Single-phase circuits

Most large power networks are three-phase but especially in low voltage systems most of the connected circuits are single-phase. When calculating S/C currents the situation is dependent on how near the generator or transformer the fault occurs. Not only due to the increasing impedance in the end of the network but also to the fact that generators and transformers are acting “strange” when they are not loaded symmetrically in all phases. In some cases the circuit may be fed from a single-phase transformer with a current carrying capacity that is not enough to make the three-phase system behave “strange”. The fact that the S/C current is easier to calculate *far from* a transformer or a generator is because the line impedances are playing an important role in the process and the impedances are often easier to know than the voltage in the beginning of the circuit. With longer lines the currents decreases and the voltage from the source will not change very much.

In single-phase low voltage circuits that are commonly used in households the S/C currents must be disconnected for different reasons. One reason is because of the touch voltage that may occur during a contact between phase and protective earth. The protective earth in a circuit is used to prevent exposed conductive parts from getting a dangerous potential referred to earth. When a direct contact between phase and exposed conductive parts is established by a fault situation the potential will rise to a dangerous level for persons to touch and therefore the circuit must be disconnected by protection devices like fuses and circuit breakers. In household situations the maximum time for disconnection is normally 0.4 seconds.

To access the clearance time under fault conditions the prospective fault current must be determined by measurement or calculation. It is the prospective current that will flow when the end of the cable being protected is connected to the protective earth conductor that is of concern. With long cable runs this prospective current can be found to be comparatively low. It should be remembered however that the first problem with long cable runs is the possibility of excessive voltage drop, and cables should be selected first for current rating, and then checked for voltage drop before determining the fault prospective. /14/

2.2.2 Three-phase circuits

Three-phase electric power is a common method of AC electric power generation, transmission, and distribution. It is a type of poly-phase system and is the most common method used by electrical grids worldwide to transfer power. It is also used to power large motors and heavy loads. A three-phase system is usually more economical than an equivalent single-phase or two-phase system at the same voltage because it uses less conductor material to transmit electrical power. The three-phase system was independently invented by Galileo Ferraris, Mikhail Dolivo-Dobrovolsky and Nikola Tesla in the late 1880s. /15/

Most single-phase circuits are just a part of a three-phase network. In a three-phase system various types of S/C can occur. For example, S/C current can be phase-to-earth (80% of faults), phase-to-phase (15% of faults — this type of fault often degenerates into a three-phase fault) and three-phase (only 5% of initial faults). These different short-circuit currents are shown in Figure 3. In China, there is another rough classification which is based on the number of the fault phase: three-phase fault, double-phase fault and single phase fault due to phase-to-earth fault which may happen for two phases.

The primary characteristics of short-circuit currents are:

1) Duration: The current can be self-extinguishing, transient or steady-state
2) Origin: it may be caused by mechanical reasons (break in a conductor, accidental

electrical contact between two conductors via a foreign conducting body such as a tool or an animal), internal or atmospheric overvoltage, and insulation breakdown due to heat, humidity or a corrosive environment

3) Location (inside or outside a machine or an electrical switchboard)

