THE INFLUENCE OF GROUNDING TRANSFORMER ON GROUND FAULT CURRENT IN MV NETWORKS

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ABSTRACT

MV networks have numerus of solutions how to perform a neutral point grounding according to demanded characteristic of a ground fault current for relay terminals and safety of people and utilities. Solution with grounding over partial compensation is widely spread in networks with significant capacitive current $I_c$ (though not too high) and where network is mostly in a steady state without often change of its configuration. In networks where secondary side of the transformer is in delta connection grounding transformer forms an artificial neutral point through its grounding bank. Use of grounding transformer changes ground fault in a way presented in this article. Through Thevenin’s symmetrical component model of a related circuit is possible to validate currents and voltages in network during a ground fault.

INTRODUCTION

Firstly, in the time of undeveloped electrical networks and especially because of the small cable ratio all distribution networks had isolated neutral point. By increasing cable ratio and size of the networks neutral point grounding started to be dominant. Since there is a high restriction due to people’s safety, grounding systems are constructed to limit a ground fault magnitude. One of the grounding solutions is grounding over partial compensation. It is performed over parallel connection of resistor and reactor whose taps are regulated only in the off state. Type of grounding like this one is applied especially in networks with high capacitive current where regulations according to people’s and utility’s safety as well as relay terminal’s demand of a current characteristic can’t be achieved in solutions without compensation. When power transformer has a delta connection on its MV side an artificial neutral point is created by grounding transformer. By using this kind of grounding, the regular model for ground fault calculation can be forgotten. Grounding bank can be in various types of connection and depends whether that transformer should be used only for providing a neutral point or also as an auxiliary transformer. Grounding transformer used in the observed network effects on decrease of a resistive fault current and increase of a remaining reactive current. Neglecting grounding transformer’s zero impedance ($R_0$ and $X_0$) can bring to the unexpected ground fault current which can have negative impact on relay protection and fatal effect on people and utility. Beside ground fault calculation this article brings the procedure of choosing thermal current for grounding system elements. Both is the base for making technical inquiries of such equipment.

1. TYPES OF GROUNDING SYSTEM IN MV NETWORKS

There are several grounding system types in distribution network. What will be applied depends firstly on a permitted touch voltage. In a case of high ground fault current it is necessary to equalize a voltage potential on the place of plausible touch with fault. Very often is more reasonable to design a grounding system that will decrease ground fault current so there is no more problem with high soil resistivity. Secondly it depends on configuration of the network. Generally it refers to the length of a network, but ratio between cable and overhead lines is also crucial. It’s well known that 1 km of cable in MV network has more than 10 times higher capacitance than 1 km of overhead line. In a past, there wasn’t need of grounding because networks weren’t that much developed so capacitive current wasn’t very high. Thereupon networks could be fully operated while having a fault because arc self-extinction happened. When arc self-extinction point is crossed, isolated neutral system is left. Since then came various types of grounding. Every grounding type is suitable for specific characteristic of the network and is in following described.

1.1. Isolated neutral system

At the beginning all MV networks were isolated because conditions for arc self-extinction were fulfilled. Therefor networks could be operated during a fault without additional risk for people and utility. Internal overvoltages in such systems can be up to $2.7U_n$. Intermittent can happen after opening operation of the interrupter and inability of extinction an arc. The factor of overvoltage in that case can be up to $3.5U_n$[3].

![Figure 1. Ground fault phasor diagram in a network with isolated neutral](image-url)
1.2. Low-ohm grounding of neutral point
People’s and utilities’ safety was the reason of letting go isolated neutral and shifting to low-ohm grounding. It manifests itself in having a ground fault current which has a dominant resistive component, $3I_R>I_C$ [2]. It affects lower internal overvoltages and intermittent can’t even happen. Overvoltages rise up to $1.9U_n$. The utility equipment such as interrupters and relay protection reacts reliable on mainly resistive ground fault current. In a contrary to isolated neutral systems, network with low-ohm grounding can’t be operated while having a fault. Thus, any line in a fault has to be interrupted and consumers stay without electricity.

