Methods of Calculation of Magnetic Fields and Static Characteristics of Linear Step Motors For Control Rod Drives of Nuclear Reactors

S. H. Khan, *Member, IEEE*
City University, Department of Electrical, Electronic & Information Engineering
Northampton Square, London, EC1V 0HB, UK

A. A. Ivanov
St Petersburg State Technical University, Department of Electrical Machines
Polytechniczeskaya Street 29, St Petersburg 195251, Russia

Abstract-**The performance of linear step motors (LSM) which are now being developed for control rod drives (CRD) in nuclear reactors is governed by their static characteristics. The reliability of control rod drive mechanisms and the safety of the reactor depend on reliable performance of these motors. This paper describes methods of calculation of magnetic fields and static characteristics of LSM. Two methods have been developed - approximate and accurate. The first method - less computationally intensive could be used for small currents and weak iron saturation, the second - based on accurate field modeling takes into account saturation effects which considerably affect motor performance.**

I. Introduction

During the last 80 years the world energy consumption has increased more than 10 times and it is expected that in the year 2020 the current energy consumption will increase nearly 3 times [1, 2]. The contribution of atomic power plants around the world in the total output of electric energy is expected to reach upto 25-30% in the year 2000. This intensive development of atomic energy and the tendency to increase unit power output of individual reactors set the complex task of ensuring their safe, reliable and economic exploitation; and from this arises the necessity for accurate measurement and control in the distribution of energy output over the entire volume of the reactor core. These functions are carried out by CRD of reactors which basically consists of movable control rods, made of neutron absorbing materials in the form of individual rods or group of rods (cassettes, clusters, etc.) and a driving mechanism to move them inside the reactor core [3, 4]. The most vital element in this driving mechanism is the electric motor upon the rational selection and reliable functioning of which, to a great extent depend the safety and reliability of the entire power plant.

In recent years countries like USA, Russia, France, Germany and Italy are developing linear and discrete electromagnetic driving mechanisms for CRD the key elements of which are hermetically sealed linear step motors with passive armature [3-6]. Comparing to existing ones CRD of nuclear reactors with LSM have the advantage of being highly reliable due to the simplicity of kinematics, fast and accurate in the fixation of control rods.

The most important performance characteristic of the LSM is the static characteristic, the calculation of which consists of determining the variation of electromagnetic force developed by the motor with armature displacement. This determines motor performance in its standing (when the armature with control rods attached to it is held at a fixed position by electromagnetic force) and dynamic modes and leads to the necessity for modeling and computation of magnetic fields in LSM the results of which are fed into the calculation of motor performance characteristics.

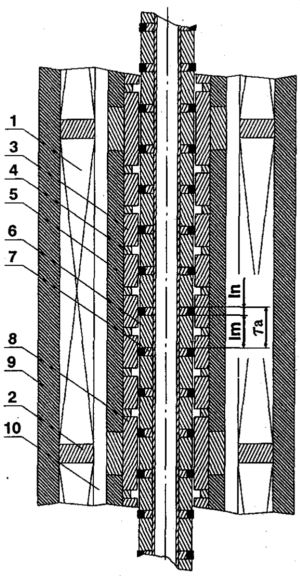

Fig. 1a. Longitudinal section of a phase of the LSM.

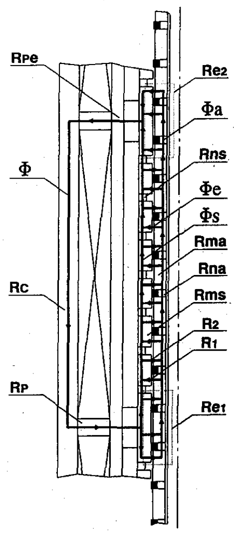

Fig. 1b. Magnetic circuit of the LSM showing flux components and various reluctances.

