The development and testing of a linear induction motor being fed from the source with limited electric power

V V Tiunov
Professor of Electrical Engineering and Electro-mechanics Department, Perm National Research Polytechnic University, 29 Komsomolskiy Prospect, Perm, 614990, Russia
tiuvas@mail.ru

Abstract. The report provides results of the research related to the tubular linear induction motors’ application. The motors’ design features, a calculation model, a description of test specimens for mining and electric power industry are introduced. The most attention is given to the single-phase motors for high voltage switches drives with the usage of inexpensive standard single-phase transformers for motors’ power supply. The method of the motor’s parameters determination, when the motor is being fed from the transformer, working in the overload mode, was described, and the results of it practical usage were good enough for the engineering practice.

1. Introduction
Linear Induction Motors (LIMs) directly convert electric power into forward motion movement of working machines or its separate parts [1-3].

Electric Drives with LIMs in many cases allow effectively automatize and mechanize of different technological processes, especially in conditions of aggressive and toxic medium.

Direct conversion of the electromagnetic field power into forward motion movement of secondary bodies gives LIMs great advantages in comparison with equipment which use mechanic, hydraulic or pneumatic (air powered) converters, and also with solenoids and electromagnets, which usually have a limited movement.

The lack of gaseous or liquid subsidiary working body is especially inconvenient under conditions of toxic or radioactive surrounding environment, as in this case there is a necessity to use extra purification systems, and so it is necessary to have special hermetic reservoirs, as well, for keeping used toxic liquid or radioactive air.

Taking into account the construction of LIMs, they can be subdivided into two main types – flat and cylindrical (tubular) ones. Nowadays, the flat LIMs are more investigated and they have rather widespread application in transport and technological systems, and in magneto hydrodynamic pumps. The tubular LIMs (TLIMs) are much less investigated theoretically, because the correct calculations of them are connected with using of special mathematical functions and, therefore, they are more complicated objects for theoretical designing and investigations, than the flat LIMs.

Moreover, the usage of TLIMs can be highly effective solution of a number of problems while working out of different acting mechanisms, pushers, systems of carrying pipes, cylindrical containers and so on, especially for application in aggressive conditions. At the same time, electric drive with TLIMs is rather simple, compact and safe and, above all, inductors and working bodies of the motors can be easily put into hermetic casing, what is extremely important when LIMs are working in conditions of chemical aggressive medium or outdoor.

In this report some examples of TLIMs for mining industry and power electro energetics are shown. Some of the motors developed have been successfully tested by the customers and introduced into production manufacture. The great attention was paid to the most urgent task of modern power industry, which was connected with the further increasing of the power sources reliability.
One of the key aspects for the technical implementation of this task is the automated distribution of electrical power through the usage of the partitioned grids with back-up lines, which are equipped with the sufficiently simple, reliable and inexpensive shut-off and diverter switching hardware.

Using TLIMs, we can significantly simplify the layout of the switchgear, reduce its dimensions and weight, reduce material consumption and increase its performances and reliability. Besides, such a switching device equipped with the power supply (step-down transformer) can be placed high off the ground at the level of the power transmission supports, hence, increasing external damage resistance. It is important, that switching and other devices, based on the TLIMs, are simple in structure and they can work in three-phase and in single-phase networks of low or high (through the inexpensive transformer) voltage.

2. Design features

Electric machines with linear or reciprocating movement of the working body also became widespread application in the mining and processing industry, in particular, in potash ore mining enterprises and mineral fertilizers producers. These are various dampers, valves, tappets, emergency locks and tech clips, shut-off valves, flow dividers, samplers, etc. [1-6, 8].

The linear induction motors, designed for some of these applications at the Electrical Engineering and Electro-mechanics Department of the Perm National Research Polytechnic University, are shown in Figures 1, 2.

