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Chapter

Tidal Turbine Generators

Faisal Wani, Jianning Dong and Henk Polinder

Abstract

Recently, tidal stream turbines have become a preferable mode of harvesting tidal energy. The main issue for low utilization of tidal energy is the high levelized cost of energy (LCoE) from tidal stream turbines. A major reason for this is the high operation and maintenance costs for submerged installations. A possible way of minimizing the LCoE and improving the availability is to use a flooded (or a wetgap) generator rather than a conventional airgap generator. Inside flooded generators, the gap between the stator and rotor is filled with the seawater. This architecture has the potential to improve cooling and reduce reliance on ancillary systems (e.g., bilge system), thereby improving reliability. The chapter begins with a brief description of the generator systems used in current tidal stream turbines. The focus of the chapter is, however, to give a basic insight into the design aspects of the flooded generators, and compares it with the currently used sealed airgap generators in tidal turbine systems.

Keywords: tidal stream turbines, permanent magnet generators, flooded generators, corrosion, rotor-can

1. Introduction

Energy from tides is predictable over a span of several years, unlike other renewable sources of energy such as solar and wind. Furthermore, tidal energy is influenced little by weather conditions. Grid operators prefer a predictable energy resource as it facilitates economic and reliable grid operation. According to [1], the estimated global potential for tidal energy is around 500 GW, as shown in **Figure 1**. There are two main ways of harnessing tidal energy: tidal range (or dams) and tidal stream turbines.

Recently tidal stream turbines have become a preferable mode of harvesting tidal energy over tidal range (or dams) technology. The commercial success of wind turbines is to a large extent responsible for this shift in harnessing tidal energy. Furthermore, the potential for tidal stream turbines is expected to be more than the tidal range technology [2].

A typical tidal stream turbine is shown in **Figure 2**, which is an example of a horizontal axis tidal turbine (HATT). Although vertical axis tidal turbines and other topologies such as oscillating hydrofoil, enclosed tip turbine and tidal kites are also used to harness tidal energy, most of the research and development efforts are focused on HATTs; see **Figure 3**. This is primarily because of their higher technology readiness level (TRL), and similarity to commercial wind turbines. Some of the main tidal energy developers are listed in **Table 1**. As is evident, most of them prefer horizontal axis tidal turbines. Consequently, the focus of this chapter will be also on HATTs.

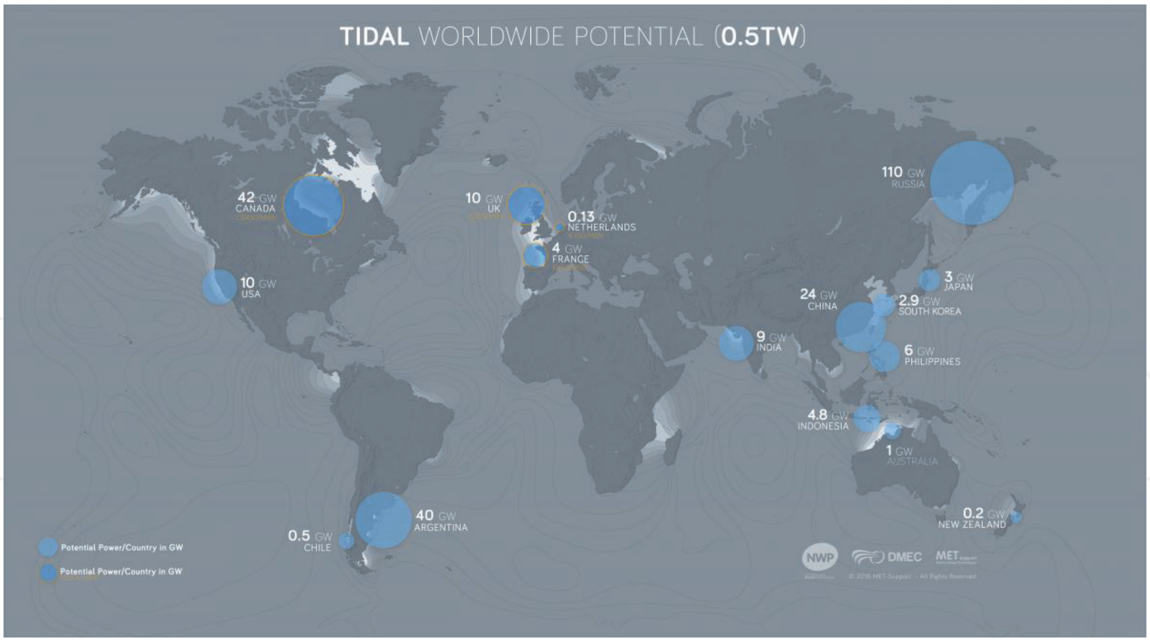

Figure 1.
Global tidal energy potential (Source [1]).

Figure 2.
Nova M100 tidal turbine (Source: ©Nova Innovation).

