# Design Processes Linear Permanent Magnet Electrical Vernier Machines For Future Research Directions: A Review

Hamid Yaghobi[1]* and Mohammad Reza Mohammadzadeh Moghaddam [2]

***Abstract*— In this study, the technology of Linear Permanent Magnet Vernier Electric Machines (LPMEVMs) is reviewed. Since the introduction of the first LPMVM designs, many designs have been proposed, and many researchers have come up with different ideas. The new LPMEVM technology has attracted the attention of many researchers, so with the efforts of researchers, it can be used in industrial applications of this machine and will be welcomed by craftsmen shortly. In the following, this article examines the work done in the field of LPMVM. In this study, the articles presented in this field are generally reviewed, the new technologies presented, and the structures have been analyzed by researchers and mentioned in the articles. Detailed more precisely on the structures presented and designs made for different parts of the machine, including the mover and translator, which include fixed and moving parts in the LPMV machine, the shape of the grooves and teeth, and the placement of permanent magnets and coils, will be discussed in this paper. This research discusses the designs presented in this LPMV machine and paves the future research path.**

***Index Terms*—** Linear Vernier machine, Permanent magnet, Winding, Core.

## I. INTRODUCTION

Linear permanent magnet Vernier machines are among those that have attracted special attention in linear motion applications due to their outstanding features. In describing the features, papers in this field state that the LPMVM machine produces high torque at low speeds and that its performance base is based on magnetic gearbox technology. Due to the problems with mechanical gearboxes, such as parts failure and maintenance of technology, Vernier machines have been able to solve this need without friction with each other and by using magnetic relations. Research and development in magnetic gearboxes in recent years show the importance of this issue in Fig. 1(the x-axis is the years, and the y-axis is the number of publications). LPMVM can involve linear, conventional, multi-harmonic, and modular LPMV primary permanent magnet machines [1], [2], [3]. That is the leading technology in the electrical linear machine industry, mainly functioning based on the magnetic gearbox. Machines are generally composed of both stationary and moving parts. The components of conventional machines include: **(i) iron core**, **(ii) north permanent magnet**, **(iii) south permanent magnet,** and **coil conductors (iv)**. For example, a linear permanent magnet Vernier machine (FP-LPMVM) in a fractional pole-pair linear force is transferred by a coiled actuator. The fixed parts include the said core and magnets [4].

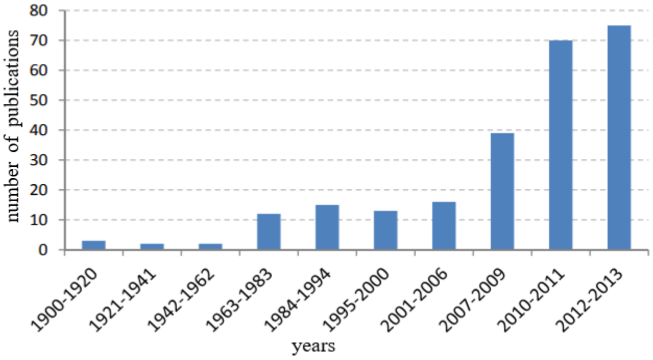

Fig. 1 - Number of publication magnetic gears (1900-2013) [2].

The histogram in Fig. 2 depicts studies on linear Vernier machines and research done by researchers and published in conferences and journals (IEEE) (the x-axis is the years, and the y-axis is the number of publications). This histogram shows researchers' growth, research, and development of linear Vernier machines in recent years.

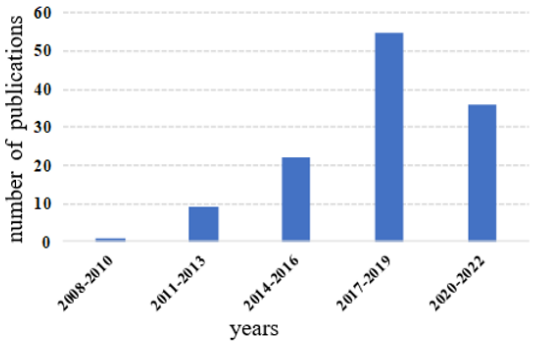

Fig.2. Number of publication LVMs (2008-2022).

