389. LINEAR ELECTRIC DRIVES FOR CONSTRUCTIONAL PURPOSES

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Abstract. The paper discusses designing, modeling and application of electric drives with linear induction motors for constructional purposes: high voltage line fault localizing and shunting system of power supply for site, application of thyristors to shunt phase fault, horizontal transport systems with linear electric drives of constructional equipment for transportation of materials, and vertical transport systems with linear electric drives of constructional materials, review of design methods of special linear induction drives, transient responces of linear induction drives.

Keywords: linear induction drive, circuit-breaker, horizontal transportation systems, vertical transportation systems, dynamics of linear induction drives.

High voltage line fault localizing and shunting system of power supply for site

Power supply of sites by temporary high voltage lines leads to high possibility of single phase fault and grounding. To avoid of burned wires, fire and overvoltages caused by single phase grounding of high voltage supply line with insulated neutral it was investigated and created technical equipment to determine location of single phase grounding and to shunt the faulted phase to grounding mesh of substation. An automated system is based on circuit-breaker with separately controlled contacts by cylindrical linear induction motors and control equipment [1, 2, 3, 4]. This system creates possibility to protect 6-10 kV electric networks from overvoltages and other negative subsequence of single-phase grounding: electric arc, fire, burned wires and destroyed isolators, step voltage. It is evident, that at temporary sites application of high voltage phase fault localizing and shunting systems remains important decision, decreasing damage and protecting personal. The main imperfection of equipment to shunt phase fault is certain delay from the single phase grounding instant therefore mentioned equipment does not protect the network from initial overvoltages. To improve automatic phase shunt and localizing system it is reasonable to develop hybrid high voltage commutators, where circuit-breaker with separately controlled contacts is supplemented by thyristor commutator with separately controlled arms which is used in portable substations for enlarged danger. The hybrid commutator allows to eliminate shortcomings both of circuit-breaker with separately controlled phases (small speediness at eliminating primary overvoltages) and thyristor commutator (danger of damage at double-line-to-neutral short circuit during shunting of phase-to-ground short circuit) shortcomings [5]**.**

Application of thyristors to shunt phase fault

In the power transmission lines, less than 1 kV, protective release equipment is used to protect human from touch voltage. The higher voltages require using high speed equipment to shunt touch voltage. High speed shunting of phase-to-ground fault replaces its location from possible to touch place to substation because the circuit-breaker shunts the damaged phase and reduces touch voltage to zero.

The first way is used in the 6 – 35 kV power lines, supplying portable equipment, for example, in quarries. The second one deals with application of high speed thyristor shunting equipment. This equipment limits the phase fault short circuit time and protects other not damaged phases from overvoltages, i.e. it reduces damage of insulation. The equipment to shunt phase fault is shown in Fig. 1. It comprises 3 thyristor commutators (one per each phase) and control unit, which is composed from faulted phase recognition circuits, automatic secondary switching units and locking units to lock phase-to-phase short circuit. Number and type of series connected thyristors in one arm is matched with dischargers protecting installation of substation equipment from overvoltages.

Hybrid commutator [5] protects the network from overvoltages and switches off the short circuit current if during the single phase grounding, the other phase also appears connected to ground and two-phase short circuit via ground happens.

During a short circuit in the network or if the human touches current leading parts, the displacement of neutral appears in the network. When phase-to-ground fault appears in 10 kV network, at first, the thyristor shunting equipment is launched after 3 ms in the substation. It reduces touch voltage to zero at the fault place. As thyristor shunting equipment cannot lead grounding current for a long time, it is complained with circuit-breaker with separately controlled contacts, which firmly connects the grounded phase with grounding mesh of substation.

The faulted phase is selected by special equipment according to the voltage reduction in the faulted phase and voltage increase in the leading phase.

Control equipment of thyristor shunting commutator and circuit-breaker with separately controlled contacts at first sends signals to thyristor controlling electrodes of thyristor shunting commutator, which shunt the damaged phase to substation grounding mesh. Electrical circuit to shunt phase fault with both thyristor commutator and circuit breaker is shown in Fig.1.

Horizontal transport system with linear electric drives for transportation of constructional materials and equipment

Discrete linear electric drive allows changing routs of material and equipment transportation in the sites. Linear induction drive comprises inductors of linear induction motors, fastened on the sleepers between rails, connected by cables with control desk. Buses, made from duralumin or other conducting material are placed at the bottom of the car, tracking by rails, serve as the secondary element, and common for all inductors of linear induction motors (LIM).

