Constructing protection against single phase-to-earth faults in electricity grids

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Abstract. The neutral of the feeding transformer is grounded through the coil of the arc suppression reactor to reduce the arc current in 6–35 kV power systems during single phase-to-earth faults. The inductance of the reactor is tuned in resonance with the network capacity relative to the ground, for which the reactor is made variable. The change in the inductance of the reactor is achieved by stepwise regulation of the number of turns of the reactor coils or a smooth change in the air gap in the circuit of its magnetic circuit. Both methods are associated with a mechanical change in the controlled parameter, which is a significant disadvantage of control systems. To improve the quality of regulation, increase the tuning accuracy and faster response, a scheme for thyristor change in the reactive power of the reactor is proposed. According to the method, the reactor inductance remains constant, while the reactor current and its reactive power are regulated, which provides a resonance mode and eliminates the disadvantages inherent in mechanical control.

1. Introduction
Single phase-to-earth faults in 6–35 kV networks account for up to 90 % of all damages [1–6]. The damage is caused by local weakening of the dielectric strength of the insulation and overvoltage. The vast majority of earth faults are accompanied by arcing. The resulting arc is maintained by the voltage of the undamaged phases. The arc self-extinguishes at low currents, however, at high currents it can burn for a long time damaging the insulation and encourage phase-to-phase faults.

2. Methods and materials
To weaken the arc current, the neutral N of the network transformer is grounded through the arc suppression reactor, Fig. 1.

With short lines, especially air lines, their capacity is small and the quick arc self-extinction occurs. With long and branched networks, the arc can burn for a long time. The extinction of the arc occurs at currents of no more than 5–10 A, and at currents of 10A and more, measures are taken to weaken it [1–2].

The equivalent circuit of a three-phase system (a) and a vector diagram of voltages and currents (b) for a phase A ground fault are shown in Fig. 2.
Using the circuit in Fig. 2, we will compose the equivalent circuit, Fig. 3, where the line capacitance is \( C_L = 3C \), \( C \) – is capacitance between a conductor and earth.

If we replace the circuit of the reactor \( L_K - r_K \) with parallel conductivities

\[
Y_K = \frac{1}{r_K + j \omega L_K} = \frac{r_K}{r_K^2 + (\omega L_K)^2} - j \frac{\omega L_K}{r_K^2 + (\omega L_K)^2}
\]

then,

\[
g \approx \frac{r_K}{(\omega L_K)^2}; \quad b_L \approx \frac{1}{\omega L_K}
\]

**Figure 1.** Scheme of closing A phase ground currents in a network with a neutral grounded through the reactor

**Figure 2.** Diagram of a three-phase system (a) and a vector diagram of currents (b) for a phase A earth fault

**Figure 3.** Equivalent circuit for one of the phases earth short circuit with an arc suppression reactor
According to Fig. 3, the arc current in the equivalent circuit is as follows:

\[ I_\beta = U \left( j \omega C_e + \frac{1}{j \omega L} + g \right) = U \cdot Y, \]

complex conductivity of the whole circuit is as follows:

\[ Y = r_k \left( \frac{1}{\omega L_k} - j \frac{1}{\omega L_k} - \omega C_e \right) = g - j (b_L - b_C) \]

If the inductance of the reactor is in resonance with the capacitance, then the arc current decreases to a value determined by the active conductivity.

\[ I_\beta = U g = U \cdot \frac{r_k}{(\omega L_k)^2} \]

During the network operation, its capacity relative to the ground can vary over a wide range [7–10]. Grounding arc suppression reactor are produced in series and are of two types [3–5]:

- with stepped control and a range of inductance regulation D=2:1;
- with stepless control and a range of inductance regulation D=5:1.

The stepped control of the inductance is carried out manually by the steering wheel on the reactor disconnected from the network; the number of branches is five.

The stepless control can be carried out by changing the air gap in the magnetic circuit controlled by an automatic compensation device without disconnecting the reactor from the network and in the absence of earth short circuit in the network. Controls are triggered when the network capacity changes with respect to the ground.

The disadvantage of the considered methods of tuning the reactor into resonance with the network capacity is the need for mechanical regulation of the reactor inductance in accordance with

\[ L = G_M \cdot (\omega K)^2. \]

Next, it is necessary to consider the possibility of tuning the resonance by the balance of reactive powers. A circuit consisting of parallel-connected branches being active conductivity \( g \), inductance \( L \) and capacitance \( C \) in the phase-to-ground fault mode can be analyzed from the power balance in the L-C branches, Fig. 5.