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Rotary Vernier machines were first introduced more than a century ago [5], and numerous designs have since been presented. Along with this advancement, linear Vernier machines have begun to gain popularity among industrialists and researchers. As a result, the following section will go over the presented plans and the growth and developments that have occurred to express the current state of this technology, as well as review the articles on linear Vernier machines to cause the future development of this technology.

## II. DESIGN PATTERN LPMVM

Linear Vernier machines can have a variety of mover and stator structures that aim to create linear motion at the machine's output and to create linear motion. Fig. 2 shows the stator of the linear machine.

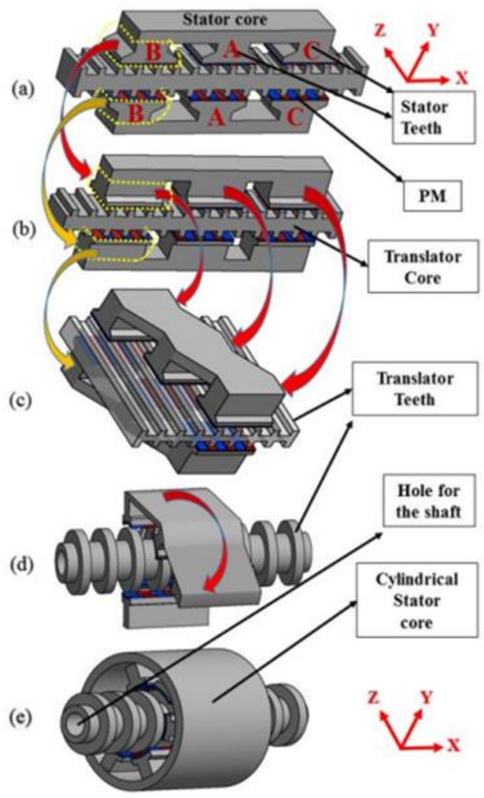


Fig.3. Development of VHM tubular technology from the flattish VHM [6].

The linear flat machine (Fig. 3a) served as the foundation for the most recent Vernier machine design technologies. Changing the tooth deformation in the stator by 90 degrees (Fig. 3b) led to the emergence of a new design (Fig. 3c). Figure 3d shows another advancement in the design of such machines.

The next step was to change the translator core. The cylindrical stator structure led to the linear motion of the mover (Fig. 3e), which was based on Fig. 3a of the linear flat machine. LPMs can have a variety of stators, movers, and toothed shape designs, but they all use linear motion [6], [7].

Magnetic materials in electric machines are classified into two types: (a) soft magnetic materials such as stator core laminations and (b) hard magnetic materials such as permanent magnets. The properties of these materials have a great impact on the performance of the linear machine. Many parameters can effectively produce a magnetic field in a linear Vernier machine. However, the most important ones are the material of permanent magnet magnets, the teeth' shapes, the coils' design, the amount of copper, and the type of placement.

It directly affects the core's magnetization and the Vernier machine's saturation points [6], [8]. Studies show that increasing the number of phases from three to six improves fault tolerance, reliability, and the sinusoidal voltage waveform of the machine [9].

## III. RECENT ADVANCES IN LINEAR VERNIER MACHINES

In recent years, a lot of research has been on Vernier machines, perhaps due to the PM feature and properties such as high energy density, which can create high torque at low speeds, and on the other hand, provide new topologies and efficiency. In addition, new skills and abilities have led to the expression of new concepts.

### A. *Application of permanent magnet materials*

The management of the use of PMs in the design has played a very important role in the final cost, and according to the different types of arrays and the variety of materials and shapes available, the best PM selections according to the design of machines.

In 1977, flux changes in air distances, the power factor of the Vernier machine, and its reliability were studied [10]. The Vernier machine has a higher torque than conventional flux modulation machines based on producing this amount of high torque due to the presence of pairs of magnetic poles in the machine design [11].

