Lighting Engineering & Power Engineering
2022, Vol. 61, No. 1, 10–20
https://doi.org/10.33042/2079-424X.2022.61.1.02

OPEN ACCESS

Method of Cylindrical Linear Induction Motor Equivalent Circuit Parameters Determination and Performance Calculation Algorithm

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Article History
Received:
10 January 2022
Accepted:
20 April 2022
Published online:
29 April 2022

Keywords
Linear Induction Motor;
Equivalent Circuit;
Parameter;
Operating Characteristics

Abstract
Cylindrical linear induction motors (LIM) are currently used in many industrial applications. Task of modeling of electrical machine is of great importance for optimization of processes of design and manufacture of engines with optimal technical characteristics. Traditional approach of construction of mathematical models of asynchronous machines based on classical theory of electrical machines, in comparison with methods of field theory and numerical methods, is much simpler. Structurally cylindrical LIM are distinguished by the absence of transverse edge effects, which contributes to the use of the methods of the classical theory of electrical machines for construction of their mathematical models. In this paper proposes an analytical method of calculation of parameters of equivalent circuit and operating characteristics of cylindrical LIM. In work engine was studied, movable part of which is made in the form of solid steel bar with a copper coating. Equivalent circuits of linear induction motors of various designs (one-sided, two-sided, cruciform, cylindrical) are considered, and assessment of the possibility of their application for research motor is made. Work of cylindrical LIM on industrial mechanisms is characterized by relatively small value of working stroke. For such engines, it is difficult to carry out standard tests, in particular idle stroke test, in order to obtain data for calculation of parameters of the equivalent circuit. The paper proposes a method of experimental determination of parameters of the equivalent circuit. Stator active resistance is measured at direct current, and stator reactance is measured using out-of-rotor method. The remaining parameters of equivalent circuit are calculated according to short circuit experience and engine work mode without load (is taken as an idle stroke experience). It is shown that exact G-shaped equivalent circuit, when calculation of parameters of which active and reactive components of correction factor and active resistance of magnetization branch are taken into account, provides acceptable accuracy in determination of values of equivalent circuit parameters. Algorithm of calculation of work characteristics of cylindrical LAM based on equivalent circuit data is presented. Comparison of calculated and experimental data showed satisfactory results, error is not more than 7%. A new model for decomposition of the total power losses, which includes four components is proposed. Each of the components of the proposed model has a certain physical meaning due to the nature of electromagnetic processes in a three-phase four-wire system. Definitions to describe each of the proposed components are formulated. It is shown that each of supplementary components of the total loss power is proportional to the minimum possible loss power and to the square of the RMS value of the power, which is caused by its occurrence in three-phase four-wire power supply system, and it is inversely proportional to the mean square of the net power loss. The synthesized Matlab-model for verification of the four-component structure of power losses showed a high degree of its adequacy. The proposed model allows us to rethink the description of power losses in three-phase AC circuits and can be used in specialized measuring instruments for electrical networks monitoring. Using the information obtained in the monitoring process, it is possible to plan technical measures to reduce losses of electrical energy in the power supply system, as well as to estimate the capital costs of these measures.

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Cite as: Okhrimenko, V., Zbitnieva, M., Glebova, M., & Lutsenko, B. (2022). Method of cylindrical linear induction motor equivalent circuit parameters determination and performance calculation algorithm. *Lighting Engineering & Power Engineering, 61*(1), 10–20. https://doi.org/10.33042/2079-424X.2022.61.1.02

INTRODUCTION

Technology of linear electric machines is in constant development [1]. Linear induction machines (LIM) (linear asynchronous motors) are characterized by high reliability, simple design, ability to obtain translational sliding without the use of booster converters [2, 3]. They are widely used in many branches of industry and transport [4–7].

PROBLEM FORMULATION

Problem of research and construction of LIM characteristics is important for optimization of design processes [2]. LIM of various designs have been developed, mathematical models have been researched and proposed that take into account design features of these engines and make it possible to calculate work characteristics. Cylindrical (tubular) LIM [8, 9] are distinguished by the absence of transverse edge effects and presence of axisymmetric magnetic field [10, 11]. In practically used installations value of LIM working stroke does not exceed several tens of centimeters, and nature of runner's movement is determined by the load on the engine. At low loads runner moves uniformly acceleration and instantaneous speed at end of working stroke approaches to speed of travelling electromagnetic field, and at high loads (close to short circuit mode) runner speed has time to take steady value. Another feature of cylindrical LIM is the nature of electromagnetic transients. Starting current, unlike conventional asynchronous machines, in cylindrical LIM is not so pronounced and takes on a steady value already within a second or third period after moment of switching. Operating characteristics of LIM, as well as conventional asynchronous machines, are conveniently obtained from data of equivalent circuits, calculation of parameters of which is based on thesis of the general theory of asynchronous machines [12, 13]. Correction factors are introduced into equivalent circuits, which take into account design peculiarities and mode of work of researched LIM [5, 14–16], or equivalent circuits with variable LIM parameters are proposed [2, 17–19].

The purpose of this research is to analyze known LIM equivalent circuits, consideration of the possibility of their application for cylindrical LIM and development of methodology of determination of parameters of the equivalent circuit. Task of construction of performance working characteristics of cylindrical LIM is solved by one of the traditional methods of the theory of asynchronous machines, namely, according to its equivalent circuit.

EQUIVALENT CIRCUIT MODELS OF LINEAR INDUCTION MOTORS

Task of choice of equivalent circuit of cylindrical LIM was solved by comparative analysis of equivalent circuits for various types of LIM. Review of published equivalent circuits, their sorting into characteristic groups is carried out.

In Fig. 1–9 shown main variants for LIM equivalent circuits used. Diagrams show designations and abbreviations adopted by authors of papers. In Fig. 1 and Fig. 2, SLIM is single-sided linear induction motor.

