NEW MODEL FOR THE CALCULATION OF HARMONICS IN THE RESIDUAL EARTH FAULT CURRENT OF MEDIUM VOLTAGE SYSTEMS

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ABSTRACT

The resonant earthed neutral is the dominant neutral point treatment for the medium voltage level in many Central European countries. Because of the growing percentage of cable and increased use of power electronics in distribution networks both the fundamental and the harmonic components of the residual earth fault current $\underline{I}_{RES}$ *rise. This can lead to a violation of the upper limits of the residual earth fault current* $\underline{I}_{RES}$ *as well as the permitted touch voltage* U_{Tp} *according to the valid standards. Thus, it is very convenient to be able to determine the residual earth fault current in case of a single phase earth fault by using the voltages measured in the faultless network. The presented model enables the calculation of residual earth fault current without the realization of complex and costly field tests. The calculation uses the voltages measured at the busbar and the current network configuration. Fault location and fault impedance can be varied as pleased.*

INTRODUCTION

In many Central European countries the resonant earthed neutral is prevalent in medium voltage networks [1]. It is chosen to obtain the optimal power supply reliability. With the growing share of cables, the fundamental component of the residual earth fault current rises in case of a single phase earth fault. The increasing use of power electronics i.e. of renewable energy sources leads to a rise of the harmonic content in the network voltage and in the residual earth fault current. While the fundamental current can be compensated by the Petersen coil, the harmonic components can exceed the fundamental by far and are not compensated by the Petersen coil. Thus, it is important to gain knowledge about the share of harmonics in the residual earth fault current. However, executing field measurements is intricate and costly and only display the conditions of a network at a specific fault location and at a specific time.

BASICS

Functionality of the resonant earthed neutral

In resonant earthed networks the neutral point is grounded via a tuneable inductivity, the Petersen coil L_M according to Fig. 1. In case of a single phase earth fault the capacitive earth fault current I_{CE} at the fault location is compensated by the inductive current I_L via the Petersen coil L_M; L_a, L_b and L_c are the transformer inductivities.

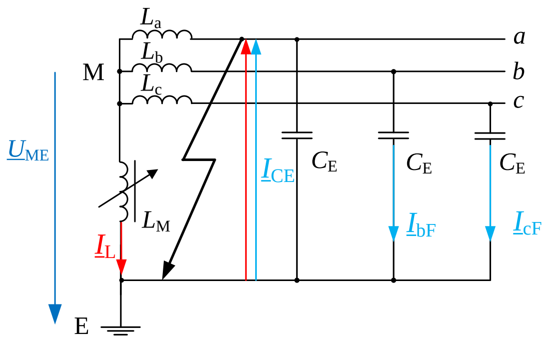

Fig. 1. Simplified equivalent circuit of a resonant grounded network after failure occurrence

In case of ideal, complete tuning

$$\frac{1}{\omega\, C_E} = 3\,\omega\, L_M \tag{1}$$

applies. In real networks the remaining 50 Hz current at the fault location only contains the residual active current $\underline{I}_{RES\,a}$. The relation of the residual active current and the capacitive earth fault current is the damping d of the network:

$$d = \frac{I_{RES\,a}}{I_{CE(50)}} \tag{2}$$

To measure the compensation of the 50 Hz component within the network the detuning v_u obtained via the resonance curve is used:

$$v_u = \frac{I_{CE(50)} - I_{L\,pos}}{I_{CE(50)}} \tag{3}$$

With $I_{L\,pos}$ as the Petersen coil position current. Using the damping d and the detuning v_u the fundamental component of the residual earth fault current $\underline{I}_{RES(50)}$ can be expressed:

$$\underline{I}_{RES(50)} = I_{CE(50)}(d + \mathrm{j}v_u) \tag{4}$$

$$I_{RES(50)} = I_{CE(50)}\sqrt{d^2 + v_u^2} \tag{5}$$

To include the harmonic currents equation (5) has to be expanded where ν is representing the ordinal number of each harmonic:

$$I_{RES} = I_{CE(50)}\sqrt{d^2 + v_u^2 + \sum_\nu \left(\frac{I_\nu}{I_{CE(50)}}\right)^2} \tag{6}$$

Single phase earth fault in symmetrical components

In case of a single phase earth fault positive, negative and zero sequence system are connected according to Fig. 2. Simplifying the network parameters are depicted as lumped elements. The transformer impedances are included in the equivalent impedances $\underline{Z}_{i\,\mathrm{eq}}$[1].

