Linear-Motion Electrical Machines

E. R. LAITHWAITE, FELLOW, IEEE, AND S. A. NASAR, SENIOR MEMBER, IEEE

Abstract—A survey of linear-motion electrical machines is presented. Although various types of dc and ac linear machines are briefly mentioned, linear induction motors are the main concern of the paper and they are discussed in considerable detail. Based on topological considerations, a classification of these machines is presented and their development through the last 70 years is reviewed. A brief qualitative description of the newly developed hybrid machine is also included. Analysis and design problems, and some solutions, as unique to linear machines are discussed. Several possible applications of these machines are included.

INTRODUCTION

THE great majority of electrical machines are designed to produce rotary motion, thereby exploiting the blessings of circularity which man has enjoyed since the discovery of the wheel. The forces of electromagnetism may, of course, also be employed to produce linear motion, as for example, in a linear induction machine in which the primary member consists of a row of coils carrying currents in phase progression. A simple method of introducing linear machines is that the primary member resembles a conventional rotary machine stator which has been cut by a radial plane and subsequently unrolled, as shown in Fig. 1. A number of different types of linear machines may be developed in this way although, as will be seen later, the linear machine family does not consist only of flat machines which result from such an unrolling process.

It is almost a general principle that when an engineer makes a device in a different size, or of a different shape, or with a new material, he changes the whole operating conditions and the new product may have such different characteristics as to change basically its field of application. In the case of linear electrical machines the effect of linearization is to introduce new phenomena which generally reduce their performance below that of corresponding conventional rotary machines. The history of linear machines tells the story first of the struggle against the factors which detract from performance and of increasing willingness to accept reduced performance for specific applications in which the linear machine offers advantages in other ways.

The changes in operating conditions imposed by changes in shape will first be discussed, using the induction machine to illustrate the processes.

TOPOLOGICAL CONSIDERATIONS

Many characteristics of ac machines and of induction motors in particular, are explained in terms of the concept that the primary member sets up a rotating magnetic field in the airgap. That the splitting and unrolling process is likely to modify the characteristics is evident from the fact that any linearly traveling field must now have a start and a finish. Moreover, it is apparently unnecessary for the primary unit to be designed to have an even number, indeed even an *integral* number of poles.

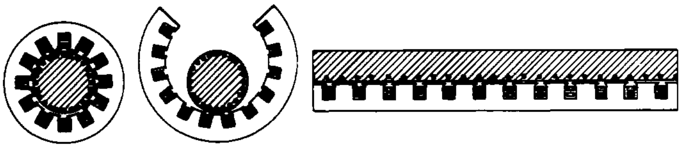

Fig. 1. Imaginary process of unrolling a conventional motor to obtain a linear induction motor.

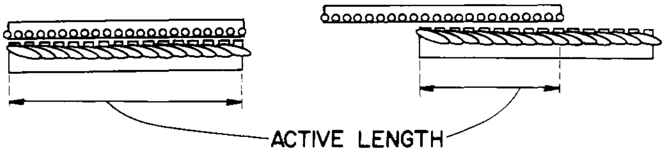

Fig. 2. Active length of primitive form of linear motor is reduced once motion takes place.

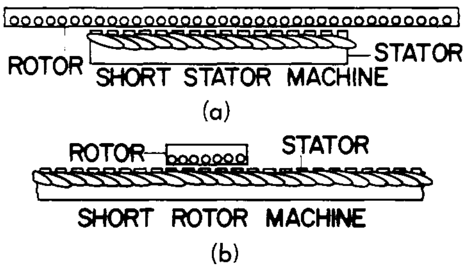

Fig. 3. Basic types of linear motor.

Perhaps even more fundamentally, a linear machine which consisted of an exact copy of the result of mentally "unrolling" a conventional squirrel-cage motor, as shown in Fig. 2, could only be used in a limited number of cases; for to allow the secondary member to move is to lose an ever-increasing amount of the motor as the "cage" emerges at one end, laying primary coils bare at the other. It is clear that where motion over a considerable distance is required with a limited amount of power, either the primary or the secondary member must be elongated.

Such elongation leads at once to two major classes of linear machine which may be designated "short primary" and "short secondary." An example of each is shown in Fig. 3. In general, the short primary is by far the cheaper to build and to run. The secondary member can be simplified in form, often to a simple sheet of conductor and the whole system is only fed with current over a small proportion of its length. In certain situations, however, a compromise arrangement may consist of a long sectionalized primary in which only the sections actually in use are energized.

Manuscript received November 13, 1969. This work was supported in part by the National Science Foundation Grant GK-10989.

E. R. Laithwaite is with the Imperial College of Science and Technology, London, England.

S. A. Nasar is with the University of Kentucky, Lexington, Ky. 40506.

The "Sheet-Rotor Motor"

The arrangements so far described have assumed both members to consist of electrical conductors in slots in a laminated steel core, which is the usual arrangement in a rotary machine. With such a structure, however, there exists, in addition to the tangential electromagnetic thrust which the machine is designed to give, a purely magnetic pull between the oppositely magnetized surfaces. In a cylindrical machine only the out-of-balance pull resulting from any asymmetry which may exist is observable. The fact that even this amount may be sufficient to worry the designer of rotary motors indicates the size of the problem which is introduced by the linearizing process.

Accordingly, double-sided flat machines have been developed in which the secondary conductors are no longer housed in slots but operate in the airgap and the magnetic circuit is closed by a steel block only in the region which is energized. Generally, it is advantageous for this second block to be fitted with a secondary primary winding to assist in driving flux through the secondary conductor. The development of the double-sided motor is illustrated in Fig. 4. In the final stage the secondary member is simplified constructionally in that it consists of a solid sheet of conductor, but even this last change of form serves to modify the operating conditions.

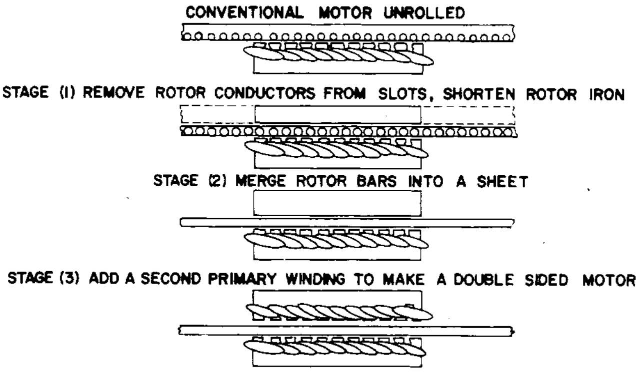

Fig. 4. Development of the "sheet-rotor" motor.

Fig. 5(a) shows a typical current flow pattern in the case of the ladder-type secondary conductor (the linear equivalent of a cage rotor). Bar-to-bar currents may only flow via the end conductors, but in the case of a solid sheet, current flow patterns, as shown in Fig. 5(b), are obtained. The effect of longitudinal currents under the active zone is to reapportion the airgap flux so that a higher density exists along the central regions of the machine than along each side. An analysis of this effect has recently been published [6].

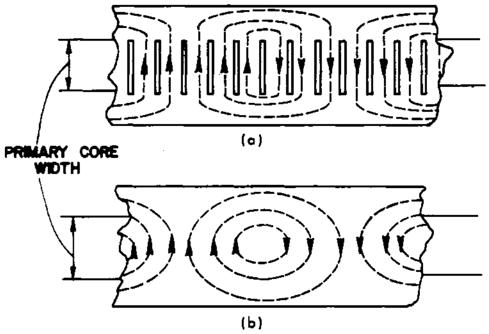

Fig. 5. Current distributions in (a) slitted secondary plate, (b) sheet rotor.

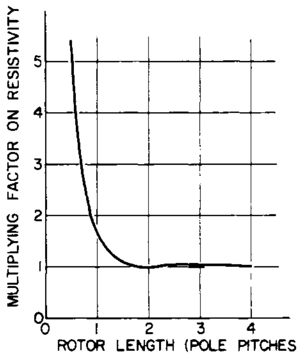

Fig. 6. Effective increase in rotor resistivity due to "short-rotor" effect.

Edge Effects

In addition to the effects of the lateral edges of the primary, further effects, not present in cylindrical machines, occur due to the front and back edges of whichever member is the shorter. In both classes of machine the action of these edges is first to produce standing waves in the magnetic core in addition to the usual traveling component. Second, when relative motion between primary and secondary members occurs, electrical transients are set up by the edges. These "entry" and "exist" edge effects have been analyzed in some detail in earlier publications [3], [12], [25], [35], [37], [59]–[62], [69], and only a summary of these results is included here.

In a short secondary machine, the effect of the transients is hardly noticeable when the length of the secondary is at least 2 pole pitches. For shorter secondaries the effects can generally be represented by an apparent increase in resistivity of the secondary conductor. Fig. 6 shows this increase varies with secondary length in a typical case. In short primary machines the effects are more complex, but the principal features are as follows.