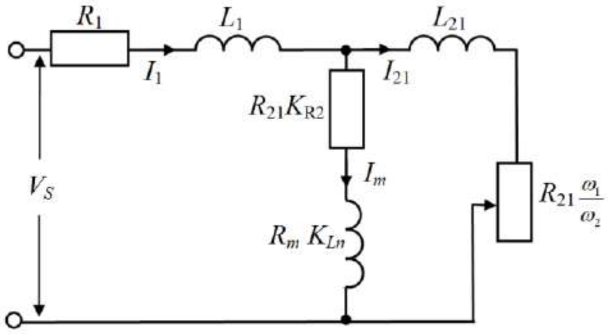

Figure 1. Equivalent circuit the SLIM with a laterally asymmetric secondary and an exponential correction factor [20, 21]

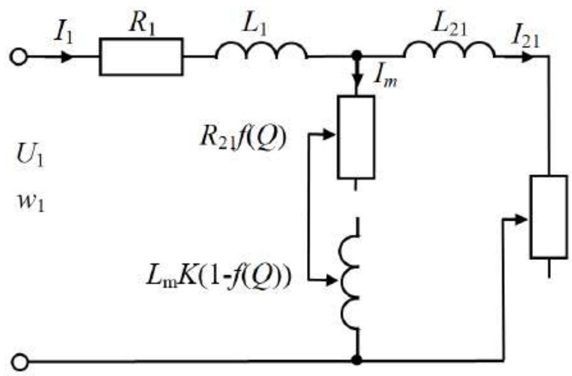

Figure 2. Equivalent circuit of the SLIM to consider the discontinuity of the secondary plate [21]

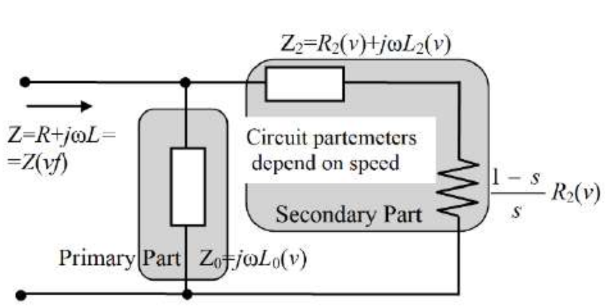

Figure 3. A per-phase equivalent circuit extended for linear induction motor [18, 23]

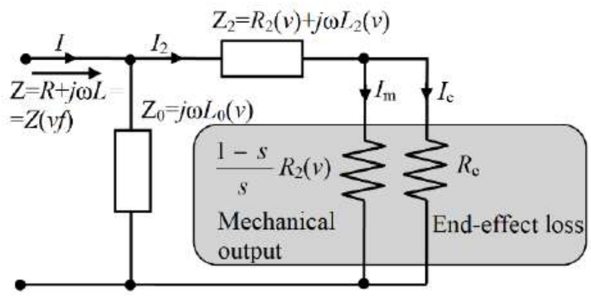

Figure 4. A per-phase equivalent circuit for linear induction motor including end-effect loss [18, 23]

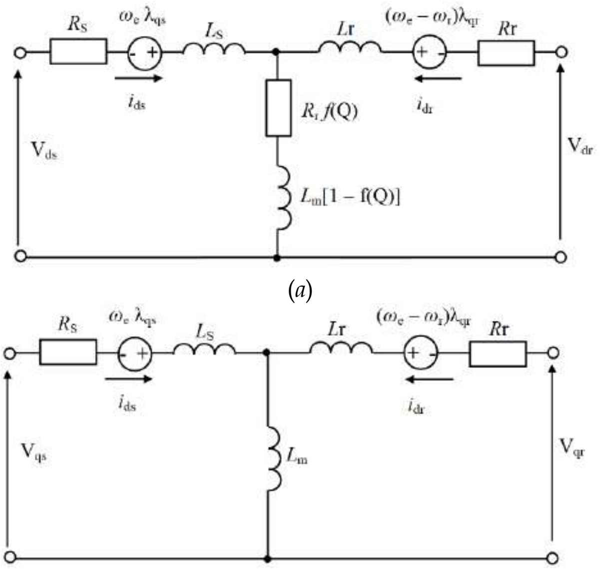

Figure 5. The equivalent linear motor circuits taking into account the end-effects: (*a*) – the equivalent d-axis circuit; (*b*) – the equivalent *q*-axis circuit [24, 25]

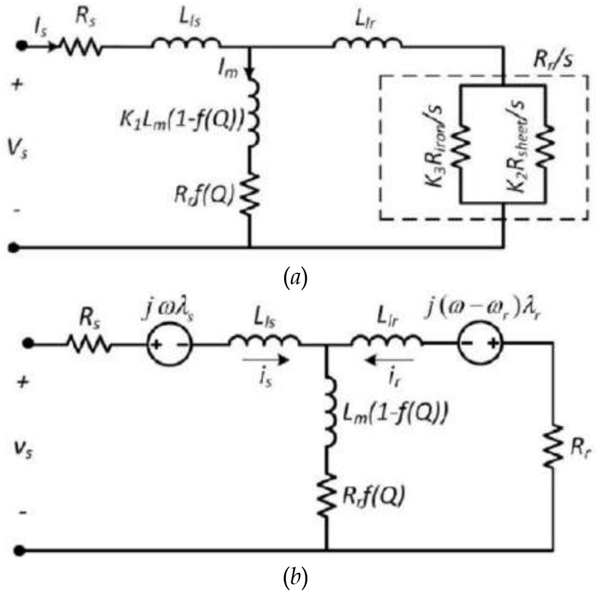

Figure 6. Equivalent circuit for a LIM: (*a*) – steady-state; (*b*) – dynamic [26]

In Fig. 7, DLIM is double-sided linear induction motor.

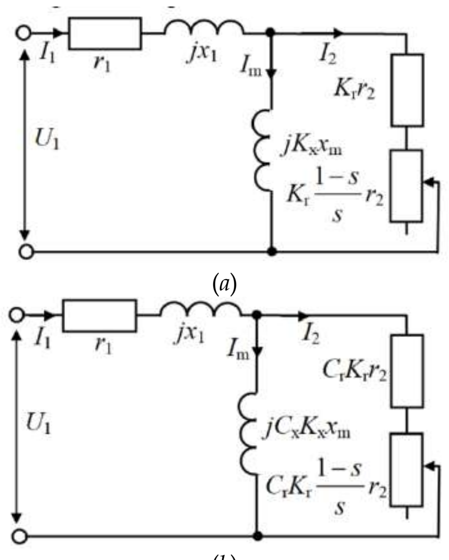

Figure 7. Equivalent circuits of DLIM: (*a*) – with skin effect, secondary leakage reactance, and longitudinal end effect; (*b*) – with longitudinal end effect, transverse end effect, and skin effect and secondary leakage reactance [27, 28]

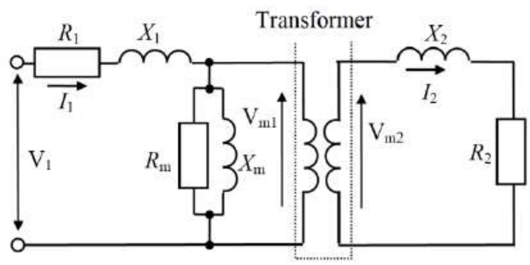

Figure 8. Equivalent circuit per phase of cylindrical linear induction motor (slip s = 1) [29]

