A highly efficient and low-cost linear TFM generator for wave power

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***Abstract*— A force-dense, low-cost and very efficient direct drive transverse flux generator aimed for wave power applications is being developed at the Royal Institute of Technology in Sweden, and a linear version is currently being built. The machine is specialized for low speeds, and the project is presented in this paper, where we focus on why TFMs are very suitable for low speed applications and why they are so hard to build. The basic electromagnetic design is given as well as an overview of the mechanical design. The benefits of such machines at low speeds are described in detail. The challenges that the machine type have are also presented, and suggestions are made on how they can be handled. Geometrical and calculated performance data is given for a prototype machine that is to be constructed during 2017. The machine is predicted to have an efficiency of about 98% at speeds as low as 0.7 m/s, and a shear stress of 100-120 kN/m², corresponding to 200-240 kN/m² if only half the active area is counted as active which is custom for such machines.**

***Keywords*— Wave power, point absorbers, transverse flux generator, power take-off, efficient**

I. Introduction

Wave power is a promising future alternative for renewable energy conversion, where the global resource is estimated to about 2.11 TW [1], corresponding to perhaps 5-15% of the world's energy demands today. Wave power has, however, still not been commercialized at large scale due to the difficulties to convert the energy at sufficiently low cost and at the same time making the energy conversion devices durable enough so that they survive at the harsh conditions at sea. One of the key challenges is that wave energy is delivered with low speeds and large forces compared to other renewable energy sources such as wind power. Since the size and cost of the Power Take-Off (PTO) units and mechanical structures are related to force rather than power, this is unfavourable. This challenge is further complicated by the fact that maintenance is likely to be very expensive at sea, and has the potential to further increase the cost of wave power substantially. The PTO challenge has been pointed out as the single most important problem to solve in wave power research [2].

Since gear boxes and hydraulic systems require maintenance, direct driven generators first seem to be a viable option for the PTO system since they can be made maintenance free with a proper bearing design. If demagnetization of the magnets in the generator is avoided, only the bearings suffer from wear since the force carrier, the magnetic fields in themselves do not wear. However, the slow speed makes the generators inefficient since the resistive losses in the copper windings become unusually large compared to the power production, especially for the case with smaller waves. At airgap speeds below 1 m/s, it is hard to build a generator which is both force dense and efficient. The more common machine types such as longitudinal or radial flux Permanent Magnet Synchronous Machines (PMSG) or induction machines will therefore operate in a suboptimal regime at these speeds.

These unusual operating conditions call for a machine type that is specialized for the task. Anders Hagnestål has therefore invented/developed and patented a machine that is specialized for these low speeds, partly described here [3], and that has very low losses and very high force density. In an ongoing project a linear version of this generator is being developed, as well as a rotating generator of a similar electromagnetic design. A linear prototype aimed for a damping force of about 200 kN will be built in the lab at KTH during 2017. The power rating is speed dependent, and the speeds ranges from 0.1-3 m/s which corresponds to 20-600 kW. The machine type is a double-sided Transverse Flux Machine (TFM) with flux-concentrating setup, which has transformer-like design features which reduces losses and increases the power factor compared to other types of TFM. The machine is suitable for all direct drive solutions where the speed is low or moderate. It is however intended for point absorbers, which is a rather popular wave power concept where the heaving movements of a buoy at the surface are used to extract energy. This machine will combine a high force density with a for the speed range extremely good efficiency of 98 % and a fairly high power factor compared to other machines of the same type, 0.4-0.5.

The machine presented here will also be suitable for phase control for point absorbers due to the extremely low losses. The low efficiency of existing generators has been a major roadblock for implementing such control by controlling the force in the generator, i.e. the current. This generator may therefore open up a new window for phase control.

Linear transverse flux machines for direct driven wave power were first suggested by H. Polinder et. al [4]. More recently, one group in Portugal [5] and one Italian group [6-7] have suggested transverse flux machines for wave power. In previous work, the main reason in general for selecting a transverse flux machine has been to reduce the generator size and cost. A 10 kW rotating prototype has been built in a by a Portuguese team [5]. A linear prototype of a similar machine from the same machine family, a Vernier Hybrid Machine

(VHM), was built by Markus Mueller's group in the beginning of this century [8]. The TFM presented here is in some ways of a similar design, but is of another type. In principle, the VHM machine is simpler to construct but has lower performance than the machine presented here in terms of shear stress, power factor and efficiency. It is therefore in some sense a trade-off between a PSMG and a TFM.

II. The Low Speed Problem – TFM vs PSMG

At airgap speeds below 1 m/s, it is hard to build a generator which is both force dense and efficient. This is in some sense well known, but is often not given sufficient attention. It is simply and well described by Polinder et al. [9], and also in [3], but is so important that it is repeated here. A high force density requires a high current density in the windings and thus a rather large electric field in the winding to overcome the resistivity. This electric field can be found from Ohms law, $E_{res} = \rho J$ where E_{res} is the modulus of the electric field in the winding, ρ is the resistivity of the conductor, J is the modulus of the current density and the skin effect and proximity effect is neglected. For annealed copper at an assumed operating temperature of 120 °C, $\rho \approx 2.4\times10^{-8}$, and with an assumed current density of 5 A/mm² this yields $E \approx 0.12$ V/m. The induced no-load electric field in the winding in a PMSG can be approximated by the motional EMF if the end windings are neglected [9], yielding $E_{ind} = vB_{avg}$ where v is the airgap speed and B_{avg} is the average magnetic flux density in the airgap. Note that this is not true for TFMs. With a typical (rather high) value $B_{avg} = 0.9$ T for a neodymium generator this yields $E_{ind} = 0.9$ V/m for $v = 1$ m/s and $E_{ind} = 0.63$ V/m for $v = 0.7$ m/s, which then yields a copper loss ratio of $E_{res} / E_{ind} = 0.133$ and 0.190 respectively. The workhorse generators in the power grid such as hydropower generators operates at efficiencies of about 97-98%, and 13-19 % copper losses in a generator (with end windings and cable connections neglected) is very high. To this, the iron losses and friction should be added, and the machine would probably end up having an efficiency of 75-85% at these speeds if it is well designed. What then can be done is to lower the current which lowers the copper losses. To lower the current density of the machine has however two important consequences. First, the machine will have a low shear stress if the current is reduced, and consequently the machine will become unnecessarily large for a certain power rating. Second, the power will decrease but the iron losses and friction will more or less remain the same, thus increase counted in percent of the power, which limits the total efficiency of the machine.

