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Grounding Transformer Transient Analysis Caused by Earth Fault Clearance in a Subtransmission Substation and Proposing Appropriate Solutions

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ABSTRACT

Power transformers used in the subtransmission substations of the Iranian power grid have YNd connection. In addition, a grounding transformer with YNd connection is used to create an artificial neutral on the medium voltage side. The phase to ground capacitor may have a high value in the medium voltage network. In some conditions, such as interruption of the phase-to-ground fault current in one of the output feeders, a kind of resonance is created in the network that not only damages the grounding transformer but also causes protection problems related to the misalignment of ground fault relays. In this paper, the resonance between the grounding transformer and the phase-to-ground capacitor of the medium voltage output feeders of a sample subtransmission substation is investigated, considering that the phase-to-ground fault is interrupted. In this regard, based on available currents and voltages, several indicators are defined to adjust the surge arrester and other elements of the subtransmission network. In addition, appropriate solutions are presented in order to damp the aforementioned resonance and avoid unwanted challenges.

1) Introduction

At present, the zero point (neutral) of most of the subtransmission and transmission networks are connected to the ground directly or through a ground current limiting device. In systems where the zero point is not grounded, in the event of an unbalanced short circuit, such as a phase-to-ground connection, the voltage of the healthy phases can increase to such an extent as to create an electric arc between the live parts of the equipment and the ground. Subsequently, the system equipment and its insulation may be damaged. Therefore, the zero point of the system should be connected to the ground [1].

In the subtransmission network, in the event of an asymmetric fault of the type of single line to ground (SLG) fault, double line to ground (DLG) fault, or line to line (LL) fault, no current is drawn and the fault is not detectable. Therefore, an artificial ground must be created [2]. In order to create an artificial ground, various ideas can be proposed, including resistive ground, capacitive ground, inductive ground, and grounding transformer (G.Tr.). However, due to the disadvantages of each, the idea that is used in practice is using a G.Tr. [3], [4]. The feature of this method of creating artificial neutral is that in the normal operation state of the network (before creating a fault), no load current passes through the G.Tr.. Therefore, in the normal state, the positive sequence impedance is seen in the YNd transformer. But in the event of a phase-to-ground fault in the network, the zero sequence impedance is seen in the YNd transformer [5]–

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[7]. The value of Z^+ of G.Tr. is equal to the magnetic reactance of the nucleus (X_m) and has a large value; while Z^0 is slightly smaller (approximately 0.9 times) than the Thevenin impedance of the transformer (Z_{th} (pu) = U_k% (pu)). G.Tr.s are manufactured in the following two ways [8], [9]:

1) G.Tr. with a zigzag winding whose neutral point is connected to the ground directly or by an impedance (ZN connection).
2) G.Tr. with two primary and secondary windings whose primary winding is with star connection and its neutral point can be connected to the ground directly or by an impedance and its secondary winding is used with triangle connection (YNd connection).

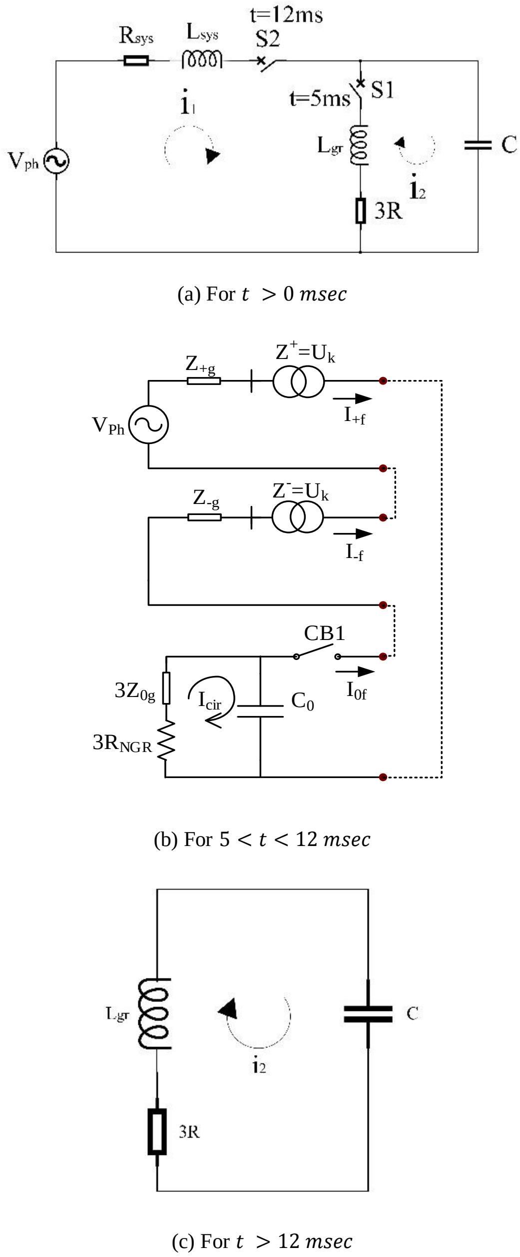
Asymmetric faults in medium voltage (MV) networks cause transient states that not only do not disappear even after the fault is interrupted by the corresponding switches but also in some cases, worse transient states may occur due to the interruption of the fault current. Therefore, due to the interruption of the fault current, a kind of resonance is created in the network and a relatively high current is created in the neutral of G.Tr., which lasts for a long time. References [10] and [11] mention that not only does this resonance damage the G.Tr., but it also causes protection problems with the misalignment of the ground fault relays. In this paper, the aim is to investigate what tools can be used to prevent these disturbances. A sample subtransmission substation is studied, but this analysis is also true for all other subtransmission substations. Moreover, by changing the elements that play a key role in creating critical states, the effect of these changes in reducing the disturbances is examined. The generator of the aforementioned current is a parallel resonance circuit consisting of G.Tr. inductance and system capacitance (cable capacitance or compensating capacitance). Therefore, the cable length is an effective factor in disturbances. One way to investigate system disturbances is to determine changes in current I_n with G.Tr. inductance and system capacitance. Then it can be checked in the case of these disturbances that by which methods (such as damping the oscillations by using resistance in the neutral of G.Tr., change in the connection of the neutrals, etc.), the severity of these disturbances can be reduced.