Controlling devices connect to power supply one inductor after another, therefore the car together with constructional load or equipment is always provided by continuous thrust. If the sleepers and rails are moved to the other position, possibility to change flexibly transport routs of constructional materials and equipment is assured. System for transportation is given in Fig. 2.

A carriage with LIM for transportation of constructional materials is shown in Fig. 3. Reactive rail from steel or aluminum serves as the secondary element.

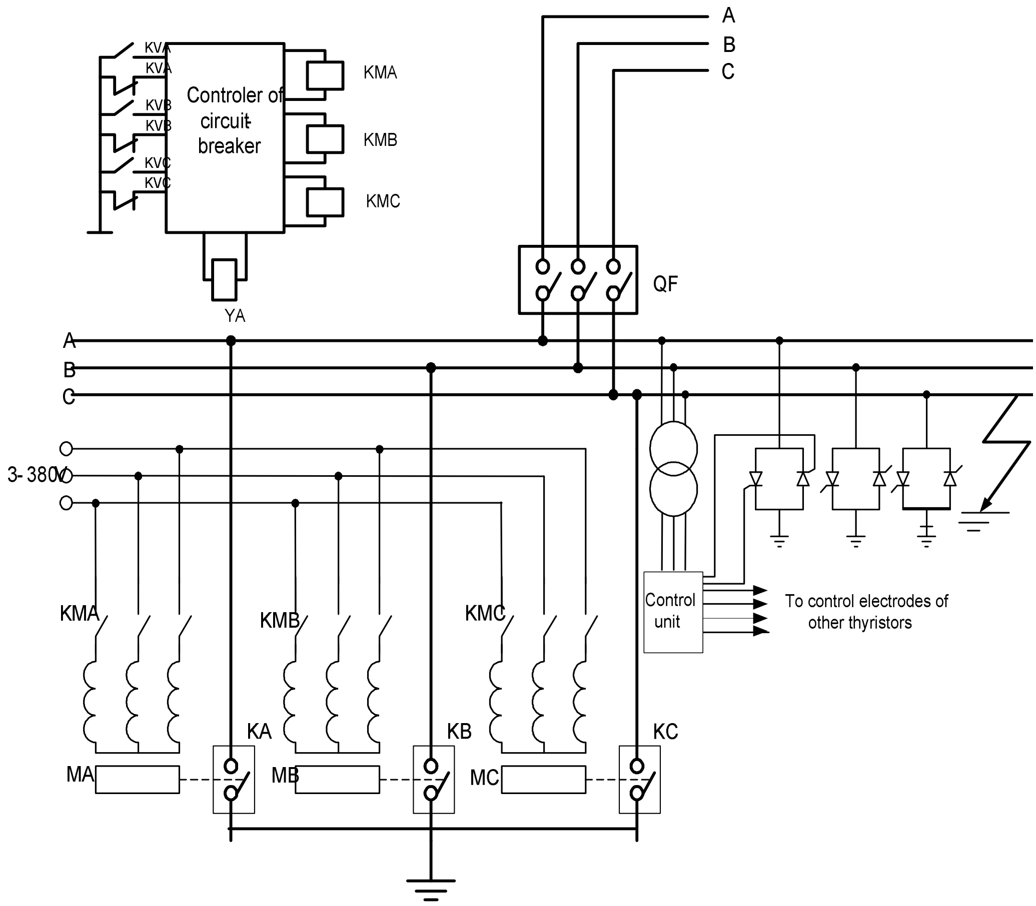

Fig. 1. Hybrid commutator to shunt phase fault: KTA, KTB, KTC – voltage relays fore each phase; KMA, KMB, KMC – contactors of linear motors; QF – the main circuit breaker of power supply line; KA, KB, KC – contacts of circuit-breaker for each phase; MA, MB, MC – linear induction motors