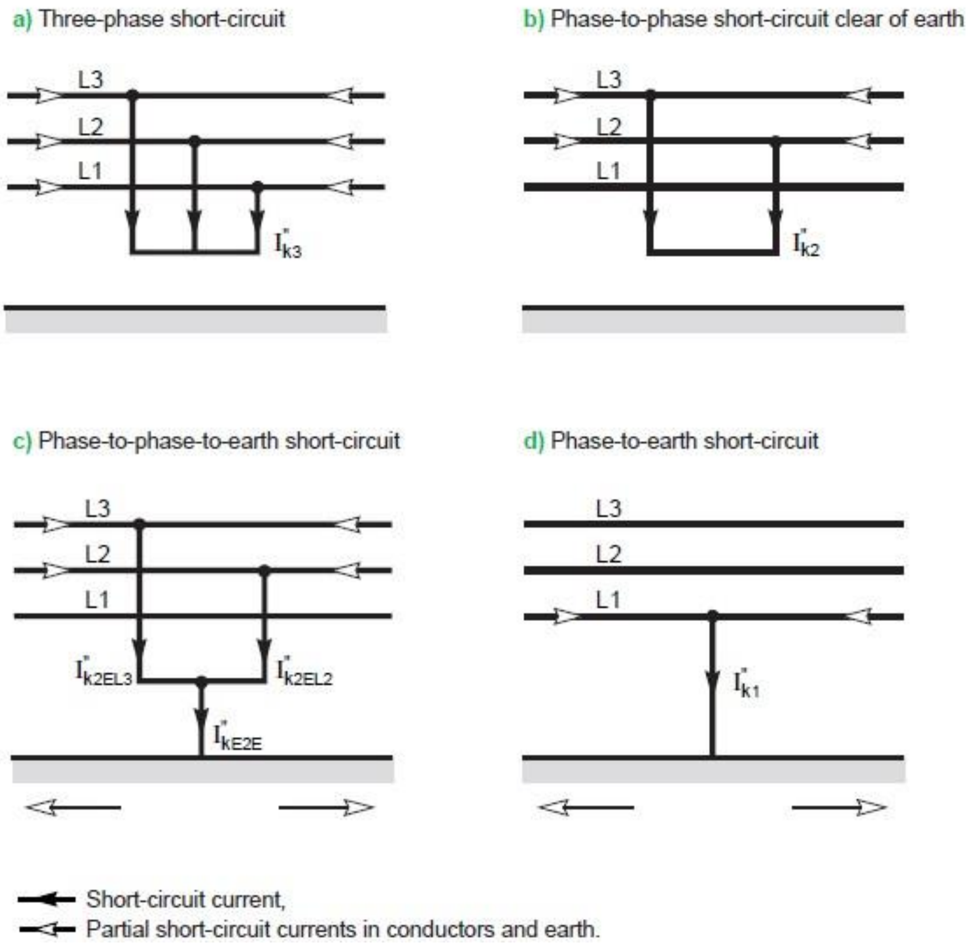

Figure 3. The fault types /16/

The consequences of S/C are depending on the type and duration of the fault and the short-circuit power available. Locally at the fault point there may occur electrical arcs causing damage to insulation, welding of conductors and fire. On the faulty circuit, electro dynamic forces may result in deformation of bus bars and cables and the excessive temperature rise may damage insulation. Other circuits in the network or in nearby networks are also affected by the short-circuit situation. Voltage drops occur in other networks during the time of S/C and shutdown of a part of a network may include also “healthy” parts of the network depending on the design of the whole network.

2.2.3 Development of short-circuit current

A simplified AC network can be represented by a source of AC power, some kind of switching device, a total impedance Z_N that represents all the impedances upstream of the switching point and a load, represented by its impedance (see figure 4). In a real network the total impedance Z_N is made up of the impedances of all components upstream. The components are for example generators, transformers, wires, circuit-breakers and metering systems.

When a fault with negligible impedance occurs between A and B a short-circuit current limited only by Z_N flows in the circuit. The short-circuit current I_{sc} develops under transient conditions depending on the relation between inductances and resistances in the whole circuit. If the circuit is mostly resistive the waveform of the current is following the waveform of the voltage but if there are inductances in the circuit the waveform of the current will differ from the waveform of the voltage during a transient time of the process. In an inductive circuit the current cannot begin with any value but zero. The influence of inductances is described by reactance X in AC circuits with a fixed frequency of the voltage. In low voltage systems where cables and conductors represent most of the impedance it can be regarded as mostly resistive. In power distribution networks the reactance is normally much greater than the resistances. Generally the total impedance Z in steady-state in an AC circuit is made up of the total resistance R and the total reactance X as the following relation shows.

$$Z = \sqrt{R^2 + X^2}$$

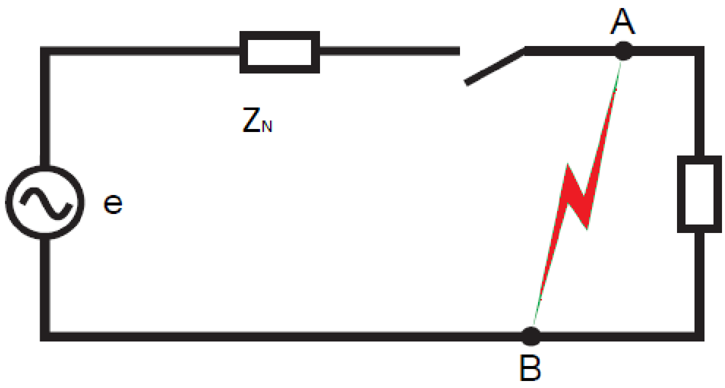

Figure 4. The simple S/C circuit

In the simplified circuit above the voltage is constant and so is the total impedance. In faults *far from* generators and transformers where most of the impedance consists of impedances from wires the calculations can be done with a good result and the transient current is almost the same as if the current would flow for a longer time. The meaning of *far from* is not necessarily physical but means that generator or transformer impedances are less than the impedance of the elements from wires. The impedance elements from wires are constant at a constant temperature but the impedances of generators vary during a short-circuit and the impedances of transformers change if the transformers are asymmetrically loaded with high currents.

