# Central or Local Compensation of Earth-Fault Currents in Non-Effectively Earthed Distribution Systems

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# Central or Local Compensation of Earth-Fault Currents in Non-Effectively Earthed Distribution Systems

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# 1 Line losses and transformer investment cost

Distributed compensation is likely to be of most use in rural networks where the load density is low. The typical size of a MV to LV transformer in these networks is 100 kVA. Every transformer substation will not have to be equipped with a Petersen coil. The required rating of each coil increases as the distance between the Petersen coils increase. One reason to limit the distance between the Petersen coils is the capacitive earth fault current flowing in the system. Large capacitive current causes resistive losses in the network. The resistive losses depend on the cable data. Simulations using AXKJ 95/25 and AXCES 95/25 cable data have shown that as long as the distance between the Petersen coils does not exceed 20 km, losses due to capacitive current transportation will not change noticeably.

The price of a Petersen coil equipped transformer is approximately two times as high as a transformer of the same rating, without the compensation coil. Assumed the price of an ordinary transformer is 1 pu, the price of an entire transformer substation is estimated at 4 pu. This means the price of the compensation coil equipped substation is 5 pu. The cost of a substation with a compensation coil equipped transformer will be 5/4 of that of an ordinary substation. If it is possible to replace only the transformers, the price difference is 2 to 1. The investment cost decrease as the distance between the compensation coils increases.

## 1.1 Correct fuse function

If the line losses and the transformer investment cost alone where to decide the optimum spacing between the Petersen coils, the coils would not be placed closer than 20 km apart, for reasons mentioned above. In addition however, the maximum rating of the Petersen coils must allow correct function of the fuses protecting the MV to LV transformer. The constraints that determine the economical optimum are schematically described in Figure 1.

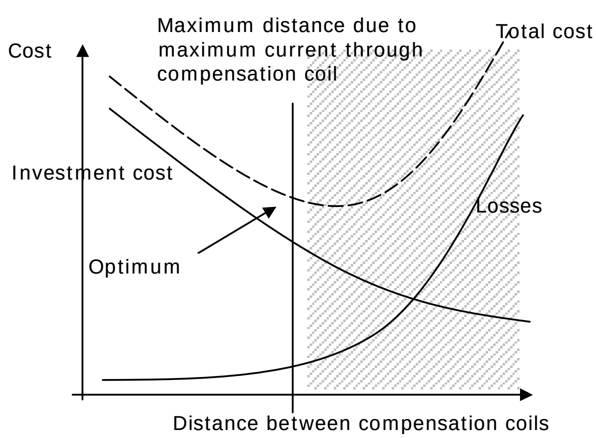


**Figure 1, Schematic picture of the constraints that determine the economical optimum of the Petersen coil placing**

When the distance between the Petersen coils is as long as twenty kilometres, the current through the coil might be too large to ensure correct function of the fuses. Correct fuse function will therefore set the limit for the rating of the Petersen coils. In addition, with a distance of approximately 5 km between the units instead of 15 or 20, it might be possible to make more use of the fact that disconnection of part of the network will include disconnection of corresponding amount of compensation.

## 1.2 Cost efficient manufacturing

To keep the price of the Petersen coil equipped transformers within reasonable limits very few Petersen coil ratings will be manufactured. Distribution network owners has opted for one 12 kV rating and one 24 kV rating to keep the manufacturing cost effective.

# 2 The ZNdyn transformer

## 2.1 Protection

The number of MV to LV distribution transformers in the power systems is extensive. It would be very expensive to protect them all with advanced equipment. Normally fuses are used for short circuit protection. The fuses on the MV and LV side of the transformer shall blow for two and three phase short circuit in the transformer. They shall also blow for one, two and three phase faults on the LV terminal.

The capacitive current flowing to the transformer during a phase to earth fault in the MV network, combined with maximum load current shall not blow the fuses, i.e. must not exceed their rated current. In case of an earth fault on the MV side in a system with tuned Petersen coiled earthed ZNyn transformers, the three phases leading to the transformers will each carry one third of the inductive compensation current. Figure 2 illustrates the zero sequence current in case of a fault between a phase and earth.