2) Problem Assumptions

2.1) Simplify the Diagram of the Under-Study Network

This paper assumes that G.Tr. does not saturate. Therefore, the G.Tr. equivalent inductance is a linear inductance and the ferroresonance phenomenon does not occur. But resonance occurs and its effect in waveforms is seen. In various disturbances that occur in 63 kV and 20 kV networks, the elements and topology of the circuit at the same voltage level affect these disturbances. That is, if abnormal fluctuations occur on the 63 kV network, these fluctuations can be eliminated or reduced by changing the elements installed on the 63 kV system, and the elements connected to the 20 kV and 230 kV networks do not affect these disturbances. Due to this fact, in order to simplify the diagram of the circuit, when, for example, the 20 kV system is studied, instead of its upstream systems, i.e. the 230 kV and 63 kV systems, the equivalent Thevenin circuit can be placed. In the event of a single-phase fault on a 20 kV system, the G.Tr. and its neutral resistance enter the circuit. The actual circuit models during the test period are shown in Fig. 1.

Switch S1 closes when the fault has occurred. The fault starting time is assumed 5 msec. Switch S2 is used to clear the fault. The switch S1 remains closed to model the establishment of fault current in the neutral of the G.Tr..



(a) For $t > 0\ msec$

(b) For $5 < t < 12\ msec$

(c) For $t > 12\ msec$

Fig. 1. (a) Equivalent circuit of subtransmission network and 20 kV lines along with modeling of fault occurrence and fault clearance. (b,c) The real model of the subtransmission network circuit considering positive, negative, and zero sequences.

2.2) Obtaining Network Equations

The network equations for **Fig. 1** in both cases, one in the time interval of occurring the fault and the other in the period after that the fault is cleared, i.e. in the interval of $0 < t < 5\,msec$ and $t < 12\,msec$, are specified as follows. The time interval of $5 < t < 12\,msec$ is considered for **Fig. 1**-b and the derivative operator is defined as $D \triangleq \frac{d}{dt}$.

$$[\,3(R_{sys} + R)\,] + (L_{gr} + 3L_{sys})D\,]i_1 - (3R + LgrD)i_2 = Va(t) \tag{1}$$

$$-(3\mathrm{RD} + L_{gr}D^2)i_1 + (3\mathrm{RD} + L_{gr}D^2 + \frac{1}{C})i_2 = 0 \tag{2}$$

L_{gr} is the ground inductance, R is the resistance installed in neutral, and C is the capacitance of the system. By specifying i_1 and i_2 by solving the set of differential equations (1) and (2), the current passing through the neutral of G.Tr. is obtained from the equation $I_{LG} = 3(i_2 - i_1)$. By obtaining i_1, i_2, and I_{LG} at $5 < t < 12\,msec$, the next step is to write the differential equations for $t > 12\,msec$ (**Fig. 1**-c).

$$L_{gr}\frac{d^2 i_2}{dt^2} + 3R\frac{di_2}{dt} + \frac{1}{C}\,i_2 = 0 \tag{3}$$

The initial conditions of equation (3) are obtained from equations (1) and (2), related to i_1, i_2, and I_{LG}. The current passing through the neutral in this case will be equal to the current $3i_2$. As it can be seen, in both time intervals, the current passing through the neutral (I_{LG}) is a function of the values of L_{gr}, C, and R, and for different values of these parameters, the peak value of the neutral current and its attenuation are different [12].

3) Research Methodology

3.1) Simulation of the Desired Network

Using transient mode software such as PSCAD or EMTP, the desired network can be designed. In this research, PSCAD software has been used for this purpose. The network diagram is shown in Fig. 2. Point "a" is connected to ten medium voltage cable feeders. The under-study subtransmission network is 63/20 kV. To model the cable, its π model is used. The network frequency is 50 Hz.

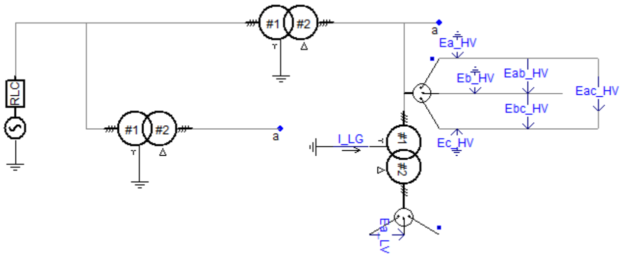


Fig. 2. Diagram of the subtransmission network designed in PSCAD software.

