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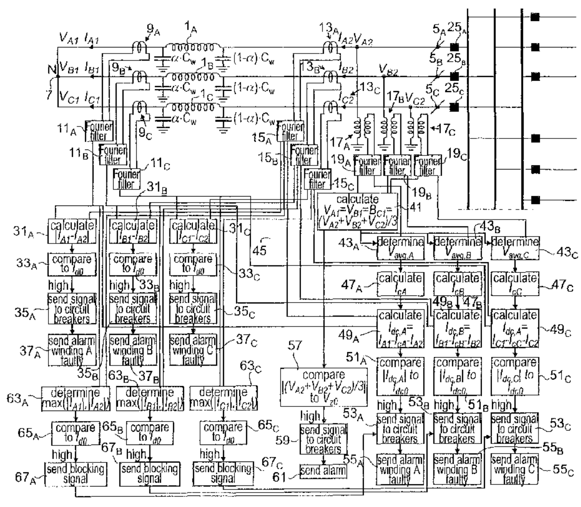

(57) Abstract: In an AC electric generator such as the Powerformer™ voltages are induced in phase windings (1_A, 1_B, 1_C) connected at one end to each other at a neutral point (5, N) and at an opposite end to phase terminals (5_A, 5_B, 5_C). For each phase winding a value indicative of the magnitude of an excess or rest electric current flowing into the winding that is not related to the currents at the neutral point and phase terminal ends not to the current flowing through the capacitance of the phase winding is calculated (47_A, 49_A, 51_A, 47_B, 49_B, 51_B; 47_C, 49_C, 51_C) and compared to a threshold value (51_A, 51_B, 51_C). Circuit breakers (25_A, 25_B, 25_C) are activated (53_A, 53_B, 53_C) and an alarm is issued (55_A, 55_B, 55_C) if the calculated magnitude is found to be high. These actions can be inhibited if some other conditions apply such as that the magnitudes of the currents at the neutral point and phase terminal ends are sufficiently high. A compensated differential protection is obtained that can detect shunt faults occurring in the windings.

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DIFFERENTIAL PROTECTION FOR SYNCHRONOUS MACHINES

TECHNICAL FIELD

The present invention relates to differential protection of AC electrical machines, particularly electrical generators such as synchronous generators, and in particular to circuits and methods for differential protection.

BACKGROUND

The differential protection method is a commonly used protective method that can detect shunt faults on the armature windings of AC electrical machines, see Fig. 1 in which windings 1_A, 1_B, 1_C of an AC electrical machine are illustrated. The windings are interconnected in a neutral point N 7 and have line terminals 5_A, 5_B, 5_C connected to some power distribution structure such as a busbar. Each winding has a relay or control device 3_A, 3_B, 3_C. Electrical currents I_{A2}, I_{B2}, I_{C2}, enter the windings and electrical currents I_{A1}, I_{B1}, I_{C1} leave the respective windings. The currents are sensed by current transformers 13_A, 13_B, 13_C and 9_A, 9_B, 9_C respectively connected to the relays. In the case where the absolute value of the difference of the two currents in one phase winding is too large the respective relay 3_A, 3_B, 3_C issues an alarm. The sensitivity of circuits using such a differential protection method depends mainly on the accuracy of the current transformers used and the risk for unwanted operation for external shunt faults. Several methods exist to increase the security when the through fault current is high. One commonly used method is to stabilize the differential protection by introducing an additional condition as described below.

Equation (1) defines the differential current I_{Ad} for phase winding 1_A whereas equation (2) defines the stabilizing current I_{As} for the same winding:

$$I_{Ad} = I_{A1} - I_{A2} \tag{1}$$

$$I_{As} = |I_{A1}| + |I_{A2}| \tag{2}$$

According to the conventional method of stabilized differential protection an alarm signal will be issued if the following relation (3) is true

$$|I_{Ad}| > \max(I_{d0}, k \cdot I_{As}) \qquad (3)$$

The condition for alarm is thus that the absolute difference of the currents leaving and incoming to a winding should be greater than a threshold value I_{d0} and for high currents in the winding also greater than the stabilizing current multiplied by a suitably chosen positive constant k. This traditional differential protection method works well for conventional AC electrical machines comprising windings having relatively small capacitances to earth. The introduction of AC electrical machines having cable windings, such as the Powerformer™ generator, has in operational experience presented application problems to the traditional differential protection method. Thus, in Fig. 2 also capacitances C to earth in the protected zone are illustrated as connected to the central points of the windings 1_A, 1_B, 1_C.

For example, a conventional generator having a rated voltage of 13.8 kV and a HV synchronous generator of the Powerformer type having a rated voltage of 138 kV can be considered for comparison. The two machines are assumed to have the same rated apparent power. It is further assumed that the phase-to-earth capacitance of each of the phase windings of the Powerformer generator is three times larger than the phase-to-earth capacitance of the conventional generator. The electrical charge on a phase winding of the Powerformer generator at voltage maximum is then $3 \cdot 10 = 30$ times larger than the charge on a phase winding of the conventional generator. The reason is the higher capacitances of the windings and the higher voltages induced. The time required to discharge the winding capacitances by the rated current of the machine is a measure of the importance of the winding capacitances. This discharge time is $30/0.1 = 300$ times longer for the Powerformer generator than for the conventional generator. This means that when as above comparing the currents leaving and incoming to a winding, they will not even for normal operation be substantially equal to each other since a relatively large AC current, the capacitive differential current, will pass the capacitance of the winding.

The capacitances in the windings to be protected by relay circuits connected for differential protection thus cause two problems:

- The operate value of the differential protection circuits must be increased to avoid unwanted operation caused by the capacitive differential current.
- The differential protection circuits must repress transients in the differential current to avoid unwanted operation caused by the capacitive outrush current.

Results from simulations of a 25 MVA and 78 kV synchronous machine such as a Powerformer generator directly connected to a resonant earthed network will now be used to illustrate these problems.

Differential Protection in Normal Operation of Exemplary AC machine

The active output power of the considered synchronous machine is approximately 10 MW. The diagram of Fig. 3 shows the current in the winding of phase A at the neutral end N or 7 of the winding as a function of time during normal operation. The diagram of Fig. 4 shows the current I_{A2} in phase A at the line terminal 5_A of the winding 1_A as a function of time during normal operation. The diagram of Fig. 5 shows the differential current I_{Ad} in phase A as a function of time during normal operation. The RMS value of the differential current is equal to 6.9 amperes. The rated current is equal to 185 amperes, which means that the differential current is 3.7% of the rated current. The diagram of Fig. 6 shows the average winding voltage on phase A as a function of time during normal operation. The RMS value of the average winding voltage is equal to 23.3 kilovolts. The differential current assumes its peak value when the average winding voltage crosses zero. The diagram of Fig. 7 shows the stabilizing current I_{As} in phase winding 1_A as a function of time during normal operation of the generator. The diagram of Fig. 8 shows the absolute value $/I_{Ad}/$ of the instantaneous differential current as a function of the stabilizing current I_{As} during normal operation. The criterion for the stabilized differential protection method is in the figure indicated by the area above the broken dotted line. For values in this region an alarm would be issued according to this protection method.

As observed in the figure, the absolute differential current $/I_{Ad}/$ reaches its maximum value when the stabilizing current I_{As} is very low. The output from the synchronous machine is assumed to be substantially active (real) power and hence the load current for each phase is in phase with the line terminal voltage V_{A2}, V_{B2}, V_{B2} of the respective winding. The average voltage on the winding is essentially half the terminal voltage and the differential current is substantially proportional to the derivative of the terminal voltage with respect to time. The fundamental frequency differential current hence leads the fundamental frequency terminal voltage by 90 electrical degrees. This means that the stabilization in the protection criterion, i.e. that for an alarm the condition that the absolute differential current must be greater than the stabilizing current multiplied by a constant must be fulfilled, is ineffective during normal operation. Furthermore the minimum operate-value I_{d0} must be set considerably higher than the steady state differential current derived from the capacitances of the windings.

