

LINEAR ELECTRIC ACTUATORS AND GENERATORS

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Abstract: Linear electric actuators and generators (LEAGs) are electromagnetic devices which develop directly short-travel progressive (or oscillatory) linear motion. Machine tool sliding tables, pen recorders, and free piston power machines are typical industrial applications for LEAGs. Their recent revival in applications in compressors, pumps, electromagnetic valve actuators, active shock absorbers, vibrators, etc. prompts this review, which presents main LEAGs configurations, their principles of operations, comparative performance evaluation, motion control and existing as well as potential applications.

I. A BRIEF HISTORY

The first linear electric motor was patented in USA more than a century ago. The next important step was in 1937 by Kemper in Germany who proposed a magnetically levitated linear motor propelled vehicle. In 1945, Electropult in the USA developed a few tonnes of thrust by a linear induction motor to assist the take-off of aircraft from aircraft carriers. A period of 10 years (1955-1965) of notable theoretical design and prototyping developments followed with important contributions by Laithwaite and his colleagues in the UK, especially in relation to linear induction motors [1]. The years 1970 through 1980 witnessed extraordinary efforts to develop full-scale people movers propelled by linear induction or synchronous motors with wheeled or magnetic (MAGLEV) suspension, especially in Germany, Japan, USA, Canada, UK and Romania. Currently linear induction motor wheeled vehicle people movers are at work at large international airports such as Chicago, Dallas, Fort-Worth, Atlanta, Toronto, Vancouver, Tokyo and Birmingham. Full-scale 400-500 km/h close to commercial stage Maglevs are undergoing tests in Germany and Japan. They both use linear synchronous motor active guideway propulsion with attraction and superconducting repulsive magnetic suspension.

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Over the years hundreds of papers, a few international conferences and monographs [2-9] have dealt with the topic of linear motors. After 1980, interest in linear motor transportation systems declined to some extent. In contrast, interest in low power controlled linear motors for short travel applications (LEAGs) has increased dramatically. Use of high energy permanent magnets [10], advances in digital control, and the fast acting solenoids are some of the main causes of this new upsurge. In the following we consider LEAGs in terms of basic principles, configurations, performance evaluations, design, control and applications aspects.

II. LINEAR INDUCTION AND SYNCHRONOUS PM ACTUATORS

In principle for every rotary electric machine configuration a linear counter part may be imagined. The mental process of cutting and unrolling an induction motor to obtain a linear induction motor, flat or tubular, (Fig. 1) is by now classic. The same process may be imagined for flat and tubular linear synchronous PM motors.

III. DC BRUSH LINEAR ACTUATORS

The dc brush linear motor is still another alternative [6,11]. The above three basic configurations have advantages and disadvantages similar to their rotary counterparts. We should mention that a mechanical airgap of 0.5 to 1 mm is feasible for travel lengths below a few meters and thus even the linear induction actuator enjoys good performance especially with a cage secondary [12]. Still the linear synchronous PM actuator retains the advantages of higher thrust density and higher efficiency and thus lower loss per thrust density. The linear dc brush motor is plagued by the brush wear, noise and EMI though the speed is low (below 3 m/s) and thus the commutation process itself is less stringent. Control of linear induction and linear synchronous PM actuators for thrust, speed, and position is very similar to that for ac rotary motors. The entire body of knowledge regarding vector control [13] with and without motion sensors may be borrowed and used for linear induction (LIA) and linear synchronous PM actuators (LSPMA). Both sinusoidal and rectangular current control of LSPMA have been proposed. For the linear dc brush actuators (LDCA) various control strategies with dc-dc converters used for rotary dc motors are used. LIAs and LSPMAs are used for progressive linear motion of short travels (up to 2-3 m).

