Earthing of previously unearthed medium voltage networks

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Abstract: A large number of public utilities adopted the concept of isolated medium network operation. Increased cabling of previously overhead lines and construction of new cable feeders resulted in capacitive earth-fault currents increase. High earth-fault currents cause unacceptable touch potentials in vicinity of fault location and inadmissible potentials of neutral conductor in low voltage installations. Resonant earthing of isolated medium voltage networks has become an attractive way of earthing isolated networks. In fact, resonant earthed networks retain all advantages of isolated networks, especially, continuity of operation under sustained earth-fault conditions. Due to the fact that an adjustable inductance is connected to main HV/MV transformer's neutral point, through fault location only a small active component of the earth-fault current flows, thus causing no thermal stress to faulted equipment and preventing restriking faults i.e. intermittent overvoltages. The "tunable" inductance is adjusted to compensate network's ground capacitance. In this paper isolated and resonant earthed networks will be compared, and expressions for normal operating conditions and fault conditions will be derived.

Key-Words: medium voltage network, isolated network, resonant earthing, earth-fault, recovery voltage

1 Introduction

Medium voltage networks (MV), located between transmission lines and customers at low voltage, need to be as available as possible and as simple as possible to maintain. A vast number of public utilities adopted, during past decades, the concept of isolated network operation i.e. neutral points of all transformers and eventual generators were held isolated from earth. Increased cabling of previously overhead lines and construction of new cable feeders resulted in overall network capacitance increase, therefore capacitive earth-fault current increase. High earth-fault currents cause unacceptable touch potentials in vicinity of fault location and inadmissible potentials of neutral conductor in low voltage (LV) installations. Resonant earthing of isolated medium voltage networks has become an attractive way of earthing isolated networks. In fact, resonant earthed networks retain all advantages of isolated networks, especially, continuity of operation under sustained earth-fault conditions. Due to the fact that an adjustable inductance is connected to main HV/MV transformer's neutral point the capacitive earth-fault current is compensated by coil's inductive current. Therefore through earth-fault location only a small active component flows, thus causing no thermal stress to faulted equipment. A direct consequence of small current at fault location is absence of restriking faults i.e. intermittent overvoltages of faulted phase and sound phases. In this paper isolated and resonant earthed networks will be compared, and expressions for normal operating conditions as well as fault conditions will be derived.

2. Isolated networks

Isolated networks have no intentional connection with earth, i.e. all neutral points of all transformers or generators are isolated from earth, see Fig. 1. Single phase faults are by far (80%) the most frequent type of faults on overhead lines [3].

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Isolated networks are "immune" to such faults and continuity of operation is maintained.

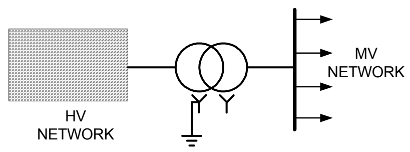

Fig. 1 Medium voltage network with isolated neutral point

2.1 Characteristics and problems of isolated network operation

Isolated MV networks are subject to switching overvoltages, dangerous to network isolation, causing severe damage. Larger earth-fault currents prevent fault currents to self-extinguish, therefore increasing the probability of more complex faults, most often two-phase earth-faults, with fault current magnitudes similar to three-phase fault. Currents of such magnitude result in considerable damage at fault location due to permanent insulation damage. Intermittent overvoltages are possible, especially for networks with small (below 10A) magnitude of earth-fault current. Intermittent overvoltages' magnitudes are of the order $3U_{nom}$ or above and most often evolve into double earth-faults too. Upon earth-fault inception overvoltages of the order $2{,}5U_{nom}$ or more, arise. Such overvoltages induce network faults, therefore considerably affecting network security and quality.

Previously mentioned problems are usually solved by proper earthing of the main HV/MV transformer's neutral point. The need for implementing such measures, comes out of regulations, which prescribe the highest level of permissible capacitive earth-fault current for different voltage levels (e.g. 20 kV MV networks can be isolated if capacitive earth-fault current doesn't exceed 15 A). Difference between permissible current ratings and typical values for isolated networks, where capacitive fault currents often reach 300A, is obvious. It is therefore clear that earthing of such MV networks is inevitable.