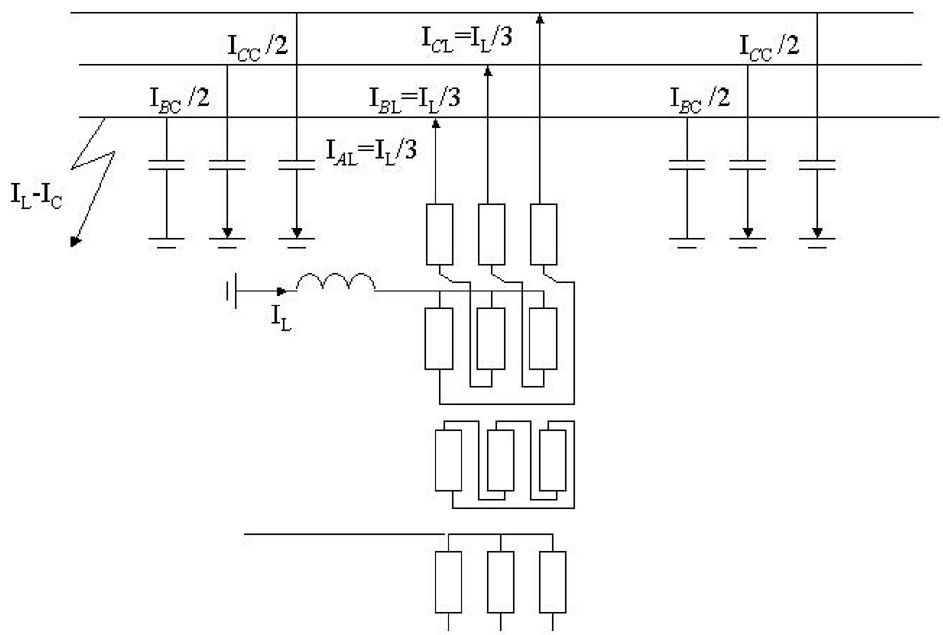


**Figure 2, The earth fault current in case of a fault between one phase and earth**

Simulations using a ZNdyn transformer model with each core modelled individually indicate that the load on the LV side does not influence the zero sequence impedance of the transformer. Hence, the MV side zero sequence current will not under any load condition be transformed to the LV side. The function of the LV side fuses has therefore not to be taken into consideration when selecting the compensation coil rating. Figure 3 shows the current phasors in case of a fault between phase A and earth in a tuned Petersen coil earthed system. During a single phase to earth fault in the MV network the capacitive currents of the healthy phases are shifted 60 degrees relative each other. The sum of the capacitive currents is of the same size as the inductive current. The inductive current will however divide equally between the three phases. Consequently, in the individual phases the inductive current will not fully compensate the capacitive current.

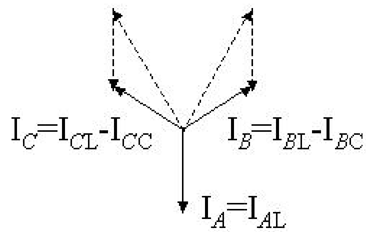


**Figure 3, Current phasors in case of a fault between phase A and earth**

The current generated in each coil is denoted $I_L$. Any excess inductive or capacitive current in the network will be balanced in the tuning of the central compensation coil. The distributed Petersen coils will not be tuned. The intention is however, to place the distributed Petersen coil at regulate intervals, so that the inductive current $I_L$ generated by each Petersen coil is equivalent to the capacitive earth fault current $I_C$ originated from the nearby conductors.

## 2.2 Winding ratio

The phase of symmetrical voltages and currents transformed by a ZNyn transformer is shifted 30°. The ratio between the MV windings and the LV winding must be designed to accomplish the rated ratio of the transformer. The phasors in Figure 4 illustrates the phase shift.