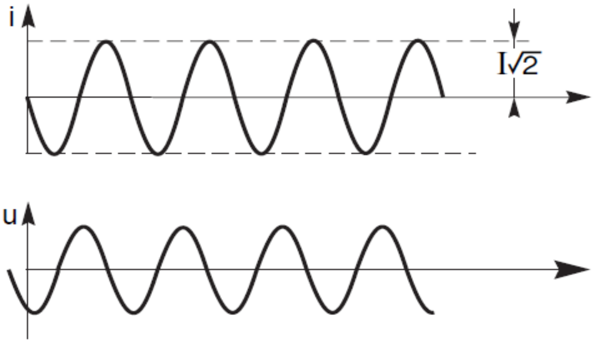

Figure 5. The currents continue symmetrically

Figure 5 shows the current in beginning of a short-circuit *far from* the generator. The short-circuit starts at a moment when the current normally is zero and continues symmetrically.

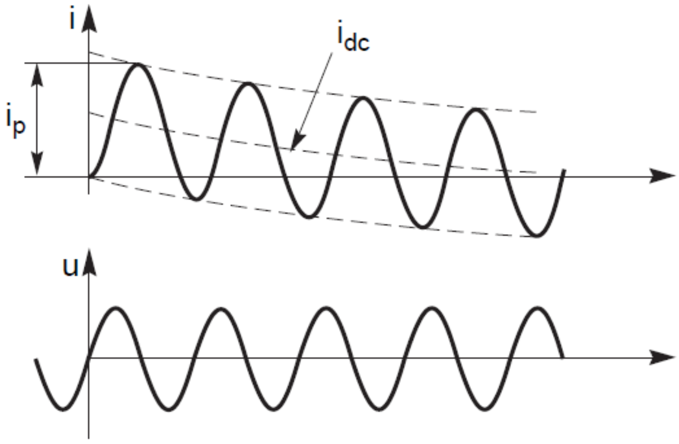

Figure 6. The currents continue asymmetrically

Figure 6 shows the current when the short-circuit starts at a moment when the voltage is zero and the current is also starting from zero but asymmetrically during a transient time.

3 Calculation methods for transformers

In Chapter 1, the data show the importance of transformer S/C current calculations and introduce the symmetrical components theory briefly. Let's discuss the calculation methods on the basis of two single transformer models in Chapter 3.

3.1 Single transformer model

In this section, I will begin with two examples:

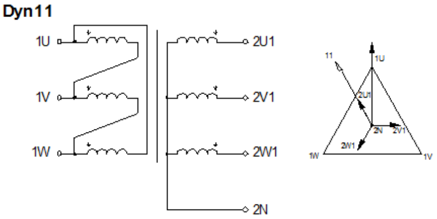

Figure 7. The Dyn11 transformer circuit

Example 1: one transformer which has S_N=100 kVA, Dyn11 connection. The transformation rate is 20500 V/ 410 V. P_0=220 W, P_k=1485W, Z_k=3.8%, Z_0=3.8%.

The calculation of its S/C current is as follows:

The rated currents:

$I_{1N}=S_N/(\sqrt{3}*U_{1N})$ = 100000/ (1.732*20500) = 2.82 A

$I_{2N}=S_N/(\sqrt{3}*U_{2N})$ = 100000/ (1.732*410) = 140.82 A

The impedance:

$Z_k^{"} = \frac{Z_k * U_{2N}^2}{S_N}$= 0.038* 410^2/100000=63.88 mΩ

$R_k^{"} = \frac{P_k}{3 * I_{2N}^2}$= 1485/ (3* 140.82^2)=24.97 mΩ

Since we have $X^2 + R^2 = Z^2$,

$X''_k=\sqrt{63.88^2-23.97^2}$ = 58.8 mΩ

If U_1=U_{1N}=20500V, the three-phase S/C at the terminals will be:

I''_k= U_{2N}/ ($\sqrt{3}$*Z''_k) = 410/ (1.732*0.0639) = 3705.6A≈3700 A

In the single phase fault accidents, the current will not change if it's the phase-neutral case. But the performance of the transformer will be abnormal. In special cases, the current may be greater (Yzn). If the transformer is Dyn connected, the single phase current will be less than the three-phase current.

