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# Application of Scaling Laws for Direct Drive Permanent Magnet Generators in Wind Turbines

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# Application of Scaling Laws for Direct Drive Permanent Magnet Generators in Wind Turbines

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*Abstract*— **The object of this thesis is to investigate the use of scaling laws for Permanent Magnet Generators (PMGs). The product is a graphical tool named the Scaling Program, which is created in MATLAB GUIDE. The most applicable of the investigated scaling laws have been implemented in the program. The scaling laws for mass are based on work by Henk Polinder from TU Delft and the scaling laws for power and losses are based on general theory of losses in PMGs. The main contribution of the thesis is to make these scaling laws available to a user through the Scaling Program.**

**The philosophy of the thesis is to make realistic predictions about a given reference machine, with input data limited to that which can be expected to be handed over by a generator supplier.**

**The implemented scaling laws are able to predict the total mass as a function of the power of the generator, as well as the losses and efficiency as a function of the length and air gap diameter of the generator. The user can also manually compare power density and torque density with state of the art wind power generators. In addition the user can change parameters such as the specific cost of materials ratio of resistive losses to iron losses. This way, the output can be more finely tuned if more detailed information about the reference generator is available. The use of some aspects of the program is showcased in a section called Practical Examples. However, the user is encouraged to try out the program independently of the example.**

**Two different philosophies are discussed concerning which parameters to change with the diameter of a reference machine. One is to keep the number of poles and slots constant while changing the pole and slot geometries with the diameter. The other is to keep the pole and slot geometries constant, and only increase the number of slots and poles as the circumferential length increase with the diameter. The first procedure opens a range of possibilities on how to change the geometry, which will alter the electromagnetic properties of the machine. Since the generator is thought to already be optimally designed in electromagnetic terms, the first procedure is deemed unpractical. Therefore only the last philosophy is applied in the scaling theory.**

**MATLAB GUIDE is deemed to be a good tool for creating a "moderately complex" graphical user interface, which the Scaling Program can be defined as. Its versatile handling of graphical objects is especially useful.**

**Regarding the scaling laws, the scaling of the output power is according to the theory. With a constant tangential stress, a larger rotor volume increases the output power.**

**The scaling of the losses are shown to be more crude than necessary. According to the presented theory of losses in an electrical machine, the iron losses are dependant on the angular frequency, which for a PMG is assumed to be increasing with diameter. The use of the developed "ring-loss-method" neglects such a dependancy.**

**The estimated efficiency increases with diameter as expected since the theory states that the output power increases with the second power of the diameter, while the losses increase with the first power of the diameter. The estimated efficiency is independent of independent of the active length. This is thought to be due to the inaccuracies in the loss-ring-method.**

**The scaling of the mass results in similar characteristics as the paper, which the method is based on. This is however not considered a sufficient verification. Because mass of commercial multi megawatt PMGs are not available, it is difficult to verify the scaling of mass.**

**It is difficult to verify a scaling law for wind power generators because the power levels of commercial generators today are not very large. One way could be to build a finite element model of the reference generator and implement the scaling laws into the model. This is work intensive and outside of the scope of this thesis. Another way could be to find two generators of similar design, one with a lower power rating than the other. Then try to scale up the smaller one to the same power rating as the larger machine, and compare the data of the two. This was attempted, but data on two such similar generators were not found for this thesis. Both verification methods are suggested as further work.**

**Even though the scaling results are subjects to uncertainty due to its simplified approach the tool is deemed to fulfil its objective of showing the user which trends to expect if a reference machine is to be scaled up or down to a given power rating or geometry.**

*Index Terms*— **Scaling, Direct Drive, Permanent Magnet, Wind Turbine Generators, GUI, GUIDE, Power, Efficiency, Mass**

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## Problem Description

The initial goal of this thesis was to continue on the author's Specialization Project [1] of making a scaling program for Blaaster Wind Technologies (Blaaster). The program was going to assist in Blaaster's effort of scaling up a 3 MW prototype generator for their wind turbine. The prototype generator is an external rotor PMG. Thus the Specialization Project focused on scaling of external rotor PMGs specifically.

The wishes of the author were to continue this work by investigating the use of optimisation algorithms to supplement some aspects of the scaling model. The goal would be to give a suggestion for design improvements of the prototype.

Blaaster Wind Technologies went bankrupt in December of 2014. When this was made known a period of much uncertainty followed. Finally it was established that the collaboration with Blaaster Wind Technologies would not continue. And it was decided that the product would be a Scaling Program for use in education.

The following problem description applies.

- Literature study on the subject.
- Learn more about programmatic graphical user interfaces and MATLAB GUIDE.
- Investigate scaling laws of generator mass, losses, efficiency and external geometry.
- Implement scaling models in a MATLAB Graphical User Interface

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# I. Introduction

## A. Background

THE wind power industry has had significant growth in Europe for the last 14 years. From Figure 1 one can see that from year 2001 to 2014 the annual installed capacity for onshore wind has had a compound annual growth rate (CAGR) of 6,8% [2]. In the same period, the annual installed capacity for offshore wind had a CAGR of 29,6 %. For offshore wind, the cost of electricity is still too high to compete with other energy sources such as coal. To ensure implementation of more offshore wind power, these costs need to be reduced, and increasing the knowledge of generator design can help. To make this knowledge more available, the objective of this thesis has been to make an easy-to-use software for scaling generators for large wind turbines.

There are many generator designs which can be used in a wind turbine. The most common ones at the time of writing are Squirrel Cage Induction Generators (SCIG), Doubly Fed Induction Generators (DFIG), Wound Rotor Synchronous Generators (WRSG) or Permanent Magnet Synchronous Generators (PMG) [4]. The generator systems can either have a direct drive solution, where the rotational speed of the generator is the same as the rotational speed of the turbine blades, or a gearbox can be used to get a higher (or lower) rotational speed in the generator than the blades. In general one can say that induction machines require gearboxes because of their high rated speed, while synchronous generators can be used for direct drive. Figure 2 shows the four most used generator systems to date [4].

The direct drive PMG (DDPMG) is an attractive choice for use in large wind turbines for a number of reasons. The self excitation of the permanent magnets eliminates the need for an excitation circuit in the rotor, which in turn eliminates winding losses in the rotor. This yields a higher efficiency than the WRSG and IGs. No rotor circuit also eliminates the need for slip rings and brushes to transfer the magnetising current to the rotor. Combined with the elimination of the gearbox this reduces the maintenance time and costs [8]. Maintenance of offshore wind turbines is more expensive than for onshore wind turbines. One of the reasons is the costly transportation by boat or helicopter. For a turbine to be used offshore, reducing the maintenance time is therefore crucial. Even though a geared DFIG would be a more light weight and have lower investment costs, the reliability, efficiency and energy yield of the DDPMG makes it more attractive for large turbines, and especially for offshore use [8]. Lower need of maintenance also result in lower operational costs offshore.

There are three main ways of designing a PMG in terms of flux flow: radial flux, axial flux and transversal flux. The dominating flux design in commercial wind turbines is radial flux. Because of this the focus of this thesis is on radial flux PMGs.

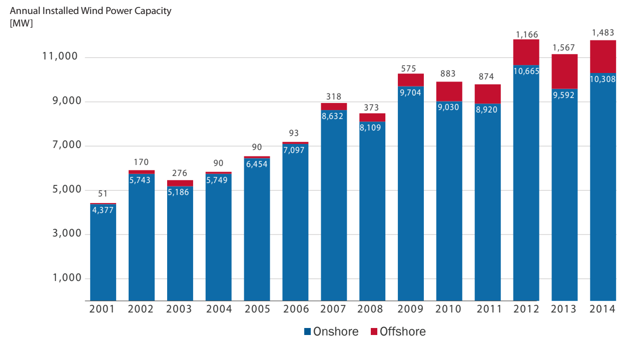



Fig. 1. Annual Wind Power Installations in the EU, Onshore and Offshore [2]

## B. Objective and Contribution of the Thesis

The main objective of this thesis has been to develop a scaling tool for direct drive PMGs. The philosophy has been to make realistic predictions about a given reference machine, based on as little input as possible. The input data has therefore been limited to that which can be expected to be handed over by a generator supplier.

The scaling laws for mass are based on work by [19] and the scaling laws for power and losses are based on general theory of losses in PMGs. The main contribution of the thesis is to make these scaling laws available to a user through a Scaling Program.

The output of the Scaling Program is divided into two parts: 1. Scaling of active and structural mass, output power and losses and 2. Using the scaled values for estimation of key parameters. The Key Parameters are generator efficiency and cost.

The user of the Scaling Program should be aware that a scaling model makes use of many simplifications. The results should therefore only be used for comparative studies of different generator designs.

# II. Scaling of an Electrical Machine

Traditionally testing and improving new electrical machine designs has been a difficult and time consuming process. With modern computer technology, testing of new designs are much easier and the use of finite element method software can give accurate solutions for electromagnetic design, structural and thermal design. However, the finite element simulations are still demanding both in terms of computational power and time. Accurate solutions also demand a deep knowledge of multiphysics modelling. There are, however, instances where the most accurate solutions are not needed. If a machine has

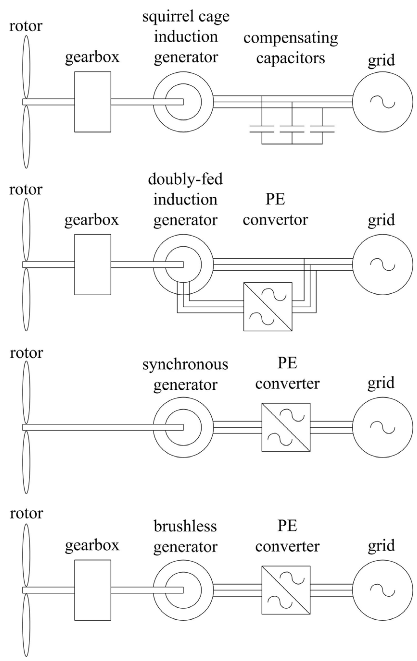



Fig. 2. Common Generator Systems for Wind Power [4]

already been built and one wants to test how certain key parameters change with for instance the output power, one can use scaling models.

