

Determination of Insulation Active Component of an Insulated Neutral Electrical Supply Network

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Abstract

During the insulation testing of an electrical supply network having isolated neutral, the capacitive component does not allow us to know the state of the cable insulation. On the other hand it is the testing of the active component that helps in the electrical danger elimination in case there is an insulation failure. The current leak being a function of the active and capacitive component that could cause the disconnection of the electrical network even in the absence of faults. A compensation of the network capacitive effect gives the possibility to measure the resistive current leak. The experimental electrical circuits built allowed us to define the whole combinations between the leakage resistance (single-phase, double-phase and three-phase) and the different levels of insulation of the network with respect to earth. The obtained results give an insight into the domains sensitivity of the protection circuits of the insulation active component while keeping the leakage current at safe value of 10 mA.

Keywords

Electrical insulation, leak current, leak resistance, harmless current, protection devices.

1. Introduction

The leak current capacitive component I_f influences the systems sensitivity and activates the protections without the real existence of a fault or an isolation degradation. J.M. Buckley (2006). The problem is to find a solution that can eliminate the capacities influence and define the insulation system sensitivity domains by taking into account the active component alone. The harmless current $I_{inof} = 10mA$ is fixed for an individual of low resistance of about 1000Ω under a safe voltage U_s . (A. Sabot and J. Michaud .1997). By taking the condition $I_f = I_{inof}$ (Harmless current), we determine the leak resistances set in function of insulation $R_f = f(r)$ defining the insulation level sensitivity domains protection system. Thus, the model proposed helps to ensure, on the one hand, operation of an electrical network without taking into account the physical quantity of the capacitive component of a leakage current due to a branch of the network and on the other hand disconnect the network if the isolation level allows the appearance of an active component of a leakage current exceeding that harmless.

2. Minimum Safe Active Component of Networks Insulation

2.1 Short electrical networks

In this case the network capacity is negligible and in case of a direct individual contact with phase A of a tree phase network, the system is not unbalanced anymore and the voltage of each phase with respect to earth is:

$$U_A = U_1 - U_O = AO'; \quad U_B = U_2 - U_O = BO'; \quad U_C = U_3 - U_O = CO' \quad (1)$$

where

- U_O : The unbalanced network voltage
- $U_1 = AO, U_2 = BO$ and $U_3 = CO$ are the simple network voltages.

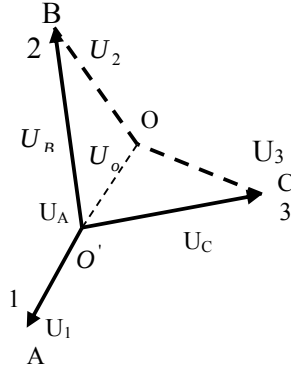


Figure 1. Diagram of a system unbalanced voltages

The current going into the insulation $r_A = r_B = r_C = r$ could be determined by the expression:

$$I_A = \frac{U_A}{r_A} = \frac{U_1 - U_O}{r_A} ; \quad I_B = \frac{U_B}{r_B} = \frac{U_2 - U_O}{r_B} ; \quad I_C = \frac{U_C}{r_C} = \frac{U_3 - U_O}{r_C} \quad (2)$$

And the current going into the individual:

$$I_h = \frac{U_A}{R_h} = \frac{U_1 - U_O}{R_h} \quad (3)$$

In the tree phase network with isolated neutral and according to KIRCHOFF law

$$\sum I = I_A + I_B + I_C + I_h = 0 \quad (4)$$

And we have :

$$\frac{(U_1 - U_O)}{r} + \frac{(U_2 - U_O)}{r} + \frac{(U_3 - U_O)}{r} + \frac{(U_1 - U_O)}{R_h} = 0 \quad (5)$$

Or

$$\frac{(U_1 + U_2 + U_3)}{r} - \frac{3U_O}{r} + \frac{(U_1 - U_O)}{R_h} = 0 \quad (6)$$