Example 2: a power transformer which has S_N = 63 MVA. The transformation rate is 110 kV/ 21 kV. P_0=32.0 kW, P_k=210 kW, Z_k=12%. Calculate the short-circuit current.

The calculation of its S/C current is as follows:

I_{1N}=S_N/($\sqrt{3}$*U_{1N}) = 63*10^6/ (1.732*110k) = 330.7 A

I_{2N}=S_N/($\sqrt{3}$*U_{2N}) = 63*10^6/ (1.732*21k) = 1732 A

The impedance:

$Z''_k=\frac{Z_k*U^2_{2N}}{S_N}$= 0.12* $(21*10^3)^2/(63*10^6)$=23.05 Ω

$Z'_k=\frac{Z_k*U^2_{1N}}{S_N}$=0.12* $(110*10^3)^2/(63*10^6)$=0.840 Ω

Short circuit current with nominal voltage (three-phase symmetrical)

I'_k= U_{1N}/ ($\sqrt{3}$*Z''_k) = 110*10^3/ (1.732*23.05) = 2755 A

I''_k= U_{2N}/ ($\sqrt{3}$*Z''_k) = 21*10^3/ (1.732*0.840) = 14.43k A

There is always a voltage drop in the upstream network. That means that the voltage will be lower than the nominal voltage when the S/C accident happens.

3.2 Practical calculation methods

The practical calculation methods are more complex than the simple model. There are two types: calculating S/C current by the impedance method and the calculation in grid network using symmetrical components.

3.2.1 The calculation by the impedance method

The impedance method, reserved primarily for LV networks, was selected for its high degree of accuracy and its instructive value, given that virtually all characteristics of the circuit are taken into account. Figure 5 shows the various S/C currents.

The three-phase S/C involves all three-phases. Short-circuit current I_{sc3} is equal to:

$I_{sc3} = U / \sqrt{3} / Z_{sc}$,

where U (phase-to-phase voltage) corresponds to the transformer no-load voltage which is 3 to 5% greater than the on-load voltage across the terminals. In fact, this is the “positive-sequence” impedance per phase in the symmetrical components theory. It is generally considered that three-phase faults offer the highest fault currents.

Phase-to-phase S/C without earthing is the fault between two phases which is supplied with a phase-to-phase voltage U. The formula is:

$I_{sc2} = U / 2\ Z_{sc}$.