The power captured by a HATT is given by the same equation as that of a wind turbine. Mathematically, power captured by the turbine is given by

$$P = \frac{1}{2} C_p(\lambda) \rho A v^3, \tag{1}$$

where C_p is the power coefficient, ρ is the density of the water, A is the area swept by the turbine blades and v is the velocity of the tidal stream. The power

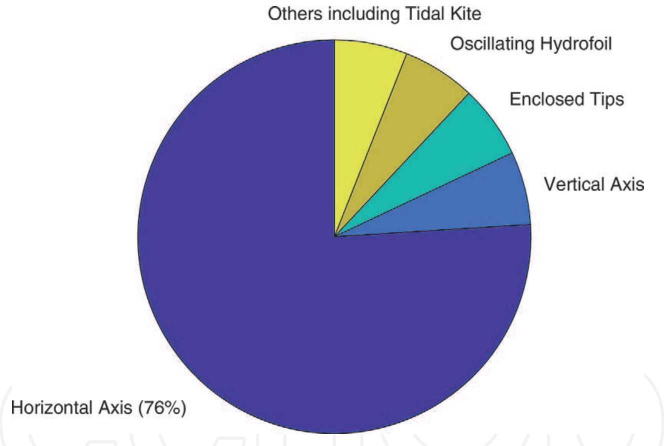

Figure 3.
Focus of R&D efforts for different tidal stream technologies (Source: [3]).

Company name	Country base	Device type	Generator type[a]	Device name[b]
Andritz Hydro Hammerfest	Norway	HATT	IG + GB	HS1000
Atlantis Resources Limited	UK	HATT	PMSG + GB	AR1500
Marine Current Turbines	UK	HATT	IG + GB	SeaGen S
Nautricity	UK	HATT	PMSG-DD	CoRMaT
Nova Innovation	UK	HATT	IG + GB	Nova M100
Schottel Group	Germany	HATT	IG + GB	SIT
Scotrenewables	UK	HATT	IG + GB	SR2000
Tocardo Tidal Turbines	Netherlands	HATT	PMSG-DD	T200
Minesto	Sweden	Tidal Kite	—	Deep Green
Deepwater Energy BV	Netherlands	VATT	—	Oryon Watermill

Source: European Marine Energy Centre (emec.org.uk).
[a]*IG: induction generator; GB: gearbox; PMSG: permanent magnet synchronous generator; DD: direct drive.*
[b]*Not all the devices from the same manufacturer are listed.*

Table 1.
Some of the main tidal energy developers around the world, and their device types.

coefficient, C_p is a function of the tip-speed ratio denoted by λ (for a constant blade pitch angle). Tip-speed ratio is the ratio of the blade tip-speed to the incoming velocity of the fluid. A typical $C_p - \lambda$ curve is shown in **Figure 4**.

A disadvantage of the tidal energy is that the levelized cost of energy (LCoE) is currently much higher than the average LCoE from more developed sources of energy [3]. In [3], minimizing the operation and maintenance (O&M) expenses, and increasing the capacity factor have been identified as major factors in minimizing the LCoE from tidal turbines; see **Figure 5**.

One possible way of minimizing the O&M expenses and improving the capacity factor is to use a flooded (or wetgap) generator rather than the sealed airgap generator [3]. In a flooded generator, instead of an airgap the stator-rotor gap is filled with the seawater. As a result, the design of a flooded generator has to be different from the airgap generator. To begin with in a flooded generator a stator and a rotor *can* (or sleeve) are required to protect the active machine parts from corrosion. This will be illustrated later in the chapter. Compared to the conventional airgap generators, the design of flooded generators has been little addressed in literature. We discuss some design aspects of the flooded generators in this chapter.

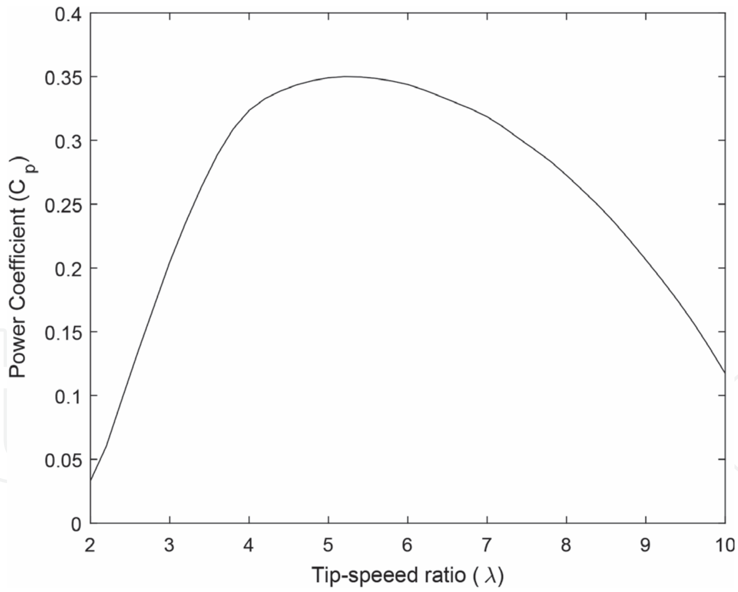

Figure 4.
A typical $Cp - \lambda$ for a tidal turbine [4]. Only indicative values are shown here; these values do not reflect the maximum Cp in a tidal turbine.

