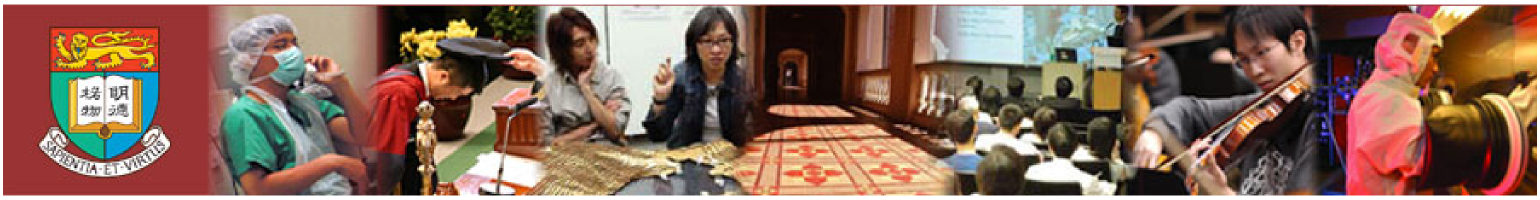

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An Efficient Offshore Wind-Wave Hybrid Generation System Using Direct-Drive Multitoothed Rotating and Linear Machines

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Abstract — This paper presents an offshore wind-wave hybrid generation (WWHG) system, which can efficiently harness the offshore wind and wave energy. The key is to use the multitoothed doubly-salient permanent-magnet (MDSPM) machines for serving the rotating generator and the linear generator. Different from the traditional wind or wave generation system, this WWHG system integrates the wind generation part and wave generation part together to directly harness the wind and wave energy without gear box. The system configuration and machine design are analyzed and discussed in detail. Also, the finite-element method is performed to verify the validity of the proposed two machine design. The results tell that the system has the high reliability and can be upgraded to the suitable size for offshore hybrid-source energy conversion in practical application.

I. INTRODUCTION

Renewable or sustainable energies are becoming more and more attractive in recent years due to increasing concerns being paid on environmental protection issues [1]-[6]. Different technologies are explored and developed to convert, integrate and transmit renewable energies, which aims to produce the friendly-usable energy style, such as the electricity style [7]-[12]. In general, renewable energies are distributed in onshore areas or offshore areas, which can be harnessed by the corresponding techniques [13]-[18].

The onshore renewable types (hydro, wind and solar) develop very fast, whereas the offshore renewable energy sources (wind, wave and tidal) virtually keep very slow steps [19]-[20]. Although the offshore renewable energy has the overwhelming advantages of enrichment, more uniform pattern and more space, its special features of higher reliability and cost, higher technology requirement and more difficult maintenance drop it far behind the onshore type.

As the core part of wind and wave energy system, electric machine has been proposed for different industrial applications [21]-[30]. However, different from the traditional industrial applications, the wind and wave generators have to meet special requirements for converting the wind and wave power to electrical power. It means that these electric machines almost need to special design and perform a wide speed range. Thus, wind and wave power generators are expected to operate with satisfying steady and dynamic performances in practical applications.

Generally, there are two types of wind and wave energy system, namely the indirect-drive topology and the direct-drive topology. The most common design is the indirect-drive topology for wind and wave power generation as shown in Fig. 1. It can be seen that the system usually needs the gear box to increase the rotating speed for generator operation. So, the indirect-drive system usually has the larger size than that of direct-drive system. By adopting the low-speed operating machine, the gear box can be reduced, and hence improving the reliability and robustness of the whole system.

This paper is to develop an efficient offshore direct-drive wind-wave hybrid generation (WWHG) system, which can effectively harness the wind and wave energy and propel the offshore energy development. Different from the traditional wind or wave generation system, this WWHG system integrates the wind generation part and wave generation part together to harness the wind and wave energy. Thus, it inherently achieves more flexible to capture the renewable energy than the single source type.

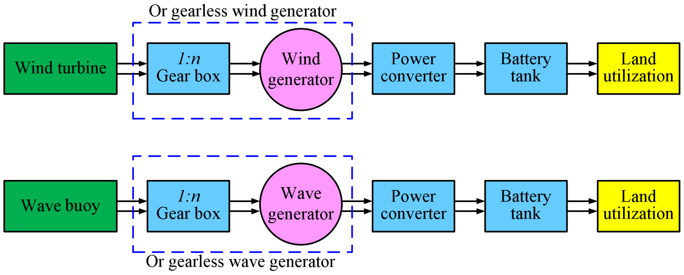

Fig. 1. Indirect-drive and direct-drive wind and wave generation system.