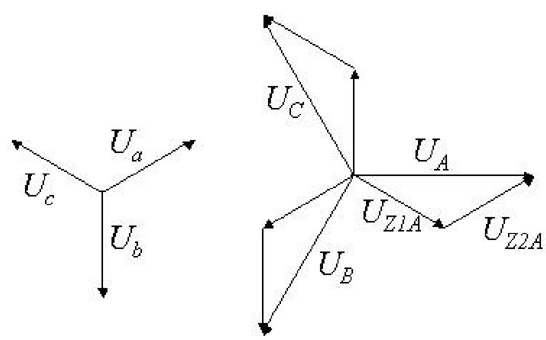


**Figure 4, Phasors illustrating the phase shift between the primary and secondary side of the ZNdyn transformer**

The transformer primary phase voltage is the sum of the voltages across the Z1 winding and the Z2 winding of the phase. These two voltages are phase shifted 60° relative each other. The phase of the sum of the two voltages is consequently shifted 30° relatively the phase of each of the two voltages. The RMS value of the voltage across each of the Z can be calculated according to Equation 1.

$$U_{Z1} = U_{Z2} = \frac{U_{MV}}{2 \cdot \cos 30^\circ} = \frac{U_{MV}}{\sqrt{3}}$$

**Equation 1**

Consider an ideal transformer. The Z1 winding of phase A, the Z2 winding of phase B and the y winding of phase a all enclose the same flux. The voltage across the winding is proportional to the number of turns of winding. The individual winding ratios can be calculated according to Equation 2.

$$\frac{U_{LV}}{n} = \frac{U_{MV}}{\sqrt{3} \cdot N}$$

$$\frac{N}{n} = \frac{U_{Z1}}{U_{LV}} = \frac{U_{Z2}}{U_{LV}} = \frac{U_{MV}}{U_{LV} \cdot \sqrt{3}}$$

**Equation 2**

There is no power loss in an ideal transformer. In the case of a symmetric load the ratio between the line currents should therefore equal the inverse of the ratio between the phase voltages, see Equation 3. This is in accordance with the winding ratios calculated in Equation 2.

$$P = U \cdot I = U_{MV} \cdot I_{MV} = U_{LV} \cdot I_{LV}$$

$$\Rightarrow \frac{I_{MV}}{I_{LV}} = \frac{U_{LV}}{U_{MV}}$$

**Equation 3**

# 3 Fault current calculations

Assume the MV to LV transformers is of 100 kVA rating. What is the maximum possible coil rating that ensures correct function of the fuses protecting the MV to LV transformer?

## 3.1 22 to 0.4 kV transformer

### 3.1.1 Three phase fault

As mentioned above the fuses on the MV and LV side of the transformer shall blow for two and three phase short circuit in the transformer. They shall also blow for one, two and three phase faults on the LV terminal. The rated impedance of the Transfix ECOBLOC transformer, a ZNdyn transformer bought by the Swedish distribution network owners, is 4 %.

A three-phase short circuit on the LV side of the transformer will result in the MV and LV currents calculated in Equation 4 and Equation 5. The three-phase short circuit current is symmetrical and will be transformed according to the rated ratio of the transformer. The current through the fuses in case of an internal three phase short circuit on the MV side of the transformer will depend on where in the MV windings the fault is located.

$$Z_{1\,pu} = 0.04\,pu$$

$$Z_{base} = \frac{U_{base}^{\ 2}}{S_{base}} = \frac{\left(22 \cdot 10^3\right)^2}{100 \cdot 10^3} = 4840\,\Omega$$

$$Z_1 = Z_{1\,pu} \cdot Z_{base} = 193.6\ \Omega/phase$$

$$I_{3\,pSC\ MV} = \frac{U_n}{\sqrt{3}Z_1} = \frac{22 \cdot 10^3}{\sqrt{3} \cdot 193.6} = 65.6\ A/phase$$

**Equation 4**

$$Z_{1\,pu} = 0.04\,pu$$

$$Z_{base} = \frac{U_{base}^{\ 2}}{S_{base}} = \frac{\left(0.4 \cdot 10^3\right)^2}{100 \cdot 10^3} = 1.6\,\Omega$$

$$Z_1 = Z_{1\,pu} \cdot Z_{base} = 0.064\ \Omega/phase$$

$$I_{3\,pSC\ LV} = \frac{U_n}{\sqrt{3}Z_1} = \frac{0.4 \cdot 10^3}{\sqrt{3} \cdot 0.064} = 3.6\ kA/phase$$

**Equation 5**

### 3.1.2 Two phase fault

Figure 5 illustrates the currents on the MV and LV side in case of a two-phase short circuit on the LV side.