2.2 Neutral voltage in normal operation

MV isolated network's neutral voltage strongly depends on the network structure i.e. on length of overhead lines due to their ground capacitance unbalance. The magnitude and phase of neutral voltage can be calculated through the general expression:

$$\overline{V}_N = -\frac{\sum_{i=1}^{3} \overline{Y}_i \overline{E}_i}{\sum_{i=1}^{3} \overline{Y}_i + \overline{Y}_n} \qquad (1)$$

$\overline{E}_i$ - steady state voltage phasor,

$\overline{Y}_i$ - phase shunt admittance,

$\overline{Y}_n$ - admittance connected to neutral point.

The expression (1) can be alternatively formulated as:

$$\overline{V}_N = \overline{K}_e \cdot \overline{V}_{in} \qquad (2)$$

$$\overline{V}_{iN} = \frac{\sum_{i=1}^{3} \overline{Y}_i \overline{E}_i}{\sum_{i=1}^{3} \overline{Y}_i} \qquad (3)$$

$$\overline{K}_e = \frac{\sum_{i=1}^{3} \overline{Y}_i}{\sum_{i=1}^{3} \overline{Y}_i + \overline{Y}_n} \qquad (4)$$

The term K_e accounts for earthing type. For isolated networks K_e equals 1. Neutral voltage dependence on voltage magnitude and phase unbalance, on transformer's HV side, is depicted in Fig. 2 and Fig. 3. respectively.

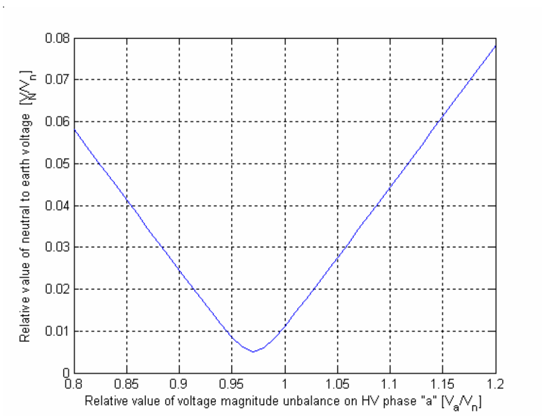

Fig. 2. Neutral voltage vs. HV magnitude unbalance

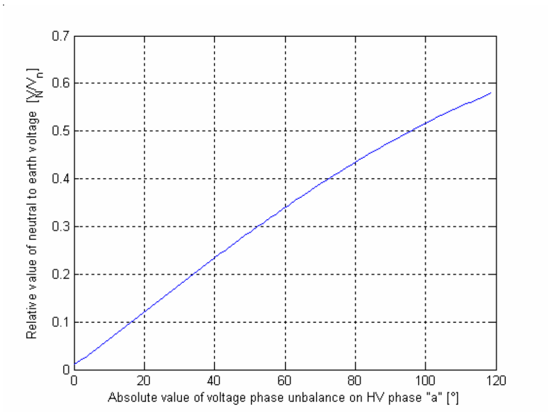

Fig. 3. Neutral voltage vs. HV phase unbalance

2.3 Earth-fault current value

The value of the earth-fault current does not depend on fault location and is determined solely by overall galvanically connected MV network's earth capacitance and leakage. The earth-fault current consists of a relatively large capacitive component I_c and a relatively small active component I_g [2]. The value of earth-fault current is determined by the general equation [1]:

$$\overline{I}_f = \frac{3\cdot\overline{V}_n}{2\cdot\overline{Z}_\alpha + \overline{Z}_0} \qquad (5)$$

$\overline{V}_n$ - steady state phase voltage phasor,
$\overline{Z}_\alpha$ - equivalent impedance of the α-sequence system,
$\overline{Z}_0$ - equivalent impedance of the 0-sequence system.