Differential Protection in a Faulty Phase of the exemplary machine

It is now assumed that a single phase-to-earth fault occurs on phase A of the busbar. This is an external fault and the differential protection circuit must not operate. The diagram of Fig. 9 shows the differential current in phase A as a function of time for an external phase-to-earth fault on phase A of the busbar.

The peak value of the differential current is equal to 58 amperes. The peak value of the rated current is equal to 262 amperes, which means that the peak value of the capacitive differential current is 22% of the peak value of the rated current. The RMS value of the differential current decreases from 6.9 amperes during steady state to 6.5 amperes after fault inception. The differential current has a phase shift of 180 degrees at fault inception. The diagram of Fig. 10 shows the average winding voltage on phase A.

The RMS value of the average winding voltage decreases from 22.3 kV before fault inception to 21.3 kV after fault inception. The average winding voltage has a phase shift of 180 degrees at the fault inception. The induced phase-to-neutral voltage is almost constant for single phase-to earth faults in non-effectively earthed systems. The neutral point displacement is close to zero before fault inception. The neutral displacement voltage becomes close to normal phase-to-earth voltage after fault inception but with a phase shift of 180 degrees in relation to the induced voltage in phase a. The diagram of Fig. 11 shows the absolute value of the differential current in phase A as a function of the stabilizing current at an external phase-to-earth fault in phase A. The fault occurs when the phase-to-earth voltage is only 25% of its peak value. It may, therefore, be expected that the peak value could be as high as 232 amperes or 90% of the peak value of the rated current.

Differential Protection in a Healthy Phase of the exemplary machine

It is now assumed that a single phase-to-earth fault occurs on phase B of the busbar. This is an external fault and the differential protection must not operate. The diagram of Fig. 12 shows the differential current in phase A as a function of time for an external phase-to-earth fault on phase B of the busbar.

The peak value of the differential current is equal to 82 amperes. The peak value of the rated current is equal to 262 amperes, which means that the peak value of the capacitive differential current is 31% of the peak value of the rated current. The RMS value of the steady state differential current increases from 6.9 amperes during the steady state as shown in Fig. 5 to 17.3 amperes as shown in Fig. 12 or to 250% of its value before occurrence of the fault. The differential current has a positive phase shift of approximately 30 degrees in relation to its value before occurrence of the fault.

The diagram of Fig. 13 shows the absolute value of the differential current in phase A as a function of the stabilizing current at an external phase-to-earth fault in phase B.

The fault occurs when the phase-to-earth voltage is 70% of its peak value. It may, therefore, be expected that the peak value could be as high as 117 amperes or 45% of the peak value of the rated current. The diagram of Fig. 14 shows the average winding voltage on phase A as a function of time for an external fault on phase B. The average winding voltage increases from 22.3 kV before fault inception to 58.0 kV after fault inception or to 2.6 times its pre-fault value. The theoretical value is equal to $\sqrt{7}$ or 2.65. The average winding voltage has a positive phase shift of approximately 30 degrees, which is equal to the theoretical value.

Concluding remarks on the exemplary machine

The steady state differential currents mainly derived from the capacitances of the windings dictate the minimum setting of a conventional differential protection circuit. The minimum value should be in the order of $1.5 \cdot \sqrt{7} \approx 4$ times the differential current measured during normal operation. In this particular case this means about 30 a or 16% of the rated current of the synchronous machine.

There is a risk that a fast differential protection circuit that uses the rectified instantaneous value of the through fault current operates at external earth faults in non-effectively earthed systems. The peak value of the capacitive outrush current may amount to more than 50% of the peak value of the rated current of the machine. Field tests and workshop tests for Powerformer generators indicate that the capacitive outrush current may be much higher than several times the peak value of the rated current. There is thus a need for a method of differential protection working also for AC machines in which the capacitances of the windings are important.

SUMMARY OF THE INVENTION

It is an object of the invention to provide reliable differential protection for an AC electric machine having significant capacitances of the phase windings to earth.

A circuit for differential protection generally comprises one current transformer at the neutral end of each phase winding, one current transformer at the line terminal of each phase winding and one voltage transformer at the line terminal of each phase winding that can provide a value of the residual voltage or the zero sequence voltage. In addition the circuit may have a voltage transformer at the neutral point but this is not necessary. Furthermore, fourier filters extract the fundamental frequency phasors from the voltages at the secondary windings of the transformers.

The general protection circuit includes first circuits for non-stabilized differential protection for main protection of the winding, second circuits for compensated differential protection for main protection of the winding, third circuits for zero sequence overvoltage protection for back-up protection and fourth circuits, a blocking element, for blocking the second circuits and optionally the first circuits.

Generally then, in an AC electric generator such as the Powerformer™ voltages are induced in phase windings connected at one end to each other at a neutral point and at an opposite end to phase terminals. For each phase winding a value indicative of the magnitude of an excess or rest electric current flowing into the winding that is not related to the currents at the neutral point and phase terminal ends and not to the current flowing through the capacitance of the phase winding is calculated and compared to a threshold value. Circuit breakers are activated and an alarm can be issued if the calculated magnitude is found to be higher than the threshold value. These actions can be inhibited or blocked if some other conditions apply such as that the magnitudes of the currents at the neutral point and phase terminal ends are sufficiently high.

A circuit for compensated differential protection is obtained capable of detecting shunt faults occurring in the windings.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be described by way of non-limiting embodiments with reference to the accompanying drawings, in which:

- Fig. 1 is a simplified circuit diagram illustrating conventional differential protection,
- Fig. 2 is a circuit diagram illustrating the capacitance in the protection zone,

- Fig. 3 is a diagram of the current in phase A at the neutral end of the winding,
- Fig. 4 is a diagram of the current in phase A at the line terminal of the winding,
- Fig. 5 is a diagram of the differential current in phase A during normal operation,
- Fig. 6 is a diagram of the average winding voltage on phase A during normal operation,
- Fig. 7 is a diagram of the stabilizing current in phase A during normal operation,
- Fig. 8 is a diagram of the absolute value of the differential current as a function of the stabilizing current during normal operation,
- Fig. 9 is a diagram of the differential current in phase A at a busbar fault on phase A,
- Fig. 10 is a diagram of the average winding voltage on phase A,
- Fig. 11 is a diagram of the absolute value of the differential current in phase A as a function of the stabilizing current at an external phase-to-earth fault in phase A,
- Fig. 12 is a diagram of the differential current in phase A at a busbar fault on phase B,
- Fig. 13 is a diagram of the absolute value of the differential current in a healthy phase as a function of the stabilizing current at an external phase-to-earth fault,
- Fig. 14 is a diagram of the average winding voltage on phase A at external fault on phase B, and
- Fig. 15 is a circuit diagram of the phase windings of a three-phase electric machine having differential protection.

DESCRIPTION OF A PREFERRED EMBODIMENT

A three-phase synchronous machine or possibly another similar AC electric device that has phases A, B, C and in particular phase windings 1_A, 1_B, 1_C and is provided with protection circuits is illustrated in Fig. 15. The line ends of the phase windings are connected to output terminals 5_A, 5_B, 5_C and their neutral ends are connected to a common node 7 or N, the neutral point or neutral node. A first group of current transformers 9_A, 9_B, 9_C are connected at the neutral ends of the windings and thus their primary windings have a low resistance and are actually portions of the phase windings 1_A, 1_B, 1_C. The secondary windings are connected to fourier filters 11_A, 11_B, 11_C. A second group of current transformers 13_A, 13_B, 13_C are in the similar way connected at the line terminal ends of the windings and their secondary windings are connected to respective fourier filters 15_A, 15_B, 15_C. Voltage transformers 17_A, 17_B, 17_C have their primary windings connected to the respective phase windings at the generator terminals and have their secondary windings connected to fourier filters 19_A, 19_B, 19_C.

