2 POWER SYSTEM PROTECTION

Section 2.1a Power System Faults

Section 2.1.1 Introduction

This section provides the calculation of the symmetrical subtransient current and the system voltage due to system faults including: **(a) single-line-to-ground**, **(b) double-line**, **(c) double-line-to-ground** (asymmetrical faults) and **(d) three-phase** (symmetrical faults). The method of calculation is based on the sequence components of the system bus-impedance matrix.

Faults develop as a result of various system malfunctions such as flash-over of insulators following a lightning strike or switching operation, insulator failure, lightning arrester failure, line being on the ground and permanent tower failure. These contingencies cause temporary or permanent short-circuits. The most frequent short-circuits are single-line-to-ground and the least frequent are three-phase. During the fault, the currents flowing through the system consist of a component which is symmetric around zero (symmetrical current) and a dc offset. Both of these components decay with time constants determined by the generator damping and the network impedance angle. The breaker size required for clearing the fault may be calculated in terms of its **required symmetrical interrupting capability**. This capability is equal to the rms value of the symmetrical current in the system immediately following the fault application, i.e. the **subtransient current**.

Section 2.1.2 System Representation

Unsymmetrical faults cause unbalanced voltages and currents in the system. Therefore, the system sequence impedance must be used for the calculation of the rms of the symmetrical subtransient current. This section describes the symmetrical component method and the modeling required for fault calculations.

Symmetrical Components

Any unbalance three-phase voltage or current can be broken down into a linear combination of three symmetrical sequence components; **the positive sequence**, **the negative sequence** and **the zero sequence**. To learn more about the method of symmetrical components, see **Section 1.6b**.

If

$$V_{abc} = \left[V_a \;\; V_b \;\; V_c \right]^{T}$$

is a three-phase voltage, then its corresponding sequence components are calculated using the following transformation.

$$V_{012} = T \cdot V_{abc}$$

where

$$V_{012} = \left[V_0 \;\; V_1 \;\; V_2 \right]^{T}$$ is the zero, positive, and negative sequence voltage components respectively

$$a1 := e^{2j \cdot \frac{\pi}{3}} \qquad a2 := a1^{2}$$

$$T := \begin{bmatrix} 1 & 1 & 1 \\ 1 & a1 & a2 \\ 1 & a2 & a1 \end{bmatrix}$$ is the symmetric transformation matrix

A similar transformation can be applied to the three-phase current. Application of the symmetrical transformation to the network impedance yields the sequence network impedance. Thus, if Zabc is the network impedance seen by the abc current, the corresponding sequence impedance is

$$Z_{012} = T \cdot Z_{abc} \cdot T^{-1} = diag\left\langle Z_0, Z_1, Z_2 \right\rangle$$

The advantage of this transformation lies in the decoupling between the three sequences which reduces the computational effort when calculating faults. Therefore, the original network can be broken down to three sequence networks. Upon solution of each sequence network, the abc quantities can be calculated using the inverse transformation. Thus,

$$V_{abc} = T^{-1} \cdot V_{012} \qquad I_{abc} = T^{-1} \cdot I_{012}$$

Generators and Motors

For the positive sequence currents, the generator is represented by its subtransient positive sequence emf, E", behind its subtransient reactance, X". The generator emf can be calculated from its terminal voltage, Vt, and current, It, known in prefault conditions using Equation (2.1.1).

$$\overline{E''} = \overline{V_t} + jX'' \cdot \overline{I_t} \qquad \textbf{(2.1.1)}$$

Synchronous motors are represented in the same way as generators, except that the transient instead of subtransient impedance of the motor is used in the calculation due to the lack of damper windings.

For the negative sequence currents, generators and motors are represented using the negative sequence subtransient and transient impedance, respectively. This impedance is connected directly to the reference node. For round rotor generators, this impedance equals the positive sequence subtransient impedance of the machine.