Voltage source: The $\frac{X}{R}$ ratio of the source is equal to 20 and its three-phase short circuit current ($I_{sc-3\varphi}$) is equal to 15 kA. Therefore L = 0.0077 H.

63/20 kV power transformer (PT): The value of U_k% of the power transformer is equal to 12.5% (or 0.125 pu) and its $\frac{X}{R}$ ratio is equal to 25. Therefore, the Thevenin resistance and the Thevenin leakage reactance are equal to 0.005 Ω and 0.125 Ω, respectively.

Cable: Data from "Simco" cable manufacturing company has been used to determine the parameters of the cable. The cable used is 20 kV Power Cable N2XSYRY and the size 1×185 has been selected. According to the information contained in the catalogs of this manufacturer, the value of DC resistance of the cable conductor at 20 °C is equal to 0.0991 Ω/km, the value of cable inductance is equal to 0.377 mH/km and the value of cable capacity is equal to 0.273 µF/km. The value of AC resistance of the cable is 0.130812 Ω/km considering the coefficient of 1.2 due to the temperature effect and also the coefficient of 1.1 due to the skin effect.

3.2) Simulation of the Grounding Transformer

The Thevenin impedance of G.Tr. is determined so that the phase-to-ground fault current passing through the G.Tr. (I_{LG}) is equal to the rated secondary current (triangle connection) of the upstream transformer ($I_{n\Delta}$). The upstream transformer here is the 63/20 kV transformer. On the other hand, the simplified diagram of the network when SLG fault occurs is assumed to be the Thevenin equivalent circuit of the subtransmission network after the G.Tr. enters the circuit and considers the positive, negative, and zero sequences. Therefore, the values of I_{LG} and $I_{n\Delta}$ are obtained as follows:

$$I_{LG} = 3I^0 = 3 \times \frac{V_{ph}}{2Z_{th}^{+} + 2Z_{Th}^{+} + 3Z_g} = \frac{V_{ph}}{\frac{2}{3}(Z_{th}^{+} + Z_{Th}^{+}) + Z_g} \tag{4}$$

$$I_{n_\Delta} = \frac{S_n}{\sqrt{3} \times V_{n_\Delta}} = \frac{15 \times 10^3}{\sqrt{3} \times 20} = 433A = 0.433kA \tag{5}$$

In equation (5), $V_{n\Delta}$ is equal to V_{line} on the triangle connection side.

$$I_{LG} = I_{n_\Delta} \;\Rightarrow\; \frac{V_{ph}}{\frac{2}{3}(Z_{th}^{+} + Z_{Th}^{+}) + Z_g} = \frac{S_n}{\sqrt{3} \times V_{n_\Delta}} \tag{6}$$

$$\Rightarrow Z_{0_{GT}} = 3Z_g = \frac{3(V_{line_\Delta})^2}{S_n}\;[\Omega/phase] \tag{7}$$

In equation (7), the value of $V_{line\text{-}\Delta}$ is equal to 20 kV, and the value of S_n (rated power of P.Tr.) is initially assumed to be equal to 15 MVA.

$$\left.\begin{aligned} Z_{0_{GT}} &= \frac{3 \times (20kV)^2}{15MVA} = 80\,\Omega \\ Z_{base} &= \frac{(V_{line_\Delta})^2}{S_{n_{GT}}} = \frac{(20kV)^2}{1MVA} = 400\,\Omega \end{aligned}\right\} \tag{8}$$

$$\Rightarrow Z_{0_{GT}} = \frac{80}{400} = 0.2\,pu \Rightarrow Z_{th} = \frac{0.2}{0.9} \cong 0.2222\,pu$$

To calculate the zero sequence impedance in per unit, Z_{base} must be obtained using a voltage of 20 kV and a G.Tr. with rated power, which is assumed to be equal to 1 MVA.

According to the above calculation, the amount of U_k% of the G.Tr. is equal to 22.22% (or 0.2222 pu). Its $\frac{X}{R}$ ratio is assumed to be equal to 25. Therefore, the Thevenin resistance and the Thevenin leakage reactance are equal to 0.00888 and 0.222, respectively. The peak current passing through the G.Tr. neutral is calculated as $I_{peak} = \sqrt{2} \times 3 \times \frac{20\times10^3}{\sqrt{3}\times80} = 612.37\,A$. The G.Tr. inductance is equal to $L_{gr} = \frac{Z_{0GT}}{2\pi f} = 254.65\,mH$. The following analysis is performed assuming the rated power of 15 MVA for P.Tr..

