BIOSCIENCES BIOTECHNOLOGY RESEARCH ASIA, September 2015. Vol. **12**(Spl. Edn. 2), p. 409-418

Linear Alternator with Reciprocating Mover: Review of Designs and Machine Types

Vladimir Yakovlevich Gecha[1], Vladimir Ivanovich Goncharov[1], Vasiliy Germanovich Chirkin[1], Sergey Vladimirovich Shirinskii[1] and Dmitry Anatolyavich Petrichenko[2]

[1]National Research University "Moscow Power Engineering Institute"111250, Russia, Moscow, Krasnokazarmennaya str, 14.
[2]Moscow State University of Mechanical Engineering (MAMI), 107023, Russia, Moscow, B. Semenovskaya str., 38.

doi: http://dx.doi.org/10.13005/bbra/2218

(Received: 01 May 2015; accepted: 06 August 2015)

Linear motors and alternators with reciprocating mover are theoretically known for a long time, but in last 10-15 years one can find several new practical applications of such machines, which are actively discussed in research papers. Such applications are as follows: direct-drive wave energy conversion, active suspension system for damping car oscillations and also embedded linear electric machines in external combustion engines (Stirling engine) and internal combustion engines with freepiston. The latter application utilizes linear electric machines in both generator mode for supplying electric power to battery and drive mode for piston motion control. At that, modern arrangements use different types and designs of linear electric machines, which are the main subject of current review.

Key words: Linear alternator, Linear electric machine, Linear permanent magnet machine.

Linear electric machine types

Almost any type of electric machine can be used as a linear motor or alternator. Only commutator electric machine is not used there due to its obvious disadvantage of brush-collector unit, but all advantages of such type of machine are realized by brushless DC machines.

PhD thesis of Samuel Chevailler (Chevailler 2006)contains a very good selection of linear electric machines of different types. Analytical analysis of different type linear electric alternators are presented in the paper of Henk Polinder *et al*.(Polinder, *et al*. 2005). Another thesis of I.A.Ivanova (Ivanova 2006) presents deep investigation of submersible linear generator with permanent magnets.

The most widely used type of linear machine is**synchronous machine with permanent magnets**. It has armature winding located at stator frame and inductor with permanent magnets located at mover. Inductor magnetic system may use different configurations of permanent magnets including surface mounted magnets with the longitudinal magnetization or transverse magnetization and so called Halbach array. Armature may have iron core with teeth and slots where armature winding is located or may have slotless design

Fig. 1 and Fig. 2 presents synchronous machine mover with permanent magnets having transverse and longitudinal magnetization correspondingly. In any case, such mover must contain iron core, which is used for magnetic flux

* To whom all correspondence should be addressed.

circuiting. In first case mover has iron yoke with permanent magnets on its surface. In second case permanent magnets and iron poles alternates in longitudinal direction.Here iron poles serve as a magnetic flux concentrators. In (Seungho and Won-jong 2009)authors use combination of twin magnets with longitudinal magnetization on a mover.

At that linear electric machine may have flat or cylindrical design, movers may be single-side or double-sided. All these features will be described later. In fact, it has no influence on operating principle of synchronous machine.

Fig. 3 presents mover design with permanent magnets of various magnetization forming magnetic array with variable magnetization. Initially Halbach decided to create an array that provides sinusoidal form of air-gap flux-density curve. Such an array must have permanent magnets with slightly changing magnetization. Nowadays one can see mostly pseudo-Halbach arrays, which contains permanent magnets with only longitudinal and transverse magnetization without intermediate magnetization directions. Such magnetic arrays can't form correct sinusoid, but its air-gap flux-density curve is much closer to sine wave than can be obtained from any combination of permanent magnets with only transverse or longitudinal magnetization.

Besides correct shape of flux-density curve Halbach arrays have two more advantages, in which many researchers are interested. First, air-gap flux-density amplitude can be obtained even higher then with iron flux concentrators. Second, such inductor needs no iron yoke to be used for magnetic flux circuiting. Sure, material of permanent magnets is too brittle to transfer significant mechanical loads, so permanent magnets of such array must be installed at bearing pad, but the latter could be made of the material that is more lightweightrather than iron.

The main disadvantage of Halbach array is its high cost. Therefore, in case of synchronous machines with permanent magnets one should consider different mover designs while taking into account air-gap flux-density amplitude, total flux per pole and total mass of mover and cost of permanent magnets.

