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Matching a permanent magnet synchronous generator to a fixed pitch vertical axis turbine for marine current energy conversion

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Abstract—Extracting energy from a free-flow marine current using a vertical axis fixed pitch turbine requires a generator that can handle varying speeds and loads, since such a turbine gives maximum power capture for a fixed tip speed ratio. A prototype of such a generator has been designed and constructed. In this paper, its variable speed and load operation is evaluated, both in terms of how the constructed generator performs in relation to simulations, and in terms of how the generator could perform with three different fixed pitch turbines. Measurements of RMS (root-mean-square) voltage and current differ 10% from simulations. Performance analysis with example turbines shows that the generator can match fixed tip speed ratio operation of several turbines for current velocities between 0.5 and 2.5 m/s.

I. INTRODUCTION

FREE flow marine currents, i.e. unregulated water courses, tides and other ocean currents, are an energy resource yet to be utilized on a commercial scale. Without dams, this non-fossil source can give an environmentally benign contribution to the world electricity production. The European tidal potential alone has been estimated to be 39-58 TWh annually [1]–[3]. A number of projects involved with extracting energy from this resource exist, and most concepts are similar to wind energy converters in that they include a turbine and a generator, e.g. [4]–[7].

Wind power is similar to marine current energy as it is concerned with harnessing the kinetic energy in a flowing fluid, and there are many relevant comparisons concerning underlying physics, practical engineering experience, etc. However, there are also a number of significant differences, e.g. resource characteristics. As most parts of the system will be submerged in water and thus not easily accessible, it is good to try to minimize needs for maintenance and repair by avoiding mechanically complex systems with many moving parts. In [8], it is concluded that up to 20 percent of the downtime for a wind power plant is due to gearbox failures, and that the majority of these failures are due to wear. Therefore, avoiding gearboxes, yawing and blade pitching is likely to be beneficial

Fig. 1. A system for marine current energy conversion. The focus of this article is the connection between the turbine and the generator.

Fig. 2. Artist's impression of a vertical axis marine current energy converter.

for system reliability, but will require certain adaptations of the rest of the system. An example of such a system is illustrated in Fig. 1 and Fig. 2.

The purpose of this paper is to illustrate some of the consequences of variations in current velocities inherent to the resource, and show how a variable speed, direct drive permanent magnet synchronous generator (PMSG) specifically designed for marine current energy extraction with a fixed pitch vertical axis turbine can handle these variations.

A. Resource characteristics

For a given cross section, A , the power in a flowing fluid can be expressed as

$$P = \frac{1}{2} \rho A v^3 \quad (1)$$

where ρ is the density of the fluid and v is its velocity [9]. The density of water is about 1000 kg/m^3 , almost 800 times higher than that of air. A consequence of this is that water currents may be relevant for energy extraction even at low speeds, possibly down to the order of 1 m/s or less, whereas in wind power a typical cut-in speed is in the range of 4 m/s [10].

Equation (1) also shows that variations in energy flux will depend on the cube of the velocity. Variations in velocity

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of a marine current will typically be very predictable and depend mainly on the driving forces of the current and local bathymetry. Tidal currents will vary between standstill and maximum spring velocities that in a few extreme cases are up to 7 m/s, but in more locations are in the order of 2-3 m/s [11]. For tides the direction of the flow will also vary. Velocities in rivers will depend on precipitation, season and local depth profiles. A system for extracting energy from free flow water currents should be able to handle the variations in power that these velocities correspond to.

B. Variable speed operation with fixed pitch vertical axis turbine

Efficient use of a turbine with fixed blade pitch in a varying flow speed requires variable speed operation. The power capture coefficient, C_p , for the turbine is usually expressed as a function of the tip speed ratio, λ

$$\lambda = \frac{\Omega r}{v}. \quad (2)$$

Ω is the rotational speed of the turbine and r is the radius. Maximum power capture will typically be obtained at a specific tip speed ratio, λ_{opt} , so keeping a fixed tip speed ratio will give maximum power capture. This means that the turbine should be operated at higher Ω for higher v , such that

$$\Omega = \frac{v \lambda_{opt}}{r}, \quad (3)$$

which will give power capture

$$P_t = \frac{1}{2} \rho A v^3 C_p^{max}. \quad (4)$$

For a directly driven synchronous generator, the rotational speed of the generator will also be Ω , and the speed of the turbine will be controlled through the generator. According to (4), the power absorbed by the turbine, and thus the input to the generator, is proportional to v^3 , or Ω^3 .