It is clear that for speeds below 1 m/s, the common types of generators will either be inefficient or unnecessarily large. Direct driven generators always become very large for their power rating since generator size is proportional to force, not power, and increasing size more than necessary will be expensive. Power is force times speed, and generators operating at speeds 10-100 times lower than typical machines naturally become 10-100 times larger for their power rating. However, one should be aware that some system anyhow needs to deal with that force, and that system, perhaps a gearbox, will also be rather large and expensive. It is therefore not obvious that the idea of direct driven systems is bad.

The main problem for low speed machines is the large winding resistance compared to the no-load voltage, where the voltage is proportional to speed. The winding resistance is

$$R = \rho \frac{l}{A} \tag{1}$$

where l is the total length of the winding and A is the cross sectional area of the winding. In a PMSG or other standard machine, A is limited since there is a competition in space between the winding and the iron. Further, due to geometry, the winding becomes long. This is illustrated in Fig. 1b, which shows a cross section of the airgap for a PMSG at the stator side where the winding is located. The winding has to encircle every other pole in the machine, which creates a zig-zag winding pattern. In Fig. 1a, the winding on a TFM machine is shown. In a TFM, the flux in all poles on the stator side for one phase goes in the same direction at any instant. This unidirectional flux makes it possible to wind around the whole phase in the stator instead of around each individual pole, which makes the stator winding several times shorter for the same amount of enclosed flux if there are many poles which there usually is. This also means that the resistance per unit induced voltage becomes several times lower in the TFM for this reason only, since the resistance is proportional to the winding length.

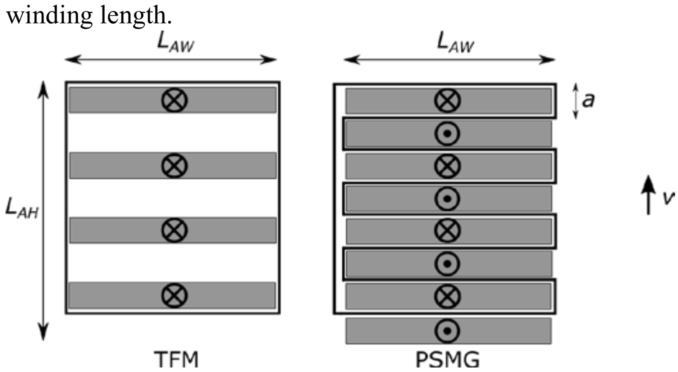

Fig. 1 A cross section of the stator of a TFM (a) and a PSMG (b), illustrating the difference in winding patterns.

A second advantage for TFM is that there is no competition in space between the iron and the winding, since the winding is located far away from the airgap. Thereby, there is sufficient space to make the winding thicker or to add more turns. Since the winding becomes much shorter, it can be made much thicker without adding much to cost, provided that substantial losses from Eddy currents and circulating currents in the winding can be avoided. If the amount of winding material is kept constant, the winding becomes as many times thicker as it becomes shorter, and the resistance becomes proportional to the winding length squared. For example, it is easily seen from Fig. 1 that with 20 poles per phase like we have and a square shape of the active area, this would approximately yield a 5.5 times shorter winding. There is also a possibility to compact the iron core of the TFM into a massive iron block, which we do. If this block has a circular cross section, the winding becomes optimally short for the amount of flux in the machine, which makes the winding about 8 times shorter than for a PMSG and thus reduces the resistance by a factor of 64. This large reduction of the winding resistance will have a profound impact on the performance of the machines in low speed applications, and with a TFM it is fully possible to have both a very high force density and a very high efficiency even at low speeds. We claim that they can even be more force dense than gearboxes.

III. Competing Technologies – Why Direct Driven TFMs?

To deal with the low speed problem, a number of different PTO systems have been proposed that are typically not direct driven but rather includes one or several mechanical conversion steps before conversion to electricity. An overview is given in [2]. The mechanical systems are better adopted for the large forces, and provide a gearing function so that an efficient standard low-cost generator of 1500 rpm or so can be used. They, however, in general has lower efficiency and generate maintenance. A short overview of some of these systems is given in Table I. The most common PTO-systems today are hydraulic systems. We do not know of any system today that is even near the performance of the TFM we propose, neither in efficiency or LCOE.

TABLE I
PTO systems for point absorbers

System	Efficiency (%)	OPEX	Other
Hydraulic systems	40-80	High	Leaks oil
Gear box systems	80-90	High	
PSMG	70-90	Low	Heavy
TFM	95-98	Low	Low pf, light
Magnetostrictive gen.	?	Low	To us unclear properties
Elastomer generator	<75 %	Low	Research stage

IV. Overall Design

The generator is a linear double-sided TFM with flux concentrating setup. Some of the rated values and properties of the generator are given in Table II. Note that the machine resembles a transformer, and that the rated voltage more or less could be chosen freely by choosing the number of winding turns. Since voltage is proportional to translator speed, the voltage rating is set for a rated speed and normally adopted to the power electronic system, where components are rated for certain voltage levels. Our power electronic system in the lab will be able to deal with 800-900 V, and thereby the speed is restricted to below 1.4 m/s for the prototype unless another power electronic system is provided. Note also that it is fully possible to output 10 kV or so by just changing the number of winding turns. By doing so, one transformer step in the grid connection can be removed, but the active rectifier must then work at these voltages and if a dynamic electric cable is connected to the WEC this must also be rated for this voltage. The electrical isolation of the winding must then also be designed with care, and the copper losses may increase due to the lower fill factor in the winding.