PM thickness significantly affects flux density and permeability and affects the machine's performance [12]. In some designs, the linear machine uses non-magnetic space between the magnet and the stator, improving the machine's efficiency and reducing the amount of leakage flux [13]. The placement of the PMs in the stator is critical to the operation of the machine. Figure 4 presents a new design that can be placed in **(i) Linear shape PM**, **(ii) V-shaped PM**, and **(iii) Linear V-shaped PM**, designed at a certain distance and angle in addition to a combination of poles with a particular magnetic orientation.

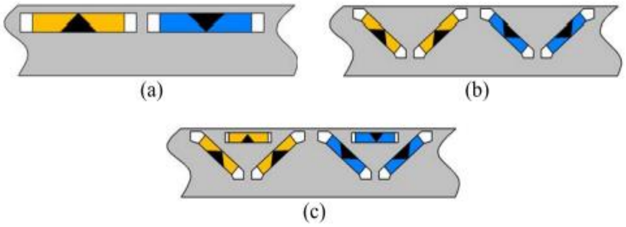


Fig.4. Three PM design types. (a) Linear shape. (b) V-shape. (c) Linear V-shape [16].

Among the new PM topologies, researchers' attention to the proposed Halbach PM arrays: where all kinds of placement in the actuator, efficiency, leakage rate, amount of flux in the air distance, ripple, and efficiency can have a significant impact on the machine's performance.

Fig. 5. shows the Halbach arrays for high-force density

Vernier machines, and the application of PMs directly impacts the final price of the machine [14], [15], [16], and [17].

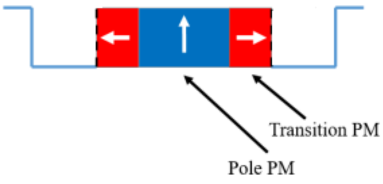


Fig. 5. Halbach PM array [18].

Fig. 6. Displays the other three PM arrays that researchers are most familiar with, in addition to the Halbach arrays. One of the factors in reducing the cost of linear machines is using fewer PMs in machine design [18].

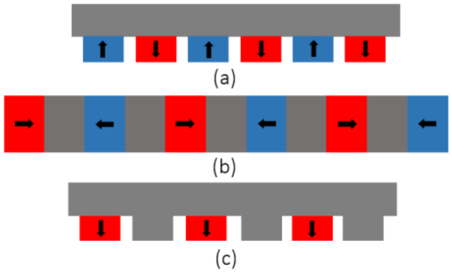


Fig. 6. Configurations (a) surface-mounted [16], (b) flux concentrator [13], (c) consequent pole [18].

The following results were obtained by comparing three designs **(a) surface-mounted** (SPM-LVM), **(b) Halbach** (SPM-LVM with Hablach), **(c) V-shape** (IPM-LVM) in LPMVMs with the same and no-load flux distribution in Fig 7. characteristics condition. In Fig. 8. the results of no-load LVPM flux linkage analysis and EMF analysis.

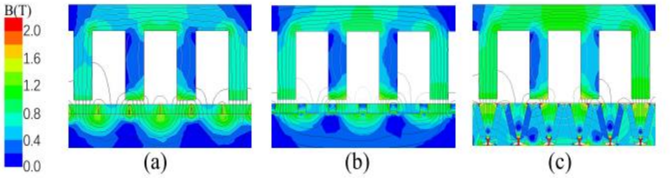


Fig. 7. No-load LVPM flux distribution three design [16].

### *B. low and High-temperature superconductor (LTS &HTS)*

One of the effective ways to get more current density from stator winding is to use high-temperature, and low-temperature superconductors (LTS and HTS) designs that can significantly improve the performance and efficiency of the machine, thus reducing the effect of the coil wire's end windings. Fig. 9 shows the proposed DCLVM-LTS machine design with a 40% improvement in current density using LTS [19].

Chaojie Shi and all colleagues in the line generator use HTS technology to receive more power and increase the power factor from 0.38 to 0.57 for DS-HTS-LVG, resulting in about 36% higher power density [20].