![Figure 4. Chain of parallel branches g-L-C](image)

3. Results
The resonance condition is formulated based on the balance of reactive powers [6–10]. Applying the first Kirchhoff’s law, we have:

\[ i = i_g + i_L + i_C \]  

Let us express the branch currents through the applied voltage:

- brunch current with active conductivity
  \[ i_g = u \cdot g \]  
- brunch current with inductance
  \[ i_L = \frac{\psi}{L} \]

where the flux linkage \( \psi \) is found from the equality

\[ d\psi = u \cdot dt, \]
\[ \psi = \int_{0}^{t} u dt + \psi(0), \]

while the branch current with inductance is as follows

\[ i_L = \frac{1}{L} \int_{0}^{t} u dt + i_i(0), \quad i_i(0) = \frac{1}{L} \psi_i(0) \text{ with } t = 0 \]

Branch current with a capacitance is

\[ i_C = \frac{dq}{dt} = \frac{d}{dt}(Cu) = C \frac{du}{dt} \]

Taking into account (2), (3), (4), the differential equation takes the following form:

\[ gu + C \frac{du}{dt} + \frac{1}{L} \int_{0}^{t} u dt + i_L(0) = i \]

Let a sinusoidal voltage be applied to the input of the circuit

\[ u = U_m \cdot \sin \omega t. \]

The current in the circuit is represented as

\[ i = I_m \cdot \sin (\omega t - \varphi), \]

where \( \varphi \) is phase angle between voltage and current.

Substituting (6) and (7) into the equation of the chain (5), we obtain:

\[ g \cdot U_m \cdot \sin \omega t + U_m \omega \cdot \cos \omega t - \frac{1}{\omega L} U_m \cdot \cos \omega t = I_m \cdot \sin (\omega t - \varphi) \]

wherein:

\[ i_g = g \cdot U_m \sin \omega t; \]
\[ i_L = - \frac{1}{\omega L} U_m \cos \omega t; \]
\[ i_C = \omega C \cdot U_m \cos \omega t. \]

Next, we find the cardinality of each branch

\[ P_a = g \cdot U_m^2 \sin^2 \omega t; \]
\[ P_L = -b_L \cdot U_m^2 \cos \omega t \cdot \sin \omega t; \]
\[ P_C = b_C \cdot U_m^2 \cos \omega t \cdot \sin \omega t. \]

Considering that \( \sin^2 \omega t = \frac{1}{2} (1 - \cos 2\omega t) \) and \( \cos \omega t \cdot \sin \omega t = \frac{1}{2} \sin 2\omega t, \)

finally, we find the following powers in the branches

\[ \begin{aligned} p_a &= gU^2 (1 - \cos 2\omega t); \\
p_L &= -b_L U^2 \cdot \sin 2\omega t; \\
p_C &= b_C U^2 \cdot \sin 2\omega t \end{aligned} \]

where \( U = \frac{U_m}{\sqrt{2}} \) is root-mean-square voltage.

Different signs of the powers \( p_L \) and \( p_C \) in (9) show their opposite direction and denote the mutual simultaneous exchange of the energies of the magnetic field of the inductance and the electric field of the capacitor [11–17].

At resonance of conductivities \( b_L = b_C \), therefore, for any moment of time we have

\[ p_L = -p_C \]

This comes from the balance of energy and, as a result, powers are as follows:

\[ \frac{d}{dt} \left( \frac{Li^2}{2} \right) = - \frac{d}{dt} \left( \frac{Cu^2}{2} \right) \]
then

\[ \frac{d}{dt} \left( \frac{L}{2} i^2 \right) = L \frac{di}{dt} = L \frac{di}{dt} \cdot i = u \cdot i_L \]

\[ - \frac{d}{dt} \left( \frac{C}{2} u^2 \right) = -C u \frac{du}{dt} = -u \frac{d(Cu)}{dt} = -u \cdot i_C, \]

Thus, the resonance condition can be defined as a balance condition in terms of the magnitude of the inductive and capacitive powers.