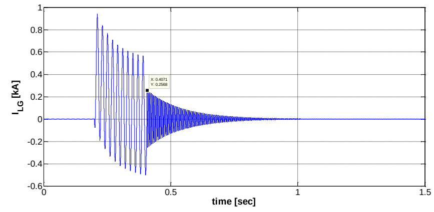
4) Simulation Results

4.1) Checking Different Quantities in Spontaneous Fault Interruption State

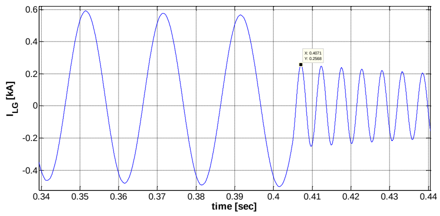
By occurring a single-phase fault at the beginning point of one of the cable feeders, the current passing through the neutral of G.Tr. ($I_{LG} = 3I_0$) is seen. The start time of the single-phase fault is 0.2 sec, and for a better view of the waveform, the fault duration has been set to 1.2 sec. Furthermore, it is assumed that the breaker is currently disabled and does not interrupt the fault. In the waveform, it is observed that after removing the transient state of the fault current (removing its DC component), the peak value of this current is equal to 0.532 kA. That is, its rms value is equal to $0.532/\sqrt{2} = 0.376\,kA$, which is slightly different from the expected value of 0.433 kA and is acceptable. This difference is due to the non-ideal G.Tr.. On the other hand, in the corresponding waveform, it is observed that after fault interruption, the fault current of the neutral of G.Tr. gradually dampens and finally reaches zero value. Because after fault interruption, as mentioned before, the positive sequence impedance is seen in the YNd transformer, which has a large value. It is also observed that the voltage of the healthy phases is increased by almost the same amount. On the other hand, due to the occurrence of resonance, similar to the E_{aHV} waveform, in the case of E_{bHV} and E_{cHV} voltage waveforms, the higher frequency harmonics of the main frequency are mounted on the main waveform and are damped after a while due to the network stability. As expected, the voltage of phase A on the secondary side did not change much due to the fault interruption considering the connection type of G.Tr. (which is YNd); except for a brief DKDC that is caused by the fault and resolves after a short time. The waveform of linear voltages was also examined and it was observed that the occurrence and elimination of fault does not change these voltages.

4.2) Analysis of Diagrams Before Adding Resistance to Neutral of Grounding Transformer

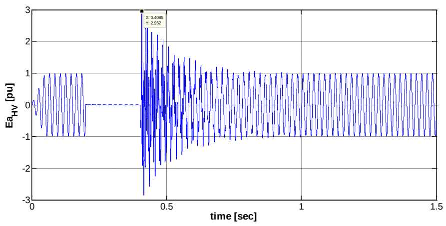
One of the main ways to reduce the high current and voltage created after the breaker is open is to put a resistance in the neutral of G.Tr.. By placing the breaker, it is possible to investigate the effect of various factors on the current I_{LG} and voltage E_{aHV} after interrupting the fault using the breaker. Here the intention is to investigate the effect of this solution on the HV side voltage of phase A as well as the current passing through the neutral of G.Tr. in the case that the total length of the cables is equal to 10 km and the rated power of P.Tr. is equal to 15 MVA. For this purpose, it is assumed that the phase-to-ground fault occurs from 0.2 sec and lasts for 0.5 sec. On the other hand, the breaker of one of the 1 km cable feeders, in which the single-phase fault occurred, operates and opens in 0.4 sec. Before placing the resistance in the neutral of G.Tr., the waveforms of the current I_{LG} and the voltage E_{aHV} are shown in **Fig. 3**.



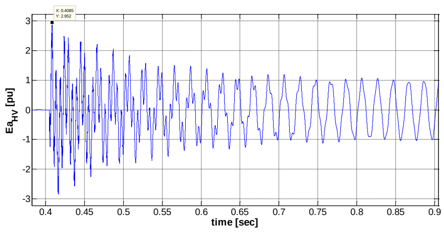
(a) Waveform throughout the simulation period (1.5 sec).



(b) Closer view of the waveform when the fault is interrupted.



(c) Waveform throughout the simulation period (1.5 sec).



(d) Closer view of the waveform when the fault is interrupted.

Fig. 3. Waveform of current I_{LG} (a and b) and voltage E_{aHV} (c and d) in the state of fault interruption using a breaker and before placing the resistance in the neutral of G.Tr..

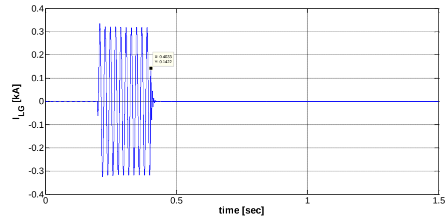
After the fault is interrupted, resonance occurs between the G.Tr. inductance and the cable capacitor. The resonance frequency is obtained from C=2.457μF and L=0.28H. Therefore, the main resonance frequency is about 191 Hz. There are also many small leakage inductances and capacitors that produce high frequencies (in the range of kHz and MHz). The reason for occurring the resonance is that after fault interruption, there are several capacitors and inductances in the circuit, none of which go to saturation, and on the other hand, each of them causes a pole in the circuit equivalent to the analyzed network. As a result of an excitation (shock or δ) entering the network (here, is interrupting the fault), the poles of the system are extracted, each of which creates a multiple of the main frequency, and in total causes a frequency spectrum in which these harmonics are mounted on the main waveform and damped after a few cycles, leaving only the main frequency. Of course, the predominant frequency is 191 Hz. Also, if the network was unstable, the main frequency harmonics would not only not be attenuated, but their amplitude would also be increased. But the inherent nature of the existing network makes it stable; because the resistance of the cables dampens the extra harmonics. The presence of resistive load also has a positive effect on the stability of the network, which, of course, in this paper, the load is not considered.