Stator of synchronous machine with permanent magnets on mover may have one of two designs: besides conventional slotted iron core with coils of single- or multi-phase winding located in the slots one can consider slotless stator design.

Fig. 4shows such electric machine design with slotless stator. In that case, armature winding has the same design, but its coils are located on the inner surface of yoke while this yoke is used not only for magnetic flux circuiting but also for mounting coils inside stator.In this case, the flux of permanent magnets is linked with coils of armature winding through increased non-magnetic gap and stator yoke almost in the same way as for conventional slotted stator (fig. 5. Modern permanent magnets are able to achieve the desired values of magnetic flux in electric machines with significantly increased non-magnetic gaps, so the operating principle and operating condition of electric machine does not change. It can be achieved at the expense of increased volume and cost of permanent magnets.

Electric machines with slotted stator demonstrate low cogging torque due to low harmonic content in the air-gap, and absence of magnetic attraction forces between mover and

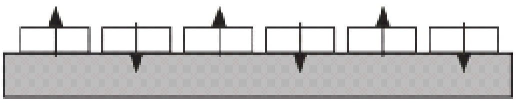

Fig. 1. Mover with permanent magnets with transverse magnetization.

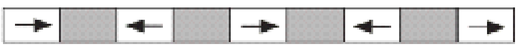

Fig. 2. Mover with permanent magnets with longitudinal magnetization.

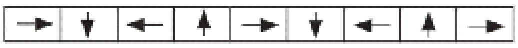

Fig. 3. Mover with pseudo-Halbach array of permanent magnets.

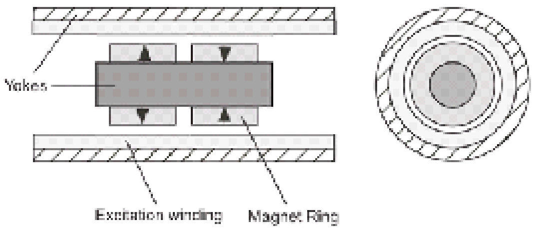

Fig. 4. Linear cylindrical machine with slotless stator design.

stator. Low volume of iron leads to low iron losses, which yields in increased efficiency of electromechanical transducer. However, increased armature current (due to increased non-magnetic gap) and correspondingly increased coper losses may compensate the total increase of efficiency.

In most cases, authors prefer to use conventional stator design with slotted core. It provides higher specific power and lower dimensions of electric machine and allows decreasing permanent magnets volume that leads to lower mover mass and total cost decrease. Significant cogging torque in slotted core machine may limit use of such conventional design in some specific applications, while significant magnetic attractive forces urge to pay more attention to mover bearings. Such magnetic attraction forces can be compensated in double-sided machine with single mover and two stators or in a cylindrical design of linear machine with accurate alignment of stator and mover. Generally, conventional slotted stator allows creating linear electromechanical transducer with higher efficiency than slotless design. Such design was used in free-piston Stirling space convertor, presented in (Brandhorst and Chapman 2008).

Transverse flux machineis of great interest in last decade. Mueller M.A. in (Mueller 2002) proves that such machines may demonstrate higher installed power than other types of electric machines. In paper (Shek, Macpherson and Mueller 2006) mathematical model of linear transverse flux machine is used for control algorithm simulation. Conventional electric machines demonstrate longitudinal spread of magnetic field – it means that magnetic field circuits in a plane parallel to movement direction. For linear machine it means exactly longitudinal field (along mover path), in rotating machines magnetic field circuits in cross-sectional plane, again along rotor movement.

In a transverse flux machine magnetic flux circuits in a plane orthogonal to the movement direction. Analysis of transverse flux machines can't be reduced to a 2-dimensional field analysis in any cross-section because its actual magnetic field in an active part of machine is significantly 3-dimensional (Fig. 6). Such machine design was first time suggested more than 100 years ago (patent of W.M. Morday in 1985), but it become attractive nowadays due to new high-coercive permanent magnets.

Fig. 7 presents an example of a contemporary design of transverse flux machine that uses array of permanent magnets and flux concentrators located on a mover and 2-sider armature with a simple voice-coil winding.

Here stator contains coils and U-shaped cores on both sides of mover. Mover in its turn consists of two rows of permanent magnets and flux concentrators with a structural material between them. The presented design with moving magnets and stationary windings has mover length greater than stator length. Therefore, some part of expensive active materials are out of use. That's why another design seems to be more desirable in which both windings and permanent magnets makes stationary part and only iron cores are moving (Fig. 8).