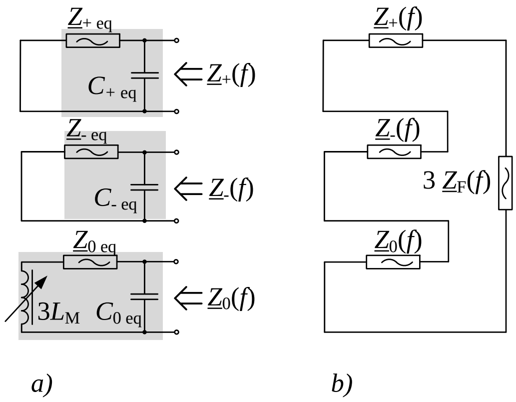

Fig. 2. Effective impedances of a network with resonant earthed neutral a) before and b) during single phase earth fault in symmetrical components without current or voltage sources

With this connection in series of the three systems the network impedance changes. This is because the impedances and admittances of the negative and zero sequence system are added to the positive sequence system that are effective before the earth fault takes place. This changes the resonance frequencies of the parallel and series resonance circuits.

The zero sequence system has a parallel resonance at 50 Hz for the tuned Petersen coil. However, the influence of the parameters of the positive and negative sequence systems on the total impedance and with that on the residual earth fault current $\underline{I}_{\mathrm{RES}}$ cannot be neglected. This variation within the network impedance can be seen in Fig. 3. A parallel and a series resonance are marked exemplarily.

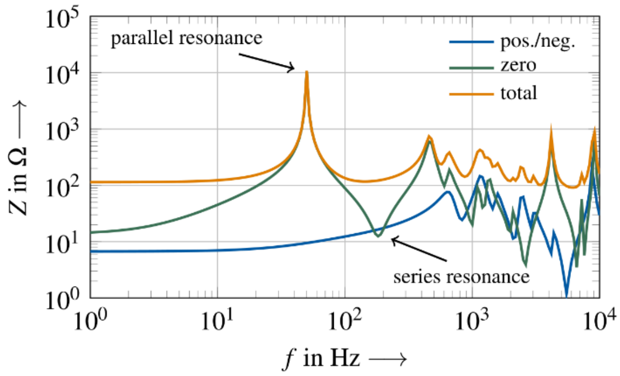

Fig. 3. Frequency dependent network impedance for positive/ negative and zero sequence system and the total impedance as of an exemplary network

If the resonance frequency of a parallel resonance circuit is equal to an exciting harmonic, the influence on the residual earth fault current is low. Reason for that is the high impedance of the parallel resonance circuit at this frequency. This can be seen at $f \approx 450$ Hz in Fig. 3. On the other hand, if harmonics coincide with a series resonance, in Fig. 3 at $f \approx 200$ Hz, the portion of harmonics of this frequency in the residual earth fault current increases. For prediction of the residual earth fault current $\underline{I}_{\mathrm{RES}}$ it is relevant to consider the frequency dependent network impedance effective during the earth fault.

MODEL FOR THE CALCULATION OF THE RESIDUAL EARTH FAULT CURRENT

Frequency Dependent Network Impedance

The share of harmonic components in the residual earth fault current $I_{\mathrm{RES}(\nu)}$ is determined by the combination of the harmonics existing within the network and the frequency dependent network impedance that is effective during the single phase earth fault. It is not sufficient to use a lumped network to model the behaviour of the network.