TABLE II
TFM linear generator rated values and properties

Rating/property	0.7 m/s	3 m/s
Rated power	140 kW	600 kW
Rated force	200 kN	200 kN
Efficiency	98 %	98 %
Electrical frequency	14 Hz	60 Hz
Peak phase voltage	~450 V	~2 kV
RMS current	360 A	360 A
Winding resistance 20 °C	1.45 mΩ	1.45 mΩ
Inductance span	4-18 mH	4-18 mH
Power factor	0.4-0.5	0.4-0.5
Max stroke length	7 m	7 m
Mass	6.6 ton	6.6 ton
Stator height	2 m	2 m
Translator dimensions	9x0.5x0.25 m	9x0.5x0.25 m
Service intervals	>20 years?	>20 years?
Speed range	0-5 m/s	0-5 m/s

The difference in geometry between single-sided and double-sided TFMs is shown in Fig. 2, where the single-sided setup in (a) has surface mounted magnets and the double-sided setup in (b) has a flux concentrating setup. The single-sided setup is easier to build but has larger leakage fluxes and thereby lower power factor. Note that both setups have a unidirectional flux.

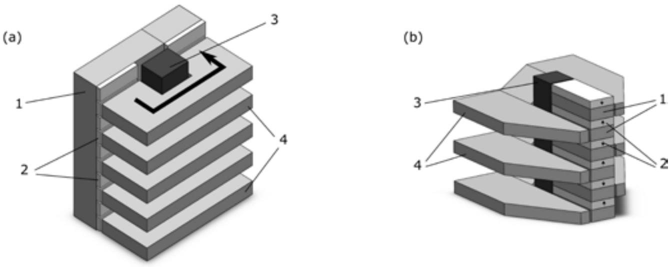

Fig. 2 A single-sided linear TFM generator with surface mounted magnets in (a) and a double-sided linear TFM generator with flux-concentrating setup in (b). In the figure, 1 represents translator iron, 2 represents magnets, 3 is the winding and 4 is the stator iron.

For linear machines, the situation is a bit special since if the stroke length is reasonably long, the translator is considerably longer than the stator. Thereby, if the magnets are placed in the translator, which would be most natural, only a fraction of the magnets would be used at the same time and the machine would contain more magnets than necessary. In our case with 7 m stroke length, 6 times more magnets than necessary would be used which would then constitute nearly half of the material cost. To avoid this, we introduce 2 extra passive airgaps and put the magnets in the stator. The translator contains then only electric steel and structure material. To reduce the impact in cost of the two extra airgaps with corresponding bearings and to reduce the amount of electrical steel, two stacks of magnets, which henceforth are called inner stators, are magnetically connected in series. Fig. 3 shows a 3D cad image of the machine where some of the structure has been removed. Fig. 4 shows a top view cross section where the inner stator sections and translator sections are seen. Fig. 5 shows a 2D FEA simulation of the magnetic fields in the machine, where the details of the flux concentration setup are shown.

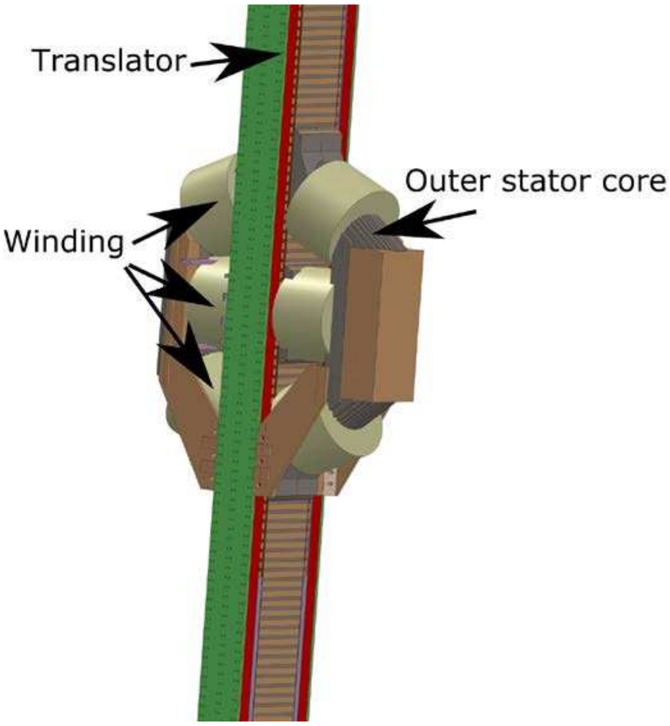

Fig. 3 An illustration of the linear TFM generator in 3D, where the 3-phase transformer layout is shown.

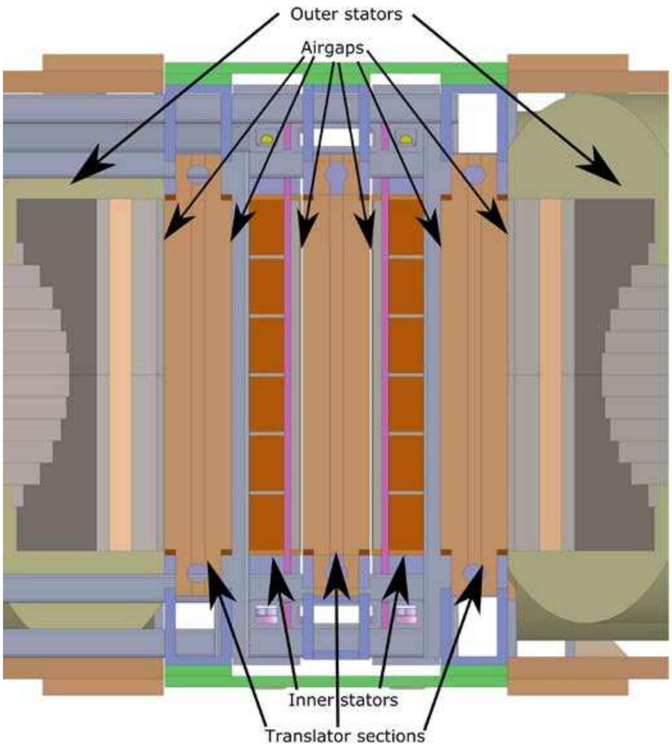

Fig. 4 A top view cross section of the machine, where the inner stators, the six airgaps and the translator sections are shown as well as the outer stators. Note that the two outermost airgaps are passive airgaps that do not produce a usable force.

