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Detection of Broken Conductor with Ground Contact Faults in Medium Voltage Power Networks

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Abstract: A major problem concerning the operation of medium voltage power networks refers to the neutral-point grounding system. Several technical solutions are in use, none of them being completely satisfactory. One criterion to appreciate the efficiency of a grounding system is the ability of the network's protective system to accurately detect various types of faults, such as broken conductor with ground contact faults. This type of fault make a relatively important figure (3 to 10 %) in the total faults statistics for a medium voltage network. In order to detect such faults, the sensed variables are the zero-sequence voltage and the neutral-grounding current. In this paper an analytical and computational analysis is performed to see how various fault and network parameters affect these variables, assuming different grounding systems. Measurements made in two real medium voltage networks show good agreement with the theoretical results.

Keywords: Medium voltage power network, broken conductor with ground contact fault.

1 Introduction

The fault impact on the electrical network is usually analyzed by numerical simulation, to include the transients in the analysis. This simulations show that, except for a few moments after the fault occurrence, the voltages and the currents are mainly harmonic and therefore a steady-state analysis can be performed [1], [2]. Such an analysis will be done in this paper, focusing on the influence of various parameters, like the fault resistance R_t, the capacitive current I'_C of the line behind the fault, the total capacitive current I_C of the network, the apparent power S_C of the consumer

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fed by the faulty line , and the consumer's negative-sequence impedance Z_{Ci} on the zero-sequence voltage and neutral-point grounding current.

Figure 1 shows the single-line diagram of the analized network, where Tr is the 110/20 kV substation transformer, $L_1, L_2, \ldots$ are the 20 kV lines, TSI is the internal service transformer, also used to creat the neutral point, Z_n is the neutral-point grounding impedance, SI are the internal services, and R_t is the fault resistance. The zero-sequence voltage at the 20 kV transformer bus for not-grounded,

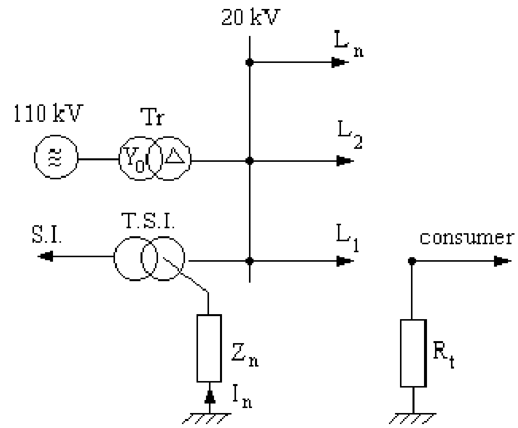

Fig. 1. Single-line diagram of the faulty network.

respectively for reactor-grounded networks, will be analytically computed. For a resistor-grounded network, the grounding current will also be calculated.

2 The Mathematical Model

The analysed type of fault may be seen as being a superposition of two single faults, namely a single-line interruption and a single-phase shortcircuit. Consequently, the faulty network can be partitioned into three symmetrical subnetworks (denoted A, B, and C in Figure 2), linked by two nonsymmetrical impedances which implement the fault: A is on the generator side, B is on the consumer side, C is the ground equivalent network; $\underline{\mathbf{Z}}_{a1a2}$ and $\underline{\mathbf{Z}}_{b2b3}$ are the sequence matrices of the linking impedances [3].