In [2, 3, 5] a model is presented to describe the frequency dependent impedance during a single phase earth fault. In order to do this, all network elements are described as two-ports and connected according to the respective network configuration as described by the two-port theory [4]. All elements are calculated up to a frequency of $f = 1$ kHz. This is acceptable as harmonics up to $f = 750$ Hz dominate the residual earth fault current. In case of a single phase earth fault the impedances of positive, negative and zero sequence system resulting from the two-ports are connected according to the fault conditions (Fig. 4).

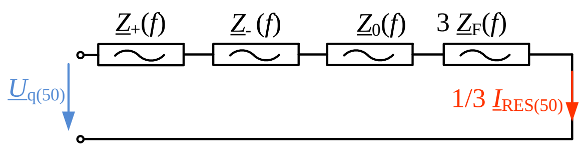

Fig. 4. Equivalent circuit to calculate the network impedance effective during a single phase earth fault

Depending on the location of the earth fault the effective network impedance changes [5].

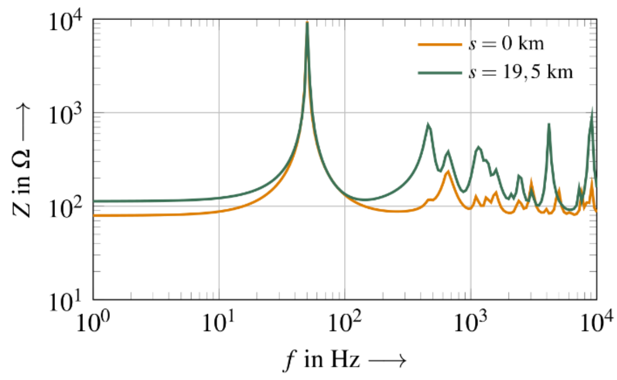

Fig. 5. Total network impedance of an exemplary network effective during a single phase earth fault with different fault locations

1 $i = +, -, 0$ for positive, negative and zero sequence system

The change of the frequency dependent impedance between an earth fault at the busbar and a distant earth fault is shown in Fig. 5.

With a growing distance s between busbar and fault location the resonances changes towards lower frequencies. It is also possible that resonances develop due to particular lines within the network [5, 6].

Harmonic Sources

To take into account the harmonics existing in the supplying 110-kV-network, it is essential to use harmonic current sources at the bus bar. The effective frequency dependent network impedance changes while an earth fault occurs as positive, negative and zero sequence system are connected in series as shown in Fig. 2.

Field measurements have shown that the 110-kV-network has to be taken into account, to calculate the harmonic components of the residual earth fault current $\underline{I}_{RES(\nu)}$ correctly. In Fig. 6 it becomes obvious that the current $\underline{I}_{S+(\nu)}$ of the harmonic current source of the positive sequence system divides into the harmonic current that goes into the 110-kV-network $\underline{I}_{+110(\nu)}$ and one that goes into the 20-kV-network $\underline{I}_{+20(\nu)}$ [2].

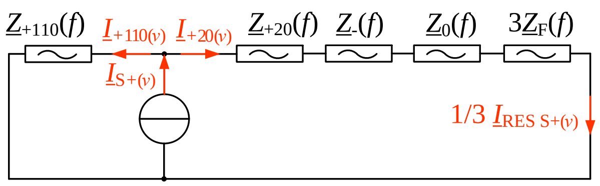

Fig. 6. Simplified equivalent circuit in symmetrical components considering the 110-kV-network in case of a single phase earth fault to calculate the residual earth fault current yielding from the positive sequence system

This can be seen in the change of the phase-to-earth voltages $\underline{U}_{Tr(\nu)}$ measured at the busbar before and during the single phase earth fault, Fig. 7 and Fig. 8.