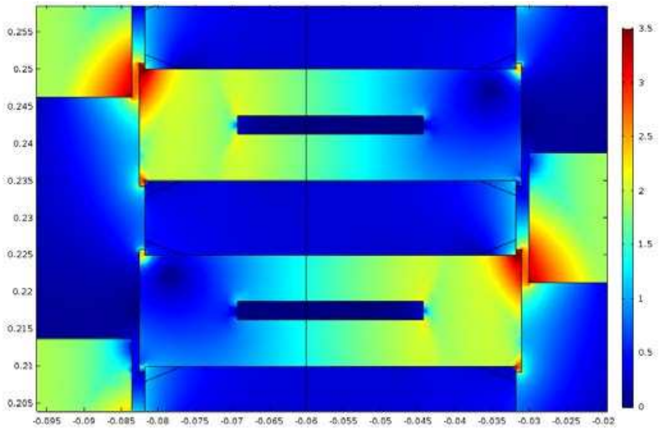

Fig. 5 A 2D FEA simulation where the flux concentrating setup is shown. The machine is in q position with a very high current loading, where the force is produced in the red corners of the iron parts in the inner stator and translator.

V. Electromagnetic design challenges

The electromagnetic design challenges for a TFM generator are very different from the electromagnetic design challenges in other types of generators such as PMSG. Generally, the design challenges are much harder and if not a substantial detailed electromagnetic analysis is made a design project is likely to fail completely, i.e. there is a large risk that the machine will have a very poor performance or not work at all. Also, such a design requires a good electromagnetic understanding and intuition to identify all the potential problems. The main differences are described in the subsections below.

A. *Global flux distribution*

In a TFM, the magnetic flux goes around in a global sense in the electric machine in large loops. This is very different from other types of machines, where the magnetic flux loop is localized. With localized flux loops, the various problems associated with leakage fluxes do not dominate the machine design and are rather straight forward to deal with. With the larger flux loops associated with TFM generators, leakage fluxes become larger and these problems become the perhaps dominant design criteria. This severely complicate the mechanical design due to the need to avoid efficiency and heating problems associated with circulating currents and Eddy currents in structure materials caused by induction from various types of magnetic fluxes. In this text, Eddy currents are defined as currents that circulate within one solid object and circulating currents are defined as currents that go through several objects and typically enclose non-conducting or even magnetic material. Most of the following challenges originally derive from this key difference in magnetic flux paths.

B. *Low power factor*

The power factor becomes lower in a TFM generator for 3 different reasons. First, the current loading is several times higher in a TFM generator than in a PSMG machine, which gives a high force density. This, however, also gives a several times larger flux from the current compared to the PSMG case which gives a corresponding increase in the voltage drop over the internal inductance, and consequently a lower power factor. Second, the leakage fluxes are larger in a TFM, both the leakage fluxes from the magnets and the leakage fluxes from the current. The leakage fluxes from the magnets become considerably lower for a double-sided machine with flux concentrating setup that we are using, but is still large and reduces the no-load voltage. The leakage fluxes from the current both go through the magnet structure (at the wrong place!) and dominate the global leakage flux described above and increases the inductance further. Both a reduced no-load voltage and an increased inductance lower the power factor. Third, at full load the iron in the machine is rather heavily saturated. This means that there is no longer a linear relationship between force and current, which also implies that the voltage induced from the magnets is lowered at high load. This further reduces the power factor. These factors together give a low power factor, and it is important to maximize it. The power factor is thereby heavily dependent on the choice of current loading.

C. Electromagnetic calculations on the geometry

To reduce leakage fluxes and get a high force density and power factor of the machine, the airgaps must be small and 1 mm is preferred. This firstly creates large mechanical challenges. However, it also creates considerable calculation challenges. The stator of the linear prototype is nearly 2 m long, and to calculate the magnetic field in such a large machine with 1 mm airgaps and 25 mm pole lengths with FEA requires a huge number of mesh elements. This is further complicated by the fact that the iron is heavily saturated which makes the problem non-linear. 2D simulation can be used in our design to determine some of the properties like force density with a fair accuracy of maybe $\pm 10\%$ or so, where end effects and global leakage fluxes then are neglected. However, to determine properties like leakage fluxes and power factor, 3D simulations are required. With the resources we have we have this far only managed to get rather inaccurate 3D static magnetic field calculations at a few points. We have from this been able to check the 2D results to some extent. To analyse leakage fluxes from the current, we have simplified the geometry by replacing the magnet structure of the inner stators with an ideal iron structure without small airgaps having a similar reluctance. Then 3D simulations are rather straight forward to perform, but the results have to be interpreted with care and such an analysis is always risky since we partly rely on intuition and simple inaccurate analytical calculations in determining if the simulation is valid or not for a certain problem.

D. Eddy current losses in structure

In a TFM generator, it is much more important to analyse the Eddy current and circulating current losses in the mechanical support structure. These can potentially form the largest contribution to the losses if not care is taken during the design.

E. Eddy current losses in electrical steel from perpendicular magnetic field components

In a TFM generator, it is much more important to analyse the Eddy currents in the electric steel that circulate in the same plane as the sheet, i.e. that arise from magnetic field components that are perpendicular to the laminations. These components become larger in TFMs due to the global leakage flux. Especially the translator positions where the magnets and the currents generate opposing fluxes should be analysed. This problem could possibly be circumvented by using Sintered Magnetic Composite (SMC), but this material has considerably higher hysteresis losses and a lower magnetic flux density saturation level which more or less disqualifies it for this application in our view.

F. Eddy current losses and circulating currents in windings

In a TFM generator of the type we consider here, it is much more important to analyse the Eddy currents and circulating currents in the winding compared to PMSG. The winding in this machine is short and thick to give a very low DC resistance. Since the winding is compact like in a transformer, the magnetic field from the winding becomes considerably larger within the winding itself compared to a PSMG case. Thereby, the winding must be formed by many strands connected in parallel. Since all the strands are connected to each other in the ends, a large number of short-circuited loops are formed by the strands and the flux will induce voltages that will drive circulating currents. To counter this, one either has to use a fairly simple braiding or twisting technique on the strands or use a considerably more expensive Litz wire. If this problem is not addressed at all, the current will go in opposite direction in some of the strands at high speeds and the AC resistance of the winding will be considerably higher than the DC resistance which will increase the copper losses.