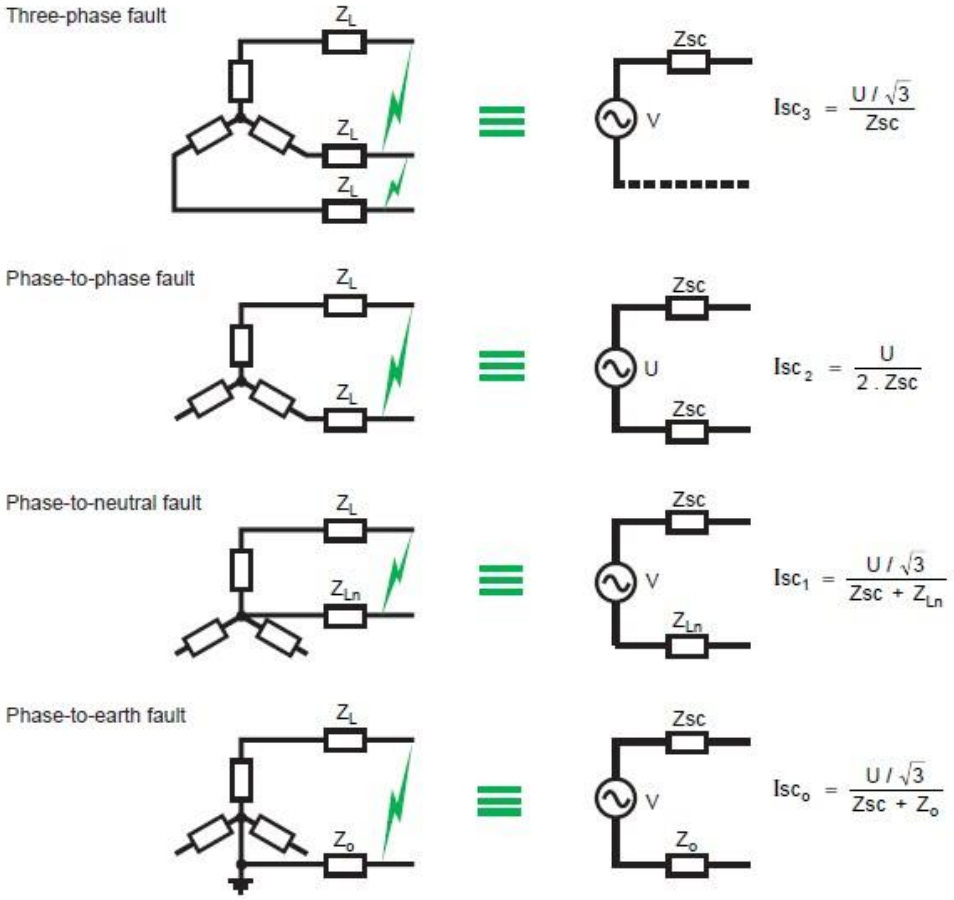

Figure 8. Various S/C currents in a calculation done according to the impedance method

The third fault type is Phase-to-neutral S/C without earthing. This is a fault between one phase and the neutral, supplied with a phase-to-neutral voltage:

$$U_f = \frac{U}{\sqrt{3}}$$

The calculation formula is:

$$\mathrm{I_{sc1}} = \frac{U_f}{\mathrm{Z_{sc}} + \mathrm{Z_{Ln}}}.$$

The final fault is Phase-to-earth fault (one or two phases). This type of fault brings the zero-sequence impedance Z_0 into play. Except when rotating machines are involved (reduced zero-sequence impedance), the S/C current I_{sc0} is less than that of a three-phase fault. Calculation of I_{sc0} may be necessary, depending on the neutral system (system earthing arrangement), in view of defining the setting thresholds for the zero-sequence (HV) or earth fault (LV) protection devices.

3.2.2 The calculation in grid network using symmetrical components

A calculation using symmetrical components is particularly useful when a three-phase network is unbalanced. This is based on IEC 60909 -0 (2001, c2002), "S/C currents in three-phase AC systems - Part 0: Calculation of currents" and uses the impedance method (as opposed to the per-unit method). /17/

Generally speaking, there are six general steps in the calculation: Step 1: Construct the system model and collect the relevant equipment parameters. Step 2: Calculate the short circuit impedances for all of the relevant equipment. Step 3: Refer all impedances to the reference voltage. Step 4: Determine the Thévenin equivalent circuit at the fault location. Step 5: Calculate balanced three-phase short circuit currents. Step 6: Calculate single-phase to earth short circuit currents.

The relevant equipment parameters to be collected are as follows:

1) Network feeders: fault capacity of the network (VA), X/R ratio of the network;

2) Synchronous generators and motors: per-unit sub-transient reactance, rated generator capacity (VA), rated power factor (cosΦ);

3) Transformers: transformer impedance voltage (%), rated transformer capacity (VA), rated current (A), total copper loss (W);

4) Cables: length of cable (m), resistance and reactance of cable (Ω/km);

5) Asynchronous motors: full load current (A), locked rotor current (A), rated power (W), full load power factor, starting power factor.

6) Fault limiting reactors: reactor impedance voltage (%), rated current (A).

When we apply this way of calculating into the practical work to obtain accurate results, we must also consider the following factors: S/C currents of the substation bus, S/C currents of the short line fault (SLF: A short-line-fault is a fault that occurs on a line a few hundred meters to several kilometers down the line from the circuit breaker terminal/18/), the marked data of the transformer and output of the power unit, even the temperature and the running style of the system(maximum load/ minimum load) and so on.

4 Reinforcement of S/C withstand capability

There are many methods applied to reinforce the S/C withstand capability of the transformers: improvement of the materials, reforming of the design and good maintenance in the operation process and so on. However, what I want to mentioned here is methods for the transformers which are in use and those which are hard to modify or expensive to modify.

4.1 Installation of neutral reactors

Usually, the probability of power systems encountering single phase S/C accidents is much higher than the probability of power systems encountering three-phase S/C accidents. The reinforcement of the S/C withstand capability for the transformers can, to a great degree, reduce the ruin of an S/C accident.