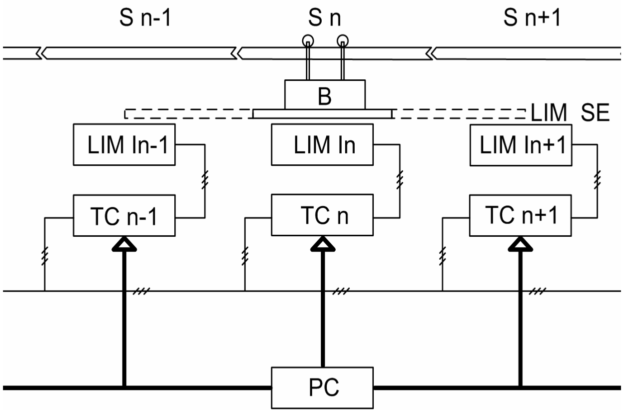

Fig. 2. Block diagram of catapult: S – segments of route of bogie movement; B – bogie: LIM SE – secondary element of linear induction motor; LIM –inductors; TC – thyristor (reversible) commutator, PC – personal computer

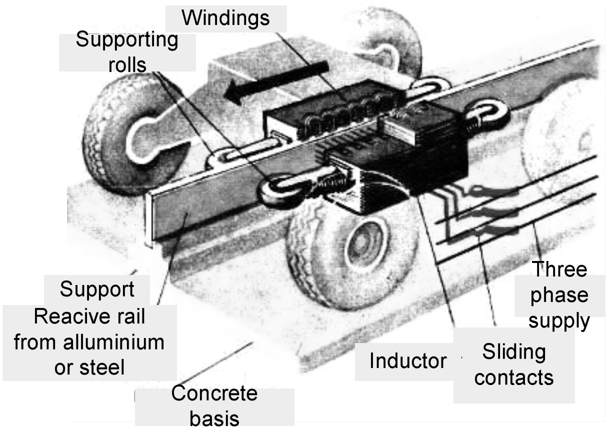

Fig. 3. Carriage with linear motor

Vertical transport systems with linear electric drives for transportaton of constructional materials

Elevators, temporary fastened to building, are used for transportation of constructional materials and equipment during works. In elevators it is purposeful to apply linear induction drives, made from moving inductor, supplied via flexible cable and secondary element – conducting bus, fastened along the elevator Fig. 4.
Heavy inductor of linear induction motor serves as counterweight also [6]. Speed of the elevator cabin can be adjusted by changing supply voltage frequency and amplitude. The advanced frequency converters are applied for this purpose.

Review of design methods of special linear induction drive

In the industry automation systems widely are used small power and relatively small speed linear induction motors (LIM) and on it base designed controlled linear electric drives [7, 8]. The speed-force characteristics of these LIM and controlled drives are close to linear.

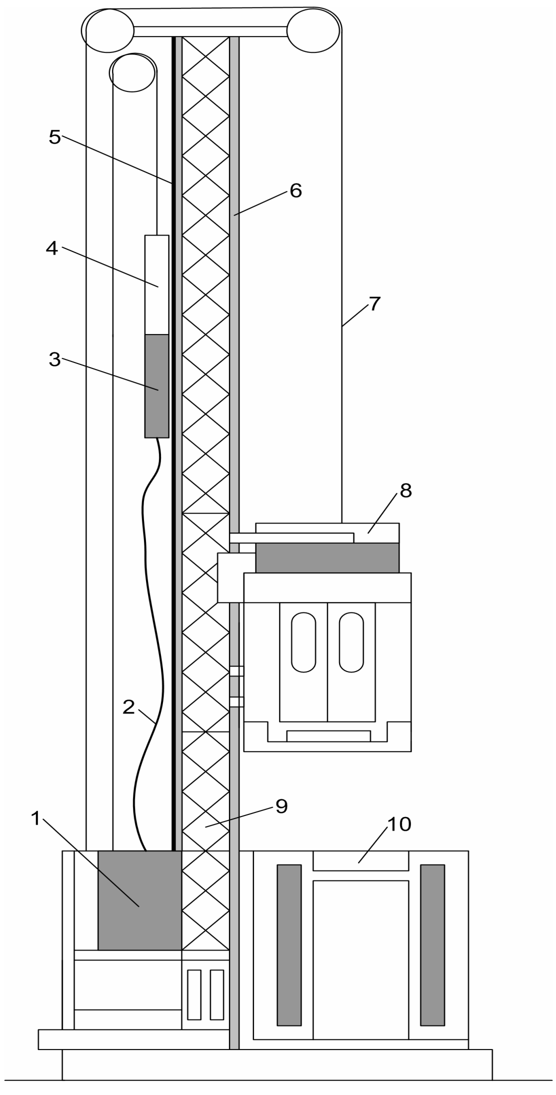

Fig. 4. Elevator for linear motors: 1 – control panel; 2 – flexible cable; 3 – LIM inductor; 4 – contra-weights; 5 – LIM secondary element; 6 –directives; 7 – lifting rope; 8 – cabin; 9 – rode; 10– entrance platform