At nodes a_1, a_2 and b_2 the following equation can be written [3–5]:

$$\begin{bmatrix} \underline{\boldsymbol{U}}_{ea1} - \underline{\boldsymbol{U}}_{ea2} \\ \underline{\boldsymbol{U}}_{eb2} - \underline{\boldsymbol{U}}_{eb3} \end{bmatrix} = \begin{bmatrix} \underline{\mathbf{Z}}_{a1a2} + \underline{\mathbf{Z}}_{a1a1} + \underline{\mathbf{Z}}_{a2a2} & -\underline{\mathbf{Z}}_{a2b2} \\ -\underline{\mathbf{Z}}_{a2b2} & \underline{\mathbf{Z}}_{b2b2} + \underline{\mathbf{Z}}_{b2b3} \end{bmatrix} \begin{bmatrix} \underline{\boldsymbol{I}}_{a1a2} \\ \underline{\boldsymbol{I}}_{b2b3} \end{bmatrix}, \quad (1)$$

where $\underline{\boldsymbol{U}}_{ek}$ is the sequences column matrix of e.m.f. at node k $(k = a_1, a_2, b_2, b_3)$, $\underline{\mathbf{Z}}_{kk}$ the sequences matrix of impedances as seen from node k, and $\underline{\boldsymbol{I}}_{a1a2}$, $\underline{\boldsymbol{I}}_{b2b3}$ are

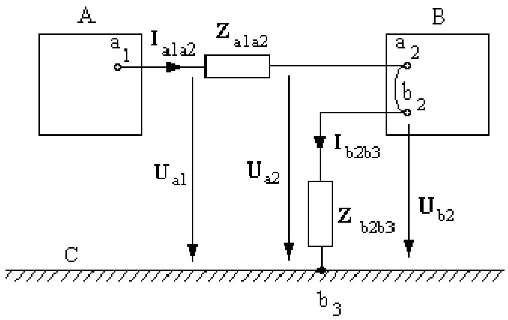

Fig. 2. Equivalent circuit of the faulty network.

the sequences matrices of the corresponding currents. After some transformations, Eq.(2) becomes

$$\begin{bmatrix} \underline{\boldsymbol{U}}_e \\ \boldsymbol{0} \end{bmatrix} = \begin{bmatrix} \underline{\boldsymbol{Z}}_S + \underline{\boldsymbol{Z}}_C + \underline{\boldsymbol{Z}}_1 & -\underline{\boldsymbol{Z}}_C \\ -\underline{\boldsymbol{Z}}_C & \underline{\boldsymbol{Z}}_2 + \underline{\boldsymbol{Z}}_C \end{bmatrix} \begin{bmatrix} \underline{\boldsymbol{I}}' \\ \underline{\boldsymbol{I}} \end{bmatrix}, \tag{2}$$

where $\underline{\boldsymbol{Z}}_S = \underline{\boldsymbol{Z}}_{a1a1}, \underline{\boldsymbol{Z}}_C = \underline{\boldsymbol{Z}}_{a2a2}, \underline{\boldsymbol{Z}}_1 = \underline{\boldsymbol{Z}}_{a1a2}, \underline{\boldsymbol{Z}}_2 = \underline{\boldsymbol{Z}}_{b2b3}, \underline{\boldsymbol{I}} = \underline{\boldsymbol{I}}_{b2b3}, \underline{\boldsymbol{I}}' = \underline{\boldsymbol{I}}_{a1a2}$ and $\underline{\boldsymbol{U}}_e = \underline{\boldsymbol{U}}_{ea1}$. The matrix $\underline{\boldsymbol{Z}}_2$ is of the form

$$\underline{\boldsymbol{Z}}_2 = \begin{bmatrix} \underline{Z}_{2h} & \underline{Z}'_2 & \underline{Z}'_2 \\ \underline{Z}'_2 & \underline{Z}_{2d} & \underline{Z}'_2 \\ \underline{Z}'_2 & \underline{Z}'_2 & \underline{Z}_{2i} \end{bmatrix}. \tag{3}$$