Neglecting losses and assuming a resistive AC load, R , one can get a rough idea of how the generator needs to perform to match fixed tip speed ratio operation. The power output of the generator, which under the no-loss assumption should be equal to P_t , should be proportional to Ω^3

$$P_t = P_g \propto \Omega^3 \quad (5)$$

The power of the generator can be expressed as

$$P_g \propto UI = \frac{U^2}{R}. \quad (6)$$

Since the voltage U is roughly proportional to Ω in a generator, one can see that the load should be allowed to vary as

$$R \propto \frac{1}{\Omega} \quad (7)$$

or that the current I should vary such that

$$I \propto \Omega^2. \quad (8)$$

In practice, a variable speed generator that is to deliver power to the grid will be connected to a rectifier and inverter

in order to adjust the voltage and frequency. In this case, the generator and turbine will be controlled through the inverter.

Taking losses into account, fixed tip speed ratio operation requires control of the generator so that

$$P_t = P_g + P_{loss} \propto \Omega^3. \quad (9)$$

Losses include mechanical, copper and iron losses. Copper losses in a permanent magnet machine are due to the resistance in the stator winding. Iron losses are mainly due to the hysteresis in magnetizing and demagnetizing soft magnetic materials in the machine and eddy currents induced in the stator steel. Copper, hysteresis and eddy current losses can be expressed as follows [12].

$$P_{Cu} = R_g I^2 \quad (10)$$

$$P_{hysteresis} = k_h B_{max}^2 f \quad (11)$$

$$P_{eddy} = k_e (B_{max} f)^2 \quad (12)$$

In the above equations, R_g is the resistance in the armature winding, k_h and k_e are material constants, B_{max} is the maximum value of the magnetic flux density and f is the electrical frequency. Since losses vary with rotational speed and load, (9) will not give a simple control scheme for the generator that gives fixed tip speed ratio operation.

Without knowledge of losses, fixed tip speed ratio operation can still be realized by continuous measurement of the current velocity and control of the rotational speed accordingly. Other control schemes for permanent magnet synchronous generators that do not require knowledge of the current velocity, such as maximum power point tracking (MPPT), vector control and control based on torque coefficient characteristics are discussed by e.g. [13]–[15] for wind energy converters. The object of this paper is however not to cover details in system control, but to relate generator performance to ideal turbine operation.

In water, a typical λ_{opt} can be around 2–3 for a fixed pitch vertical axis turbine [16]. A horizontal axis turbine with high solidity can also have a tip speed ratio as low as 1.2 [17]. Given that typical current velocities are low, i.e. around 2–3 m/s, one can see that the rotational speed of the turbine, and thus a direct drive generator, also will be low, according to (3). It is challenging to design electrical machines with high efficiency at such low speeds.

For a vertical axis turbine it is important to take the wake situation into account. One issue concerns the structural mechanics of the turbine. Another issue concerns farm implementation, where the wake from one turbine will affect other turbines. In both cases it is important to take into account the various unsteady effects due to the blades' interaction. As an illustration, detailed wake simulations for a turbine with 8 NACA0021 blades and a central tower have been carried out for the optimal tip speed ratio of 2.5. Fig. 3 shows detail of the wake close to the turbine. Fig. 4 shows the general wake characterization that needs to be taken into account in a farm implementation. The turbine used in these figures is example turbine B, presented in section IV-B and Table II. In both figures red points represent clockwise vortex

Fig. 3. Detailed wake simulation for a turbine with 8 NACA0021 blades and a central tower. Red points represent clockwise vortex particles and blue points counter-clockwise particles emitted from the blades. The unit on the axes is meters.

Fig. 4. General wake simulation for a turbine with 8 NACA0021 blades and a central tower. Red points represent clockwise vortex particles and blue points counter-clockwise particles emitted from the blades. The unit on the axes is meters.

particles and blue points counter-clockwise particles emitted from the blades. These simulations have been achieved using a two-dimensional model with innovative algorithms [18] and a new approach toward geometry using conformal mapping of multiply connected domains [19] resulting in a significant decrease in computation time.

C. Concept studied at Uppsala University

A system for extracting energy from marine currents is studied at Uppsala University, see Fig. 1 and 2. The turbine has a vertical axis and fixed blade pitch and therefore no yawing or blade pitch mechanisms. No gearbox is used as the turbine is connected directly to a permanent magnet synchronous generator, which in turn is connected to a rectifier and inverter, enabling control of the generator and turbine, as well as grid connection. The system as a whole is designed to have few moving parts in order to be robust and low-maintenance.

