IET Renewable Power Generation

Review Article

Comprehensive review of a linear electrical generator for ocean wave energy conversion

ISSN 1752-1416
Received on 25th May 2019
Revised 8th November 2019
Accepted on 2nd December 2019
E-First on 26th February 2020
doi: 10.1049/iet-rpg.2019.0624
www.ietdl.org

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Abstract: Ocean waves are an abundant source of energy. This energy of the ocean can be converted into useful electrical energy using electrical generators. Linear generators have received tremendous attention in energy harvesting technology due to its unique ability to convert the energy without any intermediate converter. The principal objective of this study is to present the various types of linear electrical generators which have been investigated so far for direct drive ocean wave energy conversion and describe the working principle of each type with the difference. In this study, after a brief description of the basic electrical generator, various types of generators, including the linear and flat generators available in the literature are reviewed and discussed based on the design configuration of different types of magnet arrangements. Linear generators have been compared in terms of core type, flux path, the location of PMs, etc. The research gaps have been identified and future research directions have been suggested.

1 Introduction

Due to the increasing power demand day-by-day, depleting non-renewable energy sources has led to producing electricity using renewable energy sources of the solar, wind, and ocean. Among all the renewable energy sources, solar energy has been widely used and implemented. The sustainable power sources, e.g. wind and daylight, ocean waves, etc. exist everywhere, and can be utilised to produce electrical power for commercial purposes. In recent years, ocean wave energy emerges as one of the cleanest and safest modes of converting mechanical energy to electrical energy. Ocean waves can be produced by various methods, e.g. gravity, solar energy, seismic tremors or planetary powers. However, the larger part of ocean waves is driven by twist blowing over a region of a liquid surface, alluded to as wind waves. Their speed relies upon the wavelength, period, wave height and depth of the sea. As shown in Fig. 1, the distance across a water molecule movement circle diminishes with water profundity [1].

Fig. 1 shows that about 95% of the vitality in the waves is accessible between the surface and a profundity equivalent to a fourth of the wavelength for profound water [2]. It is estimated that the total ocean waves energy in the world can be used to meet 2% of the world's total energy demand [3]. Contrasted with conventional vitality sources, ocean waves create fewer waste items, for example substance contamination and carbon dioxide, which implies that the negative impact of ocean waves on the earth is insignificant. Due to the critical environmental change caused by emitting carbon dioxide in the air, the sustainable power source is receiving more and more attention all over the world now than before.

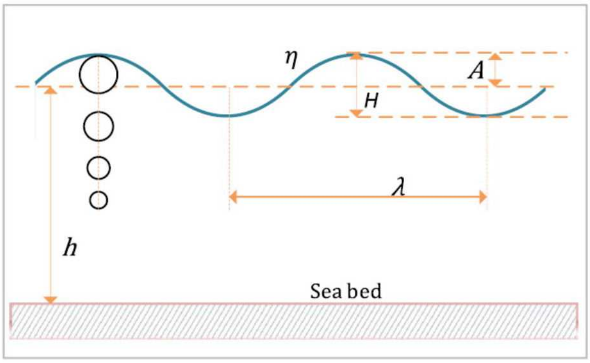

Fig. 1 *Regular wave with a finite wave-length and vitality depth [1]*

Wave energy extraction devices generate up to 90% power from the source, which is far more than solar and wind energy extraction devices, while wind and solar extraction devices generate only 20–30% power from the source [4–6]. A simple wave to wire approach has been described in [7]. The wave to wire signifies the process involved in converting the ocean waves energy to electrical energy. Some work on the wave to wire model has been reviewed in [5, 8] and presented in [9, 10].

Fig. 2 shows that the input wave is converted to electrical through primary and secondary conversions. The primary conversion includes various methods like direct and indirect harnessing and secondary conversion includes the generator. Linear electric generators have been widely used for this conversion process [11–21].

In conventional rotating generators, for high-speed operations, a mechanical interface like gearbox, hydraulic pump and turbines were required, which lengthen the size of the system and incur mechanical losses. However, with a direct drive linear electrical generator, the mechanical interface has been deleted. A direct-drive linear generator directly converts the mechanical energy to electrical energy without any mechanical interface. This direct drive system also reduces the cost of the system. For the same purpose, various types of linear generators have been designed for the utilisation of ocean wave motion energy [22]. Linear and rotational generators are different in terms of their magnetic and geometric structures. Among various types of linear generators, linear tubular generators are the most efficient and promising one.

2 Linear electrical generators

Linear electrical machines are the unfolded rotational machines. It contains a stator as a stationary part and a translator equivalent to a rotating part. The translator can be placed either inside or outside of the generator stator. It has been found that the power density of an external translator generator is seven to eight times higher than that of the internally designed translator generator [23]. Rotational machines produce torque and rotational motion while the linear machine produces force and translational motion. To improve the

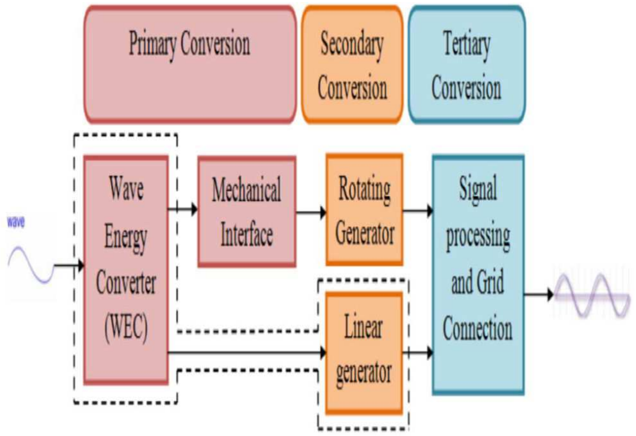

Fig. 2 *Schematic diagram of the wave to electrical energy conversion process [7]*

