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New filters for symetrical current components

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ABSTRACT

Negative- and zero-sequence-current filters based on inductance coil and magnetically operated switch with control winding without the use of current transformers are considered. The technique is presented for the calculation of coordinates of the points where the inductance coil and magnetically operated switch should be mounted for the cases of triangle and parallel arrangements of conductors of three phases of an electrical installation. The main unit for mounting the inductance coil and magnetically operated switch with the control winding near the electrical installation phases conductors is described. The relations for the parameters of filter components are derived. An example of the calculation of these parameters is given.

1. Introduction

Construction of relay protection (RP) without current transformers (CTs) was repeatedly mentioned as an urgent problem at International Conferences on Large Electric Systems (of CIGRE) [1,2]. The use of magnetosensitive elements is one of the ways of the problem solution. Works on the creation of RP on the basis of inductance coils (IC) [3,4], Hall sensors [5], magnetically operated sealed switches (MOS) [6] began in the 1970–80s; later on, magnetic transistors [7] and Rogowski coils [2] were suggested. A preferable RP version will be chosen after the completion of the works and from the operation experience of RP with the above listed sensors. However, most works are far from over. We have selected MOS and IC, since MOSs are commonly used in engineering [8,9] and have some advantages important for RP [6,8,10], and ICs have been used in RP for a long time, including like CTs [4]. This work is devoted to the design of MOS- and IC-based systems capable of operating as filters of symmetrical current components, which are widely used in RP, without the use of CTs.

2. Negative-sequence-current filter (NSCF) in the case of triangle arrangement of phases

The NSCF without CTs suggested includes (Fig. 1) MOS 1 with control winding 2, amplifier 3, phase rotation circuit 4 (PRC), adjusting resistor 5, and IC 6. The MOS and IC are mounted in the magnetic filed of currents IA, IB, and IC in conductors of phases A, B, and C of the electrical installation so as their longitudinal axes are in a plane perpendicular to the conductor axes.

The MOS serves an output relay of the filter; it switches contacts (is actuated) when the induction $\underline{B}_{\mathrm{LA}}^{\Sigma}$ of the total magnetic fields, which act along the longitudinal axis of the MOS at the point M—MOS's center of gravity, becomes sufficient for producing magneto-motive force (MMF) F of MOS actuation, i.e., $F\mu_0/l = \underline{B}_{\mathrm{LA}}^{\Sigma}$, where l is the coil length of the manufacturer's IC. It is clear that the MOS reacts to I_2, if $\underline{B}_{\mathrm{LA}}^{\Sigma} = K_1 I_2$ (K_1 is the coefficient of proportionality). It is obvious that

$$\underline{B}_{\mathrm{LA}}^{\Sigma} = \underline{B}_{\mathrm{LA}}^{\mathrm{MOS}} + \underline{B}_{\mathrm{LA}}^{\mathrm{WIND}},$$

where $\underline{B}_{\mathrm{LA}}^{\mathrm{MOS}}$ и $\underline{B}_{\mathrm{LA}}^{\mathrm{WIND}}$ are the inductions of the magnetic fields (acting along the MOS longitudinal axis) produced by the currents of the electrical installation phases and current in winding 2.

Hence, for the MOS to serves an output relay of NSCF, the device parameters and MOS and IC coordinates near the electrical installation phases should be selected so as to ensure the equality

$$\underline{B}_{\mathrm{LA}}^{\Sigma} = \underline{B}_{\mathrm{LA}}^{\mathrm{MOS}} + \underline{B}_{\mathrm{LA}}^{\mathrm{WIND}} = K_1 \underline{I}_2 \tag{1}$$

Derivation of the device parameters and MOS and IC coordinates. Let represent $\underline{I}_2$ in Eq. (1) as [11]

Abbreviations: CT, current transformers; IC, inductance coils; MOC, magnetically operated sealed switch; NSCF, negative sequence current filters; ZSCF, zero sequence current filters; NSC, negative sequence current; EMF, electromotive force; FRS, phase rotation circuit; DSC, direct sequence currents

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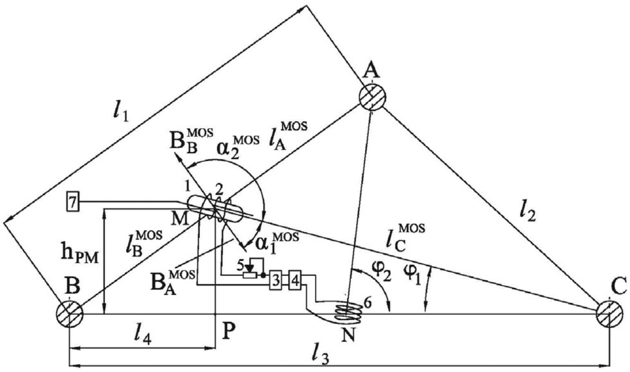


Fig. 1. NSCF in the case triangle arrangement of the electrical installation phases.

$$3\underline{I}_2 = (\underline{I}_A - \underline{I}_B) + (\underline{I}_B - \underline{I}_C)\cdot e^{-j\cdot 60} \tag{2}$$

where $\underline{I}_A$, $\underline{I}_B$, and $\underline{I}_C$ are the total current in the phases A, B, and C; $e^{-j\cdot 60}$ is the complex number that characterizes the counterclockwise 60-degree phase shift.

This representation has been chosen to exclude the effects of magnetic fields produced by zero-sequence-currents to the MOS and IC. When decomposing the phase currents into symmetrical components, the zero-sequence-currents are co-directed in all the phases and compensate each other when subtracting.