Although rotating step motors are well covered in literature, at present there are a few published papers which concerns linear step motors [7, 8]. In the following sections of this paper methods of calculation of magnetic fields and static characteristics of LSM are discussed which could be used in CAD, parameter optimization and performance evaluation of these motors. These methods were used to calculate static characteristics of LSM [9, 10] designed by researchers at 'Ijorcki Javod' (St Petersburg, Russia) for CRD of large pressurized water reactors with electric power output of 1000 MW (VVER-1000) and more. Simulation results have been compared with available experimental data which validates above methods.

II. Constructive Features of a LSM

Fig. 1a shows longitudinal section of one of the phases of the 4-phase LSM developed at 'Ijorcki Javod' which consists of the stator with cylindrical dc winding (1), poles (2) and ring elements in the form of alternately arranged magnetic (3) and nonmagnetic (4) sleeves, hermetically sealed cylinder (5), armature in the form of a hollow cylinder with magnetic (6) and nonmagnetic (7) sleeves mounted on its surface. Nonmagnetic sleeves of stator are made up of the inner nonmagnetic ring and the outer ring made of antifriction material and acts as slide bearings. Heights (lengths) of interphase magnetic sleeves (8) are different from those situated in between them (say, 3). The outer casing (9) of the motor acts as the outer magnetic circuit. Hollow cylindrical canal (10) is meant for the circulation of water which cools stator windings.

Some of the main design parameters of the motor are: armature step $\tau_a = lm + ln$, discrete step $\tau_d = \tau_a/m$, where lm, ln are heights (lengths) of magnetic and nonmagnetic sleeves of armature (and stator) respectively, m - number phases. Discrete step τ_d gives the armature displacement for unit voltage pulse in the stator winding.

III. Working Principle and Static Characteristic of the LSM

With each voltage pulse current in the stator winding produces MMF F which gives rise to magnetic flux $\Phi = F/R(x) = FP(x)$, where R(x) and P(x) = 1/R(x) are phase reluctance and permeance respectively. Armature movement changes mutual alignments of stator and armature magnetic sleeves resulting in the change of reluctance R(x) and magnetic field energy $W(x) = F\Phi/2 = F^2/2R(x) = F^2P(x)/2$. Changes in energy W(x) give rise to electromagnetic force F(x) acting on the armature -

$$F(x) = \frac{dW(x)}{dx} = \frac{F^2}{2}\frac{d}{dx}\left(\frac{1}{R(x)}\right) = \frac{F^2}{2}\frac{dP(x)}{dx} \qquad (1)$$

where x is the coordinate of armature displacement which characterizes mutual alignments of stator and armature magnetic sleeves. Force F(x) acts in such a direction as to increase field energy W(x) and hence permeance P(x). With armature movement, P(x) and so the force F(x) change periodically with a period of τ_a so that $F(x+\tau_a) = F(x)$. Fig. 2a shows how F(x) changes with coordinate x for a given phase. This is the static characteristic of the LSM shown in Fig.1a. x = 0 in Fig. 2a corresponds to a certain armature position when the central line through stator nonmagnetic sleeve aligns with that of the armature magnetic sleeve. F(x) attains its maximum for $x = x_m$ when armature and stator magnetic sleeve corners align opposite to each other and dW/dx becomes maximum. x = 0 corresponds to maximum values of permeance P(x) and field energy W(x) and hence $F(x) = dW(x)/dx = 0$; F(x) = 0 also for $x = \pm\tau_a/2$ when magnetic sleeves of stator and armature are positioned opposite to each other and P(x) and W(x) have minimum values. Fig. 2b shows static characteristics of all 4 phases of the LSM which are shifted in space by discrete step τ_d. This is because of the difference in heights of stator and interphase magnetic sleeves. For a given armature position this creates different alignments of magnetic sleeves for different phases. F_1, F_2, F_3 and F_4 in Fig. 2b correspond to electromagnetic forces from phases 1, 2, 3 and 4 respectively.

To move the armature phase windings are sequentially excited from pulse voltage source. For example, if only phase 1 is excited due to the total force $P_1 + Q$ (Q is the force due to the weights of armature and control rods) armature will take the equilibrium position corresponding to $x = x_1$ (Fig. 2b) for which $P_1 + Q = 0$. Now, if phase 1 is switched off and phase 2 is excited due to the force $P_2 + Q$ armature will move to the new position for which $x = x_2 = x_1 + \tau_d$. In this way armature is moved, each time by a distance of the discrete step τ_d by sequentially exciting phase windings in the order 1-2-3-4-1-2-... .