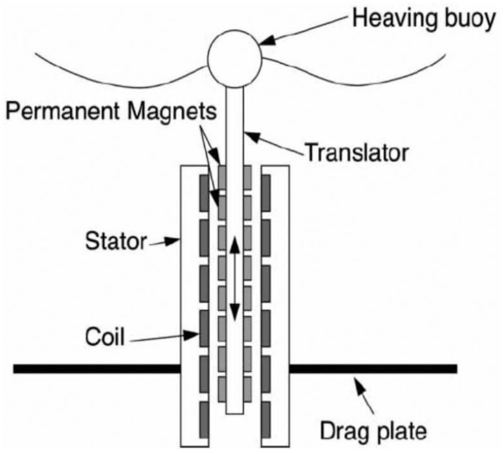

Fig. 3 *Basic linear electrical generator or power take-off device connected with buoy [13]*

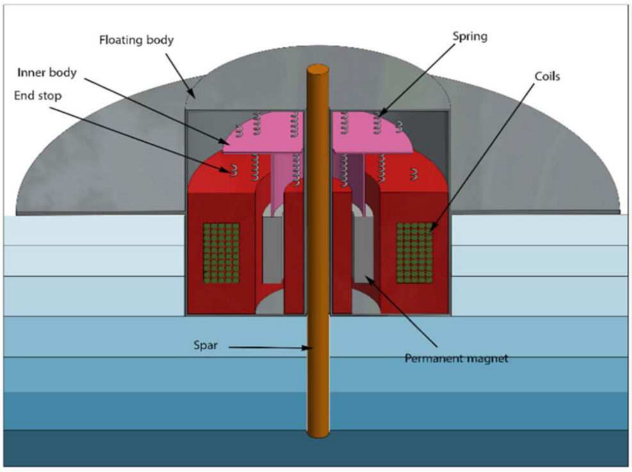

Fig. 4 *Schematic diagram of two fully floating body system with a tubular linear generator [26]*

output electromotive force efficiency of the machines, either input current or magnetic flux density in the air gap must be increased [24]. By increasing the current, the electromotive force or voltage output can be straight away increased, but this will also increase the temperature. Thus, the problem of heat dissipation will occur. Another way of increasing electromotive force output is to use large size magnets which will certainly increase the size of the system. Thus, reorganising the magnet poles can increase the efficiency of the system. For this reason, the Halbach magnet arrangement is now being used in linear generators [24, 25]. Various types of linear electrical machines have been used for ocean wave energy conversion. In Fig. 3, the principle layout of a linear permanent magnet (PM) synchronous generator is shown.

As seen from Fig. 3, the heaving buoy moves with the movement of ocean waves and this movement of the buoy will tend to move the translator, which is connected to the buoy. This gives rise to a vertical movement of the translator and hence by the principle of electromagnetic induction, the generator coils start to generate electrical current [13].

For wave energy conversion, single body heaving buoy and two fully floating body buoy wave energy converters (WECs) have been designed. A novel topology for solving the problem of mooring, seawater corrosion, is derived in [26]. Fig. 4 presents the two fully floating body systems. PMs can be installed on either translator or stator. Various linear electrical machines have been developed so far for the same purpose. These can be asynchronous or synchronous linear machines. For long term investment in the linear generator, the magnets should be selected so that it should not lose the magnetisation after a long time. A far-reaching investigation and assessment of 18 frameworks of Direct Drive Power Take-offs comprised of eight direct generators and ten straight to revolving systems have been performed in [27] for their mechanical and electromagnetic properties.

2.1 Linear induction generator

In comparison to other machine topologies, due to the absence of slip rings and collector in induction machines, linear induction machines are less costly [28]. A linear Faraday induction generator for ocean wave energy conversion is detailed in [29]. The electrical current is produced due to the relative motion between the stator and rotor. The disadvantage of this machine is that a high excitation current is required due to the low reactance of the winding. This, in turn, reduces the efficiency of the machine [30]. A new normalised control algorithm is proposed in [31] for voltage control of a single-phase self-excited induction generator. Fig. 5 shows the linear tubular induction generator. Any configuration of the flat, tubular, single-sided or double-sided generators has the bad effect of the large air gap which in turn reduces the efficiency. As mentioned in [32], linear induction generators show the extreme characteristics of the robustness and the least cogging force. The cogging force is undesirable in the generator. The cogging force is produced due to the interaction between the rotor and stator magnetic fields. The interaction of two fields tends to create jerks in the generator which are not desirable. Thus, the cogging force should be as small as possible. A linear tubular asynchronous induction generator was built in [33] and also, a large scale direct-drive linear generator test bench was successfully built by Baker *et al.* [34].