Solving Eq.(2) for the zero-sequences of the currents, and assuming $Z_{Ch} \to \infty$, after some transformations we get

$$\underline{I}_h = \underline{I}' = \frac{\underline{b}_5 (\underline{U}_{Cd} - \underline{U}_{Ch}) - \underline{b}_6 (\underline{U}_{Ci} - \underline{U}_{Ch})}{\underline{b}_1 \underline{b}_2 - \underline{b}_3 \underline{b}_4}, \tag{4}$$

where

$$\underline{b}_1 = \underline{Z}_{Sd} + \underline{Z}_{Sh} + \underline{Z}_{Cd} - \underline{Z}_{Cd} \frac{\underline{Z}_{Cd} (\underline{Z}_{2d} + \underline{Z}_{Ci}) - 2\underline{Z}'_2 (\underline{Z}'_2 - \underline{Z}_{Ci} - \underline{Z}_{2d})}{(\underline{Z}_{Cd} + \underline{Z}_{2d})(\underline{Z}_{Ci} + \underline{Z}_{2d}) - \underline{Z}'^2_2},$$

$$\underline{b}_2 = \underline{Z}_{Sh} + \underline{Z}_{Si} + \underline{Z}_{Ci} - \underline{Z}_{Ci} \frac{\underline{Z}_{Ci} (\underline{Z}_{Cd} + \underline{Z}_{2d}) - 2\underline{Z}'_2 (\underline{Z}'_2 - \underline{Z}_{Cd} - \underline{Z}_{2d})}{(\underline{Z}_{Cd} + \underline{Z}_{2d})(\underline{Z}_{Ci} + \underline{Z}_{2d}) - \underline{Z}'^2_2},$$

$$\underline{b}_3 = \underline{Z}_{Sh} + 2\underline{Z}'_2 \frac{\underline{Z}_{Cd} (\underline{Z}'_2 - \underline{Z}_{2d}) + \underline{Z}_{Ci} (\underline{Z}'_2 - \underline{Z}_{Cd} - \underline{Z}_{2d})}{(\underline{Z}_{Cd} + \underline{Z}_{2d})(\underline{Z}_{Ci} + \underline{Z}_{2d}) - \underline{Z}'^2_2},$$

$$\underline{b}_4 = \underline{Z}_{Sh} + \underline{Z}'_2 \frac{\underline{Z}_{Cd} (\underline{Z}'_2 - \underline{Z}_{2d}) + \underline{Z}_{Ci} (\underline{Z}'_2 - \underline{Z}_{Cd} - \underline{Z}_{2d})}{(\underline{Z}_{Cd} + \underline{Z}_{2d})(\underline{Z}_{Ci} + \underline{Z}_{2d}) - \underline{Z}'^2_2},$$

$$\underline{b}_5 = -\underline{Z}_{Si} - \underline{Z}_{Ci} + \frac{\underline{Z}'_2 (\underline{Z}'_2 - \underline{Z}_{2d})(\underline{Z}_{Cd} - \underline{Z}_{Ci}) + \underline{Z}_{Ci} \underline{Z}_{Cd} (\underline{Z}'_2 + \underline{Z}_{Ci}) + \underline{Z}^2_{Ci} \underline{Z}_{2d}}{(\underline{Z}_{Cd} + \underline{Z}_{2d})(\underline{Z}_{Ci} + \underline{Z}_{2d}) - \underline{Z}'^2_2},$$

$$\underline{b}_6 = -\underline{Z}_{Sd} + \underline{Z}_{Cd} + \frac{\underline{Z}'_2\left[\left(\underline{Z}'_2 - \underline{Z}_{2d}\right)\left(\underline{Z}_{Cd} - \underline{Z}_{Ci}\right) - \underline{Z}_{Ci}\underline{Z}_{Cd}\right] + \underline{Z}^2_{Cd}\left(\underline{Z}_{2d} + \underline{Z}_{Ci}\right)}{\left(\underline{Z}_{Cd} + \underline{Z}_{2d}\right)\left(\underline{Z}_{Ci} + \underline{Z}_{2d}\right) - \underline{Z}'^2_2}.$$