The fourier filters 11_A, 11_B, 11_C; 15_A, 15_B, 15_C; 19_A, 19_B, 19_C may be finite impulse response

(FIR) filters or infinite impulse response (IIR) filters. The fourier filters provide complex phasors, i.e. generally quantities describing both the magnitude, direction and phase of the respective currents or voltages, as listed below:

Table 2 Output of the fourier filters.

Symbol	Description
I_{a1}	Complex phasor representing the current at the neutral end of phase A winding
I_{b1}	Complex phasor representing the current at the neutral end of phase B winding
I_{c1}	Complex phasor representing the current at the neutral end of phase C winding
I_{a2}	Complex phasor representing the current at the line terminal of phase A winding
I_{b2}	Complex phasor representing the current at the line terminal of phase B winding
I_{c2}	Complex phasor representing the current at the line terminal of phase C winding
V_{a2}	Complex phasor representing the voltage at the line terminal of phase A winding
V_{b2}	Complex phasor representing the voltage at the line terminal of phase B winding
V_{c2}	Complex phasor representing the voltage at the line terminal of phase C winding

The complex phasors can be used in various ways for defining protection conditions under which an alarm can be issued, signalling a fault in windings and in many cases also the winding in which the fault has occurred. Before issuing the alarm the circuit breakers 25_A, 25_B, 25_C can be activated which are connected between the line terminals 5_A, 5_B, 5_C and e.g. some busbar as illustrated in the figure, the circuit breakers acting to disconnect the windings from the network/busbar.

Thus, the following equations (4), (5) and (6) define three starting criteria k_{da}, k_{db}, k_{dc} of a method for non-stabilized differential protection according to prior art. The parameter I_{d0} is an operate limit for the non-stabilized differential protection method.

$$k_{da} = \begin{cases} 1 & \text{if } |I_{a1} - I_{a2}| > I_{d0} \\ 0 & \text{else} \end{cases} \tag{4}$$

$$k_{db} = \begin{cases} 1 & \text{if } |I_{b1} - I_{b2}| > I_{d0} \\ 0 & \text{else} \end{cases} \tag{5}$$

$$k_{db} = \begin{cases} 1 & \text{if } |I_{b1} - I_{b2}| > I_{d0} \\ 0 & \text{else} \end{cases} \tag{6}$$

In order to carry out this method the following logical blocks can be used, the blocks e.g. being implemented as procedures or functions executed by one or more suitable microprocessors comprised in relays or control devices 3_A, 3_B, 3_C, see Figs. 1 and 2. Thus, in the blocks 31_A, 31_B, 31_C the absolute values of the differences I_{a1} - I_{a2}, I_{b1} - I_{b2}, I_{c1} - I_{c2} are calculated and are compared to the parameter I_{d0} in the blocks 33_A, 33_B, 33_C. If the result of the comparison is that any of the absolute values is larger than the parameter, a signal is sent to the circuit breakers 25_A, 25_B, 25_C in blocks 35_A, 35_B, 35_C, possibly with some delay, the delay being chosen so that accurate readings of the respective fourier filters are obtained. Then, in blocks 37_A, 37_B, 37_C alarms can be issued to some monitoring device, alarm indication panel or operator that a fault has occurred in the respective phase winding. The delay can be obtained by arranging a step counter, not shown, for each phase. The step counter for phase A (phase B or phase C) is incremented if the stating criterion for phase A (phase B or phase C) is equal to 1. The step counter for phase A (phase B or phase C) is decremented if the stating criterion for phase A (phase B or phase C) is equal to 0. The non-stabilized protection issues an operate-signal for phase A (phase B or phase C) if the step counter for phase A (phase B or phase C) exceeds a pre-set limit. This limit should allow the fourier filters 11_A, 11_B, 11_C to settle before the protection issues an operate-signal.

Furthermore, a procedure for compensated differential protection can be arranged in the system of Fig. 15. Such protection comprises four steps: (1) estimation of the neutral point voltage V_{np}, (2) calculation of compensating currents, (3) calculation of compensated differential current and (4) evaluation of starting criteria. Equations (7), (8) and (9) define the complex voltages V_{a1}, V_{b1}, V_{c1} at the neutral end 5 of the windings 1_A, 1_B, 1_C.

$$V_{a1} = \begin{cases} V_{np} & \text{if directly available} \\ \dfrac{V_{a2}+V_{b2}+V_{c2}}{3} & \text{else} \end{cases} \tag{7}$$

$$V_{b1} = \begin{cases} V_{np} & \text{if directly available} \\ \dfrac{V_{a2}+V_{b2}+V_{c2}}{3} & \text{else} \end{cases} \tag{8}$$

$$V_{c1} = \begin{cases} V_{np} & \text{if directly available} \\ \dfrac{V_{a2}+V_{b2}+V_{c2}}{3} & \text{else} \end{cases} \tag{9}$$

In order to estimate the current flowing through the capacitances of the windings 1_A, 1_B, 1_C, it can e.g. be assumed that one portion $\alpha \cdot C_W$ of the total phase-to-earth capacitance C_W of a considered winding can be associated with the voltage at the neutral end of the phase winding while the rest $(1-\alpha) \cdot C_W$ can be associated with the voltage at the line terminal of the winding, α being a number between 0 and 1. This is a possible representation of a winding having a graded insulation. However, more complicated representations can be easily found. Equations (10), (11) and (12) define compensating currents I_{ca}, I_{cb}, I_{cc}, i.e. the complex currents flowing through the capacitances to earth of the windings 1_A, 1_B, 1_C using the described assumption.

$$I_{ca} = j\omega \cdot \alpha \cdot C_w \cdot V_{a1} + j\omega \cdot (1-\alpha) \cdot C_w \cdot V_{a2} = \\ = j\omega \cdot C_w \cdot [\alpha \cdot V_{a1} + (1-\alpha) \cdot V_{a2}] = j\omega \cdot C_w \cdot V_{avg,a} \tag{10}$$

$$I_{cb} = j\omega \cdot \alpha \cdot C_w \cdot V_{b1} + j\omega \cdot (1-\alpha) \cdot C_w \cdot V_{b2} = \\ = j\omega \cdot C_w \cdot [\alpha \cdot V_{b1} + (1-\alpha) \cdot V_{b2}] = j\omega \cdot C_w \cdot V_{avg,b} \tag{11}$$

$$I_{cc} = j\omega \cdot \alpha \cdot C_w \cdot V_{c1} + j\omega \cdot (1-\alpha) \cdot C_w \cdot V_{c2} = \\ = j\omega \cdot C_w \cdot [\alpha \cdot V_{c1} + (1-\alpha) \cdot V_{c2}] = j\omega \cdot C_w \cdot V_{avg,c} \cdot \tag{12}$$

where the definition of the average voltages $V_{avg,a}$, $V_{avg,b}$, $V_{avg,c}$ is obvious.