2.2 Linear PM tubular generator

The operating principle of the PM tubular linear machine is electromagnetic induction. Electromagnetic or magnetic induction is to produce an electromotive force across an electrical conductor in a changing magnetic field [35]. Electrical Machines with dual Halbach array are based on the Lorentz force law, i.e. the force is generated by the interaction between the magnetic fields of PMs and the current-carrying conductors. Certain difficulties have been observed in manufacturing such PM generators. As the force is perpendicular to the direction of the translator motion, the translator must be perfectly aligned for such type of movement. Rare earth magnets have a high value of residual induction, thus possess high magnetic field strength and perfect for linear permanent generators. Neodymium magnets (NdFeB) are widely used for this purpose. Over the last 17 years, the cost of neodymium magnets has sharply increased. The total cost of a linear generator is determined by the cost of the PM. Also, PMs tend to lose magnetisation after a certain time [35], which is a drawback. Superconductor magnets with superconducting coils are a promising solution for this problem [36, 37], where the core winding is made up of superconducting material instead of steel which reduces the core losses. High-grade ferromagnetic cores namely Armco DI-MAX M27 and DI-MAX HF 10, are used in a high-temperature superconductor linear generator. These materials further reduce the heat energy dissipated due to the core losses. A direct-drive PM high-temperature superconductor linear generator (HTSLG) is proposed in [36] where high graded DI-MAX HF 10 ferromagnetic cores are used to prevent temperature rise by reducing the core loss during the generation of electrical power. Also, Vitroperm 500F and Supermendur magnetic cores are proved to be able to produce the maximum power output and larger magnetic field intensity than conventional steel cores. Instead of the NdFeB PM, N52 was used which had the highest magnetic remanence, as shown in Fig. 6 [38].

With different types of shapes of the coils, the output power can be improved. A few types of such coils have been proposed and compared in [39]. Triangularly-shaped coils were proved to have better output than square-shaped coils. A linear tubular PM generator consists of armature winding, iron core, PMs, and field winding is shown in Fig. 7. A long translator is employed in [40] to reduce the winding copper wire losses and improve the efficiency of the system. There are so many other design techniques to optimise the design of a linear generator. In [41] square-shaped cross-section is used for the stator, and design parameters have been optimised to maximise the magnetic flux density.

Linear generators are designed by utilising an iron core, which is smaller than the air-cored generator [42, 43]. Tubular PM linear generators having iron cored stator are proposed in [44]. This type of linear generator shows a significant harmonic content in the induced voltage in the generator. To reduce the iron losses, air-cored machines have been investigated in [45]. Due to the absence of iron, no need to overcome attraction forces thus leads to an advantage of easy to manufacture. Various experimental tests like no-load, on load and short-circuit tests, have been performed on the air-cored tubular generator in [45]. The results proved that the air-cored machines have an advantage in mechanical design. Exceptional ferrite cores can also be used [46]. A cost-based optimisation for the air-cored topologies using a finite element has been conducted in [47]. Though the air-cored linear generator proved to give a low cost and compact design, still it has low power output. The induced voltage is considerably higher in iron cored stator than the air-cored stator [48]. In [49] variable air gap is considered which gives better results in terms of preventing demagnetisation. Variable air gap linear generator gives more electrical power as compared to the fixed air gap length generator under the same operating conditions. A linear tubular generator presented is shown in Fig. 8. Power electronic devices are required to be set up between the generator and the power grid. The magnitude and frequency of output voltage should be nearly equal to the grid design (of 380 V @ 50 Hz). A linear tubular generator is compared with a four-sided generator in [50].

It is shown that the performances of the linear tubular and four-sided permanent magnet generators are similar regarding the induced voltage or coil magnetic flux linkage density, but the four-sided generator is heavier than the tubular generator for the same dimensions, which tends to cause larger friction losses. Flux-switching tends to reduce the cogging force effect. A tubular superconducting flux-switching PM generator produces the least cogging force as compared to the linear Vernier hybrid and linear flux-switching machine [51].

Fig. 9 shows the cogging force comparison of the three types of machines. There is no limitation of PM size in flux switching machines as compared to Vernier Hybrid Machines (VHMs). A study on multivariable linear generators showed that the structure of the linear generator could be optimised using finite element analysis software [52]. The shape of magnetic poles was so modified that the intersection between the coils and magnetic flux was increased. The finite element method magnetic (FEMM) is a powerful simulation tool for solving magnetic field problems. Radial PMs are used in [53] and FEMM software has been used to model and design the generator. Using the 2D finite element analysis, a simple linear generator has been designed in [54]. The linear generator can also be implemented in wind energy or ocean wave energy conversion.

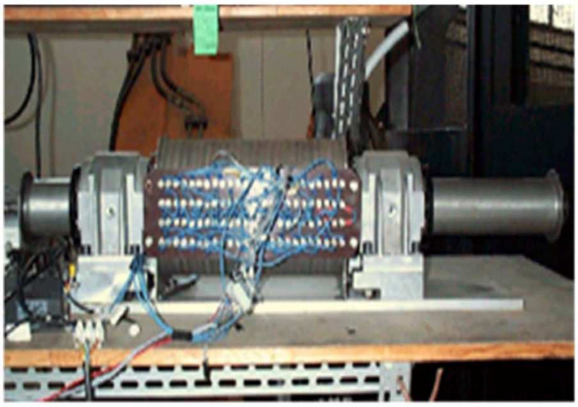

Fig. 5 *Schematic photo of linear tubular induction generator [32]*

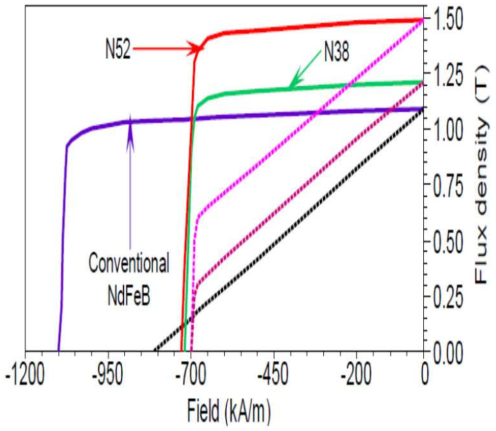

Fig. 6 *Comparison of the magnetic field characteristics of the conventional NdFeB, high graded N38, and N52 PMs [38]*