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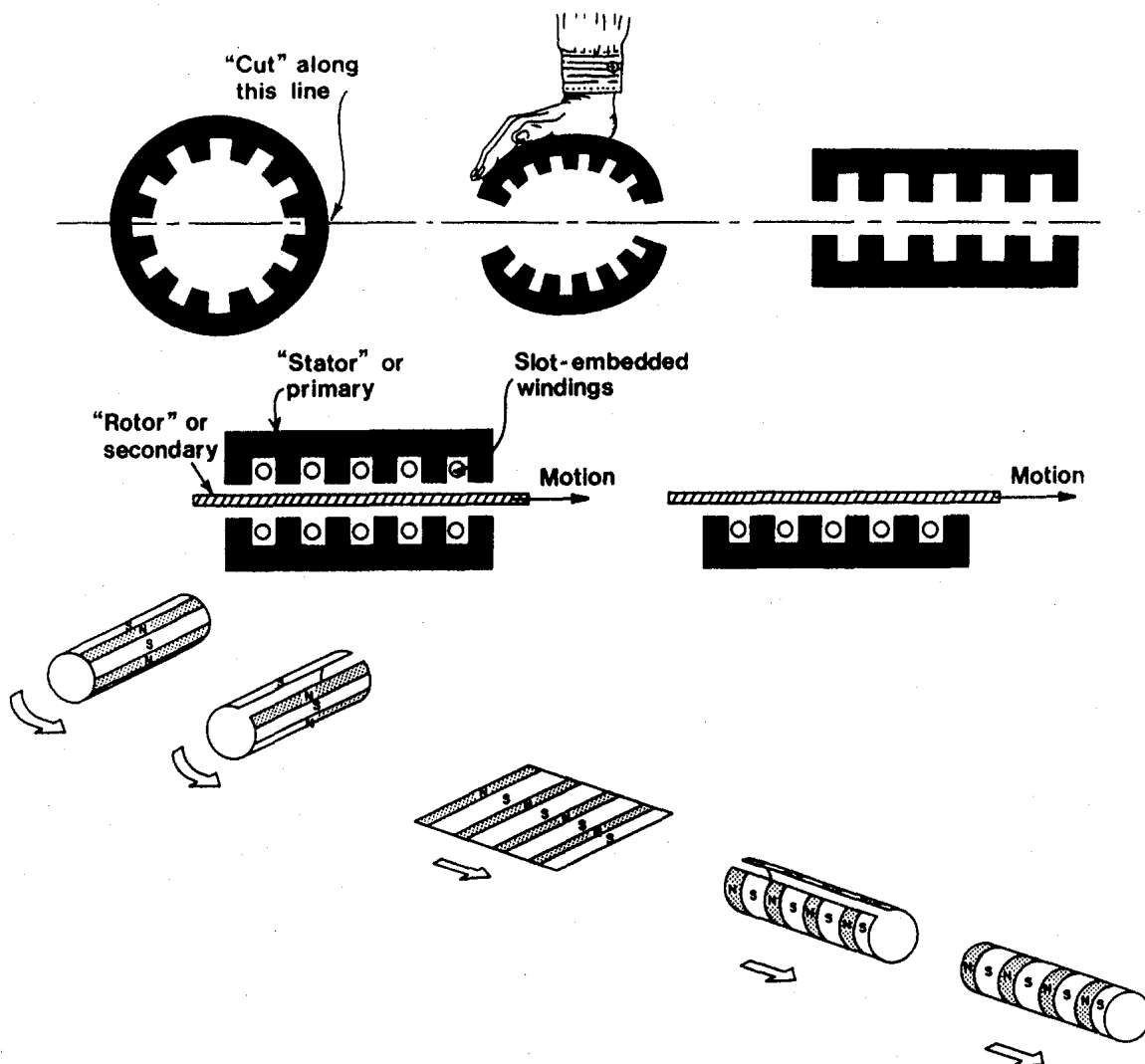


Fig. 1 Flat and tubular linear induction actuators.

In addition to these common linear electric actuators, quite a few new configurations, for precision positioning shorter travel, have also been developed.

IV. MOVING COIL PM ACTUATOR

The moving coil PM linear actuator stems from the loudspeaker principle. The thrust is exerted directly on the coil conductors but the coil inertia (mass) is low and thus with strong PMs, high accelerations are possible, despite a low thrust density. These actuators are suitable for low thrust applications with travels up to 0.4-0.5 m. FEM studies show that the thrust varies with coil position at constant current owing to the PM flux fringing at the travel ends. Also the machine inductance

is high as most of the reaction field travels through iron [15]. Stationary coils placed at travel ends may attenuate the reaction flux linkage thus reducing the machine inductance at the expense of additional losses, weight and cost. The controller is, however, simple.

