Hybrid Model for Insulation Active Component Control in an Isolated Neutral Electrical 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 [1].

Keywords

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 [2].

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 $I_{mof} = 10mA$ is fixed for an individual of low resistance of about 1000Ω under a safe voltage $U_S$ [3].

By taking the condition $I_f = I_{mof}$ (Harmless current), we determine the leak resistances set in function of insulation $R_f = f(r)$ defining the insulation level sensitivity domains protection system.

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 any more and the voltage of each phase with respect to earth is:

$$U_A = U_1 - U_O = AO$$
$$U_B = U_2 - U_O = BO$$
$$U_C = U_3 - U_O = CO$$

where $U_O$ : The unbalanced network voltage

$U_1 = AO$, $U_2 = BO$ and $U_3 = AO$ are the simple network voltages.
The current going into the insulation $r_A = r_B = r_C = r$ could be determined by the expression:

$$I_A = \frac{U_A}{r_A} = \frac{U_1 - U_O}{r_A}$$

$$I_B = \frac{U_B}{r_B} = \frac{U_2 - U_O}{r_B}$$

$$I_C = \frac{U_C}{r_C} = \frac{U_3 - U_O}{r_C}$$

And the current going into the individual:

$$I_h = \frac{U_A}{R_h} = \frac{U_1 - U_O}{R_h}$$

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

$$\sum I = I_A + I_B + I_C + I_h = 0$$

And we have:

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

Or

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

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:

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

So the unbalanced network voltage will be:
The voltage of phase A with respect to earth will be:

\[ U_A = U_i - U_O = \frac{3UR_h}{3R_h + r} \]

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

\[ I_h = \frac{U_A}{R_h} = \frac{3U}{3R_h + r} \]

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 \( I_h \leq I_{inff} \), we find the minimum safest value of the insulation level \( r_{inff} \):

\[ r_{inff} = \frac{3U}{I_{inff}} - 3R_h \]

II.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 [4], [5].

The unbalanced voltage \( U_O \) during an individual direct contact with phase A is:

\[ U_O = \left( \frac{Y_a + Y_h}{Y_a + Y_b + Y_c + Y_h} \right) \left( U_a + Y_bU_b + Y_cU_c \right) \]

Where

\( U_a, U_b, U_c \) : single phase voltages.
\( Y_a, Y_b, Y_c \) : Phases conductibility
\( Y_h \) : Leak resistance conductibility

By taking into account voltages operators

\[ U_a = U, U_b = a^2U, U_c = aU \]

The unbalanced voltage becomes:

\[ U_0 = U \frac{Y_a + Y_i + a^2Y_b + aY_c}{Y_a + Y_b + Y_c + Y_h} \]

The current unside the individual:

\[ I_h = (U_a - U_0)Y_h \]

Or
\[
I_v = U Y_a' \frac{Y_b(1-a^2) + Y_c(1-a)}{Y_a + Y_b + Y_c + Y_h}
\]

\[
Y_A = \frac{1}{Z_A} = g_A + jb_A = \frac{1}{r_A} + j\omega C_A
\]

\[
Y_B = \frac{1}{Z_B} = g_B + jb_B = \frac{1}{r_B} + j\omega C_B
\]

\[
Y_C = \frac{1}{Z_C} = g_C + jb_C = \frac{1}{r_C} + j\omega C_C
\]

And in real value

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

To facilitate the expression analysis, we suppose: \( r_A = r_B = r_C = r \) and \( C_A = C_B = C_C = C \) (reel case).

In case \( Z_A = Z_B = Z_C = Z \) and

\[
Z = \frac{1}{Y} = \frac{1}{r} + j\omega C
\]

The general expression of \( I_h \) becomes:

\[
I_h = \frac{U}{R_h + \frac{Z}{3}}
\]

And under its real form:

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

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 \( C_{cr} = 0.145 \mu F \) 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 \( r = \infty \).

\[
I_h = \frac{U\omega C}{\sqrt{9R_h^2 \omega^2 C^2 + 1}}
\]
3. Theoretical Characteristics $R_f = f(r)$

Basing ourselves on the condition $I_h \leq I_{ino}$, 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 $r_{ino}$ of insulation. These characteristics are obtained for three single phase possible faults, two phases and three phases that could appear in an electrical network.

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

$$
R_{fm} = \frac{U}{I_{ino}} - \frac{r}{3(1 + r \omega)}
$$

gives the characteristic (a).

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

$$
R_{fb} = \frac{\sqrt{3}U}{2I_{ino}}
$$

gives the characteristic (b).