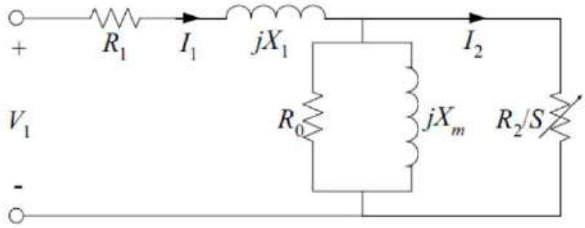

Figure 9. The modified per-phase tubular linear induction motor (TLIM) equivalent circuit with a capsule inside the entire TLIM stator [30]

Analysis of published works shows that today there are no single generally accepted variants for equivalent circuits, even for particular types of LIM. Researchers take traditional equivalent circuits of asynchronous machines [3, 7, 31] (equivalent T-circuit (Fig. 10, *a*) or Tevenin circuit (Fig. 10, *b*)) as a basis, modify and improve these circuits to obtain working characteristics of concrete engine. Various factors are taken into account [3], among which:

- design features of the investigated LIM: SLIM [15, 21, 32], DLIM [27], cross-shaped LIM [6, 33], solid rotor [34] and others, transverse edge

shape of secondary aluminum plate and its temperature secondary part without slit structure [35], etc.;
- presence of transverse and longitudinal edge effects [18, 26];
- skin effect [28].

Two trends have also taken shape in research: use of enough complex mathematical apparatus [4, 14, 15, 18, 27] and desire to obtain simplified ratios for calculation of parameters of equivalent circuit, which give satisfactory coincidence with results of experimental research [3, 23].

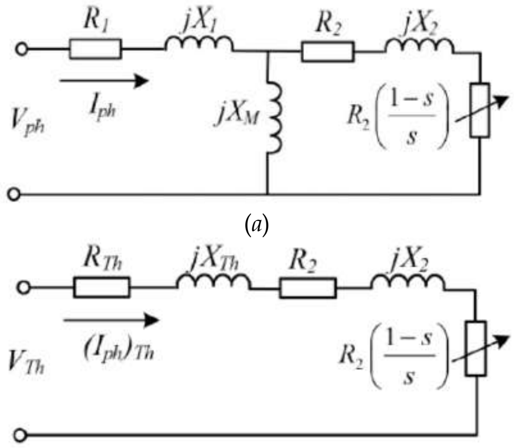

Figure 10. Equivalent T-circuit (*a*) and Thevenin circuit (*b*) of AC motor reduced to a single phase [19]

EQUIVALENT CIRCUIT OF LINEAR INDUCTION MOTORS

Research was carried out on basis of idealized LIM model, in which following assumptions are made:

- the magnetic circuit of the model is not saturated;
- there are no surface phenomena in secondary part;
- there is no transverse edge effect;
- during operation engine runner does not go beyond stator;
- magnetic field is distributed sinusoidally along length of stator;
- air gap is uniform.

SEQUENCE OF EQUIVALENT CIRCUIT PARAMETERS CALCULATION

Equivalent circuits under study are shown in Fig. 11–12. In Fig. 11 shown T-shaped equivalent circuit. Circuit includes following elements: z_1 – impedance of primary circuit; z_2' is reduced impedance of secondary circuit; z_m is impedance of magnetization circuit. These resistances can be expressed in terms of active and reactive components.

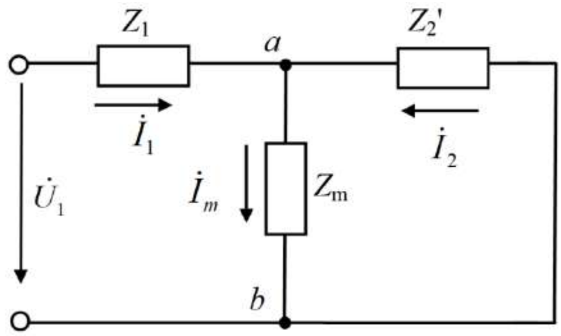

Figure 11. T-equivalent circuit LIM

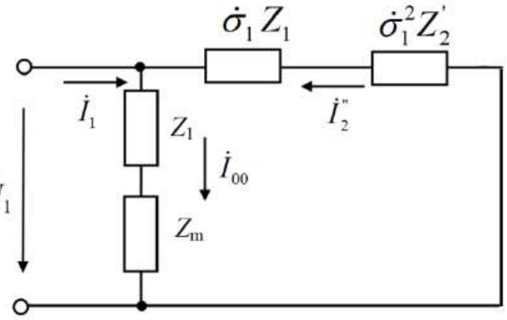

Figure 12. G-equivalent circuit LIM

$$z_1 = r_1 + jx_1, \tag{1}$$

$$z_2' = {r_2'}/_{s} + jx_2', \tag{2}$$

$$z_m = r_m + jx_m. \tag{3}$$

In Fig. 12 shown LIM equivalent circuit with magnetizing contour placed on primary network terminals. This is G-shaped equivalent circuit. Correction factor $\dot{\sigma}_1$ of circuit is generally determined by expression

$$\dot{\sigma}_1 = 1 + \frac{z_1}{z_m}. \tag{4}$$

Depending on ratio of resistances exact or refined equivalent circuit are considered. In case of exact equivalent circuit, coefficient $\dot{\sigma}_1$ is complex quantity and formula (4) can be written as

$$\dot{\sigma}_1 = \sigma_{1\mathrm{a}} + \mathrm{j}\sigma_{1r} = \sigma_1 \mathrm{e}^{-j\psi}. \tag{5}$$

After substitution (1) and (3) into (4) and separation of active σ1a and reactive σ1r parts we obtain active and reactive components

$$\sigma_{1a} = 1 + \frac{r_m r_1 + x_m x_1}{r_m^2 + x_m^2}, \tag{6}$$

$$\sigma_{1r} = \frac{r_m x_1 - r_1 x_m}{r_m^2 + x_m^2}. \tag{7}$$

In this case value of argument ψ of correction factor $\dot{\sigma}_1$ will be determined from expression

$$tg\psi = \frac{r_m x_1 - r_1 x_m}{r_m^2 + x_m^2 + r_m r_1 + x_m x_1}. \tag{8}$$

Correction factor square

$$\dot{\sigma}_1^2 = (\sigma_{1\mathrm{a}}^2 - \sigma_{1r}^2) + j2\sigma_{1a}\sigma_{1r}. \tag{9}$$

Let's calculate products

$$\dot{\sigma}_1 z_1 = r_1' + jx_1, \quad (10)$$

$$\dot{\sigma}_1^2 z_2 = r_2'' + jx_2'', \quad (11)$$

where

$$r_1' = \sigma_{1a} r_1 - \sigma_{1r} x_1, \quad (12)$$

$$x_1' = \sigma_{1a} x_1 + \sigma_{1r} r_1, \quad (13)$$

$$r_2'' = (\sigma_{1a}^2 - \sigma_{1r}^2)\frac{r_2'}{s} - 2\sigma_{1a}\sigma_{1r} x_2', \quad (14)$$

$$x_2'' = (\sigma_{1a}^2 - \sigma_{1r}^2) x_2' + 2\sigma_{1a}\sigma_{1r}\frac{r_2'}{s}. \quad (15)$$

Thus, calculated ratios (12)–(15) were obtained for resistances of main circuit of exact equivalent circuit, which is shown in Fig. 13.