1) The flux distribution along the length of the machine is nonuniform, the distribution varying with speed. In general, the effect is as if the relative motion sweeps the bulk of the flux to the back of the machine.
2) Extra losses, not calculable by conventional machine theory, are incurred in the secondary member in the case of a series-connected machine, and in the primary in the case of parallel connection.
3) The force is not calculable by conventional formulas, being, in general, somewhat lower than for conventional machines. Both this effect and the previous one are noticeably affected by the number of poles along the primary and by the speed: the lower the speed in relation to synchronism and the greater the number of poles, the less the effects.

4) As a consequence of 3). the machines will not run light, as motors, at the indicated synchronous speed. The difference is not marked, except for machines with fewer than 4 poles.

In a conventional machine with cylindrical symmetry the only difference between motors in which primary coils in each phase are connected in series and those in which they are connected in parallel is related to the operating voltage–current ratio, i.e., to the operational impedance of the machine. In linear machines the question of series or parallel connection is a vital one, affecting such questions as the effective use of the material of the electric and magnetic circuits, the efficiency, power factor, etc. This aspect has also been dealt with at length earlier [35], [37]. Generally, it is better to parallel connect a short secondary machine and to series connect a short primary motor. Parallel connection tends to fix the flux distribution at the expense of possible high local current densities or even short-circuit conditions. Series connection insures no local I^2R loss but allows nonuniform flux distributions. A complete duality between electric and magnetic circuits exists for the two types of connection.

Forces Perpendicular to the Driving Direction

Recently, applications have been found for single-sided linear motors in which the secondary may or may not contain ferromagnetic material. Examples are shown in Fig. 7. In this case there exists on the secondary conductor, in addition to the tangential thrust, a thrust away from the surface (the opposite of a magnetic pull). Indeed, the secondary conductor can be levitated in a stable condition in this manner [36]. The whole question of forces perpendicular to the pole surface is a complex one, involving the solution of a multilayer problem [17]. However, it is by no means obvious in the case of a double-sided machine, with only one primary winding in which the secondary conductor is fixed to the unwound ferromagnetic block [Fig. 7(a)], whether the normal force between the members is even attractive or one of repulsion. Also, a quite remarkable result is the fact that a sheet rotor between a pair of wound primary blocks which assist each other in driving flux through the sheet is unstable under the action of normal forces, being attracted to whichever block it happens to be nearer. In this the rotor appears to resemble a slab of ferromagnetic material, although only qualitatively for the electromagnetic side pull is relatively small.

So far, forces in the direction of field travel (which the designer seeks to produce) and forces normal to the pole faces have been considered. In a direction perpendicular to each of these two (i.e., a direction which could be described as "athwartships"), forces may also result from asymmetry of either magnetic or electric circuits. In the case of the sheet-rotor machine, for example, longitudinal currents under the active zone put the secondary sheet in lateral tension and any departure from a truly central position will result in lateral forces tending to increase eccentricity, i.e., to shoot the plate out sideways. This effect may perhaps be explained most readily in terms of the action of a linear-shaded pole motor on the lateral axis.

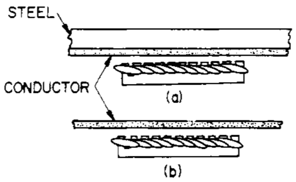

Fig. 7. Examples of single-sided motors.

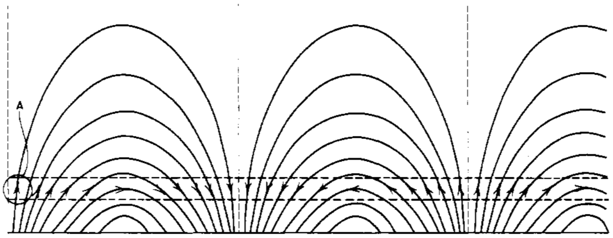

Fig. 8. Mechanism of "rack and pinion" motor.

Ferromagnetic material in the secondary member, on the other hand, tends to be pulled back into line when displaced laterally, and the question of whether a composite secondary (for example, the form shown in Fig. 2) is stable or unstable laterally is again a complex one, the net effect depending on speed, relative thickness of conductor, airgap, etc. One feature, however, appears to emerge from experimental results, although it has never been confirmed theoretically for the general case, viz., secondary members which are repelled normally from their primaries are laterally unstable. Members which are attracted are stable.

A particularly interesting feature of an open-sided machine [Fig. 7(b)] is that the field pattern above its surface contains, in addition to the expected traveling component of the field, a purely rotating component, a fact which can be demonstrated by cutting a small hole in a piece of card and placing it over Fig. 8 with the hole in the card initially over the circle A. Movement of the card across the page so that the hole traverses the space between the dotted lines reveals a continuous change of direction of magnetic field such as to produce a backward-rolling field which can be utilized to drive small cylindrical rotors in the manner of a "rack and pinion" [43]. Such an arrangement is perhaps the complete hybrid between linear and rotary machines.

Axial Flux Machines

One further form of machine remains to be described. Returning to Fig. 1, the linear motor was shown to be developed as the result of unrolling a conventional cylindrical stator. If the flat primary thus produced is rerolled about an axis parallel to the direction of field motion, as shown in Fig. 9, an entirely different form of cylindrical structure is produced in that the field now travels along the bore of the primary. The structure could be described as an electromagnetic "gun." One advantage of this type of structure is illustrated in Fig. 10. Conventional rotary machines and flat-linear machines carry primary windings which could be

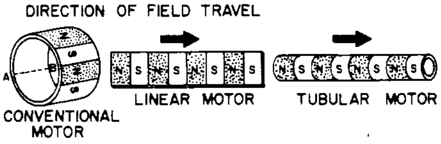

Fig. 9. Development of a tubular motor.

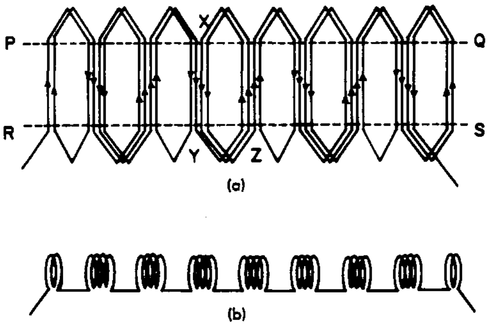

Fig. 10. End-turn advantages of tubular motor windings.

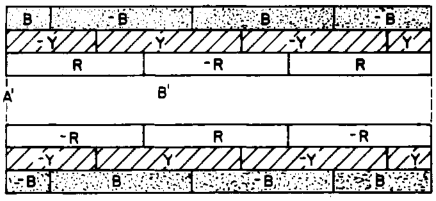

Fig. 11. Three-layer continuously wound tubular motor.

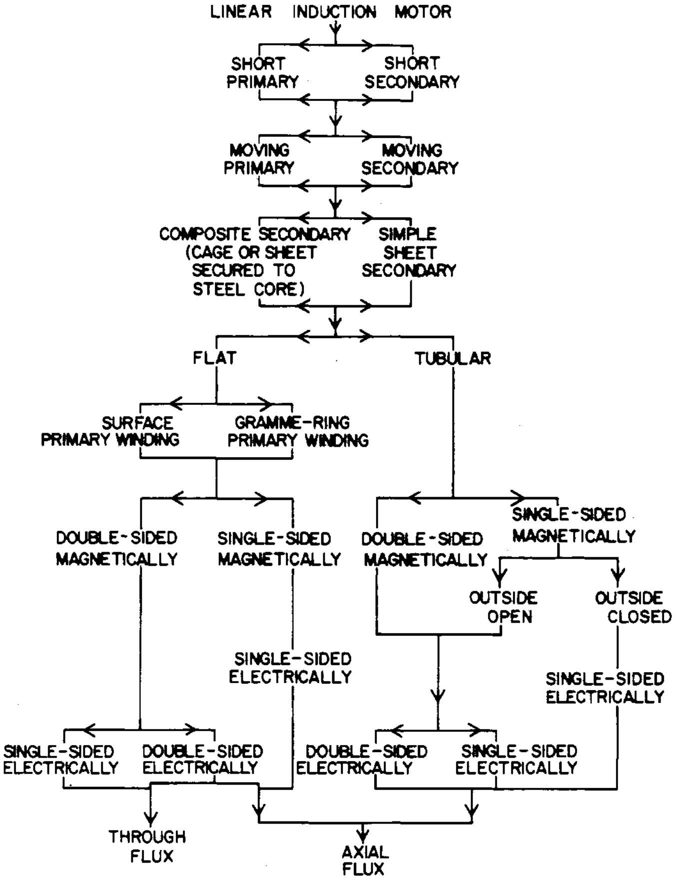

Fig. 12. Topological classification of linear induction motors.

said to be useful only where they pass through the slots, i.e., between the dotted lines in Fig. 10(a). End windings are necessary to route the currents from pole to pole, and apart from the fact that they provide cooling area, they could be said to be wasted. In a tubular motor the winding is rolled up so that PQ falls on RS and the winding may be seen to consist only of circular coils in a row, as shown in Fig. 10(b), or as continuous layers of wire (see Fig. 11), simplifying manufacture considerably.

Topological differences between the tubular motor and the flat machine do not end, however, with the electric circuit. Fig. 9 shows that all the flux emanating from, say, an N pole, must now pass *axially* through the secondary in order to reenter the S pole. It is, therefore, essential that the secondary member contain sufficient ferromagnetic material to contain the flux from a pole pitch (including 100 percent standing wave) so that the core of the secondary member is likely to impose a "bottleneck" on the magnetic circuit.