In his classical book, "A.C. Motor Design" from 1976, De Jong from University of Oxford [5] writes the following about scaling laws:

> "Scaling laws of technical objects express basic relationships between their characteristic quantities and important properties on the one hand, and their 'size' on the other hand."

One approach for scaling an electrical machine can be the following:

1. Mapping reference parameters. Data from a reference machine are mapped and used as a basis for the scaling. This can be the reference output power, mass, length and diameter

2. Key parameters are chosen or "characteristic quantities and important properties" as defined by de Jong. Some examples are the electric loading, magnetic loading, generator weight, output power, losses, efficiency, etc.

3. Main scaling parameter is chosen. This can be the length of the rotor, air gap diameter, pole pitch, aspect ratio or power.

4. The scaling is performed by using the known theory of electrical machines combined with simplifications and empirical knowledge of parameter ranges to establish the main contributors of change in certain key parameters. This can then be used to make prognoses for how the values of key parameters will evolve as input parameters such as output power and length or diameter increase or decrease.

## III. Permanent Magnet Generator Theory

The internal apparent power of a machine can be written as

$$S_i = mE_m I_s, \tag{1}$$

where $m$ is the number of phases, $E_m$ is the air gap emf and $I_s$ is the stator phase current. $E_m$ can be expressed by the air gap flux, $\phi$, and the stator current by the linear current density, $A$.

$$E_m = \frac{1}{\sqrt{2}}\omega\hat{\phi}_m \tag{2}$$

$$I_s = \frac{\pi D}{2N_s m}A \tag{3}$$

$$\hat{\phi}_m = \int_{S_p} B_\delta dS_p. \tag{4}$$

These equations are developed in detail in [12].

### A. Machine Constant

In [12] it is stated that "The machine constant is the amplitude of the internal apparent power and the active power. It varies between different machine designs".
Assuming that the air-gap flux density has a sinusoidal distribution over the pole pitch $\tau_p$ and that there is no variation with respect to the active machine length $l'$, the surface integral of the flux can be simplified as

$$\hat{\phi}_m = \int_0^{\tau_p} l' \cdot \hat{B}_\delta sin\frac{x\pi}{\tau_p}dx = l'\tau_p\alpha\hat{B}_\delta \tag{5}$$

Where $\alpha\hat{B}_\delta$ represents the average flux density in the air gap. For sinusoidal distribution $\alpha = 2/\pi$. For nonsinusoidal air-gap flux density the average value $\alpha$ can be defined from the relative magnet width $\alpha_{PM}$. With $\omega = 2p\pi n_{syn}$ Equation (1) can be expressed as

$$S_i = \frac{\pi^2}{\sqrt{2}}k_{ws1}A\hat{B}_\delta D^2 l' n_{syn} = CD^2 l' n_{syn} \tag{6}$$

with

$$C = \frac{\pi^2}{\sqrt{2}}k_{ws1}A\hat{B}_\delta = \frac{\pi^2}{2}k_{ws1}\hat{A}\hat{B}_\delta. \tag{7}$$

$k_{ws1}$ is the fundamental winding factor. When using mechanical power written in terms of apparent power, a mechanical machine constant can be introduced:

$$P_{mec} = \frac{1}{\eta}mUIcos\varphi \tag{8}$$

And then introducing the apparent power:

$$P_{mec} = \frac{1}{\eta}cos\varphi\frac{U}{E}S_i = C_{mec}D^2 l' n_{syn} \tag{9}$$

where

$$C_{mec} = \frac{1}{\eta}cos\varphi\frac{U}{E}C. \tag{10}$$

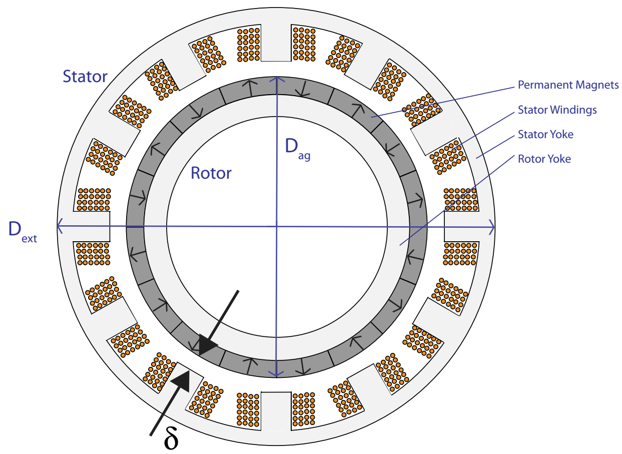



Fig. 3. Permanent Magnet Generator. $D_{ext}$ is generator outer diameter and $D_{ag}$ is air gap diameter, $\delta$ is the air gap thickness.

### *B. Stress in air gap*

The stress in the air gap is an essential component in torque generation and can be described by Maxwell's stress tensor. The function of Maxwell's stress tensor is to describe magnetic stresses, forces and torque, for instance in the air gap of an electrical machine. First a linear current density, $A$, is defined. This is the current per circumferential length with unit A/m. In short, one can say that a linear current density on a metal surface creates tangential field strength components on the metal surfaces. Such tangential field strength components are essential in both tangential stress generation and torque generation in rotating-field electrical machines [12].

According to Maxwell's stress theory, the magnetic field strength between objects in a vacuum creates a stress $\sigma_F$ on the object surfaces, given by

$$\sigma_F = \frac{1}{2}\mu_0 H^2 \tag{11}$$

where $H$ is the magnetic field strength in the air gap. The stress occurs in the direction of lines of force and creates an equal pressure perpendicularly to the lines.

*1) Tangential stress in air gap:* The tangential component of the air gap stress is

$$\sigma_{F,tan} = \mu_0 H_n H_{tan} \tag{12}$$

where $H_n$ is the normal contribution to the field strength and $H_{tan}$ is the tangential contribution.

Furthermore, Amperes law yields that in the air $H_{tan} = A$ and since $\mu_0 H_n = B_n$, $B_{\delta,n} = \mu_0 H_n$.

This means that the tangential stress in the air gap of the machine can be written in terms of the linear current density, $A$, and the flux density in the air gap, $B_\delta$ as follows

$$\sigma_{F,tan} = AB_\delta. \tag{13}$$

This is a function of time and space. Assuming a sinusoidal current and flux density distribution, $\sigma_{F,tan}$ can be expressed in terms of time and space as

$$\hat{A}sin(x)\hat{B}_\delta sin(x)cos\varphi \tag{14}$$

where $cos\varphi$ is the power factor of the machine.

The average tangential stress in the air gap then becomes

$$\bar{\sigma}_{tan} = \frac{1}{2}\hat{A}\hat{B}_\delta cos\varphi = \frac{1}{\sqrt{2}}A\hat{B}_\delta cos\varphi \tag{15}$$

Where $A$ is the RMS value of the linear current density. Comparing eq. (7) with eq. (15) reveals that the tangential stress is almost the same as the machine constant as defined by [12]. Assuming $k_{ws1}$ and $cos\varphi$ to be unity, one gets $C = \pi^2\sigma_{F,tan}$.

Equation (15) shows that if the magnetic and electric loading is kept constant, the force density will also be kept constant. As will be elaborated in the next section, a machine designer is likely to have already optimised the relation between $A$ and $B$. And when scaling the machine these two values are therefore considered to be kept constant.

*2) Radial stress in air gap:* The radial stress in the air gap is caused by the magnetic force between the permanent magnets in the rotor and the iron in the stator. As with the tangential stress, the radial stress can be described by Maxwell's stress tensor of eq. (11). The radial component is:

$$\sigma_{F,rad} = \frac{1}{2}\mu_0(H_r^2 - H_t^2) = \frac{1}{2\mu_0}(B_r^2 - B_t^2) \tag{16}$$

Where $B_r$ and $B_t$ represent the radial and tangential components of the magnetic flux density in the middle of the air gap. While calculating radial forces it is common to neglect $B_t$ for ease of calculation.

### *C. Relation between $A$, $B$ and $t_{em}$*

A basic condition for a radial flux PMG is that for a given volume, the magnetic loading, $B$, and the electrical loading, $A$, are dependant on the same space. Over one slot pitch, the current runs through the winding and the flux runs mainly through the tooth. If all geometric parameters are kept constant, but A is increased, then B must decrease.

There are two possibilities when the size of a machine increase. One is that the pole number, $p$ is kept constant and that the geometry of the poles and slots change. Another one is that $p$ changes and that the pole/slot geometry is kept constant. The procedure of optimally designing a generator is very tedious. The magnetic loading and electrical loading are optimised and optimised again with small changes of the design. Changing the geometry of the slots and poles means that a whole new optimisation process needs to be put in place. The benefit of scaling an already existing machine is to avoid such a tedious process of starting the electromagnetic design from scratch. With this in mind it is considered to be safe to assume that the geometry of the poles and slots of a reference machine are kept constant when the machine is being scaled, and rather that the pole number increases. This assumption also implies that the thickness of the electromagnetic layer, $t_{em}$ is constant. This is shown in Figure 4.

