THE ELECTRIC AND HEAT CHARACTERISTICS OF FREQUENCY-DEPENDENT RESISTOR

A.M. HASHIMOV, T.R. MEHDIYEV, N.R. BABAYEVA
Institute of Physics, Academy of Sciences of Azerbaijan,
Baku, Az-1143, H. Javid av., 33

Experimental frequency dependences of the current density distributions over the cross-section of the conducting kernel of the frequency-dependent resistor are presented. It is shown that, one can determine the frequency dependence of the resistor resistance by frequency dependences of the skin-effect in the conducting kernel and magnetic permeability of the ferromagnetic layer. Application of the frequency-dependent resistor allows effectively suppress an influence of the high-frequency wave processes.

In spite of seeming solution simplicity, the problem of element formation, in particular resistors, having significant and frequency-dependent characteristics in wide region of frequency change, voltages and currents has been still actual one.

The new investigation direction, appeared in 80^{th} of last age was connected with probability of skin-effect use for creation of frequency-dependent resistors. It is well-known, that skin-effect action in current-conducting elements reveals in inhomogeneous density distribution of alternating current on conductor cross-section. For cylindrical conductors this distribution located symmetrically in respect of the center and corresponds to increase of current density from conductor central part to its surface. The potential difference, appearing between conductor surface and center, is appearance reason of "parasitic" transversal electromagnetic wave, which causes the amplitude and frequency-phase distortions of transmitted signal, amplification of corrosion processes on conductor surface and appearance of metal chemical compounds, prohibitive to distribution of electric current in result of own dielectric and semiconductor properties. The observable decrease of conductor cross-section leads to increase of its resistance to alternating current and to amplification of dispersion processes of heat energy.

The idea of skin-effect use for creation of frequency-dependent resistor with amplification of its action by the way of use of materials, the frequency dependencies of magnetic permeability and electroconductivity of which are necessary frequency region. This is followed from definition of layer depth of skin-effect:

$$\delta = \frac{c}{\sqrt{2\pi\omega\sigma(\omega)\mu(\omega)}},$$

where $\sigma(\omega)$ is specific conductance and $\mu(\omega)$ is magnetic permeability on ω frequency.

The use probability for these aims of composition materials with use of ferromagnetic powders had been studied in papers [1-4]. It was shown, that in such materials the strong dependence of composition specific resistance on frequency could be achieved by variety of component concentration, moreover the effect increase was achieved by change of geometry and layer quantity, for example, in double-layer composition.

The additional effect increase can be achieved by the way of picking out of layer parameters in multilayer structure of ferromagnetic layer, at which the appearance of phenomena of "giant" magnetic resistance became possible, had been presented in paper [5].

The study of heat modes of work of frequency-dependent resistors is important aspect of their practical use. The heat mode of normal function for considered type of frequency-dependent resistors is defined by optimization of space configuration of temperature field, causing the stability of resistor characteristics, its reliability, stability to overloads on current and voltages at different external (pressure and temperature) work conditions. It is need to take into consideration, that most vulnerable element of frequency-dependent resistor is ferromagnetic layer; it limits the minimum and maximum values of heat temperatures and so maximum-admissible value of current strength, passing through resistor current-conducting rod. The current density distribution on rod cross-section, appearing in the result of skin-effect, influences on temperature distribution on cross-section of current-carrying rod and necessity of taking into consideration of heat flux from rod hot side face to its center appears. In general case, time parameters of temperature field change are consequence of peculiarity of alternating current passing through frequency-dependent resistor.

It is need to note, that papers in direction of skin-effect use for creation of frequency-dependent resistive elements are carried out in scientific centers of Russia, Ukraine, Japan, USA, Poland, Finland, Azerbaijan and etc. [1-13]. The results of these papers are perspective for solution of equipment defense problem from excess voltage and overcurrents at high-frequency wave processes in energy systems.

The result part, obtained at the design and creation of frequency-dependent resistors with skin-effect use, study and construction of heat process picture in work mode at conditions: pressure 760 millimeter of mercury, temperature 28°C, is presented in present paper. The paper has been carried out in project limits (Institute of Physics of NAS of Azerbaijan) on investigation, design and application of new limit methods of excess voltage in high-voltage electric nets and creation of current-limiting elements and technical devices.