Eqs. (1) and (2) show that MOS 1 reacts to current I_2, if the device parameters and MOS and IC coordinates provide for the fulfillment of equations

$$\underline{B}_{LA}^{MOS} = K_1(\underline{I}_A - \underline{I}_B)/3 \tag{3}$$

$$\underline{B}_{LA}^{WIND} = K_1(\underline{I}_B - \underline{I}_C)e^{-j\cdot 60}/3 \tag{4}$$

The induction $\underline{B}_{LA}^{MOS}$ is produced by currents of all the phases; therefore, according to the Biot–Savart–Laplace law and accounting that MOS is affected by the magnetic field of currents of all the three phases,

$$\underline{B}_{LA}^{MOS} = \frac{\mu_0 \underline{I}_A}{2\pi l_A^{MOS}}\cos\alpha_1 + \frac{\mu_0 \underline{I}_B}{2\pi l_B^{MOS}}\cos\alpha_2 + \frac{\mu_0 \underline{I}_C}{2\pi l_C^{MOS}}\cos\alpha_3 = \\ = \underline{B}_A\cos\alpha_1 + \underline{B}_B\cos\alpha_2 + \underline{B}_C\cos\alpha_3 \tag{5}$$

where $\underline{B}_A$ ($\underline{B}_B$ and $\underline{BC}$) is the induction of the magnetic field produced by the current $\underline{I}_A$, ($\underline{I}_B$ and $\underline{I}_C$) at the point M; α_1 (α_2 and α_3) is the angle between the longitudinal axis of MOS and $\underline{B}_A$ ($\underline{B}_B$ and $\underline{B}_C$); l_A^{MOS}, l_B^{MOS}, and l_C^{MOS} are the distances from the conductors of phases A, B, and C, respectively, to the point M; μ_0 is the vacuum permeability; π is the ratio of a circle's circumference to its diameter, π = 3,14.

The analysis of Eqs. (3) and (5) shows that condition (3) fulfils if

$$K_1 = \frac{\mu_0}{2\pi l_A^{MOS}}\cos\alpha_1^{MOS} = -\frac{\mu_0}{2\pi l_B^{MOS}}\cos\alpha_2^{MOS} \\ \text{and} \quad \frac{\mu_0}{2\pi l_C^{MOS}}\cos\alpha_3^{MOS} = 0 \tag{6}$$

As for condition (4), its fulfillment is supported by corresponding coordinates of IC, the amplification coefficient K_A of amplifier 3 (Fig. 1), and calculations of the angle β_{PRC} of phase angle circuit (4). The induction $\underline{B}_{LA}^{WIND}$is produced by the current I_{out} in control winding 2; I_{out} is produced by the electro-motive force (EMF) E at the leads of IC 6, and E is produced by the flux Φ (produced by the currents of the three phases) with the magnetic induction $\underline{B}_{LA}^{IC}$acting along the longitudinal axis of IC. Finally,

$$\underline{B}_{LA}^{WIND} = K_2\underline{B}_{LA}^{IC} \tag{7}$$

The formulas that connect all these parameters, as well as the coefficient K_2, are well known and are given in Appendix A.

Let us note that the induction $\underline{B}_{LA}^{IC}$is represented by similar formulas (with the corresponding angles and distances, denoted below by the superscript IC); l_A, l_B, l_C, α_1, α_2, and α_3 below mean values different from the above considered and proper for each filter, as well as the parameters of their components.

Induction $\underline{B}_{LA}^{WIND}$ (7) should coincide with $\underline{B}_{LA}^{WIND}$ (4); therefore,

$$K_1(\underline{I}_B - \underline{I}_C)e^{-j\cdot 60}/3 = K_2\underline{B}_{LA}^{IC} \tag{8}$$

Let us consider Eq. (8) as an equation in terms of K_A and β_{PRC} which enter into K_2 (see Section A). The right part of the equation should be proportional to the difference ($\underline{I}_B$ - $\underline{I}_C$) to be reduced to it (otherwise, the equation turns out to be undetermined). For $\underline{B}_{LA}^{IC} = K_3(\underline{I}_{-}\underline{I}_C)$, where K_3 is the coefficient of proportionality, it is sufficient to satisfy conditions similar to (6):

$$K_3 = \frac{\mu_0}{2\pi l_B^{IC}}\cos\alpha_2^{IC} = -\frac{\mu_0}{2\pi l_C^{IC}}\cos\alpha_3^{IC} \\ \text{and} \quad \frac{\mu_0}{2\pi l_A^{IC}}\cos\alpha_1^{IC} = 0 \tag{9}$$

Substituting K_1 from Eq. (6), K_2 from Eq. (A.3), and K_3 into Eq. (8) and transforming, we derive an equation, from which β_{PRC} and then K_A can be found: $\beta_{PRC} = 30^\circ + \varphi$, since real multipliers are in one part of the equation, and multipliers represented by e in powers that include φ, β_{PRC}, -60°, and -90° are in another part.

The MOS and IC should be mounted at the points M and N on the plane ABC (Fig. 1), which is perpendicular to the axes of the electrical installation phase conductors, and satisfy safety requirements for conditions (6) and (9) to fulfill. They fulfill strictly if the MOS and IC are centered at sides AB and BC.

For the convenience of mounting the MOS at the point M, the length of the segment l_4 (Fig. 1) and height PM = h_{PM} in the triangle BMC should be determined. The interphase distances l_1, l_2, and l_3 known at any arrangement are considered as initial data. Then, using the aspect ratio in the triangles ABM, ACM, and MBC, after simple transformations, we derive

$$a)\ l_4 = \frac{l_1^2 + l_3^2 - l_2^2}{4l_3}, \qquad b)\ h_{PM} = \frac{\sqrt{4l_1^2 l_3^2 - (l_1^2 + l_3^2 - l_2^2)^2}}{4l_3}.$$

After fixing MOS 1 and IC 6 at the points M and N with the use of corresponding constructions [12], MOS 1 and IC 6 are rotated so as their longitudinal axes coincide with the straight lines passing through the points M and C and N and B.