The single phase S/C current is affected by the positive sequence impedance and zero sequence impedance. One effective way to change the zero sequence impedance is changing the earthing methods of transformer neutral points, or installing the neutral grounding reactor. /19/

Figure 9. Neutral earthing reactor made by Hilkar®

Neutral grounding reactors are used for low-impedance grounding of the neutral point of three-phase networks in order to limit the fault current in the event of a phase-to-ground S/C (fault current will be limited to the level of the phase-to-phase S/C current). One reactor terminal is connected to the neutral of the network and the other terminal is grounded. During normal operation of the power system the current flow through the reactor is almost zero, since it is only driven by the imbalance of the three-phase network.

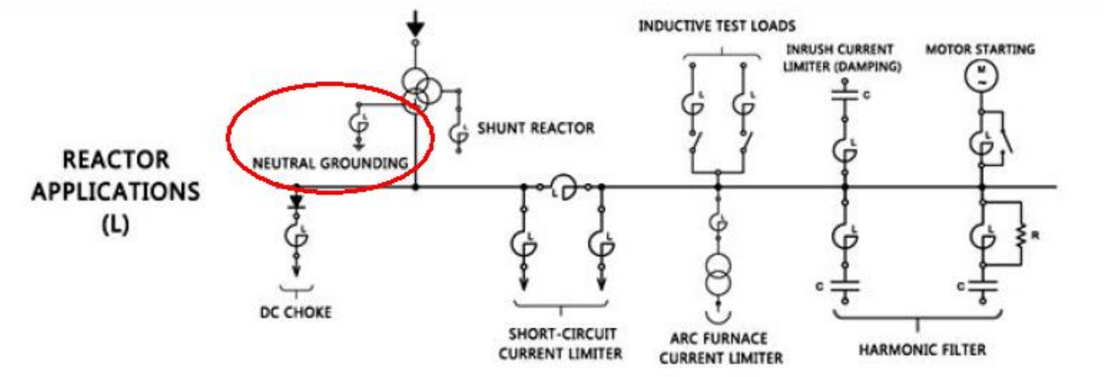

Figure 10. The neutral reactor on three-winding transformer (in red cycle) /20/

The ordinary installation place of the neutral reactor is in the compensation equipment called HV shunt reactor. In China, people often use the star connection for the HV shunt reactor, and then add a reactor in series at the neutral point of the star connection. That’s so called “high-voltage reactor grounding through small reactance at the neutral point”. The functions of reactors here are to compensate the phase to phase capacitor and grounding capacitor, speed up the termination of the secondary arc current and to make it easier to adopt the single-phase reclosers. /21/

Figure 11. Neutral earthing reactor made by ABB /22/

One application example happened in 2004, in Ningbo City, Zhejiang Province,China. Engineers installed little reactors which are 15 Ω as the neutral earthing reactor for a 500kV transformer in Lanting Substation. The S/C current decreased. The details are shown in Table 3

Table 3. The S/C current influenced by neutral reactors in Lanting Substation

	Single phase S/C current	3 phase S/C current
without reactor (kA)	48.35	55.71
with reactor(kA)	43.34	41.84

When the neutral points connect with reactors, the zero sequence impedance will change. The grounding S/C current of double phases may be larger than that of the single phase. So it’s necessary to check both the single phase S/C and double phases S/C after the installation of a neutral reactor.

4.2 Installation of current limitation series reactors

The series reactor is a high-voltage electrical apparatus designed to limit the current of a short circuit and maintain adequate voltage on the buses of distribution switchgear during a short circuit in a network. It consists of an inductance coil. Such reactors are also used to compensate reactive power in order to improve the transmission capacity of power lines. /23/

The use of reactors is a traditional and commonly used method for the limitation of the S/C current. The reactors are usually installed at the areas where the short-line-fault may happen and connect in series in the circuits which require a limit to the S/C current. The principle is decreasing S/C currents by increasing the impedance of the circuits. The advantage is that it’s easier to install and run in safe and reliable ways. The disadvantage is that the reactor will increase the losses of power. It may influence the stability of the power system. /24/

Figure 12. Core-and-coil assembly of a series reactor (made by Siemens)

The current limitation series reactor is usually applied at outlets of the LV side, and can also be applied at the 35 kV medium side in 220 kV transformer. This method is suitable for both three phase S/C and single phase S/C.

The example is ABB. They build a series reactor for the Metro Grid project which transfers the power from Sydney South to Haymarket Substation in Australia. It's the biggest reactor made by ABB.[25]

4.3 Installation of fast switches with high capacity

The representatives of fast switches with high capacity are Is-limiter (made by ABB), Pyristor (made by Ferraz) and C-Lip (made by G&W) /26/. This kind of switches can protect electric devices from larger S/C current shocks and prevent large-area electricity black-outs caused by the destruction of main equipment due to overcurrent. It has several advantages in the technical field:

1) Fast cut off ability (less than 2ms);
2) Fast limitation of the large S/C current: Is-limiter is capable of detecting and limiting an S/C current at the first rise, i.e. in less than 1ms /27/.