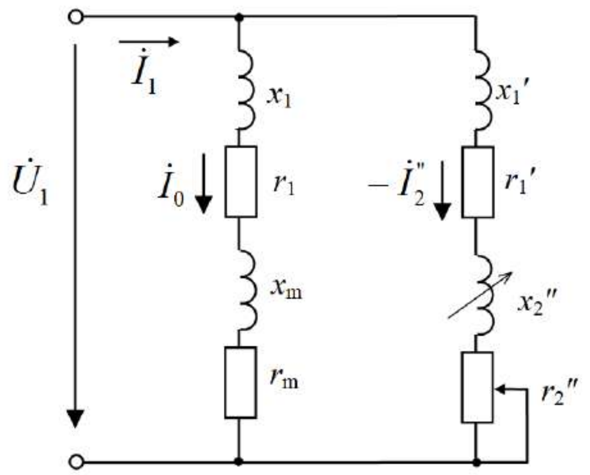

Figure 13. Exact equivalent circuit of cylindrical LIM

For refined G-shaped equivalent circuit, it is customary to take correction factor as a real number

$$\sigma_1 = 1 + x_1/x_m, \quad (16)$$

and calculated ratios for resistances of main circuit of equivalent circuit is of form

$$r_1' = \sigma_1 r_1, \quad (17)$$

$$x_1' = \sigma_1 x_1, \quad (18)$$

$$r_2'' = \sigma_1^2 \frac{r_2'}{s}, \quad (19)$$

$$x_2'' = \sigma_1^2 x_2'. \quad (20)$$

For the main variants of the equivalent circuit of a cylindrical LIM described above, an algorithm for calculating the parameters of the equivalent circuit have been developed.

ALGORITHM OF CIRCUIT PARAMETERS CALCULATION

Let's consider following variants of calculation of parameters of equivalent circuit of cylindrical LIM.

T-shaped equivalent circuit of LIM is investigated (Fig. 11) in variants No. 1 and No. 2. Resistance r_1 is measured at direct current [36], and inductance x_1 – using "out-rotor" method. Remaining parameters of equivalent circuit are calculated according to data of blocked-rotor test (rbr, xbr) and engine operation mode without load (r0, x0) – is taken as no-load test [31, 35].

In variant No. 1 calculated formulas look like:

$$x_m = x_0 - x_1, \quad (21)$$

$$r_m = r_0 - r_1, \quad (22)$$

$$x_2' = x_{br} - x_1, \quad (23)$$

$$r_2' = r_{br} - r_1. \quad (24)$$

In variant No. 2 calculation takes into account influence of resistance z_m on amount of current of short circuit current. Taking into account magnetization branch impedance of circuit between points *a* and *b* (Fig. 11) is equal to

$$z_{ab} = \frac{z_m z_2'}{z_m + z_2'}, \quad (25)$$

where impedances z_m and z_2' are determined by expressions (3) and (2). From ratio (25) we can write

$$z_2' = \frac{(r_m + jx_m)(r_{ab} + jx_{ab})}{(r_m - r_{ab}) + j(x_m - x_{ab})}. \quad (26)$$

After separation real and imaginary parts we obtain ratios for calculation of active and inductive resistances of secondary part

$$r_2' = \frac{z_m^2 r_{ab} - z_{ab}^2 r_m}{(r_m - r_{ab})^2 + (x_m - x_{ab})^2}, \quad (27)$$

$$x_2' = \frac{z_m^2 x_{ab} - z_{ab}^2 x_m}{(r_m - r_{ab})^2 + (x_m - x_{ab})^2}. \quad (28)$$

In this case resistances values z_{ab}, r_{ab} and x_{ab} will be determined

$$r_{ab} = r_k - r_1, \quad (29)$$

$$x_{ab} = x_k - x_1, \quad (30)$$

$$z_{ab} = \sqrt{r_{ab}^2 + x_{ab}^2}. \quad (31)$$

In variants No. 3 - No. 6 refined equivalent circuit is investigated (coefficient σ_1 is real number), which is shown in Fig. 14.

In variant No. 3 initial calculation is resistance r_1, which is determined, as in first variant, by measuring at direct current. Assumption is introduced that $r_1 \cong r_2'$ and $x_1 \cong x_2'$ when calculation. The coefficient σ_1 is determined from relation

$$r_k = \sigma_1 r_1 + \sigma_1^2 r_2'. \quad (32)$$

After substitution $r_2' = r_1$ into (32) we obtain quadratic equation whose positive root corresponds to the coefficient σ_1. Inductance $x_1 = x_2'$ is determined from ratio

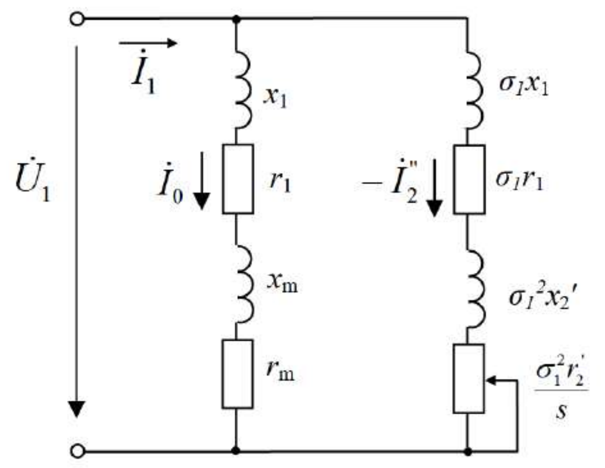

Figure 14. LAM refined equivalent circuit

$$x_k = \sigma_1 x_1 + \sigma_1^2 x_2', \quad (33)$$

and will be equal

$$x_1 = \frac{x_{br}}{\sigma_1 + \sigma_1^2}. \quad (34)$$

Resistances of magnetization branch is determined by formulas (21) and (22).

