Journal of Fundamental and Applied Sciences

ISSN 1112-9867

Available online at http://www.jfas.info

Research Article

Special Issue

ELECTRIC POWER DEVICES ELECTROMAGNETIC MODES MODELLING AND ANALYSIS

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Published online: 18 April 2018

ABSTRACT

A generalized mathematical model of the electromagnetic modes of devices with a laminated core of an arbitrary design with windings created. An algorithm and software implementation of the model developed. Practically important normal electromagnetic steady state modes of reactors' operation, transient processes occurring at commutation within the winding circuits, non-symmetrical modes determined by non-symmetry of the supplied circuitry, and phenomena originating due to magnetic core magnetization analyzed. Recommendations on electrical processes quality influencing with different magnetization modes provided.

Keywords: controlled reactor, electromagnetic mode, symmetric magnetization, forced magnetization, mathematical model

I. INTRODUCTION

In the second decade of the twentieth century, one of the problems of high-voltage transmission technology has been emerged, namely, that the capacitive conductance of the power line at large distances began to affect significantly and the capacitive current significantly increased, which reduced power line capacity.

In the early 1940s, R. Rudenberg (Germany) proposed to use strong magnetic saturation of electrical steel to solve this problem, pointing out the need to eliminate higher harmonics. Rudenberg's ideas were developed in the works of E. Friedlander (GEC, England). GEC has manufactured and installed more than 50 ferromagnetic reactors in various countries [6].

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doi: http://dx.doi.org/10.4314/jfas.v10i3s.72

In Russia, a group of organizations led by A.M. Bryantsev has mastered the industrial production of a series of high-voltage controlled reactors of 25, 32, 63, 100, 180 MVA for a 6 - 500 kV network. The development and mass introduction of a series of arc suppression magnetically controlled oil-cooled reactors (RUOM) with a capacity of 190 1520 kVA, 6-10 kV [2, 5, 9] have been implemented.

Electric power devices include saturable and controlled reactors (SP, CR). Being a means of regulating reactive power, they are necessary for controlling the regimes of electric power systems [6].

A reactor is a static power nonlinear device, which operation is based on the phenomenon of electromagnetic induction. The reactive power, it consumes, is regulated by a change in the saturation of the magnetic circuit. The active part of the reactor contains one or more windings and a magnetic core.

The advantage of transformer-type reactors is that they are performed on transformer voltages. Reactors of the electromachine type distinguish such positive qualities as compactness and simplicity of design in multiphase design, absence of inductive interconnections between windings and increased speed, as well as symmetry and sinusoidal current.

Saturated and controlled reactors are intended for use in overhead power transmission lines, in distribution networks and in industrial enterprises power supply systems, so it is important to analyze their operating modes in these power systems.

The devices research process must be preceded by a realization of the triad "model-algorithm-program", so the device is replaced by its model, which is then analyzed through experimentation on a PC using computational logic algorithms.

On the basis of the developed generalized mathematical model of electromagnetic regimes and phenomena arising during magnetization of a magnetic circuit, the behavior in the electric power system of an electric machine type reactor is studied. The reactor design is optimized using the field theory [7].

Descriptions of the developed devices and software products are presented on http://zabudsky.ru web-portal.

II. CONTROLED REACTOR OF ELECTROMACHINE TYPE

Managed reactors of this type contain an alternating current electric machines general industrial usage magnetic core. The active part of the reactor contains a magnetic core and three windings: a three-phase space-distributed working winding (WW) and, in general, two ring control windings (CW1 and CW2) (Fig. 1). The structure and theory of CR are examined in [6].

