ANALYTICAL CALCULATION OF THE NEUTRAL POINT DISPLACEMENT VOLTAGE FOR HIGH IMPEDANCE EARTH FAULTS IN RESONANT EARTHED NEUTRAL SYSTEMS

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ABSTRACT

In most distribution systems in Central European countries isolated neutral and resonant earthed neutral is applied. For systems with such neutral point treatment the detection and localisation of a single-phase earth fault is the main challenge. The neutral point displacement voltage is used as a pick-up criterion in the majority of earth fault relays. This paper presents an analytical calculation of the neutral point displacement voltage in a resonant earthed neutral system in case of a single-phase earth fault. The calculation is used for a parameter analysis of the parameters of a resonant earthed neutral system. The results of the parameter analysis and implications for the operation of distribution systems are discussed. Furthermore, a new quantity for the evaluation of a single-phase earth fault in resonant earthed neutral systems is introduced.

INTRODUCTION

In Central European countries isolated neutral and resonant earthed neutral are the most common types of neutral point treatment in distribution systems, as Fig. 1 shows exemplarily for the German-speaking countries.

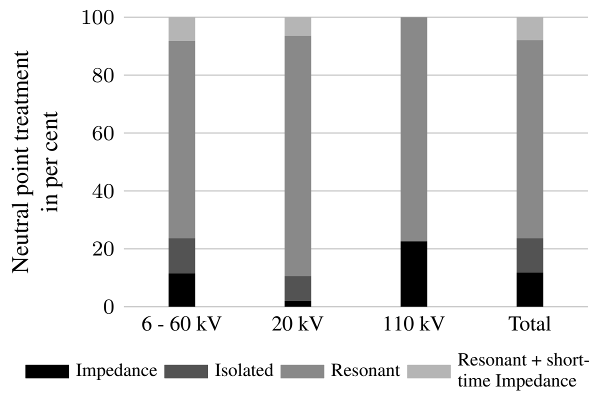

Fig. 1: Neutral point treatment in German-speaking counties dependent on voltage level [1]

Significant advantages of these neutral point treatments are the continuation of power supply during a single-phase earth fault and the self-extinction of such faults due to the small magnitude of the earth fault current [2].

The main challenge for resonant earthed neutral systems is the directional sensitive detection and the localisation of single-phase earth faults [3]. Various types of methods exist in earth fault relays, which either rely on stationary or transient phenomena [4, 5].

The majority of these methods use the neutral point displacement voltage (NPDV) or the zero sequence voltage as a pick-up condition. The pick-up value of the NPDV must be higher than the pre-fault NPDV resulting from the unbalance of the line-to-earth admittances.

In certain countries it is mandatory in resonant earthed neutral systems to detect earth faults with fault transition resistances up to several kilo ohms [6]. The NPDV caused by a single-phase earth fault with a particular fault transition resistance depends on the parameters of the considered resonant earthed neutral system. If the resulting NPDV is smaller than the pick-up value, it is not possible to detect the single-phase earth fault, even if the stationary or transient method itself is sensitive enough to do so. In such a case the NPDV limits the sensitivity of the earth fault detection.

Consequently, it is crucial for an optimal setting and thus reliable operation of earth fault relays to be able to estimate the NPDV caused by a single-phase earth fault taking into account the parameters of the considered resonant earthed neutral system.

An analytical calculation of the NPDV is presented taking into account the parameters of a resonant earthed neutral system, which are normally known to a system operator. The calculation is verified with simulations in MATLAB/Simulink. Furthermore, a detailed parameter analysis is carried out and discussed.

ANALYTICAL CALCULATION

The simplified equivalent circuit diagram of a resonant earthed neutral system for a single-phase earth fault is shown in Fig. 2.

The series impedances of the equivalent network, transformer, and lines are neglected in each component system, since they are small compared to the impedance of the parallel resonance circuit in the zero sequence system.

