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# CHALLENGES AND OPPORTUNITIES OF ELECTRIC MACHINES FOR RENEWABLE ENERGY (INVITED PAPER)

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**Abstract**—This paper gives an overview of various electric machines for application to renewable energy harvesting, and reveals the corresponding challenges and research opportunities. After introducing various renewable energies and electric machines, the concept of renewable energy machines is coined. Then, the existing machines, including the DC, induction and synchronous types, for renewable energy harvesting are challenged. Consequently, research opportunities of advanced machines, including the stator-permanent magnet (PM), direct-drive PM and magnetless types, are elaborated. Finally, both near-term and long-term renewable energy machines are identified especially the emerging stator-PM, vernier PM and stator doubly fed doubly salient types.

## 1. INTRODUCTION

The principle of electromechanical energy conversion was first demonstrated by Michael Faraday in 1821. The first electric machine, actually a DC motor, was invented by William Sturgeon in 1832. Nikola Tesla conceived the rotating magnetic field in 1882 and used it to invent the first AC machine, actually an induction motor, in 1883. While the AC machines, including synchronous generators and induction generators, have been widely accepted to work well for fossil-fuel power generation, why there are tremendous research activities on electric machines in recent years? The answer is the desire of new electric machine technologies to efficiently and effectively harness renewable energy.

Currently, all electric machines for renewable energy harvesting are extended from fossil-fuel power plants. Traditional generators

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are relatively ineffective to convert renewable energy sources into electricity, particularly inefficient for harnessing wind power or wave power. For instance, the hydropower generation was about 3427 TWh in 2010 so that only 1 day is idle due to unexpected machine maintenance will lose 9.4 TWh per annum which costs about US$1050 million per year; and the wind power generation was about 430 TWh in 2010 so that only 1% improvement in machine efficiency can produce an additional electricity of 4.3 TWh per annum which is roughly a saving of US$ 480 million per year.

Renewable energy sources such as wind or wave are intermittent in nature and slow in motion which create challenges on how to effectively capture and convert these motions into electricity. The intermittency refers not only to a large variation of magnitudes, but also to a low predictability of variations. This intermittent operation of the generator will cause sudden power outage or time-varying output voltage and frequency. The capturing of slow motion is also a difficult task. For instance, the wind speed is generally about 5–20 m/s, which is equivalent to the wind turbine rotational speed of about 5–20 rpm. Such low rotational speed desires the wind generator adopting low-speed design, leading to bulky size and heavy weight. Otherwise, a mechanical gearbox is required to step up the wind turbine speed by about 100 times which in turn drives the rotor of the wind generator. This arrangement can enable high-speed design of the wind generator, hence reducing its size and weight, but desires the mechanical gearbox which suffers from the drawbacks of additional cost and transmission loss and the need of lubrication and maintenance. Actually, the downtime for gearbox repair is the longest of all components' repairs for wind power generation. It takes about a week even though the required spare gearbox is available. Similarly, the low-speed design problem of the wave generator and the wear-and-tear problem of the mechanical gearbox occur in wave power generation.

The purpose of this paper is to give an overview of various electric machines for application to renewable energy harvesting, and to reveal the corresponding challenges and research opportunities. In Section 2, a brief introduction of renewable energy harvesting, with emphasis on those using electric machines for energy conversion, will be given. In Section 3, a comprehensive classification of electric machines will be given. Hence, the concept of renewable energy machines will be coined. Then, in Section 4, existing machines that have been developed for renewable energy harvesting will be reviewed. Consequently, in Section 5, advanced machines that are promising for harnessing renewable energy will be discussed. Finally, in Section 6, representative renewable energy machines will be identified.

## 2. OVERVIEW OF RENEWABLE ENERGY

An overview of renewable energy sources, including the wind, wave, hydro, tidal, solar-thermal, geothermal and biomass-thermal, which utilize electric machines for electricity generation is presented; whereas the solar-electric (photovoltaic) [1] and thermoelectric power generations [2] which directly produce electricity without using electric machines will not be discussed. Basically, these renewable energy sources can be categorized by their forms of energy storage before producing electricity by electric machines: namely, the wind, wave, run-of-river hydro and tidal stream are stored as kinetic energy; the large hydro and tidal barrage are stored as potential energy; the solar-thermal, geothermal and biomass-thermal are stored as heat energy. The types of electric machines are generally based on these forms of energy storage.

### 2.1. Wind Power

Wind power is basically the kinetic energy of the movement of air. In general, it is first transformed into the rotational kinetic energy of a wind turbine, and then converted into electrical energy using an electric machine. The typical size of wind turbines is from 1.5 MW to 7.6 MW. A group of wind turbines constitutes a wind farm. Currently, the largest wind farm is the Jaisalmer Wind Park in India, which has the installed capacity of 1064 MW.

For fixed-speed wind turbines, the corresponding electric machine usually adopts the synchronous generator (SG) or induction generator (IG) which can directly feed power to the grid. In order to effectively capture the wind power at different wind speeds, variable-speed wind turbine are becoming the trend of development. There are three main competing machine technologies for variable-speed wind turbines [3]: the directly coupled IG, the power conditioned doubly fed IG (DFIG), and the power conditioned IG or permanent magnet (PM) SG (PMSG) as depicted in Figure 1. The directly coupled IG can offer variable slip values to provide sufficient compliance to the power grid. However, the allowable speed variation is limited while an increased slip causes a significant reduction in efficiency. In order to have a wide range of speed variation, the power-conditioned DFIG is widely adopted. It incorporates two back-to-back AC-DC converters (so-called the AC-DC-AC conversion) to control the rotor current via slip rings and carbon brushes so that the output frequency can remain synchronized with the grid while the wind turbine speed varies. This arrangement of power conditioning takes the advantage that the converters need not handle the full output power of the generator, hence reducing the

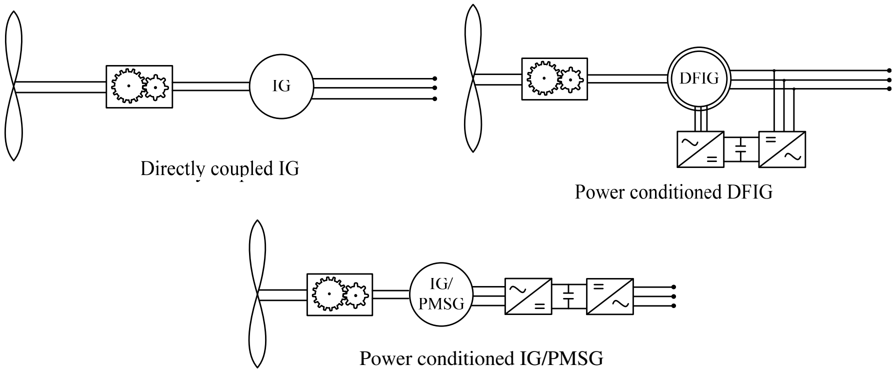


**Figure 1.** Wind power generation systems.

converter rating and cost. However, it suffers from the drawbacks of slip rings and carbon brushes such as the bulky size and need of regular maintenance. In order to provide the full operating speed range while avoiding the use of slip rings and carbon brushes, the power conditioned IG is preferable. Increasingly, in the absence of rotor copper loss, the power conditioned PMSG is becoming attractive which takes the advantages of higher efficiency and higher power density. The key drawback of this arrangement is the need of power converters with the same rating as the generator.

The key challenges of wind power generation are the intermittent production of electricity, the difficulty in harnessing low wind speeds, the need of regular maintenance if employing the SG or DFIG or using the mechanical gearbox, and the inefficient operation under time-varying wind speeds. Particularly, the mechanical gearbox needs regular lubrication or even replacement after prolonged operation.