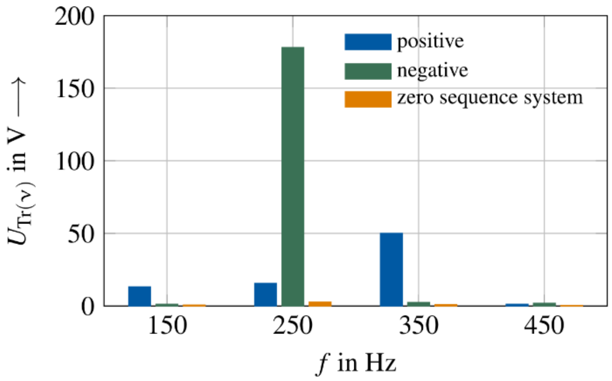

Fig. 7. Harmonic phase-to-earth voltages measured at the 20-kV-busbar before single phase earth fault

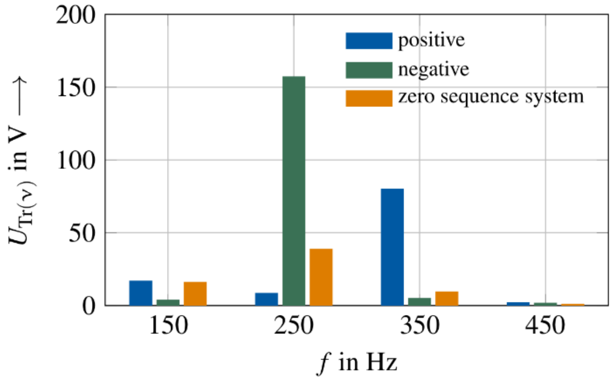

Fig. 8. Harmonic phase-to-earth voltages measured at the 20-kV-busbar during a single phase earth fault

If the 110-kV-network has a very high impedance, it hardly has an impact on the harmonic components of the residual earth fault current $\underline{I}_{RES(\nu)}$. Thus, the use of harmonic voltage sources would lead to correct results. However, if the network impedance of the 110-kV-network is low at those frequencies, using harmonic current sources is the only way to consider this behaviour.

The harmonic component of the residual earth fault current for the positive sequence system $\underline{I}_{RES\ S+(\nu)}$ is calculated as shown in Fig. 6:

$$\underline{I}_{\mathrm{RES\ S+}(\nu)} = 3 \cdot \underline{I}_{\mathrm{S+}(\nu)} \left(\frac{\underline{Z}_{+110}(f)}{\underline{Z}_{+110}(f) + \underline{Z}_{\Sigma}(f)} \right) \quad (7)$$

with: $$\underline{Z}_{\Sigma}(f) = \underline{Z}_{+20}(f) + 3\,\underline{Z}_{\mathrm{F}}(f) + \underline{Z}_{-}(f) + \underline{Z}_{0}(f) \quad (8)$$

The current $\underline{I}_{S+(\nu)}$ from the harmonic current source is calculated from the harmonic voltages $\underline{U}_{+Tr(\nu)}$ measured at the busbar and the 20-kV-network impedance before the single phase earth fault takes place [2].

In the same manner the harmonic components of the residual earth fault current for the negative sequence system $\underline{I}_{RES\ S-(\nu)}$ is calculated using the harmonic voltages of the negative sequence system $\underline{U}_{-Tr(\nu)}$. For the zero sequence system the 110-kV-network impedance and the loads are not included.

The total harmonic content of the residual earth fault current $\underline{I}_{RES\,\nu}$ is calculated by superposition of the harmonic currents, which are injected by the current sources of the positive, negative and zero sequence system:

$$\underline{I}_{\mathrm{RES}(\nu)} = \underline{I}_{\mathrm{RES\,S+}(\nu)} + \underline{I}_{\mathrm{RES\ S-}(\nu)} + \underline{I}_{\mathrm{RES\ S0}(\nu)} \quad (9)$$

Various field tests have shown that this model accurately describes the harmonic components of the residual earth fault current $\underline{I}_{RES(\nu)}$. For the tests influences on the residual earth fault current $\underline{I}_{RES}$ like fault location, network configuration and fault resistance were varied.