Neglecting the small terms of equation (5) and following further simplification, equation (5) yields:

$$\overline{I}_f = 3\cdot\overline{V}_n\left(G_0 + j\omega\cdot C_0\right) \qquad (6)$$

G_0- earth leakage per phase,
C_0- earth capacitance per phase,
ω- angular frequency.

The earth-fault current alters in accordance to the value of fault impedance at fault location. Therefore equation (5) must account for the value of fault impedance and changes to:

$$\overline{I}_f = \frac{3\cdot\overline{V}_n}{2\cdot\overline{Z}_\alpha + \overline{Z}_0 + 3\cdot R_f} \qquad (7)$$

Following the same approximations and simplifications, along with further simplifications for high impedance faults ($R_f \geq 50\text{k}\Omega$), equation (7) simplifies to:

$$\overline{I}_f = \frac{\overline{V}_n}{R_f} \qquad (8)$$

Low-ohmic faults are characterized by a fault impedance of a few ohms at fault location. Therefore, equation (7) for low-ohmic faults reduces to:

$$\overline{I}_f = 3\cdot\overline{V}_n\cdot\omega\cdot C_0\cdot\left(3\cdot R_f\cdot\omega\cdot C_0 + j\cdot 1\right) \qquad (9)$$

On basis of the afore-mentioned, high-ohmic faults are typically of ohmic type, while low-ohmic faults are characterized by a clear distinction of active and capacitive component within the fault current. Which of the two components will be higher depends on the value of fault impedance and the value of network's earth capacitance.

2.4 Neutral voltage during earth-fault

The neutral to earth voltage of the MV winding of the HV/MV transformer strongly depends on the fault impedance at the fault location, and is defined by [3]:

$$\frac{\left|\overline{V}_N\right|}{\left|\overline{V}_n\right|} = \frac{1}{\sqrt{1+(3\omega C_0 R_f)^2}} \qquad (10)$$

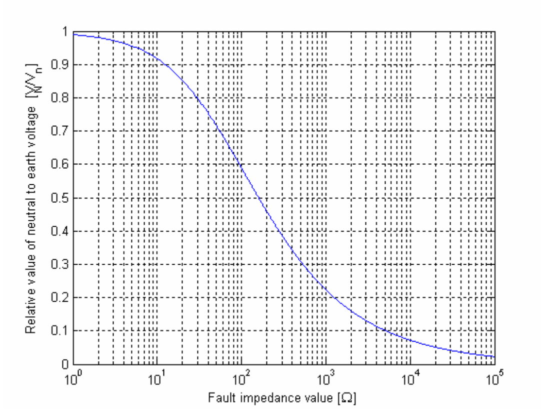

Fig. 4. Neutral voltage dependence on fault impedance value

According to Fig. 4., the absolute value of voltage at neutral point of the main HV/MV transformer can be used as a clear indication of earth-fault conditions if the value of fault impedance lies between 0Ω and approximately 1200Ω. For larger values of fault impedance the relay protection cannot, with reliability, distinguish earth-fault conditions from normal operating conditions.

2.5 Transient recovery voltage

After earth-fault current extinction the faulted phase is subject to transient recovery voltage (TRV). Depending on speed and magnitude of the first recovery voltage peak the earth-fault current will reestablish or permanently cease to flow. By analysis of a stable, metallic earth-fault at main HV/MV transformer's MV busbar, the following expression for TRV is derived:

$$\bar{u}_{TR} = \sqrt{2} \cdot \bar{V}_{nom} \left[\sin(\omega \cdot t - \varphi_0) + \sin \varphi_0 \cdot e^{-\frac{G_0}{C_0} t} \right] \quad (11)$$

$$\varphi_0 = \arctan \frac{\omega \cdot C_0}{G_0} \quad (12)$$

Parameters C_0 and G_0 are defined by the overall network's zero sequence capacitance and leakage, respectively.

A TRV profile for a 20 kV MV network with typical values of parameters C_0 and G_0 is depicted in Fig. 5.