V. THE SAWYER MOTOR

Another celebrated linear electric actuator is the so-called Sawyer motor. The Sawyer motor is basically a two-phase pulse—PM linear actuator. Both phases work simultaneously with ac current through them. Open loop or closed loop control may be used for positioning. Large inertia of the inductor (mover) leads to limited acceleration. The marginal poles

produce less thrust and normal force than the central poles and thus vibration and noise levels are rather high. Independent control of current in the four coils could solve the problem, but at the price of two additional single phase inverters.

In an effort to improve the performance of Sawyer motor, a new configuration has been proposed [16]. In this case, the normal force at zero current is smaller as the PM flux fringing is large. Also, PM flux concentration is feasible and thus higher thrust density is available (up to 4 N/cm²). For a three-phase configuration a typical sinusoidal indirect current vector control system is used for positioning. Low power factor (0.4-0.5) and good efficiency are characteristic of this configuration.

VI. LINEAR SOLENOID ACTUATORS

Impact excitation ac or dc linear solenoid actuators are best known as electromagnetics and their use spans over all this century [17]. The potential application of linear solenoid actuators to electromagnetic values [17, 18] of thermal engines has produced a new revival of this subject in the research and development community as the required speed of response is so challenging (around 1-2 ms for 0.2-0.4 mm excursions in a repetitive manner).

A basic linear solenoid configuration for electromagnetic valve actuation is shown on Fig. 2.

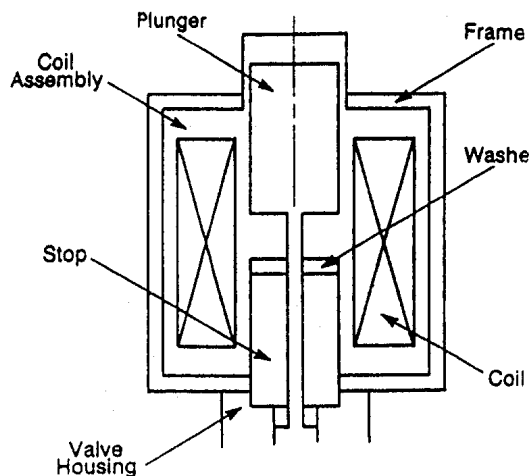


Fig. 2 Tubular synchronous PM actuator.

The plunger is attracted downwards, when the coil is dc fed. A retaining mechanical spring (not shown) brings the plunger backup after the coil is deenergized. Magnetic (variable) saturation and eddy currents induced in the core bodies surrounding the coil and the plunger, make the design methodology very complicated [19]. Whereas magnetic saturation is somewhat beneficial as it increases the magnetic field penetration depth when the coil is dc energized, eddy currents produce a time delay in the flux build-up and thus in the thrust production. Consequently, a motion delay in the

order of milliseconds occurs. Magnetic saturation speeds up the flux penetration in the plunger for the coil turn-on but it does not influence notably the flux decay at the coil turn-off. A resistor in series may be required to reduce the flux decay time to a few milliseconds.

Further on, mechanical, electromagnetic and even thermal models of the linear solenoid actuators are to be considered simultaneously in order to obtain correct information on the plunger motion [20]. Design optimization of fast action solenoids is another formidable task in view of the above interdependence of mechanical, electromagnetic and thermal aspects [20]. Whereas PM devices with double springs have been introduced under the name of solenoids we will deal with such devices under the title of linear oscilloactuators. Controlled airgap solenoids used for controlled suspension for Maglevs [6,9] or magnetic bearings [7] have also been proposed.

VII. LINEAR OSCILLOACTUATORS AND GENERATORS (LOA&Gs)

Linear oscilloactuators and generators (LOA&Gs) are characterized by sustained, rather short (less than 20-30 mm), linear-oscillatory motion of controlled frequency and amplitude. Most high performance LOA&Gs are characterized by: a cylindrical structure; the use of high energy PMs; double action mechanical springs at resonance conditions; and single coil (phase) supplied at fixed controlled frequency.

Linear oscilloactuators and generators belong to one of the following categories: moving coil stator-PM LOA&Gs; moving PM LOA&Gs; and moving-iron stator-PM LOA&Gs. Moving-coil stator-PM LOA&Gs with cylindrical (tubular) structure have been used as vibrators for frequencies up to 2 kHz and thrusts up to a few hundred newtons for motion excursion less than 10-15 mm. A low mover mass yields high frequency oscillation conditions. For higher thrust at a lower frequency some iron is attached to the coil on the mover and multipolar PM structure is adopted [21].