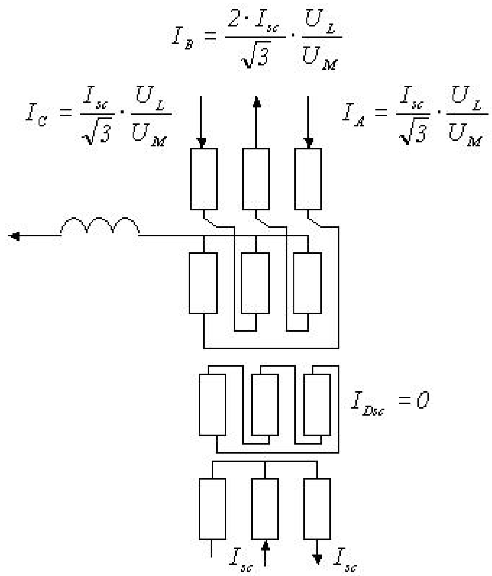


**Figure 5, Two phase short circuit on LV side**

The short circuit currents are calculated in Equation 6 and Equation 7.

$$I_{2pSC} = I_{3pSC} \cdot \frac{\sqrt{3}}{2} = 3.6 \cdot \frac{\sqrt{3}}{2} = 3.1\,kA$$

**Equation 6**

$$I_{A2p} = I_{C2p} = \frac{I_{2pSC}}{\sqrt{3}} \cdot \frac{U_L}{U_M} = \frac{3.1 \cdot 10^3}{\sqrt{3}} \cdot \frac{0.4}{22} = 32.5A$$

$$I_{B2p} = 2 \cdot I_{A2p} = 65A$$

**Equation 7**

If there is a fault resistance present in the fault, or the fault occurs a certain distance away from the transformer the short circuit currents will be smaller.

### 3.1.3 Single phase fault

The fault current due to a single phase to earth fault depends on where in the LV network the fault occurs. Assuming the fault occurs close to the transformer the current in the faulted phase will depend solely on the impedance of the transformer. The current in the faulted phase is calculated in Equation 8.

$$Z_0 \approx \frac{Z_1}{10} = 0.004\,pu$$

$$Z_1 = 0.064\,\Omega/phase$$

$$Z_0 = 0.0064\,\Omega/phase$$

$$I_{1p} = \frac{3 \cdot U}{\sqrt{3}(2 \cdot Z_1 + Z_0)} = \frac{\sqrt{3} \cdot 0.4 \cdot 10^3}{0.134} = 5.2\,kA$$

**Equation 8**

There will not be any fault current on the LV side of the healthy phases. The delta winding of the ZNdyn transformer balances the one phase fault current of the LV side. The stabilizing delta current is given by Equation 9. The per unit value of the current is independent of the number of turns of the delta winding.

$$I_{D\,pu} = \frac{I_{1p\,pu}}{3}$$

$$I_D = \frac{I_{1p}}{3} \cdot \frac{n}{N_D}$$

**Equation 9**

Figure 6 illustrates the MV, LV and delta currents in case of a phase to earth fault on the LV side.

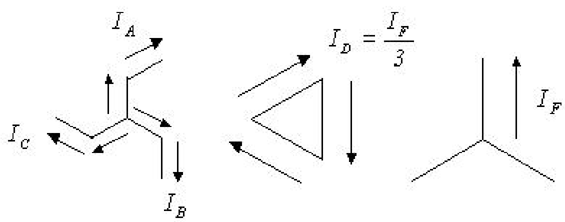


**Figure 6, Fault currents phasors while single phase to earth fault on the LV side**

To achieve MMF balance in the transformer the constraints in Equation 10 have to be fulfilled. Equation 11 shows the same constraints in per unit values when MV and LV are the base voltages. A single phase to earth fault on the LV side will not result in any current through the earthing equipment on the LV side of the transformer, which is one of the main advantageous of the ZNdyn transformer. According to Kirchoff's first law the sum of the MV currents therefore equal zero. This gives MV currents according to Equation 12.