II. HYBRID ENERGY SYSTEM CONFIGURATION

A. *Offshore Wind Energy System*

Onshore wind power generation develops very fast in recent years, which effectively supports the electricity supply for utilization in many states. For instance, German plans to install 50GW onshore wind capacity by 2020 [3]. It also means that it is hard to install much more due to the limitation of land size for wind energy system installation.

On the other hand, with enough sea areas, the offshore wind energy system is expected with more and more installation capacity in the future. Fig. 2 shows the recent development of offshore installed wind power system in Europe [3]. It can be

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seen that the installation speed will become fast and fast in the future ten years. Also, more and more states will develop their offshore wind energy system. Furthermore, offshore wind farms are expected with the installation capacity up to 20~30GW in 2030 [3]. Thus, the offshore wind energy system can be regarded as the best partner of the onshore wind energy system.

For the conventional onshore grid-connected wind system, the double-fed induction machine (DFIM) dominates the main market due to itself power regulation capability. However, for the offshore wind energy system, there may not need to connected with the grid system. If so, the energy can be first to store in the battery and then transfer to the land grid system. Moreover, the transmission line between the land and the sea may not limit to the AC bus. The DC bus becomes attractive due the less power loss for the power transmission. In this case, the single-fed winding machine is enough, which can directly convert the wind energy to the AC electrical energy and then rectify as the DC electrical energy.

Therefore, for the proposed WWHG system, it adopts the approach by which the machine only has one set of windings and rectifies the AC electrical energy as the DC electrical energy. Also, the power line adopts the DC bus for land electricity transmission. Furthermore, to improve the system reliability and performance, the direct-drive topology is preferred.

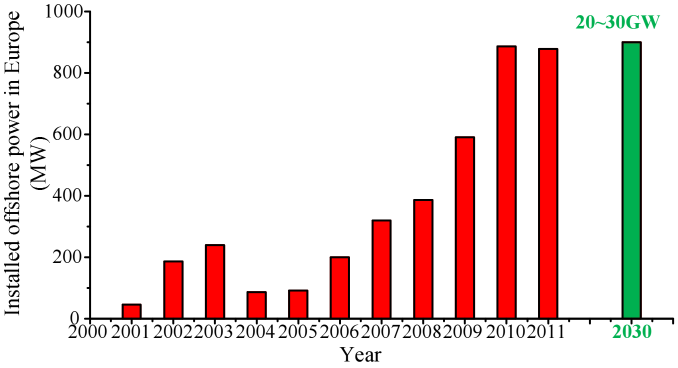


Fig. 2. Installed and plan offshore wind power in Europe.

