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Three Phases to Earth Reactors for the State Evaluation of Zero-Sequence Systems

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Abstract: In this study, we present a method for the state evaluation of the zero sequence parameters. This method consists on connecting between each phase to earth one variable impedance reactor, which permit us reducing the fault current value in the ground fault point as well as making possible the voltage imbalance compensation. This can be accomplished by setting to optimum value the phase to earth reactance of inductive character to be in tune with the network phase to earth capacitance of the corresponding phase, in order to get a parallel resonance regime. The inductive phase to earth reactance is connected across the network phase and the ground potential. In contrast to the previously used method of inductance connection between the system neutral point and the ground potential, this solution provides apart from maximum total capacitive current compensation capability even an equalization of phase voltages under failure free condition within networks with substantial phase capacitance imbalance. By goal-directed variation of the phase earth reactance in the earth fault point during the ground fault, the watt fault current component can be efficiently eliminated, which is the main advantage of this method, since the control of the zero sequence parameters (at 50 Hz frequency) can be done safety.

Key words: Current compensation, three-phase variable inductances, resonance, zero- sequence state evaluation, leakage current

INTRODUCTION

Ground fault current magnitudes depend on the system grounding method. The ungrounded and compensated distribution systems are one of the most important options in electrical network design to obtain the optimal power supply quality. The main advantage of the treatment of the neutral point is the possibility of continuing the network operation during a sustained earth-fault. Therefore, this reduces the number of interruptions of the power supply for the customer (Druml *et al*., 2001).

To prevent and be able to secure risks related to an insufficient insulation or a degradation of the level of insulation, some measurements must be taken. They relate to the electric materials as well as installations on which they are connected. These measurements are carried out at the time of the start-up, on new or renovated elements, then periodically in order to judge their evolution in time. In distribution systems, some parameters (such as : Zero sequence voltage U_0, zero sequence current I_0 for each feeder) are measured easily with voltmeter or ammeter. But other parameters (such as: Capacitance and conductance to ground, etc.) are difficult to be measured directly (Zeng, 2005). In order to solve the problem, some techniques using resonance measurement are presented.

In this research, we propose a method for evaluation the parameters of insulation of an electrical supply network, by the insertion of a variable inductance between each phase and the ground, which makes it possible to eliminate in an effective way the watt fault current component and in consequence of ensuring the safety of the people and the material.

The compensation of earth capacitive currents is usually solved by a Petersen coil connected between the network neutral point and the ground potential or a Petersen coil inserted into the secondary winding of Bauch transformer (Druml *et al*., 2001; Druml, 2002). However, such systems do not allow compensation of the watt component of the earth fault current.

Furthermore, when using those systems, the earth fault current is increased by the Petersen coil current watt component due to inductance losses. Systems providing compensation of the watt component of the earth fault current are based on the principle of current injection (Martel *et al*., 2001; Jeff *et al*., 2001) (50 Hz current

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injection) into the auxiliary inductance winding, connected across the system neutral point and the ground potential. Such system being energy inefficient are not very common (Zak, 2006). The existing algorithms are described. Section 3 presents a description of warring and parameters determination technique.

Existing algorithms: Up to now mainly the following algorithms are used to determine the network parameters respectively to tune the Petersen-Coil. The relative change of the zero-sequence voltage is normally used as the criterion for the detection of a switching operation in the network.

Artificial earth fault: By measuring the current over the artificial earth fault location and searching for the minimum of the current by tuning the Petersen-Coil, the tuning point and the parameters of the equivalent network can be determined. This method is actually only used to check the quality of a control algorithm.

Search of max | U_{NE} |: This algorithm searches the maximum of the residual voltage. Improved versions of this algorithm determine additionally the network parameters by using the method (Druml *et al*., 2001). Alternative algorithms are using least-square techniques to estimate the network parameters already from a part of the resonance curve.

Least square based on | $1/U_{NE}$|: A lower sensitivity against disturbances can be reached by using an algorithm based on the inverse of the resonance curve (Druml, 2002; Druml *et al.*, 2001).

Locus diagram of U_0: This method is based on the fact that a circle can be constructed with only three points. This method assumes that the third point of the circle is the origin of the complex plane. A short detuning can be achieved for example by switching a capacity in parallel to the Petersen-Coil. This switching results in a second point of the locus diagram of U_{NE}. Measuring the voltage with amplitude and angle it is possible to construct the locus diagram.