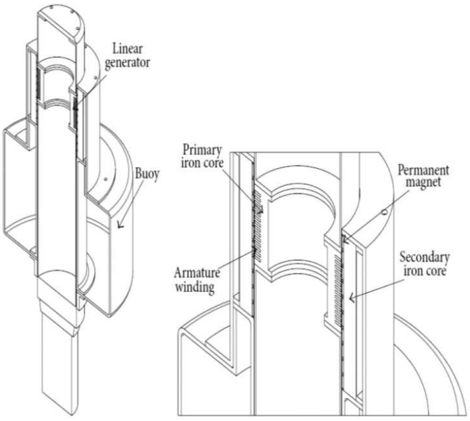

Fig. 7 *Structure of LTPMG [40]*

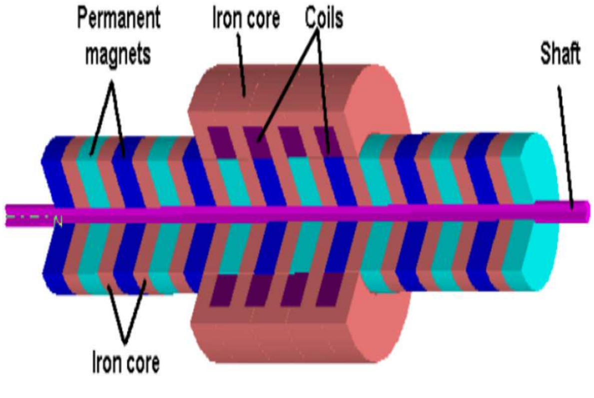

Fig. 8 *Structure of a tubular linear PM generator proposed in [44]*

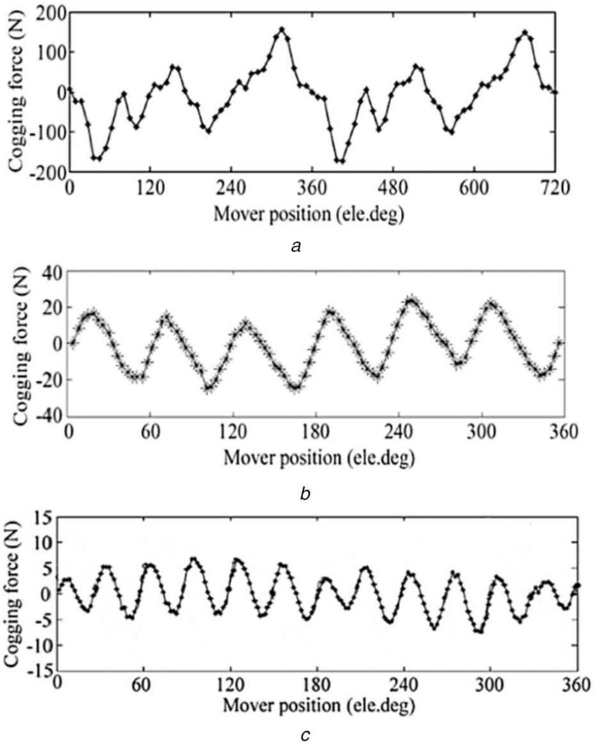

Fig. 9 *Cogging force comparison*
(a) Linear Vernier hybrid machine, ***(b)*** Linear flux switching machine, ***(c)*** Tubular superconducting flux switching machine [51]

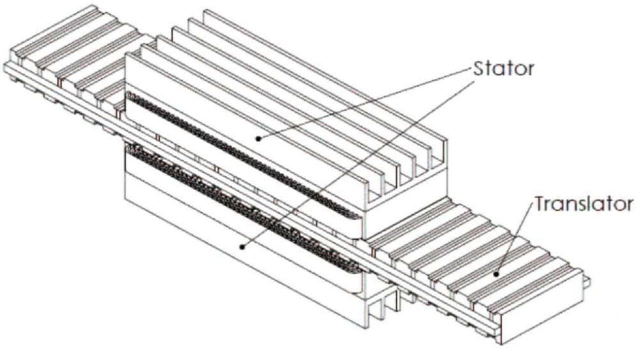

Fig. 10 *Double-sided linear synchronous generator [59]*

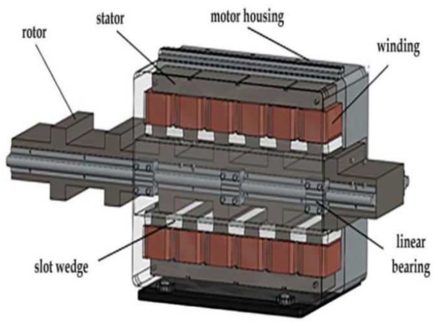

Fig. 11 *Basic structure of a double-sided linear switched reluctance generator [67]*