The impedance, Xo, which the generator or motor terminal currents see in the zero sequence, is the stator leakage impedance. This impedance is connected to the reference node through the neutral-to-ground impedance, Zn, for a Y-grounded (Y-g) stator configuration and is not connected to the reference node for ungrounded Y (Y-o) or Delta configurations. The total zero sequence impedance of a Y-g generator or motor is given by Equation (2.1.2).

$$Z_0 = X_0 + 3 \cdot Z_n \qquad \textbf{(2.1.2)}$$

Transformers

The effects of the magnetizing current are neglected in fault calculations and the transformer is represented by its pu leakage reactance between the primary and secondary buses for positive and negative sequence currents. The phase shift between the primary and secondary quantities introduced by Y/Δ connected units must be accounted for in the positive and negative sequence representation of the transformer. If IA and VA are respectively the primary current and voltage and Ia and Va are respectively the secondary current and voltage of a Y/Δ connected transformer, the relationship between primary and secondary quantities in the positive and negative sequence are given by Equations (2.1.3), assuming 90 degrees phase shift between primary and secondary.

$$V_{a1} = 1\mathrm{j} \cdot V_{A1} \qquad V_{a2} = -1\mathrm{j} \cdot V_{A2}$$

$$I_{a1} = 1\mathrm{j} \cdot I_{A1} \qquad I_{a2} = -1\mathrm{j} \cdot I_{A2} \tag{2.1.3}$$

The zero sequence impedance, Xo, of the transformer equals its leakage impedance for three single-phase units. This impedance is combined with the impedance to the ground of the Y-g side(s) of the transformer, yielding the total zero sequence terminal impedance of each side.

Transmission Lines

Fully transposed lines are represented by their sequence series impedance in pu between sending and receiving ends. Shunt reactances are neglected. The positive and negative sequence series impedances are equal and the zero sequence series impedance is 1.5 to 2 times higher. To learn more about line sequence impedance, see **Section 1.6b**.

Other Equipment

Loads and shunt compensation are neglected. Large induction motors are represented using their subtransient pu impedance.

Section 2.1.3 Fault Current Calculation

The E/X method is used for the calculation of the current at the faulted bus. The steps of this method are as follows:

(a) A single line impedance diagram of the system is constructed for the positive, negative and zero sequence networks. For each of these networks, the Zbus matrix is constructed. The diagonal elements of these matrices provide the Thevenin impedance of the corresponding sequence viewed from system buses. The off-diagonal elements of the Zbus matrices indicate the coupling between the sequence bus voltages that is due to the sequence current injections to system buses.

(b) The sequence components of the current on the faulted bus are calculated using the sequence Thevenin equivalents of the system viewed from this bus. The Thevenin voltage source of the negative and zero sequence equivalents is zero. The Thevenin voltage of the positive sequence equivalent is the prefault voltage on the faulted bus. The three sequence circuits are interconnected according to the type of fault studied. The resulting circuit yields the sequence components of the fault current. If the fault occurs through a non-zero impedance, Zf, the fault impedance should also be included in the equivalent circuit.

Figures 2.1.1 to 2.1.4 show the interconnections required between the three sequence Thevenin equivalents for each type of fault. In these diagrams, the current through and the voltage across each sequence equivalent are the sequence components of the fault current and voltage at the faulted bus. Equations (2.1.4) to (2.1.7) provide the sequence components of the fault current. These quantities are used to calculate the pu subtransient abc current in the system during the fault using the symmetrical component technique discussed in the previous section.

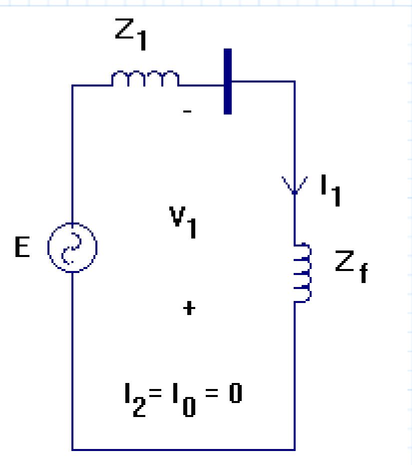

Fig. 2.1.1 Three phase symmetrical fault

$$I_{1tp}\left(E, Z_f, Z_1\right) := \frac{E}{Z_f + Z_1} \qquad \textbf{(2.1.4)}$$