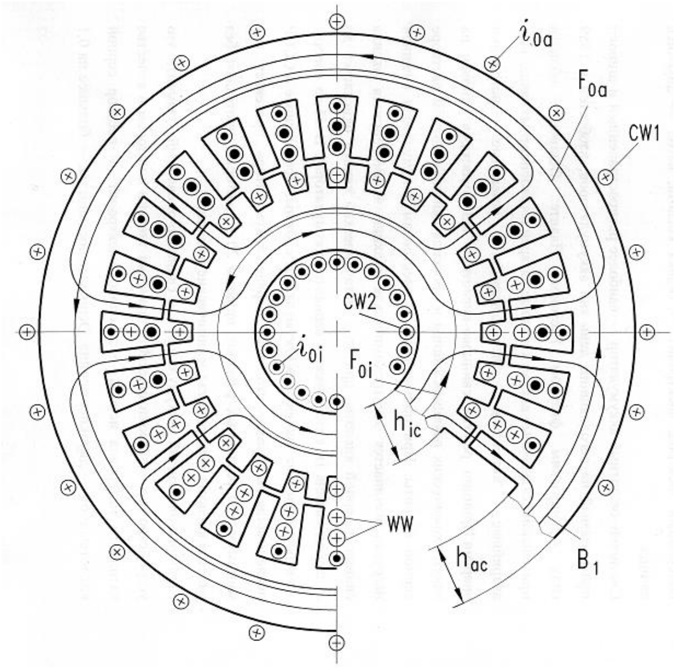


Fig. 1. Cross section of controled reactor active part

The three-phase reactor WW can be designed for a voltage not exceeding the standard voltage of the synchronous generator, therefore it is preferable to use the reactor in distribution networks and in industrial enterprises electrical supply systems. The reactor is used as a regulating element in reactive power static compensators, in parametric voltage regulators, etc.

A symmetric magnetization (SM) mode, characterized by an absence of even harmonics of the space-time spectrum, both in induction and in the magnetic field strength when the magnetic circuit is magnetically magnetized by direct current is naturally implemented in the reactor. The reactor in the SM mode favorably differs from the reactor in the forced magnetization (FM) mode by several qualities [8].

Mathematical Model of a Controlled Reactor Electromagnetic Modes

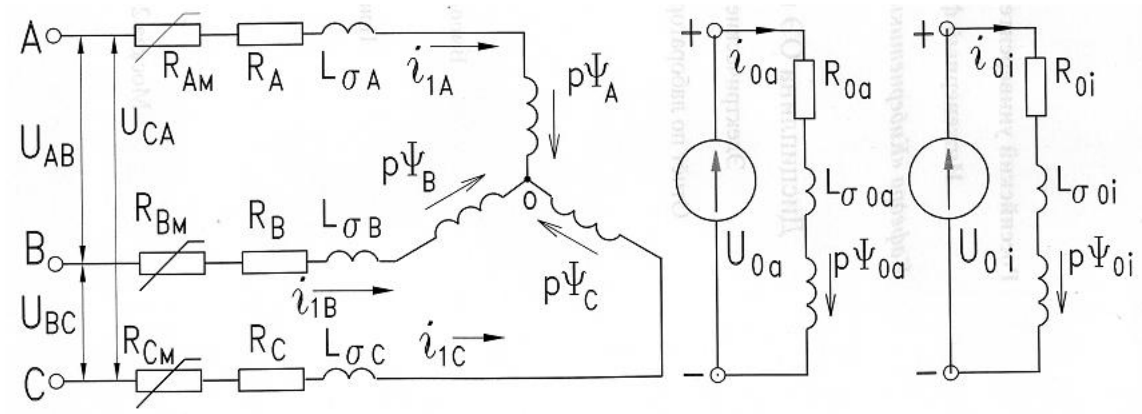
The mathematical model is designed on a basis of equivalence of a real device with an electric (Fig. 2) and a magnetic (Fig. 3) substitution schemes with nonlinear lumped parameters [6]. Fig. 2 shows the replacement circuits of a three-phase winding and a ring control winding. One of them (CW1) is laid around the cross section of the stator yoke, the other (CW2) - around the cross section of the rotor yoke.

On Fig. 2a the following designations are used:

- u_{AB}, u_{BC}, u_{CA} - instantaneous values of linear voltages, which are connected to a combined three-phase winding;
- i_{1A}, i_{1B}, i_{1C} - instantaneous values of the linear currents (the settings);
- R_A, R_B, R_C - the active resistance of the winding phases;
- $L_{\sigma A}$, $L_{\sigma B}$, $L_{\sigma C}$ - inductors, caused by magnetic fluxes of phase winding phase;
- R_{Am}, R_{Bm}, R_{Cm} - nonlinear resistances, with values approximately take into account losses in the steel of the magnetic core;
- $p = d/dt$ is the symbol of differentiation with respect to time t;
- $p\Psi_A = -e_A$, $p\Psi_B$, $p\Psi_C$ are the instantaneous EMF values induced in the winding phases by the main magnetic flux linkages Ψ_A, Ψ_B, Ψ_C of the corresponding phases.