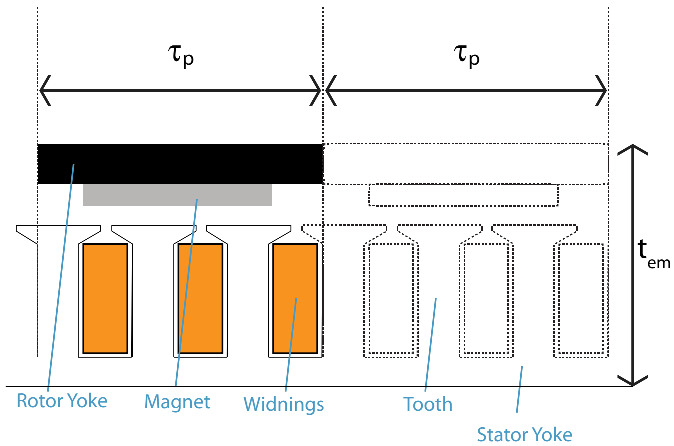



Fig. 4. Relation between pole number and diameter. When the diameter increase such that the circumferential length increase with two pole pitches, another pole pair is assumed to be added to the machine. The thickness of the electromagnetic layer, $t_{em}$ can then be considered kept constant.

### D. Internal Geometry of PGM

The parameters of the internal geometry of a machine are defined in Figure 5 and are calculated as follows. The number of poles are given by

$$p = \frac{\pi D_{ag}}{\tau_p} \tag{17}$$

where $\tau_p$ is the pole pitch. Total number of slots in the stator:

$$Q = pmq, \tag{18}$$

where $m$ is number of phases and $q$ is number of slots per pole and phase.
Slot pitch is

$$\tau = \frac{\tau_p}{mq} \tag{19}$$

The slot is described by its depth $h_s$ and its width $b_s$. The slot width can be calculated from the slot pitch and tooth width $b_d$ as

$$b_s = \tau - b_d \tag{20}$$

The winding height for one layered windings is the slot depth minus the tooth tip as shown i Figure 5.

$$h_{s3} = h_s - h_{s1} - h_{s2} \tag{21}$$

The conductor height $h_{Cu}$ and width $b_{Cu}$ are determined by the winding height, slot width and the coil insulation thickness $h_i$:

$$h_{Cu} = h_{s3} - 2h_i \tag{22}$$

and

$$b_{Cu} = b_s - 2h_i. \tag{23}$$

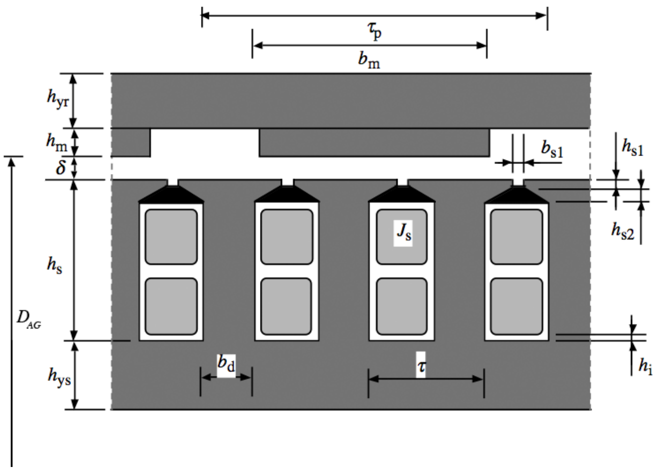



Fig. 5. Generator internal geometry [10]

The width of the permanent magnets is estimated from the ratio of magnet width to pole pitch, $k_m$.

$$b_m = k_m \tau_p \tag{24}$$

[10] gives a range for $\alpha_{PM}$ from 0.6 to 0.9.

The electrical frequency of the stator at rated speed, $n_N$, is

$$f = \frac{p n_N}{120} \tag{25}$$

with $p$ as the number of poles. The air gap should be small to minimise the amount of permanent magnets needed for producing the needed flux density. The mechanical stiffness and the thermal expansion of the generator limits the minimum air gap which can be used. A common estimation [10], [12] of the air gap thickness, which ensures that mechanical stiffness and thermal expansion are accounted for, is

$$\delta = 0.001 D_{ag}. \tag{26}$$

### E. Losses

When calculating the losses of a PMG, there are four main contributors. These are the resistive losses, $P_{cu}$, iron losses, $P_{fe}$, permanent magnet losses, $P_{pm}$ and some additional losses $P_{ad}$. In general, the resistive losses and the iron losses are the largest by far. $P_{cu}$ originates in the windings of the generator and the $P_{fe}$ in the core due to hysteresis and eddy currents.

The division of losses in relation to the input power will be different for varying design and output power. An approximate division in two different generators is shown in Table I. Due to difficulties with finding an overview of losses for PMGs, the table includes an induction generator (IG) from [12]. Since the rotor designs of a PMG and an IG are very different this is not optimal for mapping the losses of a PMG. In short the rotor of a PMG is excited by permanent magnets, whereas the induction generator uses windings. However, the stator designs are similar. Therefore the loss in the stator winding of the IG, $P_{cu,s}$ is comparable to the $P_{cu}$ of the PMG. $P_{fe}$ is very much dependant on

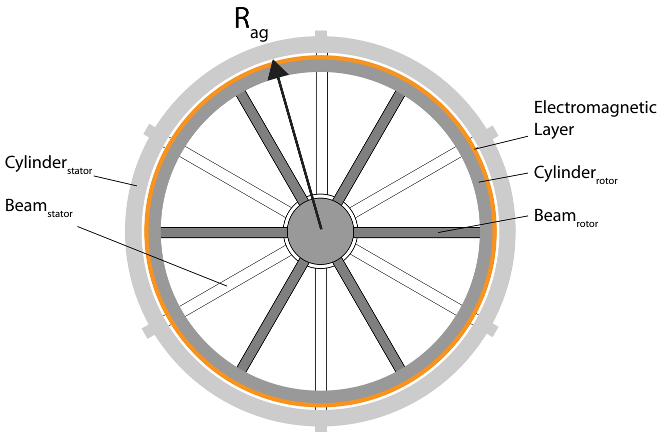



Fig. 6. Rotor and Stator Configuration of PMG. Electromagnetic layer in orange. $R_{ag}$ is air gap radius

the design and less comparable in this case, but a sense of the order of magnitude can be established. The additional losses of the PMG are included in the $P_{pm}$. What can be seen from the table is that the total losses of the PMG is clearly lower than the IG. This correlates with the claim in the introduction of this thesis, that the efficiency of PMGs are higher than that of IGs. One of the reasons for this is that the loss from rotor field excitation is lower. This can be observed by comparing $P_{pm}$ of the PMG with $P_{cu,r}$ of the IG.

*1) Resistive Losses:* Resistive losses are present in the windings of the generator. and is given by

$$P_{cu} = mI^2 R_{AC} \tag{27}$$

Where $m$ is the number of phases, $I$ is the RMS phase current and $R_{AC}$ is the alternating current resistance. $R_{AC}$ has the same order of magnitude as the direct current resistance, but due to skin effect $R_{AC}$ is larger than $R_{DC}$. The skin effect makes $R_{AC}$ a function of the frequency and winding dimensions. For given dimensions and frequency the relation between $R_{AC}$ and $R_{DC}$ can be assumed proportional [6].

$$R_{DC} = \frac{N l_{av}}{\sigma_{cu} A_{cu}}. \tag{28}$$

$$R_{AC} = k_{AC} R_{DC} = k_{AC} \frac{N l_{av}}{\sigma_{cu} A_{cu}} \tag{29}$$

Where $k_{AC}$ accounts for the skin effect and in [6] $k_{AC} = 1.2$. $N$ is the number of turns, $l_{av}$ is the average length of the turn and $A_{cu}$ is the cross-sectional area of the conductor.

*2) Iron Losses:* The iron losses are present in the laminated steel of the rotor and stator. The contributors are the hysteresis losses and the eddy current losses. Obtaining a simple, analytical expression for the iron losses is very difficult since it depends on many factors, such as material properties, frequency, harmonic contents in the flux density etc. In [34] an analytical expression is given for the iron loss density with a sinusoidally varying magnetic flux density and angular frequency, $\omega$,

TABLE I
DIVISION OF LOSSES IN IG AND PMG AT RATED LOAD. LOSSES IN % OF $P_{tot}$

| Loss [% of $P_{tot}$] | 4 kW IG [12] | 50 kW PMG [33] |
|---|---|---|
| $P_{cu,s}$ | 6.9 | 6.0 |
| $P_{cu,r}$ | 4.7 | N/A |
| $P_{pm}$ | N/A | 1.4 |
| $P_{fe}$ | 1.9 | 1.0 |
| $P_{ad}$ | 1.5 | - |
| $P_{loss,tot}$ | **15** | **8.4** |

$$p_{fe} = p_h + p_e = k_h B^\beta \omega + k_e B^2 \omega^2. \tag{30}$$

Where $k_h$ and $k_e$ are hysteresis and eddy current coefficients and $\beta$ is the Steinmetz constant, all of which depend on the lamination material. The lamination manufacturer will normally give these data. In [34] they have the following values: $k_h = 50$, $k_e = 0.06$ and $\beta = 1.9$.
Using eq. (30), the total iron losses will be

$$P_{fe} = p_{fe} V_{fe} \tag{31}$$

*3) Permanent Magnet Losses:* The losses of a permanent magnet is due to eddy currents. According to [12] the resistivity of sintered neodymium magnets is about 110-170 $10^8 \Omega m$. This is 5-10 times the resistivity of steel, and the magnets are thus conductive. And eddy current losses are produced under alternating fields. Theses losses are a function of frequency and thus the most contributing frequencies are the high frequency of switching harmonics from a frequency converter or slot harmonics.