Let us consider NSCF operation. During two-phase shorts (SC), negative-sequence currents $\underline{I}_{A2}$, $\underline{I}_{B2}$, and $\underline{I}_{C2}$ run through the electrical installation phase conductors. They are representable as $\underline{I}_{A2} = I_2 e^{j0^0}$, , and $\underline{I}_{C2} = I_2 e^{-j120^0}$($e^{j0}$, e^{j120}, and e^{-j120} are the complex numbers, which correspond to the clockwise 0- and 120-degree and counterclockwise 120-degree phase shifts). Let substitute them in Eq. (2) instead of $\underline{I}_A$, $\underline{I}_B$, and $\underline{I}_C$. Then Eqs. (1) and (3) with accounting for Eqs. (4) and (6) imply $\underline{B}_{LA}^{\Sigma} = \mu_0(\cos\alpha_1^{MOS1}/l_A^{MOS1})\underline{I}_2/2\pi$, MOS 1 acts, switches the contacts on, and feds a signal to actuator 7 (see Fig. 1). Zero-sequence currents $\underline{I}_{A0} = \underline{I}_{B0} = \underline{I}_{C0}$ run through the conductors of phases A, B, and C of the faulty electrical installation during SC. However, as seen from Eqs. (3) and (4), if $\underline{I}_{A0}$, $\underline{I}_{B0}$, and $\underline{I}_{C0}$ are substituted for $\underline{I}_A$, $\underline{I}_B$, and $\underline{I}_C$, then $\underline{B}_{LA}^{\Sigma} = 0$, and they affect neither MOS no IC. During two-phase and single-phase SC, positive-sequence currents $\underline{I}_{A1}$, $\underline{I}_{B1}$, and $\underline{I}_{C1}$ also run through the phase conductors. But the field produced by them affects neither MOS with winding no IC. It is easily seen if substituting $\underline{I}_{A1} = I_1 e^{j0^0}$, $\underline{I}_{B1} = I_1 e^{-j120^0}$, and $\underline{I}_{C1} = I_1 e^{j120^0}$into Eq. (2) for $\underline{I}_A$, $\underline{I}_B$, and $\underline{I}_C$. Thus, a signal at the exit of the filter suggested is generated only in the case of faults of the electrical installation accompanied by $\underline{I}_2$ currents.

3. Zero-sequence-current filter (ZSCF) in the case of triangle arrangement of phase conductors

Zero-sequence-current filter (ZSCF) [13] in the case of triangle arrangement of phase conductors can be constructed on the basis of a MOS without IC. Let us show this. Eq. (5) implies that $\underline{B}_{LA}^{MOS} = 3K_4\underline{I}_0$, if

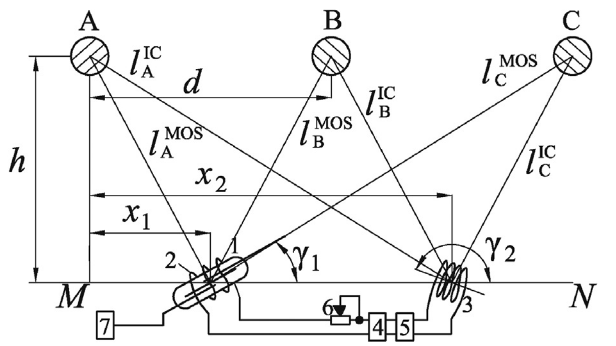


Fig. 2. Filter for symmetrical components in the case of horizontal arrangement of phases.

$$K_4 = \frac{\mu_0}{2\pi l_A^{MOS}}\cos\alpha_1^{MOS} = \frac{\mu_0}{2\pi l_B^{MOS}}\cos\alpha_2^{MOS} = \frac{\mu_0}{2\pi l_C^{MOS}}\cos\alpha_3^{MOS} \quad (10)$$

Using Eq. (10) and the cosine law, a set of equations is composed, solution of which provides for l_A, l_B, l_C, α_1, α_2, and α_3. The calculation is carried out in MathCad 11. The result is that all the points where MOS can be mounted to serve as ZSCF are on a circle circumscribed about the triangle ABC, and the longitudinal axis of a MOS should be tangential to this circle.

4. Negative-and-zero-sequence-current filters in the case of parallel arrangement of phase conductors in one plane

Let this plane be horizontal. For convenience of mounting MOS and IC and simplification of the calculations, let us arrange MOS and IC in a vertical plane symmetrically with respect to the phase B (Fig. 2). Then h is the vertical distance from the center of the phase A conductor to the horizontal line MN minimally acceptable in the sense of safety (line MN passes through the centers of gravity of the MOS and IC and, like their longitudinal axes, is in a vertical plane that crosses the phase conductors); x_1 and x_2 are the distances from these centers to the vertical; γ_1 and γ_2 are the angles between MN and MOS and IC axes.