On Fig. 2b and 2c the following designations are used:

- U_{0a}, U_{0i} are the values of DC voltages applied to windings CW1 and CW2, respectively;
- i_{0a}, i_{0i} - instantaneous values of the bias currents (sought values);



a *b* *c*

Fig. 2. Equivalent electric circuits: a three-phase winding (*a*), ring control windings CW1 (*b*), CW2 (*c*)

- R_{0a}, R_{0i} - active resistances of windings CW1 and CW2;
- $L_{\sigma 0a}$, $L_{\sigma 0i}$ - inductances caused by magnetic fluxes of windings CW1 and CW2 in the transient process;

- $p\Psi_{0a}$ = -e_{0a}, $p\Psi_{0i}$ are the instantaneous EMF values induced in the windings CW1 and CW2 by the main magnetic flux linkages Ψ_{0a}, Ψ_{0i} of these windings during the transient process.

Fig. 3 shows an equivalent magnetic circuit of the CR. The following designations are used:

- i_{1A}, i_{1B}, i_{1C} - instantaneous values of phase currents of a two-layer three-phase winding;
- W_A, W_B, W_C - the number of turns in the phase coils of a two-layer three-phase winding;
- i_{0a}, i_{0i} - instantaneous values of currents of windings CW1 and CW2;
- W_{0a}, W_{0i} - the number of the coils CW1 and CW2 turns;
- Φ_1, Φ_2, ..., Φ_{13} - contour magnetic fluxes (the settings);
- R_{a1}, R_{a2}, ..., R_{a12} - nonlinear differential magnetic resistance of the stator yoke sections;
- R_{i1}, R_{i2}, ..., R_{i12} - nonlinear differential magnetic resistance of the rotor yoke sections;
- R_{z1}, R_{z2}, ..., R_{z12} - nonlinear differential magnetic resistance of the nothes;
- R_δ is the linear magnetic resistance of the radial clearance between the stator and the rotor.

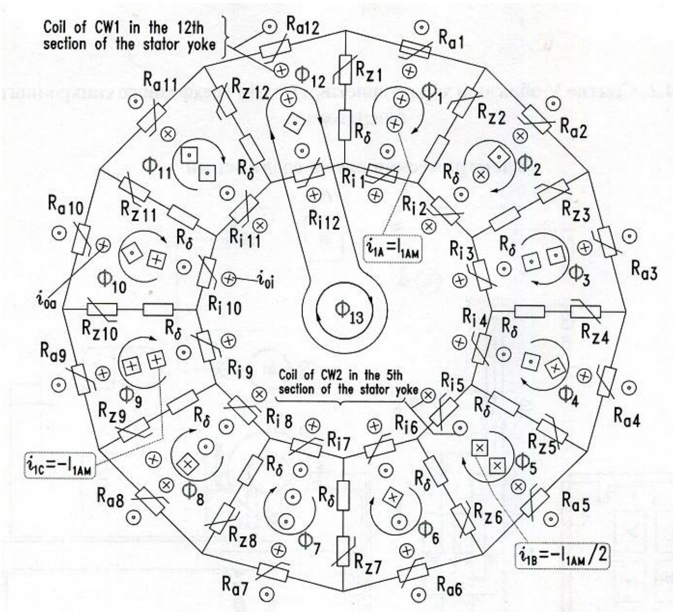


Fig. 3. Equivalent magnetic circuit of the electric machine type reactor

The mathematical model of the reactor electromagnetic modes and the phenomena that arise during magnetization of a magnetic wire is a system of nonlinear ODEs that includes 18 equations. Its variables are thirteen circuit magnetic fluxes, three linear currents of a two-layer three-phase winding and two currents of ring CWs [6]. The mathematical model in the structured (block) matrix form is written as:

$$\left[\begin{array}{c|c} R_{si}(B_{si})+R_{\delta i} & W_{mag} \\ \hline W_{el} & L \\ \hline 0 & 1 \end{array}\right] \cdot \left[\begin{array}{c} p\Phi_i \\ \hline pi \\ \hline \end{array}\right] = \left[\begin{array}{c} 0 \\ \hline U \pm i(R+R_m(B_{si})) \\ \hline 0 \end{array}\right]$$