Machine presented at Fig. 8 is also 2-sided, but it has 2 movers with iron cores located at both sides of stator structure. Such design is considered in the paper (Polinder, *et al*. 2005).The

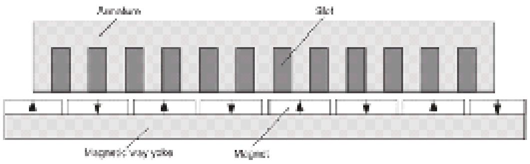

Fig. 5. Linear electric machine with conventional slotted stator core.

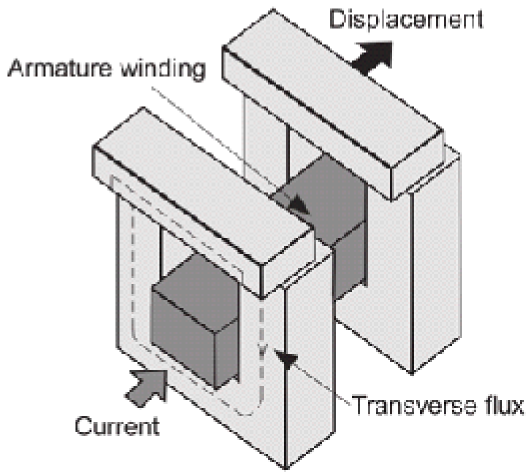

Fig. 6. Linear transverse flux machine.

authors call this design a Double-sided transverse flux machine with moving cores. Comparing to previous design here structural material between two rows of permanent magnets is replaced by voice-coil. Both coil and magnets stay stationary, while U-shaped cores get simple bar shape because now it does not have to embrace coil but serve as a yoke on a mover.

Induction motorseems to be the most familiar design that is used as a linear motor more than 50 years. Example of linear induction motor design presented at Fig. 9 is very simple and robust so it always attracts designers. Mover is made of an aluminum or copper bus or contains slotted iron core with cast winding like "squirrel cage". The latter design is more difficult for manufacturing but it provides better performance of the whole linear motor.

Unfortunately, asynchronous machine has limited use as a electric generator due to the lack of magnetic field source. Asynchronous generator for self-exciting must obtain reactive power from external electric grid or additional capacitors. Another problem is maintaining minimal air-gap between stator and mover. Comparing to synchronous machines with permanent magnets asynchronous machines have to consume more electric power in order to develop the same traction force. In practice, linear asynchronous machines are never used in generator mode. However, there are many examples of linear induction motors like 12 MW linear motor with stator 425 meters long described in the article (Korkmaz, Topaloglu and Gurbuz 2014). This motor was designed for the catapult that launches aircraft from carrier.

Linear reluctance machine is another type of simple and robust machine that is considered now in practice. Unlike other types of electric machines, reluctance machine creates traction force due to variable permeability between stator and mover that both use salient poles on its surface (Fig. 10).

Reluctance machine has simple and robust mover, which contains only iron core with salient poles (or tooth with open slots between them).Stator with slotted core contains multi-phase winding that produce moving magnetic field. Unfortunately, reluctance machine has worse

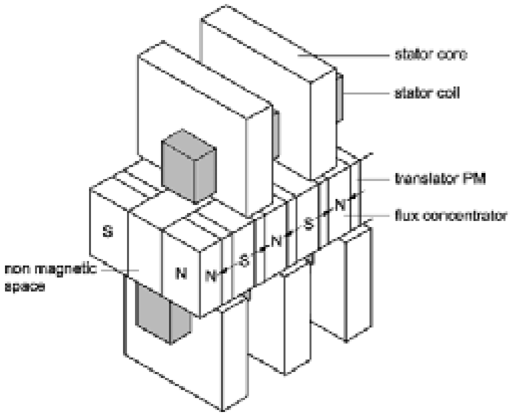

Fig. 7. Transverse flux machine with permanent magnets on a mover.