A high-temperature superconductor (HTS) can reduce the flux leakage in the LPMV machine and improve efficiency. The higher power in a linear machine and the equivalent power received from a larger machine can be obtained from a smaller machine [21].

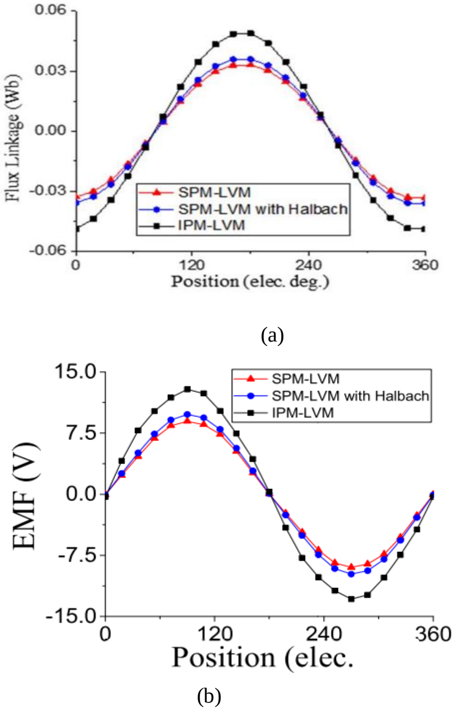


Fig. 8. Comparison three designs (a) Comparison no-load LVPM flux linkage (b) Comparison LVPM of EMF [16].

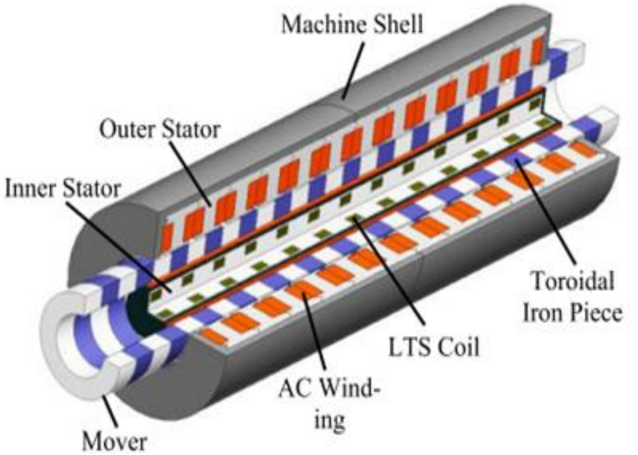
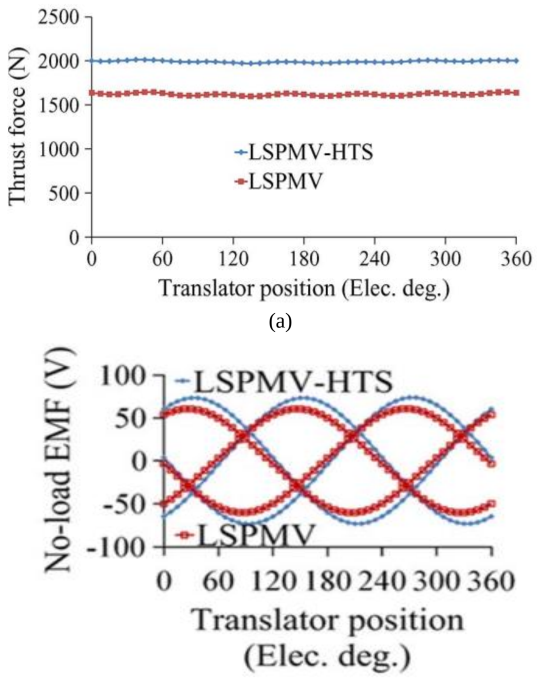


Fig. 9. View from DCLVM-LTS technology [19].

One of the applications of LPMVM with a lighter weight is the sea wave energy conversion (WEC) into electricity. A machine with less weight in the same situation would have a higher speed and, as a result, produce more electricity in generator mode and achieve more efficiency in generating energy from sea waves [22].