The parallel resonance circuit consists of the arc suppression coil L_{ASC}, the zero sequence capacitance of the lines C_0, and the conductance G_0. The conductance G_0 represents the resistive losses of the lines and the arc suppression coil.
In contrast to the standard parameters of a resonant earthed neutral system, the unbalance of the line-to-earth admittances of the system is often not exactly known and varies with the active system topology. As a simplification, it is therefore assumed that the unbalance of the line-to-earth admittances of the system is concentrated in one phase. This constitutes a special case, in which the unbalance of the line-to-earth admittances and the fault transsition resistance occur in the same phase, allowing the representation in symmetrical components in closed-form [7].

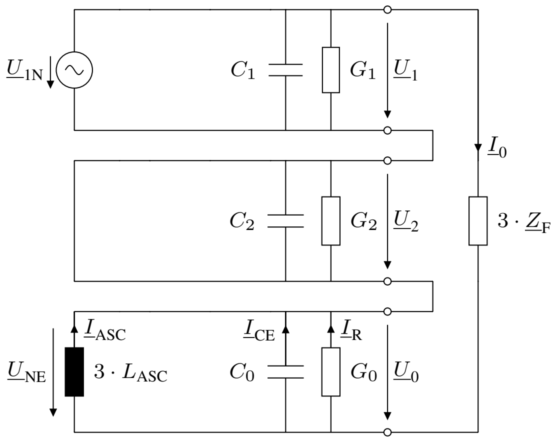

Fig. 2: Simplified equivalent circuit diagram of a resonant earthed neutral system for a single-phase earth fault

The component systems are connected in series via the complex fault impedance $\underline{Z}_F$. It consists of the parallel connection of the conductance G_F and the capacitance C_F. The complex fault impedance can be calculated according to equation (1).

$$\underline{Z}_F = \frac{1}{G_F + j \cdot \omega \cdot C_F} \quad (1)$$

In pre-fault state the conductance G_F represents the resistive unbalance of the line-to-earth admittances of the system. Usually the resistive unbalance of the line-to-earth admittances is very small and thus can be omitted. The capacitance C_F represents the capacitive unbalance of the line-to-earth admittances of the system. It depends primarily on line type, conductor layout and transposition. It can reach several percent of the zero sequence capacitance of the system [8].

In case of a single-phase earth fault, the conductance G_F is equal to the reciprocal value of the fault transition resistance R_F. The capacitive unbalance of the line-to-earth admittances C_F is assumed to remain constant.
The zero sequence current can be expressed through the current $\underline{I}_F$ at the earth fault location as shown in equation (2). The resistive part of the earth fault current is proportional to the damping d of the resonant earthed neutral system. The reactive part of the earth fault current is proportional to the detuning v. The definition of the damping d and detuning v are given in equation (3).

$$\underline{I}_0 = \frac{1}{3} \cdot \underline{I}_F = \frac{1}{3} \cdot I_{CE} \cdot (d - j \cdot v) \quad (2)$$

$$d = \frac{G_0}{\omega \cdot C_0} = \frac{I_R}{I_{CE}}$$
$$v = \frac{I_{ASC} - I_{CE}}{I_{CE}} \quad (3)$$

The impedance of the zero sequence system can be calculated according to equation (4). For a complex fault impedance of zero, the zero sequence voltage is equal to the nominal line-to-earth voltage.

$$\underline{Z}_0 = \frac{\underline{U}_0}{\underline{I}_0} = \frac{U_n/\sqrt{3}}{1/3 \cdot I_{CE} \cdot (d - j \cdot v)} =$$
$$= \frac{\sqrt{3} \cdot U_n}{I_{CE} \cdot (d - j \cdot v)} = \frac{Z_{0,Iso}}{(d - j \cdot v)} \quad (4)$$

Based on the voltage divider following Fig. 2, the NPDV can be determined as shown in equation (5).

$$\underline{U}_{NE} = \underline{U}_0 = -\frac{\underline{Z}_0}{\underline{Z}_0 + 3 \cdot \underline{Z}_F} \cdot \underline{U}_{1N} \quad (5)$$

By inserting equation (1) and (4) into equation (5), the magnitude of the NPDV can be calculated according to equation (6).

$$U_{NE} = U_0 =$$
$$= \frac{U_{1N}}{\sqrt{1 + 6 \cdot d \cdot (\mathrm{Re}(\underline{z}_F) + \mathrm{Im}(\underline{z}_F)) + 9 \cdot (d^2 + v^2) \cdot |\underline{z}_F|^2}} \quad (6)$$