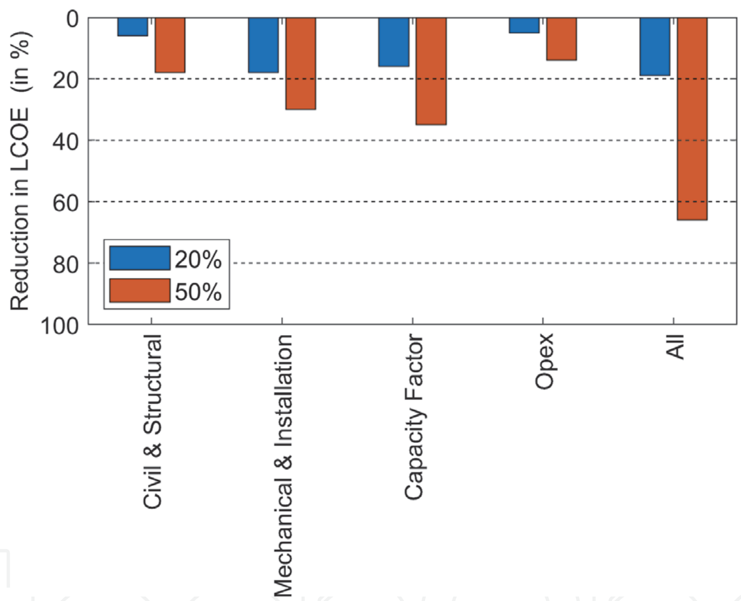

Figure 5.
Likely reduction in per unit LCoE for 20 and 50% reduction in cost component (Source: [3]).

This chapter gives a qualitative comparison between a conventional airgap and a flooded generator for tidal stream turbines. The qualitative comparison is based on the pros and cons of each generator type, followed by their structural differences. Both of these generators are assumed to be permanent magnet (PM) radial-flux direct-drive generators, unless otherwise stated. This design is used for comparison as the radial-flux PM machines are well suited to both flooded and conventional architectures.

In Section 2, a brief overview of generator technologies used in the current tidal stream turbines is given. Section 3 illustrates the conventional design of the generators used in tidal turbines, and their structural aspects and limitations. In Section 4, a relatively new concept called the flooded generator is proposed for application in tidal turbines. Section 5 gives a general guideline for design of flooded generator. Section 6 gives the conclusions from this chapter.

2. Generator types in tidal turbines

Squirrel cage induction machines and PM synchronous machines are commonly used as generators in tidal turbines. Among synchronous generators, PM machines are more attractive compared to the electrically excited synchronous generators, despite being expensive. This is primarily because of the lower failure rates and possibility of higher pole numbers in PM machines. Usually generators can be classified in either of the two categories: high-speed generators with a gearbox, and low-speed direct-drive generators [5].

2.1 High-speed generators with a gearbox

The size of the generator is directly related to its torque rating. This implies for the same power, high-speed machines are smaller. In addition to the manufacturing costs, transport and assembly costs are also likely to be lower for high-speed machines. Since tidal turbines rotate at low speeds, a gearbox is necessary between the turbine and the high-speed generator; see **Figure 6a**.

Atlantis Resources AR1500 turbine uses a radial flux surface-mounted PM synchronous generator with a two-stage epicyclical gearbox [6]. On the other hand, Andritz Hydro Hammerfest HS1000 and Schottel's Instream turbine comprises an induction generator with a three-stage and a two-stage planetary gearboxes, respectively [7, 8].

2.2 Low-speed direct-drive generators

Low-speed direct-drive generators can be directly coupled to the turbine without the need for a gearbox; see **Figure 6b**. This significantly improves the overall

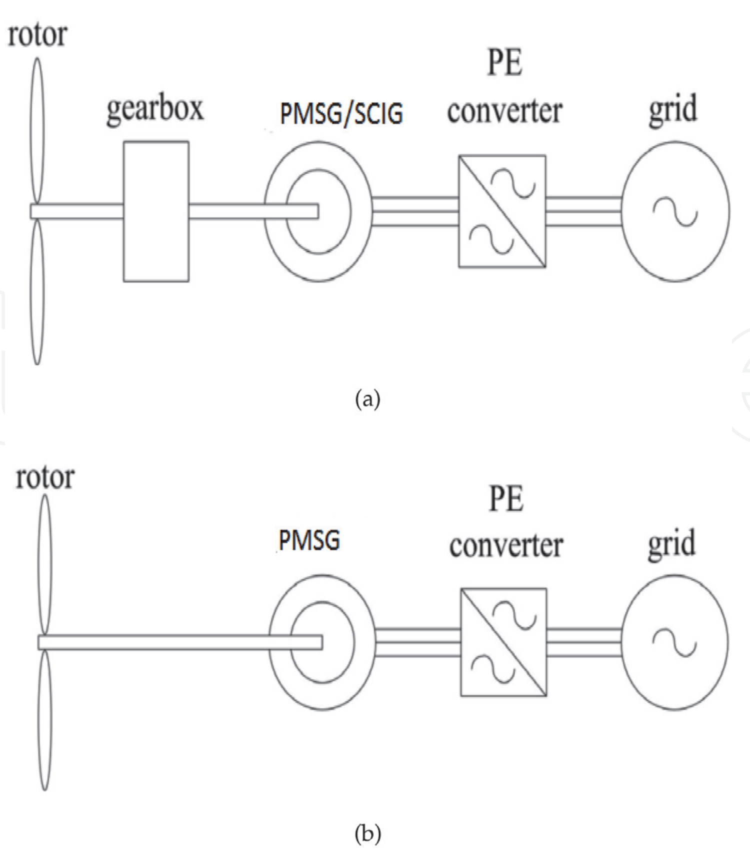

Figure 6.
(a) High-speed generator coupled to the tidal turbine via a gearbox; (b) low-speed direct drive generator. PMSG—Permanent magnet synchronous generator; SCIG—Squirrel cage induction generator; PE—Power Electronic.

reliability and efficiency of the system. Direct-drive generators usually have high pole numbers, and thus small pole-pitch. This makes PM machines suitable for direct-drive applications because induction machines with high pole numbers result in an inefficient design due to lower power factor [9].