### 2.2. Wave Power

Wave power is a kind of ocean power (or called marine power), and represents the kinetic energy of the movement of ocean surface waves. Although the global potential for wave power generation is estimated up to 12,500 TWh per year, the development of wave power plants is very slow. The world first wave farm was the Aguçadoura Wave Park in Portugal with the installed capacity of 2.25 MW, which was unfortunately shut down 2 months after the official opening in 2008 as a result of the financial crisis. There are various wave power prototypes developed, but none of them can be connected to the grid. In 2010, the Wave Hub was installed in England, which consists of an electrical hub on the seabed off the north coast of Cornwall, and initially allows 20 MW of capacity to be connected. Compared with another kind of ocean power — tidal power, the wave power is less predictable but is available at more locations.

Wave power generation systems are generally categorized by the types of wave energy converters which include the heaving buoy, Archimedes wave swing, oscillating water column, tapered channel, Pendulor device, Pelamis, wave dragon, hose pump, tube pump and Danish wave power float pump [4]. Meanwhile, the corresponding generators can be classified as the rotational generator and linear generator. Since the wave power is in the form of slow reciprocating linear motion, the rotational generator needs an additional linear-to-rotary mechanism which is bulky, heavy and inefficient. On the contrary, as shown in Figure 2, the linear generator can directly capture the linear wave motion resulted from the heaving buoy and Archimedes wave swing for electricity production.

Similar to the existing wind power generation, the SG, IG, DFIG, PMSG are applicable for the existing wave power generation adopting rotational turbines or hydraulic mechanisms. In order to directly capture the linear reciprocating wave motion, the linear PMSG (LPMSG) is preferable since the linear versions of SG, IG and DFIG are relatively bulky, heavy and inefficient. The key challenges of wave power generation are the intermittent electricity production, the difficulty in capturing slow linear reciprocating wave motion, the need of regular maintenance if employing the SG or DFIG, the mechanical problems of gearbox or linear-to-rotary mechanisms and the harsh and corrosive operating environment. Particularly, it is very difficult to perform regular lubrication or maintenance for those submersed mechanical mechanisms.

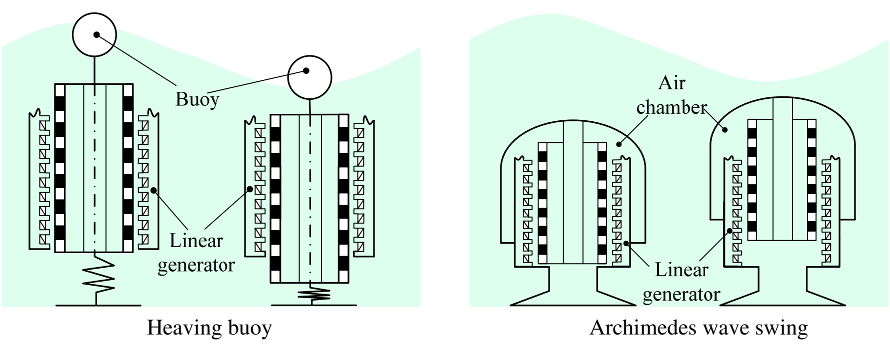


**Figure 2.** Direct-drive wave power generation systems.

## 2.3. Hydropower

Hydropower generation is the most mature renewable energy harvesting, which makes use of the flow of fresh water towards the sea to generate electricity. The most visible and successful way is by using dams to create reservoirs so that the potential energy difference in the water levels upstream and downstream of dams is converted into electrical energy. Such installation ranges from tens of megawatts to thousands of megawatts [5]. The largest hydropower station in the world is the Three Gorges Dam in China which has the installed capacity of 22,500 MW. While large hydropower stations are based on large dams which are usually located at remote areas, small hydropower stations (typically from 10 kW to 30 MW) can be based on flow of river, so-called the run-of-river type, which are usually located nearby the consumers. Sometimes, the small hydropower is classified in a more detail way: micro hydro (10–100 kW), mini hydro (100–500 kW) and small hydro (500 kW to 30 MW).

There are various machine technologies for the existing hydropower generation. For large hydropower stations, the water flow via the dam is nearly constant so that the SG is almost exclusively used. Although this SG takes the definite merit of mature technology with very high power ratings, it has the drawbacks of the inevitable power loss in the field circuit and the need of regular maintenance for the slip rings and carbon brushes. Thus, its key challenge is how to get rid of the field circuit and the corresponding slip rings and carbon brushes while maintaining such high power ratings. On the other hand, for small hydropower stations, especially the run-of-river hydro, there is a large variation in water flow while the generated power level is not very high. So, the IG or PMSG with power conditioning is preferred to the SG. The corresponding challenges are how to handle the varying flow of river, the difficulty in harnessing slow water motion and the need of regular maintenance if using the mechanical gearbox.

## 2.4. Tidal Power

Tidal power generation is a relatively mature ocean power generation, which makes use of the flow of sea water between high tide and low tide to generate electricity [6]. One common way for tidal power generation is called the tidal barrage which traps the water in dams at high tide and then releases the water to convert the potential energy to electrical energy at low tide, namely about once per 12 h; whereas another way is called the tidal stream which converts the kinetic energy of water flow to electrical energy in between the high and low tides, namely about once every 6 h. A combination of them is able to produce electricity

6 times per day. Differing from hydropower, tidal power is strongly influenced by time. Nevertheless, differing from wind power, tidal power is very predictable. The first tidal power station was built at La Rance, France in 1996, which is based on tidal barrage having the installed capacity of 240 MW. Although the potential of tidal power has been stated to be very large, around 180 TWh per year worldwide, the development of tidal power stations is slow. The largest one in the world is the Sihwa Lake Tidal Power Plant in South Korea which is also a tidal barrage type completed in 2011 with the installed capacity of 254 MW, just slightly surpassing the capacity of Rance Tidal Power Station after 45 years. The first tidal stream power station in the world was built in Strangford Lough, Northern Ireland in 2008 with the installed capacity of 1.2 MW.

Similar to the large hydro, the tidal barrage produces nearly constant water flow for high power generation so that the SG is almost exclusively used. Meanwhile, similar to the run-of-river hydro, the tidal stream involves time-varying water flow for up to a few megawatts only. So, the IG or PMSG with power conditioning is preferred to the SG. On top of the challenges similar to that for the large hydro and run-of-river hydro, the electric machines for tidal power generation inevitably suffer from the challenge in providing adequate corrosion protection against sea water.

### 2.5. Solar-thermal Power

Solar power refers to the energy that the earth receives from the sun. There are two basic technologies to convert the solar power to electricity: namely the solar-electric or commonly called photovoltaic installation which directly converts solar radiation into DC current using semiconductors that exhibit the photovoltaic effect, and the solar-thermal or called concentrated solar power installation which makes use of solar parabolic troughs and solar power towers to concentrate sunlight to boil water that in turn drives a steam turbine coupled with a generator for electricity production [7]. Between them, the solar-thermal is much cheaper per kilowatt hour so that it is more preferable for large solar power installations such as in a desert area. The largest solar-thermal installation in the world is the Solar Energy Generating Systems in California's Mojave Desert in the USA, which consists of 9 power plants with the turbine capacity of 14–80 MW and a total of 936,384 mirrors covering more than 6.5 $km^2$, leading to the installed capacity of 354 MW.

