Device for limiting single phase ground fault of mining machines

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Abstract. The paper shows the reasons and consequences of the single-phase ground fault. With all the variety of devices for limiting the current single-phase ground fault, it was found that the most effective are Peterson coils having different switching circuits. Measuring of the capacity of the network is of great importance in this case, a number of options capacitance measurement are presented. A closer look is taken at the device for limiting the current of single-phase short circuit, developed in the Far Eastern Federal University under the direction of Dr. G.E. Kuvshinov. The calculation of single-phase short-circuit currents in the electrical network, without compensation and with compensation of capacitive current is carried out. Simulation of a single-phase circuit in a network with the proposed device is conducted.

1. Introduction

The grounding device is the most important measure to prevent the risk of electric shock to people. Protective earthing refers to the electrical connection of metal parts of the installation, normally not under voltage, with a grounding electrode that is in direct contact with the soil. Such electrical connection creates a path with low resistance for the current flowing to the ground, as a result of which, when the current is close to frame of the electrical installation, there are no dangerous stresses for the person. According to the safety rules, all metal parts of electrical installations and equipment that are normally not under voltage are grounded, but may be under it due to insulation damage [1-2]. Earthing is subject to the hulls of electrical machines and apparatus, transformers, switchgears, metal cable sheaths. In the workings where there are electrical installations and wiring, pipelines, signal cables, etc., are also grounded. Any equipment is grounded by means of a grounding conductor and grounding conductors, which are connected together by welding. To ensure that the earth resistance value is as low as possible, large earth surface earthers are used, immersed in the most damp soil, and conductors of sufficient cross-section are used to connect to the electrical equipment [3-4].

Since the conductivity of rocks is usually small, it is not possible to provide a sufficiently small amount of the protective earthing resistance of the electrical installation by attaching it to a separate earthing switch. Therefore, in addition to local grounding, they arrange a common mine ground network, to which all objects to be grounded are connected, as well as local and main earthing switches.

To ensure the greatest possible reliability of the network it is necessary that short-circuit current would be so small that for a sufficiently long time (time needed to search for and eliminate damage) it could be dispensed without disabling customers. The current value of short-circuit current is declines
rapidly to a slight stabilized value if the grounded neutral point of the electric network is grounded via throttle reactor, the inductive reactance of which at the frequency of the voltage source feeding the power grid is equal to the resistance at this frequency of the total capacity of all three phases of the mains relative to the ground [5-6].

The objective of this paper is to enable improvement in a set of indicators of a device to limit the current single-phase ground short-circuit in an electrical network, while:
- reducing the weight, power and noise control unit, increasing its performance and efficiency;
- reducing noise and increasing the quality factor of the power element, compared with that inherent in the power element formed in a reactor with a gradually adjustable air gap.

2. The offered device to limit the single-phase short-circuit current

The electrical block diagram of the device to limit current $I$ of single-phase ground short-circuit in an electrical network with unearthed neutral 2 is shown in Figure 1.

![Figure 1. Schematic block diagram of the device to limit the current of single phase short-circuit.](image)

Block 3 is a three-phase voltage source. Block 9 of capacitors with capacitances simulates capacitive conductivity phase, relative to the ground. Resistor $R$ simulates the resistance of the single-phase ground fault for phase $C$. The inductive component of the device is unit 4, which includes the unit 6 - electric filter, unit 7 - multiplier, unit 8 - voltage controlled current source, unit 5 - command block. When the fault occurs, voltage appears on the neutral mains which is supplied to the input of the electric filter 6. A schematic diagram of a filter constructed as a low-pass filter is shown in Figure 2.

![Figure 2. The low pass filter](image)

The transfer function of the filter, as shown in Figure 2, has the form:
\[
W_{RC}(S) = \frac{U_{F,OUT}}{U_{N}(S)} = \frac{1}{1 + \tau \cdot s},
\]

where \( \tau = R_c C_f \) - the time constant of the filter.

This time constant is many times greater than the reciprocal of the angular frequency \( \omega_1 \) of source \( 3 \). Therefore, when the rotary frequency satisfies the condition \( \omega > \omega_1 \), the amplitude and phase frequency indicators of filter \( 6 \), which are obtained after substitution \( s = j \omega_1 \) into the transfer function \( (1) \), have small differences from an ideal integrator with a transfer function \( 1/(\tau \cdot s) \).

The output voltage of the filter is represented in complex form:
\[
\bar{U}_{F,OUT} = \frac{\bar{U}_N}{1 + j \omega_1 \tau}
\]

where \( \bar{U}_N \) is the voltage on the neutral, \( \omega_1 \) is the circular frequency.