The more simple construction of frequency-dependent resistor consists in aluminum rod by diameter 1 cm with ferromagnetic layer, coated on it. The conductivity of ferromagnetic material was considerably less than conductivity of aluminum rod. In experiments the current, passing through frequency-dependent resistor, consisted in either one frequency component 50 Hz or two once 50 Hz and 0,1 MHz. The corresponding observable changes of density current distribution on cross-section of aluminum rod are presented on fig.1 and 2, where experiment photos are given and following designations have been done: σ is current density; σ_0 is current density on rod surface, r is rod radius.

The distribution photos of current densities have been obtained on thin photographic layers, put in between two aluminum rods by diameters 1cm. The electric resistance of photographic field was value by order 10 kOm and depended on film width. All experiments were carried out at similar conditions, voltages and currents. The image, obtained on film, was scanned on recording microphotometer MF-4 and whole result was automatically treated on computer.

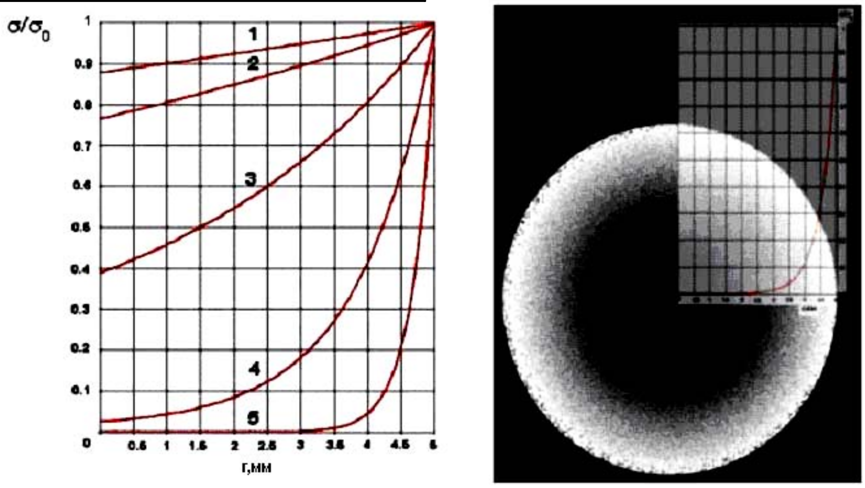

Fig.1. The axes for cylindrical aluminum rod by diameter 1 cm on frequencies 1 - 50 Hz, 2 - 200 Hz, 3 - 2000 Hz, 4 – 20000 Hz and 5 – 0,2 MHz. The photo of experimentally obtained current density distribution on cross-section of aluminum rod by diameter 1 cm on frequency 0,1 MHz.

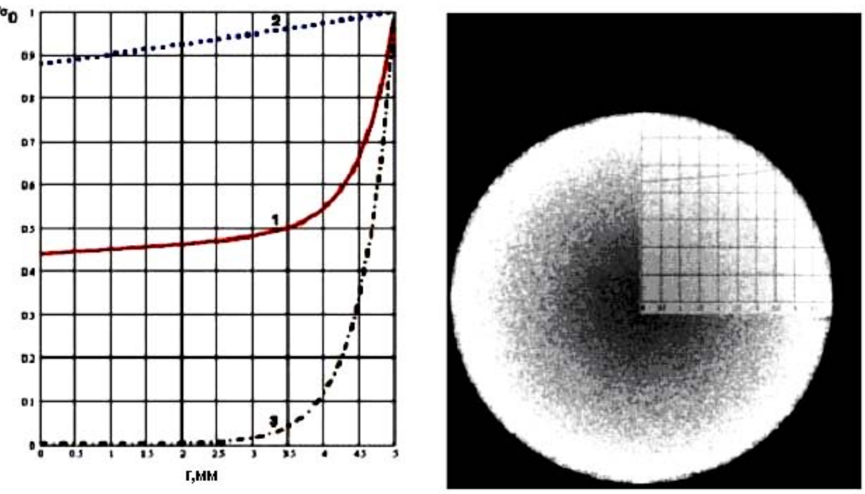

Fig.2. The experimental current density distribution on cross-section of aluminum rod in case, when current has two components: low-frequency – 50 Hz and high-frequency – 0,1 MHz (1 is entire line). For comparison the distributions (curve 2) for frequency 50 Hz and (curve 3) for frequency 0.1 MHz are given.