$$I_A \cdot N - I_B \cdot N = \frac{2 \cdot I_F}{3} \cdot n$$

$$I_B \cdot N - I_C \cdot N = \frac{-I_F}{3} \cdot n$$

$$I_C \cdot N - I_A \cdot N = \frac{-I_F}{3} \cdot n$$

**Equation 10**

$$\frac{I_A}{\sqrt{3}} - \frac{I_B}{\sqrt{3}} = \frac{2 \cdot I_{1p}}{3}$$

$$-\frac{I_A}{\sqrt{3}} + \frac{I_C}{\sqrt{3}} = \frac{-I_{1p}}{3}$$

$$\frac{I_B}{\sqrt{3}} - \frac{I_C}{\sqrt{3}} = \frac{-I_{1p}}{3}$$

**Equation 11**

$$
\begin{array}{llllll}
I_A & +I_B & +I_C & = & 0 \\
-I_A & 0 & +I_C & = & \dfrac{-I_{1p}}{\sqrt{3}} \\
0 & +I_B & -I_C & = & \dfrac{-I_{1p}}{\sqrt{3}}
\end{array}
\Rightarrow
\begin{array}{lll}
I_A & = & \dfrac{I_{1p}}{\sqrt{3}} \\
I_B & = & \dfrac{-I_{1p}}{\sqrt{3}} \\
I_C & = & 0
\end{array}
$$

**Equation 12**

Figure 7 illustrates the MV currents in case of a single phase to earth fault. The MV currents are calculated in Equation 13.

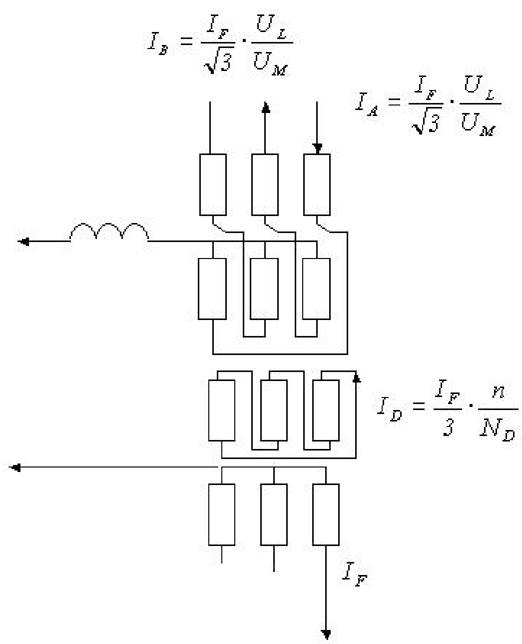


**Figure 7, Single phase to earth fault on LV side**

$$
I_A = I_B = \frac{I_{1p}}{\sqrt{3}} \cdot \frac{U_L}{U_M} = \frac{5.2 \cdot 10^3}{\sqrt{3}} \cdot \frac{0.4}{22} = 54.6\,A
$$
$$
I_C = 0
$$

**Equation 13**

The presence of a fault resistance will highly influence all the fault currents.

### 3.1.4 Simulated fault currents

A transformer model based on the data in Table 1 has been used to simulate the MV side fault currents in case of a bolted three, two or single phase LV fault. The simulated fault is located close to the transformer. The fault current will therefore depend solely on the impedance of the transformer. The simulated fault currents are listed in Table 2. $I_A$, $I_B$ and $I_C$ are the MV side currents. $I_a$, $I_b$ and $I_c$ are the LV side currents. The simulated currents differs slightly from the ideal analytical calculated currents

TABLE 1
DATA OF ZNdyn TRANSFORMER

| | |
|---|---|
| Rated power | 100 kVA |
| Short circuit impedance | 0.04 pu |
| Primary voltage | 22 kV |
| Secondary voltage | 0.4 kV |
| No load losses | 0.0023 pu |
| Load losses | 0.015 pu |
| Zero sequence impedance, earthing reactor and transformer | 0.005 + j 0.175 pu |