The influence of slip to the LIM inductor current are small also the dynamic power and current amplitudes are low in this kind of systems. Theoretically working and speed-force characteristics of motors and drives derived from the LIM electromagnetic expressions have complex expressions. Problem gets more difficult because of LIM is asymmetrical three phase electrical energy receiver with reverse current component, which creates breaking force component. Because of that, theoretical speed-force characteristic of a low speed LIM crosses the speed axis lower synchronous speed point when the low speed LIM supplied by the symmetrical three phase source. Therefore at designing the LIM and drive with them, it is useful to apply simplified LIM speed-force and working characteristic expressions derived with respect to mentioned features of linear induction motor and designed electric drive properties [9, 10].

Design of LIM according to required dynamic indices

Electric drive of high voltage circuit-breaker shall have guarantee required speed of contacts at their closing instant, i.e., linear electric drive after passing determined distance shall move with required speed. Disconnecting springs are used to get requires speed of contacts opening. These springs develop static load force for the motor, which usually is non-linear function of distance. Electric drives of other commutating apparatus must meet the similar requirements. Algorithm for designing of cylindrical linear motor according to requested phase trajectory is presented in [4]. Here determined dynamics indices of drive are optimized by changing number of turns of inductor winding. Theoretical assumptions, allowing simplifying design of linear induction motors are given also. Nevertheless expression of force, developed by cylindrical LIM, can be modified as this:

$$F_1(s) = \frac{A(s)}{B(s)} \quad (1)$$

where $A(s) = \dfrac{m_1 U_1^2 X_m \dfrac{\gamma_M \mu\, \omega_0 \tau^2}{\pi^2} \dfrac{\Delta}{\delta}}{2\tau f_1} s,$

$$B(s) = \left[\left(R_1^{'}\right)^2 + \left(X_{\sigma 1}\right)^2 w_1^2\right]\left(\frac{\gamma_M \mu\, \omega_0 \tau^2}{\pi^2}\frac{\Delta}{\delta}\right)^2 s^2 +$$

$$+2R_1^{'} X_m \frac{\gamma_M \mu\, \omega_0 \tau^2}{\pi^2}\frac{\Delta}{\delta} w_1 s + \left(R_1^{'}\right)^2 + \left(X_{11}^{'}\right)^2 w_1,$$

and:

m_1 is number of phases;

U_1 is phase voltage;

$X_m^{'} = \dfrac{X_m}{w_1^2}$ is relative magnetizing reactance of cylindrical LIM inductor winding;

w_1 is number of phase winding turns;

$R_1^{'} = \dfrac{R_1}{w_1}$ is relative resistance of cylindrical LIM inductor winding;

$X_{\sigma 1}^{'} = \dfrac{X_{\sigma 1}}{w_1^2}$ is relative leakage reactance of cylindrical LIM inductor winding; $X_{11}^{'} = X_m{}' + X_{\sigma 1}^{'}$;

$s = \dfrac{v_0 - v}{v_0}$ is slip of LIM secondary element;

$v_0 = 2\tau f_1$ is LIM synchronous speed;

γ_M is conductivity of the secondary element;

τ is LIM pole pitch;

v_0 is synchronous speed of LIM;

v is operating speed of LIM;

$\omega_0 = 2\pi f_1$ is angular frequency of supplied voltage; μ is permeability of inductor core;

Δ is thickness of secondary element;

δ is air gap between inductor teeth and ferromagnetic core of the secondary element.