As can be seen from (1) to calculate F(x) it is necessary to determine R(x) or P(x). Fig. 1b shows that the total flux Φ in the magnetic circuit can be divided into stator and armature components Φ_s, Φ_a and effective flux Φ_e which crosses the airgap: $\Phi = \Phi_s + \Phi_a + \Phi_e$. Equivalent phase reluctance R consists of reluctances of the outer casing Rc, poles RP, RPe and inner magnetic circuit Ric. The main difficulty is associated with the determination of Ric which comprises airgap reluctances R_1, R_2

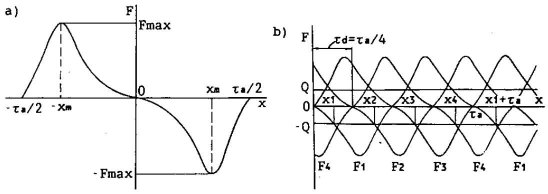

Fig. 2. Static characteristics of the LSM: a) standing mode, b) dynamic mode.

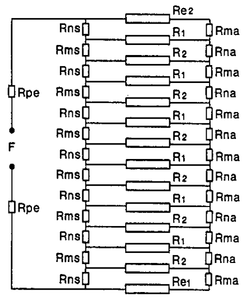

Fig. 3. Equivalent circuit of a phase of the LSM.

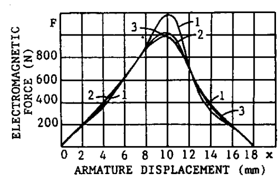

Fig. 4. Static characteristics of the LSM: 1 - approximate method, 2 - experimental, 3 - accurate method.

and reluctances of magnetic Rms, Rma and nonmagnetic Rns, Rna sleeves of stator and armature respectively. To calculate these reluctances and so the static characteristic accurately it is essential to know the precise distribution of magnetic fields and hence, the flux components in iron and airgap for various degrees of saturation of magnetic sleeves. This could be based on two different methods discussed in the following sections.

IV. Approximate Method of Calculation of Static Characteristics

For small currents and weak saturation of magnetic sleeves this method gives satisfactory results. In this method R is calculated for different values of x from respective electric circuit analogue of phase magnetic circuit shown in Fig. 3; nonmagnetic reluctances R_1, R_2, Rns and Rna are determined without taking into account saturation effects on magnetic field distributions in the inner magnetic circuit. Reluctances of magnetic sleeves Rms and Rma are found iteratively by assuming that flux distributions in magnetic sleeves are uniform and, for a given alignment of stator and armature magnetic sleeves their permeabilities μ_s and μ_a depend only on fluxes Φ_s and Φ_a and not on coordinate x. Knowing Rms, Rma and other reluctances equivalent reluctance R, total flux Φ and its components Φ_s, Φ_a and Φ_e are calculated from the equivalent circuit shown in Fig. 3. Since Rms and Rma depend on flux Φ, this is done iteratively by solving the following set of equations of MMF balance for flux paths Φ_s, Φ_a and Φ_e:

$$\begin{aligned} F &= \Phi RPe + n\Phi_s Rns + (n-1)(\Phi_s + \Phi_e/2)Rms \\ F &= \Phi RPe + (n-1)\Phi_a Rna + (\Phi_a + \Phi_e)(Re1 + Re2) + \\ &\quad + n(\Phi_a + \Phi_e/2)Rma \\ F &= \Phi RPe + \Phi_e(n-1)(R1 + R2) + (\Phi_a + \Phi_e)(Re1 + Re2) + \\ &\quad + n(\Phi_a + \Phi_e/2)Rma + (n-1)(\Phi_s + \Phi_e/2)Rms \end{aligned} \qquad (2)$$

where n is the number of nonmagnetic sleeves of stator in a phase. Iterative solution of (2) gives unknown flux components Φ_s, Φ_a and Φ_e from which total flux Φ is obtained. In each k-th iteration flux $\Phi^{(k)}$ is updated using flux components determined from (k-1)-th iteration:

$$\Phi^{(k)} = \Phi_s^{(k-1)} + \Phi_a^{(k-1)} + \Phi_e^{(k-1)} \qquad (3)$$

To accelerate convergence permeabilities of stator and armature magnetic sleeves are corrected as follows:

$$\begin{aligned} \mu_s^{(k)} &= q(B_s^{(k)}/H_s^{(k)}) + (1-q)\mu_s^{(k-1)} \\ \mu_a^{(k)} &= q(B_a^{(k)}/H_a^{(k)}) + (1-q)\mu_a^{(k-1)} \end{aligned} \qquad (4)$$

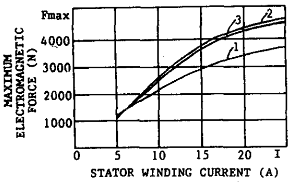

Fig. 5. Variations of maximum electromagnetic force with stator current: 1 - approximate method, 2 - experimental, 3 - accurate method.

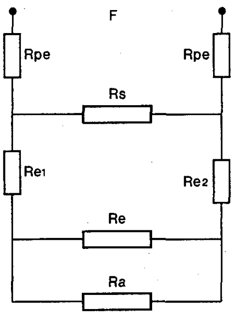

Fig. 6. Equivalent circuit of the phase for the accurate method.

where relaxation factor $0.5 \leq q \leq 0.8$; B_s, B_a - flux densities in stator and armature magnetic sleeves. In the first iteration $\mu_s^{(1)} = \mu_a^{(1)} = 100\mu_0$. This iterative process is ended when flux values in two successive iterations become very close. As a result of the above equivalent permeance $P(x) = \Phi/F$ is obtained from calculated values of Φ and finally, electromagnetic force F(x) is determined for different x by differentiating P(x) using (1).

Fig. 4 shows static characteristic (1) of the LSM calculated by the above method for a stator current of 5 A. Comparison with experimental characteristic (2) shows, in general satisfactory agreement. Maximum error of about 15% can be seen in the vicinity of highest electromagnetic force for $x \approx 11$ mm. This is due to approximate incorporation of iron saturation, especially saturation of magnetic sleeve corners which takes place (even for smaller currents) for those values of x when armature and stator magnetic sleeve corners align opposite to each other. As shown in Fig. 5 this difference between calculated and experimental values of maximum electromagnetic force increases as current increases. This is due to the saturation of magnetic sleeves at higher currents which affects magnetic field distributions not only in them but also in the airgap and nonmagnetic sleeves. In order to take into account these effects nonmagnetic reluctances R_1, R_2, R_{ns} and R_{ma} have to be determined by detailed analysis of magnetic field distributions in the inner magnetic circuit.

V. Accurate Method of Calculation of Static Characteristics

This method is based on detailed analysis and accurate calculation of nonlinear magnetic fields by finite element method [11]. By assuming that there is no displacement, eddy current or hysteresis effect and stator current density J is constant and uniformly distributed the spatial distribution of axisymmetric magnetic field in the LSM can be expressed by the following nonlinear Poisson's equation in the cylindrical system of coordinates (r, θ, z):

$$\frac{\partial}{\partial r}\left(\frac{\nu}{r}\cdot\frac{\partial\psi}{\partial r}\right)+\frac{\partial}{\partial z}\left(\frac{\nu}{r}\cdot\frac{\partial\psi}{\partial z}\right)=-J_\theta \qquad (5)$$