Apart from damping d and detuning v of the resonant earthed neutral system, the magnitude of the NPDV in equation (6) depends on the relative fault impedance $\underline{z}_{\text{F}}$, which is expressed in per units.
It is calculated by dividing the complex fault impedance $\underline{Z}_{\text{F}}$ by the absolute value of the zero sequence impedance of the same system with isolated neutral $Z_{0,\text{Iso}}$. It is therefore dependent on the earth fault current I_{CE} and the nominal voltage U_{n} of the system, as equation (7) shows.

$$\underline{z}_{\text{F}} = \frac{\underline{Z}_{\text{F}}}{Z_{0,\text{Iso}}} = \frac{I_{\text{CE}}}{\sqrt{3} \cdot U_{\text{n}}} \cdot \underline{Z}_{\text{F}} \tag{7}$$

VERIFICATION

The analytical calculation of the NPDV from equation (6) is verified with simulations in MATLAB/Simulink. Detailed models for the equivalent network, transformer, and lines are used in MATLAB/Simulink. A 20-kV-network with resonant earthed neutral consisting of radial cable feeders is used for verification. The network parameters are given in Table 1.

Table 1: Network parameters

U_{n}	I_{CE}	d	v	c_{F}
20 kV	168.2 A	6.72 %	10 %	0 %

The capacitive unbalance of the network is expressed through the relative capacitive unbalance c_{F}. It is obtained by dividing the capacitance C_{F} by the zero sequence capacitance of the network, as equation (8) shows.

$$c_{\text{F}} = \frac{C_{\text{F}}}{C_0} \tag{8}$$

The relative capacitive unbalance of the resonant earthed neutral system is zero due to the fact that single-core cables are used for the cable feeders.
The accuracy of the analytical calculation is evaluated exemplarily for a single-phase earth fault at the end of a cable feeder in Fig. 3. The fault transition resistance R_{F} is varied between 1 mΩ and 25 kΩ. In all following figures the NPDV is expressed in per unit values with the nominal line-to-earth voltage as base.

As Fig. 3 shows, the NPDV calculated with equation (6) shows very high accordance with the NPDV obtained with the simulations in MATLAB/Simulink.

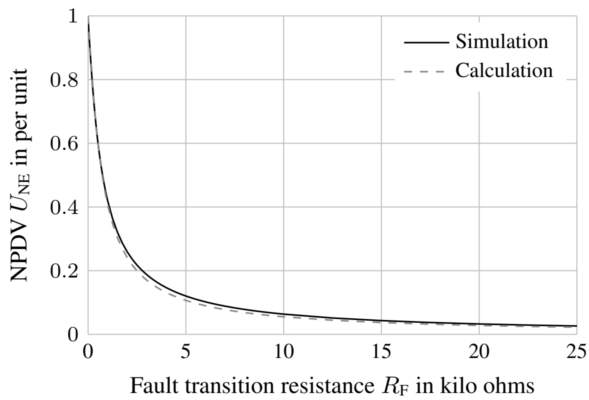

Fig. 3: NPDV U_{NE} with varying fault transition resistance R_{F}

The mean absolute error (MAE) of the analytical calculation is smaller than 1 % of the nominal line-to-earth voltage.
Further studies with different network parameters (nominal voltage, earth fault current, detuning, line type) show very high accordance between the calculated and simulated NPDV as well. It can be concluded that the simplifications made for the derivation of equation (6) are admissible.

PARAMETER ANALYSIS

Based on the analytical calculation of the NPDV in equation (6), a parameter analysis is carried out. The reference scenario is a single-phase earth fault with the fault transition resistance R_{F} in a resonant earthed neutral system with the parameters given in Table 2.
In pre-fault state the capacitive unbalance of the line-to-earth admittances generates an NPDV of 3.02 % of the nominal line-to-earth voltage.

Table 2: Reference scenario parameters

U_{n}	I_{CE}	d	v	c_{F}	R_{F}
20 kV	250 A	5 %	10 %	1 %	5 kΩ

Damping & detuning

Damping d and detuning v of the resonant earthed neutral system are varied in Fig. 4. The NPDV caused by a single-phase earth fault with the fault transition resistance R_{F} decreases with increasing damping and detuning.