G. Switching losses in the generator

Due to geometry, it is in principle impossible to calculate the losses in the generator in 3D caused by the switching transients originating from the active rectifier. This is a hard calculation task for any machine. For slow speed machines, there is always a risk that these losses will be high since the machines involve a larger mass of conducting material per kW. An advantage with the TFM in this respect is that the inductance is high which limits the current ripple. Our strategy is to put a filter on the power electronic system, and then measure the losses with and without a filter. In the end, a multilevel converter could solve the problem without a filter if a sufficient number of levels, say 5 or 7, are used.

H. Cogging forces

The cogging forces and the force ripple in a TFM could potentially be large [10]. In our design they are calculated to about 1-3 % of the maximum force rating of the machine, which is considered as a normal level for electrical machines. For low speeds where the cogging forces matter most, the current could be tailored to eliminate the torque ripple or cogging if the active rectifier allows tailored slightly non-sinusoidal currents. This requires that the force as a function of current and position is known. Since these forces depend on the actual geometry on each individual generator, the generator could be characterized before delivery where this force function is measured in a grid of measurement points. Perhaps a generic calculated grid, or a generic measured such grid, is sufficiently accurate. The cogging forces and the force ripple do not seem to be very problematic in our case.

I. Demagnetization of neodymium magnets

In this type of machine, the shear stress or useful force density is very high. Thereby, the magnets experience rather strong demagnetizing fields from the current loading, where the corners of the magnets at the airgaps are the parts that primarily could suffer from demagnetization. For neodymium magnets, the coercivity, i.e. the demagnetization field limit where permanent demagnetization occurs, strongly depend on temperature, where higher temperatures makes the magnets considerably more sensitive to demagnetizing fields. The demagnetization problem is therefore to large extent a thermal problem. The neodymium grades have the Chinese designations Nxxhh, where a high xx implies high remanent flux density and hh denotes different levels of resistance to demagnetizing fields (and thereby temperature), where the more heat resistant magnet grades are more expensive since they contain more dysprosium. The choice of magnet grade depends on the thermal situation for the magnets, and is a trade-off between coercivity, remanent flux density and cost. The thermal analysis of the machine is complex, partly since the electromagnetic losses are hard to calculate, and is ongoing but not yet complete. The winding is not located near the magnets, so the magnets are only heated by iron losses and Eddy currents in the magnets. We have selected N48H magnets for the prototype. One of the most important factors in the thermal analysis is the expected ambient temperature, which can vary greatly dependent on latitude, season and if the PTO is integrated in a buoy or at the seabed. If the thermal situation becomes problematic, it is rather straight forward to insert either passive (with funnels) or active forced air cooling for the inner stator parts. The magnets are intended to be kept below 60°C. Magnet temperatures over 90°C would have a serious impact on the machine performance, and cannot be accepted at any instant (not even at manufacturing).

VI. Mechanical Design Challenges

The mechanical design of a linear TFM generator of this size is very demanding. The main design problems for the mechanical structure derive from the combination of the small air gap of 1 mm, the intended stroke length of up to 7 m, the large magnetic attraction forces between the moving parts, the necessity to use non-conducting materials and the geometry of the long-thin inner stators that contain the magnets. The bearing problem must also be properly addressed. The problems and their prerequisites are discussed in the subsections below.

A. Magnetic forces between moving parts

The magnetic forces in the machine are the dominant forces which typically dimension the mechanical structure. We separate the magnetic forces between the moving parts into the desired forces directed perpendicular to the surfaces at the airgap that are associated with the shear stress, i.e. the damping forces along the translator, and the undesired magnetic attraction forces normal to the surfaces at the airgap which henceforth are referred to as normal forces. The normal forces are approximately proportional to the square of the magnetic flux density, and can approximately be calculated as

$$F_n = \frac{B^2 A}{2\mu_0} \qquad (2)$$

if the magnetic flux density B is assumed constant over the surface area A. In our case 60 % of the surface is iron parts, and assuming 2 T as maximum field yields a normal stress of $\sigma_n \approx 1000$ kN/m^2. The shear stress $\sigma_s \approx 100$ kN/m^2 in the machine addressed here at full load. From this, it is directly clear that the life and cost of the bearings could be problematic. Also, the friction losses which are approximately proportional to the net normal forces could potentially be problematic, especially at partial load. It is therefore necessary to use the symmetry to cancel these normal forces out. If the symmetry is perfect, these forces cancel out completely. However, due to manufacturing tolerances, thermal expansion and elastic deformations, the airgaps on the two opposing sides of each such section differ which will give different magnetic flux densities in these airgaps and different forces on the opposing sides. Thereby, these forces cannot completely cancel out, and the size of the remaining force is strongly dependent on the mechanical construction. According to Earnshaw´s theorem, an equilibrium position for a ferromagnetic material in a magnetic field is always unstable, and this negative stiffness must be counteracted by the stiffness provided by the bearings.

In the machine, the six 1 mm airgaps are magnetically connected in series and the flat sections separating them are about 50 mm thick each. There are 5 such flat sections where three of them belong to the translator and two form the inner stator, see Fig. 4. To calculate the net normal force, there is a large cancellation in accuracy which disqualifies simple calculations like in Eq. (2) and FEA simulations are required. What can be noted is that the global magnetic flux mentioned earlier passes through the airgaps on both sides of the flat sections, and does not contribute to the unbalance in magnetic fluxes between the two sides of a section. Only the leakage fluxes contribute to this unbalance, which is different compared to a PSMG generator where the main flux contribute. On the other hand, the leakage fluxes are substantial, so there will be considerable net normal forces anyway.