Having $U_1 = U_2 = U_3 = U$ in the tree phase network with isolated neutral their geometrical sum is zero $U_1 + U_2 + U_3 = 0$, in this case the previous expression becomes :

$$\frac{(U_1 - U_O)}{R_h} - \frac{3U_O}{r} = 0 \quad (7)$$

So the unbalanced network voltage will be:

$$U_O = \frac{Ur}{3R_h + r} \quad (8)$$

The voltage of phase A with respect to earth will be:

$$U_A = U_1 - U_O = \frac{3UR_h}{3R_h + r} \quad (9)$$

And the final expression of the current going into the individual will be:

$$I_h = \frac{U_A}{R_h} = \frac{3U}{3R_h + r} \quad (10)$$

This expression shows that in a network with isolated neutral, in a negligible line capacity, the value of the insulation active resistance represents a very important parameter in the safe conditions.

By respecting the condition $I_h \leq I_{inof}$, we the minimum safest value of the insulation level r_{inoff} :

$$r_{inoff} = \frac{3U}{I_{inof}} - 3R_h \quad (11)$$

2.2 Long electrical networks

In this case the current I_h is function of active and capacitive components of insulation in long cables networks that represents a Z impedance with respect to earth.

The unbalanced voltage U_0 during an individual direct contact with phase A is:

$$U_0 = \frac{(Y_a + Y_h)U_a + Y_b U_b + Y_c U_c}{Y_a + Y_b + Y_c + Y_h} \quad (12)$$

Where

- U_a, U_b, U_c : single phase voltages.
- Y_a, Y_b, Y_c : Phases conductivity
- Y_h : Leak resistance conductivity

By taking into account voltages operators:

$$U_a = U, \quad U_b = a^2 U, \quad U_c = a U \quad (13)$$

The unbalanced voltage becomes:

$$U_0 = U \frac{Y_a + Y_l + a^2 Y_b + a Y_c}{Y_a + Y_b + Y_c + Y_h} \quad (14)$$

The current unside the individual:

$$I_h = (U_a - U_0)Y_h \quad (15)$$

Or

$$I_h = U Y_h \frac{Y_b(1 - a^2) + Y_c(1 - a)}{Y_a + Y_b + Y_c + Y_h} \quad (16)$$

$$Y_A = \frac{1}{Z_A} = g_A + jb_A = \frac{1}{r_A} + j\omega C_A \quad (17)$$

$$Y_B = \frac{1}{Z_B} = g_B + jb_B = \frac{1}{r_B} + j\omega C_B \quad (18)$$

$$Y_C = \frac{1}{Z_C} = g_C + jb_C = \frac{1}{r_C} + j\omega C_C \quad (19)$$

And in real value

$$I_h = \frac{U}{2} g_h \sqrt{\frac{[3(g_C + g_B) + \omega\sqrt{3}(C_C - C_B)]^2 + [\sqrt{3}(g_B - g_C) + 3\omega(C_B + C_C)]^2}{(g_A + g_B + g_C + g_h)^2 + \omega^2(C_A + C_B + C_C)^2}} \quad (20)$$

To facilitate the expression analysis, we suppose:

$$r_A = r_B = r_C = r \text{ and } C_A = C_B = C_C = C \text{ (reel case).}$$

In case $Z_A = Z_B = Z_C = Z$ and

$$Z = \frac{1}{Y} = \frac{1}{\frac{1}{r} + j\omega C} \quad (21)$$

The general expression of I_h becomes:

$$I_h = \frac{U}{R_h + \frac{Z}{3}} \quad (22)$$

And under its real form:

$$I_h = \frac{U}{R_h} \frac{1}{\sqrt{1 + \frac{r(r + 6R_h)}{9R_h^2(1 + r^2\omega^2C^2)}}} \quad (23)$$

Solving this equation, we obtain the limit value and the active component harmless of insulation if the network reel capacity with respect to earth will remain inferior to the critical value $C_{cr} = 0.145 \mu F$ (R. Isermann and P. Balle 1997) obtained of $I_{inof} = 10mA$, $R_h = 1000\Omega$ and network voltage of 380v.