3) Less occupied space
4) Easy to install and maintain

It is a fault current limiting device that uses chemical charges and current-limiting fuses to interrupt the fault current within the first quarter to half cycle (i.e. before the first peak). In a typical Is-limiter design, the device is composed of two current paths connected together in parallel – one path is an element rated for the full load current (which can have high continuous current ratings, e.g. 3000 A), and the other path provides the current limiting function via a current-limiting fuse (which typically has a continuous current rating of <300 A at 15 kV). /28/

The work principle can be described as follows: when the S/C happens, the current transformer module detects the signal and transfers it to the control module. Then the control module is triggered and turns the disconnector on to 'move' the S/C current into the fuse module at the instant. Here, the current is cut off. The interesting thing and special feature is that the device uses the explosive to get the rapid cut-off ability. It can limit both S/C currents of single phase and three-phase. /29/

Figure 11. ABB Is-limiter insert holder with insert for 12 kV, 2000 A

The working process can be described as follows:

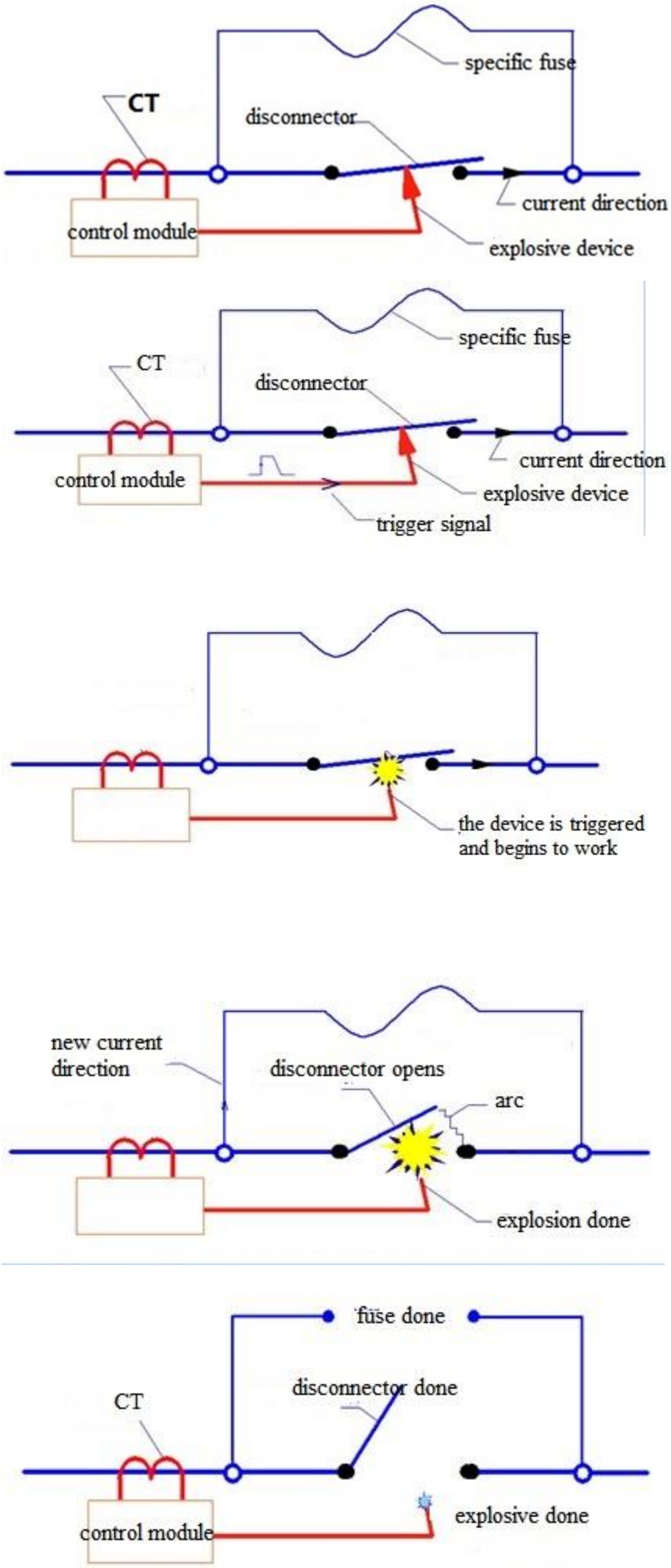

Figure 13. The Is-limiter process

4.4 Installation of controllable Fault Current Limiters

Fault Current Limiter (FCL) is also called S/C Current Limiter (SCCL). There are several different types: Superconducting Fault Current Limiter (SFCL), the one we mentioned in section 4.3, and the controllable Fault Current Limiter which is based on electronic technology and so on. /30/