2.3 PM linear synchronous generator

In a PM synchronous generator, the excitation is provided by the PMs. The translator and magnetic fields move at the same speed, which is referred to as synchronous. A PMLSM with magnets on the translator was used in [55] for Archimedes Wave Swing (AWS). A proportion differentiation (PD) controller is designed for the closed-loop control of the linear synchronous machine in [56]. In [57], a linear PM synchronous generator has been used for ocean wave energy conversion. The results show that the cogging force that is perpendicular to the motion of the translator has been reduced. Linear tubular PM generators (LTPMGs) having iron cored stator shows a significant harmonic content in the induced voltage. A linear field wound synchronous machine has been shown in [58] where the fine magnetic coupling of the longitudinal flux machine was combined with the force density of the transverse flux machine. As can be seen, the generator is double-sided which reduces the bearing load and the stator is kept shorter than the translator. Also, in [59] implementation of a double-sided flux concentrator in the synchronous generator has proved to give better flux dispersion than that of the single-sided flux concentrator.

Fig. 10 shows the double-sided linear synchronous generator. The topology of the field wound machine is like that of the existing linear induction machines, with the only difference that coil turns are built in the translator. Otherwise, in induction machines, aluminium/copper bars have been used in the translator. Force density and loading can be increased in such double-sided machines [60]. There could be two possible field configurations that can be used; longitudinal and transverse flux type configurations. The maximum power output has been observed by the self-synchronous maximum power controller for such doubly-fed field wound machines [61].

2.4 Linear switched reluctance generator

Such type of generator is comparable in certain aspects to switched reluctance rotating generator. Magneto-resistive minimisation principle is used in the switched reluctance machines [62, 63]. These machines are reliable as compared to linear induction machines. The robust nature of such machines is beneficial for ocean wave energy conversion. Due to high efficiency, and simple construction, a switched reluctance generator for variable speed wind energy conversion systems is presented in [64]. The paper conducts a comprehensive review of switched reluctance motor and generator shows that such machines are a cost-effective solution for small scale rural applications [64]. In Fig. 11, a basic structure of double-sided switched reluctance linear generator is presented. The operation of such machines is based on a power electronic converter, which is controlled by the rotor position. During the operation, active stator poles attract rotor poles. By means of power electronic switches, the current is changed to the next phase when the stator and rotor poles are close enough. The active stator drives the rotor through the power electronic converter. This machine gives high efficiency, lowest manufacturing cost due to the absence of magnets, high torque output, and low inertia. Though it has so many advantages, yet it has not been implemented successfully due to the requirement of highly accurate and efficient power electronic switches and controllers. The output voltage ripples for such switched reluctance generators have been reduced and the efficiency of the generators has been improved in [65]. A linear switch reluctance generator-based power generation system is shown in Fig. 12. The matrix and tensor approach are applied to model the switched reluctance machine in [66]. The mathematical model is validated using finite element analysis.

2.5 Linear superconducting synchronous generator

A tubular superconducting flux-switching generator (TSFSG) is presented in [52]. MgB2 superconducting windings are preferred because of their low cost and simple manufacturing [68]. The small bending radius of MgB2 makes it more suitable for electrical machine windings. In such type of generators, superconducting magnets have been used instead of conventional PM. The demagnetisation effect of the magnet is reduced to much extent by using such types of superconductor magnets. Also, various direct-drive superconducting generator topologies have been described in [69] for wind energy conversion.

2.6 Variable reluctance PM (VRPM) machine

The most reliable machine which has been used so far for ocean wave energy conversion is VRPM machines. Various topologies of such machines have been described in [70, 71]. A study on the

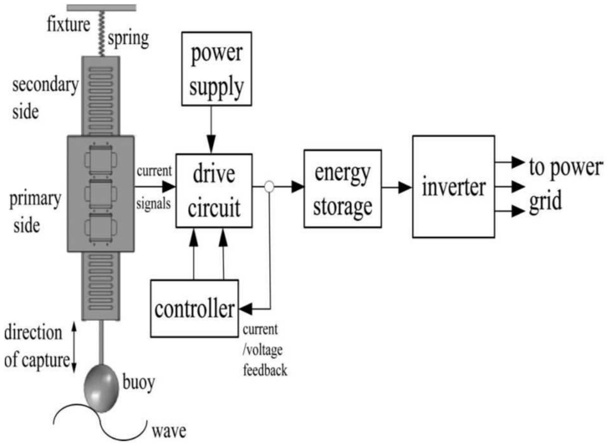

Fig. 12 *Linear switched reluctance-based generation system [65]*

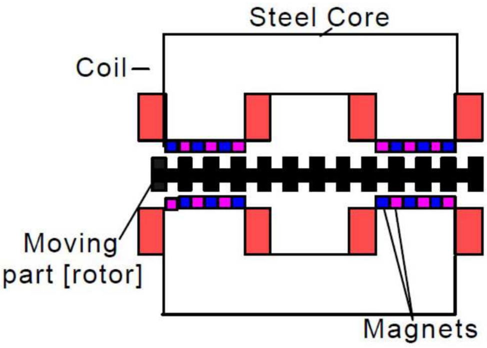

Fig. 13 *Schematic diagram of a single-phase linear VRPM machine [38]*

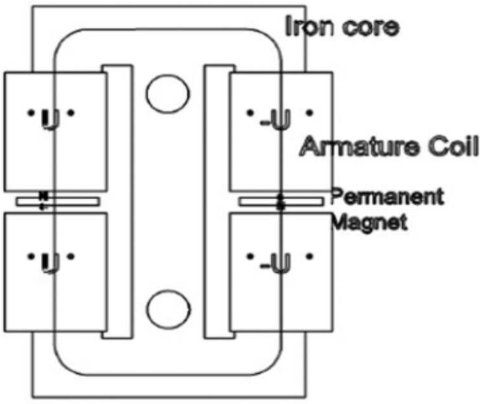

Fig. 14 *Basic configuration of transverse flux linear generator TFLG (armature and field inductor) [82]*