Similar to the traditional thermal power plants, the solar-thermal power generation is based on steam turbines so that the SG is widely used. Meanwhile, for small-scale solar-thermal installations, the IG takes the advantages of low cost and maintenance-free operation. The key challenge on solar-thermal generation is how to effectively and efficiently store the thermal energy obtained from sunlight so that electricity generation can be maintained during the cloudy days or night periods. Other challenges on electric machines are how to get rid of the field circuit and the corresponding slip rings and carbon brushes of the SG, and how to improve the efficiency, power density and power factor of the IG.

## 2.6. Geothermal Power

Geothermal power generation extracts heat from the earth's crust to drive one or more steam turbines that turn one or more generators for electricity production. There are three main geothermal power generation technologies: namely the dry steam plant which directly uses the geothermal steam of at least 150°C to drive the turbines for electricity production; the flash steam plant which transfers high-pressure geothermal hot water of at least 182°C to low-pressure tanks and uses the resulting flashed steam to drive the turbines; and the binary cycle plant which extracts heat from the geothermal hot water of at least 57°C to make the secondary fluid flash to vapor via the heat exchanger and then drive the turbines [8]. The potential of geothermal power generation in the world is estimated to be 67 TWh per year. Currently, the largest geothermal power installation is the Geysers in California, which has 22 geothermal power plants and more than 350 wells with the installed capacity of 1517 MW.

Similar to other traditional thermal power plants, the geothermal power generation is based on steam or gas turbines so that the SG or IG is widely used. Of course, the SG takes the advantages of higher efficiency and higher power rating, whereas the IG takes the merits of more robust, lower cost and maintenance-free operation. However, similar to other thermal power generation systems, the drawbacks of using the SG and IG are still challenges to be solved.

## 2.7. Biomass-thermal Power

Biomass power generation is to produce electricity based on biological material from living, which can be done by direct combustion of biomass fuels such as residues, wastes and bagasse, or by conversion to other energy products such as liquid biofuel and combustible biogas which then fuel the power plant [9]. At present, biomass power generation is mostly based on biomass-thermal plants which burn lumber and agricultural wastes to supply steam for electricity generation. A number of countries with resourceful biomass feedstock are engaging in biomass power generation, such as Bulgaria Finland, Romania and UK. The largest biomass-thermal power station in the world is the Alholmens Kraft Power Station in Finland which is a cogeneration plant with the installed capacity of 265 MW of electricity and 160 MW of heat. It mainly uses forest residues as the main fuel.

Similar to other thermal power plants, the biomass-thermal power generation is based on steam or gas turbines so that the SG or IG is widely adopted. Although the biomass fuels are very resourceful with a very low raw material cost, the key challenge of biomass-thermal power generation is the transportation cost of feedstock. Thus, grid-connected small- or micro-scale biomass-thermal power stations are becoming attractive, which have sufficient amounts of feedstock on site. While the SG and IG have their own shortcomings, it is challenging to develop a new breed of electric machines for this small- or micro-scale biomass-thermal power generation.

### 2.8. Comparison

Based on the aforementioned renewable power generation systems, the types of electric machines and the corresponding requirements of power conditioning [10] are compared as listed in Table 1. It can be observed that the machines and power conditioners are the same between wind and wave power generations in which the linear wave motion is first transformed into rotational motion, the same between large hydro and tidal barrage power generations, the same between small or run-of-river hydro and tidal stream power generations, the same between solar-thermal, geothermal and biomass-thermal power generations because they have similar characteristics, respectively. Of course, the electric machine for direct-drive wave power generation is unique.

## 3. CLASSIFICATION OF ELECTRIC MACHINES

There are many topologies of electric machines, which create various classifications. Traditionally, they were classified into two groups — DC and AC. With the advent of new machine types, this classification becomes ill-suited. Figure 3 shows the proposed classification of electric machines in which the bold types are those that have been applied to renewable power generation; meanwhile, the branches that are not viable for renewable power generation have been pruned. Basically, they are classified into two main groups — commutator and commutatorless. The former simply denotes that they have a commutator and carbon brushes, while the latter have neither commutator nor carbon brushes. It should be noted that the trend

**Table 1.** Existing machines for renewable energy.

| Renewable energy | Machine | Power conditioning |
|---|---|---|
| Wind | SG, IG, DFIG, PMSG | Optional, AC-DC-AC |
| Wave (rotational) | SG, IG, DFIG, PMSG | Optional, AC-DC-AC |
| Wave (linear) | LPMSG | AC-DC-AC |
| Large hydro | SG | NA |
| Small hydro | IG, PMSG | AC-DC-AC |
| Tidal barrage | SG | NA |
| Tidal stream | IG, PMSG | AC-DC-AC |
| Solar-thermal | SG, IG | NA |
| Geothermal | SG, IG | NA |
| Biomass-thermal | SG, IG | NA |

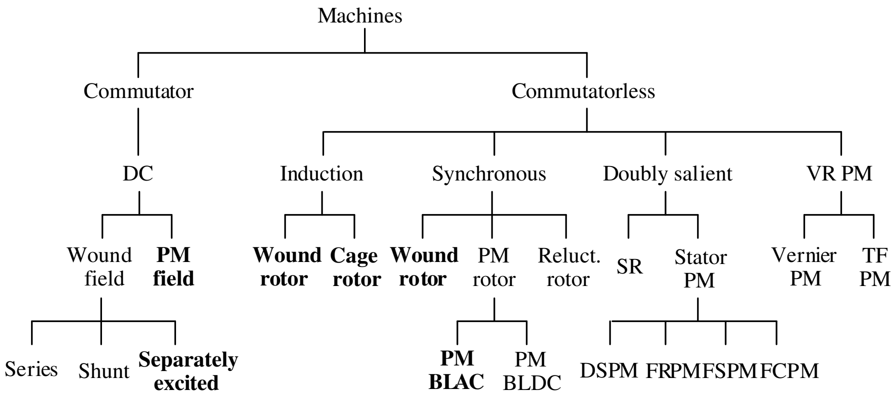


**Figure 3.** Classification of electric machines.

is focused on developing new types of commutatorless machines.

Electric machines for renewable energy harvesting should not be considered as a subset of electric machines for industrial application since they have fundamental difference in requirements. The renewable energy machine should form an individual class of electric machines, which possesses the following features:

- high efficiency over wide torque and speed ranges so as to increase the utilization of extractable energy;
- high power density so as to reduce the overall size and weight;
- wide speed range so as to harness the energy at different speeds;

- high reliability so as to reduce the operational failure or fault;
- maintenance free so as to eliminate the maintenance cost and possible outage for maintenance;
- high robustness so as to withstand harsh operating conditions and natural environment;
- good voltage regulation so as to maintain the system voltage;
- high power factor so as to enhance the power transfer;
- Low cost so as to reduce the system cost.

## 4. EXISTING MACHINES FOR RENEWABLE ENERGY

Among different types of electric machines, there are three main types that have been adopted for renewable power generation: namely the DC, induction and synchronous machines. They possess fundamentally different machine topologies as depicted in Figure 4.

### 4.1. DC Machines

Based on the methods of field excitation, DC machines can be grouped as the self-excited DC and separately excited DC types. Based on the source of field excitation, they can also be grouped as the wound-field DC and PM DC types. As determined by the mutual interconnection between the field winding and the armature winding or the use of PM excitation, the whole family consists of the separately excited DC, shunt DC, series DC and PM DC types. For the separately excited DC machine, the field and armature circuits are independent of each other. For the shunt DC machine, the field and armature circuits are connected in parallel. For the series DC machine, the field and armature circuits are connected in series. For the PM DC machine, the PM field is uncontrollable. Because of the space-saving benefit by PMs and the absence of field losses, the PM DC machine offers higher power density and higher efficiency than its wound-field counterparts.