Figure 14. Superconducting FCL (35 kV/90 MVA) made in China

The shortcomings of a superconducting fault current limiter are

1) The working environment is quite harsh: the high-temperature superconductor needs liquid nitrogen (N_2). The critical temperature is 77 K (about -196 ℃). And the low-temperature superconductor needs liquid nitrogen liquid helium (He). The critical temperature is 4 K (about 269.15 ℃). Once the working temperature is over the critical temperature, the SFCL will not able to keep the superconductor character.
2) The technique is not mature enough. In China, there are only two prototypes running. The number of SFCLs which are running in Switzerland, Germany, Great Britain and USA is less than 20.

So it’s not suitable to be applied for modifying the transformers that are running now.

However, the controllable Fault Current Limiter based on electronic technology is more mature than SFCL. There are two types: series and parallel. The operation principle is: use the electronic apparatuses to break or connect the circuit with high speed. Then the capacitor, the resistance, or the inductance in series or in parallel at bypass works immediately to increase impedance of the circuit in order to limit the S/C current. /31/

As an example, see the figure below:

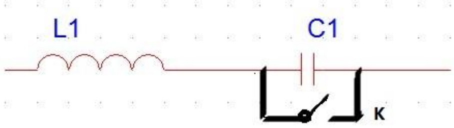

Figure 15. Series controllable FCL schematic

The controllable FCL shown is the series type. It consists of the capacitor (C), the inductance (L) and a bypass switch (K). Normally, the switch doesn't work and it's open. L and C work on the series resonance condition. The impedance could be regarded as zero, compared with the total impedance. So the influence of FCL could be acceptable. When accidents are detected, K receives the command and closes to take C away instantly. The inductance (L) begins to limit the current at the moment, so that the fault current is limited.

The advantages are: 1) no influence on the protection solution being used; 2) no influence on the stability of the current; 3) Less occupied space. The weaknesses are high cost and the maintenance.

4.5 The comparison

The table below is the comparison of 4 methods:

Table 4. The reinforcement methods of transformers' S/C withstand capability

	neutral reactors	series reactors	fast switches	Controllable FCLs
The cost	low	normal	low	high
Project time	short	short	short	normal
The limitation objects	only single phase	both	both	both
Technical maturity	high	high	normal	low
Space	little	little	quite little	large
Maintenance	easy	easy	easy	hard

4.6 Practical work applications

Based on the above materials, the technical handbooks (GB1094.5-2003, GB1984-2003 and GB15166.6—2008) and the experience of electrical engineers of SGCC, some practical work applications are offered. In the practical work, the risk of three-phase S/C accidents at the MV side of 500 kV and 220 kV transformers is quite little; the main risk is the single phase accident. The reinforcement of S/C withstand capability of the single phase or the limitation of the S/C current at the single phase can reduce the number of transformer S/C accidents significantly. In Table 4, we can find that the new devices work more effectively and respond much faster, but they are defeated by the traditional ways in the economy, the reliability, the maturity and the maintenance experience. So the best selection is to install the neutral reactor. If there does exist the need for three-phase protection, we can install the fast switch or FCL.

For the LV side accident, people can opt to install current limitation series reactors, or fast switches if the space is limited.

5 The conclusion

The thesis introduces the definition and the importance of S/C current calculations. Chapter 2 introduces the type of the fault circuits and calculation methods from basic DC circuits to AC circuits. In Chapter 3, I discuss transformers S/C calculation methods. In Chapter 4, based on the comparison of different breakers, I offer some reinforcement methods for the transformers which are running now.

The deficiency of the work is the lack of knowledge of practical calculation methods, especially in the symmetrical components field. For this reason, Chapter 4 is not that satisfactory. The reinforcement methods of the S/C withstand capability only mention the devices for the working transformers. In fact, good maintenance can also reduce the number of S/C accidents.

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