II. DESIGN AND CONSTRUCTION OF GENERATOR FOR EXPERIMENTAL SETUP

In [20], the design and construction of a prototype generator for laboratory testing is described. For a well known site and

TABLE I
GENERATOR DATA

Design power	5 kW
Design speed	10 rpm
Outer diameter	2000 mm
Stator height	270 mm
Air gap	10.5 mm
Number of poles	120
Phases	3
Resistance in winding	0.47 Ω per phase

Fig. 5. Photograph of the experimental setup with prototype generator, artificial drive system and resistive load.

turbine design, it is possible to use the reasoning above to construct a generator for a specific range of speeds and loads. In this case, a turbine according to turbine A in table II, and a typical flow of 1.5 m/s have been used to design the generator. For simplicity, initial simulations and testing are performed with a purely resistive AC load as suggested by [21].

A. Electromagnetic design

A finite element method (FEM) software tool originally made for 50 Hz machines has been used for the design and simulation of the generator. It calculates the magnetic and electric properties in a 2D generator geometry. A few design choices are $\text{Nd}_2\text{Fe}_{14}\text{B}$ magnets, 1 mm thick stator laminations and cable windings, and the generator has no cooling system. See Table I and [22] for more details. In this design process, the use of ‘rated’, or design power and speed differs somewhat from conventional use of the terms. Here, they refer to typical operational values rather than upper limits.

The upper limits of the range of operation for the generator will most likely be set by thermal and electrical properties of the winding insulation. The generator is wound with a standard cable, MK 450/750 [23], which is specified to handle RMS (root-mean-square) voltages of 450 V and temperatures of 70°C during continuous operation.

Fig. 6. Measured and simulated values of U_{rms} for various loads and speeds.

Fig. 7. Measured and simulated values of I_{rms} for various loads and speeds.

B. Experimental setup

The prototype generator is part of an experimental setup, see Fig. 5, with an artificial drive system including an induction motor and gearbox that allow operation from 0 to 16 rpm, a maximum torque of 11 kN·m and power input up to 22 kW. The power from the generator is spent in a resistive load that consists of a number of resistors that are connected in various configurations to give different load cases. The load can be varied between 10 and 2.7 Ω per phase. The experimental setup is described further in [22].

III. MEASUREMENTS

A metrix multimeter clamp MX240/MX2040 (accuracy $\pm (1\%R + 8D)$) and a Le Croy Wave Surfer 424 200 MHz Oscilloscope (accuracy $\pm (1.5\% + 0.5\%$ of full scale)) were used for measuring current and voltage. Previous measurements [20] have shown that the three phases of the constructed generator are well balanced. Therefore, measurements of voltage and current were limited to one phase. Voltage and current were measured for 2–16 rpm for four different load cases: 2.7, 4.4, 8 and 10 Ω per phase. The specific load values are determined by possible configurations of the resistors included in the experimental setup, and are chosen to illustrate a range of loads higher and lower than the design load of 4.4 Ω . Simulations of the same load and speed cases were performed.

The experimental setup has yet to be equipped with torque measurements, so the total losses were not measured at this time. Resistive losses in the armature winding can be calculated based on the current and the measured resistance of the winding. Before magnetizing the rotor, frictional losses were calculated by measuring the deceleration of the rotor in accordance with IEEE Std 115–1995. The friction, including windage, was found to be approximately 2 N·m in the range of 0 to 20 rpm. Although the friction is expected to have increased somewhat after magnetization due to radial forces on the bearings, frictional losses are still expected to be small compared to the power output and are thus neglected in the following sections.

TABLE II
EXAMPLE TURBINES

Turbine	A	B	C
Radius (m)	2.5	3	3
Height (m)	1.6	3	3
λ_{opt}	1.7	2.5	3
C_p (at λ_{opt})	0.35	0.35	0.35

IV. RESULTS AND DISCUSSION

A. Comparison of measured and simulated data

The RMS voltage (U_{rms}) and current (I_{rms}) of the generator as a function of the rotational speed are shown for three load cases in Fig. 6 and Fig. 7. Measured values of both U_{rms} and I_{rms} are 10% lower than simulated values. Measured U_{rms} vary from 84 to 92% of simulated values (standard deviation 1.3%) and measured I_{rms} vary from 85 to 92% of simulated values (standard deviation 1.3%). Peak to peak voltages show better agreement, i.e. measured values of U_{pp} are on average 6% lower than simulations. The simulations show a higher content of harmonics than measurements, which explains the difference in agreement between RMS and peak to peak values. Differences between the measurements and simulations are attributed to measurement uncertainties and inaccuracies in modeling the actual generator.

