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APPLICATION OF MAGNETIC COMPARATORS TO THE DETECTION OF CURRENT PASSAGE THROUGH THE NULL

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The paper presents and discusses the dependence between the delay in detecting current passage through the null and the dynamic coercivity of a nanocrystalline tape-wound comparator and the rate of field intensity passage through the null. The effect of loading the magnetic comparator with capacitance, resulting in a reduction in the delay of information about current passage through the null, is demonstrated.

Keywords: current, passage through null, magnetic comparator

1 INTRODUCTION

In electric power systems mainly current transformers are used to convert the electric current. Current transformers ensure the necessary galvanic insulation of the current circuit from the secondary circuit. However, they can only transform alternating current and their conversion linearity range is limited and their frequency band is narrow.

In contrast, inductive sensors have a limitless conversion linearity range and a wide frequency band [1]. Similarly as in current transformers, their secondary circuit is galvanically insulated from the current circuit. However, the signal in the secondary circuit of the inductive sensor is not proportional to the current, but to its derivative. Thus the signal does not contain full information about the current and the initial condition is needed to reproduce the current. If the current waveform is symmetric, the initial condition can be directly taken into account. If the current waveform includes even harmonics or a constant component, then in order to take into account the initial condition one needs to know the instant in which the current passes through the null.

Knowing the signal originating from the inductive sensor and the current-passage-through-null signal one can determine, for example, the constant component in alternating current and the peak values of currents of any magnitude in non-stationary states when the non-periodic component is present.

2 MAGNETIC COMPARATOR

The passage-through-null signal of the current present in the electric power system can be obtained by a magnetic comparator owing to the fact that the signal at the comparator output appears in the circuit galvanically insulated from the current circuit.

In the easily saturated magnetic core of the comparator the field intensity generated by the current in the primary winding is compared with the null. If the field intensity passes through the null (changes its sign), then a voltage pulse (Fig. 1) is produced in the secondary winding. The pulse is delayed – its peak value occurs only then when the field intensity becomes equal to the dynamic coercivity of the magnetic core ($H = H_c$).

The information about the passage of the field intensity through the null can be read off on the leading edge of the pulse, but with an error. The error is smaller when the magnetic core dynamic coercivity is smaller and the rate of field intensity increase close to the null is higher.

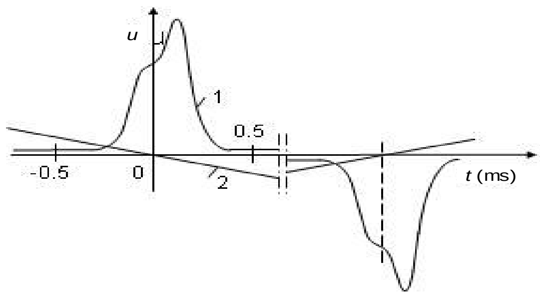

Fig. 1. Pulses of voltage induced in secondary winding of comparator with nanocrystalline magnetic core – graph 1 and magnetic field intensity close to passage through null – graph 2

If coercivity is low, then

$$H_c = \left(\frac{dH}{dt} \bigg|_{t-t_0} \right) \Delta t_m = H'(t_0) \Delta t_m \, , \qquad (1)$$

where $t = t_0$ when $H = 0$. Time slice Δt_m is measured from the instant when field intensity passes through the null to the instant when the peak pulse value occurs. This time slice can be regarded as the limiting error with which the instant at which magnetic field intensity or current passes through the null is determined.

Field intensity in interval $\pm H_c$ is exactly proportional to the current in the comparator primary winding since the magnetic core permeability in this interval is high.

$$H = \frac{iN_1}{l_0} , \qquad (2)$$

with N_1 – the number of primary winding turns, l_0 – the average length of the magnetic core. Thus the instant when field intensity passes through the null is exactly equal to the instant when current passes through the null.

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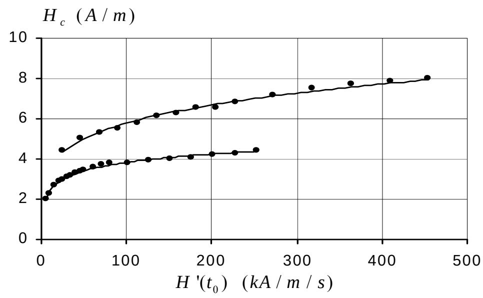

Fig. 2. Dynamic coercivity of magnetic core made of nanocrystalline tape versus rate at which magnetic field intensity passes through null

In laboratory conditions, time slice Δt_m can be directly determined. Also the rate at which field intensity passes through the null can be directly determined if a sinusoidal current is forced in the comparator primary winding. Then

$$H'(t_0) = \frac{d}{dt}\left(\frac{\sqrt{2}IN_1}{l_0}\sin\omega t\bigg|_{t=0}\right) = \frac{\sqrt{2}\omega IN_1}{l_0}, \qquad (3)$$

where I – is the rms value of current. If time slice Δt_m and the rate at which field intensity passes through the null are known, then from equation (1) one can calculate the dynamic coercivity of the magnetic core.