Usually, the positive- and negative-sequence reactances of electrical drives are different [6]. As it is difficult to evaluate how many electrical drives are fed by the faulty line, the negative-sequence reactance of the consumer is expressed as a fraction of the positive-sequence reactance, $X_{Ci} = kX_{Cd}$, where $k = 1$ for a purely static load. Eventually, the neutral-grounding current $\underline{I}_n$ and the zero-sequence voltage $\underline{U}_{hb}$ on the 20 kV bars can be expressed as follows:

$$\begin{aligned} \underline{I}_n &= -3\frac{jX_C}{\underline{Z}_{hTSI} + 3\underline{Z}_n - jX_C}\underline{I'}_h, \\ \underline{U}_{hb} &= -\frac{jX_C\left(\underline{Z}_{hTSI} + 3\underline{Z}_n\right)}{\underline{Z}_{hTSI} + 3\underline{Z}_n - jX_C}\underline{I'}_h, \end{aligned} \tag{5}$$

where $\underline{Z}_{hTSI}$ is the zero-sequence impedance of the grounding reactor, $\underline{Z}_n$ is the impedance of the neutral-point grounding system; the zero-sequence current $\underline{I'}_h$ is given by Eq.(4).

3 The Dependence of U_{hb} and I_n on the Fault Parameters

The quantities needed for computing U_{hb} and I_n depend on the following fault parameters: the fault resistance R_t, the capacitive current I'_C of the line behind the fault, the total capacitive current I_C of the network, the apparent power S_C of the consumer fed by the faulty line, and the consumer's negative-sequence impedance Z_{Ci}. In the following, the fault resistance is taken as the independent variable. The zero-sequence voltage is determined at the secondary winding of the zero-sequence filter. The numerical values needed for computing U_{hb} and I_n are the following [1], [7], [2]: pre-fault line voltage at the fault location 20 kV, source impedance (110/20 kV, 25 MVA transformer) $\underline{Z}_S = (0.1 + 2.1j)$ Ω, line impedance up to the fault location (2 km overhead line) $\underline{Z}_{Ld} = \underline{Z}_{Li} = (1.16 + 0.76j)$ Ω, $\underline{Z}_{Lh} = (1.46 + 2.28j)$ Ω, impedance of the neutral-point grounding reactor $\underline{Z}_n = (0.5 + 105.8j)$ Ω, zero-sequence impedance of the internal services transformer $\underline{Z}_{hTSI} = (2.78 + 8.35j)$ Ω, power factor of the consumer $\cos\varphi = 0{,}98$, pre-fault zero-sequence voltage at medium voltage busbars $U_{eh} = 153$ V (negative-sequence voltage assumed to be zero), resistance of the neutral-point grounding resistor $38{,}5$ Ω, apparent power of the consumer fed by the faulty line $S_C = 1076$ kVA.

Figure 3 and 4 show the dependence of zero-sequence voltage U_{hb} on the fault resistance R_t if the neutral is grounded via a reactor operating at resonance, respectively overcompensated 14%. It can be seen that the structure of the consumer

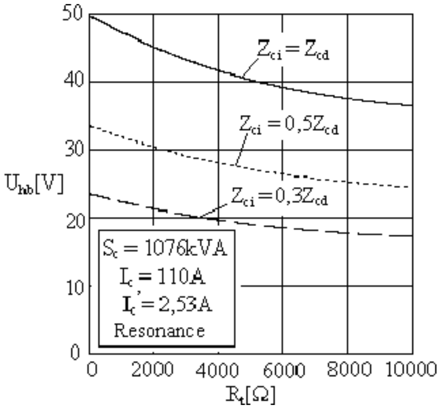

Fig. 3. Zero-sequence voltage as function of the fault resistance for a reactor-grounded network, operating at resonance.