When calculation according to variant No. 4 initial data r_1 and x_1 are determined in the same way as in first variant. It is assumed that $r_m \ll x_m$, and following formulas are used: (21) – to calculate magnetizing reactance x_m, (22) – to calculate the resistance r_m, (16) – to calculate coefficient σ_1. Remaining calculation formulas have form

$$r_2' = \frac{r_{br} - \sigma_1 r_1}{\sigma_1^2}, \quad (35)$$

$$x_2' = \frac{x_{br} - \sigma_1 x_1}{\sigma_1^2}. \quad (36)$$

In variant No. 5 initial data and prerequisites are the same as in *variant No. 4*. In addition influence of primary branch on secondary in short circuit mode is taken into account. Resistances x_m and r_m are determined by formulas (21) and (22) and coefficient σ_1 is determined by formula (16). Remaining calculation formulas look like:

$$x_{sb} = \frac{z_0^2 x_{br} - z_{br}^2 x_0}{(r_0 - r_{br})^2 + (x_0 - x_{br})^2}, \quad (37)$$

$$r_{sb} = \frac{z_0^2 r_{br} - z_{br}^2 r_0}{(r_0 - r_{br})^2 + (x_0 - x_{br})^2}, \quad (38)$$

$$x_2' = \frac{x_{sb} - \sigma_1 x_1}{\sigma_1^2}, \quad (39)$$

$$r_2' = \frac{r_{sb} - \sigma_1 r_1}{\sigma_1^2}. \quad (40)$$

In equations (37)–(40) r_{sb} and x_{sb} are active and inductive resistances of secondary branch in short circuit mode. When calculation according to variant No. 6 resistance r_1 is determined in the same way as in first option, it is assumed that $r_1 \cong r_2'$ and $x_1 \cong x_2'$ and influence of primary branch on secondary is taken into account.

Calculation formulas are similar to formulas for *variant No. 5* and have following features:

- coefficient σ_1 is defined as positive root of equation

$$r_{sb} = \sigma_1 r_1 + \sigma_1^2 r_2', \quad (41)$$

- resistance x_1 is determined from ratio

$$x_1 = \frac{x_{sb}}{\sigma_1 + \sigma_1^2}, \quad (42)$$

- active and inductive magnetization resistances are determined by formulas (21) and (22).

In variant No. 7 exact G-shaped LIM equivalent circuit is investigated. Resistances r_1 and x_1 are determined as in first variant. Resistances of magnetization branch are calculated by formulas (21) and (22), and resistances of secondary branch of equivalent circuit are calculated by formulas (12)–(15). Calculated values of active and reactive resistances of equivalent circuit for blocked-rotor test are determined

$$r_{br.c} = \frac{r_{pb} z_{sb}^2 + r_{sb} z_{pb}^2}{(r_m - r_{ab})^2 + (x_m - x_{ab})^2}, \quad (43)$$

$$x_{br.c} = \frac{x_{pb} z_{sb}^2 + x_{sb} z_{pb}^2}{(r_m - r_{ab})^2 + (x_m - x_{ab})^2}, \quad (44)$$

where

$$r_{pb} = r_1 + r_m, \quad (45)$$

$$x_{pb} = x_1 + x_m, \quad (46)$$

$$r_{sb} = r_1' + r_2'', \quad (47)$$

$$x_{sb} = x_1' + x_2'', \quad (48)$$

where suffixes: "*br.c*" is the bloc-rotor calculated; "*pb*" is the primary branch; "*sb*" is the secondary branch.

Based on calculated resistances values (43) and (44), calculated current for short circuit mode $I_{sh.c.cal}$ is determined and compared with actual short-circuit current $I_{sh.c.act}$ obtained experimentally

$$I_{sh.c.cal} - I_{sh.c.act} \leq \delta, \quad (49)$$

where δ is required calculation accuracy.

If condition (49) is not satisfied, then resistance x_1 is given increment

$$x_1 = x_1 + \Delta x \quad (50)$$

and calculation cycle is repeated. When condition (49) was held, calculation ends.

PERFORMANCE CHARACTERISTICS CALCULATION FROM EQUIVALENT CIRCUIT DATA

Calculation of performance characteristics of cylindrical LIM is carried out according to technique used for asynchronous electric motors [35, 37]. In this case to separate idle stroke losses two idle stroke voltages are selected: U_{01} in range of 100–180 V and U_{02} equal to nominal voltage U_1. For these voltage values idle stroke losses P'_{01} and P'_{02} are calculated. To calculate mechanical and additional idle stroke losses ratio can be applied

$$P_{mech} = \frac{P'_{01}U_{02}^2 - P'_{02}U_{01}^2}{U_{02}^2 - U_{01}^2}. \quad (51)$$

Remaining formulas used in calculating performance characteristics are shown in algorithm scheme of calculation exact equivalent circuit of cylindrical LAM (Fig. 15). If engine is described by refined equivalent circuit, then when entrance initial data reactive component of correction factor σ_{1p} is set equal to zero.

In Fig. 15 following designations were adopted: P_{mech} is the mechanical and additional idle stroke losses; $P_{st.st.}$ is the losses in stator steel; $P_{c.l.1}$ is the copper loss of stator winding; P_1 is the input power; $P_{e.m}$ is the electromagnetic power; F is the electrodynamic force; $P_{c.l.2}$ is the copper loss of runner; $P_{f.mech}$ is the full mechanical power; P_2 is the useful mechanical power; v is the speed of runner; η is the efficiency factor.

