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(54) Title: METHOD OF CONTROLLING AN APPARATUS COMPENSATING GROUND FAULT CURRENTS FOR COMPENSATING FOR FAULT CURRENTS IN AN N-PHASE DISTRIBUTION SYSTEM

(57) Abstract: The apparatus compensating ground fault currents (2) with controlled current sources (3, 3', 3") is, in the known method, connected between the phase conductors L_1, L_2, L_3 of an n-phase distribution system (1) and site with earth potential (5). The essence of the new method of its control, according to the invention, lies in the fact that in the occurrence of a ground fault (6), the total compensation current (l_0) is formed as a vector sum of individual (n) compensation currents (l_{01}, I_{02}, I_{03}) of all controlled current sources (3, 3', 3"), while their current amplitudes show, in absolute value, a deviation of no more than 25% from the value of l_0/n, and the angles ($_1$, $_2$, Φ_3) of their phase shifts show a difference of value of no more than 30% against the angle ($_0$) of the phase shift of the total compensation current (l_0).

WO 2014/063666 A2

Method of controlling an apparatus compensating ground fault currents for compensating for fault currents in an n-phase distribution system

Field of the invention

The invention relates to the field of electrical engineering and energy, specifically a method of controlling an apparatus compensating ground fault currents for compensating for fault currents that occur as a result of ground faults in phases of power line of an electrical distribution system.

Background of the invention

To compensate for fault currents that occur at the site of a ground fault of some phase of an n-phase distribution system (also called a "single-phase ground fault"), a ground continuously tuneable arc suppression coil (a "Petersen coil") is used as a basic apparatus compensating ground fault currents, connected between the node of the transformer and the earth potential. This arc suppression coil functions on the principle of resonance, and upon the occurrence of a ground fault it compensates for the fault current, while the active current is compensated for by an auxiliary device that injects a compensation current to the auxiliary coil of the arc suppression coil. To compensate for the phase unbalance of the distribution system, as well as to compensate for the harmonics and compensate for the reactive power, other additional devices are used.

According to document EP 1855 366 B1, another known apparatus compensating ground fault currents and method of compensating for fault current is known, wherein an electric switch is switched on, manually or automatically, connecting the respective phase conductor with the ground fault by filter circuit, which is designed as a power converter and which is arranged between the phase conductor and the site with earth potential. The generated compensation current compensates at least for one frequency of the fault current, and can also compensate for the reactive current.

In another document DE 10 2007006719A1, a similar apparatus compensating ground fault currents is described as in EP 1855 366 B1, with the difference that the filter circuit is designed as a multi-frequency filter circuit which operates at a single frequency as a suction circuit and at a different frequency as the latching circuit while blocking the fundamental frequency.

From document DE 10 2007 04 9667 B4 there is another apparatus compensating ground fault currents known similar to the apparatuses described in the two previous documents, which also mentions the integration of electronic switches directly into the filter circuit which is created as a power converter, and the filter circuit is also fitted with capacitors controlled by switches that develop a pulse DC voltage supplied to the phase conductor with ground fault. The device is designed to compensate for reactive power.

From document CZ 302920 B6 an apparatus compensating ground fault currents is known with controlled current source, formed by a power converter. It is connected between the phase conductors of the transformer of the distribution system and the earth potential. The power converter functions as a compensator for fault currents and higher harmonic orders of fault currents. In a no-fault state of a distribution system, it serves to balance its phase imbalance and compensate for reactive power. The controlled current source may be composed of single-phase power semiconductor converters or may be formed by a single multi-phase power semiconductor converter. The controlled current source may also be e.g. a voltage inverter, power inverter, or frequency inverter.

Known apparatuses compensating ground fault currents operate in the presence of a single-phase earth fault principally the same in the sense that there is a corresponding compensation current generated against each vector component of a fault current I_p. For example, in a three-phase ground system in the occurrence of a single-phase ground fault (the connection of one phase conductor with a site with earth potential), the fault current I_p consists mainly of parasitic capacitances and leads against the earth potential of a distribution system (line-to-earth impedance) and is given by the vector sum of the parasitic currents:

$$\overline{I_{P1}} = \frac{\overline{u_1}}{Z_1}; \overline{I_{P2}} = \frac{\overline{u_2}}{Z_2}; \overline{I_{P3}} = \frac{\overline{u_3}}{Z_3}$$

$$\overline{I_p} = \overline{I_{P1}} + \overline{I_{P2}} + \overline{I_{P3}}$$

$$\overline{I_p} = \frac{\overline{u_1}}{Z_1} + \frac{\overline{u_2}}{Z_2} + \frac{\overline{u_3}}{Z_3}$$

wherein:

I_p	fault current
I_{P1}, I_{P2}, I_{P3}	parasitic currents in individual phases
u_1, u_2, u_3	phase voltages (line-to-earth voltage) in individual phases
Z_1, Z_2, Z_3	line-to-earth impedance in individual phases

In an ideal earth connection in a single-phase ground fault, the voltage u_1 at the affected phase is zero, and in the phases not affected by ground fault the voltages are on the associated value, so in an ideal single-phase ground fault the ground fault current I_p can be expressed as follows:

$$\overline{I_p} = \frac{\overline{u_2}}{Z_2} + \frac{\overline{u_3}}{Z_3}$$

In the compensation of a single-phase ground fault in the known method, the apparatus compensating ground fault currents is controlled mechanically or automatically by a program in such a way that it generates the compensating current I_0, which compensates for the individual vectors of the fault current I_p, while against each vector of the fault current I_p a counter-current I_{02}, I_{03} is created, thus achieving three-phase compensation of the fault current I_p, wherein the following applies:

$$\overline{I_{02}} = -\frac{\overline{u_2}}{Z_2}; \overline{I_{03}} = -\frac{\overline{u_3}}{Z_3}$$

$$\overline{I_0} = \overline{I_{02}} + \overline{I_{03}}$$

wherein:

I_{02}, I_{03} compensating currents generated against non-zero vectors of fault current I_p
I_0 total compensation current

A disadvantage of the known process of controlling apparatuses compensating ground fault currents lies in the fact that individual current sources of the apparatus compensating ground fault currents have high current loads resulting from the fact that they have to generate sufficiently large compensation currents I_{01}, I_{02}, I_{03} to compensate for each vector of the fault current I_p. The apparatus compensating ground fault currents, respectively its individual current sources, must then have the corresponding power dimensioning, which is naturally reflected in larger construction dimensions, greater overall weight, and at a higher cost of the apparatus compensating ground fault currents. The task of the invention is therefore to find such a method of controlling the apparatus compensating ground fault currents, which would lead to a reduction in load current of individual current sources and which would permit the production and operation of small apparatuses compensating ground fault currents with less power requirements, less overall weight, and a lower cost of acquisition.

<u>Summary of the invention</u>

The solution of the task is achieved by creating a new method of controlling an apparatus compensating ground fault currents according to the submitted invention.

The apparatus compensating ground fault currents equipped with n-controlled current sources or formed by a single n-phase controlled current source is connected in the known method using n + 1 outputs between phase conductors of an n-phase distribution system. Its task is to generate the compensation current I_0 to compensate for the fault current I_p occurring as a result of the single-phase earth faults, and injecting the compensation current I_0 to the phase of the affected earth fault.

The essence of the method for controlling the apparatus compensating ground fault currents according to the submitted invention consists in the idea that the total compensation current I_0 is generated as a vector sum of individual n compensating currents, generated by individual controlled current sources or individual phase outputs of the n-phase of the controlled current source. The current amplitudes of these individual compensation currents show, in absolute value, a deviation of no more than 25% from the value of $\frac{\overline{I_0}}{n}$ I_o/n, and the phase shifts of these individual compensation currents show a difference of their values of no more than 30 ° as opposed to the total compensation current I_0 phase-shift.

In an advantageous embodiment of the method of controlling according to the invention, the apparatus compensating ground fault currents is controlled in such a way that the current amplitudes of individual compensating currents have the same size, their value being $\frac{1}{n}$ of the amplitude of the total compensation current I_0. The phase shifts of the compensation currents are also equal, and their value equals the value of the phase shift of the total compensation current.

The regulation of amplitudes and phase shifts of the components of the compensation current I_0 is done using common software and hardware resources, such as using control systems based on the technology of DSP microcontrollers and/or field-programmable gate array (FPGA).

Unlike the known method of controlling the apparatus compensating ground fault currents, the method of the submitted invention has the advantage in that the vector sum of the individual compensation currents set by the above-described parameters comprises the necessary total compensation current I_0 of the components generated at a lower current load of individual controlled current sources or individual phases of an n-phase controlled current source. The reduction of current load of current sources enables the construction of apparatus compensating ground fault currents with smaller space requirements, less weight, lower power requirements and consumption, and last but not least, with lower cost of acquisition.