As can be seen from Fig. 4, an increase of the damping leads to a higher decrease of the NPDV than the same increase of the detuning. This correlation is also reflected in equation (6).

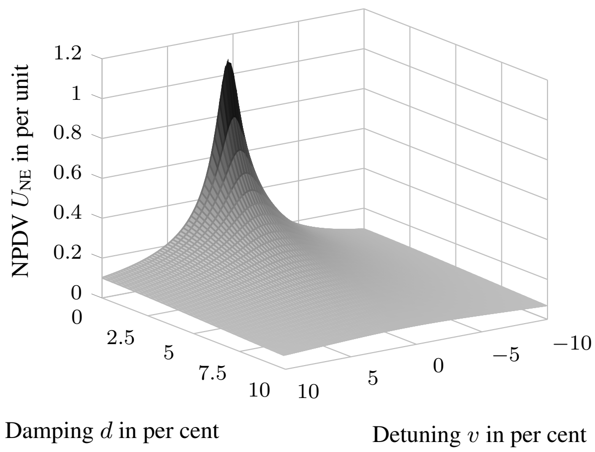

Fig. 4: NPDV U_{NE} with varying damping d and detuning v

Capacitive unbalance

The capacitive unbalance of the line-to-earth admittances is varied in Fig. 5. It is expressed through the relative capacitive unbalance c_{F} introduced in equation (8).
The NPDV generated by a single-phase earth fault with the fault transition resistance R_{F} increases with the relative capacitive unbalance c_{F}. This is due to the fact that the complex fault impedance decreases with the capacitive unbalance C_{F} as shown in equation (1).

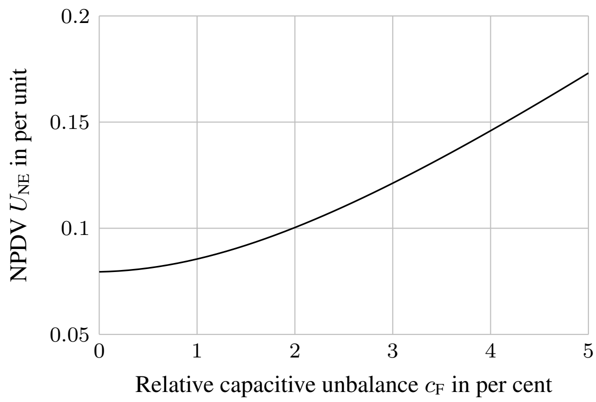

Fig. 5: NPDV U_{NE} with varying relative capacitive unbalance c_{F}

The smaller the unbalance of the line-to-earth admittances the smaller the NPDV generated by a single-phase earth fault with the fault transition resistance R_{F}.

Earth fault current

The earth fault current I_{CE} of the resonant earthed neutral system is varied in Fig. 6. It depicts the NPDV generated by a single-phase earth fault with the fault transition resistance R_{F} for two different nominal voltages.

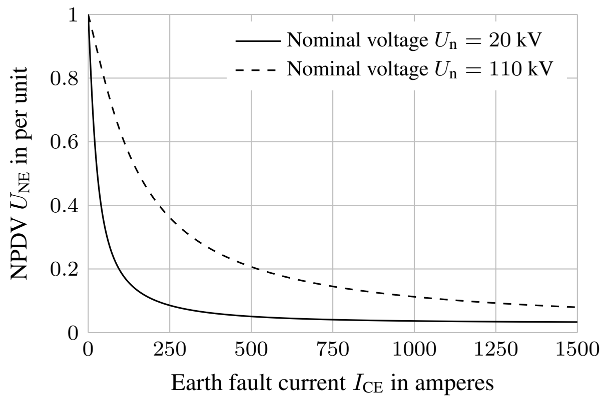

Fig. 6: NPDV U_{NE} with varying earth fault current I_{CE}

It can be seen that for the same earth fault current I_{CE} the NPDV is considerably higher for a higher nominal voltage of the resonant earthed neutral system. Furthermore, Fig. 6 shows that the NPDV decreases with the earth fault current I_{CE} of the resonant earthed neutral system.
The relative fault impedance increases with the earth fault current I_{CE} according to equation (7) and thus leading to a decrease of the NPDV.