torque production mechanism in hybrid excited variable reluctance machines (HEVRMs) is presented in [72]. The study reveals that these machines are run by reluctance torque. The torque calculation for the variable reluctance machines with different switching strategies comes out to be the same as that for DC machines, PM synchronous machines or field wound synchronous machines. The basic equations and the formulation have been derived in [72]. A doubly-fed linear generator with transverse/longitudinal flux has been discussed in [73].

In Fig. 13, a single-phase linear VRPM is shown. These machines exhibit high shear stress as compared to other conventional machines. Mueller [74] describes two types of variable reluctance generators in where it was observed that transverse flux machines (TFMs) are better than the longitudinal flux machines (LFMs).

All the flux switching PM machines consist of a heavy solid translator. A split translator secondary stator with a cavity inside the translator is introduced in [75]. The stator has been divided into the main and supporting stator. Instead of solid construction, there is a cavity inside the translator to reduce its weight and to accommodate the supporting stator. A design procedure for shape optimisation of flux switching machines using a genetic algorithm is presented in [76]. Using this method of shape optimisation any type of linear generator can be optimised for better power output results. By only varying the core shapes, electrical power generation dramatically increases. Transverse flux machines are expensive and complicated to manufacture [77].

Various types of transverse machine designs have been developed, which can increase the magnetic field intensity [78–81]. The PMs mounted on either stator or rotor provides the required magnetic flux. Trapanese and co-authors [82] presented a double-sided transverse flux linear synchronous generator as shown in Fig. 14 where the configuration designed for transverse flux machine is shown. Due to the low power factor, these machines are suitable for low-speed applications [83]. Topologies of the conventional induction generator, switched reluctance generator, PM synchronous generator and transverse flux machine have been compared and presented in [84].

In longitudinal flux configurations, the PMs are most likely placed on the translator and winding is mounted on the stator. The magnetic coupling is improved with such configuration. These longitudinal flux linear generators have an immanently low load angle. The electrical efficiency of 86% is observed for such configuration as shown in Fig. 15 [85]. The design variables of longitudinal flux generators are optimised in [86].

To increase the torque, a great number of poles are good for both the configurations, i.e. longitudinal and transverse. According to [83, 87, 88], the transverse flux linear generators are better in the performance than the longitudinal flux machines for ocean wave applications. The performance of the two has been compared in [89] for Turret application using finite element analysis.

2.7 Vernier hybrid machine

Vernier hybrid machines are a member of variable reluctance machines. These machines offer a low power factor, which is not desirable. Though the power factor can be improved by auxiliary DC field excitation winding [90]. Vernier machines using such hybrid excitations have been illustrated in [91]. Such hybrid excited machines show the characteristics of both the rotational Vernier PM [92] and consequent pole PM machines [93]. In all the Vernier hybrid machines, magnets are placed on the stator to create the magnetomotive force and the rotor is slotted to modulate the magnetic field [94, 95]. The cost and overall weight of Vernier hybrid machines are smaller than the pole splitting PM Vernier machines [96]. A dynamic model of the linear Vernier hybrid machine is presented in [97] and the configuration of the cylindrical Vernier hybrid machine is shown in Fig. 16 [98]. A new topology of linear Vernier hybrid PM (LVHPM) generator with E-core stators and a segmented chamfered translator is presented in [99]. As compared to other linear machine designs, this new topology of the LVHPM generator was proved to have a better magnetic flux path resulting in a significant reduction in the