Moving-PM LOA&Gs (Fig. 3) may have axial airgaps [22] or radial airgaps [12, 23, 24]. The mover weight is expected to be low. It has a thrust independent of motion. Care must be exercised in maintaining the PM temperature within safe limits to avoid demagnetization. The PM-iron mover is rugged but its mass is high so the frequency of oscillations is limited to a few Hertz [24]. Finally, stator-PM LOA&Gs are shown in Fig. 4 [26,27]. As all structures are tubular—to make a better use of copper—configurations in Fig. 4 are not easy to build with laminations.

In contrast to the above situation, the configuration in Fig. 5 [26] uses conventional radial laminations and is easy to manufacture while retaining good performance. At 125W, 60 Hz, ± 5 mm motion amplitude efficiencies above 0.83 at force densities of about 1 N/cm² have been demonstrated both in motoring and generating modes. The flux in the coil reverses polarity to increase the copper usage needed so badly with stator PMs. In place of mechanical springs, mechanical flexures are used to store energy at stroke ends and play the role of linear bearings. Free piston compressors for cooler

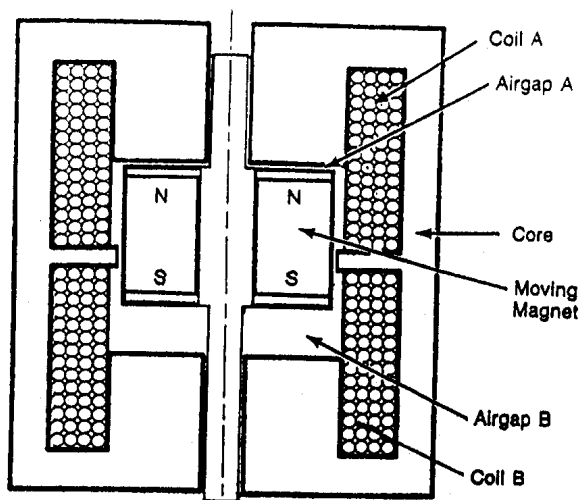


Fig. 3. Moving PM LOA&G.

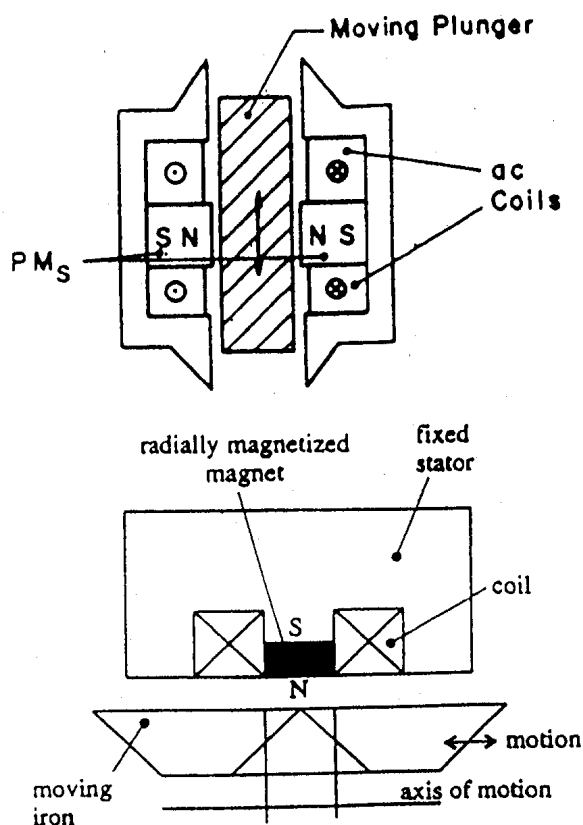


Fig. 4. Stator PM LOA&Gs.

systems are prime applications for these flux-reversal stator-PM LOAs.