The instantaneous value of the voltage is supplied to the second input of the multiplier \( 7 \), to the first input terminal of which the required value of the transfer conduction \( G_{TC} \) by voltage-controlled current source \( 8 \) is applied. Thus the output current of the current source is described by:
\[
\bar{I}_{TC} = \bar{U}_{F,OUT} \cdot G_{TC} = \frac{\bar{U}_N \cdot G_{TC}}{1 + j \omega_1 \tau}
\]

From \( (3) \), the relation \( \bar{U}_N \) to \( \bar{I}_{TC} \) is derived that determines complex impedance equivalent to the inductive component \( 4 \):
\[
Z_{IC} = \frac{1}{G_{TC}} + j \frac{\omega_1}{G_{TC}}
\]

Imaginary component of \( Z_{IC} \) is equivalent to the inductive reactance of the inductive component:
\[
X_{IC} = \frac{\tau \cdot \omega_1}{G_{TC}}
\]

The inductance of the inductive components is:
\[
L_{IC} = \frac{\tau}{G_{TC}}
\]

The real part of \( Z_{IC} \) is equivalent to active resistance and inductive component:
\[
R_{IC} = \frac{1}{G_{TC}}
\]

The \textbf{Q factor} of the inductive component is:
\[
q_{IC} = \frac{X_{IC}}{R_{IC}} = \frac{\omega_1 \cdot L_{IC}}{R_{IC}} = \omega_1 \cdot \tau
\]

The \textbf{Q factor} \( q_{IC} \) of the inductance component greatly exceeds the arc suppression coil quality factor, since the time constant \( \tau \) can reach one or more seconds. Consequently, the quality factor of the inductive component \( 6 \) or more times may exceed the quality factor of throttle reactor.

When replacing the inductive component \( 4 \) with equivalent complex impedance \( Z_{IC} \) consisting of resistance \( R_{IC} \) and inductance \( L_{IC} \), it turns into equivalent circuit (Figure 3) of the system is through an inductive component.

A capacitor with a total capacity of three phases to ground (3C) is switched on parallel to the inductive component. A circuit consisting of two parallel branches (3C and \( Z_{IC} \)) can be configured for current resonance. Then the sum of the currents of the branches becomes a minimum. This resonance is achieved at zero reactive conductivity of the parallel connection, that is, the condition \( X_{IC} = X_{c2} \) should be met. From this, the equation for the required transfer conduction voltage-controlled current source \( 8 \) is derived:
\[
G_{TC} = \tau \cdot \omega_1^2 \cdot C_Z
\]

where \( C_Z \) - the total capacity of the phase-to-earth.
Figure 3. Equivalent circuit system with grounding via inductive component.

Before connecting the inductive component \( I \) to the power supply \( 2 \), it is necessary to set the value of the transfer of the conductivity \( G_{IC} \) from command block \( 5 \). This value depends, according to (9), on the total capacity of all phases relative to the ground. The corresponding signal value with the output terminal of command block \( 5 \) is supplied to the first input terminal of the multiplier \( 7 \).

### 3. The computation of single-phase fault currents in circuits with neutral grounded via a controlled current source

The equivalent circuit of the network with grounded neutral arcing through the reactor is the same as for the case of neutral grounding via a controllable current source, which is shown in Fig. 3. Figure 3 shows that the unknown parameters are the inductance \( L_{IC} \) and resistance \( R_{IC} \) of the inductive component. As the inductive component in this case it assumes the reactor itself [7-8].

The inductance of the inductive component is found from the fact that the circuit is tuned to resonance \((X_{L} = X_{C})\), then

\[
L_{IC} = \frac{X_{IC}}{\omega_0} .
\]  
\[(10)\]

Since controlled current source with RC-filter, which has a time constant \( \tau \) equal to 1 s, is used as the device for limiting fault current component, the quality factor \( q \) is inductive:

\[
q = \omega_0 \cdot \tau = 100\pi
\]  
\[(11)\]

Active resistance \( R_{IC} \) of the inductive component can be calculated knowing the quality factor \( q \):

\[
R_{IC} = \frac{X_{IC}}{q}
\]  
\[(12)\]

Resistance of short circuit is:

\[
Z_{C}(s) = R + ((R_{IC} + S \cdot L_{IC})^{-1} + 3 \cdot S \cdot C)^{-1}
\]  
\[(13)\]

Dependence of the current \( i_{IC}(t) \) from time is found by using the inverse Laplace transform expression \( I_{IC}(s) \). The formula of this dependence has a complicated form, so it is not presented here.

Figures 4 and 5 show plots of the transient current \( i_{IC}(t) \) for the case of neutral grounding through the controlled current source with a quality factor of 100 \( \pi \) [9-10].
Figure 4. Graph of transient ground fault current in interval 0 - 0.02 s.

Figure 5 clearly shows that the amplitude of the sustained fault current is 73mA.

Figure 5. Graph of transient ground fault current in interval 0.02 - 0.05 s.

Thus, in the case of neutral grounding via a controllable current source, the amplitude of the sustained fault current is 6.2 times less than in the case of neutral grounding via arc suppression coil.