50 Hz current injection: This algorithm is based on the idea to inject an artificial current into the neutral point of the system if there is no in symmetrical current from the natural unsymmetrical. The influence of the natural unbalance can be partly compensated by using a differential measurement from two time points. Equation 1 in combination with the coil position enables to determine the network parameters (Winter, 1993; Gernot and Olaf, 2005).

$$\underline{Y}_{CI} = \frac{d\underline{I}_{CI}}{d\underline{V}_{ne}} \approx Y_W + j(B_C - B_L) \quad (1)$$

Injection two frequencies: This method uses the injection of two currents with frequencies unequal to 50 Hz into the zero-sequence system for the calculation of the network parameters (Gernot and Olaf, 2005).

$$\underline{Y}_{CI-fn} = \frac{d\underline{I}_{CI-fn}}{d\underline{V}_{ne-fn}} \approx Y_W + j(\omega_n C - \frac{1}{\omega_n L_L}) \quad (2)$$

Using two different frequenciesand one gets two complex equations with three variables

Three-phase inductance method

Description: In this new grounding method inductances between each phase and the ground are connected. The wiring provides compensation of both the watt and capacitive current in the point of ground fault. In the case of a single line to earth condition, it allows equalization of phase voltages against the ground potential. The idea is to connect a variable reactance of inductive character between each network phase and the ground. The system does not require an artificial neutral; this technique permit to transform insulated neutral networks into compensated ones (Zak, 2006). The zero-sequence impedance of a compensated system has a very high magnitude. This high value permits us to ignore the positive- and negative-sequence impedances without significant loss of accuracy when evaluating single line-to-ground faults (Winter, 1993) (Fig.1).

For the derivation of the mathematical model, the following assumptions will be made (Fig. 1):

- The line-to-earth capacitances and conductance's are symmetrical and
- The line-unbalance (capacitive and ohmic) is reduced to phase 1.

Using the Kirchhoff rules, the following equation can be set up for the case

$$I_{TL} = I_1 + I_2 + I_3 \quad (3)$$

$$U_0 Y_{LT} = I_{TL} \quad (4)$$

$$(E_1 + U_0)Y_1 = I_1 \quad (5)$$

$$(E_2 + U_0)Y_2 = I_2 \quad (6)$$

$$(E_3 + U_0)Y_3 = I_3 \quad (7)$$

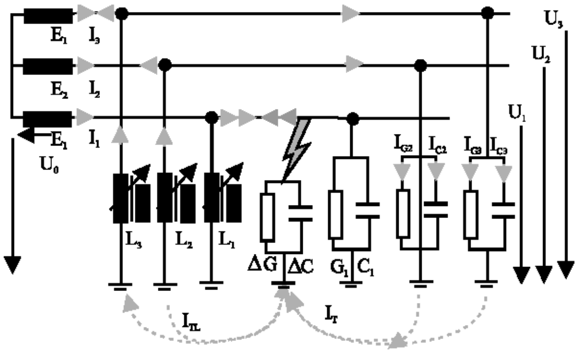

Fig. 1: Simplified representation for the three phase earth variable inductances

If we insert the Eq. 4 to 7, into the Eq. 3, we have:

$$U_0Y_{TL} = (E_1 + U_0)Y_1 + (E_2 + U_0)Y_2 + (E_3 + U_0)Y_3 \quad (8)$$

Assuming a symmetrical three-phase system and using the abbreviation $a = e^{j120°}$ with, $1 + a + a^2 = 0$ we can write the voltages E_2 and E_3 in the form and If the voltages $E_2 = a^2E_1$ and $E_3 = aE_1$ are replaced in the above Eq. 8, then we obtain:

$$U_0Y_{TL} = -U_0 (Y_1 + Y_2 + Y_3) + E_1 (Y_1 + a^2Y_2 + aY_3) \quad (9)$$

and after transformation:

$$\frac{U_0}{E_1} = \frac{Y_1 + a^2Y_2 + aY_3}{Y_1 + Y_2 + Y_3 + Y_{TL}} \quad (10)$$

Let the numerator of Eq. 10 be

$$\begin{aligned} Y_Z &= Y_1 + a^2Y_2 + aY_3 \\ &= (G + j\omega C)(1 + a^2 + a) + \Delta G + j\omega\Delta C \\ &= \Delta G + j\omega\Delta C \end{aligned} \quad (11)$$

The total admittance of the network is

$$\begin{aligned} Y_{n1} &= Y_1 + Y_2 + Y_3 \\ &= (3G + \Delta G) + j\omega(3C + \Delta C) \end{aligned} \quad (12)$$