The tubular motor is a particular example of a whole class of linear motors which includes double-sided flat machines, as shown in Fig. 4, in which the two primary windings are connected so as to produce oppositely directed fluxes into the secondary which thereafter pass axially along the latter. Such machines have been described as axial flux motors [37]. End effects in axial flux motors are different from those in flat machines. While the surface winding of a flat machine demands that a current passing in one direction across the machine must ultimately return in the other, so that $\int J dx = 0$, an axial flux machine may impose any nonintegral pole number from the excitation system. Detailed calculations on axial flux edge effects have also been carried out [37], [48].

One representation of the classes into which linear induction machines can be divided is shown in Fig. 12. By following a route from top to bottom, a particular machine is defined completely. The top three sections indicate simply that every machine falls into one of two classes as regards which member moves, which is the shorter, and whether the secondary contains ferromagnetic material or not. Some of the terminology used is explained in Fig. 13. The definition of "double-sided magnetically," for example, is that the primary structure should contain ferromagnetic material on each side of the secondary. Thus, the simple development shown in Fig. 2 is classed as "single-sided magnetically," the fact that the secondary steel moves making it a composite secondary motor. For this same structure to be double-sided, it would need to carry an additional steel block, as shown in Fig. 13(d). The steel in the secondary serves to reduce effective airgap rather than to carry axial flux. An example of such a machine would be one in which the secondary member consisted of a sheet of aluminum impregnated with steel rivets.

Fig. 12 illustrates the very large number of different kinds of linear machine which result from the combination of various features. Each of the horizontal strata involves fundamentally different factors when theoretical and/or eco-

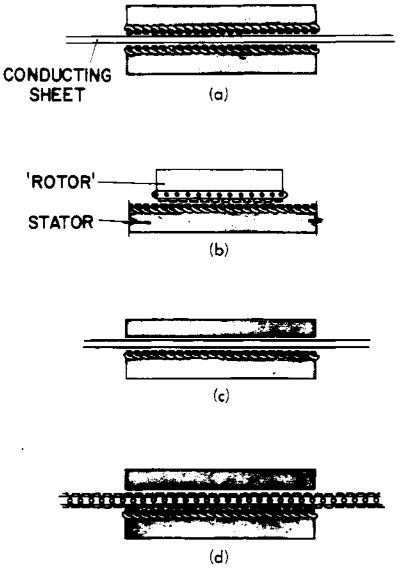

Fig. 13. Some examples illustrating the topological classification. (a) Double-sided electrically and magnetically sheet rotor. (b) Single-sided electrically and magnetically composite rotor. (c) Double-sided magnetically, single-sided electrically, sheet rotor. (d) Double-sided magnetically, single-sided electrically, composite rotor.

nomic assessment of a given system is attempted. Fig. 12, of course, may be used upside down in which case it illustrates that the through flux–axial flux dichotomy is as fundamental as that of short primary–short secondary.

Some combinations which are physically constructable have been deliberately omitted from this classification in view of their economic impracticability. For example, in a flat machine, single-sided magnetically, it is hardly likely to be profitable to fit a second primary winding in space on the opposite side of the secondary from the steel block housing the first winding. On the other hand, such a system is feasible with tubular machines, for the reluctance *outside* the outer primary winding can be relatively low even with air as magnetic circuit, as was shown previously [41].

HISTORICAL

The earliest specific reference to linear machines appears to be a patent of 1890 by the Mayor of Pittsburgh relating to induction machines [85]. This was followed by a patent in 1895 by the Weaver, Jacquard, and Electric Shuttle Company who, judging by their title, had high hopes for its use as a shuttle propelling device in weaving looms. Certainly, subsequent patent literature reveals that the most active development of linear induction motors between 1900 and 1940 was in connection with shuttle propulsion, although no one appeared to have commercial success with the device, largely no doubt, on account of the relatively high cost of the electrical system compared with the loom itself. Nevertheless, considerable ingenuity was shown by textile engineers who were sufficiently versatile to advance the ideas of double-sided motors, sheet-rotor motors and tubular motors.

In 1905 there were two separate proposals to use linear induction motors as a railway propulsion mechanism. The first of these [82] proposed short sections of primary embedded in the track which could be switched on as required. The second [84] proposed a primary unit carried on board the vehicle with a sheet-rotor reaction rail on the track. The latter idea was virtually the forerunner of several of the large-scale experiments which are being carried out in several countries at the present time. The fact that Zehden's idea had to wait over half a century before finding commercial exploitation is perhaps due primarily to the ability of other forms of propulsion to satisfy the limited demands of the day regarding speed, acceleration, and reliability.

In 1917 came the first tubular motor which was in fact a dc reluctance machine with switched primary coils [15]. Intended as a missile launcher, the evidence is that it was never developed beyond the model stage. In 1923 a flat induction motor was proposed as a drive for a continuous moving platform system to run below 42nd Street between Times Square and Grand Central Station. A test track was built, but the proposal never came to fruition.

With the development of nuclear power came the need to pump liquid metal, in particular, sodium–potassium mixtures of high conductivity. Both ac and dc types were produced: double-sided flat versions, and tubular motors [5]. The ac machines included not only induction types, but conduction machines (similar to the dc machines), and these could be said to represent the earliest (indeed, perhaps the only) linear ac commutator motors. Flat types were generally preferred to tubular machines since the latter involved breaking the pipeline in the event of a primary winding burn-out. One ingenious hybrid in this family consisted of a more or less conventional cylindrical stator, producing a rotating field, inside of which the liquid metal was routed in a helical channel from end to end of the stator; thus, it made use of the angle-field principle which was subsequently the basis of an experimental variable speed motor [80], [81].

The first large-scale transport application came in 1946 with the development of the Westinghouse aircraft launcher, the Electropult [86]. The primary coil system was mounted on a carriage and the secondary consisted of a winding in slots in a ferromagnetic structure. The motor was very similar to the primitive machine shown in Fig. 2 with extended secondary. Two full-scale tracks were built, one $\frac{5}{8}$ mile long, the other just over a mile. Fig. 14 shows the primary unit on the runway. Current collection was by means of brushes running in the slots alongside the secondary member. Fig. 15 shows an aircraft attached to the primary unit by a sling. The motor developed 10 000 hp and attained speeds over 225 mi/h. A 10 000-pound jet was accelerated to 117 mi/h in a 540-foot run in 4.2 seconds from rest. The system was finally abandoned on the grounds of high initial cost.

Another very interesting linear motor project which was also initiated through aircraft requirements was the dc linear motor developed at the Royal Aircraft Establishment, Farnborough, England, in 1954 [57]. This double-sided flat machine fired missiles weighing several pounds up to speeds of over 1000 mi/h. Space research initiated further experiments in 1961 in an attempt to exceed such

Fig. 14. The "Electropult."

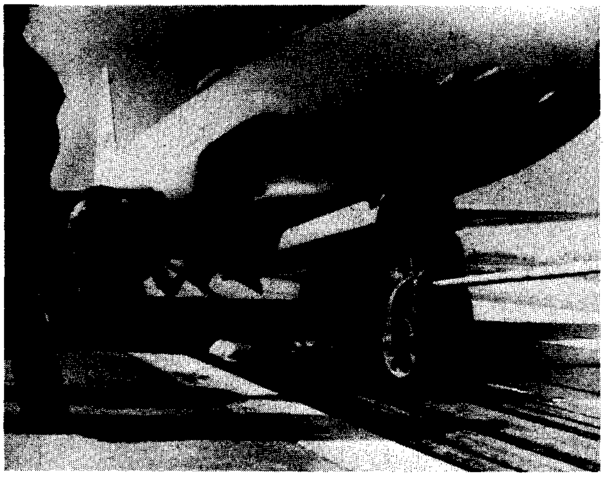

Fig. 15. Primary unit on its track.

speeds with a view to being able to simulate the impact of meteorites on space capsules at "hypervelocities" in the order of 30 000 to 160 000 mi/h [70]. The system which attempted to economize on power input while avoiding direct feed of 3-phase power to the moving part is shown diagrammatically in Fig. 16. The moving coil collects current from a rail by means of a sliding contact and returns it via the stationary coil to a second sliding contact so as to produce a leading and traveling energized section. This experiment failed, but the reason why it failed is particularly interesting because it is fundamental to such systems in that, for any given terminal velocity, there is a minimum mass of metal which can be made to reach that velocity without melting. This rule is closely allied to another which arises in the study of force production by induction systems [36] and may be thus stated: the ratio of the rate of change of temperature of a secondary conductor (assuming no loss of heat by any form of cooling) to its acceleration in unresisted motion due to the forces of induction is inversely proportional to a power of a linear dimension. This law may be paraphrased in the following manner. "As you make an object smaller you must ultimately melt it before you move it."