The effect of different harmonic frequencies on the magnet losses is complicated. And because the permanent magnet losses are contributing very little to the total losses, a rough estimation can be applied in stead. This involves using an empirical loss density factor, $p_{pm}$ which depends on the mentioned harmonics. The PM losses can now be written as

$$P_{pm} = p_{pm} S_{pm} = p_{pm} p b_m l_m \tag{32}$$

$p$ being the number of poles and $b_m$ and $l_m$ being the width and length of the magnet. Because of $l_m$ being large compared to the slot pitch, $\tau_s$, the assumption of only axial eddy currents simplifies the expression by only taking into account the radial surface area of the magnet, $S_{pm}$. The value of $p_{pm}$ for a generic PMG is in [10] equal to 300 $W/m^2$.

*4) Additional Losses:* The additional losses are the remaining losses when all other losses are accounted for. They are very hard to measure or calculate. In the electromagnetic respect, [10] lists the additional losses of a PMG as losses due to slot leakage flux, losses due to end leakage flux, short-circuit iron losses due to the armature mmf and rotor pole face losses.

In this thesis the mechanical losses are also included in the additional losses. That is windage losses and friction losses. Because of their small contribution to the total losses ($\approx 0.01P_{tot}$) this is deemed reasonable.

## IV. Theory of PMG Scaling

### A. Scaling Length and Diameter

The chosen main geometric parameters of the scaling laws in this thesis is the active length, $l$, in the axial direction and the air gap diameter, $D_{ag}$. $l$ is the length of the rotor, excluding the frame. These parameters can be used to determine the volume of the generator and thus also its weight. The shape of the machine is also given by these parameters combined with their correlation parameter or the so called aspect ratio, $k_{AR}$:

$$k_{AR} = \frac{l}{D_{ag}} \tag{33}$$

The scaling of the length and diameter depends on the philosophy behind the scaling. Specifically if the aspect ratio is kept constant or not.

If the aspect ratio is kept constant, the scaling of length and diameter is straight forward. Eq. (33) gives

$$\frac{l_1}{D_{AG,1}} = \frac{l_2}{D_{AG,2}} \tag{34}$$

If the aspect ratio is not kept constant during the scaling of the machine, eq. (33) can no longer be used and the scaling becomes more difficult. One approach is to keep the generator power constant and only change the length and diameter for a given power level. By use of the rotor volume, $V_r \approx \frac{\pi}{4}D_{ag}^2 l$, eq. (40) can be written as

$$P = \sigma_{F,tan}\frac{\pi}{2}D_{ag}^2 l\omega. \tag{35}$$

Again keeping power, speed and force density constant, one can now see that

$$D_{AG,1}^2 l_1 = D_{AG,2}^2 l_2 \tag{36}$$

### B. Scaling of Power

The power of an electrical machine can be defined as

$$P = \tau\omega \tag{37}$$

where $\omega$ is either the angular frequency of the stator or the angular speed of the rotor depending on whether the electrical or mechanical power and torque is being calculated.

When scaling the output power of a machine it is useful to start with defining the torque of the rotor.

$$\tau_r = \sigma_{F,tan} S_r R_r \tag{38}$$

where $\sigma_{F,tan}$ is the tangential component of the force density or stress as defined in the Section III and $S_r$ is the cylindrical surface area of the rotor. $R_r$ is the rotor radius. By using $S_r = 2\pi R_r l$, the torque can be written in terms of rotor volume

$$\tau_r = \sigma_{F,tan} 2V_r. \tag{39}$$

The power can now be written as

$$P = \sigma_{F,tan} 2V_r\omega \tag{40}$$

For a given wind turbine, the rated rotational speed, $\omega$, is already decided by the turbine designers. Assuming that the scaled generator is to be used in the same wind turbine as the original generator, the rated speed is kept constant. The speed could have been adjusted by inserting a gear, and there are some commercial hybrid solutions like this. However, in this thesis the PMG is direct drive i.e. with gear-less drive trains the rated speed is kept constant.

The force density depends on the relation between the magnetic loading and the electric loading of the generator. This is elaborated in Section III-C. It is assumed that the force density is fine tuned in the original design of the generator, and that as the generator is being scaled up or down, the force density is kept constant. The above arguments show that the power of the generator can be scaled proportionally with the rotor volume:

$$P = k_P V_r \tag{41}$$

$$\frac{P_1}{V_{r,1}} = \frac{P_2}{V_{r,2}} \tag{42}$$

### C. Scaling of Frequency

The electrical frequency of a PMG is given by

$$f = \frac{p}{120}n, \tag{43}$$

where n is the rotational speed of the rotor and $p$ is the number of poles. When the generator increases in size, either $p$ can be kept constant and the slot and or pole geometry change, or $p$ increase and the slot/pole geometry is constant. In this thesis it is assumed that $p$ increases with the diameter and that the slot/pole geometry is constant.

$$p = \frac{\pi D}{\tau_p}, \tag{44}$$

where the pole pitch, $\tau_p$ is assumed to be kept constant for optimum designs, as elaborated in Section III-C. Combining eq. (43) and (44) results in the following relation for the frequency:

$$f = \frac{\pi D}{120\tau_p}n, \tag{45}$$

### D. Scaling of Mass

The mass scaling model is based on the work of [19] on scaling of radial flux PMGs. As this scaling is more complex, the details are given in the Appendices.

*1) Electromagnetic components:*
The electromagnetic components consists of the stator yoke and teeth, the copper of the windings, the permanent magnets and the rotor yoke. As with the length and diameter two procedures are used; one where the aspect ratio is kept constant and the output power is varied, and one where the output power is kept constant and the aspect is ratio varied.

For a constant aspect ratio the final result i given in eq. 73 which states the following

$$\frac{m_{em1}}{m_{em2}} = \frac{P_{gen1}}{P_{gen2}}. \tag{46}$$

For a varying aspect ratio, the final result is the following

$$\frac{m_{em1}}{m_{em2}} = \sqrt[3]{\frac{k_{AR1}}{k_{AR2}}} \tag{47}$$

*2) Structural Components:*
Both the stator and rotor comprise of a cylindrical ring and beams to support the cylindrical ring and transfer the torque as shown in Figure 6. Both of these elements are assumed to be made of cast iron. The cylindrical rings holds the electromagnetic parts i.e. the copper and core of the machine as well as the permanent magnets. The structural weight is divided into two components. These are the structural cylinder weight, $m_{cy}$ and beam weight $m_{beam}$.

For a constant aspect ratio the final result is given in eq. (79) and (84) which states the following

$$\frac{m_{beam1}}{m_{beam2}} = \frac{P_{gen1}^{1.75}}{P_{gen2}^{1.75}} \tag{48}$$

$$\frac{m_{cy1}}{m_{cy2}} = \frac{P_{gen1}^{1.5}}{P_{gen2}^{1.5}}. \tag{49}$$

For a varying aspect ratio, the final result is given by

$$\frac{m_{beam1}}{m_{beam2}} = \frac{k_{aspect2}^{11/12}}{k_{aspect1}^{11/12}} \tag{50}$$

$$m_{cy1} = m_{cy2} \tag{51}$$

*3) Total Mass:*
The total weight of the generator for both constant aspect ratio and variable aspect ratio is

$$m_{tot} = m_{em} + m_{cy} + m_{beam} \tag{52}$$

Keep in mind that the weight of the cooling system is not incorporated in this calculation and has to be added to the total weight. For a commercial 3 MW PMG, where the data is available to the Thesis Author, the weight of the forced air cooling system is one ton. Due to competitive considerations the supplier will not be reviled.

### *E. Scaling of Losses*

As elaborated in Section III-E, the losses of a PMG consists of resistive losses, $P_{cu}$, iron losses, $P_{fe}$, permanent magnet losses, $P_{pm}$, and some additional losses, $P_{ad}$. As shown in the Table I the main contributor is the resistive losses and iron losses. Copper losses are located in the stator windings and the iron losses are located in the stator yoke and teeth and in the rotor yoke. Because the length of the air gap is very small, and the air gap diameter is very large in PMGs, the radial length from the centre of the PMG to the stator and rotor are not very different. In this thesis the losses of the generator is therefore modelled as a specific loss, $p_{ring}$, to be located in a electromagnetic layer in the air gap. This layer is thought to consist of both the windings, magnets and magnetic core of the machine. This electromagnetic layer can be seen in Figure 6.

$$P_{loss} = p_{ring} V_{em} = p_{ring} \pi D_{ag} l t_{em} \tag{53}$$

Where $V_{em}$ is the volume of the electromagnetic layer. As elaborated in Section III-C the thickness of this layer, $t_{em}$ is thought to be constant as the machine changes in size.

$$P_{loss,ring} = k_{ring} \pi D_{ag} l = k_{ring} A_{ag} \tag{54}$$

where $k_{ring} = p_{ring} t_{em}$. Now the scaling of the loss is given by

$$\frac{P_{loss,ring,1}}{P_{loss,ring,2}} = \frac{A_{ag,1}}{A_{ag,2}} \tag{55}$$

## V. Key Parameter Estimation

The Key Parameter are parameters which are not directly calculated with scaling laws. Rather they are based on the results of the scaling laws. The parameters are used as a good measure for comparing different machine designs. The Key Parameters of this thesis are the efficiency, the cost, the power density, torque density and heat dissipation factor.

### *A. Efficiency*

The efficiency of the machine is calculated according to IEC standard 60034-1 [11].

$$\eta = \frac{P_2}{P_1 + P_{E1}} \tag{56}$$

Where for a synchronous generator $P_1 = P_{in} = P_{mech}$, is the mechanical power of the shaft, $P_2 = P_{out} = P_{el}$, is the output electrical power and for permanent magnet excitation, the power loss in the excitation circuit, $P_{E1} = 0$.