Equations (13), (14) and (15) define the compensated differential currents $I_{dc,a}$, $I_{dc,b}$, $I_{dc,c}$:

$$I_{dc,a} = I_{a1} - I_{ca} - I_{a2} \tag{13}$$

$$I_{dc,b} = I_{b1} - I_{cb} - I_{b2} \tag{14}$$

$$I_{dc,c} = I_{c1} - I_{cc} - I_{c2} \tag{15}$$

Equations (16), (17) and (18) define the three starting criteria $k_{dc,a}$, $k_{dc,b}$, $k_{dc,c}$ of the compensated differential protection. The parameter I_{dco} is the operate limit for the compensated differential protection.

$$k_{dc,a} = \begin{cases} 1 & \text{if } |I_{dc,a}| > I_{dc0} \\ 0 & else \end{cases} \tag{16}$$

$$k_{dc,b} = \begin{cases} 1 & \text{if } |I_{dc,b}| > I_{dc0} \\ 0 & else \end{cases} \tag{17}$$

$$k_{dc,c} = \begin{cases} 1 & \text{if } |I_{dc,c}| > I_{dc0} \\ 0 & else \end{cases} \tag{18}$$

In a block 41 the complex voltages V_{a1}, V_{b1}, V_{c1} at the neutral end of the windings are calculated as the average of the voltages at the line terminal ends of the windings, i.e. the value $(V_{a2} + V_{b2} + V_{c2})/3$ is calculated. This value is provided to blocks 43_A, 43_B, 43_C in which the averages $V_{avg,a}$, $V_{avg,b}$, $V_{avg,c}$ of the voltage in the phase windings are determined as is obtained from Equations (10), (11), (12), i.e. $V_{avg,a} = \alpha \cdot V_{a1} + (1-\alpha) \cdot V_{a2}$, $V_{avg,b} = \alpha \cdot V_{b1} + (1-\alpha) \cdot V_{b2}$, $V_{avg,c} = \alpha \cdot V_{c1} + (1-\alpha) \cdot V_{c2}$. Generally, the average voltage can be determined in any suitable way, such as by using a more complex and accurate model of the distributed capacitance of the windings. The average voltages are used to determine the compensating currents I_{ca}, I_{cb}, I_{cc} in blocks 47_A, 47_B, 47_C by multiplication by a suitable constant, compare Equations (10), (11), (12). The compensating differential currents $I_{dc,a}$, $I_{dc,b}$, $I_{dc,c}$ are calculated in the blocks 49_A, 49_B, 49_C, which receive the values of the compensating currents from the blocks 47_A, 47_B, 47_C, the values of the neutral end currents from the fourier filters 11_A, 11_B, 11_C, and the values of the line terminal end currents from the fourier filters 15_A, 15_B, 15_C. The absolute values of the compensating differential currents are compared to the parameter $I_{dc,0}$ in the blocks 51_A, 51_B, 51_C. If the result of the comparison is that any of the absolute values is larger than the parameter, a signal is sent to the circuit breakers 25_A, 25_B, 25_C in blocks 53_A, 53_B, 53_C, possibly with some delay, the delay being chosen so that accurate readings of the respective fourier filters are obtained, the signal turning the circuit breakers off. Then, in blocks 55_A, 55_B, 55_C alarms can be issued to some monitoring device, alarm indication panel or operator that a fault has occurred in the respective phase winding. The delay can as described above be obtained by arranging a step counter, not shown, for each phase. The step counter for phase A (phase B or phase C) is incremented if the starting criterion for phase A (phase B or phase C) is equal to 1. The step counter for phase A (phase B or phase C) is decremented if the starting criterion for phase A (phase B or phase C) is equal to 0. The non-stabilized protection issues an operate-signal for phase A (phase B or phase C) if the step counter for phase A (phase B or phase C) exceeds a pre-set limit. This limit should allow all the fourier filters involved in the quantities required in the comparison of blocks 51_A, 51_B, 51_C, i.e. the fourier filters 11_A, 11_B, 11_C, 15_A, 15_B, 15_C and 19_A, 19_B, 19_C or optionally 23, to settle before any of the protection circuits or blocks issues any operate-signal.

Equation (19) defines the starting criteria k_{zu} for the circuit part including a zero sequence overvoltage protection. The parameter V_{z0} is the operate limit for the zero sequence overvoltage protection.

$$k_{zu}=\begin{cases}1 & \text{if } \left|\dfrac{V_{a2}+V_{b2}+V_{c2}}{3}\right|>V_{z0}\\ 0 & \text{else}\end{cases} \tag{19}$$

The comparison of Equation (19) is performed in the block 57 that receives the average value of the line end terminal voltages from the block 41. If the result of the comparison is that the absolute value of average line end voltage is larger than the parameter V_{z0}, a signal is sent to the circuit breakers 25_A, 25_B, 25_C in a block 59 and an alarm can be issued in a block 61. In the same way as above a delay of the signal from the blocks 59 and 61 can be arranged by means of a step counter, not shown. The step-counter is incremented if the stating criterion for the zero sequence overvoltage protection is equal to 1. The step-counter is decremented if the stating criterion for the zero sequence overvoltage protection is equal to 0. The zero sequence overvoltage protection issues an operate-signal if the step-counter for the zero sequence overvoltage protection exceeds a pre-set limit. This limit should allow the fourier filters 19_A, 19_B, 19_C involved in the calculation of the line end average voltage to settle before any signal is issued.

Equations (20), (21) and (22) define three blocking criteria k_{ba}, k_{bb}, k_{bc} for the compensated differential protection circuit. The parameter V_{b0} is the operate limit for the blocking element.

$$k_{ba}=\begin{cases}1 & \text{if } \max\left(\left|I_{A1}\right|,\left|I_{A2}\right|\right)>I_{b0}\\ 0 & \text{else}\end{cases} \tag{20}$$

$$k_{bb}=\begin{cases}1 & \text{if } \max\left(\left|I_{b1}\right|,\left|I_{b2}\right|\right)>I_{b0}\\ 0 & \text{else}\end{cases} \tag{21}$$

$$k_{bc}=\begin{cases}1 & \text{if } \max\left(\left|I_{c1}\right|,\left|I_{c2}\right|\right)>I_{b0}\\ 0 & \text{else}\end{cases} \tag{22}$$

The blocking element operates if anyone of the blocking criteria k_{ba}, k_{bb}, k_{bc} is equal to 1. The operation of the blocking element blocks the circuit of compensated differential protection from issuing signals but not the circuit for zero sequence overvoltage protection. Suitable time grading of the back up zero sequence overvoltage protection will create necessary coordination with circuits, not shown, for main earth fault protection. The blocking element may or may not block the circuit for non-stabilized differential protection. The blocking element is a circuit part that comprises blocks 63_A, 63_B, 63_C in which the quantities max ($|I_{a1}|$- $|I_{a2}|$), max ($|I_{b1}|$- $|I_{b2}|$), max ($|I_{c1}|$- $|I_{c2}|$) are determined. These quantities are in blocks 65_A, 65_B, 65_C compared to the parameter V_{b0}, the operate limit. If the quantities higher than the parameter, blocks 67_A, 67_B, 67_C are executed in which a blocking signal is sent to the corresponding one of the blocks 53_A, 53_B, 53_C to command them not to send any signal to the circuit breakers 25_A, 25_B, 257_C and also to the blocks 55_A, 55_B, 55_C commanding them not to issue alarm signals.

CLAIMS

1. An AC electric machine, in particular a generator, having phase windings in which voltages are induced, the phase windings connected at one end to each other at a neutral point and at an opposite end to phase terminals on which voltages are supplied, **characterized by**

- first current determining means for determining the currents in the phase windings at locations at the neutral point,
- second current determining means for determining the currents in the phase windings at locations at the phase terminals,
- first voltage determining means for determining the voltage in the phase windings at locations at the phase terminals,
- first calculating means for calculating for each phase winding, from the determined currents and the determined voltage for the respective phase winding, a value indicative of the magnitude of electric current flowing into the winding but not from the end at the neutral point to the end at the phase terminal and not through the capacitance of the phase winding,
- first comparing means for comparing the calculated value for each phase winding to a first threshold value and to signal, when at least one of the calculated values is larger than the first threshold value, to a control device for disconnecting or disabling the phase windings.

2. An AC electric machine according to claim 1, **characterized in** that each of first voltage determining means includes a voltage transformer and a fourier filter.

3. An AC electric machine according to claim 1, **characterized in** that each of the first and/or second current determining means includes a current transformer and a fourier filter.

4. An AC electric machine according to claim 1, **characterized by** second calculating means for calculating from the determined voltages, a value of the voltage at the neutral point of the windings.

5. An AC electric machine according to claim 1, **characterized by** second voltage determining means for determining the voltage at the neutral point.