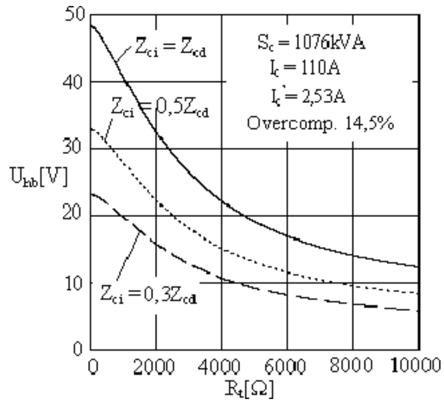

Fig. 4. Zero-sequence voltage as function of the fault resistance for a reactor-grounded network, operating overcompensated 14.5%.

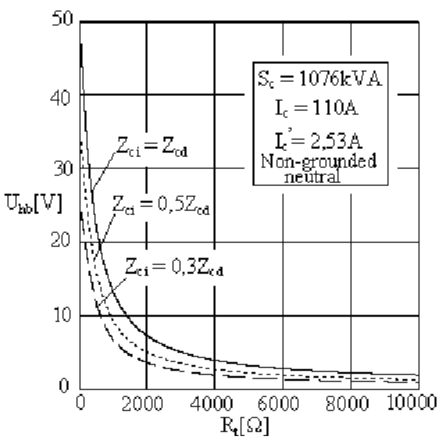

Fig. 5. Zero-sequence voltage as function of the fault resistance for a not-grounded network.

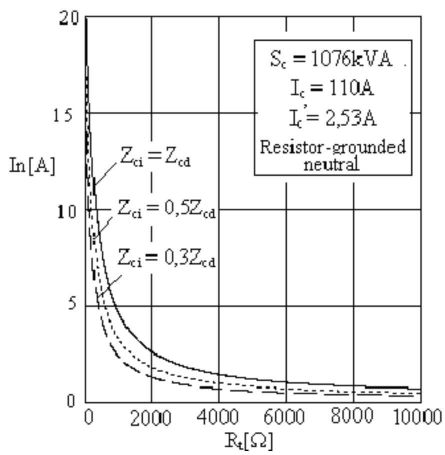

Fig. 6. Grounding current as function of the fault resistance for a resistor-grounded network.

highly affects the value of U_{hb}. For a not-grounded network, respectively a network grounded via a resistor, the structure of the consumer is of less importance, as can be seen from figures 5 and 6. On the other hand, for such networks, a more importance has the fault resistance.

4 Fault Detection

Usually, medium-voltage networks have zero-sequence voltage protection in order to detect nonsymmetrical faults. This protection senses the voltage on the secondary winding of a zero-sequence filter placed on the medium-voltage bars in the transformer substation. According to regulations in use, the maximal-voltage relay controll voltage must be at least 15 V. As Figure 3 shows, in medium-voltage networks grounded via a reactor operating at resonance, broken-conductor and grounded towards the consumer faults can be detected by the zero-sequence voltage protection even if the fault resistance exceeds 10 $k\Omega$. If the operating regime is overcompensated, and the the consumer consists mainly from asynchronous motors, such a fault can be detected only if $R_t < 2000\ \Omega$ (Fig.4), respectively $R_t < 500$ Ω, if the neutral is isolated (Fig.5). More recently, zero-sequence voltage protections use digital relays. The digital protection BHT-10a, presented in [8], needs an input voltage of at least 4 V. As Figures 3 to 5 show, broken-conductor faults can be detected up to $R_t = 2000\ \Omega$, for the considered grounding systems. The zero-sequence voltage protection is used for signalization purpose only, the broken line being detected by successively disconnections of the medium-voltage lines. This is a time-consuming process, which also implies a lot of manipulations and disconnection of the customers. A sensitive directional protection, BHAC1, is presented in [8], which senses the zero-sequence voltage on the secondary winding of zero-sequence filter, the zero-sequence current on each of the medium-voltage lines, and the phase difference between voltages and currents on each medium-voltage line. The detection is based on the fact that the zero-sequence current for the faulty line is of opposite direction as compared with the zero-sequence currents in the healty lines. This criterion allowes a fast detection, and consequently disconnection, of the faulty line. The minimum values required by BHAC-1 are 2 V, respectively 25 mA. Figure 7 shows an implementation of protective blocks BTH-10 and BHAC-1 in a medium-voltage network.