All DC machines suffer from the same problem due to the use of commutators and brushes. Commutators cause power ripples and limit the rotor speed, while brushes are responsible for friction and radio-frequency interference. Moreover, due to the wear and tear, periodic maintenance of commutators and brushes is always required. These drawbacks make them less reliable and unsuitable for maintenance-free operation. The major advantages of DC machines are their maturity and simplicity.

Because of their relatively low efficiency and the need of maintenance, DC machines are unattractive for commercial renewable

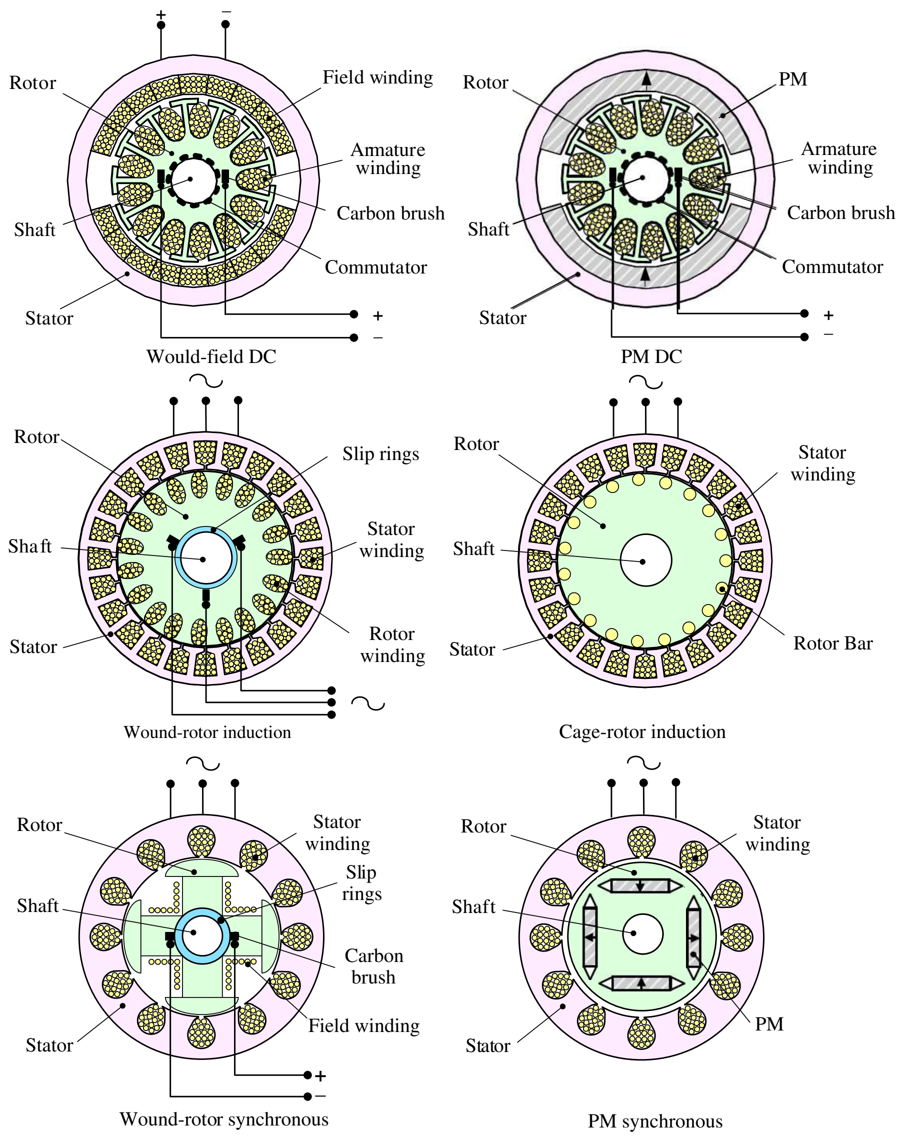


**Figure 4.** Existing machine types for renewable energy.

power generation. Nevertheless, because of their simplicity, the separately excited DC and PM DC types are attractive for educational demonstration of low-power small-size wind power generation, typically less than 1 kW.

### 4.2. Induction Machines

Induction machines are the most mature technology among various commutatorless machines. There are two types of induction machines: namely the wound-rotor and cage-rotor. The wound-rotor induction machine is also called the slip-ring induction machine since it incorporates slip rings and carbon brushes to enable its rotor winding connecting to the external circuit. When the rotor winding is fed by a frequency converter to perform slip power control while the stator winding is tied to the grid, this wound-rotor induction machine is commonly termed the DFIG which is widely used for wind power generation. The main players in the market of DFIGs for wind power generation include the Acciona, Alstom-Ecotècnia, Gamesa, General Electric, Vestas, Mitsubishi, Nordex and Repower. For example, the Alta Wind Energy Center is currently the largest wind farm in the USA with the installed capacity of 1020 MW, which adopts 390 Vestas DFIGs with 1.5 MW or 3 MW each. The key reason for the popularity of using DFIGs in wind farms is that the output frequency can remain synchronized with the grid under different wind speeds. However, because of the need of maintenance and lack of sturdiness, the wound-rotor induction machine or the derived DFIG is becoming less attractive for new-generation wind farms. For other renewable energy harvesting, the DFIG is unattractive except the case of using wind turbine technology for harnessing wave power.

The cage-rotor induction machine inherently offers higher efficiency and higher power density than its wound-rotor counterpart because of the use of squirrel cage to supersede the distributed winding in the rotor and the elimination of slip rings and carbon brushes. Also, it takes the definite advantages of high robustness and low cost. Usually, this cage-rotor induction machine is loosely termed the IG which is widely used for various renewable energy harvesting such as the wind, wave, small hydro, tidal stream, solar-thermal, geothermal and biomass-thermal. For instance, the Walney Wind Farm in UK is currently the largest offshore wind farm in the world with the installed capacity of 367 MW, which adopts 102 Siemens IGs with 3.6 MW each.

### 4.3. Synchronous Machines

Synchronous machines are almost exclusively used for fossil-fuel power generation. They are also predominant for thermal power plants and hydropower plants that respectively adopt steam turbines and hydro turbines under almost fixed speeds. There are two main types of synchronous machines, namely the wound-rotor and PM-rotor. The wound-rotor synchronous machine incorporates the DC

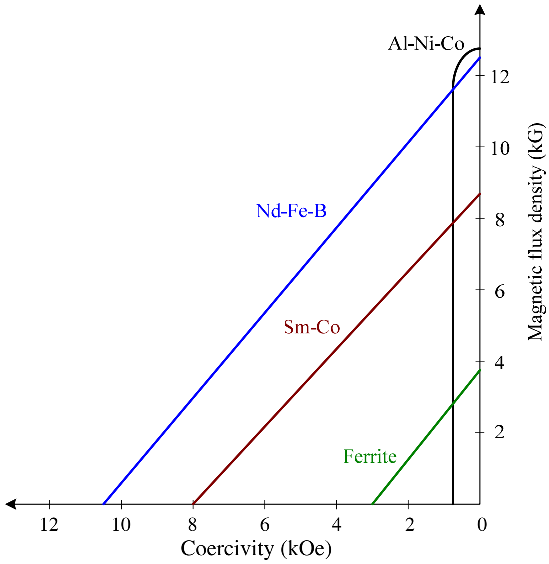


**Figure 5.** PM characteristics.

field winding in the rotor which is generally excited by the external DC supply via slip rings and carbon brushes. Usually, this wound-rotor synchronous machine is loosely termed the SG which is attractive for those renewable power generation systems with high power ratings. For instance, the Three Gorges Dam is the world's largest hydropower plant with the installed capacity of 21 GW, which adopts 30 main SGs, each with 700 MW. These SGs are manufactured by two joint ventures: one includes the Alstom, ABB, Kværner and Harbin Motor; another one includes Voith, General Electric, Siemens and Oriental Motor. Compared with the IG, this SG takes the advantage of higher efficiency for electricity production, and can operate at or close to unity power factor. However, the use of slip rings and carbon brushes causes maintenance requirement which is particularly disadvantageous to small power plants such as for wind, wave, small hydro and tidal stream energy harvesting.