For the device to serve as NSCF, it should react only to negative-sequence currents, i.e., fields produced by $\underline{I}_1$ and $\underline{I}_0$ currents should not affect the MOS and IC. As is known, zero-sequence currents match in phase in all the phases: $\underline{I}_{A0} = \underline{I}_{B0} = \underline{I}_{C0}$. Substituting them for $\underline{I}_A$, $\underline{I}_B$, and $\underline{I}_C$ in Eq. (5) and equaling the induction $\underline{B}_{LA}^{MOS}$ to zero, we derive the conditions under which the MOS and IC do not react to $\underline{I}_0$:

$$a)\ \frac{\cos\alpha_1^{MOS}}{l_A^{MOS}} + \frac{\cos\alpha_2^{MOS}}{l_B^{MOS}} + \frac{\cos\alpha_3^{MOS}}{l_C^{MOS}} = 0, \qquad b)\ \frac{\cos\alpha_1^{IC}}{l_A^{IC}} + \frac{\cos\alpha_2^{IC}}{l_B^{IC}} + \frac{\cos\alpha_3^{IC}}{l_C^{IC}} = 0. \quad (11)$$

Fulfillment of these conditions can be provided by means of variations in the angles γ_1 and γ_2 at fixed distances x_1 and x_2 (Fig. 2). Expressing the components of Eq. (11a) in terms of x_1, γ_1, h, and d (d is the distance between the conductors of neighbor phases) (Appendix B, Eq. (B.1)) let us derive Eq. (11a) as an equation in the angle γ_1 (Eq. (B.2)). The angle γ_2 is determined in the same way (expressing the components of Eq. (11b) in terms of x_2, γ_2, h, and d). Let us note that conditions (11) fulfill at $\gamma_1 = 180 - \gamma_2$ and all x_1 (x_2) except for those that turn the denominator of Eq. (B.2) into zero.

At these coordinates, the currents $\underline{I}_0$ do not affect the MOS and IC; therefore, for MOS to react only to the negative-sequence currents $\underline{I}_{A2}$, $\underline{I}_{B2}$, and $\underline{I}_{C2}$, the action of the positive-sequence currents $\underline{I}_{A1}$, $\underline{I}_{B1}$, and $\underline{I}_{C1}$ should be compensated by the current $\underline{I}_{out}$ in winding 2. This is possible if

$$\underline{B}_{LA1}^{WIND} = -\underline{B}_{LA1}^{MOS} \quad (12)$$

in Eq. (12) $\underline{B}_{LA1}^{WIND}$ and $\underline{B}_{LA1}^{MOS}$ are the total inductions of the magnetic fields produced by the currents $\underline{I}_{A1}$, $\underline{I}_{B1}$, and $\underline{I}_{C1}$ in winding 2 (run through IC) and in the conductors of phases A, B, and C.

Then, like for total currents, using Eqs. (3) and (5) and the principle of superposition (the coefficient K_2 does not change when expanding in symmetrical components), it is easy to show that

$$\underline{B}_{LA1}^{WIND} = K_2\underline{B}_{LA1}^{IC}, \quad (13)$$

where $\underline{B}_{LA1}^{IC}$ is the total induction of the field produced by $\underline{I}_{A1}$, $\underline{I}_{B1}$, and $\underline{I}_{C1}$ along the IC longitudinal axis.

The equations for $\underline{B}_{LA1}^{MOS}$ and $\underline{B}_{LA1}^{IC}$ are given Appendix C, they are very similar to Eq. (5).

Taking into account that $\underline{I}_{B,1} = \underline{I}_{A1}e^{-j120^0}$ and $\underline{I}_{C,1} = \underline{I}_{A1}e^{j120^0}$ and setting the real part of the coefficient K_2 equal to 1 (it depends only on the parameters of the device considered; therefore, it is easy to equate it to 1), from Eqs. (12) and (13), designating $\frac{\cos\alpha_1^{MOS}}{l_A^{MOS}} = A_1$, $\frac{\cos\alpha_2^{MOS}}{l_B^{MOS}} = A_2$, and so on until $\frac{\cos\alpha_3^{IC}}{l_C^{IC}} = A_6$, we derive

$$e^{j(\beta_{PRC}-90^0-\phi)}\cdot(A_4 + A_5e^{-j120^0} + A_6e^{j120^0}) = -(A_1 + A_2e^{-j120^0} + A_3e^{j120^0}) \quad (14)$$

Considering Eq. (14) in terms of the angle β_{PRC}, we can find the latter (an example of the calculation is given in Appendix B).

Zero-sequence-current filter can be performed following Fig. 2, if the following conditions are fulfilled in Eq. (1):

$$\underline{B}_{LA}^{MOS} = \frac{\mu_0}{2\pi l_A^{MOS}}\cos\alpha_1^{MOS}(\underline{I}_A + m\underline{I}_B), \quad (15)$$

$$\underline{B}_{LA}^{WIND} = \frac{\mu_0}{2\pi l_A^{MOS}}\cos\alpha_1^{MOS}(\underline{I}_C + n\underline{I}_B) \quad (16)$$

at $n + m = 1$, $1 > m > 0$, $1 > n > 0$, where m and n are the coefficient specified for ensuring the highest sensitivity of protections synthesized and convenience of mounting MOS and IC. Then

$$\underline{B}_{LA}^{\Sigma} = \underline{B}_{LA0}^{MOS} = 3\frac{\mu_0}{2\pi l_A}\cos\alpha_1^{MOS}\underline{I}_0 = 3K_5\underline{I}_0 \quad (17)$$

To derive Eq. (15) from Eq. (3), it is sufficient to have

$$m\frac{\cos\alpha_1^{MOS}}{l_A^{MOS}} = \frac{\cos\alpha_2^{MOS}}{l_B^{MOS}}, \quad \frac{\cos\alpha_3^{MOS}}{l_C^{MOS}} = 0 \quad (18)$$

Substituting Eq. (B.1) in Eq. (18) and solving the resulting equations with respect to x_1 and γ_1 at known m, h, and d, we find the MOS coordinates. Specifying m, we find n and the induction $\underline{B}_{LA}^{WIND}$, which is to be produced by the current $\underline{I}_{out}$, from Eq. (16).