The algorithm and software implementation of the model are compiled using the Runge-Kutta and Gauss numerical methods.

III. CONTROLLED REACTOR ELECTROMAGNETIC MODES ANALYSIS

A small preliminary magnetization of the CR reduces the time of the transient process [6]. The following dependencies obtained, as a result of the implementation of the mathematical model on the PC, correspond to the pre-magnetized magnetic core.

Fig. 4a and 4b show the values of the magnetic induction B_a in the cross section of the stator yoke and B_z in the cross section of the notch, which are changing as a function of time. Fig. 4a corresponds to the symmetric magnetization mode (SM), and Fig. 4b - the forced magnetization mode (FM).

Fig. 5 shows oscillograms of the magnetic fluxes Φ_a and Φ_z, respectively, in the sections of the yoke and the notch in the modes of magnetization of SM and FM. i_{0a}, i_{0i} - bias currents in the control windings CW1 and CW2; e_2 - EMF, inducted by the 2nd harmonic of the field (Fig. 5a). Oscillograms of currents in phases PO (curves i_{1A}, i_{1B}, i_{1C}) and vibrations of the magnetic circuit (curve f_B) in the modes SM and FM are presented (Fig. 5b).

As follows from the analysis of the curves, in the FM mode, even harmonics are contained in the magnetic induction, and in the SM mode they are absent, which completely complies with the experimental data (Fig. 5a).

Fig. 6a and 6b show the dependence of the three-phase winding phase currents and the control winding currents for the following transient processes:

1) $t_0 = 0.0s$ - the switching the CR on only on the voltages U_{0a}, and U_{0i} DC;
2) $t_1 = 0.1s$ – the switching the CR to the three-phase voltage;
3) $t_2 = 0.17s$ – a break of phase A of the supply voltage.