The experimentally obtained current density distribution (fig.2) from center of current-conducting element (r=0) till r, which is approximately equal to 3 mm, is similar to current density distribution for frequency 50Hz. The rest distribution part is more similar with current density distribution for high-frequency component 0,1 MHz. This contradicts to expected result, so it is seemed, total distribution of current density should be defined in this case by only high-frequency component. However, if we remember, that current density distribution presents itself the amplitude square of advancing wave and frequency spectrum consists in two components, then resulting current density distribution should present itself the sum of current density distributions for each of frequencies. By other hand, as it follows from experiments, the amplitude ratio of low-frequency (50 Hz) component and high-frequency (0,1 MHz) one turns out significant. In the case, when amplitude of low-frequency component turns out significantly higher, than amplitude of high-frequency one, the distribution becomes similar with current density distribution for low-frequency component. In opposite case, the current density distribution becomes more similar with distribution for high-frequency component.

The epoxide resin "CDA"with hardening agent and plasticizer was used for preparation of ferromagnetic layer, and ferromagnetic powder 300VNP used for the convertible contours of radio-frequency devices (mass composition of ferrite powder was 65%), was the filler. The mixture was thoroughly mixed and pressed after coating on aluminum rod.

The resin setting was carried out at temperature 20-60°C during 4-6 hours. After carrying out of given operations, the resistance dependence has taken the form, presented on fig.3a(2).

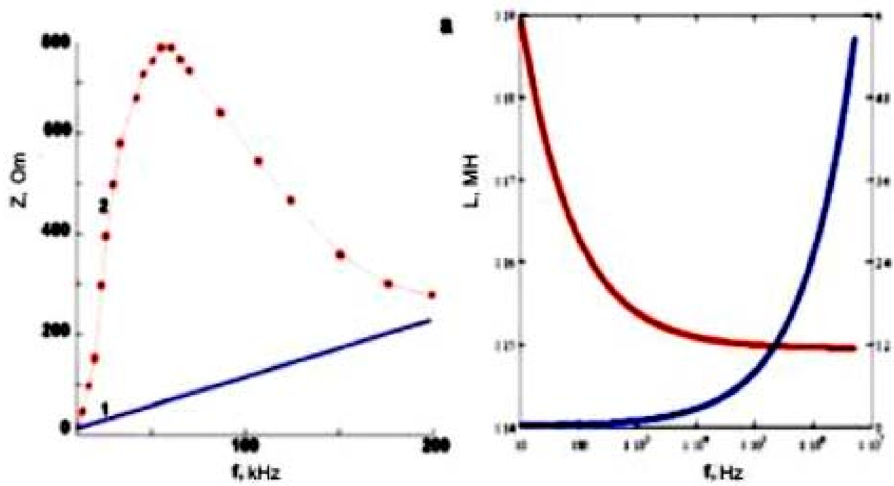

Fig.3. The frequency dependence of impedance of frequency-dependent resistor (a), inductance and resistance of aluminum rod at taking into consideration of skin- effect (b).

The impedance contribution of aluminum current-conducting rod is given on fig.3a(1). The frequency dependencies of active resistance *R* and inductance *L* of aluminum conductor by diameter 1 cm are given on fig.3b. From fig.3a it is followed, that nonlinearity *L* and increase of value of resistor total resistance in dependence on frequency are defined by frequency dependences of magnetic permeability of ferrite layer and skin-effect in current-conducting rod.

As it is known, according to law of electromagnetic induction the currents are inducted, which lead to delay of magnetization change at magnetization change inside sample. If we consider, that magnetization change is similar on all regions of cylindrical conductor, then, as it is shown in paper [14], losses are proportional to rate of magnetization change and increase proportionally to square of frequency. The detail loss calculation in real material, having many domain walls, presents complex task. However, the presence of big amount of domain walls leads to situation, corresponding to homogeneous magnetization. As it is known, the increase of core dimensions leads to appearance of stationary wave with $\lambda = \frac{c}{f\sqrt{\varepsilon\mu}}$ and dimension resonance. But in case of its absence, the frequency increase for big ferrite sizes leads to decrease of magnetic permeability, that is observed on fig.3a(2).

As experiments showed, the chosen width of ferromagnetic layer, which is equal 5mm, provided the screening from external troubles and absorption of internal ones. The oscillogram, given on fig.4a, demonstrating the suppression of high-frequency wave processes by block of frequency-dependent resistors proves these facts (fig.4b). The block construction presents itself the several frequency-dependent resistors, joint parallel and put into special casing.

All experiments have been carried out by resonance method on bridge scheme on definition of induction and resistance.