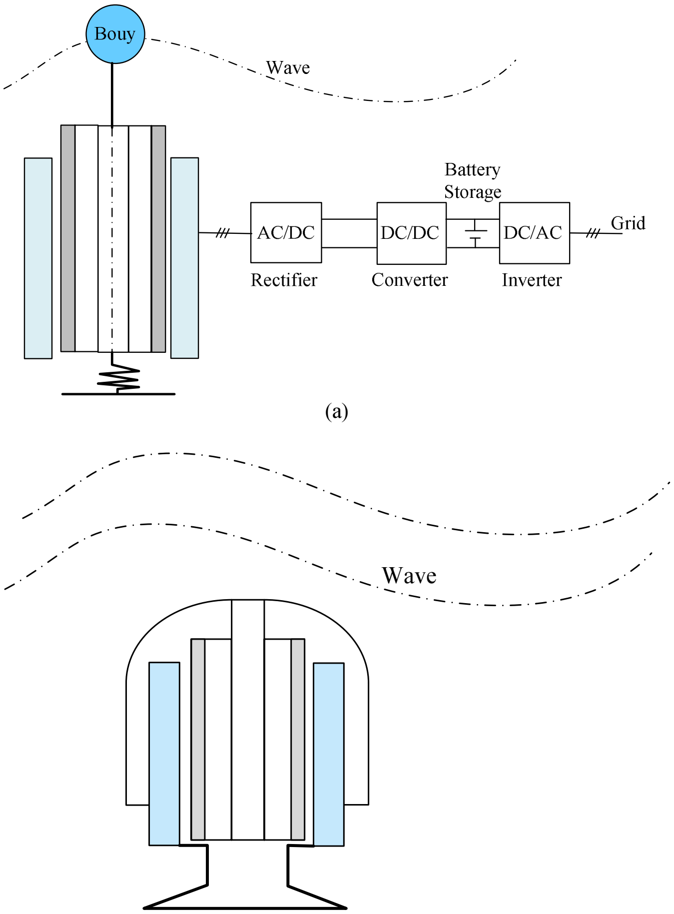
B. *Wave Energy System*

Ocean energy is significant abundant with the large scale of sea in our earth. A NASA study estimated that more than 91 trillion kilowatt-hours of accessible energy worldwide from the oceans can be harnessed annually. Although there are different energy forms for ocean energy, wave energy is one of the best convenient ways to convert the wave power to the electrical power.

Basically, there are two types of wave power generations. The rotational generator type which converts the reciprocating wave motion into rotational motion by using mechanical system and then adopts a conventional generator to produce electricity, and the linear generator type which directly utilizes the wave motion to drive a linear generator for electricity generation.

For the linear wave power generation system, the heaving buoy tube (HBT) topology and the Archimedes wave swing (AWS) topology is welcomed [13]. Fig. 3 shows these two topologies for wave power generation. As shown in Fig. 3(a), the HBT topology has a hollow tube to substitute the hose pump and with a piston installed in the hollow tube. When the water flows into and out of the tube, it causes the rise and fall movement of the piston, which can drive a linear generator. As shown in Fig. 3(b), the AWS topology is different from the HBT one, since it deploys under the water surface. Also, it operates due to the water pressure variation above its chamber. This system can avoid bad weather condition & blocking the sea way.

For the proposed WWHG system, it adopts HBT topology due to the simplicity. Of course, this topology is also easy to change as the AWS one. Also, it utilizes the direct-drive idea without any gear for capturing the wave energy. The capturing energy is then converted as the electrical energy and could store first in the battery tank.



(a)

(b)

Fig. 3. Linear type of wave power generation topology. (a) HBT topology. (b) AWS topology.

C. *Hybrid Offshore Energy System*

Hybrid sustainable energy means that several sustainable energies are integrated together for power generation, including wind energy, solar energy, hydro energy, geothermal energy, ocean energy (wave energy & tidal energy), biotic energy (study of energy transformation in living organisms), etc.. For the hybrid offshore energy sources, the wind and wave energies achieve the inherent merits of abundant resources, noise free for human, large areas for installation and sharing the same battery tank.

Fig. 4 shows he proposed WWHG system, which integrates a wind power generation branch and a wave power generation branch by adopting the high reliability machines, namely multitoothed doubly-salient permanent-magnet (MDSPM) [31], [32]. The wind power generation branch consists of a rotating MDSPM machine, a 3-phase rectifier, and a DC/DC converter, whereas the wave power generation consists of a linear MDSPM machine, a 3-phaser rectifier, and a DC/DC converter. In addition, the wind power branch offers a main DC link for power distribution, and a battery energy module directly connects with the DC link for local energy storage.

This WWHG system has the following features when harnessing the offshore wind and wave energy.

- The hybrid-source system has the better performance than the single-source type.
- The wind power generation branch and the wave power generation branch can be independently controlled, hence able to achieve the high-efficient control simultaneously.
- The hybrid-source system shares the same storage and the transmission line to the land. So, the system can save the cost of those parts. Furthermore, in special case, if one of the energy source needs to shutdown, the other energy source can still offer the energy for power conversion.
- In terms of costs, the proposed hybrid system definitely takes an advantage of lower cost than two individual wind and wave power systems since it can share the same battery tank for energy storage, the same inverter for dc/ac conversion, and the same digital hardware for the control system.

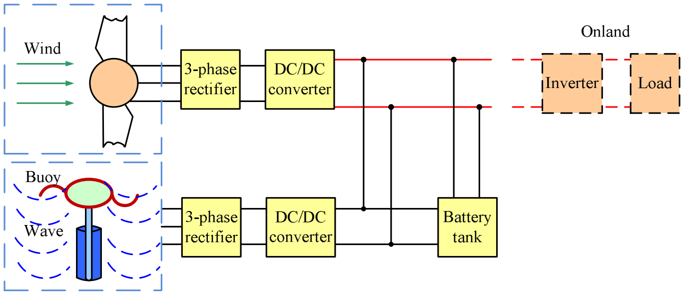


Fig. 4. Proposed WWHG system configuration.