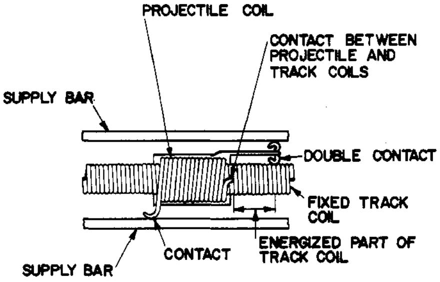

Fig. 16. The hypervelocity induction system.

The law was formulated in connection with electromagnetic levitation systems, whose devices could be said to constitute linear motors producing force vertically upwards. Much work has been done on such machines and, while their theory of operation extends and in some cases interleaves with that of more conventional linear motors in most fascinating ways, a detailed treatment of levitation systems is beyond the scope of this paper. References to published work other than [36] can be found in the excellent book by Geary [14].

One other aspect of linear motors concerns machines designed to produce oscillating motion without the use of external switching means. In 1956 it was shown that a polyphase induction system could be so designed [22]. This was extended in 1962 by West and Jayawant to include single-phase motors operating as ferroresonant devices [78]. Synchronous oscillating machines were developed in 1960 [30]. By comparison with induction machines, the linear version of the dc machine is in its infancy, although its usefulness as an actuator has now been forecast [16].

APPLICATIONS

On the basis of topological considerations, a classification of linear induction machines is given in Fig. 12. Because the applications of linear-motion electrical machines range from instrumentation (such as electromagnetic flowmeters) to high-speed ground transportation, it is rather advantageous to divide linear machines into the following classes from applications standpoint:

1) force machines and transducers,
2) power machines,
3) energy machines.

In general terms, some of the applications of linear machines have been mentioned in connection with their historical development. Based on the above classification, force machines, which operate essentially at standstill or at low speeds, find applications as transducers, relays, solenoids, and actuators. The power machines, which often operate at high speeds and must have high efficiency, have

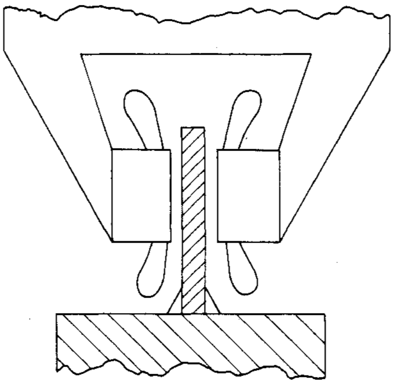

Fig. 17. A track layout.

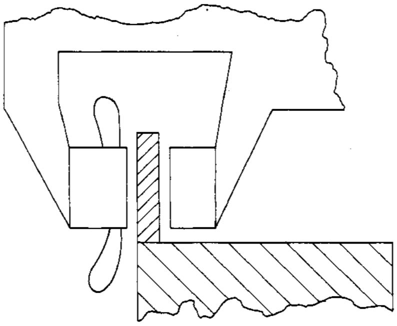

Fig. 18. An alternative track layout.

numerous applications. Some of these include electromagnetic pumps, belt conveyors, linear motors for high-speed ground transportation, magnetohydrodynamic generators, hydromagnetic converters, etc. The energy machines are often large machines and have been used as aircraft launchers (Figs. 14 and 15). Other applications of energy machines have been proposed as impact extruders and accelerators. Naturally, it is not practicable to include a detailed discussion of any of the above-mentioned topics here. In the following, only some of the unique possible applications of the linear machines are presented. For more details references cited in this section may be consulted.

Transportation

Among the various linear machines, the linear induction motor seems naturally suited for applications to transportation systems and offers certain advantages over other schemes [87]. As mentioned earlier, the idea of using a linear induction motor for transportation is an old one, and some of the recently proposed schemes seem to be based on a 1905 United States patent [84]. Between 1905 and the mid-sixties the only other development of the linear induction motor for propulsion was the Westinghouse "Electropult" (Figs. 14 and 15). However, in the fifties experiments with linear induction motors (at the University of Manchester, England) revitalized the interest in the field [22]–[26], and since then considerable progress has been made toward the applications of linear induction motors for propulsion and transportation.

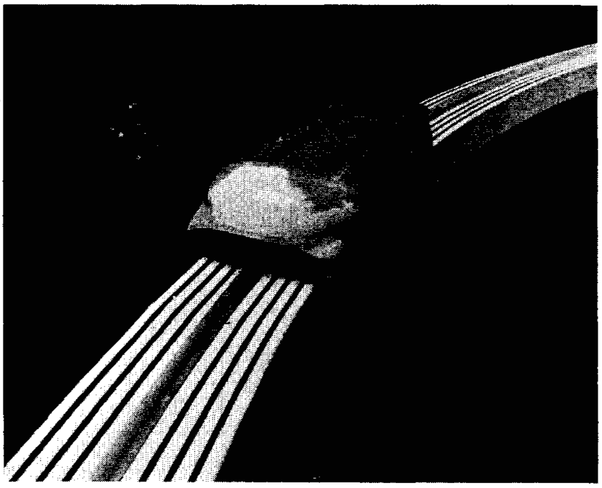

Fig. 19. A tracked hovercraft.

As pointed out earlier, the linear induction motor consists of a stator, or a primary, and a rotor, or a secondary. Various considerations indicate that for traction purposes it is desirable to mount the primary on the vehicle and let the track serve the purpose of the secondary. Track layout and economy have been considered in some detail in [42]. While [87] proposes the scheme shown in Fig. 17 for track layout, [42] suggests several alternatives, one of which is shown in Fig. 18, for electrically single-sided, but magnetically double-sided, motor. It is noted that the motor shown in Fig. 17 is double-sided electrically as well as magnetically.

Because the linear motor for transportation is essentially a power-producing machine, it must be a high-efficiency and, consequently, a high-power (or large) machine. (*Note:* Garrett Corporation is reported to have developed and built a 2500 hp linear induction motor for a 250 mi/h train [89].) The fact that the machine has to be large is a blessing, since it is possible to design large efficient machines which could operate with large airgaps and large pole pitches [34], [37], [41], [42]. While it is true that large airgap is a disadvantage to the linear motor [7], it is not the airgap that solely determines the efficiency of the motor. The relationship between the goodness factor (introduced to aid the design of electrical machines [34]) and the airgap, pole pitch, and the properties of the material is considered in the next section.

Regarding starting, speed control, and braking, methods applicable to the conventional rotary induction motor are suitable for the linear motor also. Some aspects of speed control and braking are available in [42] and [87]. In summary, the linear induction motor seems quite suitable for transportation purposes from an electrical viewpoint, although considerable mechanical problems have yet to be solved. A high-speed tracked hovercraft model is shown in Fig. 19.

Liquid-Metal Pumps

Low-density liquid metals, such as sodium and sodium–potassium alloy, are considered suitable coolants for nuclear reactors. For pumping such liquid metals, which have

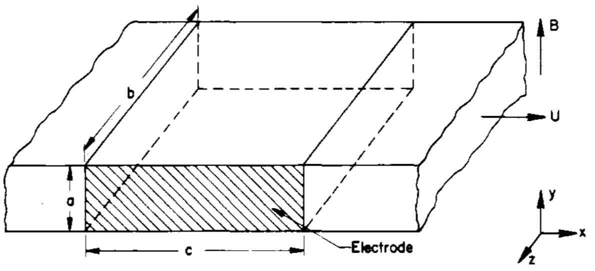

Fig. 20. A rectangular channel.

high electrical conductivities, electromagnetic pumps offer a possible application [5], [47], [77]. These pumps operate on the basis that a pressure is developed within the fluid carrying current in the presence of a magnetic field. The pressure p developed by an electromagnetic pump is obtained from the Lorentz force equation, and is given by

$$\nabla p = \boldsymbol{J} \times \boldsymbol{B} \tag{1}$$

where $\boldsymbol{J}$ is the current density at a point within the fluid and $\boldsymbol{B}$ is the flux density at that point.

Depending on how the current flow is imparted to the circulating fluid in the pump, a liquid-metal electromagnetic pump may be a conduction pump or an induction pump. Evidently, the dc pump could only be a conduction pump, whereas an ac pump may either be a conduction or an induction pump.

The dc electromagnetic pump, in principle, may be considered the simplest linear machine, and it operates on the same principle as the conventional dc motor. A simplified form of the dc pump is shown in Fig. 20, where the fluid flow, and the external magnetic field are mutually perpendicular. If I is the current through the fluid, the pump pressure p is given by

$$p = \frac{IB}{a}. \tag{2}$$

Noting that u is the velocity of the fluid, the flow q through the pump is

$$q = uab \tag{3}$$

and the pump output P_o is given by

$$P_o = pq = \frac{IB}{a}(uab) = Iuab = IV. \tag{4}$$

The ohmic loss in the fluid is

$$P_f = I^2R = \rho J^2 abc = \rho \frac{I^2 b}{ac} \tag{5}$$

where ρ = resistivity of the fluid.

In the above discussion, the effect of armature reaction has not been considered. Due to armature reaction the flux-density and current-density distributions both become distorted [Fig. 21(a)]. This leads to low pump pressure and low efficiency. A simple arrangement for compensating the armature reaction is shown in Fig. 21(b), from which it can be seen that the main current flowing through the fluid is returned back through the magnet by means of a pole-face winding.