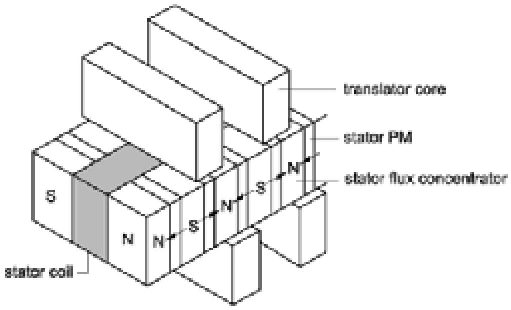

Fig. 8. Transverse flux machine with stationary magnets.

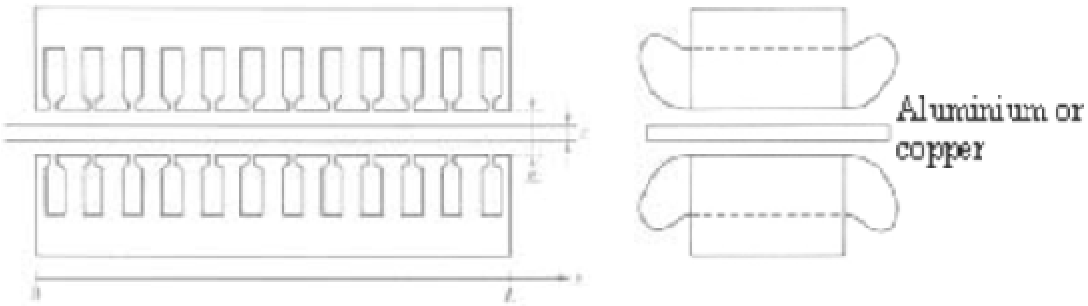

Fig. 9. Double-sided linear induction motor.

energy performance than synchronous machine with permanent magnets. It has rather low efficiency and high responsiveness to the value and uniformity of an air-gap. Besides reluctance machine can't be easily switched from motor mode to generator mode and back.Nevertheless, its simplicity urges designers to consider this type of machine as a real candidate for electromechanical transducer with reciprocating mover.

Switched reluctance machines also should be mentioned here because this type of machines became popular in last 20-30 years due to the simplicity and robustness of its electromechanical part, high-energy performance and good regulation possibilities. Its general design is similar to reluctance machine, but they need special power supply system for its operation. Fig. 11 shows an example of a flat single-side switched reluctance machine.

Fundamentals of flat switched reluctance machine design are presented in the paper of Rymsha V.V. (Rymsha 2003). Like all electric machines this switched reluctance drive is reversible, i.e. it can work in generator mode. However, we did not find publications with any example of linear generator based on switched reluctance machine.

Designs of linear electric machines with reciprocating mover

In the first part, we described different types of electric machines that are used now as direct drive linear motors and generatorswhatever particular design it use. In the second part, we focus on a possible design concept of machine that could be applied to practically any type of machine.

Different design concepts of linear electric machines are discussed in many technical papers, for instance in (Ferrari and Friedrich 2012). The number of such concepts is small, its advantages and disadvantages are well known, which allows making an optimal choice of design concept for each certain application area.Very clear conclusions are made by V.I. Dukhanin in (Dukhanin 2010).

First of all, linear electric machine may have short mover or short stator (Fig12).

Obviously, the full length of linear electric machine with reciprocating mover is the sum of shorter active part length (stator or mover) and piston stroke. The optimal design has the full length equal to twice piston stroke. Design with short

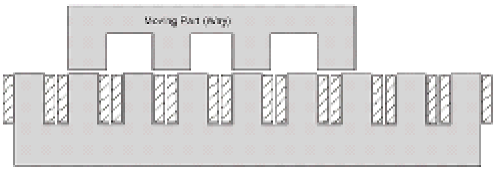

Fig.10. Linear reluctance machine.

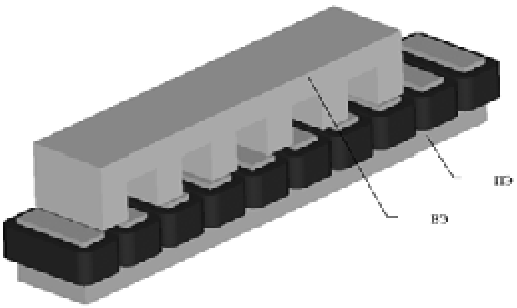

Fig.11. Electromechanical part of switched reluctance machine.