The attractive magnetic normal forces on the center translator section as well as on the inner stator sections ideally cancel due to symmetry. If they are straight and well positioned, the forces on those parts should be small or moderate. In practice, we expect them to be below 2 kN per pole in an average sense which is based on calculations for 0.5 mm displacement. On the two outer sections of the translator, there is no symmetry and the magnetic net forces will be about twice as large at most for these sections, giving 8 kN per iron block. Note that this force is largest when there is no current and the translator is in q position so that the flux through the core is zero. In Fig. 6 (a) below, the net force per phase calculated in 2D FEA is given for different displacements of the inner stator for a DC phase current of 225 A, which represent the worst case. In Fig. 6 (b), the net force is given for a non-displaced outer translator part where the asymmetric normal forces are evident. Note, that for both these cases, the maximum normal forces do not arise at maximum current. At maximum current, most iron parts will be saturated by the global flux from the current loading and the fluxes on both sides of the sections will be more similar, even if displaced.

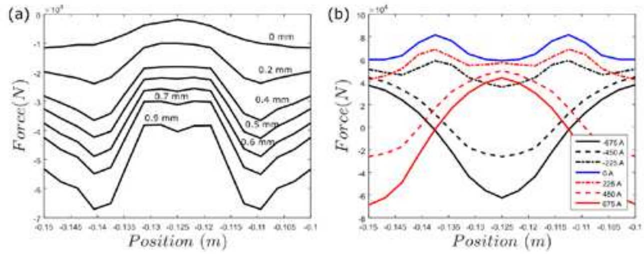

Fig. 6 The net normal forces calculated in 2D FEA for one phase in the machine for the inner stator with various displacements in (a) and for the unbalanced outer sections of the translator for various currents in (b). In (a), the current is 225 A and the displacements are rigid displacements so that a displacement of 0.5 mm gives an airgap of 0.5 mm on one side and 1.5 mm on the other side. In (b), the translator is attracted to the inner stator (i.e. where the magnets are) at no-load.

B. Mechanical structure material limitations

The mechanical structure material that can be used is at many locations limited by the leakage fluxes and the small airgaps. Generally, magnetic steel is low-cost and strong but can only be used far away from the magnetic fluxes or otherwise magnetic short circuits or excessive Eddy current losses may result. Use of non-magnetic metals are however also problematic at many locations due to induced Eddy currents and circulating currents since the electrical conductivity for metal generally is very high. It is, however, not totally restricted to use these metals, and the difference in electrical conductivity between different metals is important to keep in mind. Aluminium is generally a poor choice, partly due to the poor mechanical fatigue properties but also due to the low resistivity of 2.82×10^{-8} Ωm. Non-magnetic stainless steel is in this machine a considerably better choice. There are many types of stainless steels, with different magnetic relative permeabilities, different electrical resistivities and different cost. A representative value for the resistivity is 6.90×10^{-7} Ωm which is about 25 times higher than for aluminium, and thereby the losses from Eddy currents and circulating currents in stainless steel is lowered by a factor of 25 per unit volume. In practice, the difference is even larger since a stainless steel structure is stronger and can be made thinner. It is still necessary to avoid closed circuits, but for many details stainless steel could be suitable if the structures are kept sufficiently thin where a width of 2 cm is acceptable for most applications.

At certain places, like for example in between the iron parts in the translator, the peak leakage fluxes can reach 0.4 T or so, which makes use of stainless steel problematic. Here a material with a higher electrical resistivity is desired. A very suitable such material is FR-4, which is an isolator. This glass fiber material is strong and low-cost, but is rather elastic with a Young´s modulus of 24 GPa. Therefore, it can only be used stand-alone at locations where elastic deformations are not of importance or even desired. A considerably stiffer and stronger material is carbon fiber, where the standard grade T700 has a Young´s modulus of 230 GPa, i.e. about 10 times as high as for FR-4. Note that carbon fiber with a Young´s modulus of 780 GPa (CN-80) is available if needed, but that this material is considerably more expensive. Carbon fiber is a conducting material, but with an electrical resistivity of about 1.6×10^{-5} Ωm which is about a factor of 25 lower than for stainless steel. Also, the resistivity cross-wise the fiber direction should be higher, and thereby Eddy current losses are not a problem at these low frequencies unless very broad structures are used. Circulating currents can still be a problem, and closed loops must be avoided. Carbon fiber is expensive, but usually only small amounts are needed to reinforce glass fiber structures in a sandwich manner to make them stiff.

A general problem with non-conducting materials is that many materials suffer from creep. Fiber reinforced composite materials generally do not experience much creep along the direction of the fibers. However, the fibers are normally only oriented in two degrees of freedom, and not in the third. This implies that FR-4 and carbon fiber sheets experience creep in the thickness direction. This is problematic, since it disqualifies frictional bonds/joints tightened by screws in the mechanical design which would be the natural method to connect the mechanical parts. There is always a risk that such bonds become loose after a month or so due to creep, and they must not be used in the construction. The creep can also be problematic if glass fiber is used to electrically isolate conducting parts. One example is the bearings, where the track rollers should be isolated from the structure to avoid electrical discharges in the bearings due to induced voltages from switching transients, which potentially could reduce the life of the bearings grossly. The creep can then reduce the necessary pretension of the bearings, and cause a mechanical failure. In such cases, mica could be an alternative.

In this project, also numerous other material options have been evaluated. Many ceramic materials like aluminium oxide have very suitable properties for parts of the construction since they are very stiff. However, they are in general one order of magnitude too expensive to be an economically viable alternative. In the end, all design criteria are about economy.

C. Mechanical properties of electromagnetic materials

The machine constitutes to a large part of materials which primarily have an electromagnetic function in the machine and are selected for their special electromagnetic properties. This is in our case grain-oriented and non-oriented electrical steel laminations, neodymium magnets and aluminium winding wire. The winding wire properties are not important for the mechanical construction, but should be tightly fastened to avoid vibrations and properly designed for good heat conduction. The electrical steel is not as strong as standard steel, since about 3 % silicon is introduced in the material to reduce the electrical conductivity. It is, however, still a very strong and stiff material and has a tensile strength in the order of 350 MPa. The problem is that the coating between the sheets is not designed for taking large mechanical loads, and is typically only tested for less than 1 MPa (>345 kPa) in the stacking factor test standard [11]. The coating can probably be subjected to higher loads than this, especially the non-organic coatings, but higher loads also increase the iron losses and a moderate load of 8 MPa was found to increase the iron losses with a few percent in [12] which could be acceptable. However, to put loads in the order of 50 MPa on the steel sheets is not recommended, since the laminated sheets are not made and tested for that purpose.