The multiplicative 3 of harmonics are eliminated in the neutral current of star connection. However, due to the occurrence of asymmetric phase-to-ground faults, the network is not symmetric, and multiplicative 3 of harmonics can also be created in the neutral current of the star connection. In addition, even power harmonics are not produced in the power grid, and on the other hand, the amplitude of higher harmonics as well as harmonics other than 191 Hz is much lower than the amplitude of the main harmonic. This can be seen in the I_{LG} waveform and it can be clearly seen that after the error stopped in 0.4 sec, the frequency of the I_{LG} waveform increased approximately 4 times.

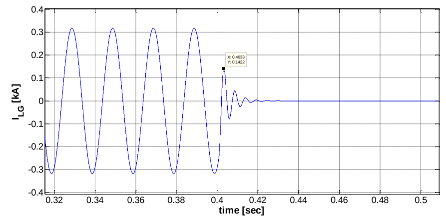
Using an FFT element, the amplitude of the first harmonic (principal harmonic) to the seventh harmonic of the E_{aHV} waveform is obtained. It was observed that after fault interruption, the fourth harmonic of the main frequency (with a frequency of 200 Hz) increases the most and consequently has the greatest effect on the E_{aHV} voltage waveform and the effect of the other harmonics is less. It is important to note that due to the use of the Fourier transform (here, FFT), which gives only the integer multiples of the main frequency, it is not possible to accurately determine the original harmonic associated with the resonance between the cable capacitors and the G.Tr. inductance, which is 191 Hz (what has been achieved before). Secondly, this method does not show the frequency of the other values accurately and provides an approximation of them.

4.3) Analysis of Diagrams after Adding Resistance to Neutral of Grounding Transformer

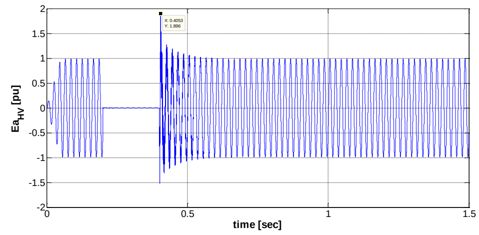
After setting a resistance equal to 50% of the zero sequence impedance of G.Tr. (which according to the above calculations is equal to 80 **Ω**), i.e. a resistance equal to 40 **Ω**, again, the aforementioned voltage and current waveforms are obtained. As it can be clearly seen from **Fig. 3** and **Fig. 4**, by adding resistance to the neutral of G.Tr., both the damping time and the peak of the voltage E_{aHV} and the current I_{LG} are reduced. Of course, in the following, this issue will be examined in more detail and in a quantitative way.



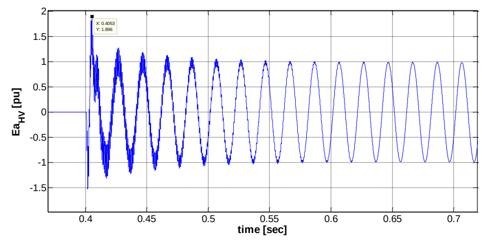
(a) Waveform throughout the simulation period (1.5 sec).



(b) Closer view of the waveform when the fault is interrupted.



(c) Waveform throughout the simulation period (1.5 sec).



(d) Closer view of the waveform when the fault is interrupted.

Fig. 4. Waveform of current I_{LG} (a and b) and voltage E_{aHV} (c and d) in the state of fault interruption using a breaker and after placing the resistance in the neutral of G.Tr..

4.4) Defining the Indicators to Adjust the Surge Arrester and Other Elements of the Subtransmission Network

First, it is assumed that a single-phase fault has occurred at the beginning of one of the 20 kV cable feeders, and it is intended to disconnect that feeder from the main network employing a breaker. This breaker should operate and open after about 100 msec from the start time of the fault. But for better viewing of the waveform, the breaker operation time is considered to be 200 msec after the start time of the fault. As mentioned earlier, the aim is to examine the neutral current peak of G.Tr. as well as the G.Tr. two side voltages in different situations and observe the effect of different factors on the change of these two values. In this paper, it is intended to define indicators and examine the effect of changing a series of factors on these indicators. The two quantities considered are the voltage of phase A on the HV side (EaHV) as well as the neutral current through the G.Tr. (ILG). For each, three indicators are considered and as a result, the following six indicators are analyzed:

1) The peak of voltage E_{aHV} after breaker opening
2) The integral of voltage E_{aHV} with this definition: $\int (Ea_{HV} - 1)^2 \; ; if \; Ea_{HV} > 1$
3) The attenuation time of E_{aHV} waveform, taking into account the time it takes for the E_{aHV} value to be less than 1.02 pu from the start of the simulation and to remain below this value
4) The peak of current I_{LG} after breaker opening
5) The integral of current I_{LG} with this definition: $\int (I_{LG})^2 \; ; if \; I_{LG} > 0.002$
6) The attenuation time of I_{LG} waveform, taking into account the time it takes for the I_{LG} value to be less than 0.002 kA from the start of the simulation and to remain below this value.