III. MACHINE DESIGN AND ANALYSIS

A. Machine Design

Fig. 5 shows the proposed generator configurations. The rotating MDSPM generator has the multitoothed structure which comprises of a 25 salient-pole outer rotor without any winding or PM, and a 30 salient-pole inner stator for accommodating the armature windings and PMs. Thus, the outer rotor inherently achieves the robust structure, which can directly couple with the wind blades and remove any intermediate mechanical transmission, as well as offer a nature cover for protecting the generator electrical parts. Also, the inner stator has a special phase-winding arrangement, which can enable each phase of armature current to have an equal chance flowing at different slots under an excitation pole.

The linear MDSPM generator is a tube structure, which has a 9*2 salient-pole outer stator for locating the armature windings, and a 10*2 salient-pole inner mover for placing the PMs. Hence, this linear machine can straightforwardly connect with the buoy moving along with wave propagation at low speeds.

The design features for these two rotating and linear MDSPM are summarized as follow.

- The multitoothed topology is effectively to reduce the cogging torque of the double-salient machine. Also, this topology is able to improve the output torque at low-speed operation.
- The proposed machines are suitable to run at low speed with the distinct design of multitoothed and multi-pole structure, which enable their direct-drive applications for wind and wave energy harness.
- The proposed rotating MDSPM machine has the outer rotor, which is capable to directly couple with the wind blades. This merit is especially suitable for small or medium scale wind power system.
- The proposed linear MDSPM machine has the simple structure for its mover, which only has the solid iron and the PMs. Meanwhile, its stator accommodates the windings and the solid iron. Thus, the whole structure is robust enough for wave power generation.

B. Electromagnetic Field Analysis

Electromagnetic field analysis has been widely developed for electric machines. Basically, it can be categorized as analytical field calculation and numerical field calculation. The time-stepping finite-element method (TS-FEM) is the one of the most popular numerical field calculation tools. In this paper, the TS-FEM is developed for analyzing the proposed two machines. In general, the electromagnetic field analysis includes three sets of equations, namely the electromagnetic field equations, the armature circuit equations, and the machine movement equations [33]-[36].

First, the electromagnetic field equation of the machine is governed by [33]-[36]:

$$\Omega : \frac{\partial}{\partial x}\left(\nu \frac{\partial A}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu \frac{\partial A}{\partial y}\right) = -J - \nu\left(\frac{\partial B_{\mathrm{ry}}}{\partial x} - \frac{\partial B_{\mathrm{rx}}}{\partial y}\right) + \sigma \frac{\partial A}{\partial t} \quad (1)$$

where Ω is the field solution region; A is the magnetic vector potential; J is the current density; σ is the electrical conductivity; and B_{rx}, B_{ry}, are the remanent flux density.

Second, the armature circuit equation of the machine at motoring is given by:

$$u_{\mathrm{s}} = R_{\mathrm{w}} i + L_{\mathrm{e}} \frac{di}{dt} + \frac{l_{\mathrm{a}}}{S} \iint_{\Omega_{\mathrm{e}}} \frac{\partial A}{\partial t} d\Omega \quad (2)$$

$$E_a = \frac{l_a}{S}\iint_{\Omega_e} \frac{\partial A}{\partial t} d\Omega = C_e \Phi n \tag{3}$$

where u_s is the applied voltage; R_w is the winding resistance; i is the phase current; L_e is the end winding inductance; l_a is the axial length; S is the conductor area of each phase winding; Ω_e is the total cross-sectional area of conductors of each phase winding; E_a is the armature back EMF; C_e is the coefficient of flux linkage; Φ is the flux linkage; and n the mechanical rotating speed. It should be noted that in normal case both two machines work as the generator. But it doesn't mean that the machine cannot operate as the motoring situation.

Third, the machine motion equation is expressed as:

$$J_m \frac{d\omega_m}{dt} = T_e - T_L - \lambda\omega \tag{4}$$

where J_m is the moment of inertia; ω_m is the mechanical speed; T_e is the electromagnetic torque; T_L is the load torque; and λ is the damping coefficient. After discretizing Equations (1)–(4), the TS-FEM can readily be deduced. This equation mainly focuses on the motoring situation. However, if the machine operates as the generator, the sign will be different.