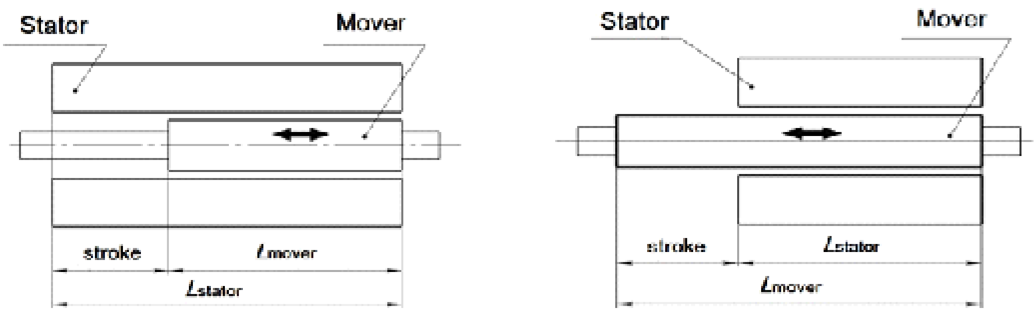

Fig. 12. Layout options with different length of mover and stator.

mover provides low mover mass, but increased mass of copper in stator windingwhich leads to increased cost of the whole machine. Design with long mover in spite of increased mover mass demonstrates higher specific productivity. For a free-piston engine, one of basic considerations is high mechanical stiffness of moving parts.That is why, designers of free-piston linear generator prefer to use the design with short mover that provides high stiffness of the whole piston.

Linear machine could have cylindrical design (sometimes it is called "tubular") or flat design – single- or double-sided. Flat machines are considered to demonstrate less productivity due to increased leakage fields in end turns region and edge effect. Besides flat design creates problems while connecting flat generator with free-piston engine having tubular shape. Some companies produce flat linear electric machines, so they can be used in labs for prototyping and research of various engines.

Another alternative layout concerns location of electric coils and permanent magnets at mover or at stationary part of machine (Fig. 13).

Movable electric coils require moving current collector consisting of brushes with conducting stripes or flexible conductors, which connect moving coils with stator. Such layout seems to be unacceptable due to its unreliability. Even flexible conductors integrity is under risk when mover reciprocates at frequencies 20-50 Hz with stroke 20-200 mm.

However, location of permanent magnets at mover is not the only choice. It is possible to make mover without any active materials, just provide salient poles in its core (Fig. 14).

One of advantages of layouts presented at Fig. 14 is an absence of active materials on moving part, which experience high acceleration; another advantage is decreased mover mass, which is highly desirable under mechanical considerations.

Design concepts at Fig. 14can be implemented in reluctance machine and inductor machine types, which were described above.

While considering armature winding design we see that usually multi-phase distributed winding is used with the number of phase usually equal to 3. The only exception was made in generator for Stirling engine, which used single-phase concentrated winding.

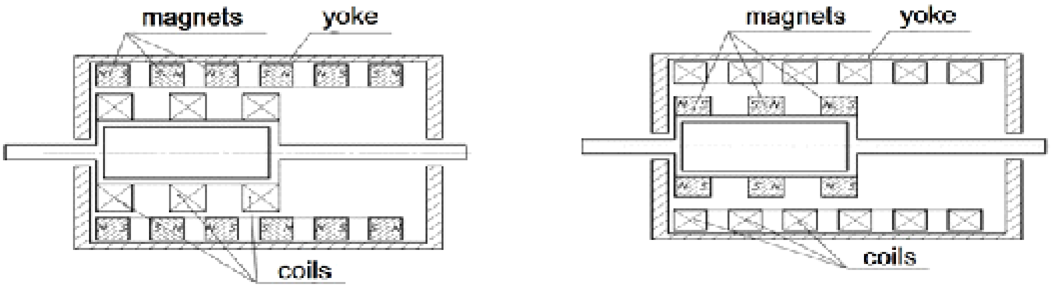

Fig.13. Layout options for coils and magnets location.

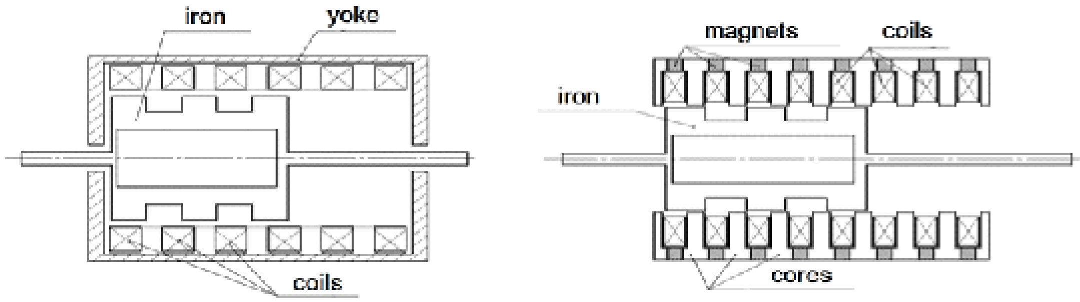

Fig. 14. Design concepts with passive mover.