where, $\nu = 1/\mu$, $\psi = rA_\theta$; A_θ, J_θ - θ components of magnetic vector potential A and current density J respectively. Equation (5) has been solved under various boundary conditions and geometric parameters using dedicated FE package developed especially for modeling and computation of magnetic fields and parameter calculations in LSM [12]. Detailed analysis of magnetic field distributions in the inner magnetic circuit allows reluctances R_{sc} due to flux paths Φ_s, Φ_a and Φ_e for various sections of the circuit to be determined. After solving (5) these reluctances R_{sc} are calculated from respective field energy W_{sc} and flux ϕ_{sc} using $R_{sc} = \int\int\int \nu B^2 dv/\phi_{sc}^2$. In this way reluctances due to flux paths Φ_s, Φ_a and Φ_e are calculated from which equivalent phase reluctance R is determined using simpler but more precisely defined equivalent circuit shown in Fig. 6 where R_s, R_a, R_e - total reluctances due to flux paths Φ_s, Φ_a and Φ_e respectively, calculated as the sum of individual reluctances R_{sc} for various sections of magnetic circuit. In this way P(x) is calculated for different x by taking into account nonlinearity of magnetic fields; forces F(x) are calculated as before a.

Results of calculation of static characteristics by the above method are shown in Fig. 4 and 5. Comparison of these characteristics (3) with experimental data shows that this method gives better agreement for a wide range of stator current variations. As shown in Fig. 5, for a variation of stator current from 5 to 25 A the approximate method gives a maximum error of about 25% while the accurate method - only 5%. As maximum error is associated with the calculation of maximum electromagnetic force these errors are the highest possible for given cases. For various other alignments of stator and armature when $F \neq F_{max}$ errors in the calculation of electromagnetic force decrease (Fig. 4).

VI. Conclusions

Methods have been developed for the calculation of magnetic fields and static characteristics of linear step motors. The approximate method gives satisfactory results for weak iron saturation and justifies the necessity for the accurate method based on precise and detailed field modeling in order to take into account iron saturation which considerably affects static characteristics and reliable motor performance.

References

[1] A. A. Besczinski and D. B. Wolfberg, "Key questions of world energy," in *World Energy* (in Russian). Moscow: Energoatomizdat, 1985, p. 232.

[2] G. Kessler, *Atomic Energy* (in Russian). Moscow: Energoatomizdat, 1986, p. 264.

[3] I. Y. Emelianov, V. V. Voskoboinikov, and B. A. Maslionok, *Fundamentals of Construction of Control Rod Drive Mechanisms in Nuclear Reactors* (in Russian). Moscow: Energoatomizdat, 1987, p. 232.

[4] I. Y. Emelianov, V. V. Voskoboinikov, and B. A. Maslionok, *Fundamentals of Design of Control Mechanisms in Nuclear Reactors* (in Russian). Moscow: Atomizdat, 1978, p. 272.

[5] A. M. Bamdas, A. I. Leontiev, E. G. Titov *et al., Electric Motors and Elements of Automation in Servo Drives of Nuclear Reactors* (in Russian). Moscow: Atomizdat, 1971, p. 238.

[6] *Patent, France* no. 2526241, Int. Cl. H02K 41/03, 1982.

[7] G. Kaminski, M. Kant, and A. Virolleau, "Study of the linear rotating motor," in *Proc. Int. Conf. Electrical Machines*, Brussels, Belgium, Sept. 1978, Part 1, pp. L3/2-1-24.

[8] H. Schoorens, Y. Guegan, and P. Favier, "New developments of reluctance linear actuators with magnetic casing," in *Proc. Int. Conf. Electrical Machines*, Lausanne, Switzerland, Sept. 1984, Part 2, pp. 559-562.

[9] G. I. Zavialova, I. V. Ivanov, and V. P. Nikolaev, "Linear step motor," *Patent, USSR* no. 920977, Int. Cl. H02K 41/035, H02K 37/00, 1982.

[10] "Investigation of the model of electromagnet of linear step motor," *Intermediate Report of the Industry G-4781* (in Russian), no. 1802.40.91.500 D1, St. Petersburg, 1979, pp. 87.

[11] P. P. Silvester and R. L. Ferrari, *Finite Elements for Electrical Engineers*, Cambridge: Cambridge Univ. Press, 1983, p. 209.

[12] S. H. Khan, "Development of the methods of calculation of magnetic fields and static characteristics of linear step motors for control rod drives of nuclear reactors," Ph.D. Thesis (in Russian), St. Petersburg State Technical University, St. Petersburg, Russia, 1987.