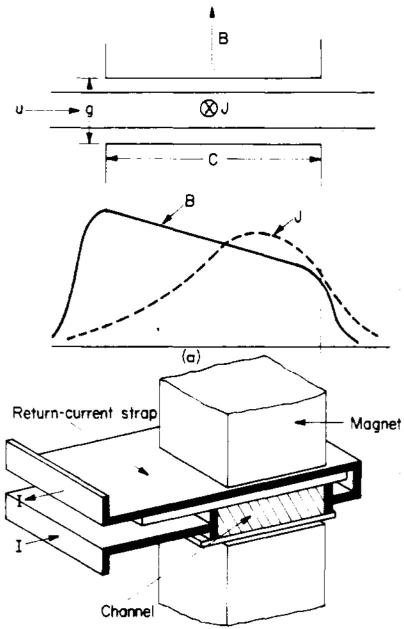

Fig. 21. (a) Armature in a dc pump. (b) Compensation of armature reaction.

The mode of operation of the dc pump can be reversed to make it operate as a generator, and a pump–generator combination can be used to make a hydromagnetic converter [47], which has the terminal characteristics of an ideal transformer.

Among the ac electromagnetic pumps, the induction pump is preferred to a conduction pump. The linear induction pump is similar, in principle, to the linear induction motor. The presence of the fluid, however, makes the analysis of the pump somewhat complicated [5]. For the channel dimensions shown in Fig. 20, the pump output P_o is given by

$$P_o = P_p(1 - s)s \tag{6}$$

where s = slip, and

$$P_p = \frac{1}{2\rho}\mu^2 ab\lambda u_o^2 H_m^2 \tag{7}$$

is known as the induction-pump parameter. In (7), u_o = synchronous speed of the traveling field, λ = wavelength (or twice pole pitch), H_m = maximum value of (a sinusoidally distributed) field intensity, and μ and ρ are, respectively, the permeability and the resistivity of the fluid. The ohmic loss in the fluid can be expressed as

$$P_f = P_p s^2 \tag{8}$$

and the ideal efficiency of the pump is $(1 - s)$.

So far only rectangular cross-section channels have been considered. However, a tubular pump is also practicable (Fig. 22) which operates on the principle of an axial flux tubular motor. A comparison of operation of various forms of liquid-metal electromagnetic pumps is given in [5] and [47].

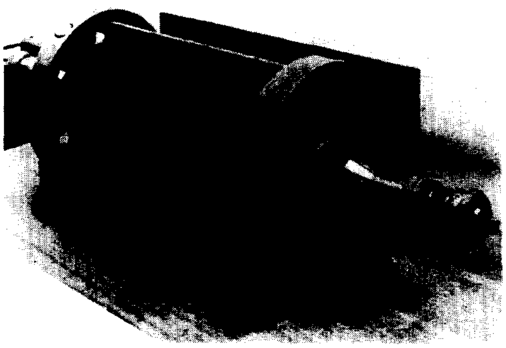

Fig. 22. A tubular induction pump.

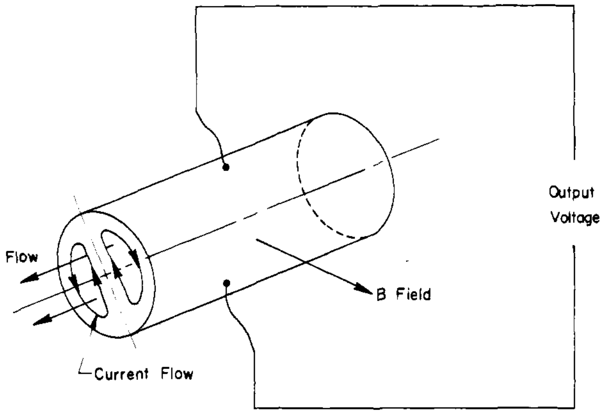

Fig. 23. An electromagnetic flowmeter.

As with the linear induction motor, there are problems associated with the induction pump, also. These are considered in the next section.

Electromagnetic Flowmeters

For transportation and liquid-metal pump applications, the linear machines operate as motors. As generators, the linear machine configuration has been proposed for use as magnetohydrodynamic ac and dc generators. These are not included here because extensive literature is available on this subject [3], [4], [10]–[12], [18], [56].

Electromagnetic flowmeters [59], [60] offer another example of generator mode of operation of linear-motion machines. These flowmeters are based on the principle that an EMF is induced in a conducting fluid moving in a magnetic field at right angles to the direction of the flow. Such a flowmeter may be called a transverse-field flowmeter (Fig. 23). Other forms of flowmeters include axial current and radial flowmeters. The main advantage of the electromagnetic flowmeter is that its output voltage is linearly proportional to the volumetric flow rate. There is, in practice, some departure from this ideal situation because of edge effects, velocity profile changes in the fluid, armature reaction, variation of the electrical properties of the electrolyte, etc.

A flowmeter may utilize a dc field or an ac field, and each has its own merit. With ac fields, polarization at electrodes and thermoelectric and electrochemical dc potentials can be avoided. The dc field flowmeter has the advantage that it avoids skin effect. The dc meter is simple and is less expensive, whereas the ac meter is suitable for electrolytic conductors, for small flow rates and for fluids with small conductivity.

The performance of the flowmeter is measured in terms of its sensitivity S defined as

$$S = \frac{V}{bBu} \tag{9}$$

where V = output voltage, u = mean velocity of the fluid, B = applied magnetic field, and b = separation between electrodes. Several expressions for sensitivity have been derived in [60]. The sensitivity for a transverse-field flowmeter with rectangular channel of nonconducting walls is unity, if the contact resistance of the fluid is zero. On the other hand, for highly conducting walls

$$S = \frac{a}{a + w\sigma_w \rho_f} \tag{10}$$

where w = thickness of the channel wall, a = semiwidth of the channel, σ_w = wall conductivity, and ρ_f = fluid resistivity.

Diverse Applications

Single-sided linear induction motors have been used in the steel industry for stirring molten metal [9], [21], [66]. The electromagnetic induction stirrer has several advantages, as pointed out in [66], but the stirrer inherently has a low efficiency because of relatively large airgap and small pole pitch.

Another interesting application of the linear induction motor has been proposed for impact extrusion [19], [31]. In this case, the machine is an energy producing machine, and although the overall energy efficiency of the original machine was low [19], it is expected that the energy efficiency could be improved.

Several applications of the linear induction motor have been suggested in the textile industry [22], [23], [27]. In particular, a back-to-back flat-linear induction motor acts as an electromechanical oscillator and has possible applications for shuttle propulsion and package winding.

Other applications of linear induction motors have been proposed for overhead cranes, automatic curtain rods, and door operators.

The application of linear motors for conveyors seems quite promising [25]. Some conveyor systems using linear motors are shown in Fig. 24 and Fig. 25.

Finally, applications of linear short-stroke actuators and thrust producers have also been proposed [16], [28], [48].

SOME ANALYSIS AND DESIGN PROBLEMS

The linear machine differs from the conventional rotary machine in two respects. First, in contrast with the rotary machine, the linear machine has a "beginning," or entry edge, and an "end," or exit edge. Second, as compared with the rotary machine, the linear machine has a larger

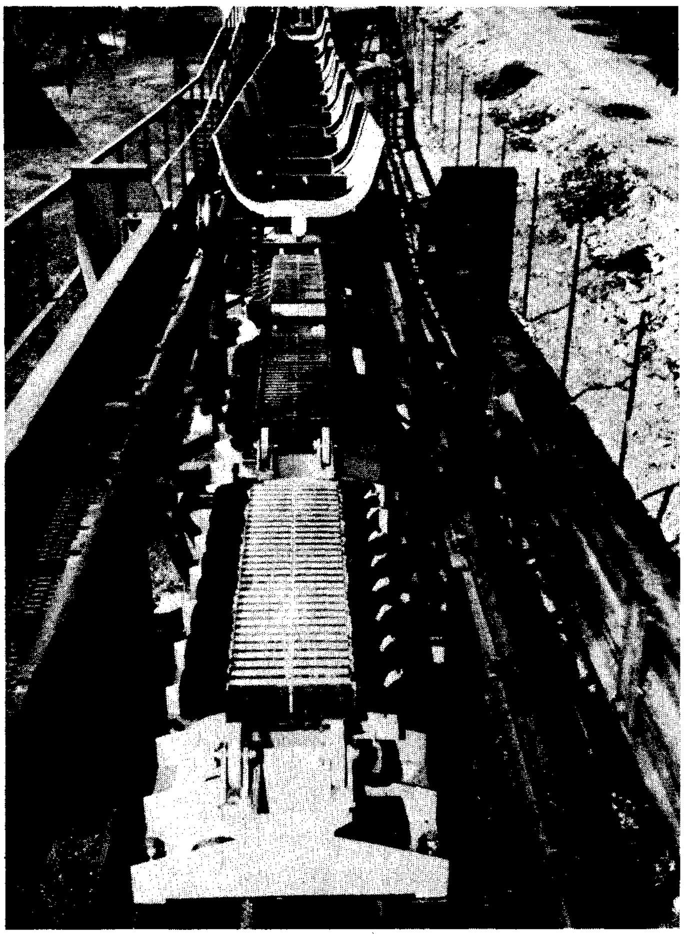

Fig. 24. Conveyor systems using linear motor drive.