Armature winding coils may be located in the core slots that leads to increased flux-linkage and contribute to lower volume of permanent magnets.However, some generator designs consider slotless stator, which allows lightening stator and decreasing iron losses, i.e. increase general efficiency. Such generator design is described by Cheng-Tsung Liu *et al*. in paper (Liu, *et al*. 2011).The main reason to exclude iron tooth in this design is the elimination of the iron losses. Besides, authors note that modern high-coercive magnets can provide desirable level of flux density even in totally ironless stator design. The above-mentioned paper is devoted to multi-factor optimization of linear generator and contains experimental proof of results achieved.

While using conventional slotted stator core one may select one of several layouts of stator core. First of all, it's impossible to produce cylindrical iron core with longitudinal lamination. So such laminated cores are made of several quasi-sectors. In fact, each core has a rectangular shape and all longitudinal cores contact each other at internal stator diameter. Fig. 15presents two iron core layouts with 6 and 8 core pieces.

Selected core layout must be taken into account while analyzing real flux density in the core because air-gap magnetic field can be considered as axisymmetric, while stator core is not really axisymmetric.

Another consideration that comes from 3-D nature of cylindrical linear machine is an ability to assemble stator and locate coils in the slots of cylindrical shape. Usually designers prefer to use semi-closed slots in order to minimize air-gap permeance variations along mover path and correspondingly minimize traction force variations. However, one cannot put coils in semi-closed slots of cylindrical shape. In that case, stator core must be assembled from separate modules which longitudinal dimension corresponds to one teeth pitch. Each module must be alternated with coil in corresponding slot (Fig. 16). This leads to additional design and technological study. Similar design was used in cylindrical linear alternator for hybrid electric vehicle presented in (Huang 2012).

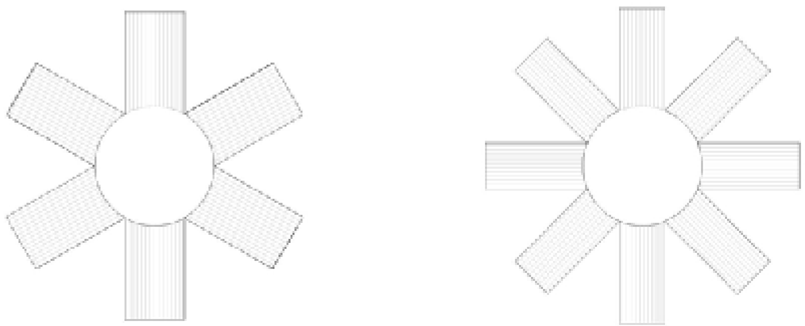

Fig. 15. Stator core cross section of cylindrical linear electric machine.

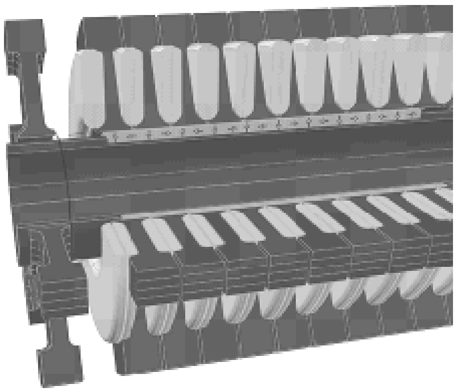

Fig. 16. Assembling stator core of cylindrical linear electric machine.

In the first part, we have mentioned different variants of mover design with installed permanent magnets. It could be surface mounted magnets with radial (transverse) magnetization located at iron yoke or embedded magnets with longitudinal magnetization located between iron flux concentrators or Halbach arrays of permanent magnets, which provide ironless mover with desirable flux-density distribution in the air-gap. The problems of optimal design of mover for cylindrical linear motor are considered in several papers, for instance (Bianchi, *et al*. 2003), (Akhondi and Milimonfared 2009), (Yasser Abdel-Rady and Milimonfared 2010),an example of linear motor design with testing facilities is described in article (Hong, *et al*. 2007), another example can be found in (Wang, Jewell and Howe 1999).