6. An AC electric machine according to claim 2, **characterized by** third calculating means for calculating from the determined voltages and a value of the voltage at the neutral point, a value of the current flowing through the capacitance of each of the windings.

7. An AC electric machine according to claim 6, **characterized in** that the third calculating means are arranged to calculate a value of the current flowing through the capacitance of each of the winding using a model including that a first portion of the capacitance is associated with the neutral point end of the winding and a second, remaining portion of the capacitance is associated with the terminal end of the winding.

8. An AC electric machine according to claim 1, **characterized by** fourth calculating means for calculating for each phase winding, from the determined currents, the maximum of the magnitudes of the currents flowing in the winding at the neutral point and at the phase terminal and arranged to block the corresponding first comparing means from signalling when the calculated maximum is higher than a second threshold value.

9. An AC electric machine according to claim 1, **characterized in** that each of the first and/or second current determining means includes a current transformer and a fourier filter.

Fig. 1

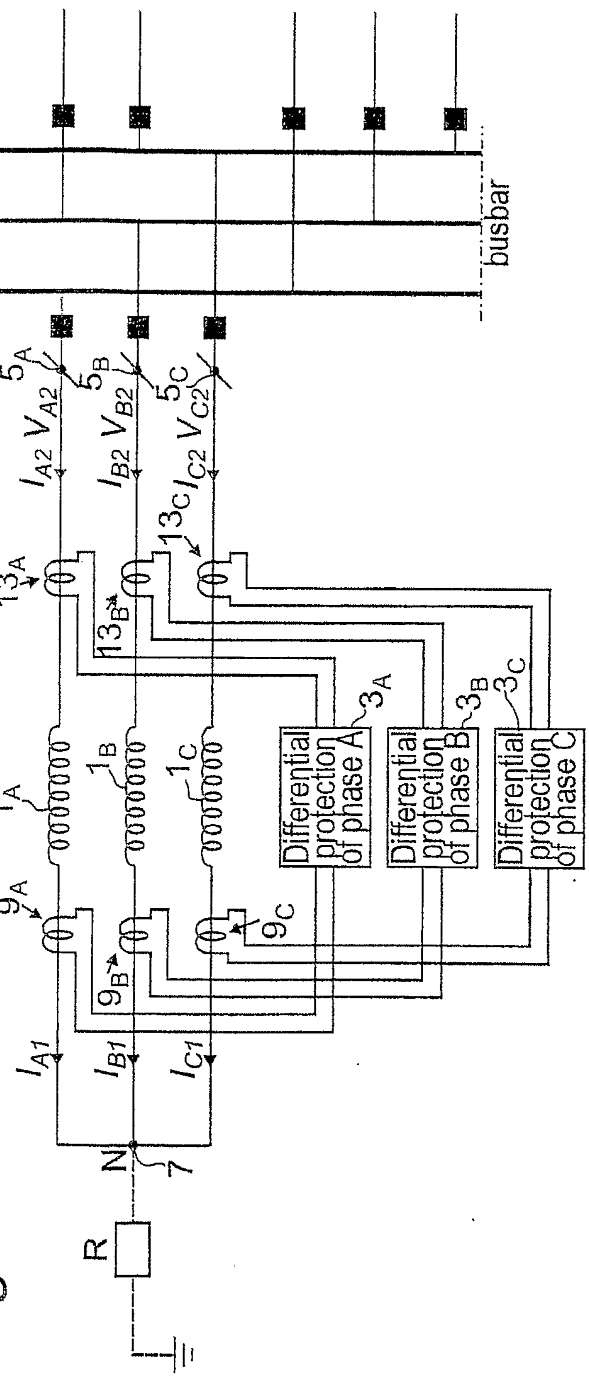
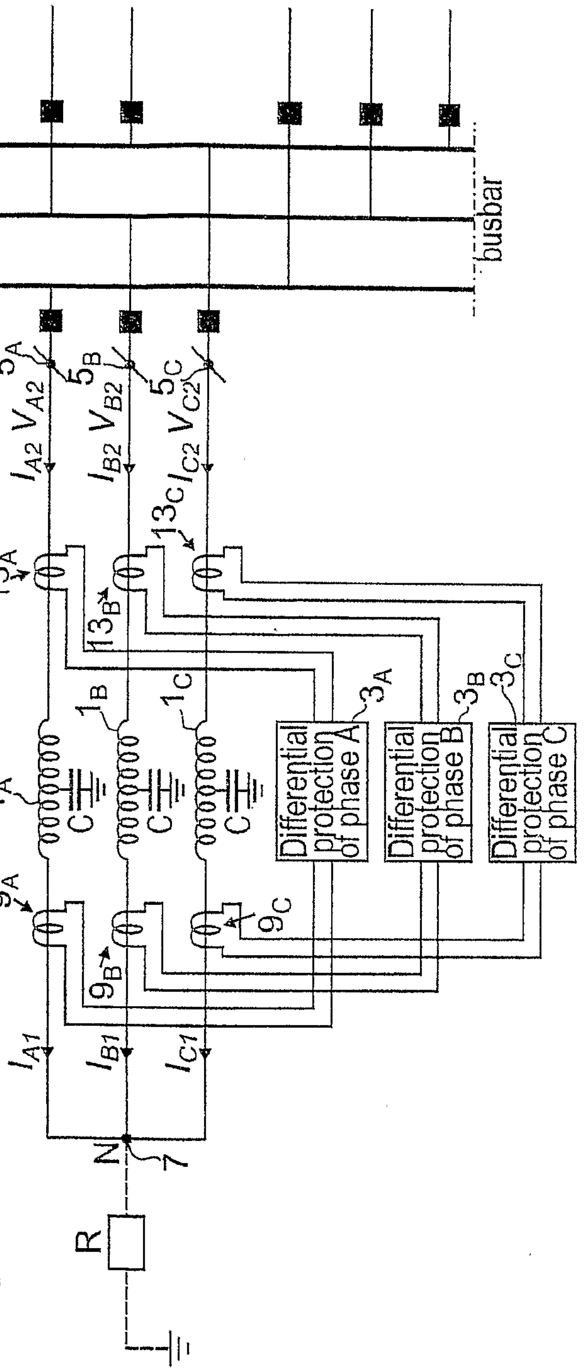

busbar
Differential protection of phase A
Differential protection of phase B
Differential protection of phase C
R
N
7

Fig. 2


busbar
Differential protection of phase A
Differential protection of phase B
Differential protection of phase C
R
N
7