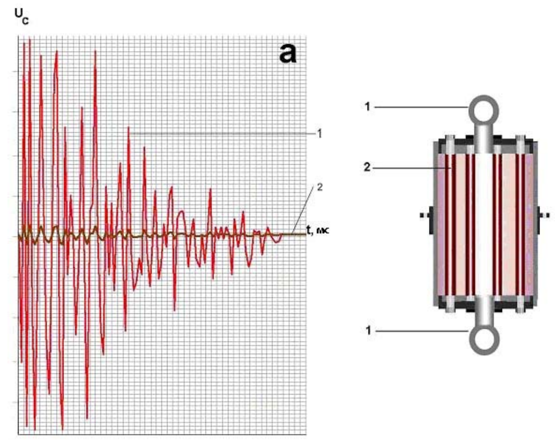

Fig.4. The oscillogram of work of block nonlinear resistor (a), where 1 is resistance oscillogram till block, scale – 100V/cm; 2 is after block, scale – 1V/cm; (b) is block construction of nonlinear resistor:1 is resistor contact, 2 is frequency-dependent resistor.

It is need to take into consideration the heating of current-conducting rod and especially ferromagnetic layer, which as calculation and experiments show, is more vulnerable at passing of big currents through frequency-dependent resistor. The temperature 50°C was considered as critical one for ferromagnetic layer, coated on surface of current-conducting rod. The temperature and volt-ampere characteristics of created frequency-dependent resistors on different frequencies are given on fig. 5, where *A* corresponds to current-conducting rod on frequency 50 kHz.; *B*, *C*, *D* correspond to ferromagnetic layer; *W* is permissible specific energy, absorbed by frequency-dependent resistor, ΔT is difference between maximum permissible and initial temperatures. The difference ΔT and permissible specific energy *W* have quadratic dependence on power of passing current. By other hand, the dependence *U* on *I* has been seemed practically linear one.

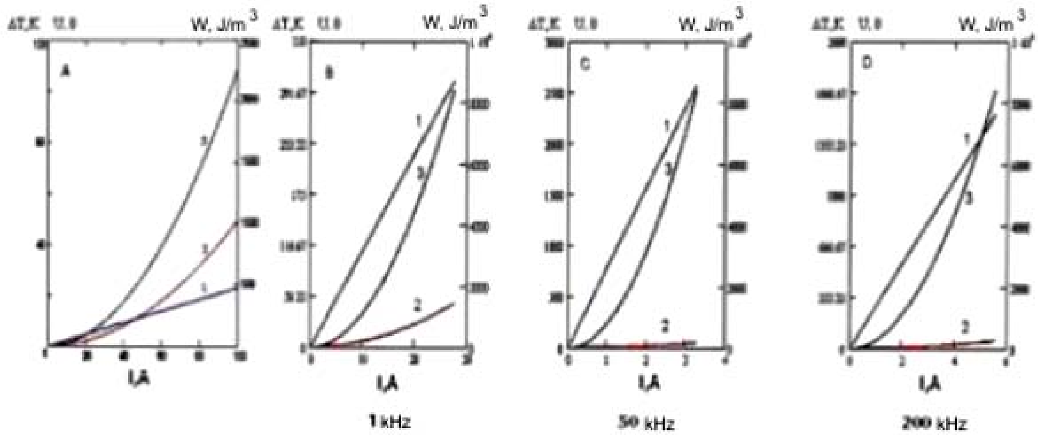

Fig.5. The temperature and volt-ampere characteristics of frequency-dependent resistor on different frequencies. *A* is for current-conducting rod on frequency 50KHz; *B*, *C*, *D* are for ferromagnetic layer. *W* is accessible specific energy, ΔT is difference between maximum permissible temperature and initial one.

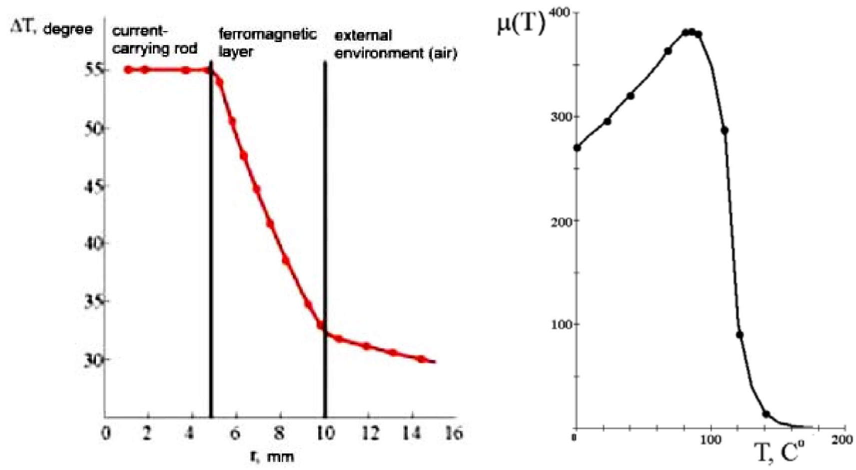

Fig.6. *a* - The temperature changes with distance change from center of current-conducting rod of frequency-dependent resistor. It is supposed, that temperature along length of current-conducting rod is constant; *b* – The temperature dependence of magnetic permeability of ferromagnetic powder.