The neodymium magnets are ceramic and are stiff and strong in compression having compression strength of about 1 GPa and a Young´s modulus of about 160 GPa. We tested one sample magnet in a compression machine, which broke at 814 MPa and had a Young´s modulus of 152 GPa. As most ceramic materials, the magnets are weak in tension and have a tensile strength of only 80 MPa. The material as such is brittle, and it is generally not recommended to use it as structure material. However, if a pretension is applied so that the magnets only work in compression, their stiffness can be used to reduce elastic deformations if the compression load is fairly low, below 50 MPa.

D. *Elastic deformations*

Since the airgaps are small, 1 mm, and the magnetic normal forces are large and strongly dependent on the deviances in the airgaps on the two sides of the different machine sections, elastic deformations form a considerable challenge both for the inner stators and the translator sections. Note that the sections never are allowed to come in contact with each other. Those sections are flat, 50 or 51.5 mm thick, but rather wide and although the active airgap is only 315 mm the distance between the center of the bearing track rollers is about 400 mm. Thereby, the area moment of inertia is small, and materials with very high Young´s modulus are required to resist deflection. However, there are also strong magnetic flux densities here, which largely exclude the use of metal beams. In our solution, we dimension for 0.5 mm displacement for the inner stators which should be considerably worse than expected. We use primarily the stiffness of the magnets to avoid elastic deformations in these parts due to the uncertainty of the behaviour of the electric steel plates under high loads, and with this displacement the elastic deformation has been calculated to below 0.2 mm using both mechanical FEA calculations and analytical beam theory. For the non-symmetric translator parts, there is space for structure beams between the iron parts. Here, beams comprised of carbon fiber, FR-4 and probably sandwich filler material is used and with this combination the elastic deformation of these sections can be kept below 0.2 mm according to calculations. For the center translator section, the forces are lower and we have not yet decided if carbon fiber inserts are required.

E. *Bearings and bearing life*

The only part of the generator that is subject to wear is the bearings. If the bearing solution could become maintenance free, the whole generator then could become maintenance free which is a very important feature. Note that the useful force from a generator is magnetic, and that magnetic fields do not wear. Linear bearings are expensive, and they should be selected with care. In this project, track rollers that roll on runways are used. These bearings are rated for perhaps surprisingly large loads, and a small 50x25 mm wheel can take 3 tons of force. However, this rating is for a life of typically 50 km. For a phase-controlled point absorber in an Atlantic wave climate, having perhaps 7 m stroke length and a wave period of 10 s, this corresponds to a life of 10 hours. This is far off from maintenance free operation. What then must be done is to reduce the load substantially, so that the rolling elements do not suffer from fatigue. Ball bearings and roller bearings have such a fatigue load limit, and it is preferable to always remain under this limit. It is here important to note that ball bearings and roller bearings have very different properties concerning the fatigue load limit. The rated load capacity for a roller bearing of the size we are considering here, about 50 mm diameter and 25 mm width, is a bit larger than for a ball bearing, but there is not a great difference. However, the fatigue load limit of the ball bearing is several times less than for the roller bearing, and although the roller bearings are more expensive and have slightly higher coefficient of friction, they are the better option. The fatigue load limit is nearly one order of magnitude lower than the rated 50 km load limit for the roller bearings we consider. There also is a lower load limit on a track roller. If the load is below this value, it is not guaranteed that the rolling elements will roll and sliding might occur which will cause wear on the rolling elements. To make a proper bearing arrangement, the track roller load must remain between these two values.

With the bearing solution we have now, we use bearings that are arranged to fulfil the criteria above under all circumstances and that are greased for life. Since the life of the bearings is much longer in this application than for the typical application, it is unclear how long this grease will last. However, if required, an automatic greasing system can most likely be implemented at an acceptable cost.

There are about 130 track rollers on one generator, and it is likely that a few of them will fail during the generator´s lifetime. To deal with that problem, the design is made so that the machine will work if single track rollers fail. If two adjacent track rollers fail there will be problems, but this is less likely to happen.

F. *Manufacturing costs and tolerances*

To make wave power economically viable, the WEC components must be low cost and cost in terms of Levelized

Cost Of Energy (LCOE) is of course in the end almost always the most important parameter. The manufacturing costs for a generator of this type could potentially become high, since the airgaps are small and the geometry is complex. A first attempt to design the machine will most likely end up in numerous separate parts with tight manufacturing tolerances and dependences between them that form tolerance chains. This applies both to straightness and length tolerances, and the manufacturing costs will then be high. These tolerances can, however, to a very large extent be avoided by using numerous different mechanical tricks. For example, it is very important to differentiate between need for absolute accuracy, i.e. that parts should be of a certain size, and need for relative accuracy, i.e. typically that many pieces should be of the same size but it is ok if that same size differ slightly from the size on the drawing. In such cases, ordinary stamping dies can be useful provided that the temperature of the die is kept constant. In general, some flexibility and adjustability can also be used to reduce these problems. In our current design, we do not have many parts that are dependent on precise tolerances, and we do not have tolerances finer than ±0.1 mm which is a standard tolerance for small parts. For many parts we do not require more than ±0.5 mm. Further, we are not dependent on demanding straightness tolerances. We intend to show that it is fully possible to build the machine in this way, but the final construction will show if we succeed or not.

VII. PERFORMANCE

The shear stress of the machine is predicted to be around 100 kN/m², where the whole active area is counted. If only half the active area is counted, which is custom for such machines [10] but make comparisons to other machines unfair, this corresponds to 200 kN/m².

The calculated efficiency of the machine is about 98%. This is valid over the speed range 0.7-3 m/s, but even at 0.25 m/s the efficiency is calculated to 97%. For lower speeds, the copper losses are more prominent and for higher speeds the Eddy current losses in the iron, winding and structure will increase. At half the load, the efficiency is expected to be about the same or perhaps down to 97.5 %, but it is hard to predict the effects on the iron losses here. In Table III, the calculated losses in percent are given for the two speeds 0.7 and 3 m/s. Due to difficulties with 3D FEA simulations, the Eddy current values have been approximated with analytical calculations. The extra losses from switching transients from the power electronic system are almost impossible to predict and are not included.