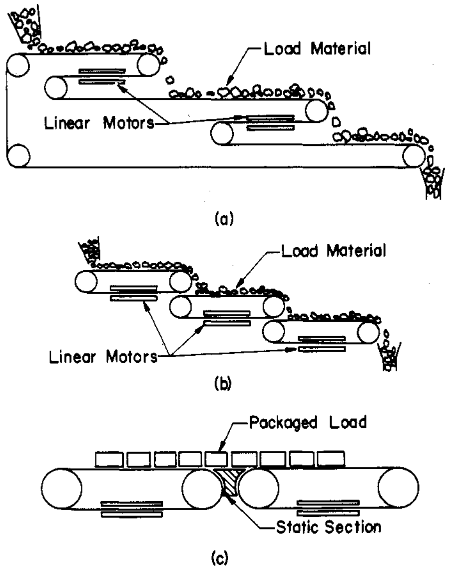

Fig. 25. A conveyor system.

gap. The usual consequences of edge effects [3]–[6], [12], [46], [64], [72]–[76], and large airgap [34], [37], [41], [42], are as follows: reduced power output in generator or motor operation; a pressure loss in electromagnetic pump [58]; nonlinear calibration of flowmeters [59], [60]; and low efficiency and small power/weight ratio in all cases. It is a challenging problem to design a linear machine to overcome the aforementioned undesirable features.

Considering the airgap problem first, the concept of the goodness factor, introduced earlier [34], is recalled. Since the force in a machine is the product of current I and flux ϕ, and the current is produced by a voltage V, and the flux by a current I_m, the product of the current/unit voltage I/V, and the flux/unit current ϕ/I_m, is a measure of the performance of the machine. The goodness factor G is thus defined by

$$G = k \frac{I}{V} \frac{\phi}{I_m} \tag{11}$$

where k = a proportionality constant. Noting that $I/V = 1/R$ (a conductance) and $\phi/I_m = L$ (an inductance), (11) becomes

$$G = k \frac{L}{R}. \tag{12}$$

For an ac machine, the velocity being proportional to the angular frequency ω, and the power being the product of force and velocity, G can finally be expressed as

$$G = \frac{\omega L}{R} \tag{13}$$

where the constant of proportionality has been chosen as unity. For a linear induction machine with sheet rotor, the goodness factor has been found to be [34]

$$G = \frac{2\mu_0 f p^2}{\pi g \rho} \tag{14}$$

where f = frequency, p = pole pitch, g = airgap, and ρ = surface resistivity of the rotor. Clearly, for machines with large airgap, the goodness factor can be increased by increasing the pole pitch.

Numerous interpretations of the goodness factor are now available in [45], [79], and [87]. It seems that the concept of the goodness factor is particularly useful in the design of linear machines. It is not that large airgap is desirable, but (14), at least, indicates that large airgaps could be tolerated and the goodness factor could be improved by adjusting one or more of the quantities p, f, and ρ. A method for optimizing the design of a slow-speed linear machine is given in [48], and could prove useful in other cases as well.

The next phenomenon that is unique to linear machines (and some special-purpose rotary machines) is the edge effect. The consequences of edge effects have been divided as transverse-edge effects [6], [55], [72]–[76], and entry- and exit-edge effects [3]–[5], [12], [37], [46], [52]–[56], [67]–[76], [87]. It is beyond the scope of this paper to present an account of the various methods. The references just cited give considerable details pertaining to the various methods. In general, however, the methods of analysis of edge effects can be considered to be based on 1) circuit theory and 2) field theory. In the circuit theory approach, a distinction is made between a series-connected and a parallel-connected machine [35] and a number of equivalent circuits have been derived for the "short-stator" as well as for the "short-rotor" machine [37]. These circuits, in turn, can be used for the analysis of the linear machine. In the field analysis, the basic equation is the equation for the magnetic vector potential A in the airgap of the machine. This equation takes the form [12], [46]

$$\nabla^2 A - \mu\sigma \frac{\partial A}{\partial t} - \mu\sigma u \frac{\partial A}{\partial x} = 0. \qquad (15)$$

The solution to this equation, subject to appropriate boundary conditions, leads to the determination of the magnetic fields in the airgap of the machine. The fields, in turn, yield some of the performance characteristics of the machine. It may be pointed out that it is not practicable to solve (15) for the most general case. Only simplified and idealized models are amenable to this method of analysis.

For the study of edge effects in dc machines several methods are available [58]–[61], [66], [67], and modifications of magnetic circuits and winding distributions have been suggested to reduce the edge effects.

CONCLUSIONS

In the changing fashions of engineering several features have emerged which have been favorable toward the use of linear motors, notably, that *overall* economic evaluation of a project is more important than the efficiency of an individual component. Of the developments in linear induction motors themselves, by far the most important have been concerned with the magnetic circuit. Throughout nearly a hundred years of rotating machine development the shape of the magnetic circuit remained virtually unchanged so that the old doctrine of "a good machine has a small airgap" was bound to be upheld. The "goodness factor" method of analysis showed that the airgap length was to be related to other physical dimensions, some of which (like pole pitch) could be more potent in their effect on performance (appearing as a squared term) than airgap length so that new *shapes* of motor offered new degrees of flexibility in design.

Perhaps one of the surprises of linear motor development has been the extent of the diversity of shapes of machine which have been possible. Fig. 12 effectively lists over 100 types of machines which are structurally different from each other and it is almost certain that this classification is incomplete. Indeed, history may record that at this time whole families of linear motor remained to be discovered.

Linear motors have presented new challenges to theoreticians, for the essential discontinuities in the magnetic field patterns have rendered them incapable of analysis by means of the so-called "generalized machine theory." The latter is now seen to be limited to conventional rotating machines, which by the nature of their small airgap and their homogeneity in the axial direction (any slice in a radial plane is the same as any other slice) makes their analysis basically a one-dimensional problem.

The history of engineering has shown how rarely the theory of a new device has preceded its utilization. The job of the engineer is to exploit physical principles by any known means. Often these means have been analogs which, while being far from rigorous, have been extremely useful. The process of discovering new analogs for linear machines is one in which the authors continue to be engaged.

ACKNOWLEDGMENT

The authors are indebted to *Westinghouse Engineer* for the reproduction of Figs. 15 and 16, and to Tracked Hovercraft, Ltd., Cambridge, England, for permission to use the photograph in Fig. 19.

REFERENCES

[1] W. J. Adams and B. A. White, "Applying linear induction motors," *Automation*, June 1967.

[2] F. T. Barwell and E. R. Laithwaite, "Application of the linear induction motor to high speed transport," *Proc. Inst. Mech. Engrs.* (London), vol. 181, Paper 3G, 1966–1967.

[3] E. B. Benson and A. L. Genkin, "Fringe effects in magnetohydrodynamic generators," *Magnetohydrodynamics*, vol. 1, no. 2, pp. 50–64, 1965.

[4] I. B. Bernstein, J. B. Fanucci, R. M. Kulsrud, and N. Ness, "Magnetohydrodynamic ac power generation," *1961 Proc. Natl. Aerospace Electronics Conf.* (Dayton, Ohio), p. 205.

[5] L. R. Blake, "Conduction and induction pumps for liquid metals," *Proc. IEE* (London), vol. 104A, pp. 49–63, 1967.

[6] H. Bolton, "Transverse edge effect in sheet-rotor induction motors," *Proc. IEE* (London), vol. 116, pp. 725–731, 1969.

[7] K. M. Chergwin, "Linear induction motor research in the USA," presented at High Speeds Symp., Vienna, Austria, 1968.

[8] E. E. Covert, L. R. Boedekar, and C. W. Haldeman, "Recent results of studies of the traveling wave pump," *AIAA J.*, vol. 2, pp. 1040–1046, 1964.

[9] L. Dreyfus, "An induction stirrer for arc furnaces," *ASEA J.*, 1950.

[10] S. J. Dudzinsky and T. C. Wang, "MHC induction generator," *Proc. IEEE*, vol. 56, pp. 1420–1431, September 1968.

[11] D. G. Elliott, "Variable-velocity MHD induction generator with rotating machine internal electrical efficiency," *AIAA J.*, vol. 6, pp. 1695–1702, 1968.

[12] J. B. Fanucci, L. J. Kijewski, and J. E. McCune, "Fringing effects in an ac MHD generator," in *3rd Symposium on Engineering Aspects of Magnetohydrodynamics*. New York: Gordon and Breach, 1963, pp. 329–343.

[13] S. Fornander, and F. Nilsson, "Inductive stirring in arc furnaces," *J. Metals*, vol. 188, pp. 22, 256, 1950.

[14] P. L. Geary, "Magnetic and electric suspensions," British Scientific Instr. Res. Assoc., 1964.

[15] L. Gradenwitz, "Le canon electromagnetique de Birkeland," *Eclairage*, vol. 26, p. 267.

[16] C. W. Green and R. J. A. Paul, "Application of dc linear machines as short-stroke and static actuators," *Proc. IEE* (London), vol. 116, pp. 599–604, 1969.