DCNS-OpenHydro and Tocardo T2 turbines respectively, used a direct-drive PM generator. Nautricitys CoRMaT is another innovative direct-drive generator with two contra-rotating rotors. CoRMaT's design is unconventional as the stator of the axial-flux PM generator is also mounted on one of the rotors to double the relative speed between the stator and the rotor. The torque is equally divided between the two rotors. Because of its peculiar design, the device is always perpendicular to the tidal flow ensuring maximum capture of the power [10, 11].

3. Conventional design for tidal generators

Most tidal turbine manufacturers use a conventional airgap generator. In an airgap generator, the stator-rotor gap inside the generator is occupied by air. Such generators are almost invariably used in energy generation, such as hydro power stations, and wind turbines. For tidal turbines, the airgap generator has to be enclosed in a water-tight nacelle. The inner nacelle space is isolated by the seawater using a high-pressure rotary seal on the rotating shaft of the turbine, as shown in **Figure 7**. Sealing the nacelle protects against the corrosion and/or electrical breakdown of critical components such as the generator coils and magnets, and bearings.

The drawback with this topology is that it makes the power take-off (PTO) system vulnerable to any water ingression in the nacelle, mostly via the leakage through the seals [3, 12]. Water-tight rotary seals on the shaft are also susceptible to wear, and generate losses due to friction. Besides decreasing efficiency, these losses may end up heating the bearings and compromising their lifetime [12]. To avoid high friction losses, small leakage of the fluid is allowed, which acts as a lubrication film between the seal faces. Whereas, a thicker fluid film decreases wear, it will also

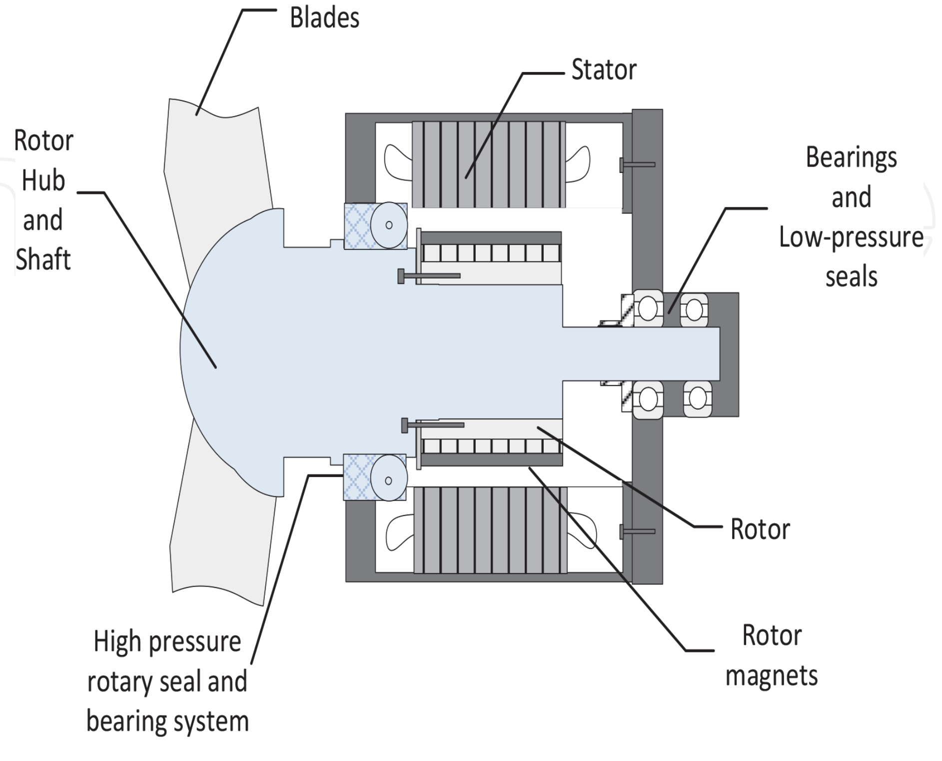

Figure 7.
A sealed airgap direct-drive generator; only necessary details for discussion are shown here.

increase leakage. Normally in ships or submarines this leakage water accumulated over time is drained using a bilge pump. Having a bilge pump in a tidal turbine will add to the cost, and may compromise reliability. However, large tidal turbines of the order of 1 MW do use bilge pumping systems alongside dehumidifiers. In addition to wear, seals usually fail when subjected to unforeseen or abnormal operating conditions [13]. This includes foreign material such as sediments intrusion in the sealing faces, imperfect shaft alignment, corrosion, sticking and clogging.

From above it is clear that the seal breakdown or deterioration is a likely possibility in tidal turbines, and thus regular maintenance of the seals is necessary. Even performing preventive maintenance can increase the O&M expenditure if the maintenance cycle is frequent or poorly timed. LCoE studies for tidal energy systems suggest that for competing with other renewable energy sources, tidal turbines must survive for about 20 years, with a service interval of 5 years [14]. Unfortunately, not much data is publicly available about the reliability of seals in tidal turbines, still it is possible to have a reasonable estimate about seal reliability from other applications. For instance, the failure rate of seals in marine propellers [15], or canned motor pumps [16], can provide a rough guide about the seal failure rates in tidal turbines. From the failure rate of seals in propellers and canned motor pumps, it appears challenging to completely rely on high-pressure seals for the aforementioned maintenance interval without any failure or leakage. This has led to a discussion about the possible use of flooded generators in tidal turbines [14, 17].