The dependence between the dynamic coercivity of the comparator magnetic core made of nanocrystalline tape and the rate at which magnetic field intensity passes through the null is shown in Fig. 2.

As the rate at which magnetic field intensity passes through the null increases, dynamic coercivity initially rapidly increases and then the rate of its increase diminishes and finally delay Δt_m decreases as the rate of magnetic field intensity increase grows. But the relative (to the period of 50 Hz current) value of this delay is sufficiently low (below 0.1%) only at a rate of field intensity increase higher than 400kA/ms (Fig. 3).

3 EFFECT OF LOADING COMPARATOR WITH CAPACITANCE

The delayed information about the passage of field intensity through the null can always be read off at the instant when the voltage pulse at the comparator output reaches its peak value. This information can also be read off on the rising edge of the pulse. But then it is necessary to set the reference voltage at a proper level. For a given rate of field intensity passage through the null one can set such a reference voltage level that the information delay will amount to zero (even an advance information is possible). When the rate of field intensity passage through the null is unknown, the reference voltage level is also unknown.

If, however, the output of the comparator (whose magnetic core is made of nanocrystalline tape) is loaded with a proper (experimentally determined) capacitance, then output pulses having the shape shown in Fig. 4 will be obtained. Although the peak values of the pulses are more delayed than the respective pulses originating from the unloaded comparator, they have one advantageous property: their voltage level at the instant when field intensity passes through the null only slightly depends on the rate of this passage [2].

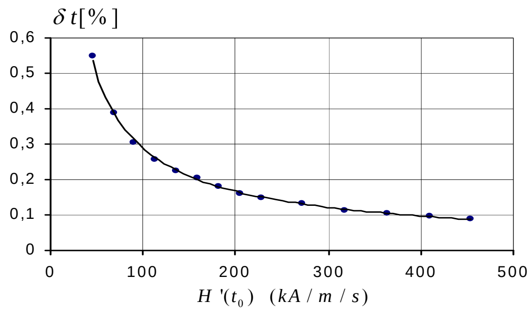

Fig. 3. Relative (to mains current period) delay of pulse peak value at magnetic comparator output versus rate at which magnetic field intensity passes through null

A magnetic comparator loaded with capacitance and an output signal converter is shown in Fig. 5.

The comparator secondary winding is symmetric and the pulses induced in this winding are converted in two circuits. One circuit converts positive pulses while the other converts reversed negative pulses. In each of the circuits instants in which the rising edges of pulses intersect reference voltage level U_0 are detected and stored.

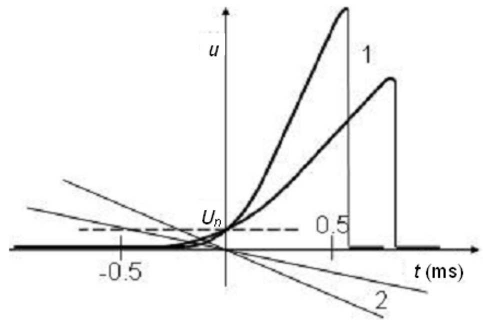

Fig. 4. Pulses at output of comparator with nanocrystalline magnetic core, loaded with capacitance – graphs 1 and magnetic field intensity close to passage through null – graphs 2

From the memory (latch) status one can also determine whether field intensity passed from a positive value to a negative one or from a negative value to a positive one. A resistor dampening vibrations on the trailing edges of the pulses is incorporated in series with a capacitor which short-circuits the secondary winding of the magnetic comparator. The parameters (capacitance and resistance) of the circuit shorting the comparator secondary winding have a decisive influence on the shape of the pulses. This is an advantage since in this way the influence of the changing parameters of the primary circuit is limited.

Using a comparator with a nanocrystalline magnetic core, loaded with capacitance one can obtain information about the passage of field or current intensity with a delay close to zero if a proper value of reference voltage U_0 is set and if the rates of passage through the null are sufficiently high for the pulses not to exceed level U_0. For arbitrarily high rates of passage, information delays below 1 μs (Fig. 6) are attainable.