The sensitivity analysis is performed on the above six indicators. For this purpose, once it is assumed that P.Tr. capacity is equal to 15 MVA and again, it is equal to 30 MVA. In each of these cases, both G.Tr.s are put in the circuit once and one is taken out of the circuit once. Then, for each of the four mentioned cases, the value of the above six indicators is obtained for different cable lengths (from 10 km to 100 km). Subsequently, the effect of changing the length of the cables (which in turn changes the size of the cable capacitor) on how to change the six outputs and how much they change will be considered.

4.5) Examining the Results for the Six Primary Defined Indicators

First, the output results for the above six indicators were recorded. Then by adding the resistor to the neutral of G.Tr. in the case of 1 G.Tr. in the circuit and also assuming P.Tr. with a capacity of 15 MVA and considering the length of 1 km for each of the cable feeders (10 km of cable feeders in total), again, the waveforms of current I_{LG} and voltage E_{aHV} were plotted and the values of 6 indicators were got. According to the calculations made in section III (research methodology), the value of the zero sequence impedance of G.Tr. (corresponding to 15 MVA P.Tr.) is equal to 80 Ω. The selected values for the neutral resistance of G.Tr. are 5%, 10%, 20%, 30%, 40%, and 50% of the zero sequence impedance of G.Tr.. The same process has been followed for 30 MVA P.Tr..

4.6) Defining the Desired Indicator to Set the Earth Fault Relay

Earth Fault relay is characterized by Normally Inverse. Its Pick-up Current is equal to 200 A and its Time Dial Setting is equal to 0.2 sec. The operating time of the relay (i.e. when the relay issues a trip command to the breaker) is obtained from equation (9).

$$t_{op} = TMS \times \frac{0.14}{(\frac{I}{I_{pick\ up}})^{0.02} - 1} \quad (9)$$

The indicator that can be considered for the proper operation of this relay is defined as "the ratio of the relay counter to the value of the performance limit". The value of this indicator is obtained from the equation $k = \sum \frac{1}{t_{op}}$.

To obtain this indicator, the elements in PSCAD software can be used. For this purpose, an Inverse Time Over-Current Relay is used and the rms value of the current I_{LG} is given to it. The Integrated Output option in the last specification window of this relay (Internal Output Variables) is related to the same indicator *k*. The Pickup Current is set to 0.2 kA and the Time Dial Setting to 0.2 sec. **Fig. 5** shows the use of the mentioned relay block.

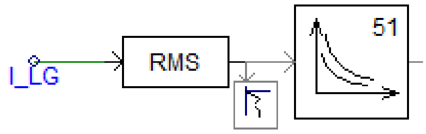
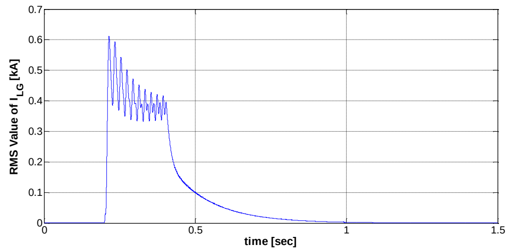
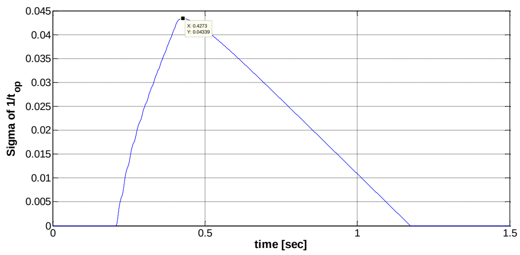


Fig. 5. Using Over-Current relay as Earth Fault relay.

Fig. 6 shows the rms value of the current I_{LG} and the value of the Integrated Output of the Earth Fault relay during the 1.5 sec simulation period.



(a) The rms value of current I_{LG}.



(b) The value of the Integrated Output of the Earth Fault relay.

Fig. 6. The rms value of the current I_{LG} and the value of the Integrated Output of the Earth Fault relay.

The peak value of **Fig. 6** (indicator *k*) should not be more than 5% or 0.05, which in **Fig. 6** is equal to 0.04339 and is desirable. The same process was performed for different cable lengths, once for 15 MVA P.Tr. and once for 30 MVA P.Tr., and the values obtained are listed in Table 2. Then, similar to the process followed for the six initial indicators defined in the previous section, by setting the NGR resistance with values equal to 5%, 10%, 20%, 30%, 40% and 50% of the zero sequence impedance (Z^0) in the neutral of G.Tr., again, the indicator *k* is obtained (for the total length of the cable which is 10 km). The new values are listed in Table 2. It is assumed that $N_{G.Tr.}$ means the number of G.Tr.s in circuit and $S_{P.Tr.}$ means rated power of P.Tr. in MVA.

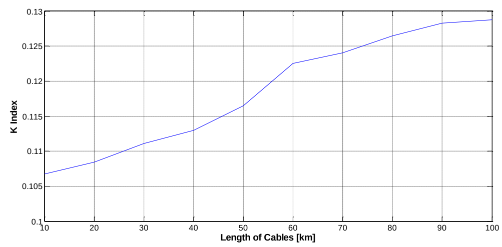
Table 1. Values of indicator $k = \sum \frac{1}{t_{op}}$.