Despite relying on the seals for their proper functioning, airgap generators have their own advantages. First of all, it is a time-tested architecture and rules-of-thumb often suffice to design a generator with desired requirements. Secondly, because of no additional sleeves in the airgap, the effective airgap length is smaller. This means that the required magnet volume is less, reducing the cost of generator. Moreover, no sleeves also mean manufacturing process is simpler and less expensive. Thirdly, if the sleeve material is electrically conductive, additional eddy current losses in the machine will reduce the efficiency of the generator. Lastly, the drag losses in the airgap are lower than in the watergap.

4. Flooded generators

Among early tidal turbine developers, DCNS-Openhydro and Voith tried to use this topology. Nautricity's CORMAT and NOVA Innovation's TiPA are two examples of tidal turbines where flooded generators are used. Envisaging the use of flooded generators in tidal energy generation has been a recent development. On the other hand, their motor counterparts—commonly known as canned motors—have been around for quite some time [18].

Inside a flooded generator, not only electromagnetic parts but also other components such as bearings are susceptible to corrosion. Same can be said about the canned motors. As far as bearings are concerned, as a starting point it might be reasonable to consider the bearings used in canned motors. Normally canned motors are used in pump applications [16]. This means there is usually a high-pressure fluid available which can be used as a lubricant in either a hydrostatic or a hydrodynamic bearing. It is obvious that non-corrosive materials with good resistance to abrasion must be used in the bearings.

In an ideal scenario, flooded generators would also be equipped with seawater-lubricated hydrodynamic bearings. But there are obvious problems to this solution for tidal turbines. First, the tidal turbines usually run at low speeds (<40 rpm); and second, the seawater has very low viscosity. Both of these would mean too thin a

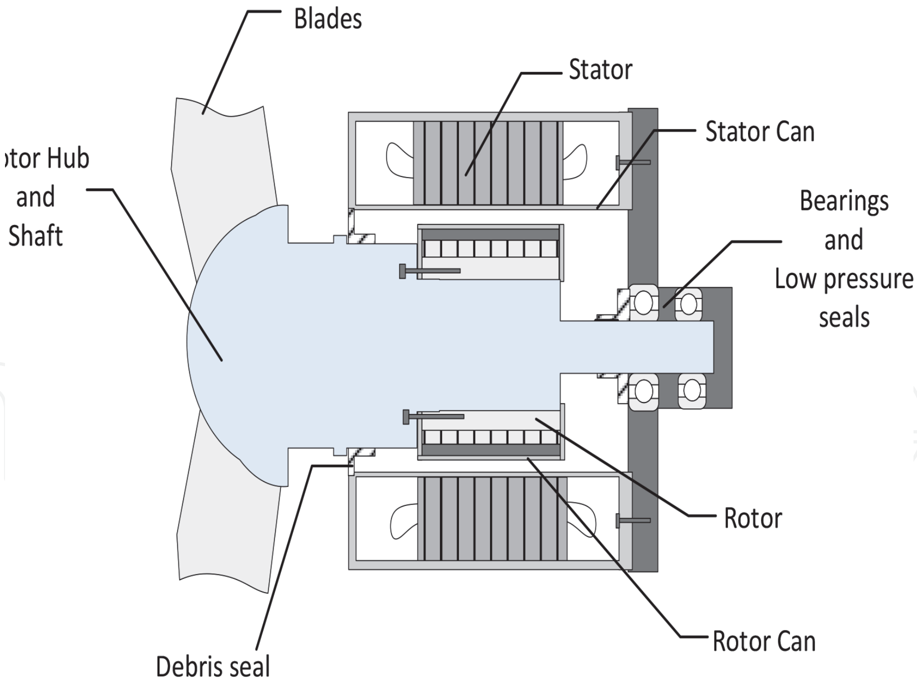

Figure 8.
A representative figure of a flooded generator; only necessary details for discussion are shown here.

fluid film thickness for good hydrodynamic lubrication [12]. Hydrostatic water-lubricated bearings would require an external motor-driven pump, which not only adds to the cost but also creates another potential fault point. Therefore, most tidal turbine manufacturers prefer commonly used roller bearings with some oil/grease lubrication.

The drawback with using roller bearings is that they are susceptible to corrosion, silt penetration and fatigue due to cyclic stresses. In such a case, a high pressure seal is still required, but it is better protected from debris and marine growth, and can often be smaller than in the sealed airgap design. Also, in a flooded generator, it is also possible to fill the space inside the generator with fresh water at a slightly higher pressure than the ambient pressure. Filling the generator with clean/fresh water might increase the life of any hydrodynamic bearings inside the generator.

To avoid fouling or clogging of organic material in the flooded gap, it is likely that a debris seal will be used in tidal turbines, thereby preventing the free water circulation in the watergap [19]. These seals are in addition to the bearing seals, as illustrated in **Figure 8**. However, debris seals are not required to provide high-pressure sealing—but only block large particles including marine life from entering the generator—which means they are cheaper and require less maintenance.