Detailed analysis of slip – force characteristic (1) indicates, that dynamic indices of electric drives of high voltage commutating apparatus can be optimized by changing other LIM parameters: pole pitch, non-ferromagnetic conducting material of secondary element, (copper, brass, bronze, etc.), thickness of this material, non-magnetic air gap between inductor teeth and ferromagnetic core of the secondary element. Generalized block diagram of algorithm for design of linear induction motor is presented in Fig.1. According to this algorithm, the transients of speed $v(t)$ and distance $L(t)$ are calculated, while the secondary element of cylindrical LIM passes distance L_{ref} corresponding to instant of circuit-breaker contacts closing. Then condition or $v = v_{ref} \pm \Delta v_{ref}$ is checked, where Δv_{ref} is allowed speed error. If $v_{L=L_{ref}} < v_{ref} - \Delta v_{ref}$ parameter $x_{1initial}$ is changed by value Δx_1 (increased or reduced to increase the drive speed; for example, number of turns of the winding is reduced but thickness of non-ferromagnetic coating is increased and etc.) If $v_{L=L_{ref}} > v_{ref} + \Delta v_{ref}$, mentioned parameters are changed in inverse direction. This procedure is repeated while condition $v_{ref} - \Delta v_{ref} \le v_{L=L_{ref}} \le v_{ref} + \Delta v_{ref}$ becomes true.