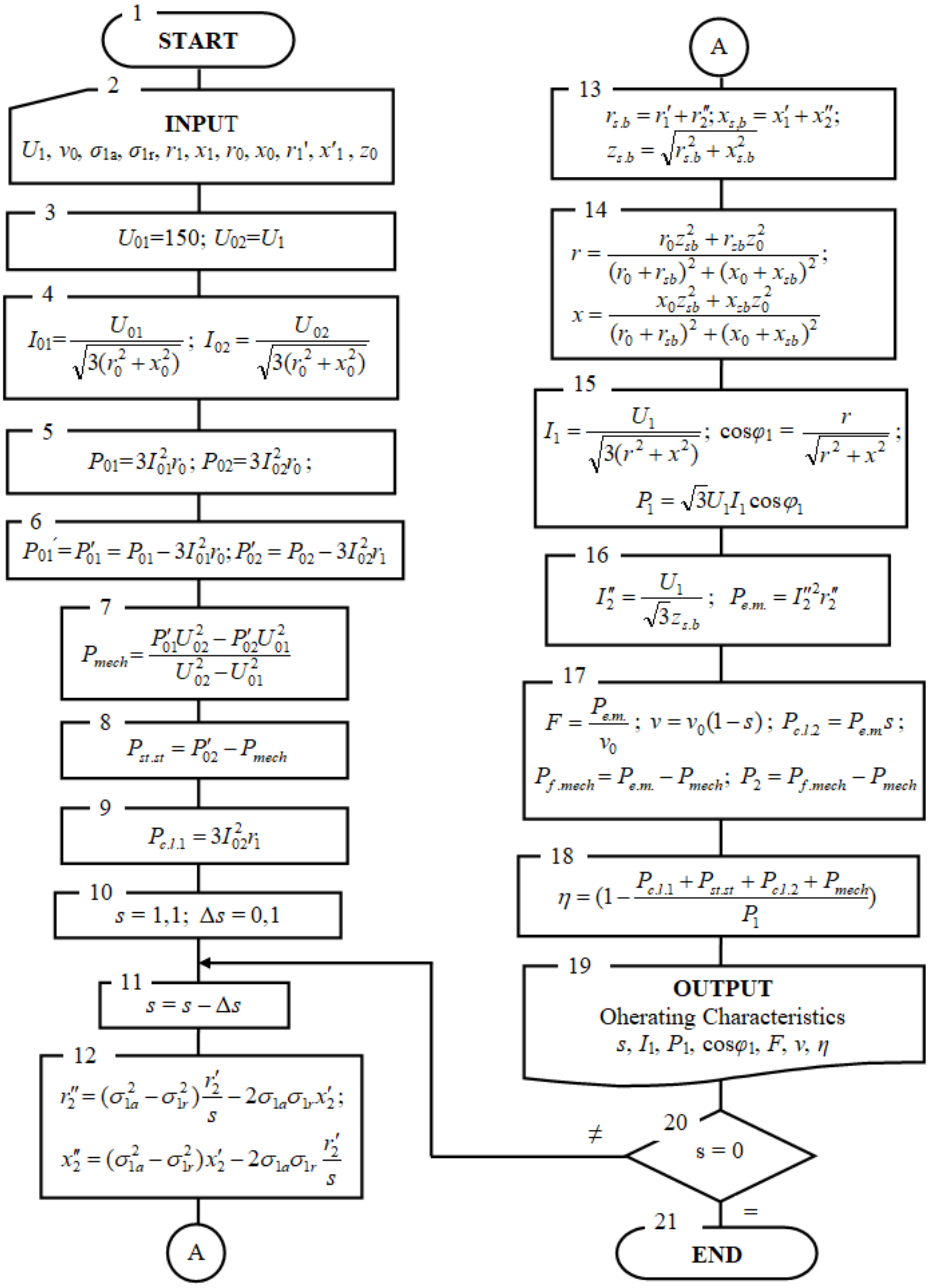

Figure 15. Algorithm for calculating performance

Table 1. Design parameters of equivalent circuits, Ω

Variant of equivalent circuit	r_1	x_1	r_m	x_m	σ_1	r_{21}	x_{21}
1	7.5	5.2	4.89	0.8		3.18	-0.03
2	7.5	5.2	4.89	0.8		7.92	-2.44
3	7.5	2.71	4.89	0.8	0.97	7.5	2.71
4	7.5	2.71	4.89	0.8	4.39	-1.15	-0.35
5	7.5	2.71	4.89	0.8	4.39	2.31	1.32
6	7.5	3.17	4.89	2.83	2.97	6.24	3.17
7	7.5	3.85	4.89	0.8			
	σ_{1a} = 2.62 r_1'' = 17.63 r_2'' = 38.87		σ_{1r} = 0.52 x_1'' = 14.00 x_2'' = 45.89				

Table 2. Stator current

Mode	no-load	S = 0.1	S = 0.3	Short Circuit
Variant №6, I_1, A	14.51	14.89	15.24	16.68
Variant №7, I_1, A	14.51	14.93	15.5	16.64
Experiment, I_1, A	14.4	14.7	-	16.9

Table 3. Calculated engine performance characteristics

s	*0.1*	*0.2*	*0.3*	*0.4*	*0.5*	*0.6*	*0.7*	*0.8*	*0.9*	*1.0*
I_1, A	14.93	15.24	15.5	15.74	15.95	16.13	16.29	16.42	16.54	16.64
P_1, W	8088.6	8232.4	8351.0	8447.4	8524.9	8586.2	8634.1	8670.9	8698.5	8718.6
cosφ	0.9	0.9	0.89	0.89	0.89	0.88	0.88	0.88	0.87	0.87
F, N	46.02	81.71	105.5	127.8	141.0	149.3	153.6	154.8	153.7	150.7
V, m/s	3.24	2.88	2.52	2.16	1.08	1.44	1.08	0.72	0.36	0
η, %	1.96	3.15	3.86	4.14	4.19	4.08	3.86	3.59	3.3	3.01

Let's consider sequence of performance characteristics calculation (Fig. 15). After input initial data calculation of mechanical losses P_{mech}, losses in steel P_{st} and copper loss of stator winding P_{c1} are performed. Then sliding cycle is set (step 10). On Fig. 5 cycle of ten steps with step size ΔS = 0.1 is shown. In 11th step slip takes initial value S = 1.0 (which corresponds to short circuit mode) and then equivalent circuit resistance is calculated for this slip value (steps 12–14).

In steps 15–28 equivalent circuit currents are calculated and motor performance characteristic are calculated and printed out (step 19). Next (action 20) it is checked for equality to zero of current slip value. If condition is not satisfied, return to step 11, slip takes on new value, and performance characteristics calculation for this slip are performed. When condition S = 0 was held, performance characteristics calculation is ended.

EXPERIMENTAL VERIFACATION OF DEVELOPED METODS

Method of calculation of parameters of equivalent circuit and working characteristics of coaxial LAM was tested on drive motor of bus disconnectors for traction substations of urban electric transport. Results of calculation of parameters of engine equivalent circuit for variants No. 1 – No. 7 are shown in Table 1.

Validity of obtained data was checked based on matching of calculated values of stator current with experimental values obtained by researching motor on test bench. Table 2 presents matching results for scheme according to option No. 6 and No. 7. Remaining variants give errors that go beyond permissible values.

Results of calculation of operating characteristics of cylindrical LIM are shown in Table 3. Calculation was performed according to initial data for equivalent circuit according to variant № 7: U_1 = 348 V; v_0= 3,6 m/s; r_1 = 7,5 Ω; x_1 = 3,85 Ω; σ_{1a} = 2,65; σ_{1r}= 0,71; r_0 = 12,39; x_0 = 6,0; z_0 = 13,37 Ω; r_{11} = 16,47 Ω; x_{11} = 18,05 Ω.