From Eqs. (A.1)-(A.3) and (16), where the parameters of winding 2, amplifier 3, PRC 4, resistor 5, and IC 6 are used, we find

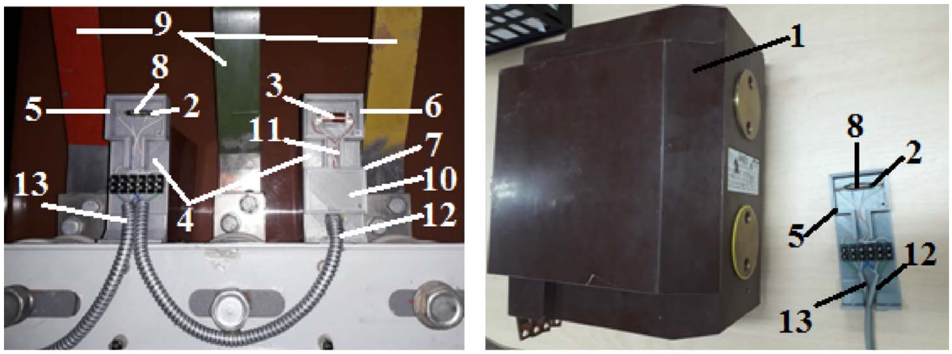
$$K_2\underline{B}_{LA}^{IC} = \underline{B}_{LA}^{WIND} \quad (19)$$

Eqs. (16) and (18) imply that IC should be mounted so as the induction $\underline{B}_{LA}^{IC}$ is proportional to the sum of currents $\underline{I}_C + n\underline{I}_B$. This is possible, if, by analogy with MOS,

$$\underline{B}_{LA}^{IC} = \mu_0\frac{\cos\alpha_3^{IC}}{2\pi l_C^{IC}}(\underline{I}_C + n\underline{I}_B) = \kappa_6(\underline{I}_C + n\underline{I}_B) \quad (20)$$

$$n\frac{\cos\alpha_3^{IC}}{l_C^{IC}} = \frac{\cos\alpha_2^{IC}}{l_B^{IC}}, \quad \frac{\cos\alpha_1^{IC}}{l_A^{IC}} = 0 \quad (21)$$

Considering Eq. (21) in terms of x_2 and γ_2, we can find coordinates of IC. Since inductions $\underline{B}_{LA}^{IC}$ (16) and (19) should coincide, the condition for filter operation is defined by the equation $K_2 = K_5/K_6$, from which (since K_5 and K_6 are real) $\beta_{PRC} = 90^0 + \varphi$. The analysis shows that K_2 changes significantly as m and n vary from 0.1 to 0.9; however, MOS and IC should be arranged symmetrically with respect to the vertical axis that passes through the phase B in all the cases. The value $m = 0.5$ ensures the coordinates convenient for mounting the devices and



a b

Fig. 3. (a) Construction designed and its mounting and (b) CT with substituting construction.

calculations. Equating K_5/K_6 to the real part of K_2 according to Eq. (5) and ensuring $K_2 = 1$, we find K_A (assuming that the number of winds W_2 и W_6 is known and the resistance z is variable). Then $x_1 = d/2$, $\gamma_1 = \arctan(2h/3d)$, $x_2 = 3d/2$, $\gamma_2 = -\arctan(2h/3d)$.

5. Constructions for mounting MOS and IC

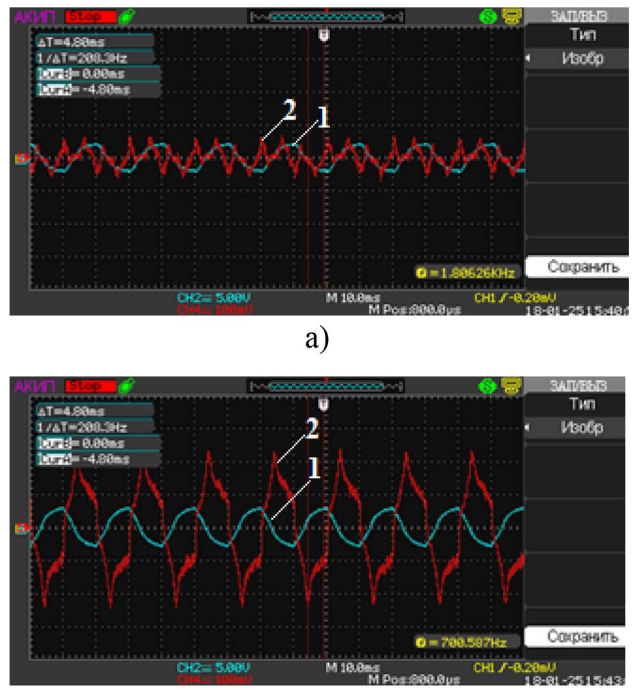
To mount MOS and IC at the points calculated, several construction have been designed, e.g., [12] for triangle arrangement of phase conductors and [14] for their parallel arrangement in one plane. Fig. 3a shows the filter suggested with a construction for its mounting, which is placed in a cell of a 6-kV switch gear with parallel arrangement of conductors in a plane. Fig. 3b shows common transformer 1 used in such cells and a construction for mounting the MOS.

A general unit for the constructions for mounting MOS 2 and IC 3 are straps 4, where cases 5–7 are fixed. MOS 2 with winding 8 and IC 3 are mounted in cases 5 and 6 so as their longitudinal aces are in a plane perpendicular to the longitudinal axes of conductors of phases 9. PRC, amplifier, and resistor are mounted in case 7 (under cover 10 in Fig. 3). IC 3 is connected to PRC, winding 8, to the resistor, and MOS 2, to the protection logic by means of cables 11–13 in a corrugated tube. Straps 4 and cases 5–7 are made of a nonmagnetic material, e.g., plastic. Our device serves as a traditional filter of symmetrical components with two CTs. An approximate price of the device (Fig. 3a) and the dimensions are 10–20 lower, and the mass is 50–200 times (versus the electrical installation power and CT transformation coefficient) smaller than of these CTs. For example, 6-kV CTs, from which FCR 8 receives information, with a negative-sequence-current filter (manufactured by Cheboksary Electric Apparatus Plant, Russia) are about 10-time more expensive and 70-time heavier, like those produced by "Asea Brown Boveri" (ABB).