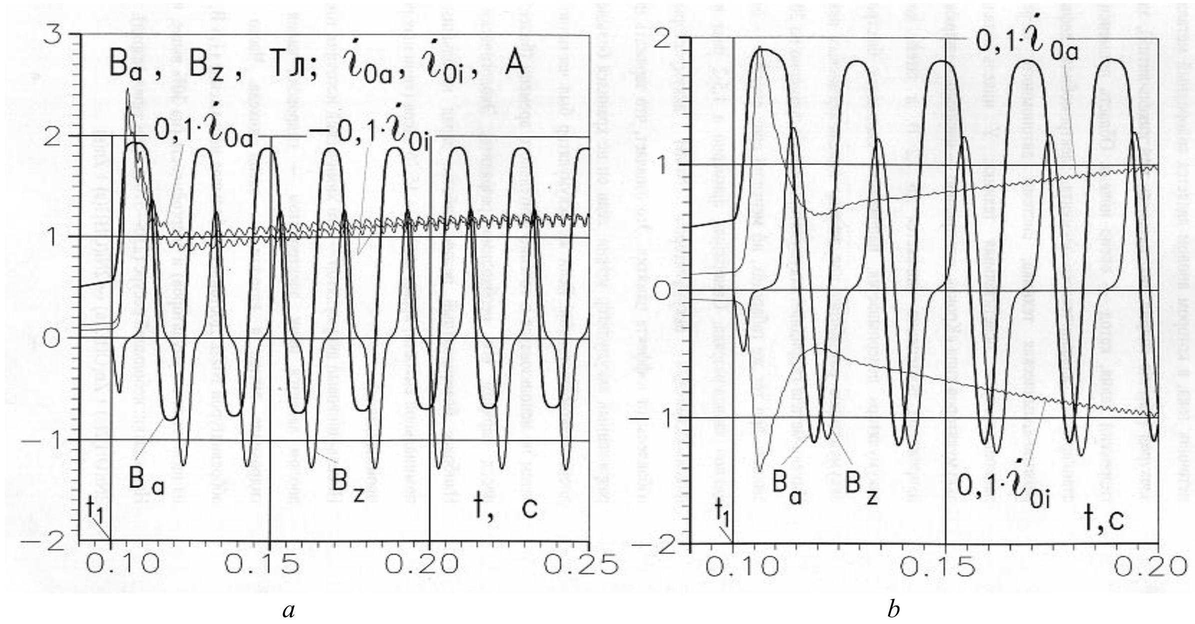


Fig. 4. Changes of the magnetic field induction and the bias currents in the SM (*a*) and FM (*b*) modes. At $t_1 = 0.1s$, the working winding of the pre-magnetized reactor is connected to the network

Fig. 6a corresponds to the SM mode, and Fig. 6b - the FM mode everything else being equal. As follows from the comparison of the curves, the reactor in the SM mode has the following advantages:

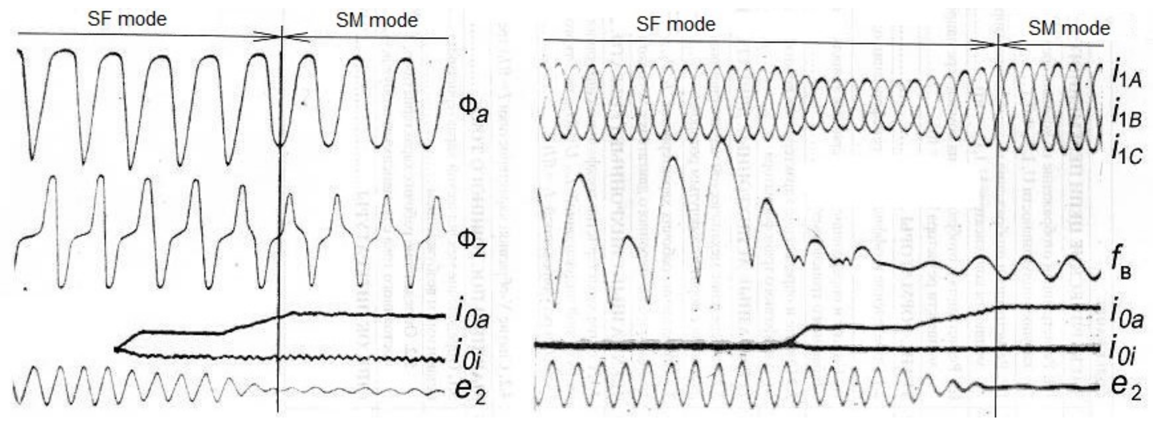
1) the bias currents and the current of the three-phase working winding assume a steady value ~ *0.015s* after the supply of the three-phase voltage, and in the FM mode this time is much longer;

2) the range of current control in the SM mode is higher than in the FM mode by about *15-20%*;

3) absence of "shaking" vibrations of the magnetic circuit, which is confirmed by the experimental data (Fig. 5b).

When the phase A of the supply voltage breaks down, in both magnetization modes even harmonics appear in the bias currents, and in the linear currents - odd third harmonics, multiples of three, and the operation of the reactor becomes impossible.