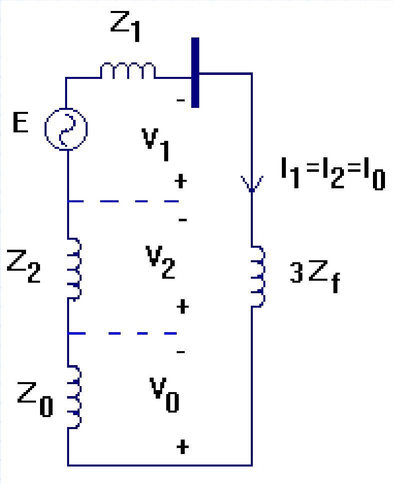

Fig. 2.1.2 Line-to-ground Fault

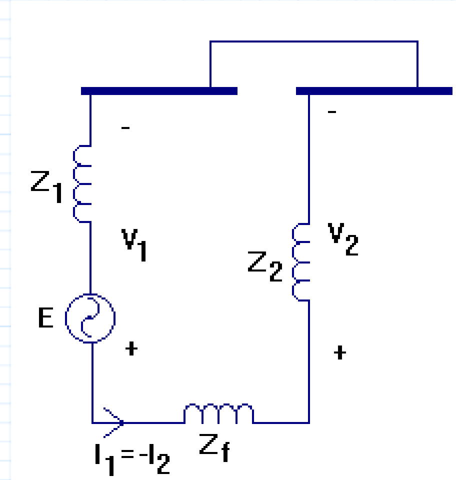

Fig. 2.1.3 Line-to-line Fault

$$I_{1lg}(E, Z_1, Z_2, Z_0, Z_f) := \frac{E}{Z_1 + Z_2 + Z_0 + 3 \cdot Z_f} \qquad \textbf{(2.1.5)}$$

$$I_{1ll}(E, Z_1, Z_2, Z_f) := \frac{E}{Z_f + Z_1 + Z_f} \qquad \textbf{(2.1.6)}$$

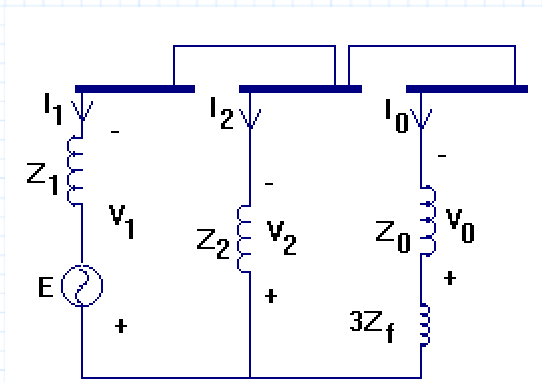

Fig. 2.1.4 Double-line-to-ground Fault

$$I_{1dlg}(E, Z_1, Z_2, Z_{eq}) := \frac{E}{Z_1 + Z_2 \cdot Z_{eq}} \qquad \textbf{(2.1.7)}$$

$$I_2(I_1, Z_{eq}) := -I_1 \cdot Z_{eq}$$

$$I_0(I_1, Z_0, Z_2, Z_f) := -I_1 \cdot \left(\frac{Z_2}{Z_2 + Z_0 + 3 \cdot Z_f} \right)$$

where

$$Z_{eq}(Z_0, Z_2, Z_f) := \frac{Z_0 + 3 \cdot Z_f}{Z_2 + Z_0 + 3 \cdot Z_f}$$

Section 2.1.4 System Voltage Calculation

The sequence components of the bus voltage can be calculated by injecting the sequence components of the fault current into the sequence equivalents of the system. If V1, V2, and V0 are vectors corresponding to the positive, negative and zero sequence components of the bus voltages, the relationship between these voltages and the sequence components of the fault current are given by Equations (2.1.8).

$$V_0 = -Z_{bus0} \cdot I_0$$

$$V_1 = VF - Z_{bus1} \cdot I_1 \qquad \textbf{(2.1.8)}$$

$$V_2 = -Z_{bus2} \cdot I_2$$

where VF is a vector containing the prefault voltage on each bus. If the unloaded system is considered, these voltages are equal to the prefault voltage on the faulted bus.

The positive and negative sequence voltages obtained above represent the bus voltages as seen from the fault side of system transformers. For the proper calculation, the positive and negative sequence voltages across Y/D transformer terminals must be phase shifted according to Equations (2.1.3) to obtain the values of the abc voltages at the other side of the transformers.

Section 2.1.5 Component Subtransient Current Calculation

The subtransient current through system devices is calculated from the sequence components of the device current. Therefore, if a device is connected between buses i and j and its sequence impedances are X1, X2, and X0 for the positive negative and zero sequence respectively, the sequence current through the device is

$$I_1 = \frac{V_{1i} - V_{1j}}{X_1}$$

$$I_2 = \frac{V_{2i} - V_{2j}}{X_2} \qquad \textbf{(2.1.9)}$$

$$I_0 = \frac{V_{0i} - V_{0j}}{X_0}$$

As in the case of the sequence voltages, the positive and negative sequence currents of Y/D transformers must be phase shifted to obtain the correct values of the abc currents.