6. Experimental study of NSCF performance in the case of parallel arrangement of phases in one plane

For the experiments, a laboratory setup and a NSCF have been assembled (Appendix D). In the NSCF (see Fig. 2), control windings of RGK-49 reed switch were used as control winding 2 and IC 3. An additional winding was wound on MOS 1 to measure the EMF induced by the total magnetic flux (with the induction $\underline{B}_{LA}^{\Sigma}$) that affects MOS 1. This EMF is proportional to $\underline{B}_{LA}^{\Sigma}$, while the PRC output voltage (see Fig. 2) is proportional to the induction $\underline{B}_{LA}^{WIND}$. Therefore, voltages 1 and 2 in the oscillogram in Fig. 4 completely characterize the filter operation. Fig. 4a shows a load oscillogram, when MOS 1 is under the imbalance induction effect (curve 2) caused by inaccurate mounting of MOS 1 and IC 3 and calculations and NSCF errors. Fig. 4b, under two-phase shorts when SC currents are equal to the load current.

In both cases, the same current was fed to the busbars. The comparison between the oscillograms shows that the resulting magnetic



a)

b)

Fig. 4. Voltage oscillograms at the leads of PRC 6 of NSCF and IC used instead of MOS 1: (a) under load and (b) at phase (A)-to-phase (B) fault.

field induction (Fig. 4b) that affects MOS 1 at SC doubles the imbalance induction. This witnesses the functionality and high sensitivity of the filter (SC current is usually higher than the load current maximum). However, at small SC currents and long distances between MOS 1 and a busbar, the MOS sensitivity can be insufficient for the actuation. In this case, an addition winding should be used to construct the output relay of the filter.

7. Comparison with conventional filters

It is well known [15] that the sensitivity of conventional filters depends on frequency variations, SC type, and SC current wavefront. These dependences exist for the filters under study. In addition, during the standard electrical installation operation, MOS is affected by the magnetic field with the imbalance induction $\underline{B}_{IB}$ from which it is necessary to turn out. This induction is caused by deviations of the device parameters from design values due to inaccurate mounting of MOS and IC, admissible current asymmetry, and effects of magnetic fields produced by currents in phases of neighboring electrical installations. Studies [6,10,16] have shown that this effect is significant when building protection to MOSs which react to the total phase currents. Therefore, there are reasons to suppose that the sensitivity of the filters suggested can be insufficient in some cases. The comparison in reliability is difficult, since these filters do not commercially produced and have not been field tested. However, being mounted as doublings of commonly used filters, they can significantly improve the reliability of protections that use filters of symmetrical current components, in particular, by means of doubling CTs (which is not currently practiced for reasons of economy). As is mentioned above, the new device significantly excels conventional ones in cost, dimensions, and mass, while sensitivity and reliability depend on PRs and conditions they are to be used in. Detail estimates of these parameters will be considered in the next works devoted to the use of the filters suggested in specific PRs.

8. Conclusions

1. The principles suggested allow construction of negative- and zero-sequence-current filters (NZSCF) on the basis of IC and MOS with saving copper and steel, which are used for manufacturing current transformers applied in common PR with filters. The filters suggested are cheaper, smaller, and lighter, but sometimes less sensitive than common filters with TC.
2. For functioning as NZSCF under parallel arrangement of the electrical installation phase conductors in the plane “P”, the MOS and IC are to be mounted at safe distances from the phase conductors in a plane perpendicular to the plane “P” at points symmetrical with respect to the axis that passes through the phase B at angles γ_1 and γ_2 defined from conditions (11) for ZSCF and (15) and (18) for NSCF.
3. To implement NSCF under triangle arrangement of conductors of the phases A, B, and C the MOS and IC are mounted at midpoints M and N of sides AB and BC, respectively, so as their longitudinal axes coincide with the medians MC and NB. To implement ZSCF, only MOS (without IC) is used. It is mounted on a circle circumscribed around the triangle ABC.
4. It is necessary to study further how the sensitivity and reliability of the filters suggested depend of the peculiarities of their construction and use in different protection relays.

9. Formatting of funding sources

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Appendix A

According to [17],

$$\underline{B}_{\mathrm{LA}}^{\mathrm{WIND}} = \underline{I}_{\mathrm{out}} \cdot \mu_0 \cdot W_2 / \sqrt{l_{\mathrm{WIND2}}^2 + D_{\mathrm{M2}}^2} \tag{A.1}$$

where W_2 is the number of turns of winding 2 (it could be wound directly on MOS 1; l_{WIND2} and D_{M2} are the spool length and its mean diameter.