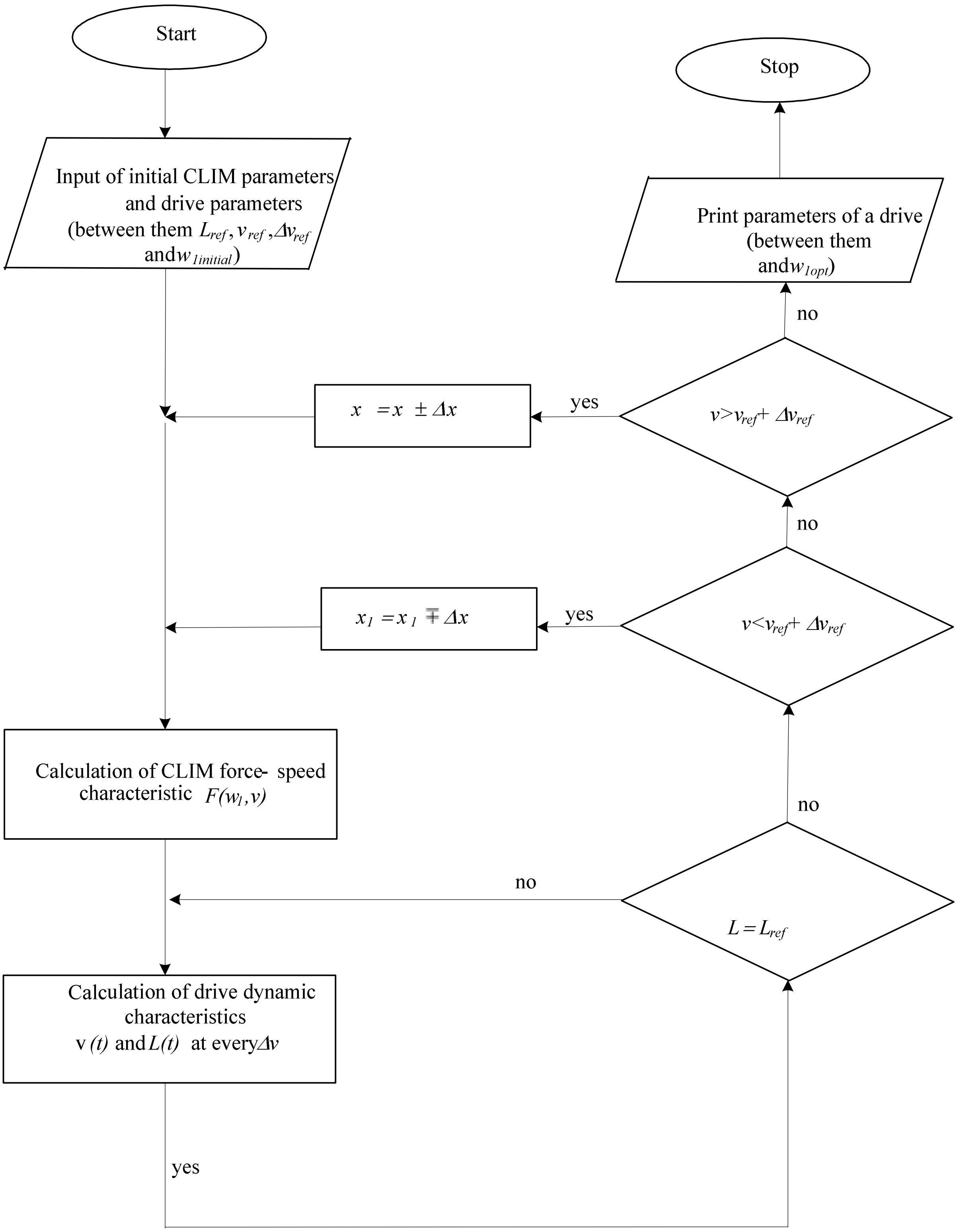

Fig. 5. Algorithm to design cylindrical linear induction motor

Dynamics of linear induction drives for constructional purposes

There are a lot of modifications of mathematical models of induction motor and each one has its area of application. Advanced electric drive is a mechatronic system which contains both mechanical and electronic units. Linear induction drive operates at transients when the supply voltage amplitude and frequency are variable or speeds vary in time. The typical examples of induction motor transients are: direct starting after turn off, sudden mechanical loading, sudden short circuit, and reconnection after short supply fault, behavior during short intervals of supply differential voltages reduction, performance with PWM converter fed. Mathematical model of linear induction drive is described by system of nonlinear equations with varying in time parameters [11]. This model is called model in phase coordinate system. For simplification of solution, Park transformation and reference frames moving with different speed are used. Computer models for investigation of transients in the phase coordinate system and synchronous coordinate system as well as fixed to stator are developed and are presented in the articles [12-16] and monograph [17].

The mathematical model of linear electric drive in a fixed reference frame for investigation of transients was developed [9]. It looks like this:

$$\left.\begin{aligned}
u_{1\alpha} &= \left[\left(\frac{1}{L_1}+\frac{L_m k_1}{L_1 L_2"}\right)\Psi_{1\alpha}-\frac{L_m}{L_1 L_2"}\Psi_{2\alpha}\right]R_1+\frac{d\Psi_{1\alpha}}{dt};\\
u_{1\beta} &= \left[\left(\frac{1}{L_1}+\frac{L_m k_1}{L_1 L_2"}\right)\Psi_{1\beta}-\frac{L_m}{L_1 L_2"}\Psi_{2\beta}\right]R_1+\frac{d\Psi_{1\beta}}{dt};\\
u'_{2\alpha} &= \left[\frac{1}{L_2"}(\Psi_{2\alpha}-k_1\Psi_{1\alpha})\right]R'_2+\frac{d\Psi_{2\alpha}}{dt}+\frac{\pi}{\tau}v\cdot\Psi_{2\beta};\\
u'_{2\beta} &= \left[\frac{1}{L_2"}(\Psi_{2\beta}-k_1\Psi_{1\beta})\right]R'_2+\frac{d\Psi_{2\beta}}{dt}-\frac{\pi}{\tau}v\cdot\Psi_{2\beta}
\end{aligned}\right\},\tag{2}$$

$$F=\frac{3}{2}\frac{\pi}{\tau}\left(\Psi_{2\beta}i_{2\alpha}-\Psi_{2\alpha}i_{2\beta}\right),\tag{3}$$

$$\frac{dv}{dt}=\frac{1}{m}\left(F-F_L\right),\tag{4}$$

where $L'_{2\sigma}$ is magnetizing inductance $L_m=\frac{3}{2}L_{12}$; L_{12} is the greatest inductance between any inductor winding operating in the short time or the intermittent periodic modes. Model of linear induction motor, elaborated according to equations (2, 3, 4) is presented in Fig. 6.