C) The three phases leak resistance $R_f$, ($R_{fAC} = R_{fBC} = R_{fCA}$ the most dangerous case) expressed by the relation:

$$
R_f = \frac{U_f}{rI_{ino}} - U(1 + r \omega)
$$

gives the characteristic (c).

We notice that characteristic (c) 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 (fig.1).

4.1.1 Measuring circuit of operational current:

The electrical circuit based on the operational current measurement is composed of a tree phases rectifier bridge with a direct connection to the network (fig.1).

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

\[
U_w = \frac{R_2}{R_2 + R_1} \sqrt{3}
\]

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

\[
I_{op} = \frac{U_{op}}{R_d + R_l} \quad \Rightarrow \quad R_l = \frac{U_{op} - R_d}{I_{op}}
\]

\( R_d \) : Elements total resistance contained in the protection circuits.
\( R_l \) : Leak resistance if \( I_{op} = I_{inof} \)

Taking into account the most dangerous case \( r_a = r_b = r_e = r [6] \), 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 \( r \neq \infty \)

\[
R_{eq,f,m} = \frac{r}{\omega c} \left( \frac{U_{op}}{I_{inof}} - R_D \right)
\]

\[
r + \frac{1}{\omega c} + 3 \left( \frac{U_{op}}{I_{inof}} - R_D \right)
\]

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

\[
R_{eq,f,b} = \frac{2r}{\omega c} \left( \frac{U_{op}}{I_{inof}} - R_D \right)
\]

\[
r + \frac{1}{\omega c} + 3 \left( \frac{U_{op}}{I_{inof}} - R_D \right)
\]

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

\[
R_{eq,f,t} = \frac{3r}{\omega c} \left( \frac{U_{op}}{I_{inof}} - R_D \right)
\]

\[
r + \frac{1}{\omega c} + 3 \left( \frac{U_{op}}{I_{inof}} - R_D \right)
\]

So the most dangerous case is the one that gives the (a) characteristic expressed by the last equation \( R_{eq,f,t} = 3R_{eq,f,m} \).

It is obvious if the protection trip happens for \( r = \infty \) and \( R_f \leq R_{eq,f,t} \) it would be the same for \( R_{eq,f,t} = \infty \) when the isolation decreases to \( r_{inof} \leq r_{ex} \).
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 $R_1 = R_2$ with a star connection (fig.1). 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 conductibility.

$$U_O = \frac{U_r}{3 R_{f,\text{diseq}} + r}$$

$R_{f,\text{diseq}}$: due to unbalanced phases leak.

If $U_O$ becomes equal to the threshold voltage $U_S$ corresponding to $I_{inof}$, we will have:

$$R_{f,\text{diseq}} = \frac{r(U - U_S)}{3U_S}$$

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

$$R_{f,\text{diseq}} = \frac{(U - U_S) r}{3U_S \left( r + \frac{1}{\omega C} + R_D \right)}$$

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.

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Figure 1: 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 (fig2). The network is supplied with a transformer having a 380V at the output [7]. The influence of the line capacity before the transformer is completely eliminated [8]. 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.

6. Results and Discussion

6.1 Experimental testing system

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 $(r \leq r_{inof}; \quad r \geq r_{inof})$ [9], [10].
A) Symmetrical state
Test:  \( r_a = r_B = r_C = \infty \)
Result:  \( I_{op} \leq I_{inof} \): armature equilibrium
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 \( R_j = f(r) \)

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 \( R_j = f(r) \) confirm the theoretical predictions.

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 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:

\[
R_{moy} = \frac{R_{r_1} + R_{r_2} + \ldots + R_{r_n}}{n}
\]
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.

\[
\delta_{\text{max}} = \frac{R^2_{f_1} + R^2_{f_2} + \ldots + R^2_{f_\text{n}}}{n}
\]

\[
R_{f_1} = R_{f_1\text{max}} - R_{\text{moy}}; \quad R_{f_2} = R_{f_2\text{max}} - R_{\text{moy}} \quad \text{and} \quad R_{f_\text{n}} = R_{f_\text{n}\text{max}} - R_{\text{moy}}
\]

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. So the active and harmless \( r_{\text{inof}} \) component control of the network insulation could be done automatically and in real time. For every relay triggering we have a value of \( r_{\text{inof}} \) that correspond to \( R_f \) for a current \( 10mA \) 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 characterise the single phase fault and represents the frontier between two domains having as coordinates points \( R_{fA} \) 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 \( r \leq r_{\text{inof}} \). 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.

References