From calculations results that the zero-sequence current for the broken line, in the secondary winding of a current transformer having a transformation ratio of 20, is less than 15 mA. Hence, a broken-conductor with ground contact fault cannot be detectect with the common protections.

The zero-sequence current in the secondary winding of a current transformer, with a transformation ratio of 10, as function on the fault resistance R_t, is shown in Figure 8. It follows that a broken-conductor with ground contact fault can be selectively detected if the neutral is grounded via a reactor operating at resonance, as long as $R_t < 1000\ \Omega$.

5 Experimental results

The results from analysis were compared with measurements performed in two medium-voltage networks. The first network is a reactor grounded network, with a

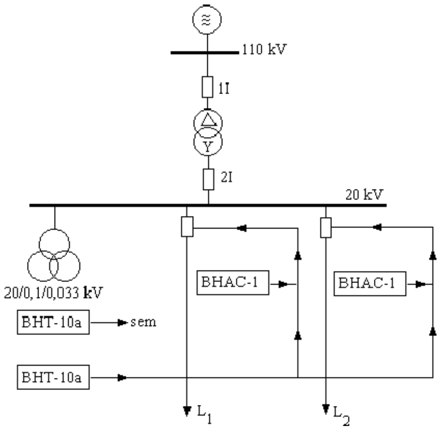

Fig. 7. Implementation of the BTH and BHAC protections in a medium-voltage network.

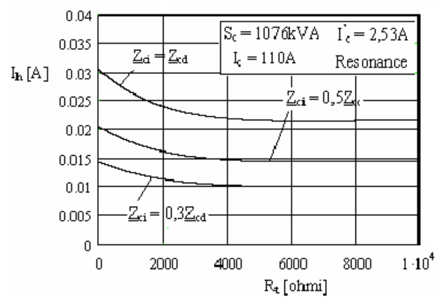

Fig. 8. Zero-sequence current as function of the fault resistance for a reactor-grounded network, operating at resonance.

measured total capacitive current of 110 A. Two reactors, each having the current adjustable in the range 10 - 110 A, were used to compensat this capacitive current. The fault was provoked on a 20 kV line, with a 3 A capacitive current, 4825 m far away from the substation's medium-voltage busbars. The measured values are given in Tab.1, for $\underline{Z}_{Sd} = \underline{Z}_{Si} = 0.1 + 2.1j\ \Omega$, $\underline{Z}_{hTSI} = 2.28 + 8.39j\ \Omega$, $\underline{Z}_{Ld} = \underline{Z}_{Li} = 2.94 + 1.8j\ \Omega$, $\underline{Z}_{Lh} = 3.18 + 5.4j\ \Omega$, and $I'_C = 2.53$ A. It can be seen that the zero-sequence voltage is lower than the sensitivity level of the classical ground contact sensing relay RPP, and therefore the fault cannot be detected.

Table 1. Reactor-grounded network.

S_C [kVA]	R_t [Ω]	U_R [V]	U_S [V]	U_T [V]	$(U_{hb})_c$ [V]	$(U_{hb})_m$ [V]	ε [%]	Oper. reg.
1076	50	55.2	79.4	46	45	40.8	10.3	Reson.
1076	50	64	77	46.2	35	34.7	0.8	Overc.
1076	8000	67.1	63.3	56	14.1	15.5	9	Overc.
816	8000	59	65.5	50	13.8	14.5	4.8	Overc.
816	5000	58.8	69.4	46.3	20.8	21.6	3.7	Overc.