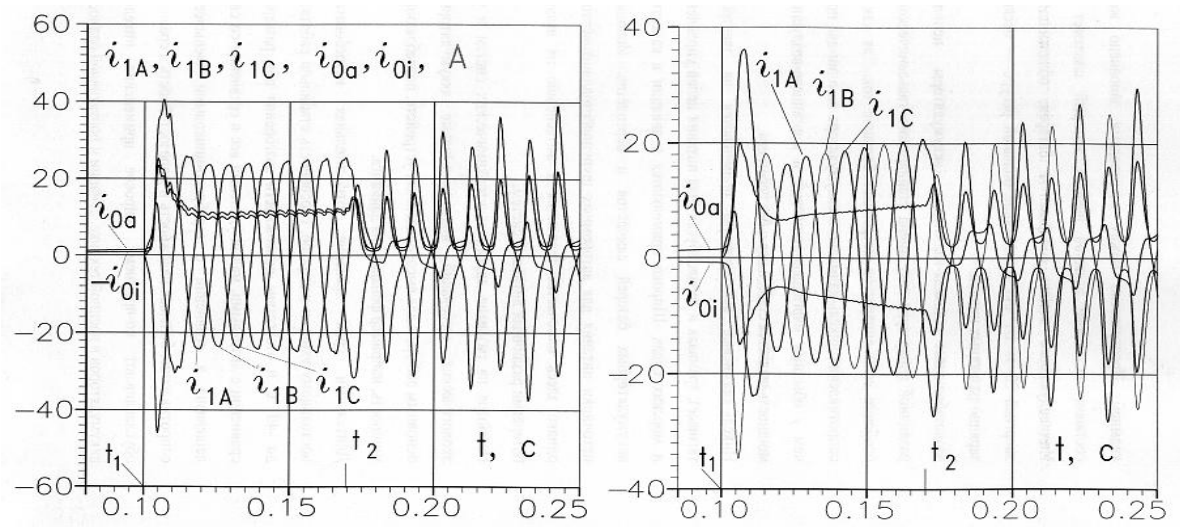
Fig. 7 shows the active part of the reactor with a rotating magnetic field, made of the stator plates of the asynchronous motor VAO14-4 (the outer diameter of the plate is *0.85m*). The reactor is designed for operation in the symmetric magnetization mode, as a regulating element of the power source of the plasmatron [6].



a b

Fig. 5. Oscillograms of the magnetic fluxes Φ_a and Φ_z (*a*) and three-phase current i_{1A}, i_{1B}, i_{1C} in the SM and FM modes (*b*);

e_2 - the EMF induced by the 2nd harmonic of the field; f_B - magnetic core vibration



a b

Fig. 6. Change of three-phase current and bias currents in the modes SM (*a*) and FM (*b*); At $t_1 = 0.1$ s, the working winding of the pre-magnetized reactor is connected to the network

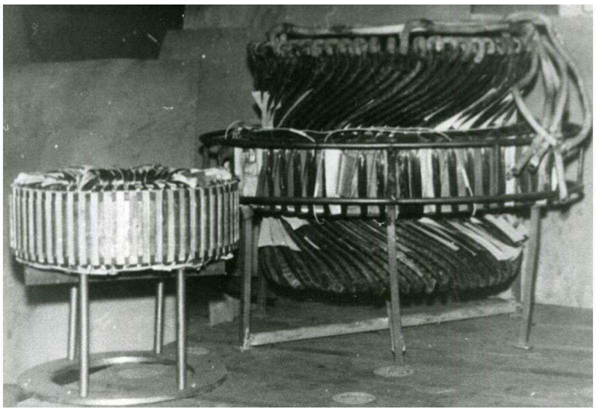


Fig. 7. Photo of the controlled reactor active part

IV. CONCLUSIONS

1. A generalized mathematical model, its algorithm and software implementation, electromagnetic modes of devices with a laminated magnetic core of arbitrary design has been developed.
2. The most important normal steady-state electromagnetic reactor operation modes, transient processes, asymmetric modes, phenomena that arise when the magnetic cores are magnetized have been analyzed. Recommendations on the effect on the quality of processes by using various magnetization modes has been given.
3. It is found out that qualitatively electromagnetic processes in the reactors of the transformer and electromachine types proceed almost identically. Therefore, studies of reactors of these types could be carried out in parallel, complementing each other. At the same time, quantitative differences electromagnetic processes are revealed, due to the circuitry and design features of the reactors of these types.
4. The relevance of the mathematical model is confirmed by the experimental data and is determined mainly by the assumptions made.
5. After the generalized mathematical model is specified with differential equation of motion, it becomes possible to study not only the electromagnetic but also the electromechanical operating modes of electrical machines, contactors, relays, etc.

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How to cite this article:
Zabudskiy E I, Balandina G I. Electric power devices electromagnetic modes modelling and analysis. J. Fundam. Appl. Sci., 2018, *10(3S), 836-845.*