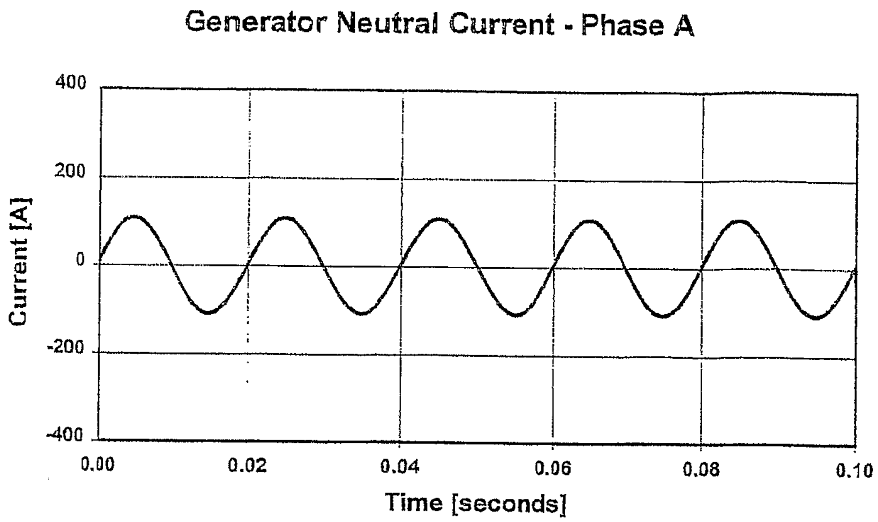


Fig. 3

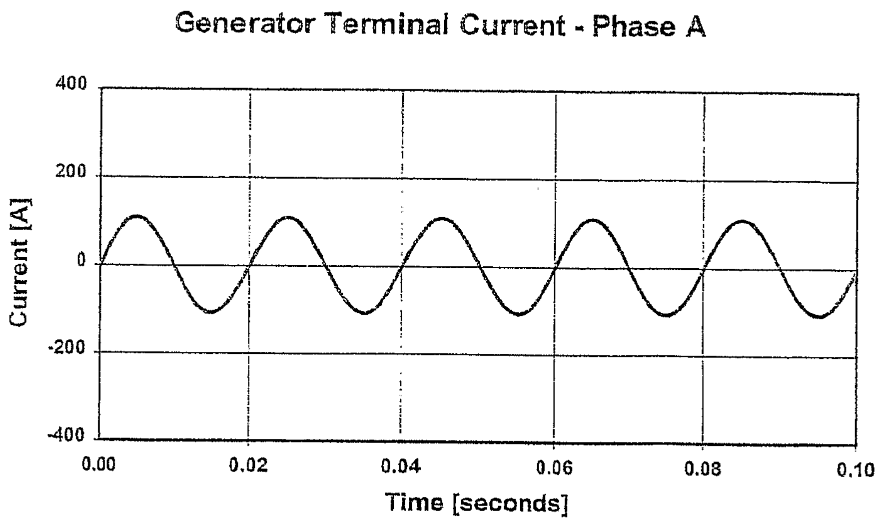


Fig. 4

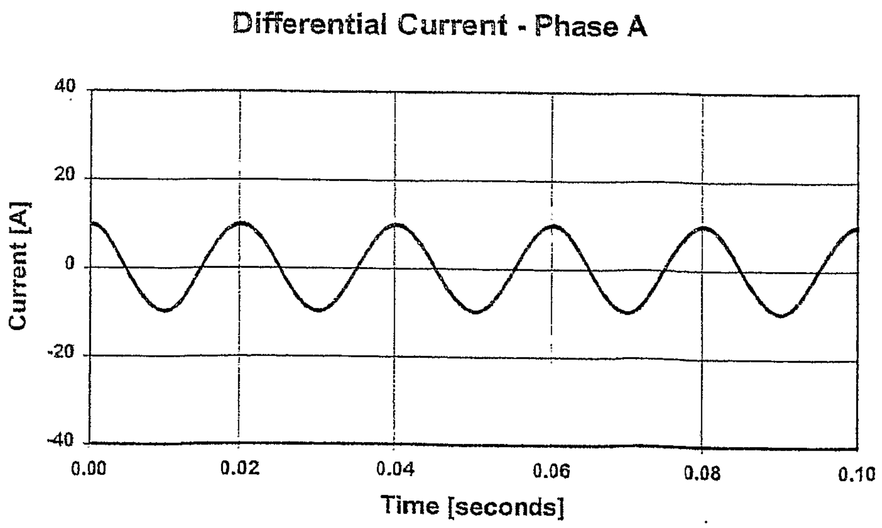


Fig. 5

Fig. 6

Average Winding Voltage

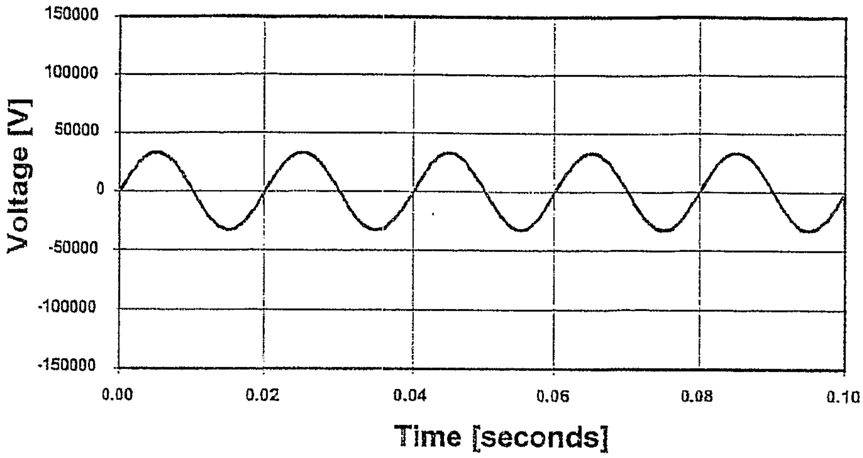


Fig. 7

Stabilising Current