Considering HTS in a similar design, the LSPMV with HTS has more capabilities. Considering HTS in a similar design, the LSPMV with HTS has more capabilities. Compared to LSPMV with the LSPMV-HTS, more output values can be received from HTS in Fig. 10. [23].



(a)

(b)

Fig. 10. In (a) the thrust force of LSPMV and LSPMV-HTS (b) and the no-load EMF of LSPMV and LSPMV-HTS [23].

Most operating costs can be covered by the cooling system and HTS, which improve thrust performance while also raising the machine's overall cost. Consideration is given to the trade-off between cost and thrust performance [24].

The use of direct drive WEC (DD-WEC) line generators with HTS technology can extract higher power and, similarly, reduce winding losses [25], [26].

The DD-WEC extraction with HTS-DSTVM topology, located on the coil in the outer layer of the stator, increases the thrust and reduces the leakage flux and end-flux lines [27].

Fig. 11. shows that a DC field excitation coil can increase power multiplication, and an HTS high-temperature superconductor can improve stability [28].

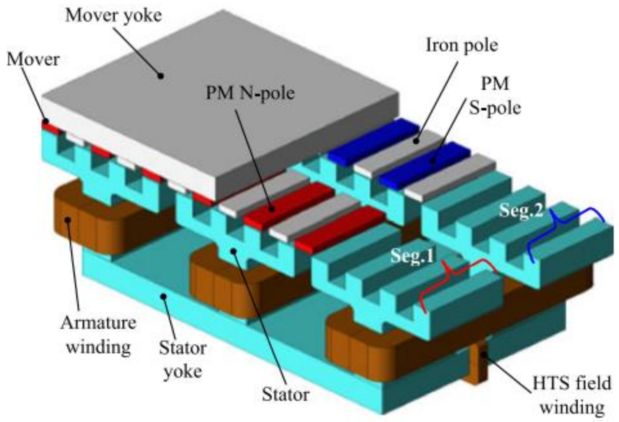


Fig. 11. A new LVPMM using HTS by DC field excitation [28].

In the double stator structure of the HTS-DSSLVM type, the application of HTS can improve the power factor by reducing the inductance and, thus, reducing the leakage flux in the machine [29], resulting in less electrical loss and higher torque stability [30]. In LPMV, the combination of permanent-magnet arrays can improve flux density and reduce leakage flux [31]. Here, the structures frequently introduced in different studies have been compiled to provide a better analysis. Also, the used parts were discussed in detail to identify the different structures. The collected data is summarized in Table I.

TABLE I
an Overview of the Issues Under Analysis

| An Important Structure Of Lvpmms | Highly Repetitive Content | References | Number Of References |
|---|---|---|---|
| **PM structure** | • Dimensions<br>• Arrangement<br>• Shape of placement<br>• Number<br>• PM distribution | [1], [11], [12], [13], [16], [18], [37], [38], [50]. | 9 |
| **Core & Tooth structure** | • Core with Flux barrier<br>• slot / pols<br>• Number of teeth<br>• Tooth dimensions | [4], [8], [31], [36], [47], [48]. | 6 |
| **Machine structure** | • Several phases<br>• Structure double<br>• Combined structures<br>• Tubular structures | [3], [6], [7], [14], [15], [19], [22], [27], [42], [45], [49]. | 11 |
| **winding structure** | • Coil shape<br>• How to place the coil<br>• Connections between coils | [9], [46], [51]. | 3 |
| **Conductor structure** | • HTS<br>• Superconducting | [20], [21], [23], [24], [25], [26], [28], [29], [30]. | 9 |
| **Controller structure** | • Control methods | [17], [32], [33], [35], [39], [40], [41], [43], [44]. | 9 |

## IV. WINDING, STATOR, AND MOVER DESIGN

From the design point of view, the three main parts of Vernier machines are discussed: **1) patterns of winding** and **2) mover and stator design**. Before that, the given general information in Table 1 is presented to get acquainted with the designers' ideas. It has hoped that the information collected will be beneficial and open doors for the advancement of future researchers.