TABLE III
LOSSES IN THE MACHINE, FULL LOAD

Material	0.7 m/s (%)	3 m/s (%)
Conductive losses	0.55	0.13
Iron losses	0.7-0.9	0.9-1.1
Friction	0.3-0.6	0.3-0.6
AC losses winding	0-0.05	0-0.2
Iron losses perp. B fields	0-0.1	0-0.3
Eddy currents in structure	0-0.1	0-0.2
Sum:	**1.55-2.3**	**1.33-2.53**

The reader should be aware that these numbers are rather inaccurate, especially for the iron losses and friction that form the majority of the losses. For the iron losses, a simple Bertotti model was used, where only Eddy currents losses and hysteresis losses were addressed. Representative material data was taken and scaled with frequency dependence, a representative flux density was selected and then the losses per kg were multiplied with the mass. For the small iron parts, the losses were multiplied with 2 and for the core with 1.5 to take increased iron losses from manufacturing and rotating and non-sinusoidal fields into account. This model is very rough and should be refined, but for now it is not so important for the design. The friction is also very inaccurate, where we have assumed a typical normal force for each bearing and used the typical friction coefficient given by the manufacturer.

VIII. COST

The cost of a machine is rather hard to predict in advance due to the large uncertainties in costs for manufacturing the parts and the assembly costs. Also, both some of the material costs and manufacturing costs can be reduced grossly in mass production. It is nevertheless one of the most important parameters, and a rough estimate will be presented here. These costs will not be for mass production, but rather for a few units and is taken from the manufacturing costs of our prototype, where we guess on the parts that are not yet ordered. The costs of stamping dies, mounting tools etc. have however been reduced to correspond to a considerably larger production series. In Table IV, estimates on the cost of the manufactured parts as well as their mass are given. The assembly cost is not included, but could be estimated to maybe 5-10 k€.

TABLE IV
MANUFACTURED PARTS, MASS AND COST

Material	Mass (kg)	Estimated cost (€)
Grain-oriented electrical steel	3900	18 000
Non-oriented electrical steel	210	525
Neodymium magnets N48H	130	5 000
Aluminium winding wire	300	1 500
Carbon fiber	90	6 000
FR-4 (glass fiber)	700	7 000
Epoxy resin	100	1 000
Sandwich foam	50	750
Stainless steel support	500	3 500
Steel support beams etc.	400	1 000
Screws, bolts and springs	100	1 750
Linear bearings	60	6 500
Track roller mountings	80	3 500
Sum:	**6 620**	**56 025**
Per kN	**33.1**	**280**
Per kW 0.7 m/s (140 kW)	**47**	**400**
Per kW 3 m/s (600 kW)	**11**	**93**

Note here that the estimate is rough. Almost 2/3 of the machine mass and 1/3 of the cost is electrical steel. The manufacturing costs of the steel depend on manufacturing technique, cutting length, sheet thickness and on the percentage of scrap. Note also that 1200 kg of grain-oriented steel could be replaced by non-oriented steel with a ~0.2 % reduction of the efficiency. This would save €3 500. In a commercial application, this would be done.

If we compare these values for 3 m/s with a standard off-the-shelf generator, MarelliGenerators MJB 355 MB4, 1500 rpm [13] the differences are actually surprisingly small. This rotating machine has properties 50 Hz, 800 kVA, 640 kW, 96 % efficiency, 2050 kg mass and cost around €20 000 for a single unit. A similar generator would anyway be needed regardless of PTO system if electrical energy conversion is performed locally in the WEC. Such a unit needs a gearing function, has lower efficiency, has an efficiency that drops markedly with speed due to copper losses and does not provide the conversion from linear to rotating motion with 7 m stroke.

IX. Discussion

This design project is vastly complex, both regarding electromagnetics, mechanics and to some extent also power electronics. We have identified a large number of design pitfalls that completely could destroy the machine mechanically, shorten the bearing life or cause very large losses. All these pitfalls have been avoided in the design, but there is a non-negligible risk that undetected such problems remain. The prototype is planned to be fully mounted in the beginning of 2018, and only then will we know if we can reach this performance. Even if the design is correct, there is of course still a risk that the mounting or the manufacturing may fail. We are however convinced that this type of machine can be built with a similar performance and cost as we present here, disregarded whether our prototype will work or not next year. One thing is, however, clear: it is not an easy task to design and build such a machine. But if one machine is successfully built, it is probably not hard to build another one.

The machine is not only hard to design, it is also hard to analyse since the small airgaps require very fine mesh elements and since the geometry necessitates 3D FEA simulations. Even static simulations are quite hard to make. This makes the design task even harder.

This type of PTO solution can potentially give a great contribution to wave power technology, and we intend to commercialize the machine if it works as expected.

X. Conclusion

An ongoing design project for a TFM linear generator is presented. The machine is predicted to get unparalleled performance in terms of efficiency, force/power density and cost when compared to other PTO solutions with a large margin, but it is also very challenging to design and build. Calculated values suggest an efficiency of about 98% between 0.7 and 3 m/s. The machine is rated for 200 kN, has a stroke length of 7 m (prototype has 4 m), a mass of about 6.6 tons and a force density of about 30 N/kg. For 0.7 m/s this corresponds to 140 kW and for 3 m/s 600 kW respectively.

Acknowledgment

The Swedish Energy Agency is acknowledged for funding this project with project number P-40430-1. J. Gust. Richerts foundation and Lars Hiertas Minnesfond is also acknowledged for financial support. The numerous master thesis and bachelor thesis students that have been involved in designing and evaluating different parts of the machine and issues related to it are acknowledged for their contribution to the project and for providing good company during this very hard but very interesting work. Finally, the department of Electric Power and Energy Systems is greatly acknowledged for providing a true scientific work environment where true scientific values like freedom of thought and search for the truth regardless of personal prestige are honoured and encouraged. Special thanks are directed to Oskar Wallmark and Hans-Peter Nee. Ulf Sellgren at the machine design department at KTH is also acknowledged for support during the mechanical design. Prof. Dan Zenkert is acknowledged for useful discussions on fiber composites.

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