![Figure 2. Ground fault phasor diagram in low-ohm grounding network](image)

1.3. Partial compensation grounding of neutral point
Resistor and reactor connected in parallel create a partial compensation grounding system. Advantage of using this grounding is the reduction of a ground fault current with compensating capacitive current. Overvoltages seem to be small too. Without lots of network changes it looks like a good way of grounding. Disadvantages of this solution lay in the reactor’s inability to adjust its inductance to the network’s capacitance. If changes in the network capacitance are often it can lead to the state where compensation is not assured. Then, use of this type of grounding brings risk to the people and equipment.

![Figure 3. Ground fault phasor diagram in partial compensated network](image)

1.4. Resonant grounding (Arc suppression coil)
Arc suppression coil with automatic adjustment of inductance is used in the resonant grounding systems. The biggest advantage of this type of grounding is the improvement of SAIDI and SAIFI indexes without bringing people and utilities in danger. Overvoltages go up to $2.5U_n$ and intermittent voltages don’t exist. [3] Ground fault current has inductive character and has the value according to the set $U_0$ on regulator. Value is determined to be enough high for fault detection but still enough low to satisfy an arc self-extinction point and assured ground resistance in MV/LV substations.

![Figure 4. Ground fault phasor diagram in resonant grounding network](image)

2. GROUNDING OVER GROUNDING TRANSFORMER
When a network is supplied from delta connection of the transformer, only way for grounding a system is the use of grounding bank. Grounding bank can be connected in variates of connections. The most generic design is the $Y$-$\Delta$ connection which provides the neutral point on its primary side. There are couple of designs of grounding bank, but the most used one is a form of ZNyn(d) which is used in the actual network. In contrary to connection $Z$ or Y-$\Delta$ this connection can be applied for supplying consumption of the utility. Tertiary of the grounding transformer provides a path for $I_0$ current in the case of ground fault on LV side. The most important electrical parameters when ordering a grounding transformer are: nominal apparent power $S_n$, thermal current $I_{th0}$ and zero impedance $Z_{G0}$. Nominal apparent power $S_n$ is determined according to utility needs. While thermal current $I_{th0}$ determines current which is permitted to flow through neutral during a certain period, zero impedance $Z_{G0}$ changes ground fault current and voltages on which this article mostly orientates.
2.1. Grounding transformer variates
As it is mentioned before, the most generic form of creating an artificial neutral point is Y-Δ and an interconnected star (Z connection). They are applied only for providing an artificial neutral point of the network. Following types can serve for feeding the utility with electricity as well as for creating a neutral.
- ZNyn is a connection often used despite its disadvantage. This grounding provider serves as an auxiliary transformer too and feeds the utility.
- ZNyn(d) is a connection which has an advantage compared to the previous one because in a case of ground fault on LV side ground fault current is around three times lower without delta in grounding transformer than with it [4].
- ZNzn is a connection that fulfils all the requirements for grounding transformer with adequate secondary winding which supplies consumption of the utility.

2.2. Determination of electrical parameters
The most important technical parameters except apparent power are thermal current \(I_{th(s)}\) and zero impedance \(Z_{G/T}\). When making an inquiry for thermal current \(I_{th(s)}\) of grounding transformer, the buyer has to know in what spectrum of currents this element might be exposed. Thermal current \(I_{th(s)}\) of grounding transformer is often specified for 5 s, 10 min and permanent or in a similar way. Beside set delay-time on ground fault protection relay, automatic reclosing and operational time of interrupter are taken into consideration. By using the law of conservation of energy thermal current can easily be determined. Energy that current \(I_1\) has produced for period \(t_1\) is equal to the energy that current \(I_2\) has produced for period \(t_2\).

\[
I_{th1}Z_1t_1 = I_{th2}Z_2t_2 \quad (2-1)
\]
\[
\bar{Z}_1 = \bar{Z}_2 = \bar{Z}_x \quad (2-2)
\]
\[
I_{th2} = I_{th1}\sqrt{\frac{t_1}{t_2}} \quad (2-3)
\]

While there is almost a negligible zero impedance \(Z_0\) of power transformer, grounding transformer makes it difficult to compensate a capacitive current \(I_C\). However, it has a similar influence on the resistive current in observed network, although using grounding transformer with other characteristic can have totally opposite influence. Distribution Company is responsible for determination of a zero impedance \(Z_{G/T}\) which should suit requirements of a certain network. Grounding transformer’s \(Z_{G/T}\) mainly depends on the form, used material and dimensions of the core and windings, but also on the type of the connection between wounds [5].