By using PMs to replace the DC field winding in the rotor, the PM synchronous machine takes the definite advantages of high efficiency due to the absence of rotor copper loss, high power density due to the elimination of DC field winding and fast response due to the lower electromechanical time constant of the rotor. Figure 5 shows the demagnetization characteristics of viable PM materials, including the ferrite, aluminum-nickel-cobalt (Al-Ni-Co), samarium-cobalt (Sm-

Co) and neodymium-iron-born (Nd-Fe-B). It can be observed that the Nd-Fe-B is most preferable since it can offer high remanence which measures the strength of magnetic field, high coercivity which denotes the resistance to becoming demagnetized and large energy product ($BH_{\max}$) which represents the density of magnetic energy.

Based on the operation waveforms, the PM synchronous machine can be categorized as the PM brushless AC (BLAC) and PM brushless DC (BLDC) machines [11, 12]. The PM BLAC machine is characterized by sinusoidal back electromotive force (EMF) and sinusoidal AC current, whereas the PM BLDC machine is characterized by trapezoidal EMF and rectangular AC current. Actually, the PM BLAC machine is loosely called the PM synchronous machine. According to the position of PMs in the rotor, the PM synchronous machine can be classified as the surface-mounted, surface-inset, interior-radial and interior-circumferential topologies as shown in Figure 6. For the surface-mounted topology, the PMs are simply mounted on the rotor surface by using epoxy adhesives. Since the permeability of PMs is near to that of air, the effective air-gap is the sum of the actual air-gap length and the radial thickness of the PMs. Hence, the corresponding armature reaction field is small and the stator

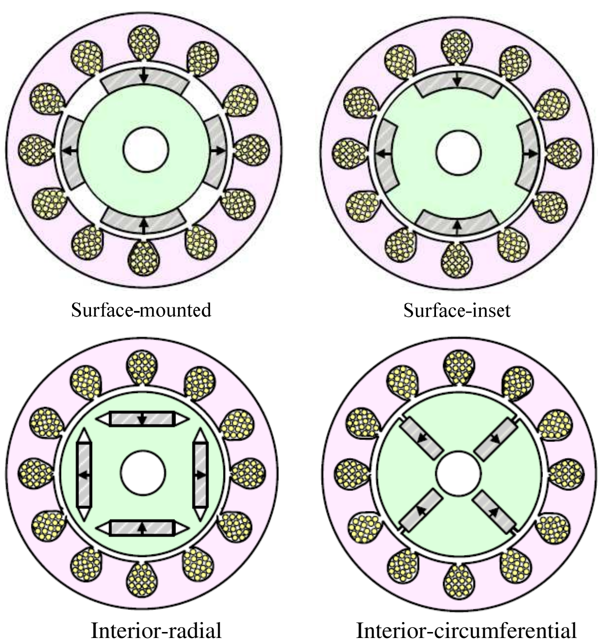


**Figure 6.** PM synchronous machine topologies.

winding inductance is low. Also, since the $d$-axis and $q$-axis stator winding inductances are nearly the same, its reluctance power is almost zero. For the surface-inset topology, the PMs are inset or buried in the rotor surface. Thus, the $q$-axis inductance becomes higher than the $d$-axis inductance, hence producing an additional reluctance power. Also, since the PMs are inside the rotor, it can withstand the centrifugal force at high-speed operation, hence offering good mechanical integrity. For the interior-radial topology, the PMs are radially magnetized and buried inside the rotor. Similar to the surface-inset one, the PMs are mechanically protected, hence allowing for high-speed operation. Also, because of its $d$-$q$ saliency, an additional reluctance power is generated. Differing from the surface-inset one, this interior-radial topology adopts linear PMs which are easier for insertion and can be easily machinable. For the interior-circumferential topology, the PMs are circumferentially magnetized and buried inside the rotor. It takes the definite advantage that the air-gap flux density can be higher than the PM remanent flux density, the so-called flux focusing. Also, it holds the merits of good mechanical integrity and additional reluctance torque. However, because of significant flux leakage at the inner ends of PMs, a nonmagnetic shaft or collar is generally required.

Because of its high efficiency and high power density, the PM synchronous machine is becoming more and more attractive for renewable energy harvesting at medium power ratings, although it suffers from the drawbacks of relatively high PM material cost and uncontrollable PM flux. It is usually termed the PMSG, and particularly attractive for the latest development of wind, wave, small hydro and tidal stream power generation systems. For instance, the Siemens PMSG can achieve up to 6 MW for offshore wind power generation in Høvsøre, Denmark.

## 4.4. Comparison of Existing Machines

In order to evaluate the aforementioned machines for application to renewable energy harvesting, they are compared in terms of their efficiency, power density, power factor, power conditioning requirement, robustness, maturity, cost, power level and maintenance requirement. A point grading system (1 to 5 points) is used in which 1 is the worst and 5 is the best. As listed in Table 2, both the wound-field and PM DC machines are unacceptable; both the wound-rotor and cage-rotor induction machines and the wound-rotor synchronous machine are acceptable but not preferable; whereas the PM synchronous machine is most preferable.

**Table 2.** Evaluation of existing machines for renewable energy.

| | Wound DC | PM DC | Wound Ind | Cage Ind | Wound Syn | PM Syn |
|---|---|---|---|---|---|---|
| Efficiency | 2 | 3 | 3 | 4 | 4 | 5 |
| Power density | 2 | 3 | 3 | 4 | 3 | 5 |
| Powerfactor | 5 | 5 | 4 | 3 | 5 | 5 |
| Power conditioning | 3 | 3 | 5 | 3 | 3 | 3 |
| Robustness | 2 | 2 | 4 | 5 | 4 | 4 |
| Maturity | 5 | 5 | 5 | 5 | 5 | 4 |
| Cost | 3 | 3 | 3 | 4 | 4 | 3 |
| Power level | 2 | 2 | 4 | 4 | 5 | 4 |
| Maintenance | 2 | 2 | 3 | 5 | 4 | 5 |
| Total | 26 | 28 | 34 | 37 | 37 | 38 |

## 5. ADVANCED MACHINES FOR RENEWABLE ENERGY

The latest development of renewable energy machines is focused on three directions: the stator-PM machines aiming to achieve high reliability and high robustness; the direct-drive PM machines aiming to directly harness the renewable energy without any transmission mechanism; and the magnetless machines aiming to avoid using expensive rare-earth PMs.

### 5.1. Stator-PM Machines

The stator-PM (SPM) machines are with PMs located in the stator, and generally with salient poles in both the stator and the rotor [13]. Since the rotor has neither PMs nor windings, this class of machines is mechanically simple and robust. Hence, they are very suitable for renewable energy harvesting which is intermittent in nature. According to the location of the PMs, it can be split into the doubly-salient PM (DSPM), flux-reversal PM (FRPM) and flux-switching PM (FSPM) types. Additionally, with the inclusion of independent field or magnetizing windings in the stator for flux control, the class further derives the flux-controllable PM (FCPM) type. Their typical machine topologies are shown in Figure 7.