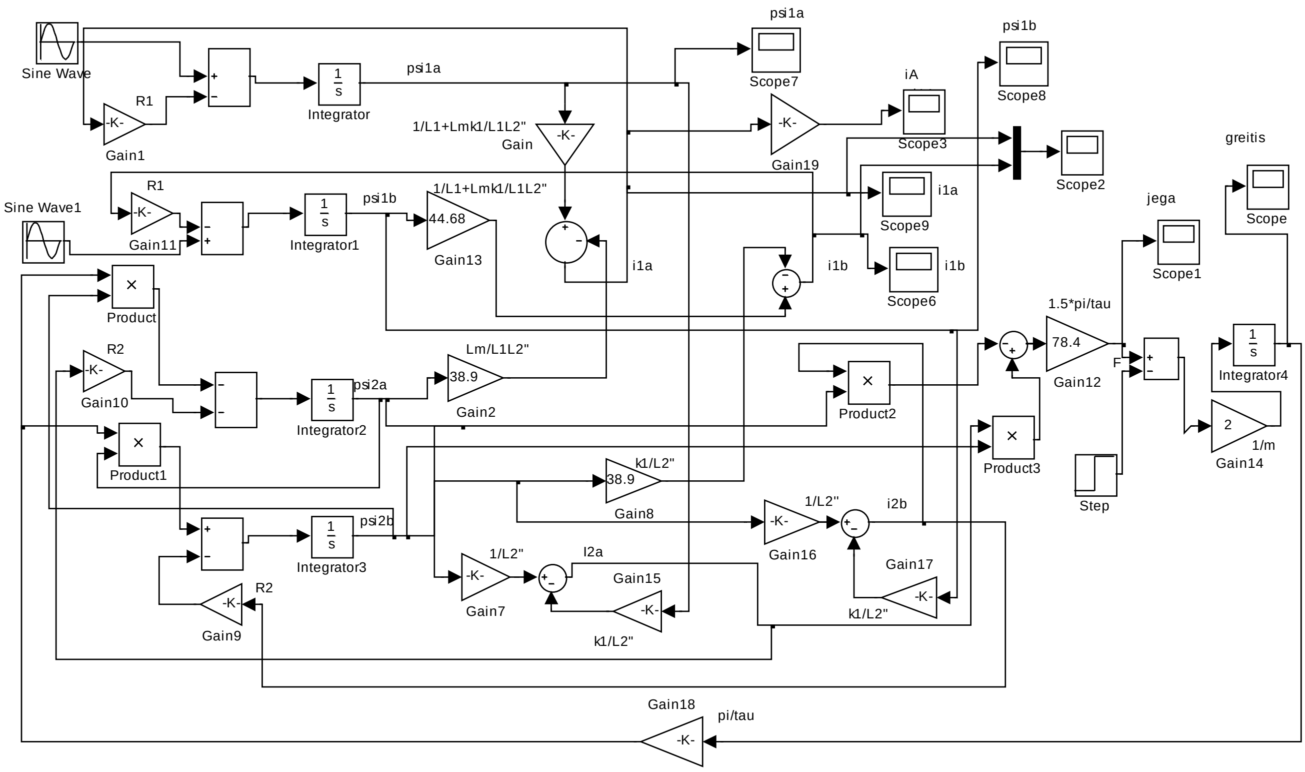

Fig. 6. Model of linear induction motor in reference frame, fixed to stator

Fig. 7 and Fig. 8 show LIM developed transient force and speed during starting at no load.

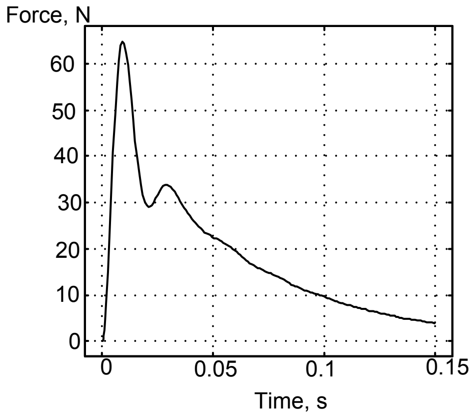

Fig. 7. Dependence of no load LIM developed force against time

Elaborated models of linear electric drive in moving with synchronous speed reference frame and fixed to stator show the same results [10]. They give possibility to investigate transients of controlled and non-controlled linear electric drives, operating with load or at no load.

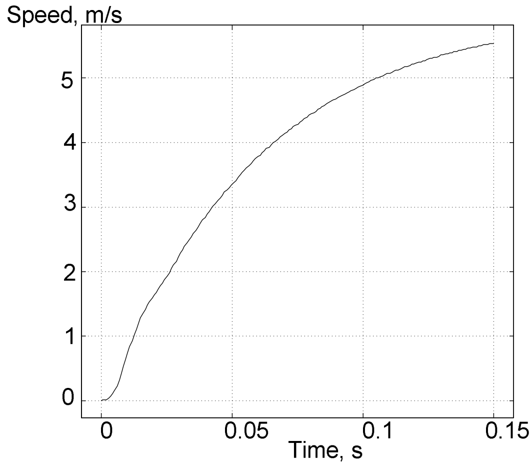

Fig. 8. Dependence of no load LIM speed against time

Experimental investigation of linear electric drives

In order to prove theoretical results, experimental stand with controlling and measuring devices was elaborated. View of stand is presented in Fig. 9.