And the total admittance of the three inductances is

$$Y_{TL} = Y_{L1} + Y_{L2} + Y_{L3} \quad (13)$$

If we add Y_{TL} to Y_{nl}, the Eq. 10 can be rewritten as:

$$\frac{U_0}{E_1} = \frac{\Delta G + j\omega\Delta C}{(3G + \Delta G + 3G_L) + j\omega(3C + \Delta C) - j\dfrac{3}{\omega L}}$$

or

$$\frac{U_0}{E_1} = \frac{Y_U}{Y_U + Y_W + j(B_C - B_L)} \quad (14)$$

with

$Y_U = \Delta G + j\omega\Delta C$: Unbalance admittance of the fault location

$Y_w = 3\omega C$: Watt metric part of Y_0

$B_c = 3\omega C$: Capacitive part of Y_0

$B_L = \dfrac{3}{\omega L}$: Inductive part of Y0

We represent the ground fault by connecting an equivalent Thevenin source in series with a resistance at the point of fault in the zero-sequence network. Figure 2 shows an approximate zero-sequence representation of a ground fault in the system depicted in Fig. 1.

The circuit is described by Eq. 14 and it is valid for low ohmic single line-to-earth-faults as well as for the natural capacitive unbalance of the sound network provided that the previous assumptions are satisfied.

Obtaining resonance characteristics: By the variation of the variable phase to earth inductances values of the sound phases, the susceptance changes, this leads to the variation of the voltage ratio Eq.14. Figure 3 present the resonance characteristic (the absolute voltages ratio in function of the current position) is presented.

The zero sequence voltage is maximal, if the susceptances in the denominator are cancelled mutually. In the other cases, either capacitive or inductive proportion adds itself, so that the zero sequence voltage becomes smaller. In practice, the zero sequence voltage U_0 is usually logarithmically scaled, in order to identify small values of U_0 or its variation Fig. 4.

Usually, the inductance of the coils is indicated indirectly in (A)$(I_{pos} = B_L E1)$. The current flowing in the inductance-coil depends in case of a ground fault on the error resistance and on the other hand of a high impedance ground fault substantially smaller.

Figure 5 shows the locus diagram of the zero sequence voltage U_0 at the fault location as a function of the inductance-coil position I_{pos}.

In the above representation at some points, the appropriate coil position was be added. The resonance curve of the sound network can be describted by the following three parameters:

U_{res}: Maximum voltage of the resonance curve
I_{res}: Corresponding coil position to U_{res}
I_w: Watt metric current over the fault location in the case of a low ohmic earth-fault

These parameters can be determined from the resonance curve. At the resonance point ($B_L = B_C$) (Eq. 14) simplifies to:

$$U_{res} = E_1 \frac{Y_U}{Y_U + Y_W} \quad (15)$$

Network capacitive current compensation: No current is passing during an earth fault through the corresponding

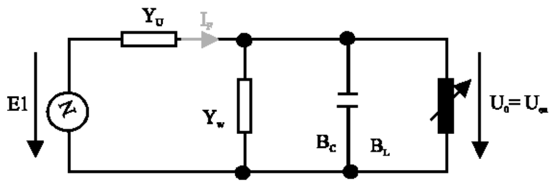

Fig. 2: Zero-sequence representation of a ground fault in Fig. 1

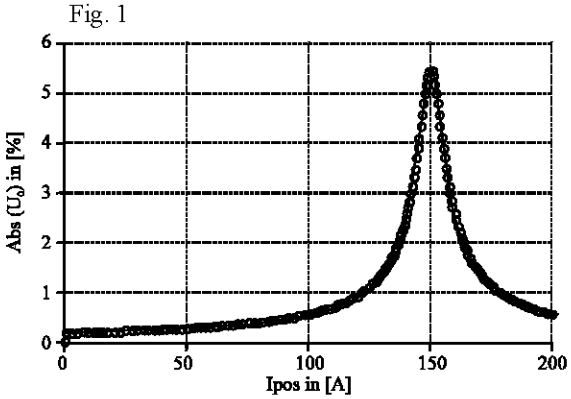

Fig. 3: Resonance characteristic

phase to earth reactor. The both remaining phase to earth reactance acquire a line-to-line voltage to the ground. The value of the earth capacitance current in both sound phases is $\sqrt{3}$ times increased too (Zivanovic, 2004; Zak, 2006). When a failure on the phase 1 occurs, the phase *2* being the next one after the faulty phase regarding the phase sequence, then we have:

$$\underline{I}_{L2} = I_{L2} e^{j\alpha} \quad (16)$$

the phase *3* being the next after the faulty phase in the counter sense of the phase sequence, then :

$$\underline{I}_{L3} = I_{L3} e^{-j\alpha} \quad (17)$$

knowing that $I_{L2} = I_{L3}$

$$\underline{I}_{L2} + \underline{I}_{L3} = 2 I_{L2} \cos\alpha = I_L \quad (18)$$