The current $\underline{I}_{\mathrm{out}}$ in winding 2 is produced by the EMF $\underline{E}$ at the leads of IC 6, which is amplified by amplifier 2. EMF $\underline{E}$ is induced by the flux $\underline{\Phi}$ with the magnetic induction $\underline{B}_{\mathrm{LA}}^{\mathrm{IC}}$.The flux is directed along the IC axis and passes through its cross section S. EMF $\underline{E}$ is counterclockwise 90-degree shifted with respect to $\underline{\Phi}$. Thus,

$$\underline{I}_{\mathrm{out}} = \underline{K}_{\mathrm{A}}^{j\beta_{\mathrm{PRC}}} / z \cdot e^{j\phi}, \underline{E} = (2\pi f W_6 S) \underline{B}_{\mathrm{LA}}^{\mathrm{IC}} e^{-j90^\circ} \tag{A.2}$$

where W_6 and $\underline{E}$ are the number of turns of IC 6 and EMF induced; f is the industrial current frequency; K_{A} is the amplification factor of amplifier 3; β_{FRC} is the rotation angle ensured by PRC 4; $z = \sqrt{X_{\mathrm{WIND2}}^2 + R_\Sigma^2}$, $\phi = \arctan\frac{X_{\mathrm{WIND2}}}{R_\Sigma}$, $R_\Sigma = r_{\mathrm{WIND2}} + r_5$; $r_{\mathrm{WIND2}}$and $X_{\mathrm{WIND2}}$are the resistance and inductance of winding 2, and r_5 is the resistance of control resistor 5.

Substituting I_{out} from (A.2) in (A.1), we derive

$$\underline{B}_{\mathrm{LA}}^{\mathrm{WIND}} = \frac{2\mu_0 \pi f S \cdot W_2 \cdot W_6 K_{\mathrm{A}} e^{-j90^\circ} e^{j\beta_{\mathrm{FRC}}}}{z \cdot e^{j\phi} \cdot \sqrt{l_{\mathrm{WIND2}}^2 + D_{\mathrm{M2}}^2}} \underline{B}_{\mathrm{LA}}^{\mathrm{IC}} = K_2 \underline{B}_{\mathrm{LA}}^{\mathrm{IC}}. \tag{A.3}$$

Appendix B

Let us consider NSCF parameters for a 110-kV electrical installation with a rated phase current of, e.g., 1000 A. The calculation procedure presented below is an algorithm for calculation of MOS-based NSCF for electrical installation of any voltage rating.

For 110-kV electrical installations from [18], the advised distance between conductors of neighboring phases $d = 1$m and the minimal distance $h = 0.9$ m.

For convenience of calculations, $x_1 = d/2 = 0.5$ m and $x_2 = 3d/2 = 1.5$ m for MOS 1 and IC 6.

Using the elementary geometry rules, express components of Eq. (11a) in terms of x_1, γ_1, h, and d:

$$\frac{\cos\alpha_1^{\mathrm{MOS}}}{l_A^{\mathrm{MOS}}} = \frac{h\cos\gamma_1 + x_1\sin\gamma_1}{h^2 + x_1^2}; \frac{\cos\alpha_2^{\mathrm{MOS}}}{l_B^{\mathrm{MOS}}} = \frac{h\cos\gamma_1 + (x_1 - d)\sin\gamma_1}{h^2 + (x_1 - d)^2}; \frac{\cos\alpha_3^{\mathrm{MOC}}}{l_C^{\mathrm{MOC}}} = \frac{h\cos\gamma_1 + (x_1 - 2d)\sin\gamma_1}{h^2 + (x_1 - 2d)^2} \tag{B.1}$$

and find

$$\gamma_1 = \arctan\frac{h(4d^4 - 12dx_1(h^2 + x_1^2 + d^2) + \quad +3(h^2 + x_1^2)^2 + 2d^2(5h^2 + 9x_1^2))}{(x_1 - d)(4d^3x_1 + 12dx_1(h^2 + x_1^2) - \quad -3(h^2 + x_1^2)^2 - 2d^2(3h^2 + 7x_1^2))}. \tag{B.2}$$

Find $A_1 = 0.66$, $A_2 = -0.25$, $A_3 = -0.41$. Change x_1 and γ_1 to x_2 and γ_2 and find $A_4 = 0.41$, $A_5 = 0.25$, $A_6 = -0.66$.

Take into account that positive-sequence currents $\underline{I}_{A1} = 1000 \cdot e^{j0}$, $\underline{I}_{B1} = 1000 \cdot e^{-j120}$, and $\underline{I}_{C1} = 1000 \cdot e^{j120}$, calculate the magnetic field strength at the point that coincides with the MOS and IC centers of gravity by the equation $\underline{H}_{\mathrm{LA}}^{\mathrm{MOS}} = (A_1 \cdot \underline{I}_{A1} + A_2 \cdot \underline{I}_{B1} + A_3 \cdot \underline{I}_{C1})$: $\underline{H}_{\mathrm{LA}}^{\mathrm{MOS}} = 999.1 e^{-j8^\circ}$A/m, $\underline{H}_{\mathrm{LA}}^{\mathrm{IC}} = 999.1\ e^{-j51.8^\circ}$A/m.

Select the parameters of IC and control winding 2 (see Fig. 1). Let it be windings of a standard relay with $w_2 = w_6 = 92$; $r_{\mathrm{WIND2}} = 0.05$ Ohm; wire PEV-2/1.56; inner winding diameter $D_{\mathrm{in}} = 7.5 \cdot 10^{-3}$ m; outer winding diameter $D_{\mathrm{out}} = 26 \cdot 10^{-3}$ m; $l_{\mathrm{WIND2}} = 36 \cdot 10^{-3}$ m, $S_2 = S_6 = 531 \cdot 10^{-6}$ m^2; mean winding diameter $D_{\mathrm{M2}} = 16.75\ 10^{-3}$ m; $x_{\mathrm{WIND2}} = 0.49$ Ohm; $Z_{\mathrm{IC}} = Z_{\mathrm{WIND2}} = 0.05 + j0.49$ Ohm.