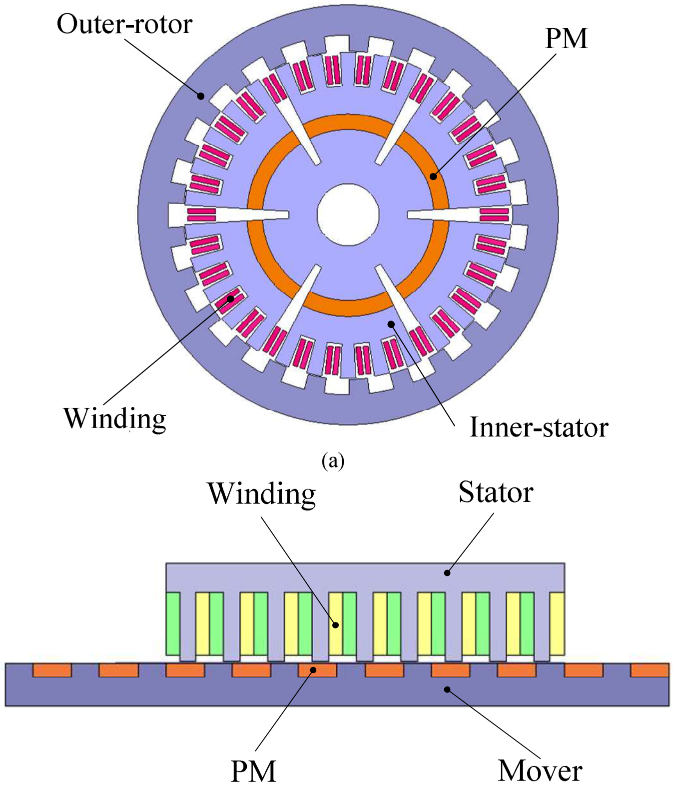


Fig. 5. Proposed machine configuration. (a) Rotating MDSPM machine. (b) Linear MDSPM machine.

IV. RESULTS AND DISCUSSION

By using the finite-element method (FEM) with JMAG tool [33]-[36], the performances of these two MDSPM machines are calculated. Then, the specific results are discussed as follow.

Firstly, the basic characteristics of these two machines are given in Fig. 6 and Fig. 7. Fig. 6 shows their flux distributions under no-load condition. It can be found that the flux paths of both machines have the regular patterns. So, the machines have the expected flux distribution with the concentrated winding arrangement, which can also shorten the flux path. Furthermore, it tells that pole-pair arrangements for both machines are reasonable to convert the mechanical energy to the electrical energy through airgap. Fig. 7 is the corresponding airgap flux density of both machines. It can be found that the airgap flux density is nearly up to 1.4T for the rotating type. Also, the linear type has the value of 1.0T. Thus, it means that both machines achieve the acceptable airgap flux density for energy conversion.

Secondly, the generation performances when the machines accomplish for renewable energy conversion are given in Fig. 8 and Fig. 9. Fig. 8 shows the no-load electromagnetic force (EMF) waveforms of the proposed generators. It can be seen that both machines have the symmetrical three-phase voltage waveforms. Also, it tells that when the wind speed is at normal case of 7 m/s (corresponding to 200rpm of the rotor speed) and the wave motion of 1 m/s, the generators will have nearly 40V and 30V outputs. Thus, the generated three-phase electricity can be rectified and/or store in the battery tank first. Moreover, Fig. 9 shows the torque and thrust ability of the machines. It can be seen that the rotating or linear MDSPM machines can produce about 17Nm and 380N during adding armature current of 8A and 7A, respectively. It should be noted that the demonstrated machines are designed with the small size. But, it also reveals the value of their potential application in real environments.