4. The modelling of single-phase fault currents in circuits with various devices to recompense for capacitive current

1. Using the current source with low-pass filter of the second order on the basis of the operational amplifier

Second-order low-pass filter can be implemented with operational amplifiers. Scheme of the feedback of amp is selected on the basis of its conduction transfer tables found in [11-13].

The transfer function of such filter is:
\[ W_f(S) = \frac{U_2(S)}{U_1(S)} = 2 \frac{R_2}{R_1} \frac{0.5 \cdot R_2 \cdot C \cdot S + 1}{(R_1 \cdot C)^2 S^2 + 2 \cdot R_2 \cdot C \cdot S + 1} \]

If \( R_1 = 10 \text{ MOhm}, \) \( R_2 = 139 \text{ kOhm} \), \( C_1 = C_2 = C = 2 \mu \text{F} \).

Then the module of the filter of the second order is
\[ K = \frac{2 \cdot 139 \cdot 10^{-3} \cdot 0.5 \cdot 139 \cdot 10^{-3} \cdot 2 \cdot 10^{-6} \cdot j \cdot 100 \pi + 1}{10^{-6} (139 \cdot 10^{-3} \cdot 2 \cdot 10^{-6} \cdot j \cdot 100 \pi + 1)} = 15.9 \cdot 10^{-5} \]

The output voltage of the filter is:
\[ U_{f, \text{out}} = K \cdot U_N \quad (14) \]

The equation of dependent current source is:
\[ I = U_{f, \text{out}} \cdot G_{TC2} = K \cdot U_N \cdot G_{TC2} \quad (15) \]

To make fault current was minimal one needs to \( \frac{U_N}{I} = X_{ce} \), then the transfer conductance of the current source is:
\[ G_{TC2} = \frac{1}{K \cdot X_{ce}} \quad (16) \]

Then, taking into account the known parameters \( K \) and \( X_{c2} \) the transfer conductance of the current source with a filter of the second order will be equal to:
\[ G_{TC2} = \frac{1}{K \cdot X_{ce}} = \frac{1}{15.9 \cdot 10^{-5} \cdot 212.2} = 29.6 \quad (17) \]

2. Using the source of current with an RC filter high pass

The transfer function of RC high-pass filter is:
\[ W_{RC}(s) = \frac{\tau \cdot s}{1 + \tau \cdot s} \quad (18) \]

where \( \tau = C \cdot R \) is the time constant of the filter.

Moreover \( \tau \ll 1 \).

The output voltage of the filter written in complex form is:
\[ \overline{U}_{f, \text{out}} = \frac{U_N \cdot \tau \cdot j \cdot \omega_0}{1 + \tau \cdot j \omega_0} \quad (19) \]

The current-controlled source equation, written in complex form, is:
\[ \overline{I}_{TC} = \overline{U}_{f, \text{out}} \cdot G = \frac{U_N \cdot \tau \cdot j \cdot \omega_0}{1 + \tau \cdot j \omega_0} \cdot G \quad (20) \]

Complex impedance (as is the relationship of \( U_N \) to \( \overline{I}_{TC} \)), equivalent to inductive component, is:
\[ Z = \frac{1 + \tau \cdot j \cdot \omega_0}{\tau \cdot j \cdot \omega_0 \cdot G} = \frac{1}{G} \cdot \frac{1}{j \omega \cdot \tau \cdot G} \quad (21) \]

In this case, the resonance current can be achieved if the following condition is satisfied:
\[ -X = -X_{RC} = 0, \quad \text{where} \]
\[ -X = -\frac{1}{\omega \cdot \tau \cdot G} \] is the imaginary component \( Z \). Then the transfer conductance of the controlled current source is:
\[ G_{RC} = -\frac{1}{\omega \cdot \tau \cdot X_{ce}} \quad (22) \]

Thus the filter resistance is \( R_f = 10 \text{ Ohm}, \) capacity is \( C_f = 1 \mu \text{F}, \) time constant \( \tau \) is \( 10 \times 10^{-6} \) s.

Transfer conductivity is:
\[ G_{TC} = - \frac{1}{\omega \cdot \tau \cdot X_{C_T}} = \frac{1}{100 \pi \cdot 1 \cdot 212.2} = -1.5 \text{ cm} \]  

(23)

With the sustained value high-pass filter circuit current was 1.54 A, but, in contrast to the low-pass filters, the transition process is much lower.

5. Conclusion

Various devices of the throttle reactors that reduce current-phase grounding short-circuit were considered. The device is designed for single-phase fault current limitation, which provides a lower set value of this short-circuit current. Schemes of model of the device with different filters were given. These models have shown the superiority of neutral grounding via the controlled current source as compared to the neutral grounding through the throttle reactor:

- steady-state short-circuit current decreased, because the quality factor of the strength member increased;
- the speed of the device increased (from the current source with a high-pass filter).

In addition, the control unit of the device has a lower weight and less noise than the control unit of throttle reactors.

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