Calculate the EMF at the IC leads by Eq. (A.2):

$$\underline{E}_{\mathrm{IC}} = (2\pi f w_6 S_6 \underline{B}_{\mathrm{LA}}^{\mathrm{IC}})e^{-j90^0} = (2\pi f w_6 S_6 \mu_0 \underline{H}_{\mathrm{LA}}^{\mathrm{IC}})e^{-j90^0} = 19.2e^{-j142^0}$$

Since $\underline{B}_{\mathrm{LA}}^{\mathrm{WIND}} = -\underline{B}_{\mathrm{LA}}^{\mathrm{MOS}}$, find the current $\underline{I}_{\mathrm{out}}$, which should be fed into winding 2 of MOS 1 so as a magnetic field with the strength $-\underline{H}_{\mathrm{LA}}^{\mathrm{MOS}}$ is produced at its axis:

$$\underline{I}_{\mathrm{out}} = \frac{-\underline{H}_{\mathrm{LA}}^{\mathrm{MOS}}\sqrt{l_{\mathrm{WIND2}}^2 + D_{\mathrm{M2}}^2}}{W_2} = 0.43 \cdot e^{j172}\mathrm{A}.$$

Find K_{A} and β_{PRC} substituting $\underline{I}_{\mathrm{out}}$ in Eq. (A.1) at $r_5 = 0$ O:

$$0.43 \cdot e^{j172} = 19.2 \cdot 10^{-3} \cdot e^{-j141.8} K_{\mathrm{A}} e^{j\beta_{\mathrm{PRC}}}/0.492 \cdot e^{j84.2} \tag{B.3}$$

Hence, $\beta_{\mathrm{FRC}} = 172 + 141.8 + 84.2 = 398^0 = 38^0$ and $K_{\mathrm{A}} = 11$.

It is difficult to implement this K_{A}; therefore, let $K_{\mathrm{A}} = 1000$. Find r_5 and β_{PRC} from Eq. (A.2): $r_5 = 44.59$ Ohm and $\beta_{\mathrm{PRC}} = 314.78^0$.

Appendix C

$$\underline{B}_{\mathrm{LA1}}^{\mathrm{MOS}} = \mu_0\left(\frac{\cos\alpha_1^{\mathrm{MOS}}}{l_A^{\mathrm{MOS}}}\underline{I}_{A1} + \frac{\cos\alpha_2^{\mathrm{MOS}}}{l_B^{\mathrm{MOS}}}\underline{I}_{B1} + +\frac{\cos\alpha_3^{\mathrm{MOS}}}{l_C^{\mathrm{MOS}}}\underline{I}_{C1}\right)/2\pi, \tag{C.1}$$

$$\underline{B}_{\mathrm{LA1}}^{\mathrm{IC}} = \mu_0\left(\frac{\cos\alpha_1^{\mathrm{IC}}}{l_A^{\mathrm{IC}}}\underline{I}_{A1} + \frac{\cos\alpha_2^{\mathrm{IC}}}{l_B^{\mathrm{IC}}}\underline{I}_{B1} + +\frac{\cos\alpha_3^{\mathrm{IC}}}{l_C^{\mathrm{IC}}}\underline{I}_{C1}\right)/2\pi, \tag{C.2}$$

where α_1^{MOS} ($\alpha_2^{\mathrm{MOS}}$and α_3^{MOS}) and α_1^{IC} ($\alpha_2^{\mathrm{IC}}$and α_3^{IC}) are the angles between the MOS and IC longitudinal axes and the induction of the magnetic field produced by the positive-sequence current $\underline{I}_{A1}$ ($\underline{I}_{B1}$ and $\underline{I}_{C1}$); l_A^{MOS}, l_B^{MOS}, and l_C^{MOS} are the distances between the conductors of the phases A, B, and C, respectively, to the MOS center of gravity; l_A^{IC}, l_B^{IC}, and are distances from the conductors of phases A, B, and C, respectively, to the IC center of gravity; μ_0 is the vacuum permeability.

Appendix D

Fig. D.1 shows the laboratory setup and NSCF. The setup consists of laboratory autotransformer 1, with the primary winding connected to a 380-V network via automatic breaker 2, and the secondary winding, to the primary winding of load transformer 3. The secondary winding of load transformer 3 is connected to wye-connected buses 4. Control winding 5 with IC 6 and IC 7 wound are mounted between buses 4 with the coordinates $x_1 = d/2$, $h = d$, $\gamma_1 = 75°$, and $x_2 = 3d/2$, $h = d$, $\gamma_2 = 105°$. IC 6 is used instead of MOS to show that only imbalance induction acts on MOS under load during three-phase faults. An amplifier and PRC are placed in unit 8, with two 9-V storage batteries as power supply of the amplifier. Connection of the NSCF components corresponds to Fig. 2. Oscillograph 9 is used for recording variations in the voltage at PRC and IC 9 leads.

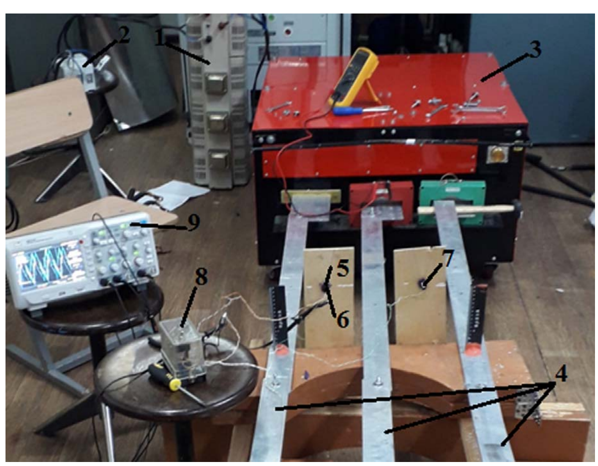

Fig. D.1. Laboratory setup and NSCF; two-phase SC between phases A and B.

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