Earth current considerations for earth mat design in HV substations

Grid potential rise (GPR) gets worse as the fault current and earth impedance increases. One way of limiting the GPR in high fault current substations is by adding more copper in the earth mat, thus reducing the earth impedance. This, however, is an expensive approach. An overstated fault current can result in an uneconomical substation earth mat design. It is therefore very important to know the maximum current that will flow to earth via the grid for various possible earth-fault locations. For the design and specification of power system equipment, it is necessary to know what the maximum system fault currents will be at the specific location. It is normal practice to compile databases of maximum earth fault levels, using specialised power flow software. However, the maximum earth current required in order to calculate the GPR in a substation applies strictly to the current that flows into the earth itself.

In most cases a lower level of resistance is effective due to the presence of parallel earth paths through shield wires of overhead lines, tower footing resistances, etc. These parallel paths cause the fault current to divide into multiple paths to complete the return path to the source. In such cases, the calculated level of fault current may well be considerably greater than the actual current that will flow through the earth grid. Ignoring the parallel paths and only considering these high fault current levels could result in an over design of the substation earth grid. In this paper, different transformer configurations and fault locations are analysed. Each analysis is approached by drawing the phase-sequence network based on the single line diagram of the faulted circuit. The actual phase currents and grid current are then calculated from the per unit values and shown on the three-phase circuits. Finally the rise in grid potential and the step and touch potentials may be calculated using the maximum grid current values.

The design of substation earth grids is involved with limiting grid potential rise (GPR), which is a result of earth fault currents that flow to earth through an earth grid impedance. Overstated substation fault current can potentially result in an uneconomical substation earth mat design. This paper illustrates that it is necessary to get a clear understanding of the specific substation configuration in order to design a safe and economical earth grid.

The following abbreviations are used in the diagrams:
- \( R_e \): Equivalent earth resistance of all parallel paths
- \( T \): Transformer
- \( H \): High voltage winding
- \( M \): Medium voltage winding
- \( L \): Low voltage winding (tertiary)
- Configuration 1: Dyn, HV/MV transformer
- Configuration 2: YNd, HV/MV transformer
- Configuration 3: YNa(d), auto-transformer with delta connected tertiary windings

The phase sequence networks for HV earth faults are straight-forward (Fig. 1b), \( I_f \) flows through \( R_e \), which is series-connected in the fault path.

GPR, \( E_{yz} \), is the product of \( R_e \) and the current in it. In this case the current is \( 3 \cdot I_0 \), therefore the zero sequence voltage, \( E_{yz} \), is:

\[
E_{yz} = 3I_0R_e \quad \text{(p.u.)}
\]

The simplest case is that of a single line feeding a substation containing a Dyn, HV/MV transformer where the MV neutral is earthed via a resistor (Fig. 1a). In the case of an HV earth fault within the substation, fault current flows down the line from the remote source. All of the current returns to the source neutral via \( R_e \). If the earth fault level is high, coupled with a significant value of \( R_e \), the GPR may be excessive.
The GPR is determined by the earth current, \( I_{0S} \), which is less than the total fault current, \( I_F \). Therefore the GPR is given by

\[ GPR = I_{0S} R_{g0} \text{ (p.u.)} \]

Configuration 3: YNa(d), Auto-transformer with delta connected tertiary windings

Now consider a step-down substation with an autotransformer of which the tertiary winding is delta connected (Fig. 3a).

Earth fault on primary side

When the earth fault is on the primary side of the autotransformer the current distribution is very similar to that for a YNd transformer. The three phase networks are shown in Fig. 3b.

The phase sequence networks are shown in Fig. 3c. \( R_g \) must be connected in the path of \( Z_{NO} \), definitely not in the path of \( I_0 \), which is the total zero-sequence component of the fault current.

Similar to Eqn. 4, GPR is \( E_g = I_{0S} R_{g0} \text{ (p.u.)} \) and again the earth current is less than the total fault current.

Earth fault on secondary side

When an earth fault occurs on the secondary side of an autotransformer, calculations are rather more complicated. There are two distinct paths for zero-sequence current flow in the transformer windings (\( I_{0S} \) and \( I_{0T} \)) in Fig. 4b. Each path and the division of current must achieve ampere-turn balance in the windings.

The currents in the main windings are made up of all three of the phase-sequence components. For the secondary earth-fault, a component of zero-sequence current flows in the tertiary winding, matched by components in the main (series and common) windings. Additional components of zero sequence current flow also in the series and common windings, to oppose one another and achieve ampere-turn balance without the aid of the tertiary current.

The star point of the common windings is not representable in the phase-sequence networks. The per unit values of the currents in the common windings are not manifest in the analysis of these networks, because the currents in the HV windings are combined directly with the currents in the common windings so there is no convenient base. To obtain actual currents the procedure in the example may be followed.

The phase-sequence networks should now be analysed to obtain per unit values. To calculate the current distribution in the windings, Kirchoffs law may be used. In many cases, where the source fault level is very high, the source current, \( I_s \), will be greater than 3 \( I_1 \). But the reduction in GPR is still substantial when 3 \( I_1 \) is correctly eliminated from the calculation.

References