### *A. Patterns of winding*

The winding design is influenced by the design of other parts of the LVPMV machine. The design of the coils and winding has been subjected to the design of the core of the machine. It can be done according to the design, and the behavior of the winding must be done carefully enough because it has a direct relationship with the performance and behavior of the machine.

According to the basic principles of the voltage of the input terminals of the PM machine, papers that have been in this field [23] define the 3-phase voltage relationship:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} R + \frac{d}{dt}\left\{ \begin{bmatrix} L_a & M_{ab} & M_{ac} \\ M_{ba} & L_b & M_{bc} \\ M_{ca} & M_{cb} & L_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} \varphi_{PMa} \\ \varphi_{PMb} \\ \varphi_{PMc} \end{bmatrix} \right\} \tag{1}$$

Where $i_c$, $i_b$ and $i_a$, are the currents, resistance the winding is the $R$, and $M_{ab}$, $M_{ac}$, $M_{ba}$, $M_{bc}$, $M_{ca}$ and $M_{cb}$ are mutual inductances, $L_c$, $L_b$ and $L_a$ are self-inductances, $\varphi_{PMc}$, $\varphi_{PMb}$ and $\varphi_{PMc}$ are PM flux linkage.

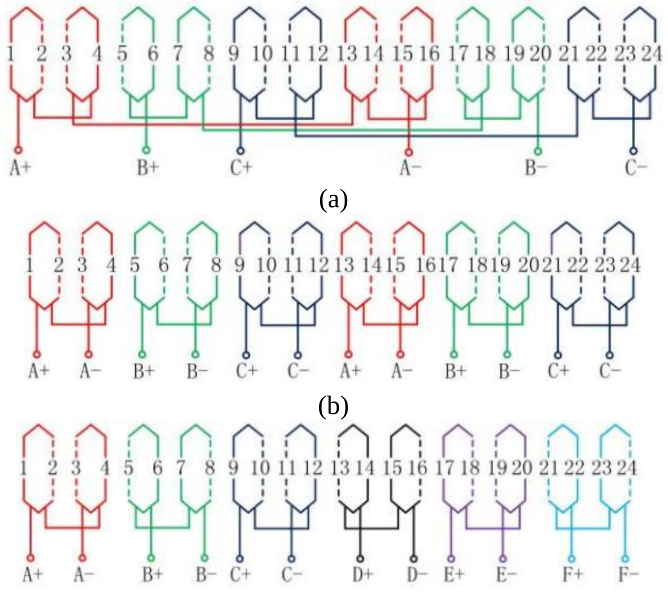
The most important relationship is given (2) in a Vernier machine

$$P_{pm} = N_s \pm P \tag{2}$$

In this relationship, $P_{pm}$ the PM pairs are the mover and mean the number of poles of the winding and the number of the stator flux teeth. Power factor equation (3) without considering the resistance [27].

$$PF = \frac{1}{\sqrt{1+(\frac{L_s I}{\varphi_m})}} \tag{3}$$

The windings' design is directly related to the machine's output parameters. Fig. 12. shows three nodes of the machine design for a better understanding [8].



(a)

(b)

(c)

Fig. 12. Three structures winding. (a) Machine three-phase (b) Machine of dual three-phase (c) Machine six phase [8].

Vernier machines have direct-drive systems, including the power supply, switches, and logic arrangements that improve engine control [32]. Vernier machine is a direct drive; if it is conventionally controlled, it is controlled $I_c$ by a three-phase and a sinusoidal waveform [33].

$$I_a = I_{rms} \sin(\omega t) \tag{4}$$

$$I_b = I_{rms} \sin\left(\omega t - \frac{2\pi}{3}\right) \tag{5}$$

$$I_c = I_{rms} \sin\left(\omega t + \frac{2\pi}{3}\right) \tag{6}$$

Since linear machines have a beginning and an end, several studies have been conducted on their initial and end effects (Fig. 13). The system's performance was affected by these machines because the flux rate in LPMVM's end effect is different [34].