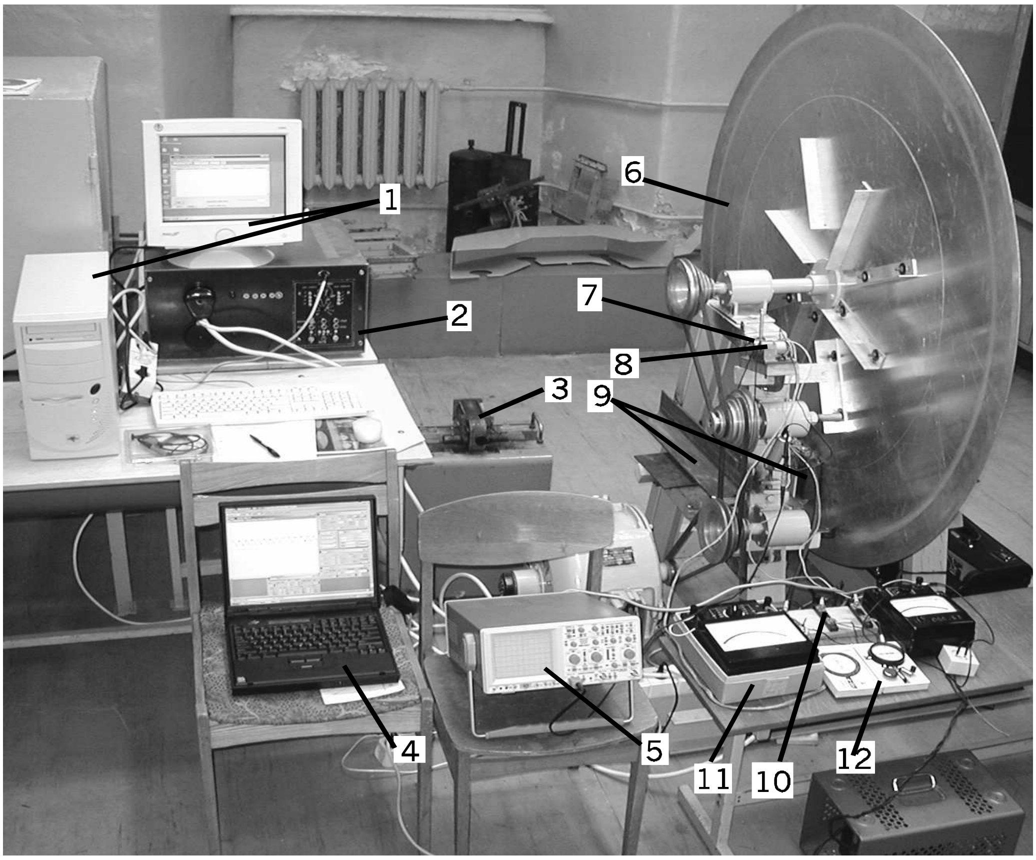

Fig. 9. Universal discoid stand for experimental investigations of LIM

Experiment stand, shown in Fig. 9 comprises pulse control transducer and equipment to measure and record transients of current, speed and dynamic force, where is used personal computer (1), pulse transducer IK (2), autotransformer (3), PC with software controlling oscilloscope and recording of results (4), digital oscilloscope (5), aluminum disc as the secondary element of LIM (6), tachogenerator (7) with holder (8), LIM inductor with fastening elements (9), shunts (10), voltmeter (11) and tachometer (12). Start-stop operation mode allowed investigating speed and force characteristics at different durations of motor switching on and off, resulting to determine required characteristics of drive operating in concrete mechanism.

Conclusions

Results of investigation and elaboration of linear electric drives shows possibilities to apply them successfully in temporary equipment of power supply sites for avoiding of damages from overvoltages, step and touch voltage. Horizontal and vertical transport systems with linear induction drives simplify construction of mechanisms and provides with desired characteristic of movement. Elaborated original computer models of linear induction drives allow investigating various control modes of that and applying results in optimizing carried out drives.

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