Since the given reference data from the supplier in most cases will be the output power $P_{el}$ and not $P_{mech}$, the development of a scaling formula for the efficiency will assume that $P_{out}$ is known and that $P_{mech}$ is not. $P_{mech}$ can however be estimated by adding the output power with the total losses of the machine.

$$P_{mech} = P_{out} + P_{loss} \tag{57}$$

Inserting this into eq. (56) gives

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}} \tag{58}$$

The "ring-loss-method" of Section IV-E is implemented in the Scaling Program. Using equation 54 this approach gives

$$\eta = \frac{P_{out}}{P_{out} + P_{loss,ring}} \tag{59}$$

### B. Heat dissipation factor

The heat dissipation factor tells how much heat that has to be dissipated through the external surface area, $S_{ext}$, of the generator. It is useful for comparing temperature rise of different designs, and to give an indication on which kind of cooling that needs to be implemented.

$$P_{diss} = \frac{P_{loss}}{S_{ext}} \tag{60}$$

The higher the value of $P_{diss}$, the more heat per area and the more intensive cooling is needed. For very high $P_{diss}$ liquid cooling might have to be installed.

The heat dissipation factor was not included in the program, but is included as further work.

### C. Power Density

Power density of a machine is the power divided by the mass of the generator. It is also possible to divide it by the volume of the generator, but since the Scaling Program already calculates the total mass, power per volume was not included.

$$P_d = \frac{P}{m_{gen}} \tag{61}$$

The mass of the generator is a critical parameter. The higher the mass, the higher the costs. It is therefore desirable to have a high power density, and thus a large power produced per unit mass.

### D. Torque density

Torque density of a machine is the torque divided by the mass the generator.

$$\tau_d = \frac{\tau}{m_{gen}} \tag{62}$$

A high torque density implicates that the torque produced per unit mass is high. A high torque density is desirable if the rotational speed is low, so that the product of torque and speed still can yield a large power (eq. (37)). This is the case for direct drive PMGs, which is why one will find direct drive generators in the lower right corner of the State of the Art map in the Scaling Program.

TABLE II
SPECIFIC COSTS OF ACTIVE PARTS [29]

| Cost parameter | Nominal value |
|---|---|
| $c_{Cu}$ | 27 €$/kg$ |
| $c_{Fe}$ | 16 €$/kg$ |
| $c_m$ | 80 €$/kg$ |

### E. Cost Estimation

The active material cost consist of the direct costs of the parts of the machine which are carrying current or contributing to creating or transporting the magnetic flux. It is assumed that the stator core consists of stacks of standard magnetic steel sheets (e.g. M400-65A). The material cost of the active parts is estimated from the mass of the active materials. The following formula is used:

$$C_{act} = c_{Cu}m_{Cu} + c_{Fe,c}m_{Fe,c} + c_m m_m, \tag{63}$$

where $c_{Cu}$, $c_{Fe,c}$ and $c_m$ are the specific costs of copper, magnetic steel sheets of the core, and magnets, respectively. $m_{Cu}$, $m_{Fe,c}$ and $m_m$ are naturally the masses of the copper, steel and magnets, respectively. The values for the specific cost of the different materials are collected from [29] and reproduced in Table II.

Assuming that the same structure as presented in Figure 6 is used, the following formula can be used for estimating the cost of the structural mass:

$$C_{str} = c_{Fe,str}(m_{cy} + m_{beam}) \tag{64}$$

Keep in mind that material costs are subject to change. For instance, in the sources investigated for material prices, the cost of PMs has ranged from 25 $EUR/kg$ to 80 $EUR/kg$. The user of the scaling program should investigate the updated material prices when evaluating the accuracy of the cost estimation. The user can also easily change the specific cost of the materials in the program.

## VI. GUIDE

### A. General introduction to GUIDE

There are two ways of building a Graphical User Interface in Matlab. The first way is to use Matlab's own interactive construction kit, GUIDE (GUI Development Environment). The second way is to create code files that generate GUIs as functions or scripts; this is called programmatic GUI construction.

For detailed information about creating a Matlab Graphical User Interface the reader is recommended to investigate the "MATLAB Graphical User Interface" created by the MathWorks Inc. [23] and the "Introduction to MATLAB Graphical User Interfaces" created by the Australian Department of Defence [20]. These two manuals have been indispensable in the work of this project; [20] as a tutorial and [23] as a look-up table and complete manual.

### B. The Choice of GUIDE instead of Programmatic GUI

In this paper the MATLAB GUIDE construction kit was chosen as the preferred tool for creating the graphical user interface. This is because it is a good enough tool for achieving the purpose of this paper: the GUI of this project is considered to be ”moderately complex”, and according to [23] GUIDE is suitable for creating such a GUI. Also, the combination of a What You See is What You Get environment combined with programmatic fine tuning makes it a good tool for beginners. All in all, GUIDE is deemed sufficient for fulfilling the purpose of this project.

## VII. Scaling Program

The layout of the resulting Scaling Program from this project can be seen in Section VII-E. The following section will be a walkthrough of the functionality of the different aspects of the Scaling Program. The theory behind the calculations can be studied in Section II.

### A. Generator Scaling Interface

The first interface of the program is called the Generator Scaling Interface. Here the user can choose input from an already defined reference generator and calculate parameters as a function of output power. If the user wants to define his or her own reference generator, the Scaling Interfaces in the Scaling Menu should be used.

*1) The Reference Generator:* This panel let’s the user choose a predefined reference generator for the scaling of the machine. Three generators are available, whose data are based on commercial wind turbine generators made available from an industrial partner. Due to competitive considerations the suppliers are anonymised by the tags ”ref1”, ”ref2”, ”ref3”. The machine that is highlighted is used as the reference generator for the scaling script. A summary of the machine details is displayed in the table.

*2) The Scaled Generator:* The scaling of the predefined reference generator takes place in the Scaled Generator Panel. Under ”User input” the user chooses the wanted rated power. Under ”Calculated Values” some key parameters of the scaled version of the reference machine are displayed. The calculated values are the active length and air gap diameter of the generator, total mass, active mass and inactive mass. The length and diameter is calculated with a constant aspect ratio.

*3) Cost Estimation:* The cost of the different parts of the generator can be calculated in the cost panel. Here the specific cost of the materials can be set by the user. Due to highly fluctuating prices of permanent magnets specifically, this is considered a necessity. The division of the cost of active parts is done based on the value of the global parameters $k_{Cu}$, $k_{Feys}$, $k_{Feyr}$ and $k_{PM}$. They represent fractions of the total mass for copper, stator yoke and teeth, rotor yoke and permanent magnets, respectively. The standard values are based on data from Blaaster Wind Technologies. Due to time restrictions the cost estimation is unfortunately not implemented in the other Scaling Interfaces with user defined reference machine. This is suggested as further work.

*4) The Scaling Menu:* More Advanced Scaling Interfaces can be chosen from the Scaling Menu. In each Interface, the relevant reference data is defined by the user. The interfaces have two panels; one calculation panel and one graphing panel. The graphing panel is meant to give a visual comparison of the different generators.

*5) The State Of the Art Map:* The map is from [29] where Zhaoqiang Zhang has conducted a comparison of the state of the art designs within generators for wind turbines. Mr. Zhang has compared the power density and torque density of over 90 Wind Power Generators. It is an excellent tool to evaluate the goodness of a generator design. Zhang writes the following about the map:

> ”Most of these generators are commercial iron-cored PMGs, some are academic designs, and the drive trains include multi-stage and direct-driven solution. [...] Note that this map shows only the best available designs from each power range. The generator speed is not indicated in the map, but it is possible to find the corresponding speed of the plotted generators on the map, and it is easy to conclude that low-speed machines will tend to lie on the lower right, and high-speed machines on upper left. An area, which clearly demonstrates the technology limitations, is marked out to represent today’s technology frontier. Some declared coming designs (e.g. superconducting generators) on the lower right corner of the map (i.e. in the low speed region) look very promising. This map can be used to evaluate the goodness of any generator design. The designs located to the right and up relative to the area will stretch the technology limits, whereas the designs to the left and down relative to the area will be worse than the state of the art.”

Additionally the torque density and power density of a generator can be plotted in the map. This was originally thought to be calculated in the Scaling Interfaces, but due to time restriction this was not implemented and a version of the beta functionality where the user inserts these values himself was kept. By using the theory of Section V the user should be able to calculate the torque density and power density of the scaled machines from the output of the Scaling Interfaces. The implementation of the automatic calculation is recommended as further work.

*6) The Global Parameters:* In the MATALB code of the Generator Scaling Interface, the global parameters of Table III are defined. These parameters control the division of mass, and the ranges of plots.