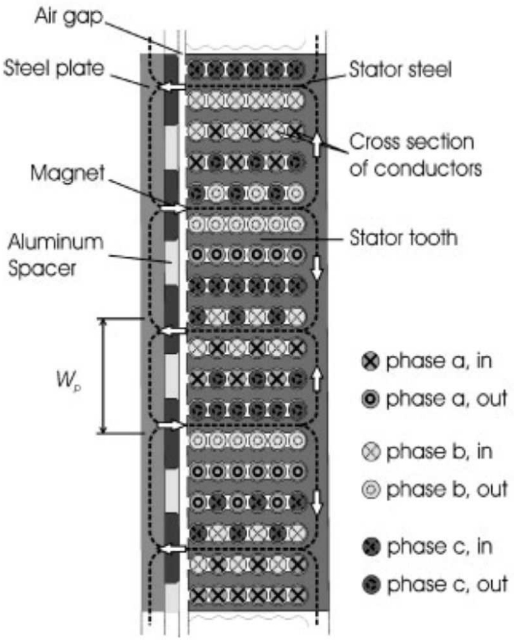

Fig. 15 *Cross-sectional view of longitudinal flux generator [85]*

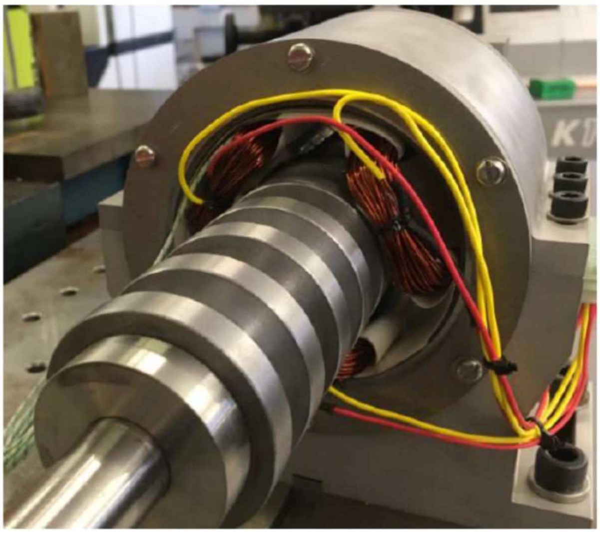

Fig. 16 *Cylindrical Vernier hybrid machine [98]*

Table 1 Design requirement and constraints for various types of linear generators

Type	Requirement	Constraint
Linear PM synchronous generator	Translator and magnetic field move at the same speed, i.e. synchronous	PM's on translator
	Double-sided stator	Low shear stress
Linear switched reluctance generator	Power electronic switches and controllers	Low inertia
LTPMG	Force is perpendicular to the direction of the translator motion. So, the translator must be perfectly aligned for such type of movement.	Requires a large amount of PM's
	No end winding	
	High force density	
	Can have ironless stator	
Linear flux switching generator	High Power factor	Requires a large amount of PM's
	PM's in the stator	Expensive and complicated
Vernier hybrid machine	PM's in the stator	Low power factor
	Slotted translator	
	Combine C core units to make one E core to reduce the volume of the machine	
	High shear stress	

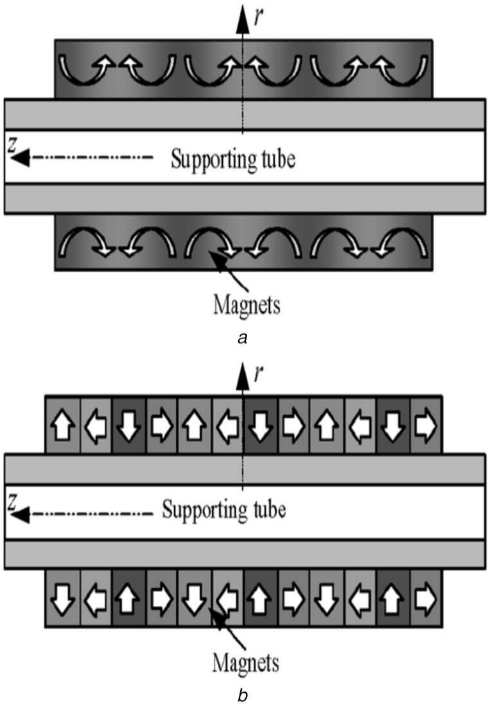

Fig. 17 *Armature of the tubular PM machine*
(a) Halbach magnetisation, ***(b)*** Quasi-Halbach magnetisation [103]

translator mass while improving the performance. The E-core model was proved to have a higher back EMF than the baseline C-core model. This is due to the greater magnetic flux density and reduced leakage across the air gap to the segmented chamfered translator. The optimisation can be improved by using various other techniques like genetic algorithms and neural networks. The design requirements and constraints for various types of linear generators have been summarised in Table 1.

3 Linear machine with different types of magnetisation patterns

Several machines have been designed with different magnetisation patterns, which certainly improve the magnetic flux density and output power. The magnetisation patterns of PMs in linear generators have been designed to be radial, axial, Halbach, and quasi-Halbach. In radial magnetisation patterns, PMs are surface mounted whereas, in axial magnetisation patterns, magnets are buried and magnetised parallel to the air gap. Two neighbouring opposite pole magnets are separated by ferromagnetic pole pieces [100]. Due to easy construction, axial magnetisation is preferred in [101]. Lower cogging force and fewer ripples are the benefits of the radial magnetisation design [102]. Halbach arrangement patterns of magnets give the best result in terms of less cogging force, fewer harmonics in the electromotive force and high efficiency [103].

The magnet arrangement patterns of the Halbach and quasi-Halbach arrays have been shown in Fig. 17. Halbach magnets give the maximum magnetic effect. In such an arrangement, the magnetic field resides on one side of the PM, and the other side remains unmagnetised. This gives a strong magnetic field on the one side. To enhance flux density in the air gap and achieve better output performance, our research team proposed a dual Halbach arrangement of magnets, which is believed to perform better than

Table 2 Comparison of different magnetisation directions [105]

Configuration	Force density	Force ripple	Construction cost	Mechanical integrity	Technological maturity
axial	very good	high	average	high	average
radial	good	average	low	average	high
quasi-Halbach	excellent	low	high	low	low

Table 3 Summary of the linear generator prototypes for ocean wave energy conversion