3. THEORETICAL AND PRACTICAL ANALYSIS OF THE MODEL

![Figure 5. Thevenin’s equivalent model for grounding over artificial neutral point](image)

3.1. Calculation and scheme model
Thevenin’s equivalent scheme of affected symmetrical components is the base for calculation. Scheme consists of direct, inverse and zero impedance. Zero impedance has the biggest impact. In a conventional grounding there is a \(Z_0\) of a power transformer which is apparently low and can almost be neglected due to transformer’s big apparent power. When using power transformer in Yd5 connection, grounding on the MV side can be performed only over grounding transformer. In the system of zero sequence components, \(Z_{G/T}\) has three times smaller impedance in a calculation model than \(Z_0\) of the grounding elements.

\[
\bar{Z}_{dTR} = \bar{Z}_{dTR} = \frac{u_{knL}}{100} \quad (3-4)
\]
\[
\bar{Z}_{deq} = \bar{Z}_{eq} = \bar{Z}_{dTR} + \bar{Z}_{dline} \quad (3-5)
\]
\[
\bar{Z}_{eq} = \frac{u_{knL}(\frac{u_{knL}}{100}))^{-jx_c}}{x_{GOT} + 3R_F + \bar{Z}_{dline}} \quad (3-6)
\]
\[
\bar{Z}_{eq} = \bar{Z}_{deq} + \bar{Z}_{eq} + \bar{Z}_{deq} \quad (3-7)
\]

Equations describe a procedure of calculating an influence of grounding transformer on ground fault variables. The main focus in the model should be given to \(Z_{G/T}\) which affect a voltage drop in the zero sequence circuit. Therefor parallel connection of the resistor and reactor get diminished voltage and leads to lower inductive \(I_R\) and resistive current \(I_R\).

First step after calculating equivalent impedance \(Z_{eq}\) is to calculate a ground fault current \(I_{1t}\):
\[ I_{k1} = \frac{\sqrt{2}U_L}{Z_{deq} + Z_{eq} + Z_{reactor}} \]  

As model scheme denotes, capacitive current leads the voltage and doesn’t flow toward grounding system. Therefore current that flow toward grounding system has particularly inductive character. According to the model, these two currents compensate each other just in the neutral point. Following equations explain statement:

\[ I_{n.p.} = I_{k1} - I_c \]  

\[ U_{ac} = \frac{U_i}{\sqrt{3}} - I_{n.p}Z_{GT} - f_{k1}(Z_{deq} + Z_{eq} + Z_{reactor} + R_F) \]  

\[ I_L = \frac{[U_{ac}]}{Z_{reactor}} \]  

\[ I_R = \frac{[U_{ac}]}{R_n} \]  

\[ U_{ab} = f_{k1}(Z_{deq} + Z_{eq} + Z_{reactor} + R_F) \]  

\[ I_c = \frac{[U_{ac}]}{X_c} \]  

By neglecting ground fault resistance, lines’ and transformers’ impedance, capacitive current is calculated as following:

\[ I_c = \sqrt{3} \cdot |U_L| \cdot \omega \cdot C_{sn} \]  

Broken delta voltage is the vector addition of all three phase-to-ground voltages. As more emphasized line impedances are less voltage will be on broken delta. Broken delta is the most reliable detector of the ground fault. Even when relay protection can’t detect a fault regarding to small current or its unsuitable characteristic, broken delta voltage warns on the ground fault. The output rated voltage on the broken delta of voltage transformer in the analyzed case is 100/3 V per phase. In a case of fault-free state phase voltage of every winding is 33.3 V and voltage of broken delta is 0 V.

![The lowest ground fault current (inflection point)](image)

Table 1. Comparison between ground faults in grounding over PT’s and GT’s neutral point (R_F= 0 Ω)