The safeguarding of the electromagnetic parts of the generator—the stator windings and the rotor magnets—is addressed in the next section.

5. Design choices for flooded generators

It has already been stated that the main difference between the airgap and the flooded generators is the presence of stator and rotor *cans* in the latter. These *cans* are used to enclose the stator windings and rotor magnets, and prevent their exposure to the seawater. Previous sections mainly dealt with the structural features of the conventional and flooded generators. The focus of this section is to look at the flooded generator design more from the electromagnetic and thermal perspectives.

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5.1 Rotor-can materials

In **Figure 8** we see that a protective layer of some material has to be used to protect the active electromagnetic parts of the generator against contact with water. In literature, we find instances of both metallic as well as non-metallic materials being used for the rotor-can in flooded generators or canned motors [20].

With metallic materials, such as stainless steel, a high eddy-current loss in the rotor can or may occur because of the asynchronously rotating components of the stator magneto-motive forces (MMF). However, the magnitude of these losses could either be significant or insignificant depending on the winding layout in the stator, wetgap dimensions, thickness of stator and rotor-cans, conductivity of the material and electrical current loading in the stator. A PM machine with integer slot distributed winding usually results in very low losses for low-speed direct drive generators, even with conductive rotor-can material [21]. **Figure 9** shows the eddy current loss density in the rotor-can and the permanent magnets. The image is taken from a study conducted on comparing different rotor-can materials in a flooded generator [20]. The PM generator in the study is rated at 300 kW at 30 rpm. The winding layout used in the machine is a fractional slot winding (total no. of slots = 132, no. of poles = 120), and thus has a relatively high loss in the rotor. The total eddy-current loss in the rotor from the stator MMF is about 5 kW, which is about 1.7% of the rated power.

Obviously, for non-conductive can material such as Carbon/Glass fiber, eddy-current loss in the rotor-can is negligible. However, the catch with using fiber materials is that water-proofing needs a thicker can. This increases the total magnetic reluctance, which implies thicker magnets are required to set up adequate magnetic field increasing the cost of the generator. Moreover, a relatively poor thermal conductivity may result in slight increase in the rotor temperature [20].

In a more novel concept of using a flooding generator with active magnetic bearings, a non-conductive material would be more suited for the rotor-can. A conductive rotor-can would result in very high losses, and could degrade the performance of the magnetic bearings because of the shielding effect of the rotor-can.

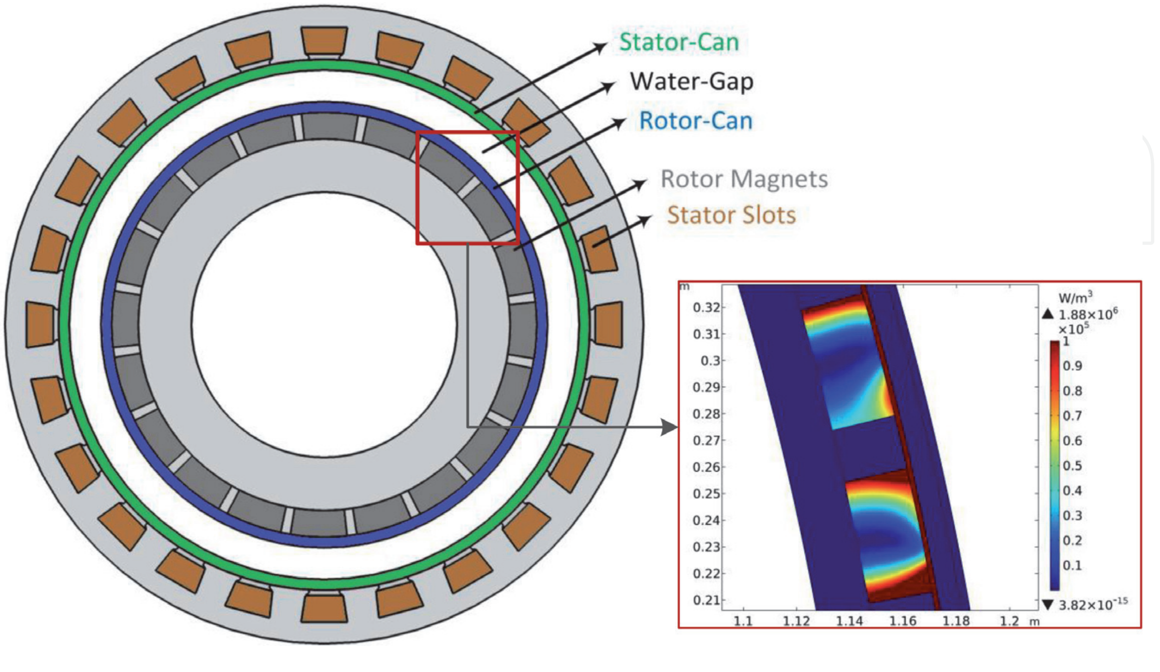


Figure 9.
Eddy current loss density in rotor-can and magnets of a test case PM flooded generator. For sake of clarity, the cross-section of the generator shown in the figure does not show all the stator slots and magnet poles of the test case PM generator.

However, the magnitude of losses and the shielding effect is a function of the speed. Hence, such effects could be less critical in low-speed tidal generators. A detailed analysis should thus be carried out before drawing any sweeping conclusions.