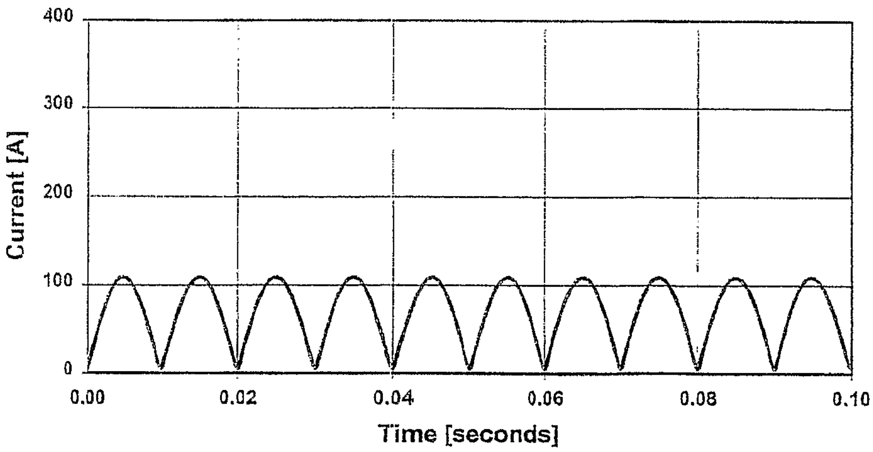


Fig. 8

ABS(Differential Current) vs Stabilising Current

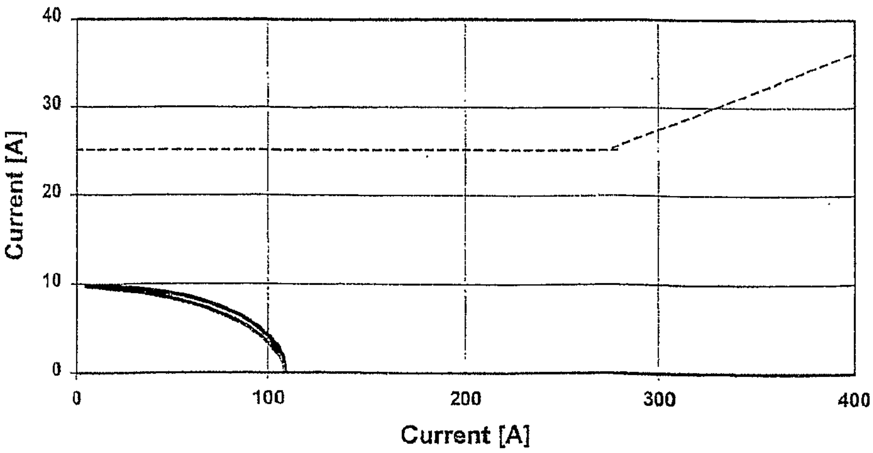


Fig. 9

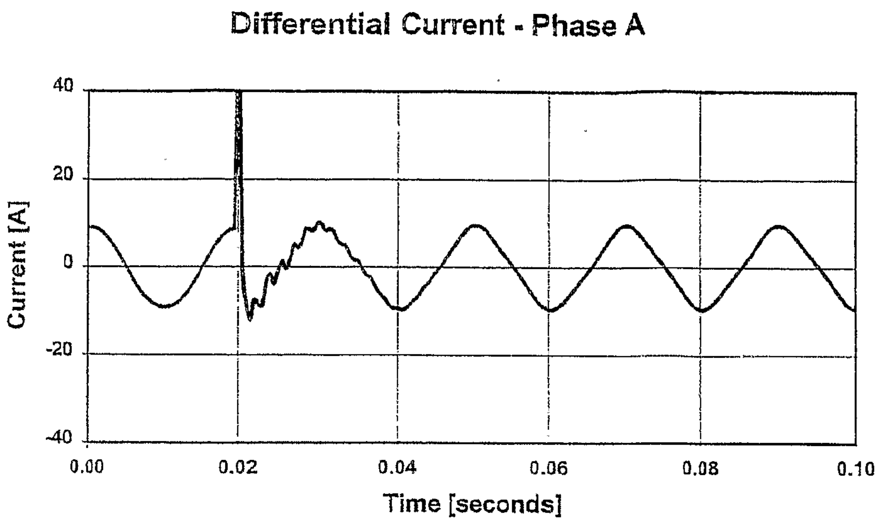


Fig. 10

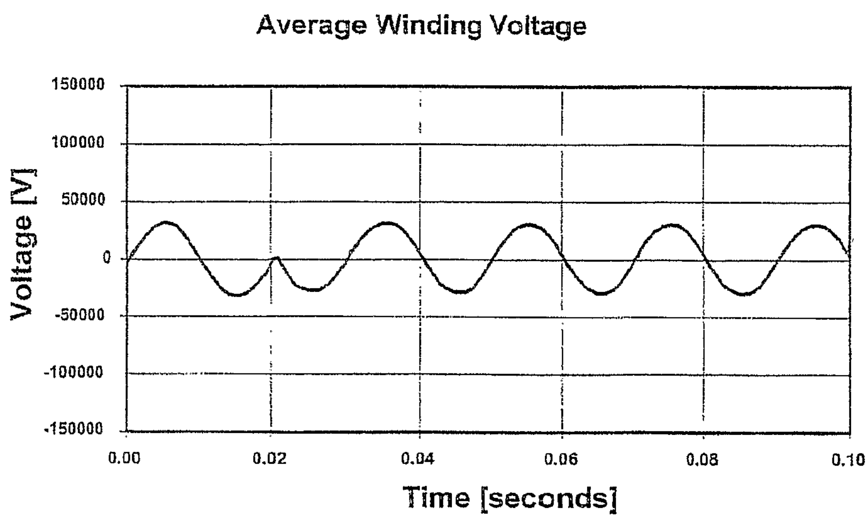
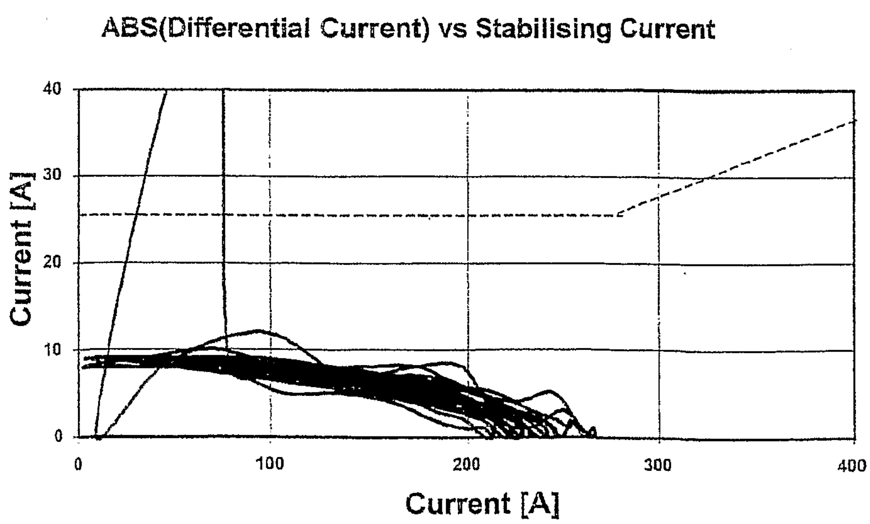