It is interesting to note, that no article describes design of semiconducting rectifier though many authors mention that multi-phase winding is connected to electrical load through rectifier. One can suppose that usually 3-phase generator winding is connected to conventional bridge rectifier. In case of implementation of the sophisticated control methods, electric machine is connected to the DC bus via reversible active bridge inverter (rectifier). An example of such control algorithm is described in the article(Vese and Radulescu 2010).Particularly, it concerns linear actuator with 2-phase stator winding.

Another note should concern the fact that almost all researchers prefer to use rare-earth permanent magnets NdFeB. This type of magnets is usually characterized by outstanding magnetic properties but rather low operating temperature. While linear alternator may be combined with engine which leads to increased temperatures. The reason of that choice is the availability of new materials that are characterized by much higher operating temperatures. For example, look at product list of Chinese company SINE Magnetic Products(Ningbo Sine Industrial Company Limited 2015).In2014,it was able to provide customers NdFeB magnets with operating temperatures 150°C, 180°C, 200°C and even 230°C.

CONCLUSIONS

The authors of all abovementioned papers who develop linear electric machines for motor and generator modes of operation in most cases use cylindrical linear machine with multi-phase distributed winding at stator core and permanent magnets at short mover.

Usually authors use conventional distributed winding with unit value of slots per phase per pole$q$=1 (single- or double-layer) with 6 tooth pitches per pole period. Sometimes stator winding has$q$=0,5. Such winding allows using only 3 tooth pitches per period, i.e. use rather wide stator tooth. Such machines can avoid problems with high saturation of stator tooth and high current density in stator coils. But armature winding with q=0,5 has very low value of winding factor that leads to the necessity to increase total slot current. The latter leads to increased current density and sophisticated cooling system.

Slotless stator design seems to be very perspective for some authors. Such stator arrangement use conventional armature winding, but high-coercive magnets allow avoiding iron tooth in this arrangement while preserving desired value of phase flux-linkage. In any case, the main reason to use slotless stator design is to improve flux-density curve shape and decrease cogging force. This aspect could be of very high importance for linear motor project, but not so important for generator mode of operation.

The most typical mover of linear electric machine contains permanent magnets that allow avoidingthe use of the sliding contacts and allows providing desirable value of air-gap flux density. At that, different authors use different configurations of permanent magnets. Multi-pole mover with permanent magnets is often implemented by quasi-Halbach arrays. However, other author prefer using more conventional layouts with longitudinally magnetised permanent magnets altering with iron poles (which work as a magnetic flux concentrators). Some authors use very simple layout with radially (transverse) magnetized permanent magnets located on iron yoke surface. However, in this case iron yoke significantly increase mover mass that is undesirable from mechanical point of view.

Some authors note potential advantage of transverse flux electric machine. Such machine types are in demand for low-speed multi-pole motors or for linear motors and generators. While the whole machine consists of a number of similar modules it can easily be located on a circular arc or on line.Thus, such design is practically the same for rotational and reciprocating movement. While the use of modern high-coercive permanent magnets allows obtaining high values of power density in such machine.Unfortunately, we saw only theoretical papers that consider transverse flux machines. Moreover,the corresponding publications have no information about experimental proof of expected high performance of such machines. At the same time we know the examples of transverse flux machines that are practically built for high power ship low-speed rotating motor.

Inductor machine with linear layout (like hybrid linear Vernie machine) may be interesting due to its design simplicity and low costs – its mover has no permanent magnets or field windings, only iron core with slotted surface, and stator may contain only concentrated winding.However, authors of the corresponding papers agree that the inductor machine loses itself comparing to the other types of electric machines due to high total mass ofactive materials and poor energy performance.

There is almost no information concerning power electronics, which is necessary to connect linear reciprocating generator to DC load or to supply multi-phase stator winding from an on-board DC power system, in papers. However, one can notice at figuresin these papers the conventional bridge active rectifier or inverter. More attention is paid to algorithms for controlling linear motor by active inverter.

The present article was written under the Agreement on subvention No.14.577.21.0120 (unique identifier of the applied research RFMEFI57714X0120) with the financial support of the Ministry of Education and Science of Russian Federation.The research was heldat Moscow State University of Mechanical Engineering (MAMI) and National Research University "Moscow Power Engineering Institute".