Taking into account the total wattmetric current I_{TL} in the inductances, the total current passing through phase to earth total inductance can be written as:

$$\underline{I}_{RL} + \underline{I}_{L2} + \underline{I}_{L3} = \underline{I}_{RL} + \underline{I}_L = I_{TL} e^{j\theta} \quad (19)$$

The total current in the network is

$$\underline{I}_G + \underline{I}_C = I_T e^{j\beta} \quad (20)$$

Even during the earth fault, the parallel resonance circuit remains permanently tuned. Through the earth fault point (GND) the same total inductive current I_L of phase

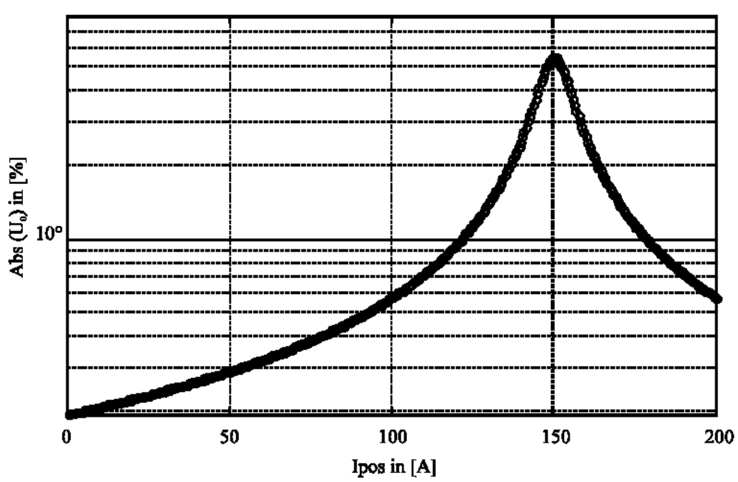

Fig. 4: Resonance characteristic logarithmic

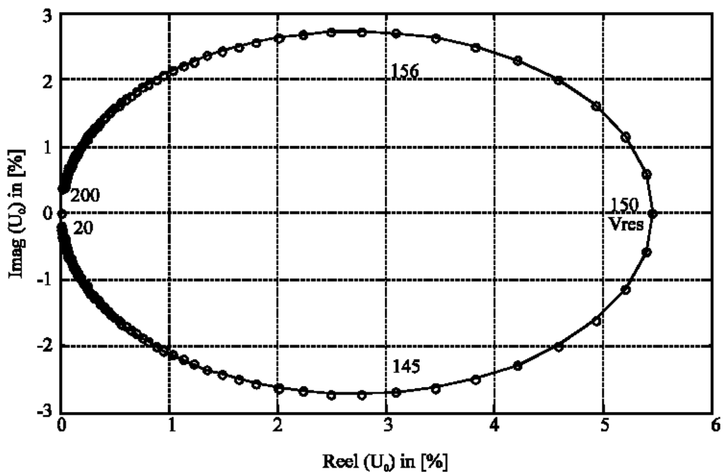

Fig. 5: Locus diagram of the zero sequence voltage U_0

earth reactance as well as the total network capacitance current I_C is flowing. Because the total inductive current I_C of phase earth reactance and the total network capacitance current are eliminating each other.

$$I_F = I_{RL} + I_G + I_L - I_C \text{ then}$$

$$\underline{I}_F = \underline{I}_{RL} + \underline{I}_G + (\underline{I}_L + \underline{I}_C) \tag{21}$$

The earth fault point (GND) is carrying only the total network watt leakage current and the watt current of phase earth inductance. The occurrence of the watt current I_{RL} is caused by watt losses within their magnetic circuits and windings (Zak, 2006) and then finally we have:

$$I_F = I_G + I_{RL} \tag{22}$$

The phasor diagram of Fig. 1 for a SLE with $Y_F = \Delta G + j\Delta C = \infty$ or $Z_F = 0\ \Omega$ is depicted in Fig. 6.