Fig. 11



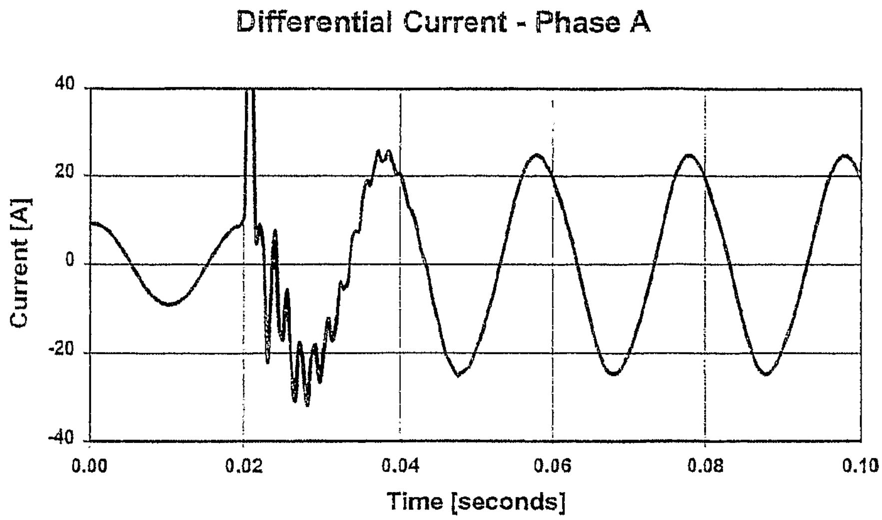


Fig. 12

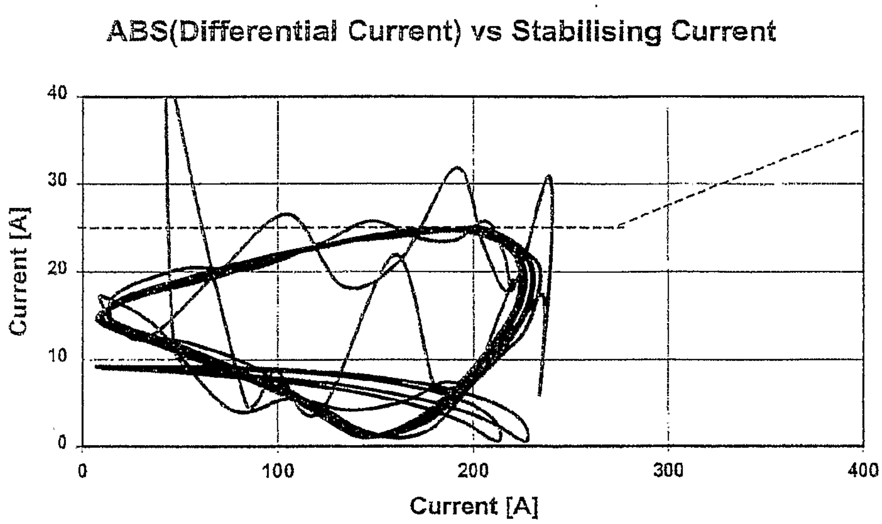


Fig. 13

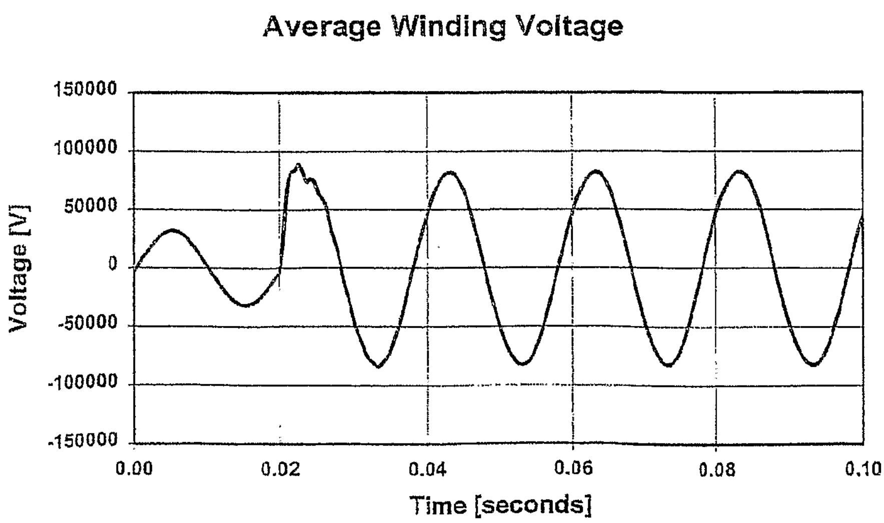


Fig. 14

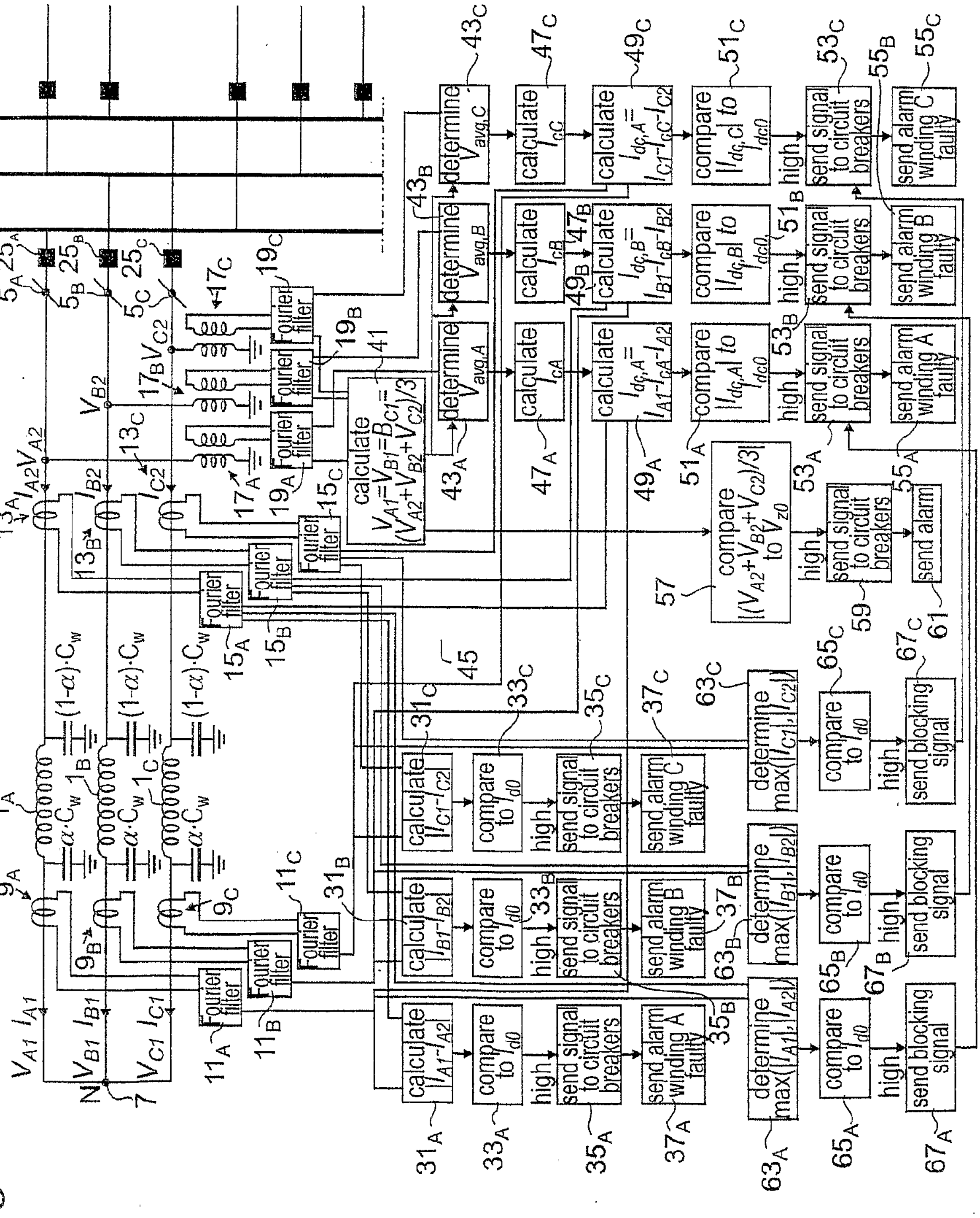

determine $V_{avg,C}$
determine $V_{avg,B}$
determine $V_{avg,A}$
calculate I_{cC}
calculate I_{cB}
calculate I_{cA}
calculate $I_{dq,C}=I_{C1}-I_{cC}-I_{C2}$
calculate $I_{dq,B}=I_{B1}-I_{cB}-I_{B2}$
calculate $I_{dq,A}=I_{A1}-I_{cA}-I_{A2}$
compare $|I_{dq,C}|$ to I_{dc0}
compare $|I_{dq,B}|$ to I_{dc0}
compare $|I_{dq,A}|$ to I_{dc0}
high
send signal to circuit breakers
send alarm winding C faulty
send alarm winding B faulty
send alarm winding A faulty
calculate $V_{A1}=V_{B1}=B_{C1}=(V_{A2}+V_{B2}+V_{C2})/3$
compare $|(V_{A2}+V_{B2}+V_{C2})/3|$ to V_{z0}
send alarm
Fourier filter
calculate $|I_{C1}-I_{C2}|$
calculate $|I_{B1}-I_{B2}|$
calculate $|I_{A1}-I_{A2}|$
compare to I_{d0}
determine $\max(|I_{C1}|,|I_{C2}|)$
determine $\max(|I_{B1}|,|I_{B2}|)$
determine $\max(|I_{A1}|,|I_{A2}|)$
send blocking signal
$\alpha \cdot C_w$
$(1-\alpha) \cdot C_w$
V_{A1} I_{A1}
V_{B1} I_{B1}
V_{C1} I_{C1}
I_{A2} V_{A2}
I_{B2} V_{B2}
I_{C2} V_{C2}
N
7
1_A 1_B 1_C
5_A 5_B 5_C
9_A 9_B 9_C
11_A 11_B 11_C
13_A 13_B 13_C
15_A 15_B 15_C
17_A 17_B 17_C
19_A 19_B 19_C
25_A 25_B 25_C
31_A 31_B 31_C
33_A 33_B 33_C
35_A 35_B 35_C
37_A 37_B 37_C
41
43_A 43_B 43_C
45
47_A 47_B 47_C
49_A 49_B 49_C
51_A 51_B 51_C
53_A 53_B 53_C
55_A 55_B 55_C
57
59
61
63_A 63_B 63_C
65_A 65_B 65_C
67_A 67_B 67_C

Fig. 15

INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 03/50710

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H02H7/06 H02H3/28

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H02H

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 1 658 704 A (DAUT CAMHY MUSAFFER) 7 February 1928 (1928-02-07) page 1, column 2, line 67 -page 2, column 2, line 72; figure 1 ---	1-9
A	US 1 731 971 A (JOHANN BAYER ET AL) 15 October 1929 (1929-10-15) page 1, column 2, line 73 -page 2, column 2, line 113; figure 1 ---	1-9
A	US 3 160 787 A (SONNEMANN WILLIAM K) 8 December 1964 (1964-12-08) column 2, line 21 -column 5, line 46; figure 1 -----	1-9

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
19 February 2004	02 APR 2004

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	SARA THULIN/MN

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/EP 03/50710

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
US 1658704	A	07-02-1928	NONE		
US 1731971	A	15-10-1929	NONE		
US 3160787	A	08-12-1964	CH	387149 A	31-01-1965