Description of the drawings

The invention is described in detail by means of the drawings, in which Figure 1 is a diagram of a three-phase distribution system with earth connection in the first phase and with the apparatus compensating ground fault currents containing three controlled current sources; Figure 2 is a phasor diagram of voltages and currents of a three-phase power distribution system according to Figure. 1, showing phase shifts of the individual compensation currents ϕ_1, ϕ_2, ϕ_3 = ϕ_0, i.e. in the most preferred design of the method of control according to the invention; Figure 3 is a phasor diagram of voltages and currents of a three-phase power distribution system according to Figure 1, showing the individual compensating currents generated by the known method, representing the present state of technology; Figure 4 is a phasor diagram of voltages and currents of a three-phase distribution system according to Figure 1, showing phase shifts of the individual compensation currents ϕ_1, ϕ_2, ϕ_3 in the maximum angular tolerance with regard to ϕ_0; Figure 5 is a diagram of the connection of an n-phase distribution system with ground connection in the first phase and with the apparatus compensating ground fault currents containing an n-phase current source.

Examples of the preferred embodiments of the invention

It should be understood that the following described and illustrated specific examples of the realization of the invention are presented solely for illustrative purposes and not as a limitation of the examples of the embodiments of the invention for the cases indicated. Experts who are familiar with the state of technology shall find, or using routine experimentation will be able to determine, a larger or smaller number of equivalents to the specific realizations of the invention which are specifically described here. These equivalents shall also be included into the scope of the claims.

Figure 1 shows a three-phase distribution system **1** with phase conductors L_1, L_2, L_3. Between the phase conductors L_1, L_2, L_3 and the site with earth potential **5** the apparatus compensating ground fault currents **2** is connected containing three controlled current sources **3**, **3´**, **3´´**. The first phase conductor L_1 of the distribution system **1** is affected by the ground fault **6**, which causes fault current I_p as the sum of parasitic currents in individual phases:

$$\overline{I_p} = \overline{I_{P1}} + \overline{I_{P2}} + \overline{I_{P3}}$$

$$\overline{I_p} = \frac{\overline{u_1}}{Z_1} + \frac{\overline{u_2}}{Z_2} + \frac{\overline{u_3}}{Z_3}$$

The apparatus compensating ground fault currents **2**, using controlled current sources **3**, **3´**, **3´´**, generates a total compensation current I_0 against fault current I_p formed by the vector sum of individual compensation currents I_{01}, I_{02}, I_{03} generated by the controlled current sources **3**, **3´**, **3´´**. The controlled current sources **3**, **3´**, **3´´** are, in the specific example of implementation, created by controlled power converters. These also may be voltage inverters, current inverters, or frequency inverters. The control of current sources **3**, **3´**, **3´´** in terms of the regulation of current amplitudes and angles ϕ_1, ϕ_2,ϕ_3 of the phase shift is performed by a control system functioning on the basis of DSP microcontrollers and/or field-programmable gate array (FPGA).

Figure 2 shows an example of the most preferred method of controlling the apparatus compensating ground fault currents **2** to compensate for the fault current I_p in the distribution system **1** according to Figure 1. The total compensation current I_0 is created as a vector sum of individual compensation currents I_{01}, I_{02}, I_{03} generated by individual controlled current sources **3**, **3´**, **3´´**. Meanwhile, the values of the individual compensation currents I_{01}, I_{02}, I_{03} are guided so that the current amplitudes of the individual compensation currents I_{01}, I_{02}, I_{03} have the same size on the value of 1/3 of the amplitude of the total compensation current I_0, namely:

$$I_{01} = \frac{I_0}{3};\ I_{02} = \frac{I_0}{3};\ I_{03} = \frac{I_0}{3}$$

At the same time, the values of the angles ϕ_1, ϕ_2,ϕ_3 of the phase-shifts of the individual compensation currents I_{01}, I_{02}, I_{03} are controlled so that they have the same size as the value of the angle ϕ_0 of the phase-shift of the total compensation current I_0, namely:

$$\phi_1 = \phi_2 = \phi_3 = \phi_0,$$

In the case depicted in Figure 2, $\phi_0 = 90°$. Figure 2 is a phasor diagram of a 3-phase distribution system **1** according to Figure 1, showing the voltages and currents in the complex (Gaussian) plane, where the x-axis (RE) shows the real part of the complex number and the y-axis (IM) shows the imaginary part of the complex number. The depiction assumes that the phase voltage (line-to-earth voltage) affected by the ground fault **6** is zero, i.e. $u_1 = 0$. In practice, the voltage u_1 may have a minimum value. The remaining two phase voltages, then, have values of line-to-line voltage $u_2 = u_{21}$, $u_3 = u_{31}$.