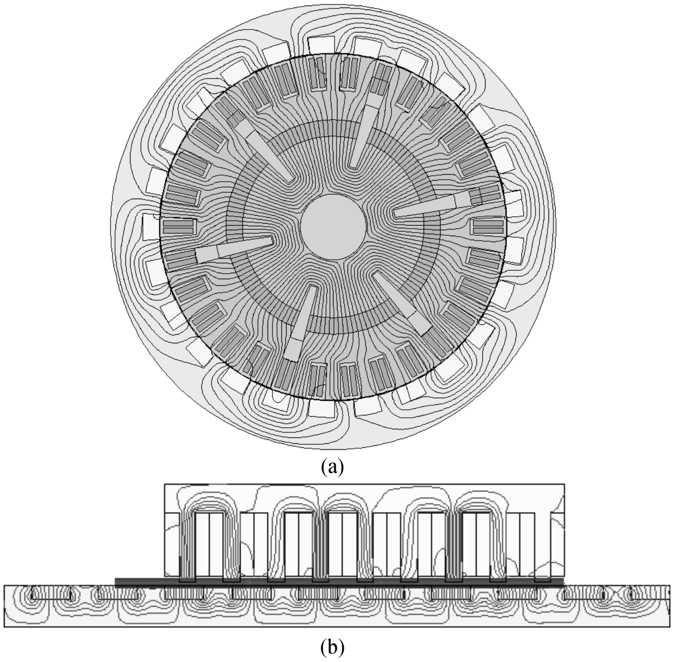


Fig. 6. Magnetic field distributions. (a) Rotating MDSPM machine. (b) Linear MDSPM machine.

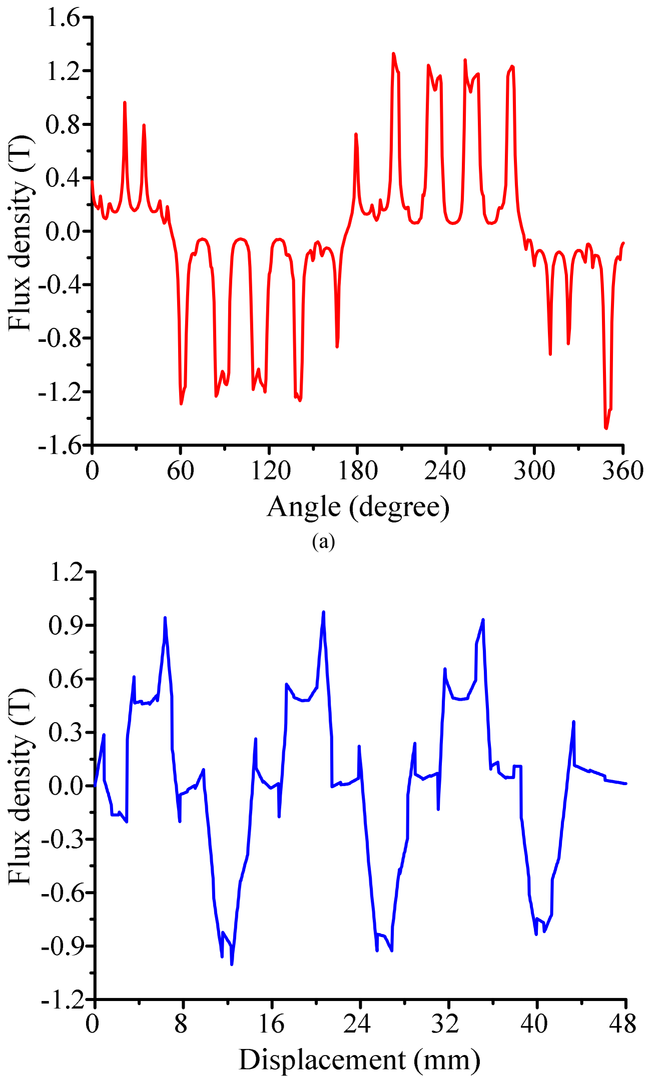


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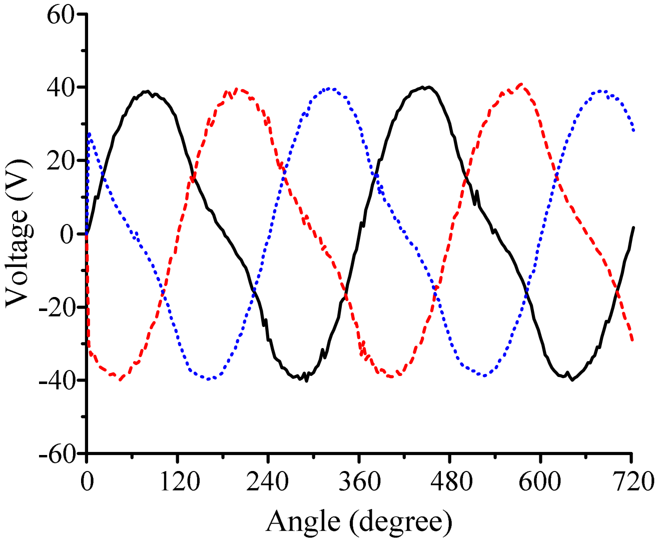
Fig. 7. Airgap flux density. (a) Rotating MDSPM machine. (b) Linear MDSPM machine.