[17] J. Greig and E. M. Freeman, "Travelling wave problem in electrical machines," *Proc. IEE* (London), vol. 114, pp. 1681–1683, 1967.

[18] H. A. Haus, "Alternating-current generation with moving conducting fluids," *J. Appl. Phys.*, vol. 33, pp. 2161–2172, 1962.

[19] W. Johnson, E. R. Laithwaite, and R. A. C. Slater, "Experimental impact-extrusion machine driven by linear induction motor," *Proc. Inst. Mech. Engrs.* (London), vol. 179, pp. 15–35, 1964–1965.

[20] M. F. Jones, "Launching aircraft electrically," *Aviation*, October 1946.

[21] E. S. Kopecki, "Induction stirring in electric furnace steelmaking," *Iron Age*, pp. 73–78, September 22, 1949.

[22] E. R. Laithwaite and P. J. Lawrenson, "A self-oscillating induction motor for shuttle propulsion," *Proc. IEE* (London), vol. 104A, pp. 93–101, 1957.

[23] E. R. Laithwaite and V. Druxbury, "Electromagnetic shuttle propelling devices," *J. Inst. Textiles*, vol. 48, p. 214, 1957.

[24] E. R. Laithwaite, "Linear induction motors," *Proc. IEE* (London), vol. 104A, pp. 461–470, 1957.

[25] E. R. Laithwaite, D. Tipping, and D. E. Hesmondhalgh, "The application of induction motors to conveyors," *Proc. IEE* (London), vol. 107A, pp. 284–294, 1960.

[26] E. R. Laithwaite and G. F. Nix, "Further developments of the self-oscillating induction motor," *Proc. IEE* (London), vol. 107A, pp. 476–486, 1960.

[27] E. R. Laithwaite, G. F. Nix, D. Brunnschweiler, and J. Bina, "Self-oscillating induction motor as traverse mechanism for cone-winding mechanism," *J. Textile Inst.* (Proc. Sect.), vol. 52, pp. 625–634, November 1961.

[28] E. R. Laithwaite, "Linear induction-motor propulsion for high-

speed railways," *Engineers' Digest*, vol. 23, pp. 61–68, 1962.

[29] ——, "Oscillating machines, synchronous and asynchronous," *Proc. IEE* (London), vol. 109(A), pp. 411–414, 1962.

[30] E. R. Laithwaite and S. Mamak, "Oscillating synchronous linear machines," *Proc. IEE* (London), vol. 109(A), pp. 415–429, 1962.

[31] E. R. Laithwaite, R. A. Slater, and W. Johnson, "Appraisal of linear induction motor concept for high-energy-rate metal forming," *Sheet Metal Ind.*, vol. 40, pp. 237–243, 1963.

[32] E. R. Laithwaite and F. T. Barwell, "Linear induction motor for high-speed railways," *Electronics and Power*. vol. 10. pp. 100. 103. 1964.

[33] E. R. Laithwaite, "Propulsion without wheels," inaugural lecture, Imperial College, London, February 1965.

[34] ——, "The goodness of a machine," *Proc. IEE* (London), vol. 112, pp. 538-541, 1965.

[35] ——, "Differences in series and parallel connection in machines with asymmetric magnetic circuits," *Proc. IEE* (London), vol. 112, pp. 2074–2082, 1965.

[36] ——, "Electromagnetic levitation," *Proc. IEE* (London), vol. 112, pp. 2361–2375. 1965.

[37] ——, *Induction Machines for Special Purposes*. London: George Newnes, 1966.

[38] ——, "Linear induction motors," *Engineering*, Publ. no. Engineering Outline 17, April 29, 1966.

[39] ——, *Propulsion Without Wheels*. London: English Universities Press, 1966.

[40] ——, "Propulsion without wheels," *Advancement of Science*, pp. 119–128, September 1967.

[41] ——, "Some aspects of electrical machines with open magnetic circuits," *Proc. IEE* (London), vol. 115, pp. 1275–1283, 1968.

[42] E. R. Laithwaite and F. T. Barwell, "Applications of linear induction motors to high-speed transport systems," *Proc. IEE* (London), vol. 116, pp. 713–724, 1969.

[43] E. R. Laithwaite and M. T. Hardy, "Rack and pinion motors," *Proc. IEE* (London), to be published.

[44] A. E. Mikel'son, V. A. Saulite, and A. Ya. Shkrestna, "Characteristics of coreless cylindrical induction pumps," *Magnetohydrodynamics*, vol. 1, no. 2, pp. 67–74, 1965.

[45] S. A. Nasar, Correspondence on [34], *Proc. IEE* (London), vol. 112, p. 2146, 1965.

[46] ——, "Electromagnetic fields and forces in a linear induction motor, taking into account edge-effects," *Proc. IEE* (London), vol. 116, pp. 605–609, 1969.

[47] ——, *Electromagnetic Energy Conversion Devices and Systems*. Englewood Cliffs, N. J.: Prentice-Hall, 1970, pp. 99–141.

[48] G. F. Nix and E. R. Laithwaite, "Linear induction motors for low speed and standstill applications," *Proc. IEE* (London), vol. 113, pp. 1044–1056, 1966.

[49] W. T. Norris and J. B. Heywood, "End region of a single-load cross-connected m.h.d. generator," *Proc. IEE* (London), vol. 115, pp. 555–561, 1968.

[50] G. G. North, "Linear induction motors," M.S. thesis, University of California, Berkeley, December 1959.

[51] N. M. Okhremenko, "An investigation of the spatial distribution of the magnetic fields and electromagnetic effects in induction pumps," *Magnetohydrodynamics*, vol. 1, no. 1, pp. 72–80, 1965.

[52] ——, "Transverse fringe effects in flat linear induction pumps," *Magnetohydrodynamics*, vol. 1, no. 3, pp. 65–70, 1965.

[53] ——, "Travelling-field induction pumps," *Magnetohydrodynamics*, vol. 1, no. 4, pp. 1–14, 1965.

[54] T. W. Preston and A. B. J. Reece, "Transverse edge effects in linear induction motors," *Proc. IEE* (London), vol. 116, pp. 973–979, 1969.

[55] A. P. Rasehepkin, "Field in the gap of induction machines for a variable linear winding load," *Magnetohydrodynamics*, vol. 1, no. 3, pp. 71–75, 1965.

[56] R. J. Rosa, *Magnetohydrodynamic Energy Conversion*. New York: McGraw-Hill, 1968.

[57] J. M. Shaw, H. J. H Sketch, and J. M. Logie, "The theory, design, construction and testing of an electric launcher," RAE Rept. Aero. 2523 E.L. 1484, 1954.

[58] J. A. Shercliff, "Edge effects in electromagnetic pumps," *J. Nuclear Energy*, vol. 3, pp. 305–311, 1956.

[59] ——, "Entry of conducting and non-conducting fluids in pipes," *Proc. Cambridge Phil. Soc.*, vol. 52, pp. 573–583, 1956.

[60] ——, *The Theory of Electromagnetic Flow Measurement*. London: Cambridge University Press, 1962.

[61] G. I. Shturman and R. L. Aranov, "Edge effect in induction motors with open magnetic field," *Elektrichestvo*, vol. 10, pp. 43–51, 1946.

[62] R. A. C. Slater, W. Johnson, and E. R. Laithwaite, "Appraisal of linear induction motor concept for high-energy-rate metal forming," *Sheet Metal Ind.*, vol. 40, pp. 237–243, 1963.

[63] ——, "An experimental investigation relating to the accelerated motion of various 'translators' in the airgap of a linear induction motor," *Internatl. J. Machine Tool Design Res.*, vol. 3, pp. 111–135, 1963.

[64] R. N. Sudan, "Interaction of a conducting fluid stream with a traveling wave of magnetic field of finite extension," *J. Appl. Phys.*, vol. 34, pp. 641–651, 1963.

[65] Y. Sundberg, "Magnetic traveling fields for metallurgical processes," *IEEE Spectrum*, vol. 6, pp. 79–88, 1969.

[66] G. W. Sutton, H. Hurwitz, Jr., and H. Poritsky, "Electrical and pressure losses in magnetohydrodynamics channel due to end current loops," *AIEE Trans. Communication and Electronics*, vol. 80 (I), pp. 687–695, January 1962.

[67] G. W. Sutton and A. W. Carlson, "End effects in inviscid flow in a magnetohydrodynamic channel," *J. Fluid Mech.*, vol. 11, pp. 121–132, 1961.

[68] M. Tama, "Electromagnetic pumping of molten metals," *Iron Age*, pp. 68–70, December 4, 1947.

[69] D. Tipping and D. E. Hesmondhalgh, "General method for prediction of the characteristics of induction motors with discontinuous exciting windings," *Proc. IEE* (London), vol. 112, pp. 1721–1735, 1965.

[70] K. Thorn and J. Norwood, Jr., "Theory of an electromagnetic mass accelerator for achieving hypervelocities," NASA Tech. Note D-886, 1961.

[71] L. Ya. Ulmanis, "To the problems of edge effects in linear induction pumps," *Applied Magnetohydrodynamics*. Latvian SSR: Academy of Sciences, 1956, pp. 78–90 (translated by the U. S. AEC, 1958).