The DSPM machine is relatively the most mature type of SPM machines [14, 15]. Although it has salient poles in the stator and rotor, the PM torque significantly dominates the reluctance torque, hence exhibiting low cogging torque. Since the variation of flux linkage with

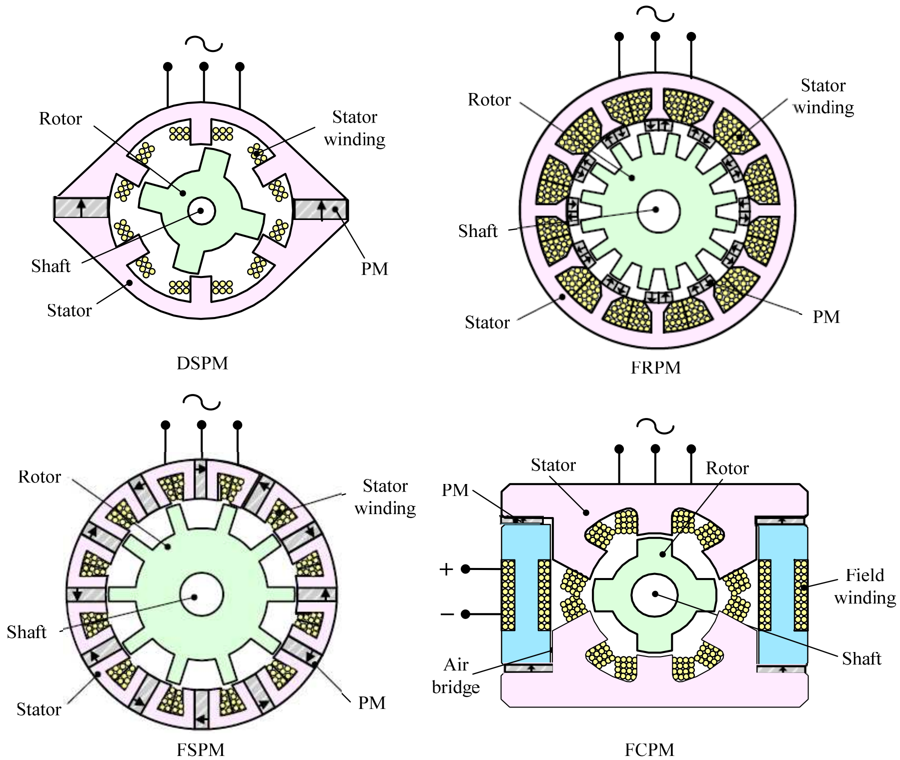


**Figure 7.** SPM machine topologies.

each coil as the rotor rotates is unipolar, it is very suitable for the BLDC operation. On the other hand, when the rotor is skewed, it can offer the BLAC operation. This machine takes the definite advantages of high reliability and high robustness for wind power generation [16].

The FRPM machine exhibits the feature of bipolar flux linkage variation because the flux linkage with each coil reverses polarity as the rotor rotates [17]. Each stator tooth has a pair of PMs of different polarities mounted onto each tooth surface. Since the bipolar flux linkage variation can have better utilization of iron core than the unipolar counterpart, the FRPM machine inherently offers higher power density than the DSPM machine. However, since the PMs are attached on the surface of stator teeth, they are more prone to partial demagnetization. Also, significant eddy current loss in the PMs may be resulted.

The FSPM machine has attracted wide attention in recent years [18, 19]. In this topology, each stator tooth consists of two adjacent laminated segments and a PM, and each of these segments is sandwiched by two circumferentially magnetized PMs. Hence, it enables flux focusing. Additionally, this FSPM machine has less armature reaction, hence offering higher electric loading. Since its back EMF waveform is essentially sinusoidal, this machine is more suitable for the BLAC operation.

The FCPM machine takes the definite advantage that the air-gap flux density is directly controllable. One basic type of FCPM machines is the hybrid-field DSPM topology [20, 21]. The stator incorporates two types of windings, namely the 3-phase armature winding and the DC field winding, and the PM poles. The rotor has neither PMs nor windings, hence offering high mechanical integrity. The 3-phase armature winding operates like that for the DSPM machine, whereas the DC field winding not only works as an electromagnet but also as a tool for flux control. Also, there is an extra air bridge in shunt with each PM. If the field winding MMF reinforces the PM MMF, this extra flux path will assist the effect of flux strengthening. On the other hand, if the field winding MMF opposes the PM MMF, this extra flux path will favor the PM flux leakage, hence amplifying the effect of flux weakening. As a result, with a proper design of the air-bridge width, a wide flux-regulating range can be obtained by using a small DC field excitation.

Although this topology takes the definite advantages of high mechanical integrity and flexible air-gap flux control which are highly desirable for online voltage regulation and efficiency optimization, its stator is relatively bulky and the corresponding leakage flux is also significant. An improved version is to employ an outer-rotor topology [22]. This outer-rotor topology can enable full utilization of the space of inner stator (the part beneath the armature windings) to accommodate both the PMs and the DC field windings, hence improving the power density. Also, since both the PMs and the DC field windings are embraced by the rotor, the problem of flux leakage can be minimized. Because of the outer-rotor arrangement, it can readily be mounted with wind blades for wind power generation [23, 24]. However, this hybrid-field DSPM machine still suffers from a key drawback — the continual excitation of DC field windings for flux control will significantly increase the copper loss, hence deteriorating the inherent merit of high efficiency.

By incorporating the concept of the memory machine (also called the flux-mnemonic PM machine or AC-excited memory machine) [25] into the outer-rotor hybrid-field DSPM machine, the memory DSPM machine (also called the DC-excited memory machine) is resulted, which can offer effective and efficient air-gap flux control [26, 27]. The high effectiveness is due to its direct magnetization of PMs by

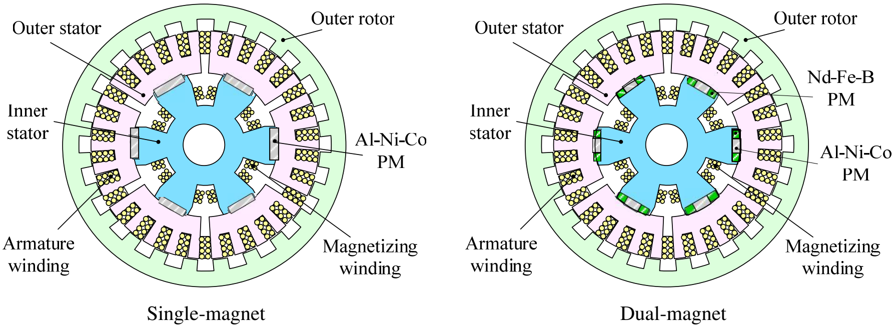


**Figure 8.** Outer-rotor memory DSPM machine topologies.

magnetizing windings, while the high efficiency is due to the use of temporary current pulse for PM magnetization. The configuration of this machine is shown in Figure 8 which adopts an outer-rotor double-layer-stator structure. The use of double-layer-stator structure is to enable the PMs immune from accidental demagnetization by armature reaction. The PM material used in this memory DSPM machine is the Al-Ni-Co alloy which offers a relatively low coercive force to enable online magnetization. However, the Al-Ni-Co PM has a smaller energy product than the Nd-Fe-B, thus degrading the machine power density. In order to maintain high power density while offering the flexible flux-tuning and flux-mnemonic function, the concept of dual magnets, namely the use of both Al-Ni-Co and Nd-Fe-B PMs to form a PM pole [28], is developed as shown in Figure 8. It should be noted that this memory DSPM machine can offer all operating features of the hybrid-field DSPM machine for wind power generation [29], namely the flux strengthening, flux weakening and flux optimization; meanwhile, the required energy consumption for PM magnetization or demagnetization is temporary and insignificant as compared with the energy consumption for continual hybrid-field excitation.