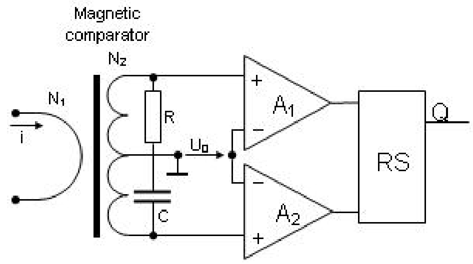

Fig. 5. Magnetic comparator loaded with capacitance (C) and signal converter

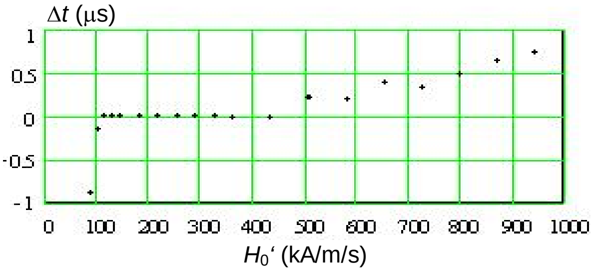

Fig. 6. Dependence of delay with which field (current) intensity passage through null is detected on the rate of passage, determined by comparator loaded by C

4 MODULATION METHOD

A detector of field or current intensity passage through the null, operating on the principle of output pulse phase modulation includes two magnetic comparators (Fig. 7a) with ferrite magnetic cores. In the magnetic comparators the field intensity generated by a current with a low energy frequency is compared with the intensity of a high-frequency field. The intensity of the high-frequency field is generated by a current whose waveform is close to sinusoidal. A sinusoidal voltage generator with a power amplifier forces this current through a resistor and a capacitor which blocks a possible constant current component.

If in a given instant in one of the comparators the instantaneous intensity values of the low- and high-frequency fields add up, they are mutually subtracted in the other comparator. For a zero intensity of the low-frequency field the pulses originating from the two comparators coincide (Fig. 7b). For positive field intensity the positive pulses from comparator 2 are delayed relative to the positive pulses from comparator 1. As the field intensity increases so does the delay while the peak values of the pulses decrease. For negative intensity of the low-frequency field the pulses behave similarly as for positive intensity, but in this case the pulses from comparator 1 are delayed relative to the pulses from comparator 2. Thus a change in the sequence of pulses occurs in the instant when the current generating low-frequency field intensity passes through the null. For field intensity significantly different from the null the magnetic cores become saturated and the output pulses decay.

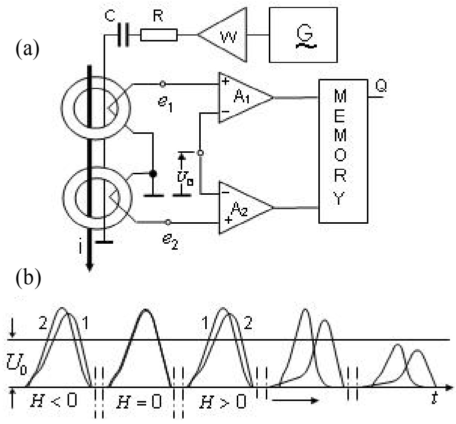

Fig. 7. Detector of field (current) intensity passage through null operating on output impulse phase modulation principle: (a) – circuit, (b) – positive pulses originating from comparators

The passages of the leading edges of positive pulses through the fixed level of voltage U_0 are detected in the signal processing system. A change in the status of voltage comparator A_1 sets 1 at the input of the first memory element, stores the second memory element input status and erases the first memory element. Similarly, a change in the status of voltage comparator A_2 sets 1 at the input of the second memory element, stores the first memory element input status and erases the second memory element. A change in the status of each memory element determines the instant in which the low-frequency current passes through the null and the direction of the passage. The change occurs always later than the change in the sequence of pulses. The delay depends mainly on the operating speed of the signal processing circuits, but it can also be due to the unrepeatability of the parameters of the magnetic cores, the occurrence of even harmonics in the high-frequency current and to the polarization of the magnetic cores when the peak values of the high-frequency current are not sufficiently high.

Therefore in order to read the information about the passage of the current through the null the phase of the impulses originating from the individual comparators must be sufficiently shifted. At lows rates of low-frequency current increase, a sufficiently large phase shift may occur only after many high-frequency periods k ($k > 1$). The shortest delays in information reading occur when a proper increase in low-frequency field intensity takes place in a time shorter than the high-frequency period ($k = 1$). The delay in the detection of a change in the sequence of pulses will not exceed then one period. At too high rates of low-frequency field increase the magnetic cores become saturated in a time comparable with the high-frequency field intensity waveform period. Then the pulses from the magnetic comparators no longer exceed level U_0, which means that passages of the current through the null are not detected.