TABLE 2
FAULT CURRENTS FOR THREE, TWO AND SINGLE PHASE FAULT

| | Three-phase short circuit | Two-phase short circuit | Single phase to earth |
|---|---|---|---|
| $I_A$ | 58.7 A | 29.33 A | 31.66 A |
| $I_B$ | 58.7 A | 58.65 A | 31.66 A |
| $I_C$ | 58.7 A | 29.33 A | 0 |
| $I_a$ | 3228.5 A | 2793 A | 3015 A |
| $I_b$ | 3228.5 A | 2793 A | 0 |
| $I_c$ | 3228.5 A | 0 | 0 |

### 3.1.5 Maximum load current and single phase MV fault

Neither the fuses on the MV side or the LV side shall blow due to maximum load current combined with a compensation current due to a phase to earth fault in the MV network. The maximum combined current on the MV side is calculated in Equation 14.

$$I_{Max\ Load} = \frac{S_n}{\sqrt{3}U_n} = \frac{100 \cdot 10^3}{\sqrt{3} \cdot 22 \cdot 10^3} = 2.6\ A/phase$$

$$I_{L\ Healthy\ phase} = \frac{I_L}{3}$$

$$I_{Max} = \left| 2.6 + \frac{I_L}{3} \right| A/phase$$

**Equation 14**

The capacitive earth fault current in a 22 kV network consisting of underground cable is approximately 3 A per km. If the fuses are constructed to withstand currents up to 20 A the distance between the Petersen coils can be calculated as in Equation 15.

$$I_{MV\ fault} < 20\ A/phase$$

$$\left|2.6 + \frac{I_L}{3}\right| < 20\ A/phase$$

$$I_C < 52\ A/phase$$

$$d = \frac{52}{3} \approx 17km$$

**Equation 15**

## 3.2 Vattenfall and e.on transformers

The two major Swedish distribution companies Vattenfall and e.on have decided to use 100 kVA transformers equipped with 15 and 10 A rated Petersen coils in their 24 and 12 kV networks. The coil rating corresponds to a distance of 5 km between the Petersen coil equipped transformers. One reason they have chosen this solution can be advantageous related to keeping the same distance between the compensation units, independent of voltage level. It is utterly important to limit the number of different transformers in discussions with manufacturers. The opted alternative might not be the ideal, but it is certain to avoid the risk of unwanted fuse operation, which is of great importance.

The current in the healthy phases on the MV side of a 24 kV system in case of a phase to earth fault in the MV network combined with the maximum load current is calculated in Equation 16.

$$I_C = 15A$$

$$I_{L\ Healthy\ phase} = \frac{I_L}{3} = 5A$$

$$I_{MV\ fault} = |2.6 + 5| = 7.6\ A/phase$$

**Equation 16**

The corresponding maximum MV current for a 12 kV network are calculated in Equation 17.

$$I_C = 10A$$

$$I_{L\ Healthy\ phase} = \frac{I_L}{3} = 3.3A$$

$$I_{Max\ Load} = \frac{S_n}{\sqrt{3}U_n} = \frac{100 \cdot 10^3}{\sqrt{3} \cdot 11 \cdot 10^3} = 5.2\ A/phase$$

$$I_{Max} = 5.2 + 3.3 = 8.5\ A/phase$$

**Equation 17**

## 3.3 12 to 0.4 kV transformer

Table 3 gives the analytical calculated ideal short circuit currents on the MV and LV side in case of a fault on the 0.4 kV terminal of a 12 to 0.4 kV transformer.

TABLE 3
FAULT CURRENTS FOR THREE, TWO AND SINGLE PHASE FAULT

| | Three-phase short circuit | Two-phase short circuit | Single phase to earth |
|---|---|---|---|
| $I_A$ | 131 A | 65.1 A | 109 A |
| $I_B$ | 131 A | 130 A | 109 A |
| $I_C$ | 131 A | 65.1 A | 0 |
| $I_a$ | 3.6 kA | 3.1 A | 5.2 A |
| $I_b$ | 3.6 kA | 3.1 A | 0 |
| $I_c$ | 3.6 kA | 0 | 0 |

**Table 1, Fault currents in case of faults in a 11 to 0.4 kV transformer**

The fault currents are much larger than the maximum load current combined with the capacitive earth fault current. Transformers equipped with 10 A rated coils can therefore be used in 12 kV network without any risk of unwanted fuse function in case of a phase to earth fault in the MV network.