In case, if the reel network capacity becomes superior to the critical capacity, the I_h current would be always superior to I_{inof} whatever the active resistance value of the insulation even if it tends to infinity $r = \infty$.

$$I_h = \frac{U\omega C}{\sqrt{9R_h^2\omega^2C^2 + 1}} \quad (24)$$

3. Theoretical Characteristics

$$R_f = f(r)$$

Basing ourselves on the condition $I_h \leq I_{inof}$, and during a network fixed capacity C , we seek the theoretical characteristics giving the leak resistances values R_f in function of the harmless active components r_{inof} of insulation. These characteristics are obtained for tree single phase possible faults, two phases and tree phases that could appear in an electrical network.

A) The single phase leak resistance R_{fm} is expressed by the relation:

$$R_{fm} = \frac{U}{I_{inof}} - \frac{r}{3(1 + r\omega c)} \quad (25)$$

gives the characteristic (a).

B) The two phases leak resistance R_{fb} , ($R_{fbA} = R_{fbB}$ the most dangerous case) expressed by the relation:

$$R_{fb} = \frac{\sqrt{3}U}{2I_{inof}} \quad (26)$$

gives the characteristic (b).

C) The tree phases leak resistance R_{ft} , ($R_{ftA} = R_{ftB} = R_{ftC}$ the most dangerous case) expressed by the relation:

$$R_{ft} = \frac{Ur}{rI_{inof} - U(1 + r\omega c)} \quad (27)$$

gives the characteristic (c).

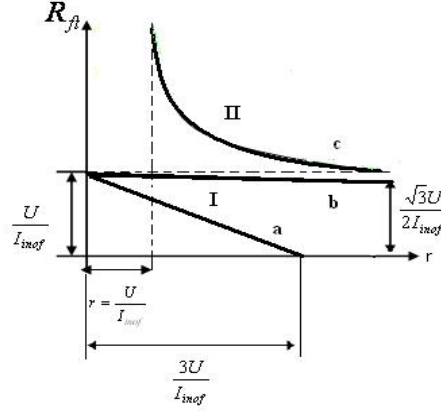


Figure 2. Theoretical characteristics $R_f = f(r)$

We notice that characteristic (c) (see Figure 1) defines the safety level whatever the leak type that happens in the electrical network.

4. Materials and Methods

4.1 The control hybrid model of the harmless active component of electrical networks insulation

The control model principal of the insulation active component must be composed of the circuits based on the measurement of the operational current and the homopolar voltage measurement (see Figure 3).

4.1.1 Measuring circuit of operational current:

The electrical circuit based on the operational current measurement is composed of a three phases rectifier bridge with a direct connection to the network (see Figure 3).

Between O_1 and O_2 there is the existence of a voltage called operational voltage equals to :

$$U_{op} = \frac{R_2}{R_2 + R_1} \frac{U}{\sqrt{3}} \quad (28)$$

For a determined operational voltage U_{op} and a perfect isolation where $r = \infty$, the operational I_{op} is:

$$R_l = \frac{U_{op}}{I_{OP}} - R_D \Rightarrow R_l = \frac{U_{op}}{I_{OP}} - R_D \quad (29)$$

R_D : Elements total resistance contained in the protection circuits.