Figure 3, for comparison, shows the course of the control of the apparatus compensating ground fault currents **2** in a distribution system **1**, with ground fault **6** by the current i.e. known method, in which a corresponding compensation current is generated against each vector component of the fault current I_p. Given that $u_1 = 0$, u_2

= u_{21} and u_3 = u_{31}, then only two current sources **3´**, **3´´** generate individual compensating currents I_{02}, I_{03} for which the following applies:

$I_{02} = \frac{I_0}{\sqrt{3}}$; $I_{03} = \frac{I_0}{\sqrt{3}}$; while $I_{01} = 0$

The current flowing through each controlled current source **3´**, **3´´** thus has an amplitude of size $\frac{I_0}{\sqrt{3}}$ and corresponding phase shift (ϕ_2,ϕ_3).

A comparison of values of the amplitudes of the current load ($\frac{I_0}{3}$ according to Figure 2 and $\frac{I_0}{\sqrt{3}}$ according to Figure 3) then clearly shows that the current load of the controlled current sources **3**, **3´**, **3´´** is, in the known method of control according to Figure 3, about 70% greater than in the current sources **3**, **3´**, **3´´** controlled by the method according to the submitted invention according to Figure 2.

Figure 4 shows a further variant of the method of controlling the apparatus compensating ground fault currents **2** according to the invention, different from the variant depicted in Figure 2 and described above. The method of control of individual controlled current sources **3**, **3´**, **3´´** is different in the sense that neither $I_{01} = I_{02} = I_{03} = \frac{I_0}{3}$ nor $\phi_1 = \phi_2 = \phi_3 = \phi_0$ applies. To improve the control and to reduce the current load of the controlled current sources **3**, **3´**, **3´´** it is sufficient when the current amplitudes of individual compensation currents I_{01}, I_{02}, I_{03} are not equal to $\frac{I_0}{3}$, but differ in an absolute value deviation of no more than 25% of the value $\frac{I_0}{3}$, and the angles ϕ_1, ϕ_2,ϕ_3 of the phase shifts of the individual compensation currents I_{01}, I_{02}, I_{03} show a difference of their value of no more than 30° against the angle ϕ_0 of the phase shift of the total compensation current I_0. Figure 4 shows a situation in which the first controlled current source 3´ generates compensating current I_{01} with size of amplitude $\frac{I_0}{3}$, i.e. one third of the total compensation current I_0 and has the same angle ϕ_1 of phase shift, thus $\phi_1 = \phi_0$. Compensation currents I_{02} and I_{03} generated from the other controlled current sources 3´, 3´´ have an amplitude size about 15% greater than I_{01} and the phase shift angles ϕ_2 = -30°and ϕ_3 = 30° shifted by the indicated value from the vector of the compensation current I_{01} respectively of the total compensation current I_0. Even in this case, the current load of individual controlled current sources 3, 3´, 3´´ is less than in the known method of control depicted in Figure 2, where the current load of the controlled current sources 3, 3´, 3´´ is 50% higher.

Figure 5 illustrates another implementation of the invention. This is an n-phase distribution system 1 with ground fault 6, as in Figure 1, but the apparatus compensating ground fault currents 2 here is comprised of an n-phase controlled current source 4 instead of three controlled current sources 3, 3´, 3´´.

The method of control of the n-phase controlled current source 4 is completely the same as the method of control of the apparatus compensating ground fault currents 2 with three controlled current sources 3, 3´, 3´´ in the above-described examples, with the difference that the size of the amplitude of the individual compensation currents (I_{01}, I_{02}, I_{03} ....I_{0N}) of the generated individual phase outputs is equal to $\frac{1}{n}$ of the total compensation current I_0.

Industrial applicability

The method of controlling the apparatus compensating ground fault currents according to the invention can be used to compensate for fault currents that occur as a result of ground faults in an n-phase distribution system.