B. Generator performance with example turbines

In order to relate the performance of the generator to a setting with a turbine in a water current, three example vertical axis turbines with fixed blade pitch are used, see Table II. Turbine A, which is the fictive turbine used in dimensioning the generator, has a high solidity, i.e. a long blade chord length in relation to the turbine radius, as in [17]. Turbine B and C have higher optimal tip speed ratios and a larger cross section than turbine A. Turbine B is designed with 8 blades with chord length of 0.25 m, while turbine C has 6 blades with chord length 0.23 m. The C_p -curves in Fig. 4 have been generated by a double multiple stream tube model including secondary effects (flow curvature, dynamic stall, edge effects, strut losses) and based on a local flow description [24]. This

Fig. 8. C_p -curves for two example turbines.

Fig. 9. Power output of three turbines and electromagnetic power of the generator (power output of generator plus copper and iron losses) for different loads.

tool has been validated in the case of vertical axis wind turbines as a good power curve estimation tool. These results have been compared to another three dimensional stream tube model [25] with very good agreement. Turbine B has been used in the generation of Fig. 3 and 4.

In Fig. 9 simulated values of the electromagnetic power for four different loads, including power output, copper losses and iron losses, are shown together with the power capture of the three example turbines when run at constant tip speed ratio, λ_{opt} . It is clear that the generator can accommodate the turbine it was designed for, but also other turbines. For turbines A, B and C, operation at 16 rpm corresponds to current speeds of 2.5, 2 and 1.7 m/s respectively. Fig. 9 shows that a single generator with a wide range of operation in terms of speed and power can be used with various turbines, in various water currents.

In Fig. 10 the power capture of turbine A is shown together with simulated generator performance. To the left data is presented with a log scale to highlight the loss characteristics at low speeds. A suitable load has been chosen for each rotational speed corresponding to fixed tip speed ratio operation. Fig. 11 shows the electromagnetic efficiency and the RMS current of the generator corresponding to Fig. 10. Figures 12 and 13 show

Fig. 10. Generator performance when matching fixed tip speed ratio operation of turbine A. For each speed, the load has been chosen so that the sum of output power and losses for the generator (based on simulations) equal the turbine power. Rotational speeds of 4–16 rpm correspond to water current speeds of 0.6–2.5 m/s. The graphs show the same data, but to the left in logarithmic scale and to the right linear. Iron losses exceed copper losses at low speeds, as can be seen in the left-hand graph.

Fig. 11. Efficiency and RMS current of generator corresponding to Fig. 10, i.e. when operated to match fixed tip speed ratio operation of turbine A. Rotational speeds of 4–16 rpm correspond to water current speeds of 0.6–2.5 m/s.

the same data when operating the generator to give fixed tip speed ratio operation of turbine B.

Iron losses are the main cause of the reduced efficiency for low rotational speeds seen in Fig. 11 and 13. A rotational speed of 2 rpm corresponds to 0.31 m/s for turbine A and 0.25 m/s for turbine B. At that rotational speed, total iron losses are approximately equal to the power capture of the turbines, but at 4 rpm an efficiency of about 70% can be obtained for the generator. At low speeds, the electrical frequency is also low, and the iron losses are mainly explained by the size of the stator. The fact that the iron losses are high relative to the power output is due to the low power flux in such a slow water current.

The electrical current in the winding increases approximately as Ω^2 , see Fig. 11 and 13, which means that the copper losses increase as Ω^4 according to (10), and is the main reason for the lower efficiency at high rotational speeds in Fig. 13. Iron losses are frequency dependent, and the frequency is proportional to the rotational speed. Therefore, hysteresis losses increase with Ω and eddy current losses with Ω^2 . However, the power captured by the turbine increases with Ω^3 and the iron losses do not dominate at higher speeds.

The combination of turbine and generator strongly affects the overall performance of the system, and the choice of generator and turbine design can be made to suit a specific site

Fig. 12. Generator performance when matching fixed tip speed ratio operation of turbine B. For each speed, the load has been chosen so that the sum of output power and losses for the generator (based on simulations) equal the turbine power. Rotational speeds of 4–16 rpm correspond to water current speeds of 0.5–2.0 m/s. The graphs show the same data, but to the left in logarithmic scale and to the right linear. Iron losses exceed copper losses at low speeds, as can be seen in the left-hand graph.