R_f : Leak resistance if $I_{op} = I_{inof}$

Taking into account the most dangerous case $r_a = r_b = r_c = r$ (R. Isermann et P. Balle 1997), for a completely compensated capacity and also taking into account the parallel connection of resistance (R_D) with the equivalent network resistance, we will have:

A) The single phase equivalent leak resistance when $r \neq \infty$

$$R_{eq.f.m} = \frac{\frac{r}{\omega C} \left(\frac{U_{op}}{I_{inof}} - R_D \right)}{r + \frac{1}{\omega C} + 3 \left(\frac{U_{op}}{I_{inof}} - R_D \right)} \quad (30)$$

B) The two phases equivalent leak resistance when $r \neq \infty$

$$R_{\acute{e}q.f.b} = \frac{2 \frac{r}{\omega C} \left(\frac{U_{op}}{I_{inof}} - R_D \right)}{r + \frac{1}{\omega C} + 3 \left(\frac{U_{op}}{I_{inof}} - R_D \right)} \quad (31)$$

C) The tree phases equivalent leak resistance when $r \neq \infty$

$$R_{\acute{e}q.f.t} = \frac{3 \frac{r}{\omega C} \left(\frac{U_{op}}{I_{inof}} - R_D \right)}{r + \frac{1}{\omega C} + 3 \left(\frac{U_{op}}{I_{inof}} - R_D \right)} \quad (32)$$

So the most dangerous case is the one that gives the (a) characteristic expressed by the last equation ($R_{\acute{e}q.f.t} = 3R_{\acute{e}q.f.m}$). It is obvious if the protection trip happens for $r = \infty$ and $R_f \leq R_{\acute{e}q.f.t}$ it would be the same for $R_{\acute{e}q.f.t} = \infty$ when the isolation decreases to $r_{inof} \leq r_{cr}$

4.1.2 Measuring homopolar voltage circuit

The electrical circuit based on the homopolar voltage measurement is composed of a filter that contains identical resistances $R_1 \div R_2$ with a star connection (see Figure 3). In case of phases unbalance the U_o homopolar voltage would appear between the artificial neutral formed by the filter and imaginary neutral of the phases conductivity.

$$U_o = \frac{Ur}{3R_{f.d\acute{e}seq} + r} \quad (33)$$

$R_{f.d\acute{e}seq}$: due to unbalanced phases leak .

If U_o becomes equal to the threshold voltage U_s corresponding to I_{inof} , we will have:

$$R_{f.d\acute{e}seq} = \frac{r(U - U_s)}{3U_s} \quad (34)$$

With regard to the R_D influence on the insulation level and the C network capacity the preceding expression becomes:

$$R_{f.d\acute{e}seq} = \frac{(U - U_s) \frac{r}{\omega C} R_D}{3U_s \left(r + \frac{1}{\omega C} + R_D \right)} \quad (35)$$

4.1.3 Combined action of the two measuring circuits

The (c) characteristic is obtained under the combined action of two considered measuring circuits above.

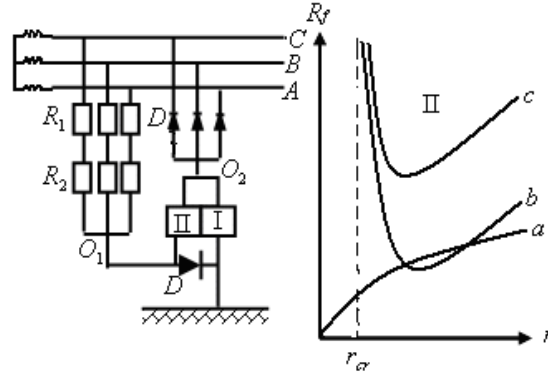


Figure 3. Characteristics $R_f = f(r)$ measuring circuits of operational current, of homopolar voltage and combined action of two measuring circuits

5. Physical simulation of an electrical network

This simulation is conceived for a low voltage three phase electrical network (see Figure 4). The network is supplied with a transformer having a 380V at the output (Becker and Beylot 2006). The influence of the line capacity before the transformer is completely eliminated (Becker and Beylot 2006). The network isolation is obtained by the installation of resistances and capacitances connected between the phases and the earth manipulated by means of switches. The electrical faults simulation consists of connecting between the phases and earth real resistances manipulated by a switch.