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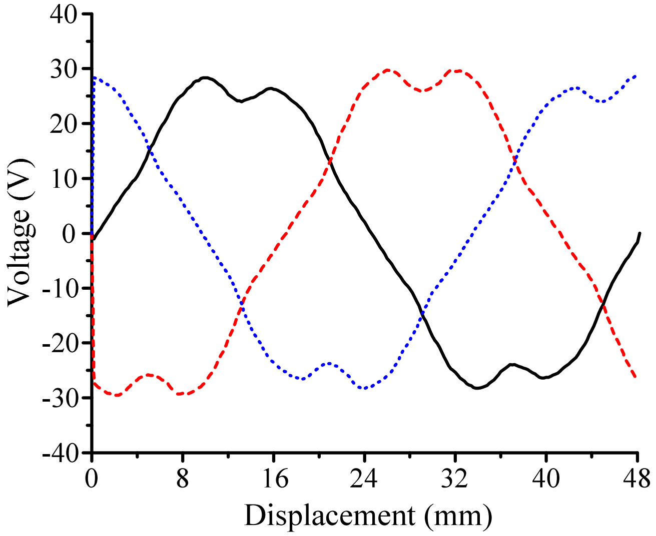

(b)

Fig. 8 No-load EMF waveforms. (a) Rotating MDSPM machine. (b) Linear MDSPM machine.

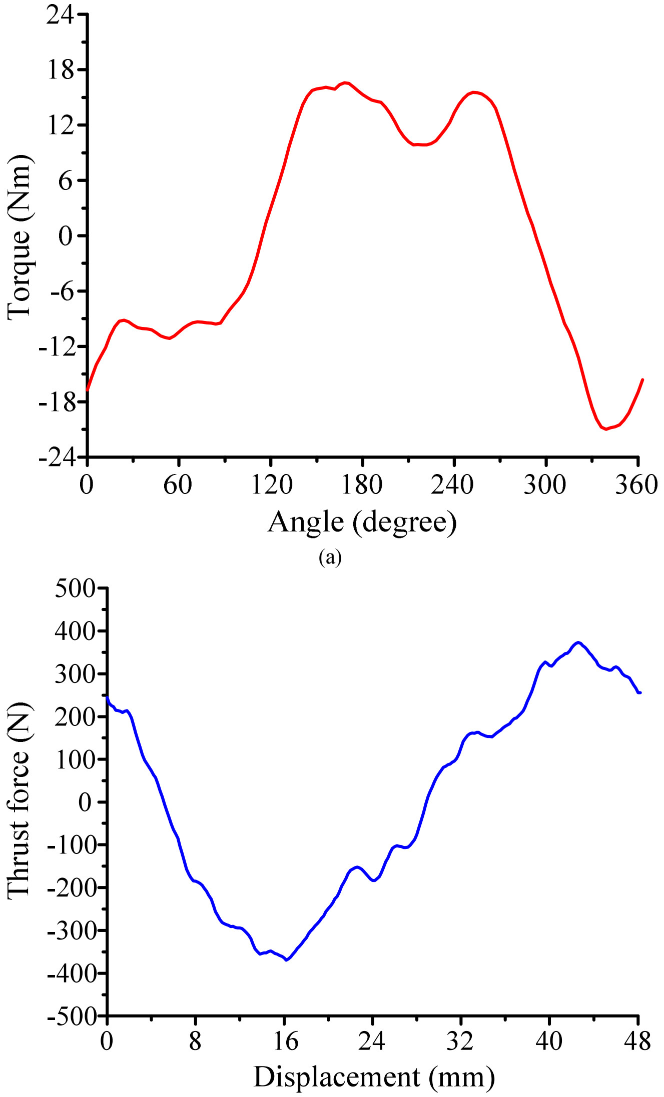

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Fig. 9 Torque and thrust force performances. (a) Rotating MDSPM machine. (b) Linear MDSPM machine

V. CONCLUSION

In this paper, a new WWHG system is proposed for wind and wave energy harness and conversion. The system adopts the rotating and linear MDSPM machines, which can effectively perform the expected functions. The FEM is utilized to demonstrate the design of both machines. Also, the system-level analysis is executed. The analysis and verification results indicate that the proposed WWHG system is capable to operate in offshore condition and convert the renewable energy and then transfer the electrical energy to the land.

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