## 5.2. Direct-drive PM Machines

Most of the renewable energy harvesting devices, such as the hydro turbine, wind turbine and wave turbine, inherently operate at low speeds. In order to directly convert this low-speed motion into electricity, this low-speed machine has to be designed with many poles, leading to be bulky and heavy. So, the turbine speed is usually stepped up by a gearbox before feeding into a high-speed machine. For instance, as depicted in Figure 9, the planetary-geared high-speed machine takes the merits of reduced overall size and weight over the gearless low-speed machine for wind power generation. However, the use of planetary

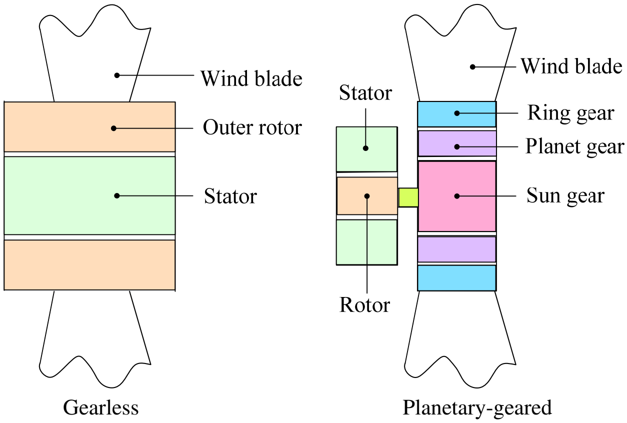


**Figure 9.** Comparison of gearless and geared machines for wind power generation.

gear inevitably involves transmission loss, acoustic noise and regular lubrication.

Recently, magnetic gears are becoming attractive, since they inherently offer the merits of high efficiency, reduced acoustic noise, and maintenance free [30–32]. They can adopt the interior-magnet arrangement [33] or Halbach-magnet array [34] to further improve their performances. By artfully integrating the magnetic gear into the PM synchronous machine, the low-speed direct-drive requirement and the high-speed machine design can be achieved simultaneously. Figure 10 shows the magnetic-geared machine which not only offers reduced size and weight, but also eliminates all the drawbacks due to the mechanical gear [35]. Its artfulness is the share of a common PM rotor, namely the outer rotor of the PM synchronous machine and the inner rotor of the magnetic gear. The outer-rotor arrangement is particularly attractive for direct-drive wind power generation because the wind blades can be directly mounted on the surface of this outer rotor [36]. Nevertheless, this magnetic-geared machine may suffer from the drawback of manufacturing difficulty due to the presence of three air-gaps and two rotors.

The variable-reluctance (VR) PM machine is a class of PM brushless machines dedicated to low-speed high-torque direct-drive applications. The operating principle is that the flux-linkage to the armature windings changes along with the interaction between a set of PMs and a set of teeth. Based on the modulation function of the toothed-pole structure, the heteropolar fields can interact with one another to develop the steady torque [37]. According to the relationship of motion plane and flux plane, the VR PM machine

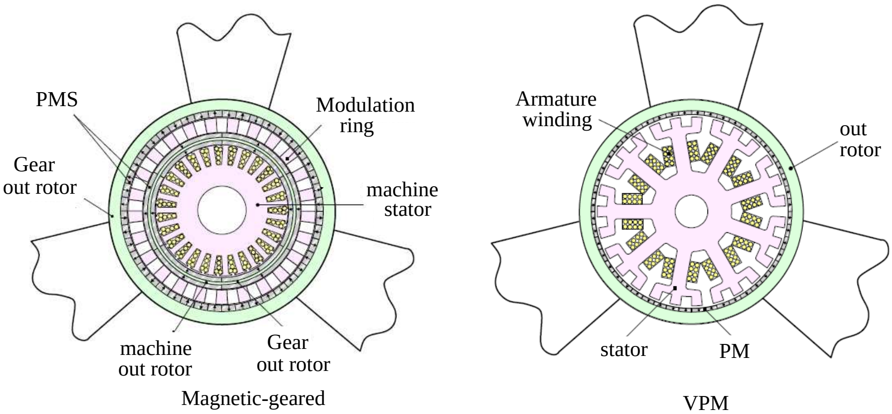


**Figure 10.** Direct-drive PM machine topologies.

can be split into the transverse-flux PM (TFPM) machine and the vernier PM (VPM) machine types. Since the TFPM machine involves a 3-dimensional flux-path configuration which precludes the use of laminated iron core, it is unattractive for renewable energy harvesting. On the contrary, the VPM machine can adopt a simple toothed-pole-stator PM-rotor configuration [38, 39]. Namely, each stator tooth is split into small teeth at the end, termed flux-modulation poles, so that a small movement of the PM rotor can cause a large movement of flux-linkage in the stator armature winding. This is the so-called magnetic gearing effect. The outer-rotor VPM machine directly mounted with wind blades is also shown in Figure 10, indicating that it offers the definite merit of only one air-gap and one rotor as compared with the magnetic-geared counterpart [40]. Furthermore, based on the same principle of operation, the VPM machine allow the PMs located in the stator [41] so as to improve the mechanical integrity of the rotor.

When using the heaving buoy or Archimedes wave swing to extract wave energy, the linear machine is preferred to the rotational machine because the wave motion is inherently linear. Also, the rotational machine inevitably desires a bulky and inefficient linear-to-rotary transmission mechanism which should be eliminated. Because of the low-speed nature of reciprocating wave motion (typically 0.5 m/s), the linear direct-drive PM machine is highly desirable. Borrowing the concept of coaxial magnetic gears, the linear magnetic gears can readily be used to amplify the linear motion [42, 43]. Hence, the linear magnetic-geared PM synchronous machine can be deduced as shown in Figure 11, which offers the low-speed direct-drive operation for wave power generation and the high-speed machine design for maximizing power density [44]. Meanwhile, the rotational VPM machine can also be extended to form the linear VPM machine which exhibits the low-speed high-force feature for directly harnessing wave energy [45, 46].

## 5.3. Magnetless Machines

With ever increasing popularity of PM machines for wind generators and electric vehicles, the demand of Nd-Fe-B PM is drastically soaring. The price of the raw material neodymium is the determining factor in pricing the Nd-Fe-B PM. As shown in Figure 12, it increased about 18 times between July 2009 and July 2011, and recently settles at about 6 times [47]. Both the absolute value and volatility of the neodymium price severely add uncertainty to the development of PM machines, and stimulate the research of advanced magnetless machines.