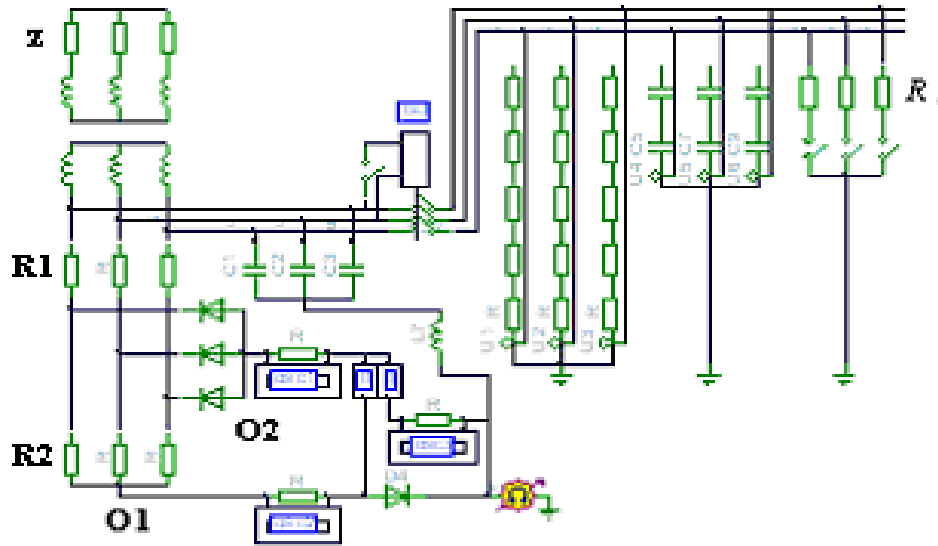


Figure 4. Testing system and simulation circuits for the electrical network.

- r_x : Insulation values simulated
- c_x : Capacity values of simulated lines
- R_f : Values of resistors artificial leak
- C_1, C_2, C_3 : compensation
- R : Measuring resistors
- Osc_1, Osc_2, Osc_3 : Oscilloscope measurement
- $R1-R2$: Voltage divider
- D : Diode. Three-phase rectifier
- Z : Impedance of the network upstream
- O_1-O_2 : Artificial neutral
- $Disj$: Breaker

6. Results and Discussion

6.1 Experimental testing

Indirectly we measure the rectified internal current I_r by the use of an oscilloscope, the operational current I_{op} and the homopolar current I_0 . This experiment is executed for three principal insulation fault states and two values for the level of insulation ($r \leq r_{inof}$; $r \geq r_{inof}$) (Welfonder 1998), (A.S. Abdulmutaleb 2001).

A) Symmetrical state

Test: $r_A = r_B = r_C = \infty$; Result: $I_{op} \leq I_{inof}$: armature equilibrium system

Test: $r_A = r_B = r_C \leq r_{inof}$; Result: $I_{op} \geq I_{inof}$: armature non equilibrium

B) Single phase faulty state

Test: $r_A \geq r_{inof}$; $r_B = r_C = \infty$; Result: $I_{op} + I_{o+} \leq I_{inof}$: armature equilibrium

Test: $r_A \leq r_{inof}$; $r_B = r_C = \infty$; Result: $I_{op} + I_{o+} \geq I_{inof}$: armature non equilibrium

C) Two phase faulty state

Test: $r_A = r_B \geq r_{inof}$; $r_C = \infty$; Result: $I_{op} + I_{o+} \leq I_{inof}$: armature equilibrium

Test: $r_A = r_B \leq r_{inof}$; $r_C = \infty$; Result: $I_{op} + I_{o+} \geq I_{inof}$: armature non equilibrium

6.2 Variables determination $R_f = f(r)$

The tests are carried out by the variation of insulation simulated values of artificial faults and network capacities. This in order to obtain threshold values of leak resistances and that of leak currents. The combinations obtained $R_f = f(r)$ confirm the theoretical predictions.