				Length of 20 kV Cables									
				10*1 km	10*2 km	10*3 km	10*4 km	10*5 km	10*6 km	10*7 km	10*8 km	10*9 km	10*10 km
$N_{G.Tr.}$	1	$S_{P.Tr.}$	15	0.1068	0.1084	0.1111	0.1130	0.1165	0.1225	0.1241	0.1264	0.1283	0.1287
			30	0.2166	0.2195	0.2230	0.2284	0.2312	0.2377	0.2436	0.2484	0.2519	0.2572

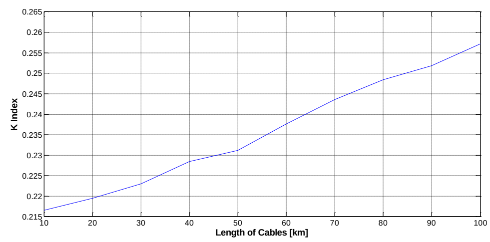
Table 2. Values of indicator $k = \sum \frac{1}{t_{op}}$ considering NGR in the neutral of G.Tr..

				NGR as a Percentage of Z^0						
				0%	5%	10%	20%	30%	40%	50%
$N_{G.Tr.}$	1	$S_{P.Tr.}$	15	0.1068	0.0330	0.0290	0.0209	0.0134	0.0074	0.0030
			30	0.2166	0.1690	0.1532	0.1212	0.0912	0.0670	0.0488

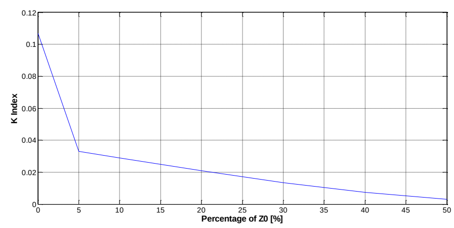
Fig. 7 shows how the indicator k changes with increasing cable length and with increasing resistance.



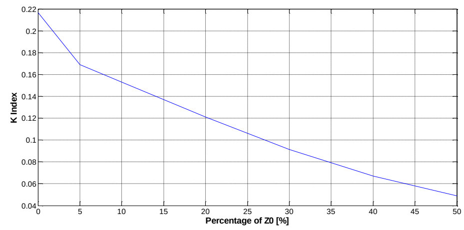
(a) For 15 MVA P.Tr. neglecting NGR in the neutral of G.Tr..



(b) For 30 MVA P.Tr. neglecting NGR in the neutral of G.Tr..



(c) For 15 MVA P.Tr. considering NGR in the neutral of G.Tr..



(d) For 30 MVA P.Tr. considering NGR in the neutral of G.Tr..

Fig. 7. Curve of changes in the value of the indicator $k = \sum \frac{1}{t_{op}}$ in terms of increasing the length of cables (a and b) and in terms of increasing the resistance (c and d) assuming 1 G.Tr. in the circuit.

According to the results obtained in section IV, the following summarized points can be presented. It is assumed that the M indicator means $\frac{Last\ Value}{First\ Value}$.

1. The manner and the amount of changes of 3 indicators related to the neutral current of G.Tr. (I_{LG}) and the voltage of phase A in the HV side of G.Tr. (E_{aHV}) for different cable lengths and in case the neutral of G.Tr. is grounded directly, is according to Table 3 and Table 4 respectively.
2. The manner and the amount of changes of 3 indicators related to the neutral current of G.Tr. (I_{LG}) and the voltage of phase A on HV side of G.Tr. (E_{aHV}) in case the neutral of G.Tr. is grounded by a resistance and for different values of NGR, is according to Table 5 and Table 6 respectively.
3. The manner and amount of changes in the indicator $k = \sum \frac{1}{t_{op}}$ for different cable lengths and in the case where the neutral of G.Tr. is directly grounded, is according to Table 7. Also, the manner and amount of changes in the indicator $k = \sum \frac{1}{t_{op}}$ in the case that the neutral of G.Tr. is grounded by a resistance and for different values of NGR, is according to Table 7.

According to the results mentioned in Table 1, Table 2 and Table 3 and considering that the value of indicator k should not exceed 5% or 0.05, it can be concluded that for proper operation of Earth Fault relay for 15 MVA P.Tr. and for a cable length of 10 km, a resistance equal to or greater than 5% of the impedance Z^0 must be used, i.e. equal to or greater than 4 Ω. However, if a 30 MVA P.Tr. is used and still for the same cable length (i.e. 10 km), the minimum amount of resistance required for use in neutral will be 50% of the zero sequence impedance of the corresponding G.Tr., i.e. 20 Ω. Due to the increasing trend of the value of indicator k for increasing the length of cables (according to Table 7), to keep the value of indicator k at less than 5%, the length of larger cables must be greater than the value of NGR (greater than the corresponding values mentioned in the previous paragraph). However, accurate determination of the corresponding values for 15 MVA and 30 MVA P.Tr.s requires the expansion of studies to cable lengths greater than 10 km.