In linear circuits ensuring resonance conditions at \( \omega = const \)

\[ \omega^2 LC = 1 \]

is required when changing one of two parameters, for example, capacitance \( C \), changing another parameter – inductance \( L \).

Thus, in the case of a neutral grounded through the reactor, the inductance of the reactor must be mechanically adjusted to tune into resonance.

The need to regulate inductance is one of the problems of protecting systems against single-phase earth faults. Protection here implies minimizing the arc current and the time of its self-extinction achieved due to resonance.

Mechanical regulation of the reactor inductance is difficult and does not provide tuning accuracy, and also does not have the desired response speed.

It is proposed to solve the problem of fast and accurate tuning of the reactor into resonance by regulating the current through the reactor, according to the following formula:

\[ Q_L = \omega L_p i^2, \]

due to a single-phase AC breaker [13–14] connected in series with the reactor coil.

The maximum current through the capacitance occurs at the longest line length, that is, at the highest possible network capacity relative to the ground \( C_m \). Based on this capacitance value, the maximum capacitive current will be as follows:

\[ I_m = \omega C_m \cdot U_f \]

Based on the magnitude of this current, we determine the power balance required for resonance as follows:

\[ \omega \cdot L_p \cdot I_m^2 = \omega \cdot C_m \cdot U_f^2, \]

where find

\[ L_p = C_m \left( \frac{U_f}{I_m} \right)^2 \]

(12)

Reactor power is

\[ S_L = U_f \cdot I_m = \omega C_m U_f^2 \]

(13)

Subsequently, the inductance is not regulated, that is, \( L_p = const \). Since the capacitance of the line can only decrease, the current must decrease to maintain the balance \( Q_L = Q_C \). Based on condition (11), we have:

\[ \frac{I_L^2}{I_m^2} = \frac{C}{C_m} \Rightarrow I_L = \frac{C}{\sqrt{C_m}} \]

(14)

That is, the reactor current should change in proportion to the square root of the relative value of the line capacitance.

AC breakers in high voltage circuits (tens of kilovolts) began to be used after the development of high-voltage power semiconductor control units [3]. A symmetrical thyristor element made according to the scheme, Fig. 5, can be the simplest breaker.
Figure 5. Symmetrical thyristor element operating on inductive load

The current starts flowing through the thyristor VT1 provided that there is a positive potential at the anode A with respect to the cathode K when a positive narrow pulse is applied to the control electrode. When a positive voltage appears, pulsing blocks the thyristor VT1 since the counter current still flowing through VT2 shunts VT1 and the voltages at its anode A and cathode K are practically the same, that is, \( u_{12} = 0 \). And only when the counter current through VT2 decreases to zero, an unlocking pulse can be applied to the thyristor VT1. With a purely inductive load, the control angle \( \alpha \) turns out to be greater than 90° \((\pi/2)\) [5-6]. The load current in the interval of one half-cycle can be determined by solving the following differential equation

\[
L \frac{di}{d(\omega t)} = \sqrt{2}U \cdot \sin \omega t
\]

with the initial condition \( i_n = 0 \) with \( \omega t = \alpha \).

The solution to this equation has the following form

\[
i(t) = \frac{\sqrt{2}U}{\omega L} (\cos \alpha - \cos \omega t)
\]

The effective value of the inductance circuit current with symmetric control will be expressed by the following formula:

\[
I = \frac{\sqrt{2}U}{\omega L} \frac{1}{\pi} \int_0^{2\pi/\omega} (\cos \alpha - \cos \omega t)^2 dt,
\]

which gives the following calculated current formula after integration:

\[
I_L = \frac{2U}{\omega L} \frac{1}{\pi} \left( (\pi - \alpha) \left( \cos^2 \alpha + \frac{1}{2} \right) + \frac{3}{2} \sin \alpha \cdot \cos \alpha \right)
\]

Thus, with \( \alpha = \pi/2 \) and \( \cos \alpha = 0 \)

\[
I_L = \frac{2U}{\omega L} \left( \frac{1}{\pi} - \frac{1}{2} \cdot \frac{1}{2} \right) = \frac{U}{\omega L}
\]

With an increase in \( \alpha > \pi/2 \), the current in the inductor \( I_L \) will decrease. The change in the current from the control angle (p.u.) is shown in Fig. 6.

