Directed protection of the generator

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Abstract. In addition to periodic components of industrial frequency, the aperiodic ones arise in windings and on the generator output leads under the conditions of shortcuts. These aperiodic components slow down the operation of the main differential protection of a generator up to ten periods of a network frequency with the application of saturated magnetic cores of current transformers as well as zero current relays and transformer differential protection [1]. This slowing down promotes accidents and can even lead to generator’s winding and steel burn-out at high-ampere currents. The present paper considers the ways to reduce the impact of aperiodic components on the operation of digital relay protection of generators and generator-transformer blocks and proposes generator’s directional digital protection.

1. Introduction

Digital protections gain considerable attention. Predominately, the algorithms of existing analog protections are implemented [2–4]. The difference between digital relay protections and analogue ones is that analogue protections receive operational information continuously while digital ones receive it discretely at equal intervals of time called sampling intervals and are processed by microprocessors. Particular attention is paid to the protections which apply information about changes in currents [5, 6]. This article proposes a method for determining a sinusoidal component of the short circuit current on the basis of four samples of instantaneous values.

Methods of implementing digital directional protection of a generator and a generator-transformer block are considered. An algorithm aimed to exclude aperiodic components from the measured currents is proposed and investigated. The measurement time of four samples does not exceed 2.0 – 2.5 milliseconds with the sampling intervals from 0.5 to 0.625 milliseconds. During this period the magnetic cores of current transformers do not saturate, i.e. relay protection receives undistorted information.

2. Research objective

Winding and steel burnout is the damage to generators stators caused by short circuits. Damage recovery is carried out in the factory by generator dismantling, which often results in the long-term shortage of electricity among consumers of a large territory even in the case of current repairs at the stations. The process of assembling generators after repairs can take several days. Accidents in the power system during this period can lead to a long period of power cutoff of both domestic and industrial consumers.
[2]. The amount of a burned-out metal substantially depends on the short circuit duration. Aperiodic components in short-circuit currents slow down relay protection response time up to 0.2 s or more. Therefore, modern relay protection is launched after analog or digital filtering [3 – 5]. In addition, the current distance generators protections fail due to zero voltage [1]. Therefore, the development of relay protection algorithms shortening the faults identification period by several times being triggered when the voltage is zero proves to be rather relevant [5, 6]. Unfortunately, turning analog relay protections into digital ones does not contribute to a significant reduction in the time of its operation. The present paper proposes a digital relay protection algorithm able to recognize a short circuit during 2–2.5 ms.

![Figure 1 Scheme of the power system’s electrical network](image)

3. Materials and methods
Let us consider a part of the electrical network shown in Fig. 1. A three-phase short circuit occurred on the generator buses. The voltage dropped to zero. Remote protection is not able to determine the short circuit current direction and can be triggered at short circuit on the generator buses outside the protection zone. The probability of an external fault is several times higher since the generator current transformers are installed in the generator chamber and the generator buses from the camera to the generator voltage switchgear or the generator-transformer unit transformer are ten times longer than the buses from the generator terminals to its chamber. Additionally, there is a chance of a false shutdown. The situation can be improved by applying voltage $U_2$ rather than voltage $U_1$ due to the fact that $U_2$ has a value equal to the product of a short circuit current by the transformer $T_1$ resistance reduced to the generator voltage and surpasses the voltage $U_1$ by $30^\circ$ angularly. This voltage is sufficient for correct short circuit identification. It is possible to use voltages $U_3$ and $U_4$.

As it was mentioned above, an aperiodic component, which is always present in the fault current, firstly, slows down relay protection and, secondly, can lead to its false work.
Let us consider the ways to exclude the aperiodic component within 2.0–2.5 ms. If we fix the values of four measurements of instantaneous currents at equal sampling intervals $\Delta t$, then at the time instants $2\Delta t$ and $3\Delta t$ and a sinusoidal current $i(t) = \sin(\omega t)$ we obtain the following:

$$
i_v(\Delta t) = \frac{2i(2\omega \cdot \Delta t) - i(\omega \cdot \Delta t) - i(3\omega \cdot \Delta t)}{4\sin^2 \left(\frac{\omega \cdot \Delta t}{2}\right)}$$

$$v(2\Delta t) = \frac{2i(2\omega \cdot \Delta t) - i(\omega \cdot \Delta t) - i(3\omega \cdot \Delta t)}{4\sin^2 \left(\frac{\omega \cdot \Delta t}{2}\right)}$$

(1)

where $\omega$ is angular frequency, $t$ is current time, $\Delta t$ is discretization interval per second.