In Fig. 9 the measured and calculated harmonic content of the residual earth fault current $\underline{I}_{RES(\nu)}$ is shown for a single phase earth fault with a distance of s=19.5 km from the busbar.

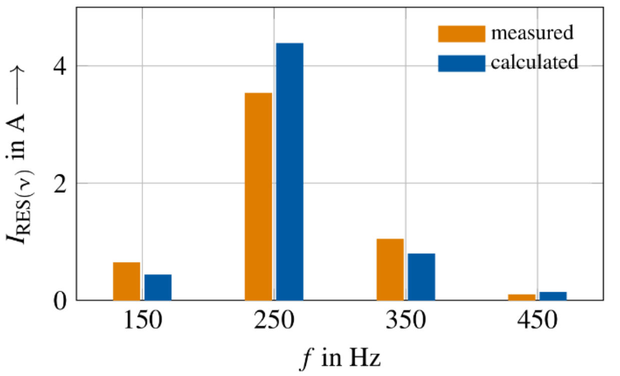

Fig. 9. Measured and calculated harmonic content of the residual earth fault current using harmonic current sources, earth fault with a distance of 19.5 km from the busbar

The harmonic content of the residual earth fault current $\underline{I}_{RES(\nu)}$ calculated using harmonic voltage sources is shown in Fig. 10. Comparing Fig. 9 and Fig. 10 it becomes obvious that the approach of using harmonic voltage sources does not yield the desired results.

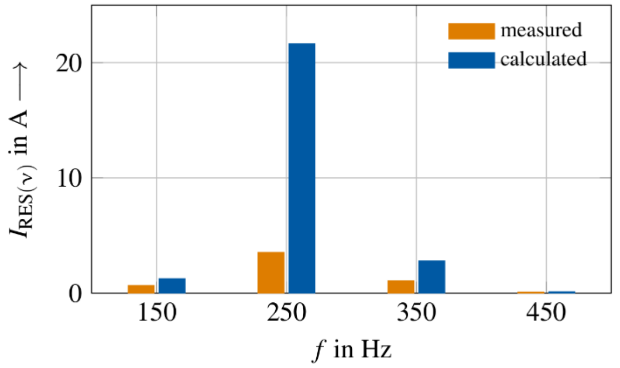

Fig. 10. Measured and calculated harmonic content of the residual earth fault current using harmonic voltage sources, earth fault with a distance of 19.5 km from the busbar

Considering Fig. 11 it becomes clear that when using constant harmonic voltage sources $\underline{U}_{S(\nu)}$ the frequency dependent 110-kV impedance is not taken into account. This is the reason for the inaccuracy of the results.

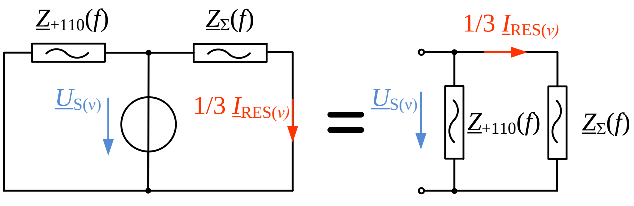

Fig. 11. Equivalent circuit to calculate the residual earth fault current using harmonic voltage sources

SIMPLIFIED MODEL

To simplify the calculation of the harmonic content in the residual earth fault current $\underline{I}_{RES(\nu)}$ and to facilitate the input of the network parameters a simplified network model is developed. For this model only the feeder with the single phase earth fault is modelled in detail. The remaining, healthy network is depicted by a single substitute capacity C_{RN} in the zero sequence system as shown in Fig. 12. This substitute capacity C_{RN} is topology and frequency depending in order consider to the size and configuration of the remaining network.