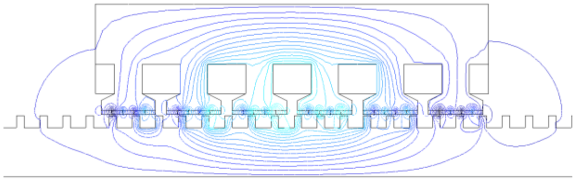
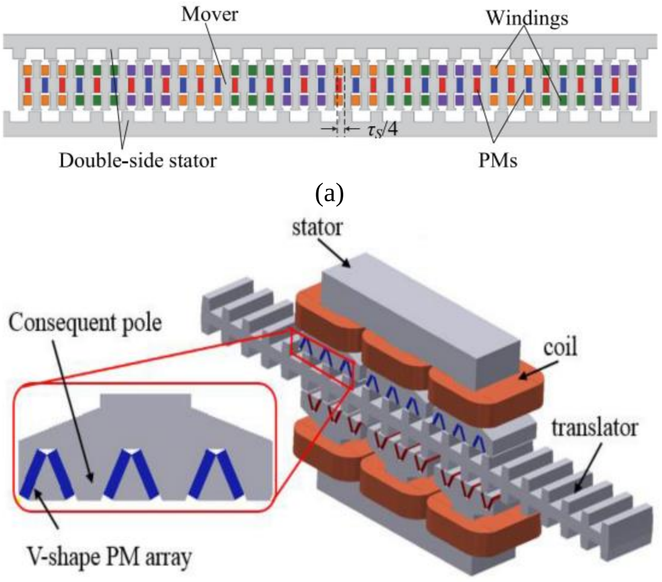


Fig. 13. End effect flux-line of LVPM [34].

## B. Mover and stator design in LPMVM

According to the research done in the design of the LPMVM machine, the operation conditions are a very important point and have been one of the important points in the design of the mover and stator. The design of the mover and stator depends on the conditions in which the LPMVM operates so that it can have the best performance.

There is a lot of research on the structure of linear Vernier machines, which can be referred to as double stator and double mover structures in Fig. 14. [35].



(a)

(b)

Fig. 14. (a) Double mover design [35], (b) Double stator design [37].

Of course, researchers have proposed many designs, such as cylindrical linear Vernier machines or the use of different PM arrays in the design.

Linear Vernier machines can be used to **(i) produce compressive**, **(ii) ascending or descending**, and **(iii) tensile forces** [34].

Changing the three phases in a linear machine can be asymmetrically reduced using a different coil (copper) and core (iron) structural design. The design of a three-phase linear machine (3MS) is based on three separate parts with non-magnetic spacers, such as aluminum. The places of the phases are ABC, CAB, and BCA, respectively; each coil with the same phase is in the other part of the series machine (Fig. 15), leading to asymmetric reduction, reduced ripple, and better control. Various designs involving putting magnets in the primary and secondary parts can help alter the thrust density of the machine [36].

The diameter of the magnet, type of magnet, and placement of magnets can considerably influence the function of the electric machine. Moreover, they affect another critical parameter, the air distance, which changes the air density flux, affecting the force density and, thus, the power factor in the machine [37].

Fig. 1. presents a new design that has been able to provide a special arrangement for the coils and a special arrangement for placing the coils in the DFM-CP-LPM and with two flux barriers made of aluminum, the machine is divided into three parts, including module 1, module 2, module 3, able to have an almost symmetrical magnetic circuit.

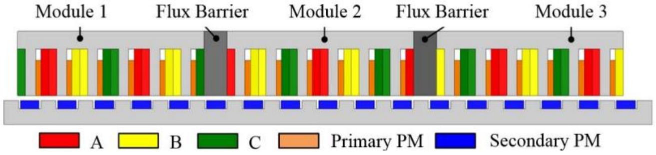


Fig. 15. Configuration of the DFM-CP-LPM [36].

## V. FAULT TOLERANCE AND RELIABILITY

Reliability is a recognized feature of linear Vernier machines in industrial applications. One way researchers have proposed is to use more than three phases. In the event of an error in one phase of a multi-phase machine and being in a situation where the machine must continue to operate, the machine can be forced to operate, which has increased the reliability of multi-phase machines [8], [9].