Overview of the positions and symbols used in the drawing and in the description

1	n-phase distribution system
L_1	phase conductor
L_2	phase conductor
L_3	phase conductor
2	apparatus compensating ground fault currents
3	controlled current source
3´	controlled current source
3´´	controlled current source
4	n-phase controlled current source
5	earth potential
6	ground fault
u_1	phase voltage (line-to-earth voltage)
u_2	phase voltage (line-to-earth voltage)
u_3	phase voltage (line-to-earth voltage)
I_{p1}	parasitic current in phase
I_{p2}	parasitic current in phase
I_{p3}	parasitic current in phase
I_p	fault current
Z_1	line-to-earth impedance
Z_2	line-to-earth impedance
Z_3	line-to-earth impedance
I_0	total compensation current
I_{01}	compensating current in phase 1
I_{02}	compensating current in phase 2
I_{03}	compensating current in phase 3
u_{12}	line-to-line voltage
u_{23}	line-to-line voltage
u_{31}	line-to-line voltage
ϕ_1	compensating current I_{01} phase-shift

ϕ_2	compensating current I_{02} phase-shift
ϕ_3	compensating current I_{03} phase-shift
ϕ_0	total compensation current I_0 phase-shift
L_N	n-phase conductor of distribution system
I_{0N}	compensating current in a n-phase of controlled current source
U_N	phase voltage in a n-phase of distribution system
Z_N	line-to-earth impedance in a n-phase of distribution system

CLAIMS

1. The method of controlling the apparatus compensating ground fault currents (2) to compensate for fault currents (I_p), connected using (n + 1) outputs between phase conductors (L_1, L_2, L_3) of an n-phase electric distribution system (1) and site with earth potential (5), and equipped with (n) controlled current sources (3, 3´, 3´´) or with one n-phase controlled current source (4) to generate the compensation current (I_0) and its injection into the phase affected by the ground fault (6) **characterized in that** the total compensation current (I_0) is formed as a vector sum of individual (n) compensating currents (I_{01}, I_{02}, I_{03}) generated by individual controlled current sources (3, 3´, 3´´) or by individual phase outputs of the n-phase-controlled current source (4), while the current amplitudes of individual compensation currents (I_{01}, I_{02}, I_{03}) show, in absolute value, a deviation of no more than 25% from the value of I_0/n, and the angles (ϕ_1, ϕ_2, ϕ_3) of the phase shifts of the individual compensation currents (I_{01}, I_{02}, I_{03}) show a difference in value of no more than 30° against the angle (ϕ_0) of the phase shift of the total compensation current (I_0).

2. The method according to claim 1, **characterized in that** the current amplitudes of the individual compensation currents (I_{01}, I_{02}, I_{03}) have the same size in the value of 1/n of the amplitude of the total compensation current (I_0) and the same angles (ϕ_1, ϕ_2,ϕ_3) of the phase shift, the size of which is the same as the value of the angle (ϕ_0) of the phase shift of the total compensation current (I_0).