CONCLUSIONS

Based on analysis of equivalent circuits used in the research of LAM, main variants of equivalent circuits for coaxial LAM are considered. Technique and algorithm of calculation of parameters of equivalent circuit have been developed.

It is shown that in research of cylindrical LAM exact equivalent circuit should be used, when calculation of parameters of which active and reactive components of correction factor σ_1, active resistance of magnetization branch is taken into account. Calculated ratios of parameters of the exact equivalent circuit of cylindrical LAM are given.

Algorithm of calculation of performance characteristics of coaxial LAM based on equivalent circuit data is proposed.

Experimental checking of developed methods of calculation of parameters of equivalent circuit and performance characteristics of cylindrical LAM was carried out.

DISCLOSURE STATEMENT

No potential conflict of interests was reported by the author(s).

REFERENCES

1. Eguren, I., Almandoz, G., Egea, A., Ugalde, G., & Escalada, A.J. (2019). Linear machines for long stroke applications—A review. *IEEE Access, 8*, 3960–3979. https://doi.org/10.1109/ACCESS.2019.2961758

2. Escalada, A. J., Poza, J., Luri, S., & Gonzalez, A. (2006). Equivalent circuit of a linear induction motor with variable parameters. In *IECON 2006-32nd Annual Conference on IEEE Industrial Electronics* (pp. 1569–1574). IEEE. https://doi.org/10.1109/IECON.2006.347651

3. Teriaiev, V., & Dovbyk, A. (2021). Special considerations for the mathematical modeling and control of the multisectional asynchronous motor. *Scientific Works of VNTU*, (4), 1–7. https://doi.org/10.31649/2307-5392-2020-4-25-31

4. Wang, H., Zhao, J., Xue, J., Chen, H., Guo, G., Xiong, Y., & Yan, S. (2022). Optimal design of a short primary double-sided linear induction motor based on derived Quasi-3D equivalent circuit model using an improved differential evolution. *IET Electric Power Applications, 16*(12), 1521–1541. https://doi.org/10.1049/elp2.12238

5. Lu, Q., Li, Y., Ye, Y., & Zhu, Z.Q. (2013). Investigation of forces in linear induction motor under different slip frequency for low-speed maglev application. *IEEE Transactions on Energy Conversion, 28*(1), 145–153. https://doi.org/10.1109/TEC.2012.2227114

6. Zhou, W., Sun, Z., Qian, H., Mao, Y., & Zhuang, Z. (2022). Equivalent circuit and performance investigation of cross-shaped linear induction motor. *IEEE Canadian Journal of Electrical and Computer Engineering, 45*(2), 124–131. https://doi.org/10.1109/ICJECE.2021.3135272

7. Lv, G., Zeng, D., Zhou, T., & Degano, M. (2021). A complete equivalent circuit for linear induction motors with laterally asymmetric secondary for urban railway transit. *IEEE Transactions on Energy Conversion, 36*(2), 1014–1022. https://doi.org/10.1109/TEC.2020.3026334

8. Okhrimenko, V., Zbitnieva, M., & Kolontaevsky, Y. (2019). Construction features of cylindrical linear asynchronous motors. *Lightning Engineering & Power Engineering, 56*(3), 120–124. https://doi.org/10.33042/2079-424X-2019-3-56-120-124

9. Liu, A., Li, J., Li, Y., & Lin, X. (2009). Motion control system simulation of cylindrical linear induction motor used in circuit breaker operating mechanism. In *2009 IEEE International Conference on Automation and Logistics* (pp. 460–464). IEEE. https://doi.org/10.1109/ICAL.2009.5262877

10. Okhrimenko, V., & Zbitnieva, M. (2021). Mathematical model of tubular linear induction motor. *Mathematical Modelling of Engineering Problems, 8*(1), 103–109. https://doi.org/10.18280/mmep.080113

11. Liu, A., Zhang, J., & Lv, Z. (2014). Design and simulation of cylindrical linear induction motor used in circuit breaker operating mechanism. In *2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific)* (pp. 1–6). IEEE. https://doi.org/10.1109/ITEC-AP.2014.6940894

12. Hameyer, K. (2001). Electrical Machine I: Basics, Design, Function, Operation. RWTH Aachen University

13. Knight, A. (2022). Induction Machine Equivalent Circuit Model. *Hosted by University of Calgary*. https://people.ucalgary.ca/~aknigh/electrical_machines/induction/im_circuit.html

14. Mirsalim, M., Doroudi, A., & Moghani, J. S. (2002). Obtaining the operating characteristics of linear induction motors: A new approach. *IEEE Transactions on Magnetics, 38*(2), 1365–1370. https://doi.org/10.1109/20.996026

15. Nonaka, S. (1995). Investigation of equivalent circuit quantities and equations for calculation of characteristics of single-sided linear induction motors. *IEEJ Transactions on Industry Applications, 115*(3), 223–232. https://doi.org/10.1541/ieejias.115.223

16. Lu, J., & Ma, W. (2011). Research on end effect of linear induction machine for high-speed industrial transportation. *IEEE Transactions on Plasma Science, 39*(1), 116–120. https://doi.org/10.1109/TPS.2010.2085089

17. Xu, W., Zhu, J. G., Zhang, Y., Li, Z., Li, Y., Wang, Y., ... & Li, Y. (2010). Equivalent circuits for single-sided linear induction motors. *IEEE Transactions on Industry Applications, 46*(6), 2410–2423. https://doi.org/10.1109/TIA.2010.2073434

18. Nozakia, Y., Yamaguchia, T., & Kosekib, T. (2007). Equivalent circuit model of linear induction motor with parameters depending on secondary speed for urban transportation system. *The University of Tokyo, Department of Electrical Engineering Report*.

19. Rajput, S., Bender, E., & Averbukh, M. (2020). Simplified algorithm for assessment equivalent circuit parameters of induction motors. *IET Electric Power Applications, 14*(3), 426–432. https://doi.org/10.1049/iet-epa.2019.0822

20. Lv, G., Zeng, D., & Zhou, T. (2018). An advanced equivalent circuit model for linear induction motors. *IEEE Transactions on Industrial Electronics, 65*(9), 7495–7503. https://doi.org/10.1109/TIE.2018.2807366

21. Zeng, D., Lv, G., Zhou, T., & Degano, M. (2019). A complete equivalent circuit model for linear induction motor considering thrust, vertical and transversal forces. In *2019 IEEE International Electric Machines & Drives Conference*

(IEMDC) (pp. 1766–1771). IEEE. https://doi.org/10.1109/IEMDC.2019.8785311

22. Lv, G., Yan, S., Zeng, D., & Zhou, T. (2019). An equivalent circuit of the single-sided linear induction motor considering the discontinuous secondary. *IET Electric Power Applications, 13*(1), 31–37. https://doi.org/10.1049/iet-epa.2018.5184

23. Nozaki, Y., Yamaguchi, T., & Koseki, T. (2006). Practical equivalent circuit model of linear induction motors for urban transportation system depending on secondary speed based on electromagnetic analysis. *The University of Tokyo, Department of Electrical Engineering Report*.