References	Generator type	Structure	Excitation	Core type	Location of PM	Installation of PM	Flux patterns	Power rating
Polinder *et al.* [55]	synchronous	flat (double sided)	PM (NdFeB)	iron	translator	surface mounted (radial)	longitudinal	1 MW
Leijon *et al.* [106]	synchronous	flat (four-sided)	PM (NdFeB)	iron	translator	surface mounted (radial)	longitudinal	10 kW
Cappelli *et al.* [107]	synchronous	tubular	PM (NdFeB)	iron/ slotless	translator	interior (axial)	longitudinal	3 kW (small scale)
Mueller *et al.* [45]	synchronous	tubular	PM	air	translator	interior (axial)	longitudinal	30 kW
Prudell *et al.* [108]	synchronous with a seawater air gap	tubular	PM (NdFeB)	iron	translator	surface mounted (radial)	longitudinal	1 kW
Mueller and Baker [109]	Vernier hybrid	flat (double-sided)	PM	iron cored (modular)	stator	surface mounted (radial)	longitudinal	3 kW
Zhao *et al.* [110]	Vernier hybrid	flat (single sided)	PM	iron (non-modular)	stator	surface mounted (radial)	longitudinal	—
Huang *et al.* [46, 111]	flux switching	flat (4 sided) and tubular	PM	iron cored	stator	interior	longitudinal	—
Zhang *et al.* [25]	single-phase synchronous	tubular	PM (NdFeB)	iron cored	translator	quasi Halbach	longitudinal	—
Hodgins *et al.* [112]	synchronous	flat (double sided)	PM	air cored (modular)	translator	surface mounted (radial)	transverse and longitudinal	50 kW
Vermaak and Kamper [113]	synchronous	tubular	PM (NdFeB)	air cored (stator and translator)	translator	radial	transverse	1 kW
Clifton *et al.* [114]	synchronous	tubular	PM	iron cored (slotless)	translator	axial	longitudinal	30 kW
Cozier *et al.* [115]	snapper	flat (double-sided)	PM	iron cored (slotless)	stator and translator	radial	longitudinal	—
Cao and co-authors[116]	switched reluctance	flat (double-sided)	DC power supply	iron cored	—	—	longitudinal	—
Huang *et al.* [51]	flux-switching	tubular	DC superconductor	iron cored	—	—	longitudinal	—
Hong *et al.* [117]	synchronous	flat (double-sided)	PM	iron cored	translator	—	—	20 kW

the single Halbach arrangement. The magnetic field in three dimensions is predicted using Laplace and Poisson equations and optimised in order to enhance flux density in the air gap and achieve better power output performance [104]. Cogging force is reduced by eight times when such an arrangement of magnets is used [105]. Different types of magnetisation patterns have been compared in Table 2, where the quasi-Halbach arrangement pattern of PMs is shown to have produced a large force density with high construction cost [105].

4 Conclusion

With the continuous increase of the use of the linear topologies to convert the ocean wave energy into electrical energy, it is very difficult to find the best generator. This paper presented a comprehensive review of the linear generators for ocean wave conversion and summarised all the types of the linear generator which can work with ocean wave energy conversions. The design and choice of generator structure depend on the application requirement whether high-power or low-power application is required. For the high-power applications, the flat synchronous generators are mostly used and for the low-power applications, the tubular synchronous generators are preferred. The studies by so far show that the design of a linear generator is restricted to the synchronous generator for the high-power rating applications, whereas in the case of the low-power rating applications, the Vernier hybrid double-sided flat generators give almost the same result as the synchronous generators. There are certain directly and indirectly driven generators. A discussion of various recently developed linear generators prototypes is presented in Table 3. From the table, it is seen that the synchronous generators produce the largest power output when magnets are fixed on the translator. The direct-drive linear synchronous tubular generator has been identified as the best choice. Several attempts have been made to incorporate the prototypes into real sea conditions for harvesting the energy of sea waves. Examples of full-scale sea trials summarised in Table 4 based on three categories, i.e. Oscillating

Table 4 Real Sea Trials of wave energy conversion

Type	Device	Testing location	Rated power	Conversion system	Reference
oscillating water column	LIMPET	Scotland	500 kW	turbine generator	[118]
	PICO	Portugal	100 kW	turbine generator	[119, 120]
overtopping	Wave Dragon	Portugal	1.5 MW	turbine generator	[121]
		Denmark	7 MW	turbine generator	[122]
attenuator hydraulic system	Wavebob	Ireland	500 kW	hydraulic circuit	[123, 124]
	Pelamis	Scotland	750 kW	frequency tuning	[125–127]
direct drive	Lysekil Project	Sweden	10 kW	linear generator	[128–131]
	AWS	Portugal	2 MW	linear generator	[132–136]
	Oregon L10	USA	10 kW	linear generator	[137–139]

water column, Overtopping and direct drive of wave energy conversion.

The conclusive feedback from experience says that there is an advantage of such a linear generator because of a less complex mechanical system with potentially a smaller need for maintenance. Also, one of the drawbacks observed is a more complicated transmission of the power to the grid, since the generated voltage will vary in both frequency and amplitude.

A tubular linear generator with longer translator located inside the generator possesses better performance in terms of power output and cogging force. Switched reluctance generators are promising but a better control approach is required for such machines. Superconducting linear generator tends to give maximum power output but has a high manufacturing and material cost hurdle. The change in magnetisation pattern can increase the power output. With a different type of magnetisation like quasi-Halbach arrangement, the efficiency of the system can be improved. Thus, it is suggested that magnetic pattern change can lead to better performance results in the near future with minimum losses.

5 Acknowledgments

The authors thank the Australia Research Council Discovery Project grant no. DP170101039 for financial support.

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