FIG. 1

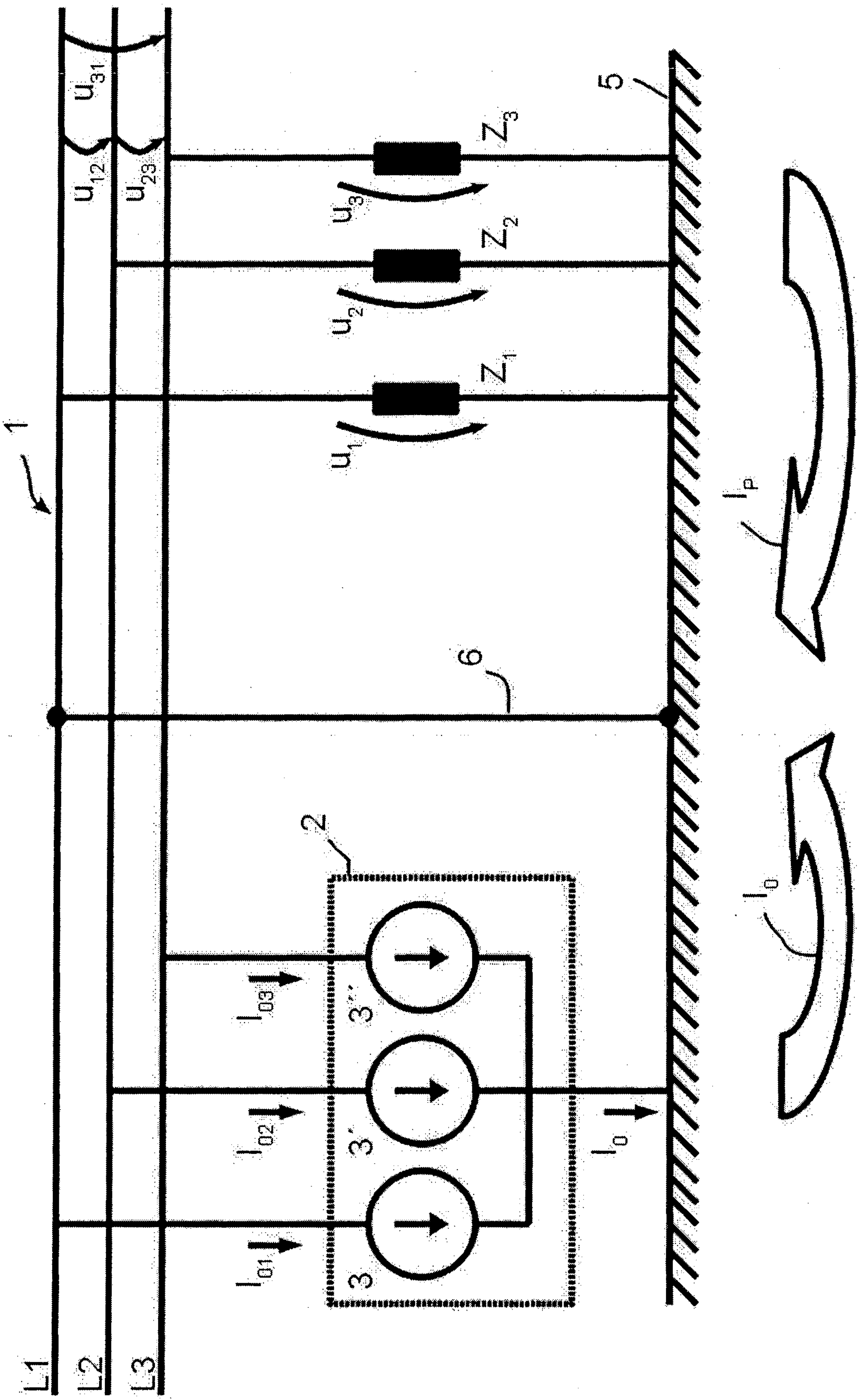

FIG. 2