Many researchers have researched linear Vernier machine drives. Vernier machines are direct drives. These drives have been gradually inspired by the drives of conventional permanent magnet electric machines. Sensors can provide accurate parameter data to ensure better machine control to get the phase's location, speed, voltage, and current and measure the force [38]. With the advantages of linear machines in electric trains, the need for location, and the increased cost of implementing position sensors, the article [39] introduced a drive without a position sensor for this project.

Control with two inverters is a design including two voltage power supplies. The first is a DC power source, and the second is a capacitor responsible for supplying reactive power and correcting reactive power, suitable for heavy-load conditions [40]. The controller with a floating capacitor in OEW-LVPM can operate under open fault conditions in open circuit conditions [41]. In linear Vernier generator strategic applications, such as wave energy due to voltage and current tolerances, the output power from the generator terminals is rectified and converted to DC (Fig. 16). The DC is converted to AC by the inverter to output the voltage, and current waveform with the ripple fluctuations lower (the sea wave is not always uniform) power factor and the capacitor improve it [42]. An optimally designed controller can significantly reduce the amount of THD and extract maximum power from the system [43]. The DTFC controller in the LVPM machine is error-resistant [44].

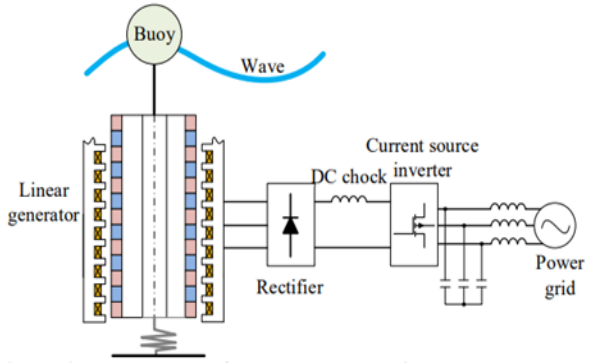


Fig. 16. LPMVG technology for wave power [42].

## VI. APPLICATION OF LINEAR VERNIER MACHINES

The linear Vernier machine has been designed based on a magnetic gearbox. This machine has unique features, making it one of the choices in the industry for linear movement. With recent advances, the linear Vernier machine is a good choice in linear applications.

Vernier machines are low-speed and have a high driving force density. Depending on the structure of the Vernier machine, it can have multiple industrial applications. The structure of LPPMV machines provides more thrust and less toothed force than LVH machines, making them more suitable for low-speed applications [45].

The high torque originates from various features of this machine, including the ability to stretch the linear movement of objects, lift heavy loads, generate a compressive force, etc.

- ***Wave energy*****:** Vernier linear machine is suitable for converting the energy of waves in the sea or ocean into electrical energy, ~0.5 m/s, and >1MW;
- ***Free-piston generator:*** The application of the machine is linear, 10~20m/s and ~10kW.
- ***Railroad transportation*****:** It has been used in the traction system of rail transport and inner-city trains.

The use of the linear device largely depends on the device's design. The number of slots/poles affects the performance and application of the machine [46], [47].

The amount of leakage flux in PMLV differs in various conditions: the highest amount of leakage flux is in the machine teeth, and its amount varies according to the machine's location [48].

The yoke thickness in the design of a DSTWLPMVM results in a tendency to create a small thrust wave for the machine, although it imposes a restraining force on the end tooth, which can be reduced by design optimization [49]. In the LVPM machine, the coils and the machine's structure affect thrust density, despite the high thrust density provided by the Halbach array [50], [51].

## VII. CONCLUSION

An overview of what has been said about the various methods and designs that have been expressed so far. Due to the many efforts made by researchers developing the trend of this machine, the attention toward the machine is increasing. Located and see more enthusiasts than in the past due to the developments. Many designs have been proposed for this machine so far with development approach, performance improvement, power factor, economical designs, efficiency increase, accuracy increase, drive performance improvement, power density, development plans, and efficiency, and it is hoped that this research can be used to effective development steps will help future researchers. In this article, the most critical comprehensive plans have been done to help dynamic researchers in this field with a review approach.

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