[72] Ya. Ya. Valdmanis, P. E. Kunin, Yu. Ya. Mikel'son, and I. M. Taksar, "Conducting strip in the traveling electromagnetic field of a plane inductor," *Magnetohydrodynamics*, vol. 1, no. 2, pp. 75–82, 1965.

[73] S. V. Vasil'ev, N. M. Okhremenko, and L. G. Smirnova, "Experimental study of the magnetic fields in induction pumps," *Magnetohydrodynamics*, vol. 1, no. 2, pp. 83–91, 1963.

[74] T. A. Veske, "Solution of electromagnetic field equations for a plane linear induction machine with secondary boundary effects," *Magnetohydrodynamics*, vol. 1, no. 1, pp. 64–71, 1965.

[75] A. K. Veze and Yu. K. Krumin, "Electromagnetic force acting on an infinitely wide conducting sheet in the traveling magnetic field of plane inductors," *Magnetohydrodynamics*, vol. 1, no. 4, pp. 62–68, 1965.

[76] T. C. Wang and S. J. Dudzinsky, "Theoretical and experimental study of a liquid metal MHD induction generator," *AIAA J.*, vol. 5, pp. 107–112, 1967.

[77] D. A. Watt, "The design of electromagnetic pumps for liquid metals," *Proc. IEE* (London), vol. 106A, pp. 94–103, 1958.

[78] J. C. West and B. V. Jayawant, "A new linear oscillating motor," *Proc. IEE* (London), vol. 109(A), pp. 292–300, 1962.

[79] D. C. White, *et al.*, "Some problems related to electric propulsion," M.I.T., PB-173-639, November 1966.

[80] F. C. Williams, E. R. Laithwaite, and L. S. Piggott, "Brushless variable-speed induction motors," *Proc. IEE* (London), vol. 104A, pp. 102–118, 1957.

[81] F. C. Williams, E. R. Laithwaite, and J. F. Eastham, "Development and design of spherical induction motors," *Proc. IEE* (London), vol. 106A, pp. 471–484, 1959.

[82] H. W. Wilson, "Electrification of railways," *Trans. Liverpool Engrg. Soc.*, vol. 26, pp. 218–229, 1905.

[83] H. H. Woodson, "Ac power generation with transverse-current magnetohydrodynamic conduction machines," *IEEE Trans. on Power Apparatus and Systems*, vol. PAS-84, pp. 1066–1072, November 1965.

[84] A. Zehden, U. S. Patent 732,312, 1905.

[85] Mayor of Pittsburgh, U. S. Patent, 1890.

[86] "A wound rotor motor 1400 ft. long," *Westinghouse Engineer*, vol. 6, p. 160, 1946.

[87] "Study of linear induction motor and its feasibility for high speed ground transportation," U. S. Dept. of Transportation Study, Contract C-145-66, PB 174866, January 1967.

[88] "Going the straight and narrow," *Business Week*, pp. 134–136, January 20, 1968.

[89] K. M. Chirgwin, private communication.

[90] "A preliminary study of the linear induction motor for high speed ground transportation," U. S. Dept. of Transportation Rept. 06818-W454-RO-12, 1968.

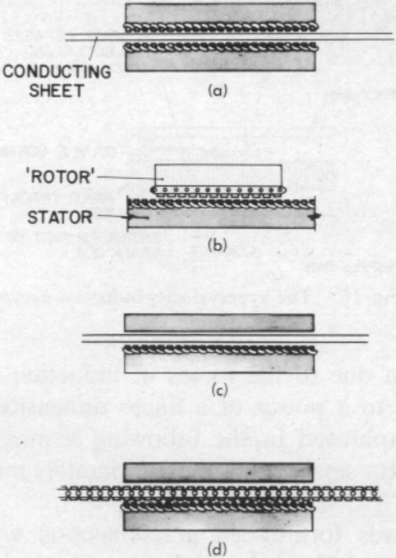

Fig. 13. Some examples illustrating the topological classification. (a) Double-sided electrically and magnetically sheet rotor. (b) Single-sided electrically and magnetically composite rotor. (c) Double-sided magnetically, single-sided electrically, sheet rotor. (d) Double-sided magnetically, single-sided electrically, composite rotor.

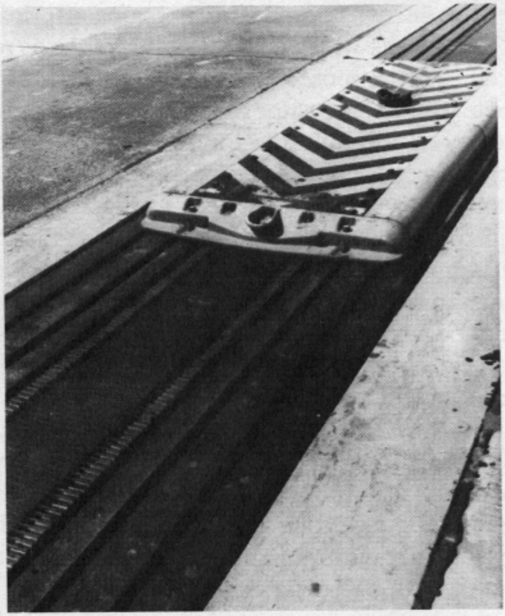

Fig. 14. The "Electropult."

Fig. 15. Primary unit on its track.

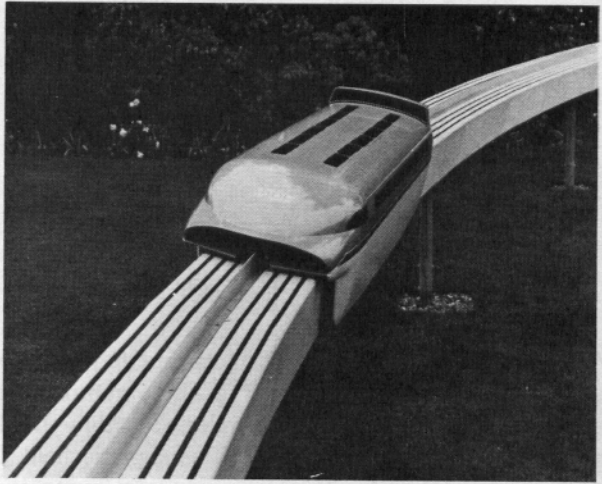

Fig. 19. A tracked hovercraft.

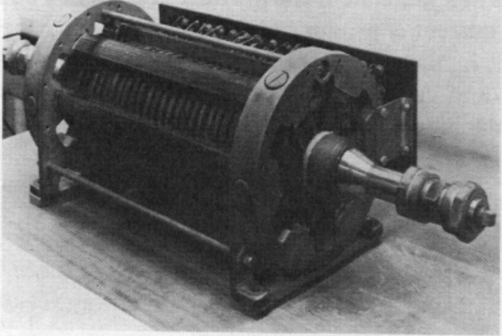

Fig. 22. A tubular induction pump.

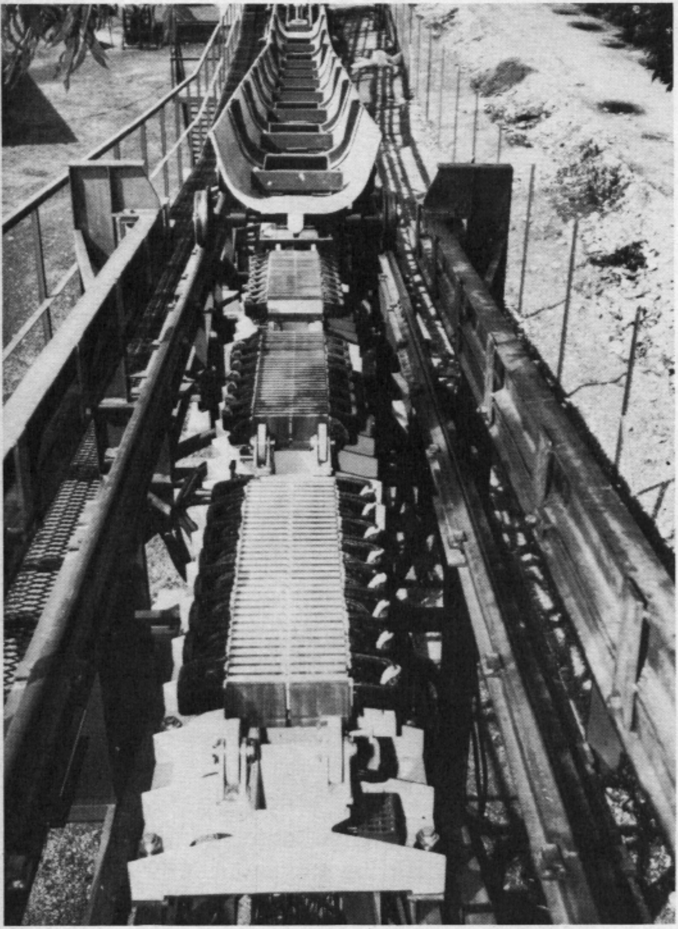

Fig. 24. Conveyor systems using linear motor drive.