Generally,

$$i_v(t) = \frac{2i(n \cdot \omega \cdot \Delta t) - i((n - 1) \cdot \omega \cdot \Delta t) - i((n + 1) \cdot \omega \cdot \Delta t)}{4\sin^2 \left(\frac{\omega \cdot \Delta t}{2}\right)}$$

Let us consider this method by the example of a short circuit current equal to [7]:

$$i(t) = \frac{E_{eq}}{\sqrt{R_{eq}^2 + X_{eq}^2}} \left(\sin(\omega \cdot t + \psi - \varphi) - \sin(\psi - \varphi) \cdot e^{-\frac{\Delta t}{T_N}}\right)$$

(2)

where $t$ is current time, $E_{eq}$ is equivalent electric force, $R_{eq}$, $X_{eq}$ is equivalent active and reactive resistances with respect to a short circuit point, $T_N$ is the time constant of the network relative to the short circuit point, $\psi$ is an angle between an equivalent electromotive force and short circuit current, $\varphi$ is an angle between an equivalent electromotive force and short circuit current.

Let us compute the values of the currents $i_v(t)$ at the time $(\Delta t)$ and $(2\Delta t)$ according to (1) and distract $i_v(\Delta t)$ and $i_v(3\Delta t)$ correspondingly. The time constant is determined as:

$$T_N = \frac{-\Delta t}{\ln \left(\frac{i_v(2\Delta t) - i(3\Delta t)}{i_v(t) - i(2\Delta t)}\right)}$$

(3)

Angle $\varphi$ is determined via the network constant and angular frequency:

$$\varphi = \arctan(T_N \cdot \omega)$$

(4)

The aperiodic component is as follows:

$$i_A(t) = \frac{U_{eq}}{\sqrt{R_{eq}^2 + X_{eq}^2}} \left[\sin(\varphi) - \sin(\psi - \varphi) \cdot e^{-\frac{\Delta t}{T_N}}\right]$$

(5)

The sinusoidal component is determined as follows:

$$i_{\sin}(t) = i(t) - i_A(t)$$

(6)

while a total current of short circuit is determined as follows:

$$i(t) = \frac{U_{eq}}{\sqrt{R_{eq}^2 + X_{eq}^2}} \left(\sin(\omega t + \psi - \varphi) - \sin(\psi - \varphi) \cdot e^{-\frac{\Delta t}{T_N}}\right)$$

(7)

The sinusoidal component and its derivative can be determined through the following equations at any time:

$$i_{\sin}(t) = \frac{U_{eq}}{\sqrt{R_{eq}^2 + X_{eq}^2}} \left(\sin(\omega t + \psi - \varphi)\right) \quad i'_{\sin}(t) = \frac{U_{eq}}{\sqrt{R_{eq}^2 + X_{eq}^2}} \left(\cos(\omega t + \psi - \varphi)\right)$$

(8)

The amplitude value of the short circuit current is equal to its argument:

$$I = \sqrt{i_{\sin}^2(t) + i'_{\sin}(t)^2} \quad \varphi = \arctan \left(\frac{i'_{\sin}(t)}{i_{\sin}(t)}\right)$$

(9)

Active and reactive powers are determined as follows:

$$P = \frac{U \cdot I}{2} \cdot \cos(\varphi), \quad Q = (U \cdot I)/2 \cdot \sin(\varphi)$$

(10)

The complex power is calculated through the product of the voltage and the conjugate current complex.
\[ S(t) = \frac{(u \sin(t) + u' \sin(t) \cdot j)}{2} \cdot \frac{(i \sin(t) - i' \sin(t) \cdot j)}{2} \] (11)

4. Research

Let us consider an example of a short circuit on the generator tires with the following parameters: 120 MW power, rated voltage equal to 10.5 kV, \(\cos \varphi\) is 0.85, \(x_{d}^\prime\) is 0.189, \(x_2\) is 0.23. The time constant of the stator windings is 0.03 s. Three-winding transformer 250/220 parameters are as follows: power is 250 MVA, rated voltage of the higher winding is 242 kV, medium voltage is 37.5 kV, low voltage is 10.5 kV, \(U_{k-h}\) av is 11\%, \(U_{k-h-l}\) is 24\%, \(U_{k-l}\) av is 36\%, \(\Delta P_k\) is 0.6 MW, \(\Delta P_{\text{oh}}\) is 0.207 MW, high voltage windings are grounded. Line parameters are the following: L is 100 km, R is 0.33 ohm/km, X is 0.36 ohm/km.