24. Raju, M.N., & Rani, M.S. (2018). Mathematical modeling of linear induction motor. *International Journal of Engineering & Technology, 7*(4.24), 111–114.

25. Toro-García, N., Garcés-Gómez, Y. A., & Hoyos, F. E. (2020). Discrete and continuous model of three-phase linear induction motors considering attraction force and end-effects. *International Journal of Power Electronics and Drive Systems, 11*(4), 1737. https://doi.org/10.11591/ijpeds.v11.i4.pp1737-1749

26. Heidari, H., Rassõlkin, A., Razzaghi, A., Vaimann, T., Kallaste, A., Andriushchenko, E., ... & Lukichev, D. V. (2021). A modified dynamic model of single-sided linear induction motors considering longitudinal and transversal effects. *Electronics, 10*(8), 933. https://doi.org/10.3390/electronics10080933

27. Zhang, Q., Liu, H., Song, T., & Zhang, Z. (2021). A novel, improved equivalent circuit model for double-sided linear induction motor. *Electronics, 10*(14), 1644. https://doi.org/10.3390/electronics10141644

28. Zhang, Q., Liu, H.J., Zhang, Z.Y., Song, T.F., & Wang, Y. (2021). Comparative study on improved and traditional equivalent circuit of long primary double-sided linear induction motor. *The Applied Computational Electromagnetics Society Journal (ACES), 36*(11), 1499–1508. https://doi.org/10.13052/2021.ACES.J.361115

29. Yamada, H., Mizuno, T., & Nihei, H. (1997). Equivalent circuit of a cylindrical linear induction motor with unbalanced phases. *Journal of the Magnetics Society of Japan, 21*(4-2), 849–852. https://doi.org/10.3379/jmsjmag.21.849

30. Plodpradista, W. (2009). Dynamic performances of tubular linear induction motor for pneumatic capsule pipeline system. *World Academy of Science, Engineering and Technology, 53*, 891. https://doi.org/10.5281/zenodo.1062928

31. Hirahara, H., Inoue, M., & Yamamoto, S. (2022). A method for determining equivalent circuit constant of linear induction motors using locked mover and standstill impedance tests. In *2022 International Power Electronics Conference (IPEC-Himeji 2022-ECCE Asia)* (pp. 807–812). IEEE. https://doi.org/10.23919/IPEC-Himeji2022-ECCE53331.2022.9806981

32. Xu, W., Zhu, J.G., Zhang, Y., Li, Y., Wang, Y., & Guo, Y. (2010). An improved equivalent circuit model of a single-sided linear induction motor. *IEEE Transactions on Vehicular Technology, 59*(5), 2277–2289. https://doi.org/10.1109/TVT.2010.2043862

33. Zhou, W., Sun, Z., Cui, F., & Mao, Y. (2021). Electromagnetic design of high-speed and high-thrust cross-shaped linear induction motor. *IEEE Access, 9*, 87501–87509. https://doi.org/10.1109/ACCESS.2021.3058331

34. Guo, S., Zhou, L., & Yang, T. (2012). An analytical method for determining circuit parameter of a solid rotor induction motor. In *2012 15th International Conference on Electrical Machines and Systems (ICEMS)* (pp. 1–6). IEEE.

35. García, N.T., Garcés Gómez, Y.A., & Hoyos Velasco, F.E. (2020). Parameter estimation of three-phase linear induction motor by a DSP-based electric-drives system. *International Journal of Electrical & Computer Engineering, 10*(1), 626–636. https://doi.org/10.11591/ijece.v10i1.pp626-636

36. IEEE Std 112-2017 (Revision of IEEE Std 112-2004). IEEE Standard Test Procedure for Polyphase Induction Motors and Generators. https://doi.org/10.1109/IEEESTD.2018.8291810

37. Knight, A. (2022). Determining Induction Machine Parameters. *Hosted by University of Calgary*. https://people.ucalgary.ca/~aknigh/electrical_machines/induction/i_params.html

Методика визначення параметрів схеми заміщення циліндричного лінійного асинхронного двигуна та алгоритм розрахунку робочих характеристик

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Анотація. Циліндричні лінійні асинхронні двигуни (ЛАД) в даний час використовуються в багатьох промислових цілях. Задача моделювання електричної машини має важливе значення для оптимізації процесів проектування та виробництва двигунів з оптимальними технічними характеристиками. Традиційний підхід до побудови математичних моделей асинхронних машин, заснований на класичній теорії електричних машин, у порівнянні з методами теорії поля та чисельними методами є значно простішим. Конструктивно циліндричні ЛАД відрізняються відсутністю поперечних крайових ефектів, що сприяє використанню методів класичної теорії електричних машин для побудови їх математичних моделей. У роботі запропоновано аналітичний метод розрахунку параметрів схеми заміщення та робочих характеристик циліндричного ЛАД. Досліджувався двигун, рухома частина якого виконана у вигляді суцільного сталевого стержня з мідним покриттям. Розглянуто схеми заміщення ЛАД різних конструкцій (односторонніх, двосторонніх, хрестоподібних, циліндричних) та оцінено можливість їх застосування для досліджуваного двигуна. Робота циліндричних ЛАД у промислових механізмах характеризується відносно невеликим значенням робочого ходу. Для таких двигунів важко проводити стандартні випробування, зокрема випробування холостого ходу, щоб отримати дані для розрахунку параметрів еквівалентної схеми. У роботі запропоновано методику експериментального визначення параметрів схеми заміщення. Активний опір статора вимірюється при постійному струмі, а реактивний опір статора – методом винутого бігуна. Решта параметрів схеми заміщення розраховуються за дослідами короткого замикання і режиму роботи двигуна без навантаження (береться за досвід холостого ходу). Показано, що точна Г-подібна схема заміщення, при розрахунку параметрів якої враховуються активна та реактивна складові поправочного коефіцієнта та активний опір гілки намагнічування, забезпечує прийнятну точність визначення значень параметрів схеми заміщення. Наведено алгоритм розрахунку робочих характеристик циліндричного ЛАД на основі даних схеми заміщення. Порівняння розрахункових і експериментальних даних показало задовільні результати, похибка не більше 7%.

Ключові слова: лінійний асинхронний двигун, еквівалентна схема, параметр, робочі характеристики.

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