In another study, it was also found that the losses induced in the rotor from higher order time harmonics introduced from the switching of the power converter are insignificant for low-speed generators [21]. **Figure 10** shows the contributions from different frequency components of the stator current for the same 300 kW PM machine as above.

5.2 Stator-can materials

In principle, it is possible to use the same materials for the stator-can as the rotor-can. However, the use of metallic materials for the stator-can will result in excessive eddy current losses [20]. This does not mean that designs with metallic

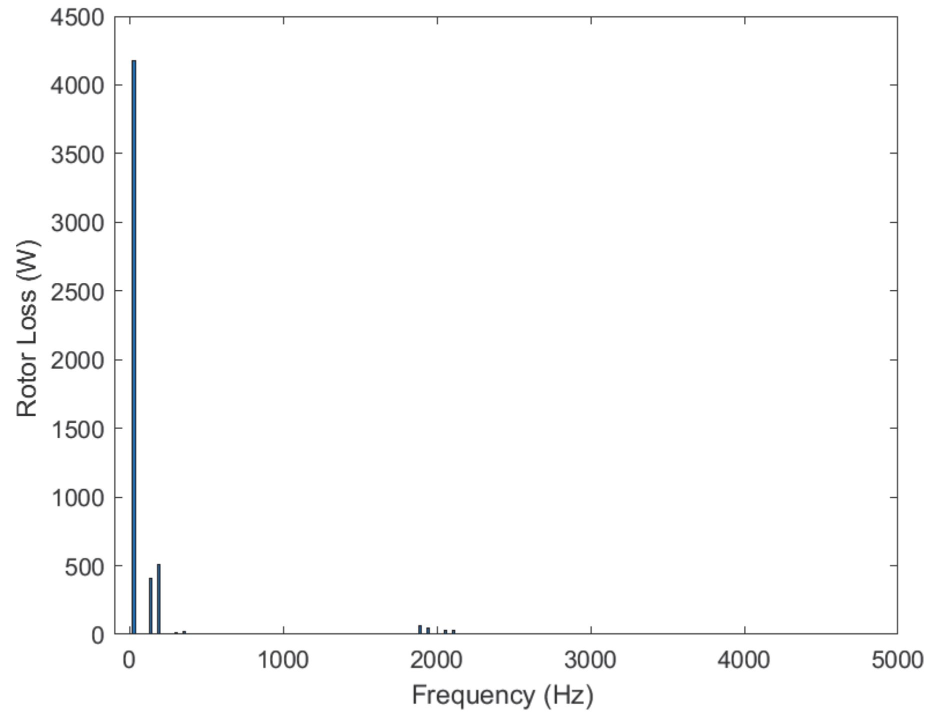


Figure 10.
Rotor eddy-current loss in the stainless steel rotor-can as a function of time harmonic component of current. Switching frequency is 2 kHz.

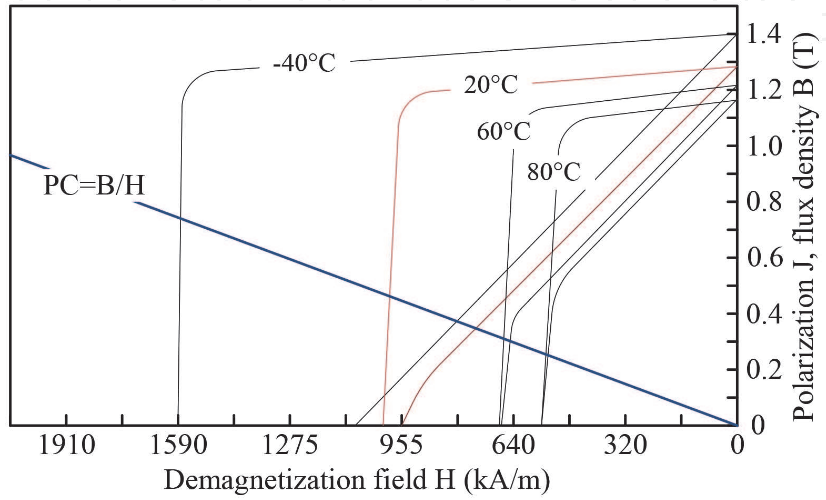
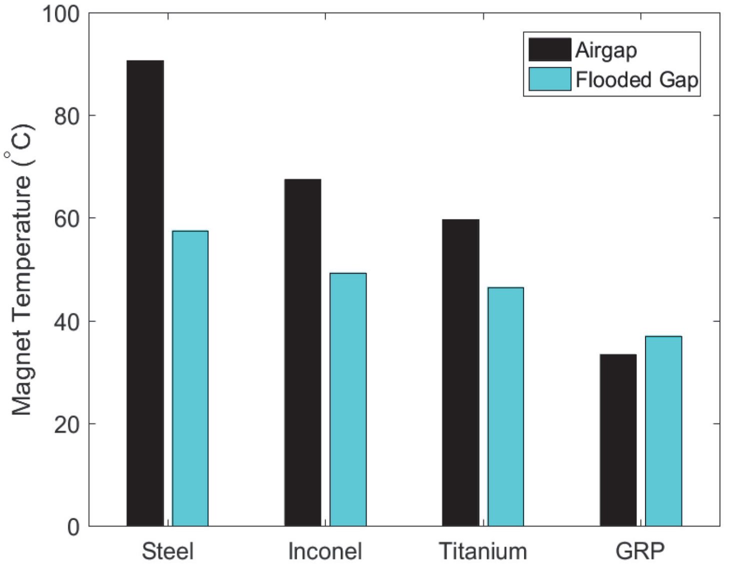