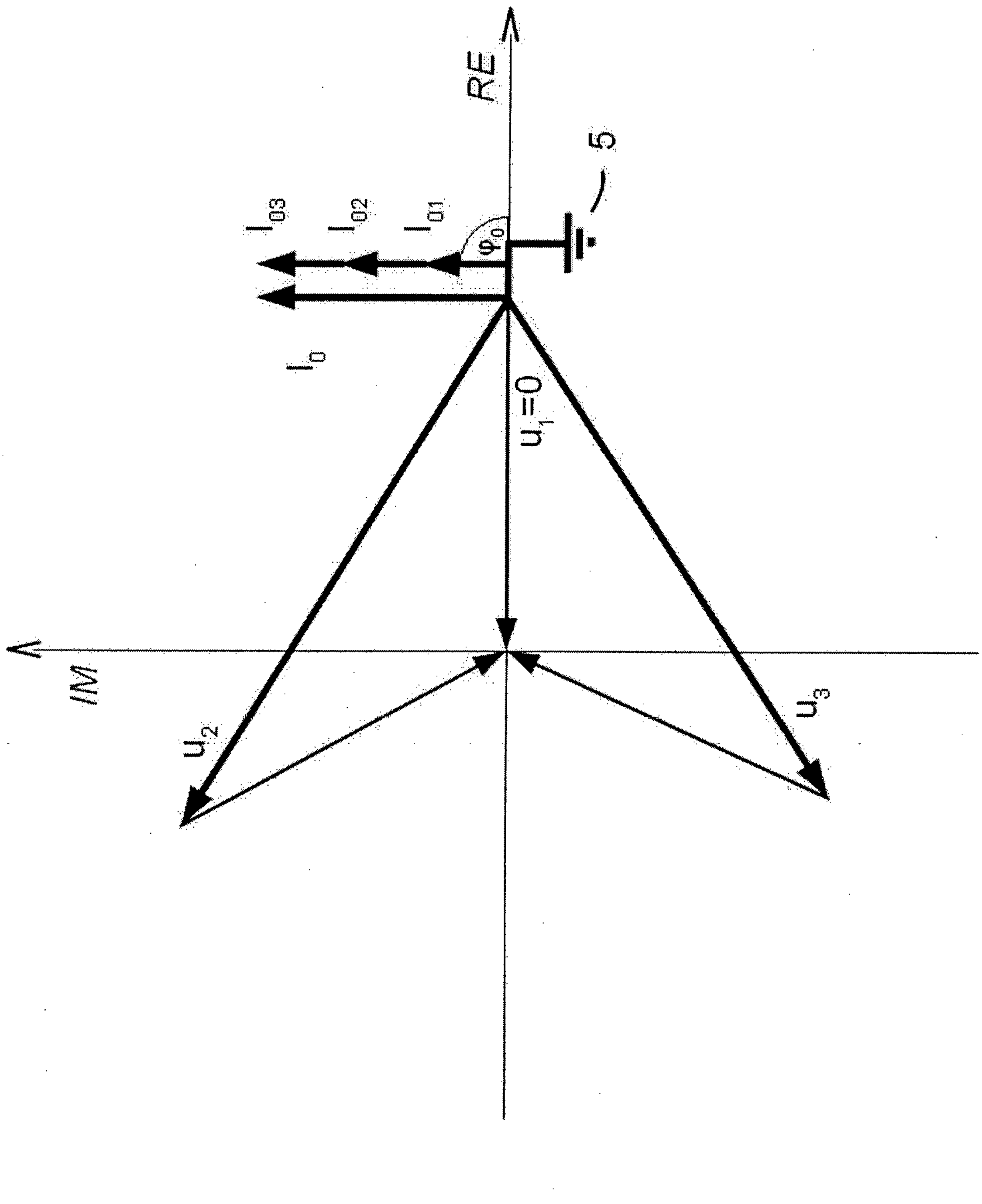

FIG. 3

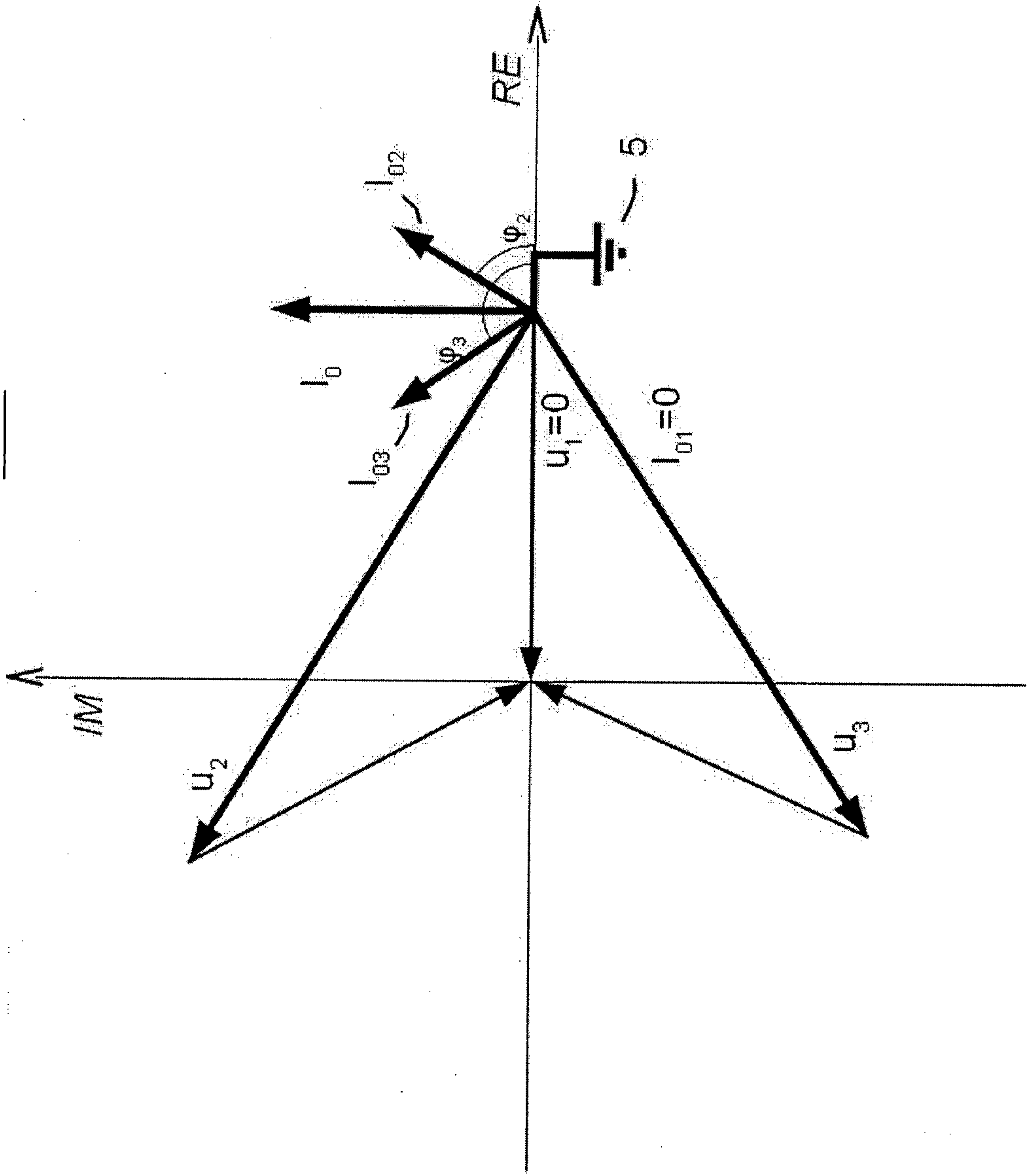