TABLE III
GLOBAL PARAMETERS USED IN SCALING PROGRAM

| Parameter | Value | Description |
|---|---|---|
| **Mass** | | |
| $k_{act}$ | 0.45 | Ratio of active mass over total mass<br>Source: [19] |
| $k_{cy}$ | 0.50 | Ratio of cylinder mass over total mass<br>Source: [19] |
| $k_{Cu}$ | 0.295 | Ratio of copper mass over active mass<br>Source: Industrial Partner |
| $k_{Feys}$ | 0.385 | Ratio of stator yoke and teeth mass over active mass<br>Source: Industrial Partner |
| $k_{Feyr}$ | 0.260 | Ratio of rotor yoke over active mass<br>Source: Industrial Partner |
| $k_{PM}$ | 0.06 | Ratio of permanent magnet mass over active mass<br>Source: Industrial Partner |
| ***Losses*** | | *(As suggested in further work)* |
| $k_{ad}$ | 0.2 | Ratio of $P_{ad}$ over $P_{cu}$ and $P_{fe}$<br>Source: [10] |
| $k_{fc}$ | 0.167 | Ratio of $P_{fe}$ over $P_{cu}$<br>Source: [33] |
| **Plot Ranges** | | |
| $k_l$ | 0.5 | Allowed Change of Length |
| $k_D$ | 0.2 | Allowed Change of Air Gap Diameter |
| $n$ | 20 | Resolution of Plot |

## B. Mass Scaling Interface

In the Mass Scaling Interface the user can calculate the mass of a user defined reference generator. The interface has two panels; one calculation panel and one graphing panel. In the calculation panel the user may set the reference data to be used for calculation of the generator mass. An option to chose a constant aspect ratio or a variable aspect ratio is available and depending on the choice, the mass will be calculated as elaborated in Section IV-D The layout of the Mass Scaling Interface is shown in figure 8.

There are two plots available. One where a constant aspect ratio is used and one where a variable aspect ratio is used. For the constant aspect ratio, the mass is plotted for power levels from 1 to 10 MW. For the variable aspect ratio, the mass is plotted from 0.05 to 1.00. Since it is difficult to verify a scaling law, it is also difficult to know for which ranges the mass can be plotted. The used ranges are considered to be a realistic scope for this scaling interface based on the discussion of [19]. The plots can be used by the user to see the estimated division of masses for different power levels (constant aspect ratio) or different aspect ratios (constant Power).

## C. Efficiency Scaling Interface

In the Efficiency Scaling Interface the user can estimate the change in efficiency of a user defined reference generator. In the calculation panel, the parameters of the reference machine can be set. These are output power, efficiency, active length and air gap diameter. The standard efficiency is set to $\eta_0 = 95.5\%$, which is the rated load efficiency for low speed generators PMG in [31]. Based on the reference data, the volume of the rotor can be calculated as well as the estimated losses. The reference loss is calculated by solving eq. (58) for $P_{loss}$

$$P_{loss,ref} = \frac{P_{out,ref}}{\eta_{ref}} - P_{out,ref} \tag{65}$$

The scaled loss and efficiency are then calculated based on the theory presented in Section IV-E and Section V-A, respectively. The "ring-loss-method" is used to scale the losses.

The graph shows the estimated efficiency for the reference generator as well as the efficiency of the scaled generator. This can be used to compare estimated efficiencies of two different generators. The graph is only plotted for what is assumed realistic ranges for the length and diameter. This is due to uncertainty of validity for the constant force density for large changes in diameter and length. For the diameter the range is set to a 20 % change from the reference diameter and for the length this is set to 50 % change from the reference length. This is controlled by the global parameters $k_l$ and $k_D$, which are used in the $ranges.m$ script. The layout of the Efficiency Scaling Interface is shown in figure 10.

## D. Power Scaling Interface

Here the user can calculate the power of a user defined reference generator in terms of length and air gap diameter. The theory behind the calculation is presented in Section IV-B.

The new calculated power can be plotted and compared with the given reference generator. The range of the plots are fixed to [0-3]m for the rotor length and [0-10]m for the air gap diameter. These maximum values are too high to be realistic for commercial PMGs. The values gives a possibility of an output power of 40 MW. The largest output power for commercial wind turbines is 8 MW. However the wide range gives the user a possibility to try out the extremes. The layout of the Power Scaling Interface is shown in figure 9.

### E. Program Layout

The following section shows the layout of the Scaling Program.

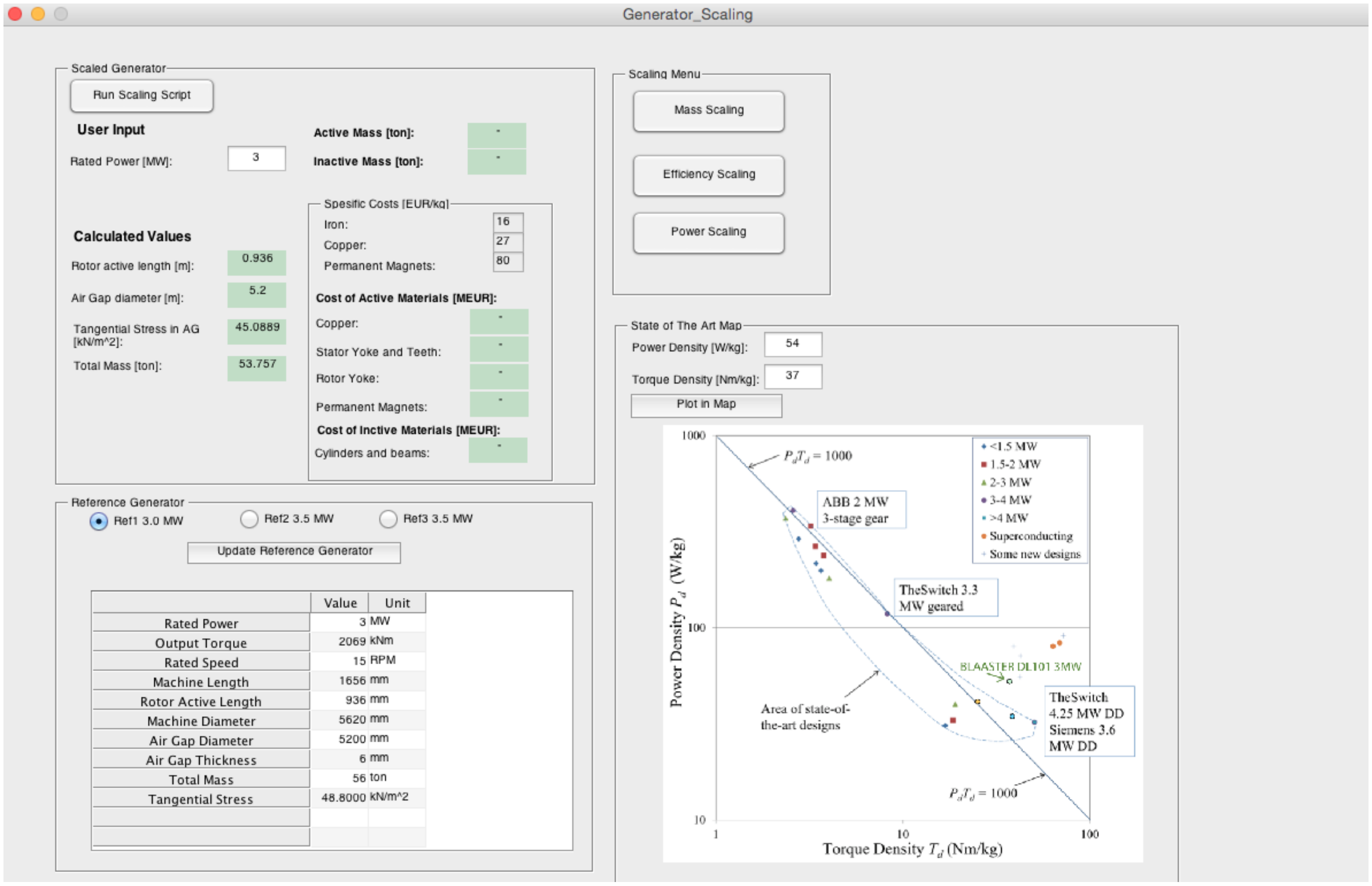



Fig. 7. Generator Scaling Interface. For scaling of predefined reference generators and torque and power density comparison with state of the art generators.