![Figure 1](image1.png)

**Figure 1.** The tubular linear induction drives for mining industry.

Currently, actuation of such mechanisms is effected by a geared motor equipped with a mechanical converter of rotational-to-linear motion of the working body at the outlet of the converter. Hands-on experience demonstrates that these Linear Actuators (LAs), for example of PTV-type (in Russian-‘ПТВ’, it means - the electro-mechanical drive of explosion-roof execution), are not sufficiently reliable and are not easy to maintain (especially when operating in aggressive saline environment), and, at the same time, they have a very significant size, weight and cost. In addition, in some cases, response performance (speed of acting) of these linear actuators is unsatisfactory.
3. Description of the TLIMs’ design

Aiming to find a solution for this issue of creating a linear actuator on the basis of TLIMs for power and mining industry, we have designed the series of three-phase and single-phase TLIMs of 50-1000 N pulling force (see, for example, Figures 1, 2). Its design features and characteristics were presented in the report.

It is known, that projecting of TLIMs for such linear actuators is rather complicated, as it is conditioned by the influence of edge effects, appearing in the LIM, and also by the great variety of the motors’ constructive executions. To take into account the above mentioned peculiarities of TLIMs, the calculation method of its electromagnetic field and integral characteristics was developed based on the usage of presentation about anisotropic media. This calculation method allows getting comparatively simple solutions available for engineering calculations.

The distribution of electromagnetic field in the TLIMs because of the complex geometric configuration of the motor, and the presence of slots on the inductor and on the secondary body as well, is extremely difficult. Because of irregularity of electric and magnetic peculiarities of the TLIMs in axis, the saturation of the motor’s ferromagnetic materials influences greatly on the character of magnetic field. If magnetic fields of the flat LIMs are described in aspects of exponential functions [3], then the fields of the TLIMs are more complex and are defined more often by means of sums of special cylindrical functions of Bessel.

To get enough simple calculation correlations, describe the field of the TLIM, it is necessary to define the exact ideal task which allows considerably simplify mathematic correlations without distorting the main physical processes in the motor. In this case, the real motor is usually substituted by the simplified electromagnetic calculating model. While investigating the distribution of electromagnetic field of the TLIM, it is expedient to use calculation model which was offered and described in [4] and it is introduced in Figure 3. This calculation model was used for design of some of the motors described above.

This report specifically provides the results of the single-phase TLIMs elaboration for the high voltage switches drives with usage for its power supply inexpensive single-phase transformers, for example, of the ‘OM’ - type transformers (in Russian: ‘OM’-type means: single-phase-‘O’, oil-cooled-
‘M’, power transformer with natural circulation of oil and air) and, for example, of the ‘NOL’-type transformers (in Russian: ‘HOJ’ mean the inductive voltage power transformers of the ‘NOL’-type, single phase, cast resin, size 08-10.05.1) or their equivalents, being fed from the networks of 6.3 or 10 kV in the short-term overload mode (at the time of tripping power lines). This allows us to significantly simplify the construction and reduce the cost of complete package of linear actuators for different purposes and, in particular, for switching devices.

The common single-phase oil transformers of the ‘OM’-series (with a power capacity of 1.25-4.0 kVA, with the High Voltage/Low Voltage -HV/LV-of 10; 6.3/0.23 kV, frequency of 50 Hz), are mainly intended to supply power to the rail-road locking equipment and electrical power centralized control. A scheme and windings’ connection group of the transformers is a star and 1/1-0. They have a different climate design for outdoor and for indoor installation with the ambient temperatures from minus 50°C to plus 45°C. The transformers are manufactured as leak-tight items due to valves in a body design, and they have a special bracket for installation at the power line supports.

The inductive voltage transformers ‘NOL 08-10.05.1’-type (single phased, cast resin) are designed to supply power to instruments and vacuum circuit breaker actuators of the ‘HVTP’-type (‘High-Voltage Three-Pole’ actuator), and also for installation in mining electrical switchgears with the voltage of 10 kV for the underground potash mines networks. Theirs data: voltages of the HV/LV windings are of 10/0.1; 0.127 kV; the power capacity is of 630 VA or more; the frequency is of 50 Hz; the scheme and winding connection group is the star of 1/1-0. The windings and magnetic circuit are encapsulated in the epoxy resin to form a robust monolithic block which includes threaded sleeves for the transformer erection at the installation site.

Our calculation model of a tubular linear induction motor is shown in Figure 3. This model was being used for the TLIMs’ design.