Fig. 13. Efficiency and RMS current of generator corresponding to Fig. 12, i.e. when operated to match fixed tip speed ratio operation of turbine B. Rotational speeds of 4–16 rpm correspond to water current speeds of 0.5–2.0 m/s.

Fig. 14. Generator efficiency versus water current speed when the generator is run according to optimal tip speed ratio with turbine A and B.

with known bathymetry and water current velocity variations. As can be seen in Fig. 14, operation with two different turbines results in different generator efficiencies. The combination with the prototype generator and turbine B gives good performance at slower water current speeds than the combination with turbine A. Apart from the fact that the turbines have different cross sections, turbine B would be a better choice at a site where water currents often are below 1 m/s but seldom

Fig. 15. Temperature in a segment of the stator. The figure shows a single stator slot and halves of the adjoining teeth. The simulation is for 10 rpm with 0.001Ω per phase load, resulting in an RMS current of $I_e \approx 60$ A. Maximum temperatures of approximately 70°C are reached by the winding in the middle of the slot.

exceed 1.5 m/s. Operation with both turbines, though more pronounced with turbine A, results in a wide efficiency ‘peak’ as can be seen in Fig. 14, i.e. an efficiency of about 80% or more for a wide range of speeds. One can also note that in general, electrical machines with low power rating have lower efficiency.

C. Upper limits of operation

As mentioned in section II, the upper limits of the range of operation for the generator are expected to be given by the winding insulation. Fig. 6 shows that the voltage stays well within the range of what the insulation can handle during these circumstances, as expected, and fixed tip speed ratio operation implies that the load increases with the rotational speed, thus limiting the voltage.

The measurements presented in Fig. 6 and Fig. 7 did not pose any temperature problems for the generator. In order to find a rough upper limit concerning temperature, analysis was performed using the simulation tool. As the generator has no active cooling mechanism, cooling takes place through heat transfer to the surroundings and the temperature will be determined by heat transfer and losses. In general, losses increase with rotational speed and load. Under such circumstances, resistive losses dominate, as can be seen in Fig. 10 and 12, and therefore, the stator temperature is expected to be affected mainly by the electrical current in the armature winding. Simulations show that continuous operation with an electrical current of approximately 60 A and an ambient temperature of 20°C will lead to maximum temperatures in the stator close to 70°C , see Fig. 15. This simulation should ideally be calibrated with measurements of actual heat transfer, and will in an outdoor setting be affected by ambient water temperatures and the design of the generator housing.

Considering the turbine, the rotational speed should be limited in order to prevent cavitation of the turbine blades. Cavitation causes wear of the turbine through the collapse of small vapor pockets that are created when the speed of the blades is high enough to cause local pressure drops below the vapor pressure of the water. The exact limitation of rotational speed set by cavitation depends on a number of parameters including water depth and turbine radius, but as a rule of thumb, [1] suggests an upper limit of the relative velocity of the blades of 7 m/s. Structural mechanics issues may also limit the rotational speed of the turbine.

For the system as a whole it is not possible to determine a general upper limit for rotational or water current speeds since the turbine characteristics affect how the generator should be operated. For a specific turbine, generator and site, these limitations can be determined and guide the control of the system. In practice, if water current speeds become too high, the turbine can be operated at a lower tip speed ratio than λ_{opt} , in order to limit rotational speed and armature current.

For the example turbines presented here, one can see in Fig. 13 that fixed tip speed ratio operation of turbine B can result in RMS currents of about 54 A at 16 rpm. In an outdoor setting, the cooling may be improved by ambient water temperatures being lower than the 20°C used in the simulation, allowing higher electrical currents than 60 A. The maximum relative velocity for turbine B at 16 rpm is approximately 7 m/s. In combining the prototype generator and turbine B, 16 rpm, or 2 m/s, is approximately where it is appropriate to stop operating the turbine at λ_{opt} .

Economical considerations have not been highlighted in this article, but will of course guide the choice of installed power capacity for a given site. Installing generators and turbines that give best efficiency at maximum speeds may not be the most economical choice as illustrated for tides in [26].

V. CONCLUSION

A generator suitable for variable speed and load operation has been designed and constructed. A comparison of measurements and simulations of effective values of voltage and current show that measurements are 90% of simulated values.

Comparisons with three example fixed pitch vertical axis turbines show that the prototype generator can match fixed tip speed ratio operation of several turbines for current speeds between approximately 0.5 and 2.5 m/s. For other water current speeds, a different combination of turbine and generator may be more suitable.

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