Watt current component compensation: The watt fault current component of a ground fault can be eliminated, through variation of phase to earth inductances in phases 2 and 3. The variation of the values of the inductances, as it has been described previously in Eq. (16,17) leeds to the increase of the current I_{L3} by ΔI_L

$$\underline{I}'_{L3} = (I_{L3} + \Delta I_L)e^{-j\alpha} \tag{23}$$

as well as the decrease of the current by I_{L2} by ΔI_L

$$\underline{I}'_{L2} = (I_{L2} - \Delta I_L)e^{j\alpha} \tag{24}$$

$$\underline{I}'_{L2} + \underline{I}'_{L3} = -j2\Delta I_L \sin\alpha + 2I_{L2}\cos\alpha \tag{25}$$

$$\text{With } -2\Delta I_L \sin\alpha = -I_R \text{ and } 2I_{L2}\cos\alpha = I_L \tag{26}$$

Taking into account the total wattmetric current in the inductances, the total current passing through phase to earth total inductance can be written as:

$$\underline{I}'_{L2} + \underline{I}'_{L3} + \underline{I}_{RL} = (I_{RL} - I_R) + I_L = I_{TL}e^{-J\beta} \tag{27}$$

Consequently, the vector of current through phase to earth inductance will contain a component of blind current I_{LT}, having the same current I_L value as the total network capacitance current I_c, as well as the watt current-I_R component, having opposite orientation than the network leakage current I_G. The watt component of the current I_{TL}then compensates the watt component of the network leakage current. In case of a substantial shift of the total current due to phase to earth reactance, even an inversion of the watt component current flow in the ground fault point can be occur (Fig. 7).

We have a total compensation, if there is no current flowing at the ground fault point, so

$$I_G + I_{RL} - I_R + (I_L - I_C) = 0 \tag{28}$$

$$I_G + I_{RL} - I_R = 0 \tag{29}$$

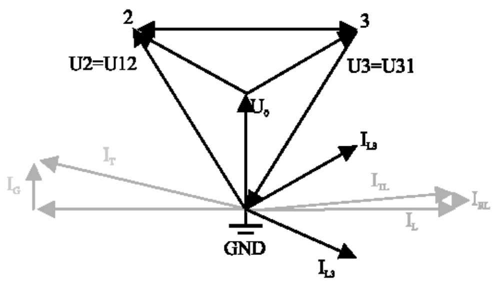

Fig. 6 : Phasor diagram for a Single Line-to-Earth-fault (SLE) with $Z_F = 0\ \Omega$

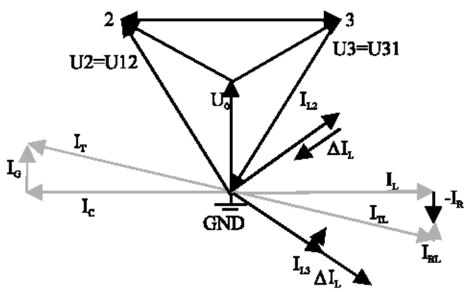

Fig. 7: Phasor diagram for compensation watt and capacitive current

In this case, the watt current component has been determined at the resonance point. In the previously methods(Druml *et al.*, 2001) this is done at approximately of the resonance point.

CONCLUSION

In this method, the parameters of insulation are determined in an ungrounded distribution system with three phases to earth variable inductances. This proceeding manner allows us to:

- Satisfy the assumption of a network unbalancing voltage by using capacitor batteries in the secondary winding of the variable inductances.
- Transform the insulated neutral network into compensated network.
- Determine at the resonance, the zero sequence network parameters during an earth fault under steady state free conditions.
- Compensate leakage current in addition to the compensation of the capacitive currents, therefore the equalization of the phase to ground voltage to the ground potential in the fault point, consequently the complete elimination of the ground fault current.

Finally, the fact of placing the three phases to earth variable inductances makes the distribution network more tolerant to the ground faults.

Variables and parameters used in this study.

ΔC, ΔG	:	Unbalance (capacitance, conductance)
C_1, C_2, C_3	:	Line-to-earth capacitances;
L_1, L_2, L_3	:	Line-to-earth inductances;
Y_1, Y_2, Y_3	:	Line-to-earth admittances
Y_{TL}	:	Total admittance of the three inductances
Y_{nI}	:	Total admittance of the network
EI, E2, E3	:	Phase voltage;
U1, U2, U3	:	Line voltages
U_0	:	Zero sequence voltage
I_F	:	Current at the fault location
I_1, I_2, I_3	:	Lines current
I_{C1}, I_{C2}	:	Capacitive currents of the two sound lines
I_{G1}, I_{G2}	:	Leakage currents of the two sound lines
I_{L1}, I_{L2}	:	Inductive currents of the two sound lines
I_T, I_L	:	Total current (network, inductances)
I_C, I_L	:	Total current (capacitive, inductive)
I_G, I_{RL}	:	Total current wattmetric (network, inductances)
ΔI_L	:	Current variation in inductances
α, θ, β	:	Current angles (I_{L2}, I_{TL}, I_T, respectively).

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