<table>
<thead>
<tr>
<th>Power transformer’s N.P.</th>
<th>Grounding transformers artificial N.P.</th>
</tr>
</thead>
<tbody>
<tr>
<td>U_n</td>
<td>21000 V</td>
</tr>
<tr>
<td>C_{sn}</td>
<td>1.55819x10^{-3} F</td>
</tr>
<tr>
<td>R_F</td>
<td>0 Ω</td>
</tr>
<tr>
<td>Z_{OPT} (Z_{0GT})</td>
<td>j24 Ω</td>
</tr>
<tr>
<td>Z_L</td>
<td>j74.83 Ω</td>
</tr>
<tr>
<td>R_n</td>
<td>240 Ω</td>
</tr>
<tr>
<td>Z_{eq}</td>
<td>653.25 – j224.60 Ω</td>
</tr>
<tr>
<td>I_c</td>
<td>j178.05 Ω</td>
</tr>
<tr>
<td>I_{k1}</td>
<td>52.65+18.97° A</td>
</tr>
<tr>
<td>I_R</td>
<td>49.79 A</td>
</tr>
<tr>
<td>I_{remain}</td>
<td>j17.12 A</td>
</tr>
<tr>
<td>I_{n.p.}</td>
<td>168.47-72.81° A</td>
</tr>
<tr>
<td>U_{bal}</td>
<td>105.31 V</td>
</tr>
</tbody>
</table>

Table 2. Comparison between ground faults in grounding over PT’s and GT’s neutral point (R_F=350 Ω)

<table>
<thead>
<tr>
<th>Power transformer’s N.P.</th>
<th>Grounding transformers artificial N.P.</th>
</tr>
</thead>
<tbody>
<tr>
<td>U_n</td>
<td>21000 V</td>
</tr>
<tr>
<td>C_{sn}</td>
<td>1.55819x10^{-3} F</td>
</tr>
<tr>
<td>R_F</td>
<td>350 Ω</td>
</tr>
<tr>
<td>Z_{OPT} (Z_{0GT})</td>
<td>j24 Ω</td>
</tr>
<tr>
<td>Z_L</td>
<td>j74.83 Ω</td>
</tr>
<tr>
<td>R_n</td>
<td>240 Ω</td>
</tr>
<tr>
<td>Z_{eq}</td>
<td>1703.25 – j228.74 Ω</td>
</tr>
<tr>
<td>I_c</td>
<td>j71.59 Ω</td>
</tr>
<tr>
<td>I_{k1}</td>
<td>21.73+14.45° A</td>
</tr>
<tr>
<td>I_R</td>
<td>20.99 A</td>
</tr>
<tr>
<td>I_{remain}</td>
<td>j27.7 Ω</td>
</tr>
<tr>
<td>I_{n.p.}</td>
<td>71.95–73.04° A</td>
</tr>
<tr>
<td>U_{bal}</td>
<td>42.34 V</td>
</tr>
</tbody>
</table>

3.2. Testing the model in 20 kV network

In TS 110/20 kV Vincent in HEP, Elektroistra test of the ground fault was made to prove a testing model and to set a relay terminal and a reactor’s tap in the right position. During the test, tap on the reactor was on 7th position, with inductance X_L= j74.83 Ω. The first test was performed without ground fault resistance and the second one with resistance R_F=350 Ω.
Grounding transformer’s influence is reduction of resistive and inductive current. For a consequence it can have unreliabilities of relay protection, too high ground fault current and high capacitive current. Therefore unknowing or neglecting $Z_{G\text{GT}}$ in calculation model causes danger for people, utilities and consequently interruption of electrical energy.

In resonant grounding networks this influence is even more emphasized. There are a lot of examples where arc suppression coils “ARC” with their nominal current $I_L$ can’t compensate much lower nominal $I_F$ of network. In these cases only solution is operating a system with both ARCs in parallel which actually has a negative effect on safety of people, utility and energy supply. Distribution Operator Company has to bring a standard for selecting grounding transformers depending on their purpose and according to this model. Model is suitable for partial compensated network as well as for other types of grounding (low-ohm, resonant and static) networks.

### 5. CONCLUSION

Grounding transformer which was taken into consideration in this model has predominantly inductive impedance which is not always a case. Since there are types for different application purposes, i.e. generator grounding etc. it can have different characteristics. Hence, distribution Operator Company has to have good educated engineers so they can answer on challenges in such networks.

In this model of partial compensating network the result of grounding transformer’s influence is reduction of resistive and inductive current. For a consequence it can have unreliabilities of relay protection, too high ground fault current and high capacitive current. Therefore unknowing or neglecting $Z_{G\text{GT}}$ in calculation model causes danger for people, utilities and consequently interruption of electrical energy.

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### 6. REFERENCES