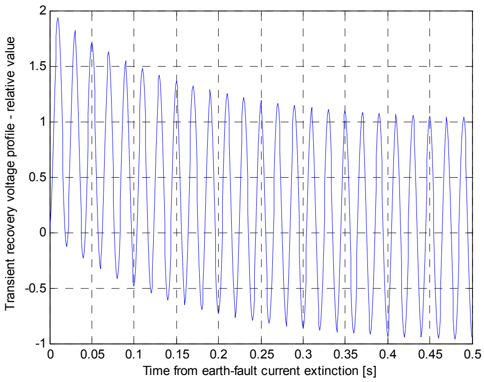

Fig. 5. TRV profile

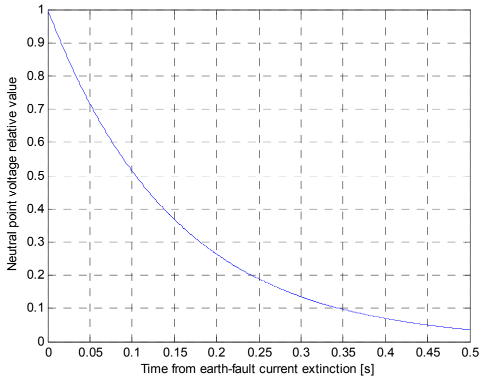

Fig. 6. Neutral point voltage profile

According to TRV profile in Fig. 5. it is clear that the first peak appears immediately after earth-fault current extinction with a peak value that is considerably greater than nominal voltage. The transient phenomenon settles down after approximately 1 second, when the DC component dies out. Network's capacitance increase prolongates the transient while increase of network's leakage damps out faster the transient.

Neutral point voltage is described by an exponential function that slowly or fast tends to zero, depending on network's damping level i.e. zero leakage to zero capacitance ratio. Fig. 6. depicts an idealized profile of the neutral point voltage after earth-fault extinction. In fact, due to inductive voltage transformers, connected to main HV/MV transformer's busbars, the neutral point voltage profile often contains oscillatory terms.

3. Resonant earthed networks

Resonant earthed networks have the MV neutral point of the main HV/MV transformer earthed through a variable inductance. The variable inductance is "tuned" to the overall MV network's earth capacitance.

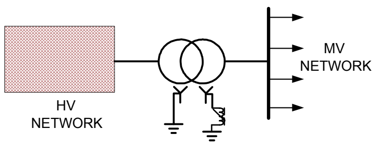

Fig. 7. Medium voltage network with resonant earthed neutral point

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3.1 Characteristics and problems of resonant earthed network operation

Increase of cable feeders share in overall MV network length results in network's capacitance increase, thus increasing earth-fault currents and switching overvoltages levels.
A solution that would preserve advantages of isolated network operation, i.e. continuity of supply during one-phase ground faults, otherwise applicable to networks with relatively small capacitive earth-fault currents (<10A), but applicable to networks with relatively high earth-fault currents (100, 300 to 1000A) is adoption of resonant (Petersen coil, Arc suppression coil - ASC) grounding. The role of ASC is to compensate network's capacitance by continuously or discretely adjusting coil's inductance to match network's capacitance. The inductive coil, as an active network component, is connected to main HV/MV transformer's MV neutral point.

3.2 Neutral point voltage in normal operation

Neutral point voltage during normal operation, like for isolated networks, depends on network's structure, i.e. overhead lines share, as they are the main cause of voltage unbalance. Moreover, neutral point voltage depends on ASC mismatch, i.e. coil's position deviation from full resonance, and network's damping. The neutral point voltage is defined by the next equation during normal operation:

$$U_N = \frac{k \cdot U_{in}}{\sqrt{v^2 + d^2}} \tag{13}$$

$$v = \frac{I_{Lp} - I_c}{I_c} \tag{14}$$

$$d = \frac{I_{Gz}}{I_c} \tag{15}$$

k ground capacitance (C_0) and leakage (G_0) unbalance factor,
v mismatch factor
d damping factor
U_{iN} neutral point voltage, if the network were isolated, expression (1)
I_{Lp} coil position expressed in inductive current
I_c network's capacitance expressed in earth-fault current