The amplitude of the periodic component is 23.7 kA and the maximum aperiodic component is equal to the periodic one. Four measurements since the occurrence of a short circuit are as follows: sampling interval of 0.625 milliseconds: \(i(\Delta t) = 0.4547\) kA, \(i(2\Delta t) = 1.7891\) kA, \(i(3\Delta t) = 3.9333\) kA, \(i(4\Delta t) = 6.7866\) kA.

According to (3), the time constant with an accuracy of 4 characters is \(T_N = 0.0297\) s. By putting \(T_N\) into (4) we get \(\varphi = 1.464\) radian or 83.88\(^0\). The effective value of the sinusoidal current is 23.7 kA.

According to (5), \(i_A(t) = 23.7 \cdot [\sin(\psi - \varphi)] \cdot e^{\frac{-t}{T_N}}\) kA. If \(i(\Delta t) = 0.45\) kA, \(i(2\Delta t) = 1.78\) kA, \(i(3\Delta t) = 3.93\) kA, \(i(4\Delta t) = 6.78\) kA, \(T_N = 0.03235\) s, we get \(\varphi = 1.473\) radian or 84.40\(^0\), the effective value of the sinusoidal current is 23.69 kA. A further decrease in the measurement accuracy practically does not affect the calculation of the current amplitude. If the currents are measured with two decimal places after comma, the calculated amplitude of the sinusoidal component decreases to 23.695 kA. The periodic component is obtained by applying (6): \(i_{\text{sin}} = i(t) - i_A(t) = 23.7 \sin(\omega t - \varphi)\). Power is determined according to (11). The calculated currents and powers are given in Fig. 2 and 3.

\[ i_1(t) = [i_\alpha(\omega \cdot t) + (i_\beta(\omega \cdot t + \frac{\pi}{2})) - i_\gamma(\omega \cdot t + \frac{\pi}{2})]/\sqrt{3}/2 \] (12)

\[ i_2(t) = [i_\alpha(\omega \cdot t) - (i_\beta(\omega \cdot t + \frac{\pi}{2})) - i_\gamma(\omega \cdot t + \frac{\pi}{2})]/\sqrt{3}/2 \] (13)

The outcomes are the same when using the following equations:
\[ i_1(t) = \left( i_A(\omega \cdot t) + i_B \left( \omega \cdot t + \frac{2\pi}{3} \right) \right) / 3 + \frac{[i_C \left( \omega \cdot t - \frac{2\pi}{3} \right)]}{3} \tag{14} \]

\[ i_2(t) = \left( i_A(\omega \cdot t) + i_C \left( \omega \cdot t + \frac{2\pi}{3} \right) \right) / 3 + \frac{[i_B \left( \omega \cdot t - \frac{2\pi}{3} \right)]}{3} \tag{15} \]

Equations (12) and (13) have fewer calculations.

Figure 3. Design power. The dashed line is the product of voltage by the current in accordance with (1) and (6), solid line is the product of voltage by the conjugated current complex calculated in accordance with (11)

The advantage of the proposed method is the opportunity to apply only four measurements of short-circuit currents. In this case, the instantaneous values of the aperiodic and sinusoidal periodic components, the amplitude values and arguments of the short-circuit currents, the active and reactive powers in the elements of the electric network for at least three or four periods of the frequency of the electric network are calculated. The proposed method enables to create high-speed protection with a short circuit identification time for a quarter of the frequency period of the electrical network. It is possible to create algorithms for all protections using currents and algorithms for determining the location of damage on power lines. The aperiodic components in the fault currents have a significant effect on the accuracy of determining fault locations by modern fault localization systems. The error of current measurements during 2.0–5.0 ms can reach 30% of the line length. Saturation of the magnetic cores of current transformers as well as zero current relay and differential relay, which slow down protection at least up to 0.2 s, does not affect the accuracy of separating sinusoidal components from the short circuit currents.

5. Conclusions
The method of selecting periodic components of short circuit currents from currents equal to the sum of the periodic and aperiodic components has been developed.

The algorithm based on this method uses only four samples separated by three sampling intervals, which eliminates the possibility of saturating the magnetic cores of current transformers by using information in the areas of sufficiently accurate transformation.

The method enables to calculate the currents of the forward and reverse sequences as well as any combination of these sequences, the resistance and power used in relay protection and emergency control at any time by measuring only four short-circuit currents in the following range: 2.0–2.5 ms.

Directional protection for generators is being proposed. It is proposed to use the voltages of adjacent elements of the electric network connected to the protected objects with the purpose to eliminate dead zones with closed three-phase short circuits.
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