The properties of the modulation method of detecting current passages through the null were investigated using a detector model [3].

A pair of selected ferrite magnetic cores with repeatable rectangular hysteresis loop parameters and the following dimensions: outside diameter – 2.6 mm, inside diameter – 1.8 mm, cross-sectional area – 0.4 mm^2 were used in the comparators.

The magnetic cores were remagnetized with an approximately sinusoidal current with an amplitude of 1 A and a frequency of 100 kHz, flowing through one turn. The converted current covered by the magnetic cores flowed through a section of copper wire 1 mm in diameter and a length of 8 mm, whose ends were fixed to radiators. For a given speed of processing the signals originating from the magnetic comparators the delay in detecting the passage of the current through the null depends mainly on the rate of field intensity passage. The dependence for a remagnetizing current frequency of respectively 100 kHz (solid line) and 50 kHz (measuring points only) is shown in Fig. 8. A delay in the current passage through the null shorter than the high-frequency current period was obtained when the rate of low-frequency field intensity passage was above 100 MA/m s. For the remagnetizing current frequency of 100 kHz, the delay shorter than the period persisted up to passage rates higher than 10MA/m/s. The range of delay shorter than the period depends on the remagnetizing current frequency and on the adopted level of voltage U_0 (Fig. 7). For the remagnetizing current frequency of 100 kHz this level was assumed to be located at half the height of the pulses arising at the output of the magnetic comparators at the zero value of the low-frequency current.

For current frequencies higher than 100 kHz the investigated detector model did not work properly due to the too large phase shifts in the signal processing circuits.

5 CONCLUSION

Thanks to the use of the magnetic comparator, information about current passage through the null is obtained by directly detecting the extreme values of the output impulse originating from the magnetic comparator. The delay depends on the dynamic coercivity of the comparator magnetic core and on the rate of field intensity passage through the null. The delay is shorter when the coercivity is lower and the rate is higher. When nanocrystalline tape-wound cores are used, the delays shorter than 20 μs are attained only at passage rates higher than 400 kA/m/s.

For a given rate of field intensity passage through the null one can set such a voltage level that the information read delay will amount to zero. Unfortunately, as the rate of passage changes so does the voltage level. If, however, the comparator output is loaded with a suitable experimentally determined capacitance, then the set voltage level only slightly depends on the rate of passage. In this way one can achieve an information delay shorter than 1 μs for all the rates due to which the peak pulse value at the output of the loaded comparator exceeds the set voltage level.

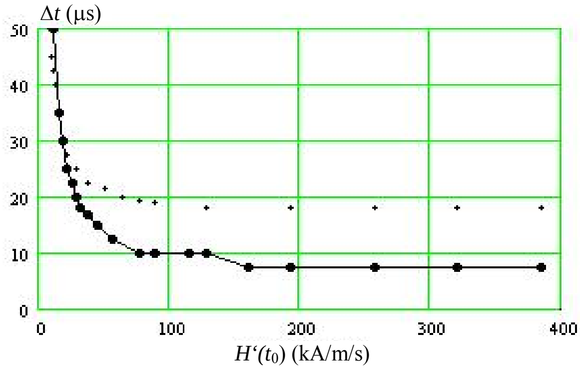

Fig. 8. Dependence of delay in detecting passage of field (current) intensity through null on the rate of passage, determined by means of detector modulating phase of output pulses

Information about current passage through the null can also be obtained using the modulation method. As a result of comparing the low-(energy) frequency field intensity with the high-frequency field intensity, the phase of the output pulses originating from the comparator is modulated. The sequence of the pulses originating from the two comparators changes when the field intensity passes through the null if at the given instant field intensity in one of the comparators add up while in the other comparator they are mutually subtracted. The information delay is mainly due to the finite operating speed of the signal processing circuits, which limits the high-frequency level. For sufficiently high rates of low-frequency field passage through the null (higher than about 100 kA/m/s) the information delay does not exceed one high-frequency period. The delay remains at a constant level up to about one hundred times higher rates of passage.

The modulation method and the use of the moderator loaded with capacitance yield comparable results. In the case of comparators operating as modulators, ferrite magnetic cores with repeatable parameters must be used. They can be miniature comparators enabling also the detection of passages of low currents through the null. The comparator loaded with capacitance is a very simple detector of current passage through the null, but it must incorporate a magnetic core with proper magnetization characteristics and stable parameters.

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