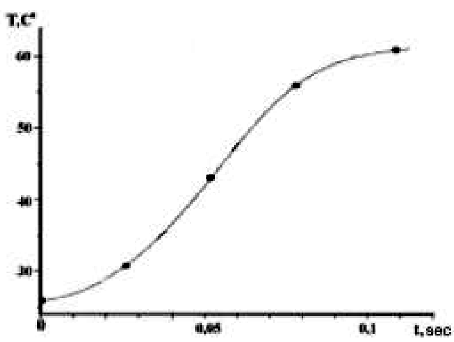

Fig.7. The time dependence of heating temperature in center of current-conducting rod of frequency- depended resistor.

Thermal conductivity equation was solving at following conditions: temperature of medium (air) was equal to 28°C; heat temperature of current-conducting rod shouldn't exceed 100°C. The inhomogeneous current density distribution on cross-section of current-conducting rod, excluding the temperature inhomogeneity along resistor length, was taken into consideration. The obtained result is presented on the fig.6. The influence of skin-effect, which is especially noticeable on high frequencies, leads to appearance of thermal gradient between center and surface of current-conducting rod and as result, to appearance of heat flow from surface to center. The time dependence of heating temperature of center of current-conducting rod in mode till 60°C is given on the fig.7. It is need to note, that this effect leads to skin-effect decrease in current-conducting rod.

The heating of current-conducting rod of frequency-dependent resistor leads to heating of ferromagnetic layer, the magnetic properties of which are defined by temperature dependence of magnetic permeability of ferromagnetic powder and as it follows from fig.6, the temperature increase of ferromagnetic layer higher, than 100°C, strongly decreases the inductive parameters of frequency-dependent resistor. Thus, optimal work temperature of frequency-dependent resistor lies in temperature region lower, than 100°C. As dynamic investigations of time changes of temperature field on ferromagnetic layer show, the frequency-dependent resistor is able to endure the short-time overloads on temperature (till 300°C) during time periods by order 5 sec, at repetition frequency of one impulse for 15 sec. Such repetition frequency guarantees total reconstruction of magnetic properties of ferromagnetic layer and inductive parameters of frequency-dependent resistor, correspondingly.

Conclusion

The result analysis of experimental investigations points out:
- distribution complex character of alternating current on cross-section of aluminum rod, depending on quantity of its frequency components and their amplitude ratios;
- the role of frequency dependencies of magnetic permeability of ferrite layer and skin-effect in formation of frequency properties of created frequency-dependent resistors;
- the equation of heat conduction has been solved, heat parameters and functioning conditions of frequency-dependent resistor have been defined.

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А.М. Гашимов, Т.Р. Мехтиев, Н.Р. Бабаева

ЭЛЕКТРИЧЕСКИЕ ХАРАКТЕРИСТИКИ ЧАСТОТНОЗАВИСИМОГО РЕЗИСТОРА

Представлены экспериментальные частотные зависимости распределений плотностей тока по сечению токоведущего стержня частотнозависимого резистора. Показано, что частотная зависимость сопротивления резистора определяется частотными зависимостями скин-эффекта в токоведущем стержне и магнитной проницаемостью ферромагнитного слоя. Применение частотнозависимого резистора позволяет эффективно подавлять влияние высокочастотных волновых процессов.

A.M. Həşimov, T.R. Mehdiyev, N.R. Babayeva

TEZLİK ASILILIQLI REZİSTORLARIN ELEKTRİK XASSƏLƏRİ

Tezlik asılılıqlı rezistor cərəyan daşıyıcı milinin en kəsiyində cərəyan paylanmasının eksperimental tezlik asılılıqları verilmişdir. Göstərilmişdir ki, rezistor müqavimətinin tezlikdən asılılığı skin-effektin cərəyan daşıyıcı mildə və ferromaqnit layın maqnit nüfuzluğunun tezlik asılılıqları ilə müəyyən olunur.

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