\[
I_s(\alpha) = \frac{I(\alpha)}{I(\pi/2)} = I(\alpha) \frac{\omega L}{U}, \quad (15)
\]
Figure 6. Current control characteristics of a symmetrical element operating on an inductive load

The scheme for connecting the grounding arc suppression reactor to the neutral of the transformer through the STE thyristor breaker is shown in Fig. 7

Figure 7. Functional diagram of high-speed arc protection against phase-to-earth fault

The current regulation range is determined in the range from nominal (maximum, at $\alpha = \pi/2$) to zero ($\alpha = \pi$). The maximum current value is found from the condition of powers equality $Q_c = Q_L$

$$3\omega C_0 l_{max} U^2 = \omega L l^2_{u(\pi/2)} = x_l l^2_u,$$

where on the left is the power supplied from the ground through the capacitor to the line, and on the right is the power through the reactor to the ground.

Based on the resonance, we select the reactor with the maximum line length and the largest line capacitance relative to the ground

$$\frac{1}{\omega L} = \omega C_0 l_{max}.$$  

Then, the inductance value is as follows:

$$L_{min} = \frac{1}{\omega^2 C_0 l_{max}}$$

$$l_{max} = \frac{U^2}{\omega L_{min}}$$

Design power of the reactor is

$$Q_L = L_{min} \cdot l_{max}^2 = \frac{U^2}{\omega L_{min}}.$$  

In neutral’s effective grounding circuits, the reactive power $Q_L$ is regulated by changing the inductance of the reactor $L_p$ [6].
In the proposed method, the regulation of the inductive power of the reactor $Q_L$ in accordance with the changing capacitive power of the line $Q_C$ is carried out by changing the reactive current $I(\alpha)$:

$$L_{\text{min}} I_L(\alpha)^2 = Q_C(I)$$

If the capacitive power $Q_C$ changes, then the required value of the reactor $I_L$ current for balancing $Q_C = Q_L$ can be determined by the formula:

$$I_{L,\text{max}}(\alpha) = \sqrt{\frac{Q_C}{L_{\text{min}}}}$$

The maximum current will be determined at the minimum inductance $L = L_{\text{min}}$ and angle $\alpha = 90^\circ$.

4. Discussion

The required current magnitude coming through the reactor should be determined by measuring the capacitive power of the network $Q_C$ or the capacitive current. In this case, the reactor current should decrease with a decrease in the capacitive current due to $\alpha$ regulation. The control angle $\alpha$ of the symmetric thyristor element STE (Fig. 7) is found on the basis of the inverse function $\alpha = f^{-1}(I_\alpha)$ with respect to the dependence $I_\alpha = f(X)$ obtained earlier.

The diagram presents power thyristor control unit receiving information through two channels: the channel of the neutral voltage and the phase of this voltage, which depends on the core of the network cable (or line wire for the overhead line) closed to the ground; and through the channel for receiving measurement information about the current value of the line capacitance with respect to ground or capacitive power. From these data, the required control angle $\alpha$ of the STE thyristors is determined.

Shapers with a pulse repetition rate synchronized with the mains frequency are used to form the control pulses. With the appearance of a phase-to-earth short circuit, a reverse voltage of the phase closed to ground appears in the STE and choke circuit. The angle $\alpha$ of supplying pulses to the control electrodes of thyristors provides a set value of the current $I_\alpha$ and, therefore, the balance of reactive powers $Q_C = Q_L$, that is, the parallel resonance mode [6, 7].

A separate task is to form the signal and the control angle $\alpha$ for STE operation in the reactor coil circuit. It should be noted that the solution to this issue is possible on the basis of equipment and measuring technology, which modern arc suppression reactors are equipped with.

5. Conclusion

The research resulted in a solution to the problem of fast and accurate tuning of the reactor into resonance with the network capacitance obtained to reduce the burning of the arc current with the phase shorted to ground. A more perfect control method based on modern methods of power electronics is proposed and substantiated. The reliability of the results is ensured by the use of proven methods of theoretical and experimental research and does not contradict the works [3–11].

The proposed scheme of the thyristor change in the reactive power of the reactor significantly improves the quality of regulation, increases the tuning accuracy and the response speed. According to the proposed method, the inductance of the reactor remains constant, while the reactor current and its reactive power are regulated, which provides the resonance mode and eliminates the disadvantages inherent in mechanical control.

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