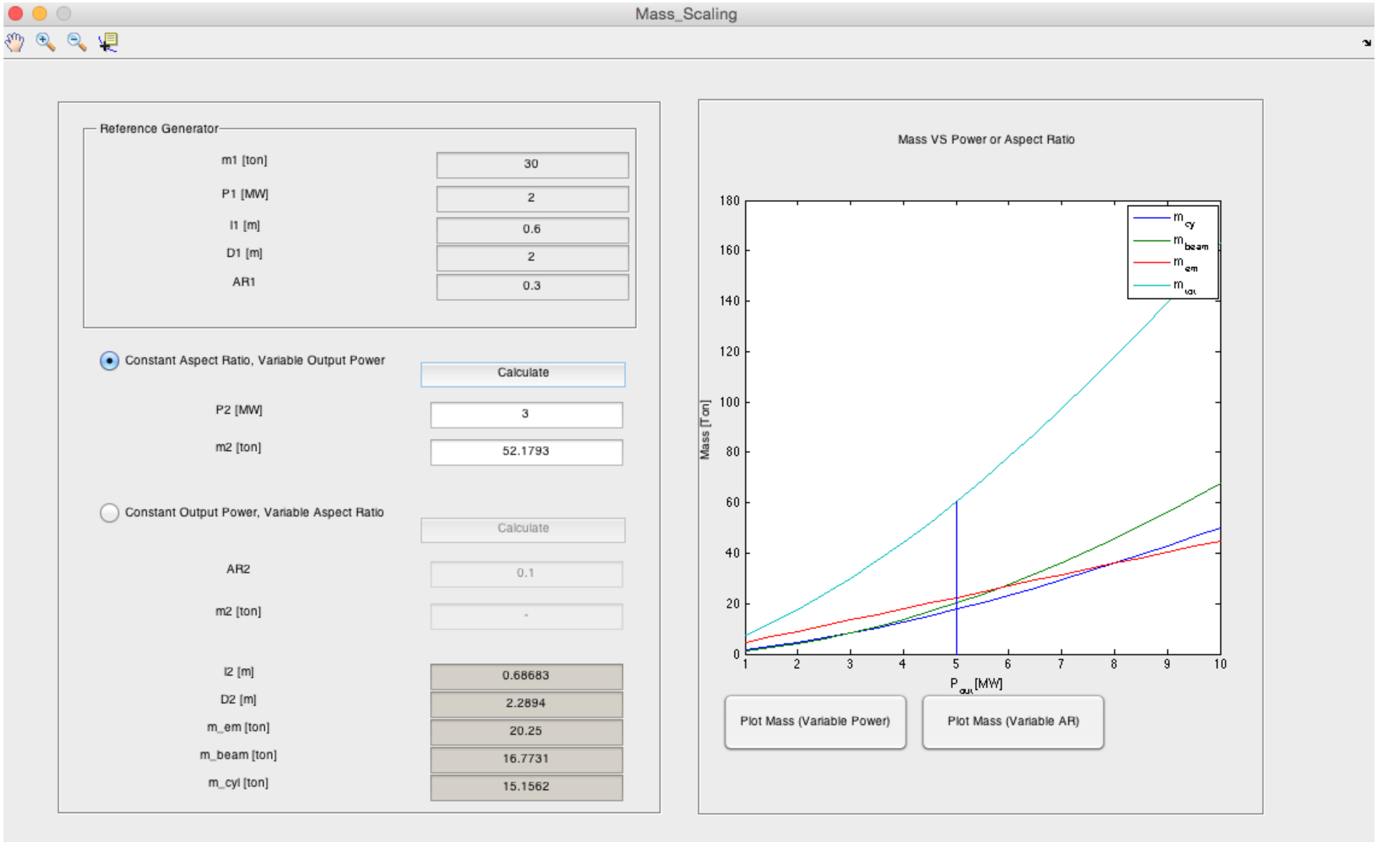



Fig. 8. Mass Scaling Interface. $P$ is output power. $l$ is active length, $D$ is air gap diameter, $AR$ is aspect ratio, $m$ is total mass, $m_{em}$ is mass of electromagnetic components. $m_{beam}$ is mass of structural beam. $m_{cyl}$ is mass of structural cylinder.

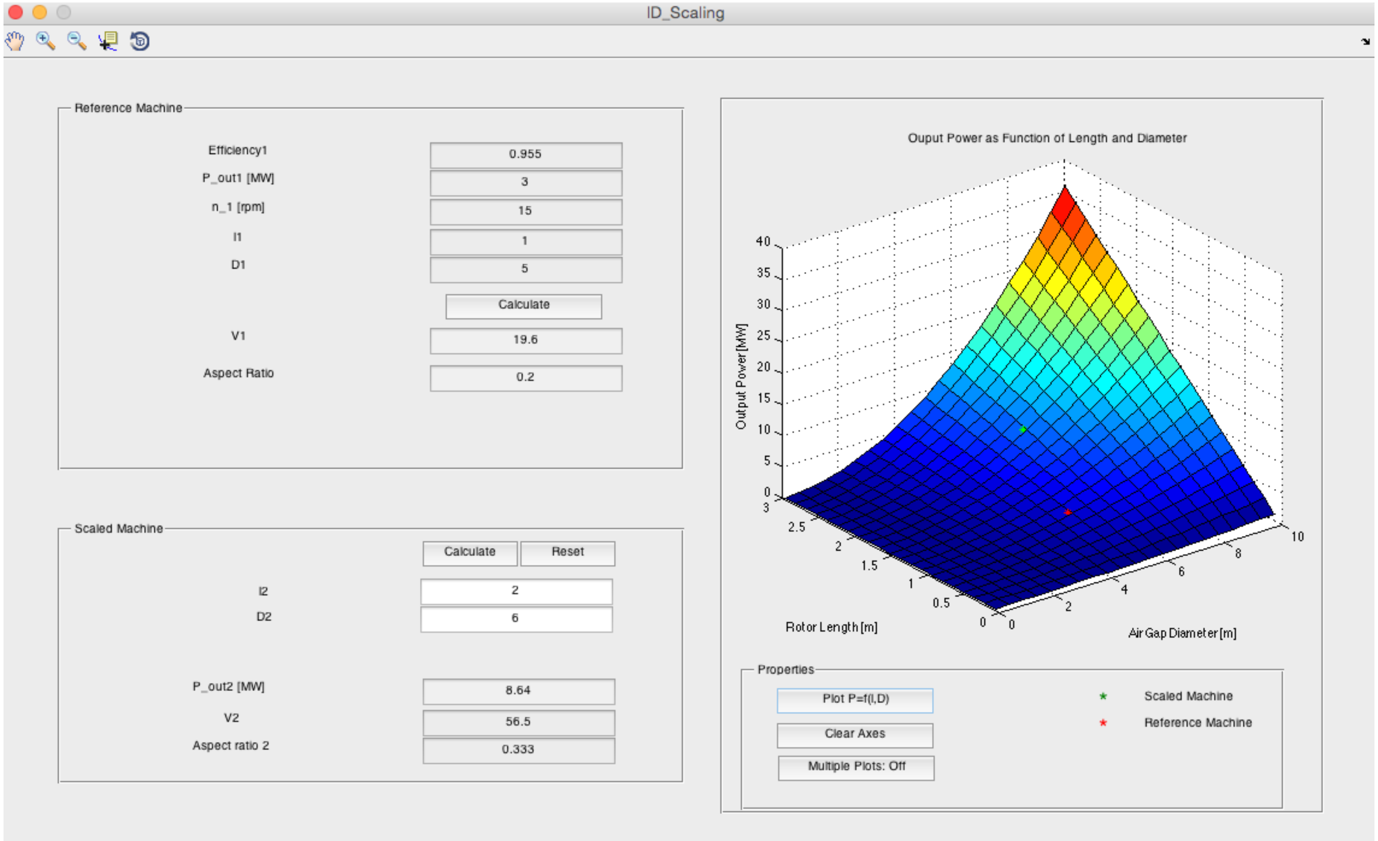



Fig. 9. Power Scaling Interface. $P_{out}$ is output power. $n$ is rotational speed. $l$ is active length, $D$ is air gap diameter. V is volume of rotor.

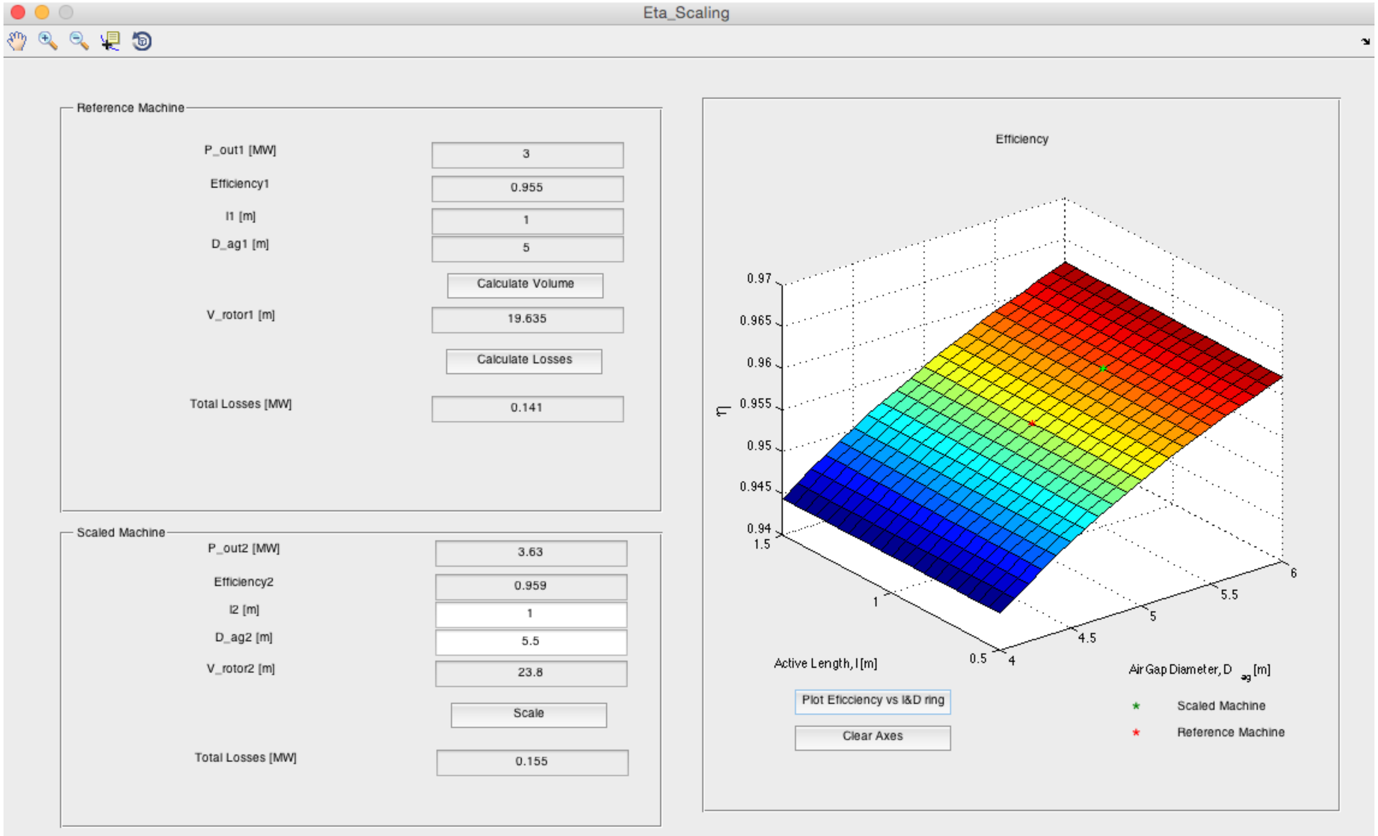



Fig. 10. Efficiency Scaling Interface

TABLE IV
INITIAL VALUES OF EXAMPLE REFERENCE MACHINE

| Parameter | Value | Unit |
|---|---|---|
| **Rated Power, $P_{out,1}$** | 2 | MW |
| **Rated Efficiency, $\eta_1$** | 0.955 | - |
| **Mass, $m_{gen,1}$** | 30 | ton |
| **Length, $l_{gen,1}$** | 0.6 | m |
| **Airgap Diameter, $D_{ag,1}$** | 2 | m |
| **Aspect Ratio, $k_{AR,1}$** | 0.3 | - |

## VIII. PRACTICAL EXAMPLE OF MASS SCALING INTERFACE

In the following section a practical example of the Mass Scaling Interface is introduced. The user is encouraged to work with the program independently, the example will work as a suggested approach only. An example reference generator is defined in Table IV.