Fault transition resistance

In Fig. 7 the fault transition resistance is varied between 1 mΩ and 25 kΩ. It can be noted that the NPDV approaches the pre-fault NPDV resulting from the capacitive unbalance of the line-to-earth admittances. This pre-fault NPDV constitutes the lower limit of the NPDV caused by a single-phase earth fault.

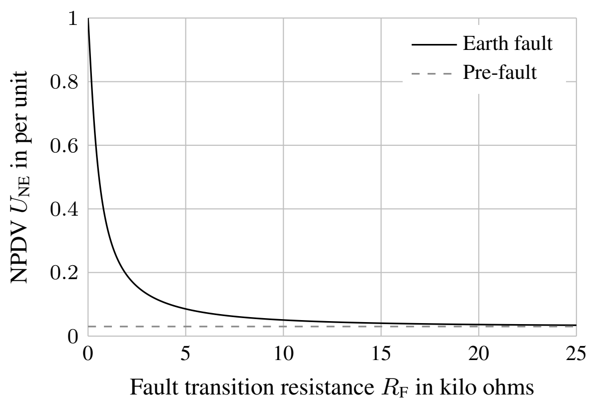

Fig. 7: NPDV U_{NE} with varying fault transition resistance R_{F}

For a higher capacitive unbalance this limit is reached at a lower value of the fault transition resistance R_F.

DISCUSSION

The parameter analysis in the previous section has shown that apart from damping and detuning, capacitive unbalance, earth fault current, and nominal voltage of a resonant earthed neutral system influence the NPDV caused by a single-phase earth fault with the fault transition resistance R_F. The lower limit of the NPDV is its pre-fault value resulting from the primarily capacitive unbalance of the line-to-earth admittances.
The relative fault impedance z_F from equation (7) takes the nominal voltage, earth fault current and capacitive unbalance into account. It is a useful quantity to evaluate the impact of a single-phase earth fault in resonant earthed neutral systems since it refers the fault transition resistance R_F to the parameters of the resonant earthed neutral system. The NPDV with varying relative fault impedance z_F is shown in Fig. 8.

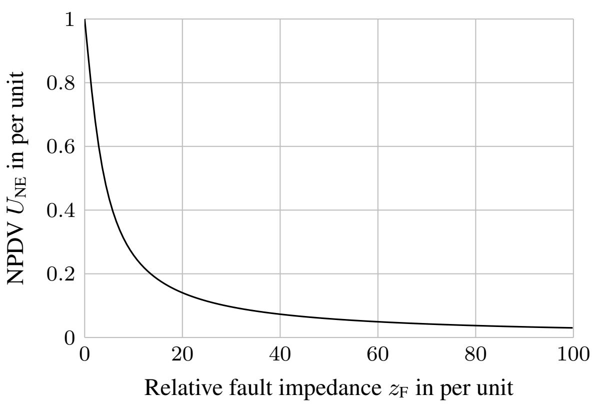

Fig. 8: NPDV U_{NE} with varying relative fault impedance z_F

In resonant earthed neutral systems where the earth fault current is subject to great variation, e.g. through coupling of different sections, it has to be taken into consideration that the NPDV caused by a single-phase earth fault with the fault transition resistance R_F varies as well. If this is not accounted for, e.g. by changing the set point of the detuning of the arc-suppression coil or the pick-up values of earth fault relays, the sensitivity of the earth fault detection regarding the fault transition resistance can decrease.
The substantial replacement of overhead lines by cables in resonant earthed neutral systems poses a similar challenge. It leads to a decrease of the capacitive unbalance, assuming that single-core cables are used, and an increase of the earth fault current. Both aspects result in a smaller NPDV caused by a single-phase earth fault with the fault transition resistance R_F. Changing the set point of the detuning of the arc-suppression coil or the pick-up values of earth fault relays may be necessary if the same sensitivity of the earth fault detection regarding the fault transition resistance is required.

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