5) Conclusion

In this paper, the resonance between the grounding transformer and the phase-to-ground capacitor of the MV output feeders of a sample subtransmission substation was investigated due to the phase-to-ground fault interruption. It was also shown that in case of such kind of resonance, a relatively high current is created in the neutral of G.Tr., which lasts for a long time. In this way, several indicators were defined to adjust the surge arrester and other elements of the subtransmission network. Appropriate solutions to reduce this resonance were also suggested. The results obtained for the six mentioned primary indicators related to the voltage E_{aHV} and the current I_{LG} can be used according to the desired characteristics for the surge arrester and other elements of the subtransmission substation and can be generalized to more cases if necessary. In fact, using these results to determine the appropriate value for NGR requires determining a large number of other characteristics related to the elements used in the subtransmission network (e.g. the energy stored in the arrester). Finally, it is possible to determine the appropriate values of network parameters, such as MV cable lengths, NGR, etc. for proper operation of Earth Fault relay.

6) References

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Table 3. Analysis of how the I_{LG}-related indicators change in the case of direct neutral to ground connection.

				Damping Time of I_{LG}			The Result of Integral $\int(I_{LG})^2$			Peak of I_{LG}		
				M	Changing Procedure		M	Changing Procedure		M	Changing Procedure	
					Qualitative	Quantitative (%)		Quantitative (%)	Quantitative (%)		Quantitative (%)	Quantitative (%)
$N_{G.Tr.}$	1	$S_{P.Tr.}$	15	1.266	Slight Increase	26.6	3.074	High Increase	207.4	1.855	Increase	85.5
			30	1.296	Slight Increase	29.6	3.129	High Increase	212.9	2.256	High Increase	125.6
	2		15	1.438	Slight Increase	43.8	3.199	High Increase	219.9	2.217	High Increase	121.7
			30	1.441	Slight Increase	44.1	2.424	High Increase	142.4	2.547	High Increase	154.7

Table 4. Analysis of how the E_{aHV}-related indicators change in the case of direct neutral to ground connection.

				Damping Time of E_{aHV}			The Result of Integral $\int(Ea_{HV}\text{-}1)^2$			Peak of E_{aHV}		
				M	Changing Procedure		M	Changing Procedure		M	Changing Procedure	
					Qualitative	Quantitative (%)		Quantitative (%)	Quantitative (%)		Quantitative (%)	Quantitative (%)
No. of G.Tr.s in Circuit	1	Rated Power of P.Tr. (MVA)	15	1.019	Slight Changes	1.9	0.302	Decrease	-69.8	0.618	Slight Decrease	-38.2
			30	1.168	Slight Changes	16.8	0.475	Decrease	-52.5	0.556	Slight Decrease	-44.4
	2		15	1.305	Slight Changes	30.5	0.491	Decrease	-50.9	0.751	Slight Decrease	-24.9
			30	1.094	Slight Changes	9.4	0.690	Slight Decrease	-31.0	0.774	Slight Decrease	-22.6

Table 5. Analysis of how the I_{LG}-related indicators change in the case of neutral to ground connection by NGR.

				Damping Time of I_{LG}			The Result of Integral $\int(I_{LG})^2$			Peak of I_{LG}		
				M	Changing Procedure		M	Changing Procedure		M	Changing Procedure	
					Qualitative	Quantitative (%)		Quantitative (%)	Quantitative (%)		Quantitative (%)	Quantitative (%)
$N_{G.Tr.}$	1	$S_{P.Tr.}$	15	0.033	Decrease	-96.7	0.041	Decrease	-95.9	0.554	Slight Decrease	-44.6
			30	0.036	Decrease	-96.4	0.081	Decrease	-91.9	0.620	Slight Decrease	-38.0

Table 6. Analysis of how the E_{aHV}-related indicators change in the case of neutral to ground connection by NGR.

				Damping Time of E_{aHV}			The Result of Integral $\int(Ea_{HV}\text{-}1)^2$			Peak of E_{aHV}		
				M	Changing Procedure		M	Changing Procedure		M	Changing Procedure	
					Qualitative	Quantitative (%)		Quantitative (%)	Quantitative (%)		Quantitative (%)	Quantitative (%)
$N_{G.Tr.}$	1	$S_{P.Tr.}$	15	0.297	Decrease	-70.3	0.028	Decrease	-97.2	0.642	Slight Decrease	-35.8
			30	0.183	Decrease	-81.7	0.028	Decrease	-97.2	0.558	Slight Decrease	-44.2

Table 7. Analysis of how indicator $k=\sum\frac{1}{t_{op}}$ changes in two cases of neutral to ground connection, directly (Case A) and by NGR (Case B).

				The Indicator $k=\sum\frac{1}{t_{op}}$ in Case A			The Indicator $k=\sum\frac{1}{t_{op}}$ in Case B		
				M	Changing Procedure		M	Changing Procedure	
					Qualitative	Quantitative (%)		Quantitative (%)	Quantitative (%)
$N_{G.Tr.}$	1	$S_{P.Tr.}$	15	1.206	Slight Increase	20.6	0.028	Decrease	-97.2
			30	1.187	Slight Increase	18.7	0.225	Decrease	-77.5