REFERENCES

1. Akhondi, Hamidreza, and Jafar Milimonfared. "Design and Optimization of Tubular Permanent Magnet Linear Motor for Electric Power Steering System." *Journal of Asian Electric Vehicles*, 2009; **7**(2).
2. Bianchi, Nicola, Silverio Bolognani, Dario Dalla Corte, and Francesco Tonel. "Tubular Linear Permanent Magnet Motors: An Overall Comparison." *IEEE Transactions On Industry Applications*, 2003; **39**(2).
3. Brandhorst, Henry W. Jr., and Peter A. Jr. Chapman. "New 5kW free-piston Stirling space convertor developments.", 2008; **63**: 342-347.
4. Chevailler, Samuel. *Comparative study and selection criteria of linear motors. PhD.* Lausanne: Ecole Polytechnique Federale de Lausanne, 2006.
5. Dukhanin, V.I. "Automotive alternator with reciprocating movement. Design analysis." 2010.
6. Ferrari, Cornelius, and Horst E. Friedrich. "Development of a Free-Piston Linear Generator for use in an Extended-Range Electric Vehicle." *EVS26 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium.* Los Angeles, California, 2012.
7. Hong, Sun-Ki, Jae-Won Lim, Hyo-Jae Lim, Ho-Yong Choi, and Hyun-Kyo Jung. "Analysis of Tubular-type Linear Generator for Free-Piston Engine." International conference on renewable energies and power quality, 2007.
8. Huang, L. "An Opposed-Piston Free-Piston Linear Generator Development for HEV." *SAE Technical Paper*, 2012.
9. Ivanova, I.A. *Research and development of PM linear generator for sea waves energy conversion. PhD Thesis.* St. Petersburg, 2006.
10. Korkmaz, F., I. Topaloglu, and R. Gurbuz. "Simulink Model of Vector Controled Linear Induction Motor with End Efect for Electromagnetic Launcher System." *Elektronika Ielektrotechnika*, 2014; **20**(1).
11. Liu, Cheng-Tsung, H N Lin, H C Yeh, and C C Hwang. "Optimal Design of a Direct Driven Slotless Tubular Linear Generator for Renewable Energy Extraction." *(Journal of Physics: Conference Series)* **266** (2011).
12. Mueller, M.A. "Electrical generators for direct drive wave energy converters." *Proc.Inst.Elect.Eng*, 2002; **149**: 446–456.
13. *Ningbo Sine Industrial Company Limited.* 2015. www.sinemagnetic.com (accessed 06 01, 2015).
14. Polinder, Henk, Barrie C. Mecrow, Alan G. Jack, Phillip G. Dickinson, and Markus A. Mueller. "Conventional and TFPM Linear Generators for Direct-Drive Wave Energy Conversion." *IEEE Transactions on energy conversion*, 2005; **20**(2).
15. Rymsha, V.V. "Design of linear switched reluctance motor." *Electrical and Power Engineering*, 2003, Transaction of Donetsk National Technical University ed.
16. Seungho, Lee, and Kim Won-jong. "Active Suspension Control with Direct-Drive Tubular Linear Brushless Permanent-Magnet Motor." *American Control Conference.* St. Louis, MO, USA, 2009.
17. Shek, Jonathan K.H., D. Ewen Macpherson, and Markus A. Mueller. "Control of Linear Electrical Generators for Direct Drive Wave Energy Conversion." *International Conference on Electrical Machines.* 2006.
18. Vese, Ioana-Cornelia, and Mircea M. Radulescu.

"Direct Thrust Control Scheme For A Tubular Linear Brushless Permanent-Magnet Actuator." (Annals of the University of Craiova, Electrical Engineering series), 2010; **34**.

19. Wang, Jiabin, Geraint W. Jewell, and David Howe. "A General Framework for the Analysis and Design of Tubular Linear Permanent Magnet Machines." (*IEEE Transactions on magnetics*), 1999; **35**(3).

20. Yasser Abdel-Rady, Mohamed I., and Jafar Milimonfared. "Optimum Design of Tubular Permanent-Magnet Motors for Thrust Characteristics Improvement by Combined Mahdi Ashabani Taguchi–Neural Network Approach." *Ieee transactions on magnetics*, 2010; **46**(12).