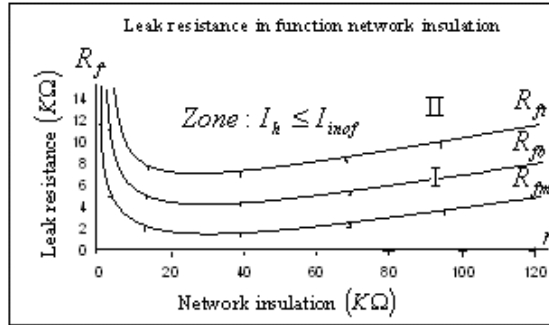


Figure 5. Leak resistance in function of the network insulation

Curve1: single phase fault, capacity= $0\mu f$ and $1\mu f$; Compensation, capacitance= $0.15\mu f$ and $0.85\mu f$

Curve2: two phase fault, capacity= $0\mu f$ and $1\mu f$; Compensation, capacitance= $0.15\mu f$ and $0.85\mu f$

Curve3: three phase fault, capacity= $0\mu f$ and $1\mu f$; compensation, capacitance= $0.15\mu f$ and $0.85\mu f$.

Every curve (see Figure 4) represents the mean curve obtained with six successive tests. The mean value of the mean leak resistance that triggers the protection control circuits sensitivity is calculated by the expression:

$$R_{moy} = \frac{R_{f1} + R_{f2} + \dots + R_{fn}}{n} \quad (36)$$

Where

$n = 6$ number of tests.

To avoid large errors during the tests results interpretation we have taken into account the typical allowed error. The error found must not be superior to three times the quadratic mean error.

$$R_{f \max} = 3\delta ; \quad \delta = \sqrt{\frac{R_{f1}^2 + R_{f2}^2 + \dots + R_{fn}^2}{n}}$$

$$R_{f1} = R_{f1 \max} - R_{moy} ; \quad R_{f2} = R_{f2 \max} - R_{moy} \quad \text{and} \quad R_{fn} = R_{fn \max} - R_{moy}$$

7. Conclusion

The practical tests done on the hybrid model allowed us to obtain the characteristics $R_f = f(r)$ according to various fault conditions. We have taken into account the most dangerous cases such as the tree phases fault with equal leaks $R_{fA} = R_{fB} = R_{fC}$. We noticed that the variables obtained $R_f = f(r)$ during the different tests with the practical curve are similar to the theoretical ones (c) representing the graphical sum of curves (a) and (b) of homopolar voltage circuits and operational current. Thus the aim is that only the control of the active component of the isolation of the network regardless of the capacitive component may be carried out continuously and in an automatic manner. For every relay triggering we have a value of r_{inof} that correspond to R_f for a current $I_{inof} = 10mA$ and a fixed network capacity value. During all the tests, the model sensitivity was proved with different faults conditions and a symmetrical decrease of phases insulation with respect to earth.

Regarding the artificial influence of the network capacity $0\mu F$ to $1\mu F$, we have introduced in the model suggested a compensation of the variable capacity $0,15\mu F$ to $0,85\mu F$ eliminating the leak current capacitive component. The curve 1 (see Figure 5) characterise the single phase fault and represents the frontier between two domains having as coordinates points R_{fm} and r . The first domain (I) gives the dangerous zone where the relay triggering is executed. The second domain (II) represents the safe network zone of exploitation. This characteristic takes into account the single phase faults. The third curve characterise the tree phase fault which is the most dangerous having as leaks $R_{fA} = R_{fB} = R_{fC}$. This type of fault allowed us to get the final hybrid model exploitation characteristic. This characteristic gives a good relay sensibility every time $r \leq r_{inof}$. So the hybrid model allowed the long network exploitation without risk as long as the insulation level r remains superior to the harmless case. The measurements of the leak currents done during the different tests have proved that in the currents values have never gone beyond the harmless value.

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