The switched reluctance (SR) machine is a kind of doubly salient machines, and also a kind of advanced magnetless machines. As shown in Figure 13 the stator of this SR machine is a simple iron core with salient poles wound with the concentrated armature winding, while the rotor is simply an iron core with salient poles having no windings or PMs. Its operating principle is simply based on the 'minimum reluctance' rule. So it offers the definite advantages of simple construction, high robustness, low manufacturing cost and low moment of inertia. Because of these advantages, this SR machine is

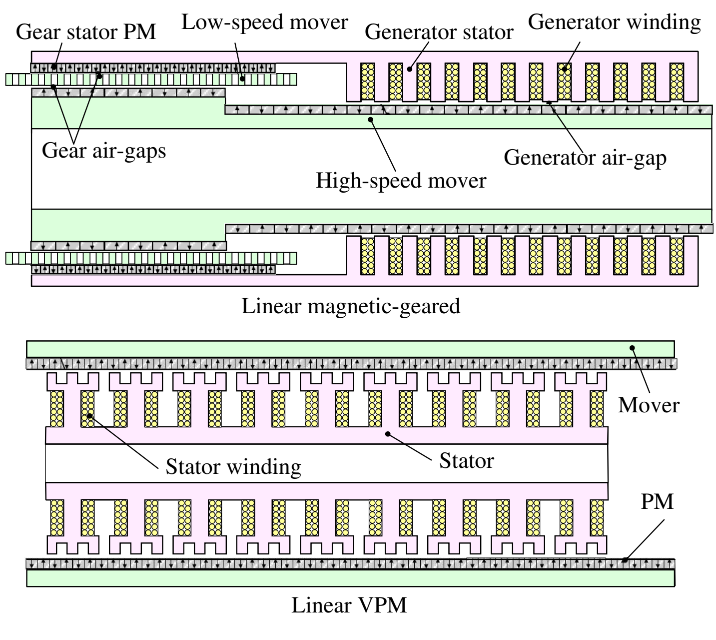


**Figure 11.** Linear direct-drive PM machine topologies.

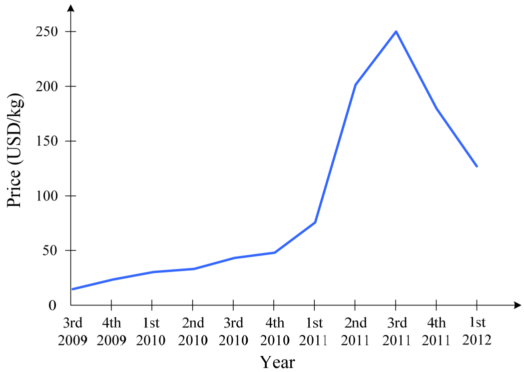


**Figure 12.** Price for neodymium.

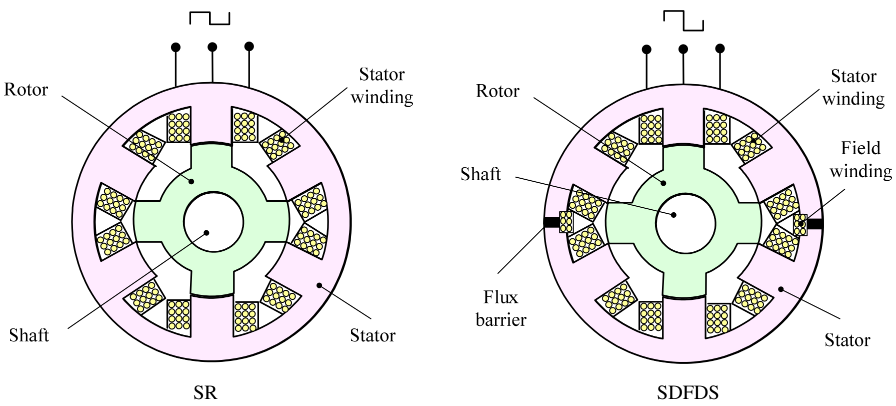


**Figure 13.** Doubly salient magnetless machine topologies.

becoming attractive for wind power generation [48]. Nevertheless, it suffers from the problem of no self-excitation capability. To overcome this problem, some researchers have made use of an external DC power source to create magnetic field around the armature winding so that electricity can be generated when the rotor moves.

The stator doubly fed doubly salient (SDFDS) machine is an emerging magnetless machine, which is actually derived from the aforementioned DSPM machine [49]. As shown in Figure 13, it adopts the same rotor structure as the SR machine, namely the solid iron with salient poles. Differing from the SR machine, the SDFDS machine has two types of windings on the stator — the 3-phase armature winding and the DC field winding. Since the current flowing through the field winding is independently controlled, this machine can retain the inherent merit of higher power density than the SR machine while enjoying the additional merit of controllable air-gap flux density. Consequently, when the generated output voltage deviates from the preset value, the DC field current can be controlled in such as way that the output voltage is kept constant. Also, based on the measured mechanical input power and electrical output power, the DC field current can be tuned in such a way that the system efficiency is maximized. These two features are highly desirable for wind power generation [50].

## 6. REPRESENTATIVE RENEWABLE ENERGY MACHINES

Table 3 summarizes the near-term and long-term representative machines for renewable energy harvesting. Because of the merits of high efficiency, high power density and maintenance-free operation, the PMSG and SPM generator (SPMG) will be the most preferable generators for most kinds of renewable energy harvesting in near term. With ever increasing concern on the supply of rare-earth materials and volatility of their price, the SR generator (SRG) will be equally important. For wave energy extraction, the linear versions, namely the LPMSG, LSPMG and LSRG, will be preferable. Nevertheless, for hydropower with very high power ratings, the SG can maintain its attraction in near term due to its maturity. In long term, the VPM generator (VPMG) will be more attractive than the PMSG or SPMG for those renewable energies with slow intermittent motion, whereas the PMSG and SPMG will still be preferable for the large hydro or those renewable energies in thermal nature. The SDFDS generator (SDFDSG) will supersede the SRG in long term. Of course, the linear VPMG (LVPMG) and linear SDFDSG (LSDFDSG) will be preferred for wave energy.

**Table 3.** Representative machines for renewable energy.

| Renewable energy | Near-term | Long-term |
|---|---|---|
| Wind | PMSG, SPMG, SRG | VPMG, SDFDSG |
| Wave | LPMSG, LSPMG, LSRG | LVPMG, LSDFDSG |
| Hydro | SG, PMSG, SPMG, SRG | PMSG, SPMG, VPMG, SDFDSG |
| Tidal | PMSG, SPMG, SRG | VPMG, SDFDSG |
| Solar-thermal | PMSG, SPMG, SRG | PMSG, SPMG, SDFDSG |
| Geothermal | PMSG, SPMG, SRG | PMSG, SPMG, SDFDSG |
| Biomass-thermal | PMSG, SPMG, SRG | PMSG, SPMG, SDFDSG |

It should be noted that the acceptability of advanced magnetless machines depends on the price and abundance of future PM materials. If there are new PM alloys without using any rare-earth elements while offering similar magnetic properties as the Nd-Fe-B, the magnetless machines will not be so attractive. Moreover, there are many factors, such as new machine materials and new machine topologies, affecting the long-term preference of electric machines for renewable energy harvesting. For instance, high temperature superconducting (HTS) materials and soft magnetic composites (SMC) have potentials to change the long-term development of renewable energy machines.

## 7. CONCLUSION

In this paper, an overview of electric machines for renewable energy harvesting has been presented, with emphasis on discussing the challenges and research opportunities. After introducing various renewable energies and electric machines, the concept of renewable energy machines is coined. Then, the existing machines for renewable energy harvesting, including the DC, induction and synchronous types, are critically compared, indicating that the PMSG is most preferable. Consequently, the advanced renewable energy machines, including the SPM, direct-drive PM and magnetless types, are discussed, hence identifying that the PMSG, SPMG and SRG are most promising in near future, and the PMSG, SPMG, VPMG and SDFDSG are most viable in long term. It should be noted that this overview is focused on renewable energy harvesting only, the electric machines for renewable energy storage such as ultrahigh-speed flywheels or for renewable energy application such as electric vehicles are of different features which will form the substance for future papers.

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