FIG.4

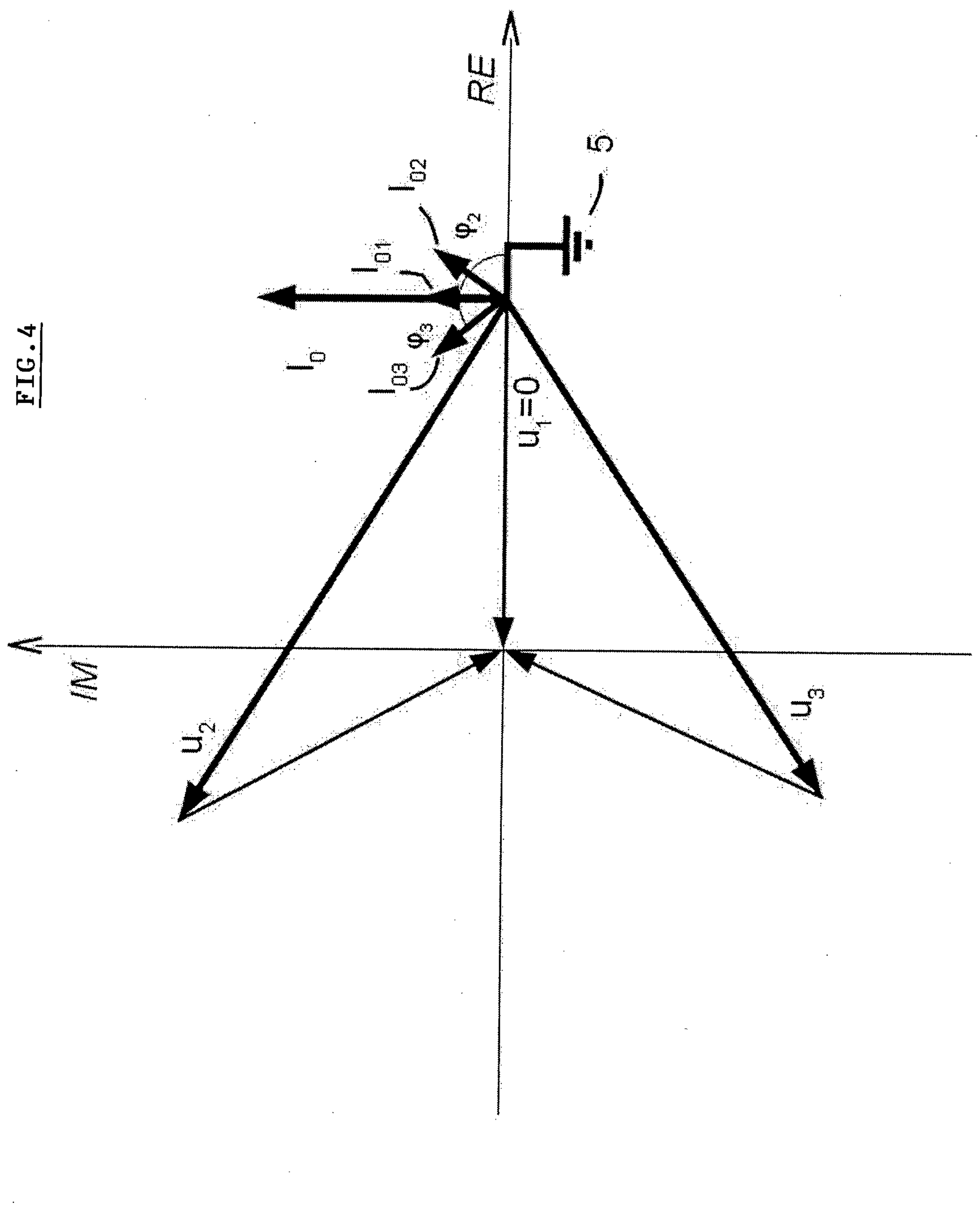

FIG.5