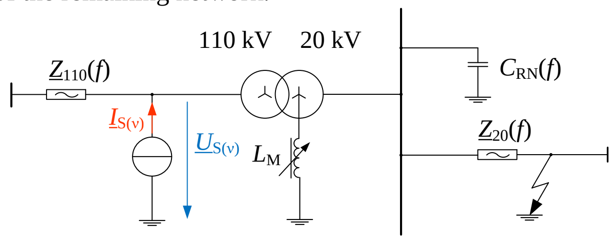

Fig. 12. Equivalent circuit of the simplified network with the remaining network as substitute capacity

The simplified model has been tested on two specific networks, which both have more than five line feeders. It has yet to be examined if the substitute capacity can describe the frequency dependent behaviour for networks with a smaller number of line feeders [7]. A small share of cables within the network also leads to deviations. In Fig. 13 the harmonic components of residual earth fault current calculated using the simplified model is compared to the measured values.

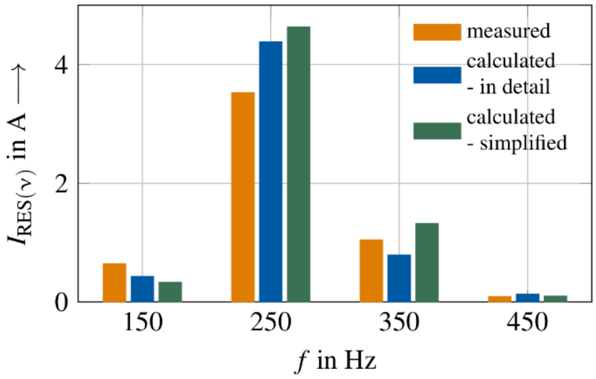

Fig. 13: Measured and calculated residual earth fault current using the simplified model for the distant earth fault

CONCLUSION

A detailed model was developed to describe the harmonic content of the residual earth fault current $\underline{I}_{RES(\nu)}$ in case of a single phase earth fault in a network with resonant earthed neutral. The calculation is based on the easily accessible line-to-earth voltages $\underline{U}_{Tr}$ measured at the busbar of the faultless network. The placement and implementation of the harmonic sources are important.

It is hardly possible to execute a sufficient number of complex and costly field tests to find critical sections of a network. Conveniently, the model's calculation is based on the easily accessible line-to-earth voltages $\underline{U}_{Tr}$ that are measured at the busbar of the healthy network any time.

Residual earth fault currents for the worst case can be calculated using the voltages with the maximum harmonic content.

The resulting model can accurately describe the residual earth fault current $\underline{I}_{\mathrm{RES}}$ by calculating the network impedance for each frequency. Considering the impedance and the harmonics within the network the residual earth fault current of each frequency is calculated.

It could be shown that harmonic current sources $\underline{I}_{\mathrm{S}(\nu)}$ have to be used to include the influence of the 110-kV network. Discrepancies result from the imprecision of the input parameters and from the simplification of influencing factors.

The harmonics existing in the network can but don't necessarily have a major influence on the residual earth fault current depending on the resonances of the network impedance that is effective during the earth fault. Especially series resonances with a frequency close to characteristic harmonics lead to high residual earth fault currents.

The fault location and fault impedance have a crucial influence on the residual earth fault current. The fault impedance of a distant earth fault in a real network with overhead lines usually is a lot higher than when conducting tests at a substation. Thus, the residual earth fault current would be smaller. A distant earth fault can lead to a shift of the resonances of the network impedance and cause certain harmonics in the residual earth fault current to either rise or fall. This can be described using the model.

A simplified model is developed to facilitate the input of the network. The healthy network is only described by a substitute capacity in the zero sequence system while the feeder with the earth fault is modelled in detail. The results are less accurate than those of the detailed model. However, the simplified model allows to estimate the harmonic content of the residual earth fault current close enough to identify risky network configurations.

The models have only been verified with the analysed networks. To confirm the accuracy of the model and the verity the above statements more field tests and investigation are necessary.

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