![Figure 3](image-url)

Figure 3. The calculation model of a tubular linear induction motor:
1- a zone of the surrounding air;
2- a zone of the frame and inductor’s core;
3- a zone of the slots and teeth structure of an inductor;
4- a zone of the inner case of an inductor;
5- a zone of the air gap between inductor and working body;
6- a zone of the working body’s cover;
7- a zone of the slots and teeth structure of a working body;
8- a zone of an inner working body’s core.
To verify the single-phase capacitor’s TLIMs efficiency to be used for high voltage power disconnector, TLIM was supplied from the limited power source, namely OM-type transformer (single-phase oil transformer with natural circulation of oil and air). We used one of the tubular single-phase linear motor with length and diameter of respectively 256 mm and 72 mm. The motors had a variety of combined working bodies: copper-plated secondary ferromagnetic element; secondary ferromagnetic element with the ‘twisted’ (rolled up or ring-shaped) squirrel cage in a ferromagnetic array, etc. All elements had the outer diameter of 20 mm. During the process of an experiment, in the laboratory conditions we measured pulling force (F), currents in the both phases of the two-phase winding (I_A, I_B); total motor power capacity (P_w) at different supply voltage \( U_T \). These phases’ relationships are shown in Figures 4, 5.

**Figure 4.** The linear motor’s and the feeding transformer’s characteristics:

\( (-) \) – the motor’s characteristics; \( (---) \) – the transformer’s approximate external inversed characteristic.

**Figure 5.** The windings current of the linear motor with different secondary elements:

\( (-) \) — a secondary element with a combined layer; \( (--) \) — a secondary element with a total cooper layer.
However, these dependencies were applicable when power to the motor was supplied from a stationary source of considerable power, and they gave no answer to the question of what parameters will have the motor when it is powered from a source of limited power - low-power transformer, for example, OM-type transformer. Therefore, graphs of experimental dependencies \( F, I_w = f(U_T) \) were subjected to application of the calculated "upside-down" external volt-ampere curve \( I_T = f(U_T) \) (see Figure 4) of OM-type transformer, being calculated according to the recommendations of the monograph [7].

The intersection points of this external curve with the curves \( F, I_w, T = f(U_T) \) allow us to determine the real value of the pulling force and the power consumption of the motor in the ‘motor - power supply transformer’ system, during a significant short-term transformer overload.

The resulting graph-analytical calculation values of the force and of the motor’s current comply with the specifications for high-voltage loading switch.

Practical testing of the system of ‘linear motor - transformer power supply with the limited power’ at the existing facility proved its good performances and compliance of the calculated and experimental data with an accuracy of about 5%.

Based on the proposed methodology of graph-analytical determination of pulling force and current of linear induction motors we also investigated the possibility of single-phase LIM to be powered from a group of transformers of NOL– type which were connected in parallel to keep the overload mode.

4. Conclusion
The work we did, at the first step clearly shows the ability to power the linear actuators on the basis of LIMs from the high-voltage power lines through individual low-power step-down transformers in the short term overload mode.

In summary, we can say that the graph-analytical motors parameters determination methodology, developed during this work, is useful for practical engineering calculations and it is to be put to a number of uses, in particular of LIMs application in the short-term modes.

In accordance with the foregoing, the author is ready to consider the proposals which are concerned about the development of similar linear electric drives for the different systems which are similar in design for the installations described above.

There is a possibility of trade, on the principle of "as is", of already developed installations with nonconventional electric machines of different movement (for example, with motors for Linear Electric Drives, or for Rotational Electric Drives, or for Disk Drives, or for Electric Rotationally Oscillatory Drives, etc.) with open or close magnetic circuit. A brief description of these motors for Electric Drives of some systems and installations is presented in [1-6].

For those, who are interested in more detailed information concerning the theory and practice of LIMs, the author can offer English or Russian versions of the lecture’s course of 8-16 hours [8], lecturer: Dr. Vasiliy TIUNOV, Certified International Engineering Educator (ING-PAED IGIP, Register: RUS-35). The illustrative material of the course is contained in more than 600 slides for presentation, which might be very helpful for engineers and research workers, for organizations of the staff development, postgraduates’ and students’ study. The course or its fragments were presented and received a high appreciation in Russia, in Austria, in China, in Spain, and in the USA (in four universities of California and at the meeting of Los Angeles Chapter of IEEE Industry Application Society) during the author’s lecturing and presentations in the USA.

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