Fig. 8. presents neutral point relative voltage in dependence of ASC mismatch (υ) and damping (d).
It is clear that ASC mismatch positively affects neutral point voltage decrease during normal operation, as well as damping increase, see Fig. 8. Further more, considering typical values for parameter d, in case of full compensation, neutral point voltage can be as high as 10 to 20 times as would appear if the network was isolated [4]. Therefore compensated networks are rarely fully compensated, but rather overcompensated.

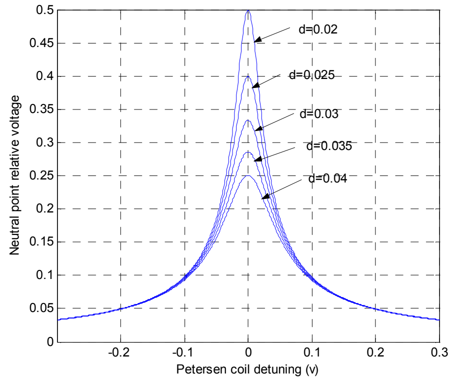

Fig. 8. Neutral point voltage in dependence of detuning (v) and damping (d)

3.3 Earth-fault current

Earth-fault current and neutral point voltage, following a single-phase to earth fault, in dependence of fault impedance at fault location, neglecting coil's leakage, can be calculated from the following relation:

$$I_f = \frac{U_{nom}\sqrt{1 + (\frac{1}{G_e})^2 (3\omega C_e - \frac{1}{\omega L_p})^2}}{\sqrt{(R_f + \frac{1}{G_e})^2 + R_f^2 (\frac{1}{G_e})^2 (3\omega C_e - \frac{1}{\omega L_p})^2}} \tag{16}$$

In case of full compensation expression (16) simplifies to:

$$I_f = \frac{U_{nom}}{\frac{1}{G_e} + R_f} \tag{17}$$

Neutral point voltage strongly depends on fault impedance and is defined by:

$$U_N = \frac{I_f}{\sqrt{G_e^2 + (3\omega C_e - \frac{1}{\omega L_p})^2}} \quad (18)$$

Again, for full compensation expression (18) simplifies to:

$$\frac{U_N}{U_{nom}} = \frac{\frac{1}{G_e}}{\frac{1}{G_e} + R_f} \quad (19)$$

As in isolated network operation, fault impedance considerably affects earth-fault magnitude and neutral point voltage. Influence of fault impedance to neutral point voltage is presented in Fig. 9.

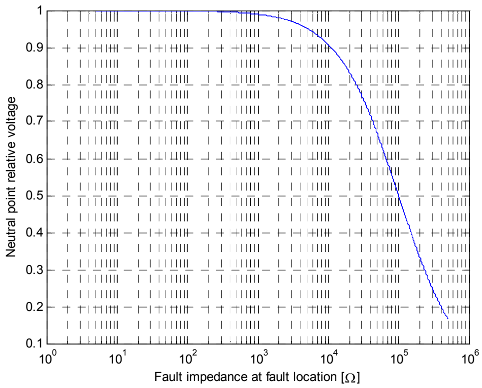

Fig. 9. Neutral point voltage dependence on fault impedance

Comparing Fig. 9. to Fig. 4. it can be concluded that fault impedance at fault location decreases less neutral point voltage this being more favorable for earth-fault protection relays.

3.4 Transient recovery voltage

Again, by analysis of a stable, metallic earth-fault at main HV/MV transformer's MV busbar, the following expression for TRV is derived for compensated network operation:

$$u = \sqrt{2} \cdot U_{nom} \left(\cos \omega t - e^{-\delta t} \cos \omega_{1i} t \right) \quad (20)$$

Fig. 10. presents TRV profile for typical values of coefficients δ i ω_{1i} that match a 20 kV MV network. The network is fully compensated.