VIII. INDUSTRIAL APPLICATIONS ISSUES

Linear electric actuators and oscilloactuators have already found some applications and are fabricated in moderate numbers for machine-tool sliding tables, pen recorders, textile sewing machine, free piston pumps and compressors. They are built in very large numbers as solenoids for a wide range of applications from lifting iron to door-locks. Recently they have been proposed for rope-less elevators, artificial hearts and for electromagnetic valves in thermal engines. Extensive use of high energy PMs has brought the thrust densities and energy conversion ratios to market competitive levels. A similar impact has been made by power electronics and digital nonlinear control. Thus, vigorous research and industrial developments in LEAGs are expected in the near future with an ever wider range of applications.

IX. DESIGN ISSUES

LEAGs are essentially three dimensional electromagnetic devices with linear motion. Magnetic field distribution may be only at times reduced to a two dimensional solution. Most of the time it is 3D. Analytical preliminary design methodologies, most in simplified forms are available in the literature [7, 12, 11, 17, 18]. Also, elaborate FEM analyses of field distribution—2D and lately 3D—have been performed recently in relation to LEAGs. No commercial design software on LEAGs is available to the best of our knowledge. Design optimization attempt on LEAGs have been recently published [12] and they use essentially analytical field (circuit) models with some FEM checks for special (defined) information in the end. In contrast, however, in [29] a direct FEM design optimization search is run for a moving coil LEA, using Rosenbrock's methods. For this simple configuration notable improvements are obtained by direct search 2D FEM optimization within a reasonable amount of time. It seems that FEM method is to be used in the analytical model design optimization only to provide some information at some points while, in the second stage, a direct search FEM optimization methodology is to be used for reasonable computation time and good performance. A FEM linker to analytical design optimization methodologies seems the way to speed-up the FEM use by LEAGs designers.

X. CONCLUSION

This paper presents an overview of linear electric actuator and generator topologies, applications performance and design methodologies. The industrial use of LEAGs is on the rise and new interesting developments are expected in the near future.

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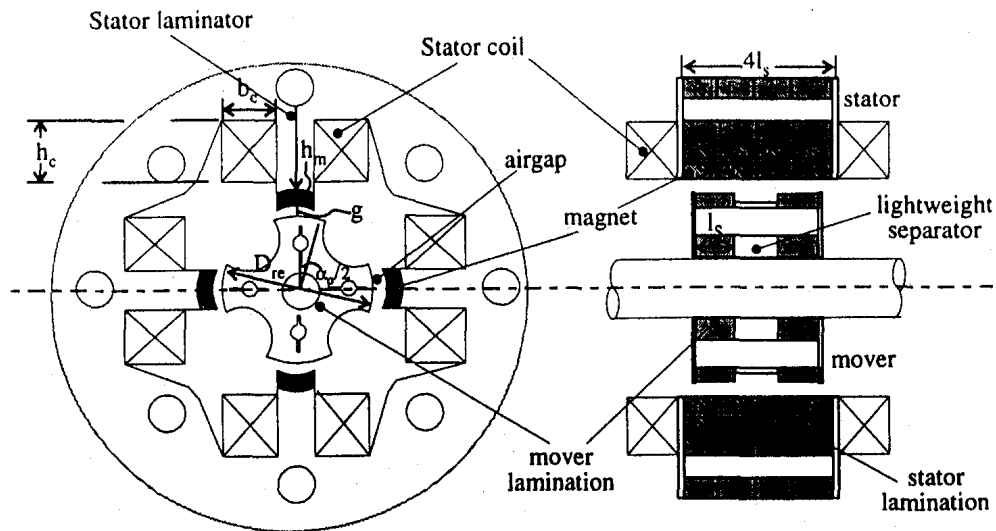


Fig. 5. A novel flux reversal linear alternator.

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BIOGRAPHIES

Ion Boldea (M'77, SM'81, F'96) received M.S. in electrical engineering in 1967 and PhD in electrical machines in 1973, from the University Politehnica of Timisoara, Timisoara, Romania. He has been associated with the University Politehnica of Timisoara since 1968 and is currently a Full Professor of Electrical Engineering. He served as an Associate Dean of Electrical Engineering from 1982 to 1997. He has also repeatedly been a Visiting Professor at the University of Kentucky, Lexington, the University of Manchester Institute of Science and Technology, Manchester, UK, and the University of Glasgow, UK. His scientific work is related to linear and rotary electrical machines and drives. He has authored 11 monographs, published more than 50 papers, and is the holder of 16 Romanian patents. He has also taught intensive courses and delivered special lectures in the US and Europe.

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