Experiments on real networks, made in different conditions, clearly show that RPP relays do not detect ground contacts in networks with grounded neutral but in very particular conditions. Ground contact faults in medium-voltage networks are nonselectively detected by zero-sequence voltage protective relays connected at the substation's busbars. The minimum-voltage relay is usually set at 15 V, with no possibility to lower this value for the in use RPP relays. For a proper ground contact fault detection it would be necessary at least a level of $(5-10)$ V, condition fulfilled by the "Digital Protective Block BHT 10a" , which has a level setting range of $(5...20)$ V [9]. The second network has the neutral grounded via a resistor, and a measured total capacitive current of $103,4$ A. The results are shown in Tab.2.

Table 2. Resistor-grounded network.

R_t [Ω]	S_C kVA	I'_C [A]	$(I_n)_m$ [A]	$(I_n)_c$ [A]	ε %
2.6	63	6.98	1.6	1.71	6.9
5000	63	1.77	0.83	0.92	10.8
10000	63	1.77	0.71	0.78	9.8
5000	563	1.77	1.28	1.34	4.7
10000	563	0.46	0.52	0.53	1.9

The measurements revealed that the RPP can detect high R_t faults. Therefore, resistor grounded networks are better protected than reactor grounded networks against broken-conductor with ground contact faults.

The computed and measured results are in good agreement with each other, for the assumed precision level of the system's parameters.

6 Conclusion

The performed analysis shows the zero-sequence voltage on the medium voltage busbars and the neutral-point grounding current, during a broken conductor with ground contact on the consumer's side fault, are affected as follows:

- the fault resistance R_t significantly affect the zero-sequence voltage in not-grounded network, or grounded via a resistor;
- in networks with the neutral grounded via a reactor operated at resonance, the apparent power fed by the faulty line has litlle effect on the zero-sequence voltage if $Z_{Ci} = Z_{Cd}$; however, the effect is significantly greater if $Z_{Ci} < Z_{Cd}$;
- for not-grounded networks, an increase of the consumed power yields an increase of the zero-sequence voltage;
- for networks grounded via a resistor, at low consumed power, the structure of the consumer practically has no influence on the grounding current; however, for increased consumed power, lower values for Z_{Ci} yield lower values for the current;
- in a reactor-grounded network, operated at resonance, a lower value for the capacitive current of the line section behind the fault means a lower value for the zero-sequence voltage;

- the total capacitive of current I_C of the medium voltage network has a less pronounced effect on U_{hb}. Thus, by reducing I_C from 100 A to 50 A, U_{hb} reduces with 5.5 % if $Z_{Ci} = Z_{Cd}$, with 1.9 % if $Z_{Ci} = 0.5Z_{Cd}$, respectively 1.4 % if $Z_{Ci} = 0,3Z_{Cd}$.

In most $110/20$ kV transformer substations, for reactor-grounded networks, respectively not-grounded networks, nonselective detection of grounding faults are performed by sensing the voltage on the secondary winding of a zero-sequence filter connected at the medium-voltage busbars. The minimum voltage level for this protective device is 15 V, and consequently broken conductor with ground contact can be detected only in few situations. Selective grounding detection is performed using RPP type relays. Measurements in real networks showed again that only in few situations broken conductor with ground contact have been detected by these devices. We conclude that such faults cannot be properly detected, if the neutral-point of the network is grounded via a reactor.

The situation is even worse for not-grounded networks, as in this case the zero-sequence voltage is less than the sensing level of the relay.

Resistor-grounded networks are provided with protective devices which can selectively detect faults that causes a zero-sequence current of minimum 3 A. Therefore, broken conductor with ground contact on the consumer's side faults can be selectively detected in most situations in this networks.

For not-grounded medium-voltage networks, or grounded via a reactor, to make the period in wich the broken conductor stays in touch with the ground as short as possible, high sensitivity protective devices are necessary. Protective devices with low minimum-voltage level, like the Digital Protective Block BHT-10a, make possible proper detection of broken conductor with ground contact faults in a large variety of situations.

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