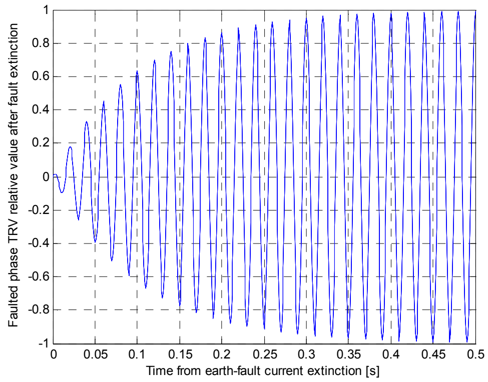

Fig. 10. TRV profile for fully compensated MV network

From the TRV profile a slow rise can be discerned which favorably affects preventing fault restriking, i.e. generation of intermittent earth-faults, accompanied by severe overvoltages. If the network were not fully compensated the TRV would have a slightly pulsating profile, as presented in Fig. 11.

Regardless ASC compensation level, the DC component present in the TRV profile for isolated networks lacks for resonant earthed networks (Fig. 10, 11).

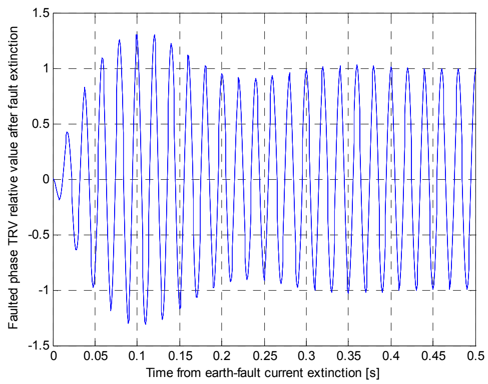

Fig. 11. Overcompensated network TRV

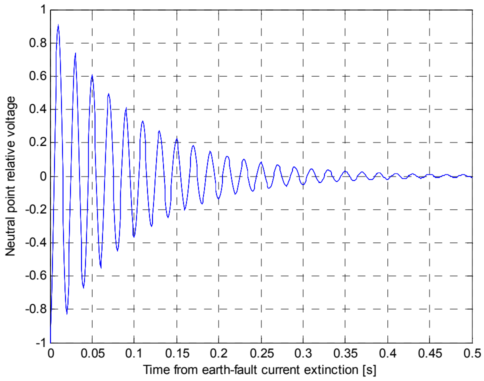

Fig. 12. Compensated network neutral point voltage

Neutral point voltage, after earth-fault extinction, is obtained if on the TRV the voltage of the neutral point during stable earth-fault is superimposed (Fig. 12.):

$$u_0 = -e^{-\delta t}\cos\omega_{1i}t \qquad (29)$$

4. Conclusion

Difference between permissible capacitive earth-fault current values and real values for isolated networks forces earthing of such networks. By resonant earthing of MV isolated networks, continuity of electric supply is maintained, what is normally considered the main advantage compared to low-impedance earthing. Due to relatively slow rising of TRV, intermittent overvoltages are not likely to occur. When the ASC is in full compensation mode, the current at fault location is limited to the active component, which is defined by neutral inductor and MV network active leakage, thus causing no thermal stress to faulted equipment. Fast and selective detection of single-phase earth-faults alongside with application of automatic reclosure (AR), is achieved through application of a resistor connected in parallel to the coil. Due to small currents at fault location, regulatory conditions on potentials in LV network (U + 1200V, i.e. 1430V) are alleviated. Besides previously mentioned advantages, resonant earthing poses several problems. Overvoltages due to phase-to-ground capacitance unbalance and transient overvoltages during switching operations are the most serious. Further more, overvoltage for one-phase-to-earth faults are of the order of overvoltages in isolated networks. Resonant earthing investment costs are greater than costs for e.g. low-impedance earthing due to ASC costs and ASC automation costs. Finally, protection and selective signalization is complex and not always reliable, especially during high-ohmic earth-faults.

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