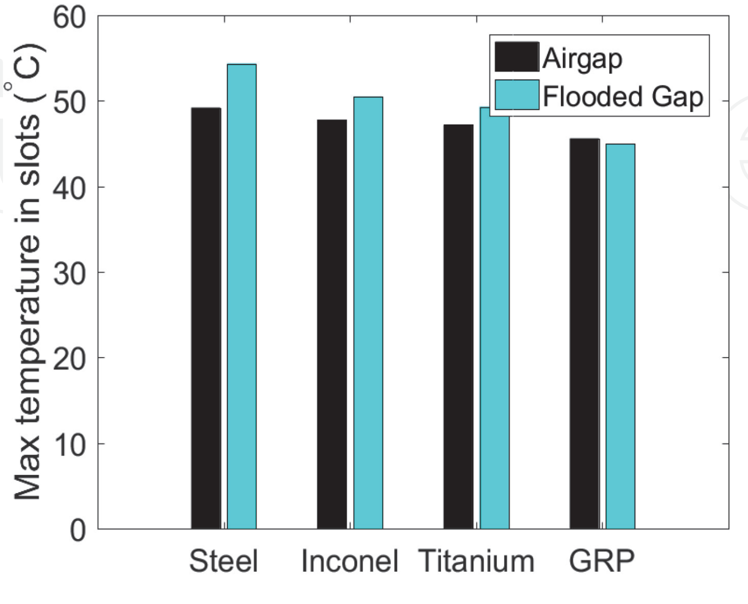
Figure 11.
A typical BH-curve for a NdFeB type permanent magnet.

stator-cans are never used. In fact canned motors have in the past invariably used metallic materials on the stator-can, and in some applications, materials such as 316 Stainless steel or Hastealloy 276, still continue to be used as stator-cans [16]. However, these days, materials such as carbon fiber or glass fiber can offer adequate protection against water ingression, albeit again making the stator-can thicker compared to a metallic-can. This increased thickness of the stator-can is more justified than the corresponding increase in the rotor-can thickness because of the significant improvement in efficiency. Obviously, such design choices also need to consider the ease in manufacturing.

As mentioned earlier, increased thickness of the can material increases the total magnetic airgap, thereby increasing the magnet volume and total generator cost. However, improved efficiency can recover the initial cost. The final choice must be carefully made based on whether a good protection can be provided by non-metallic



(a)



(b)

Figure 12.
(a) Temperature inside permanent magnet for different rotor-can materials; (b) maximum temperature in the stator slots for different rotor can materials. Cooling effect of flooded gap is clearly evident [20].

materials, and its structurally feasibility. If yes, then they should be selected over metallic materials.

5.3 Thermal considerations

Another point in the favor of flooded generators is the possibility of better cooling. This means flooded generators could be designed with high power density. For permanent magnet generators, this can happen in a two-fold manner. Firstly, the current density in the stator can be higher. And secondly, the magnets can operate at a higher permeance coefficient and the risk of demagnetization is lower. This can be seen from the BH-curve of a typical NdFeB permanent magnet, as illustrated in **Figure 11**. In other words, the temperature distribution within the machine is more uniform. However, this should not be universally assumed to be true. As Judendorfer et al. [22] suggest, it is possible that the significant improvement in cooling may only be achieved if forced circulation of water is possible.

The presence of water in the stator-rotor gap of the flooded generator facilitates the transfer of heat between the stator and the rotor. This happens even if the water in the gap is not continuously replenished with the ambient seawater. Whether the flow of heat is from the rotor to the stator or vice-versa depends on the stator losses, rotor losses (including eddy current losses in the can and permanent magnets), thermal impedance from stator to ambient and from rotor to ambient via bearing, shaft, etc.

As illustrated in **Figure 12**, the difference in the stator slot and the rotor magnet temperature is lower in the flooded generator as compared with the airgap generator (also with a similar rotor-can). **Figure 12** is taken from [20], where an airgap generator is compared with a flooded generator; both generators are assumed to have rotor-cans to illustrate the transfer of heat in the watergap. Note that the presence of water in the stator-rotor gap may result in either the increase of average temperature of the stator or rotor. This is provided that all the external thermal impedances remain the same.

6. Conclusions

In this chapter a brief overview of generators used in tidal turbine systems was given. The drawbacks of the conventional generator designs for tidal turbine applications were discussed. Although conventional designs are normally designed to operate for longer terms and there is a sense of reliability in the design, innovative solutions for submerged applications will be required. The primary consideration (even more than the efficiency) must be reliability. Lower failure rates of the generator would mean fewer maintenance expenses, and lower cost of energy. Flooded generators were proposed for applications in the tidal stream turbines. Different design considerations for flooded generators were explained in this chapter to give reader an overview about the design guidelines of such generators.

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Author details

Faisal Wani[1]*, Jianning Dong[2] and Henk Polinder[1]

1 Department of Maritime and Transport Technology, Delft University of Technology, Delft, The Netherlands

2 Department of Electrical Sustainable Energy, Delft University of Technology, Delft, The Netherlands

*Address all correspondence to: f.m.wani@tudelft.nl

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