The Mass Scaling Interface is divided into two parts. One part for constant aspect ratio and variable output power, and one part with variable aspect ratio and constant power.

A suggested use of the mass scaling interface is for testing different aspect ratios. It is not certain that the aspect ratio of the first generator is the best choice when the power is increased. One possible way of doing this is to first decide a new power level using the constant aspect ratio option, this gives a new mass, length and air gap diameter. Then the variable aspect ratio script can be used to find an optimum aspect ratio in terms of mass. The new aspect ratio can be adjusted until the new mass is at a minimum.

### A. Stepwise approach

First the relevant values of the example generator (Table IV) is input in the reference data. The new rated power of the upscaled generator, $P_2$, is chosen to be be 3 MW. When the calculate button is pressed, the new values are given as shown in Table V. The table shows that the mass is estimated to increase from 30 ton to 52.15 ton with the increase in power. The length is estimated to increase to 0.687 m and the air gap diameter is estimated to increase to 2.289.

Now the variable aspect ratio option can be used to investigate whether a better aspect ratio for the given power level is possible to achieve. First the data of the Reference Generator must be changed to that of Table V. When this is done, the ”Constant output power, variable aspect ratio” option is chosen. Finally the new aspect ratio to be investigated can be input and the calculate button pressed.

If one keep the aspect ratio of 0.3, the graph (Figure 11b) indicates that an aspect ratio of 0.4 can give a lower total mass. With some experimentation, a value for the aspect ratio of 0.45 is found to give a mass of 51.12 ton, which is 2% lower than the original mass for 3 MW of 52.18 ton.

The new length and diameter of the generator is not calculated by the software because it would need either the length or the diameter to be restricted. If the user chooses to keep the diameter constant, $D_3 = D_2 = 2.289$m. The new length can be calculated by using eq. (33): $l_3 = 1.03$m

The scaled generator of 3 MW now has the expected data of Table VI.

TABLE V
SCALING OF MASS OF EXAMPLE REFERENCE GENERATOR, CONSTANT ASPECT RATIO

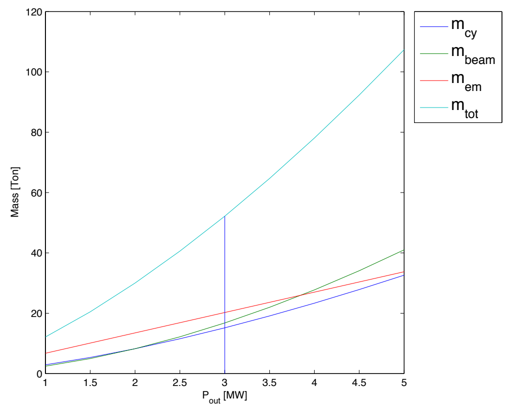
| Parameter | Value | Unit |
|---|---|---|
| **New Rated Power, $P_2$** | 3 | MW |
| **Scaled Total Mass, $m_2$** | 52.18 | ton |
| **Scaled Length, $l_2$** | 0.687 | m |
| **Scaled Diameter, $D_{ag,2}$** | 2.289 | m |
| **Aspect Ratio, $k_{AR,2}$** | 0.3 | - |

TABLE VI
SCALING OF MASS OF EXAMPLE REFERENCE GENERATOR, VARIABLE ASPECT RATIO

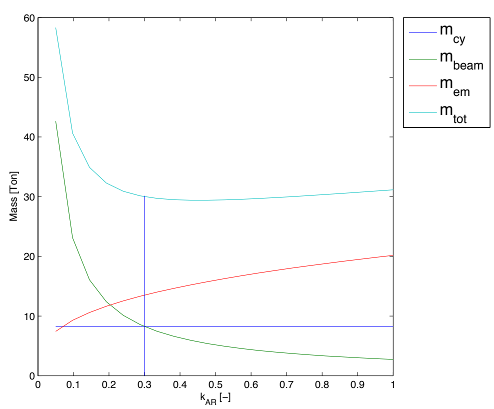
| Parameter | Value | Unit |
|---|---|---|
| **New Rated Power, $P_3$** | 3 | MW |
| **Scaled Total Mass, $m_3$** | 51.12 | ton |
| **Scaled Length, $l_3$** | 1.03 | m |
| **Scaled Diameter, $D_{ag,3}$** | 2.289 | m |
| **Aspect Ratio, $k_{AR,1}$** | 0.45 | - |

## IX. Figures from Scaling Laws

This section contains figures from the scaling of the Example Generator of Table IV.

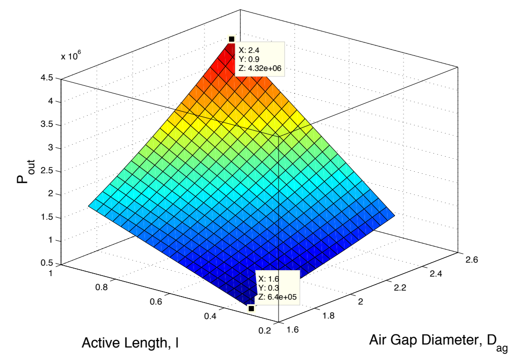



(a) Mass scaling with constant aspect ratio

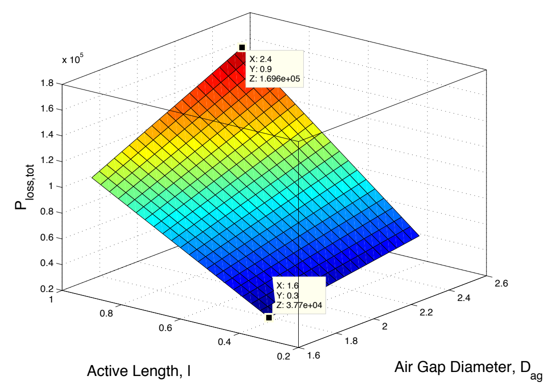



(b) Mass scaling with variable aspect ratio and constant power

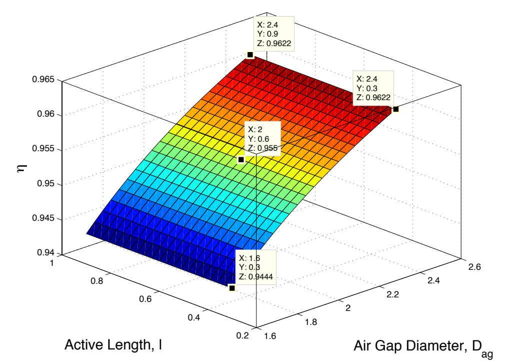
Fig. 11. Mass scaling of example reference generator. Characteristic is similar to that of [19]




(a) Rated Power as function of active length and air gap diameter for example reference machine




(b) Losses as function of active length and air gap diameter for example reference machine




(c) Efficiency as function of active length and air gap diameter for example reference machine

Fig. 12. $P_{out}$,$P_{loss}$ and $\eta$ of example generator

# X. Discussion

## A. Scaled Output Power

From Figure IX, the output power as function of active length $l$ and air gap diameter $D_{ag}$ is shown. The losses are calculated with eq. (42). The surface plot shows a linear dependancy on length and a second order dependancy on diameter. This is as expected, since eq. (42) is a function of the rotor volume, which is linearly dependant on $l$ but dependant of $D_{ag}^2$.

## B. Scaled Losses

From Figure IX, the losses as function of active length $l$ and air gap diameter $D_{ag}$ can be observed. The losses are calculated with eq. (55). The surface plot shows a linear dependancy on both length and diameter. This is as expected, since eq. (55) is a function of the air gap surface area, which has a first order relation to length and diameter. Comparing the loss and output power of a generator with $D_{ag}$ = 2.4m and $l$ = 0.9m shows that the losses are 3.9 % of the output power. Which is a bit low, but reasonable, considering that the efficiency of the example generator was set to be 95.5 %.
The use of the "loss-ring-method" implies that all the individual loss components ($P_{cu}$, $P_{fe}$, $P_{pm}$ and $P_{ad}$) are all proportional to the first order of $l$. Though some of the components may very well be proportional to $l$, it is not considered very realistic that all of them are.
A more accurate loss estimation is thought to be achievable if the individual loss components were scaled as functions of $l$ and $D_{ag}$. From the theory on iron losses as presented in eq. (30) and (31), it is suspected that these losses do not to have a linear relation to both length and diameter. This is based on the fact that the angular frequency of eq. (30) is for a PMG assumed to increase with the diameter, as elaborated in Section IV-C. With that taken into account, the relation to the diameter becomes more complex. An investigation of this relation is recommended as further work.

## C. Estimated Efficiency

As can be seen in Figure IX, the calculated efficiency increases with diameter. This is as expected since the output power increases faster than the losses. With the output power increasing with $D_{ag}^2$, while the losses increase with $D_{ag}^1$. The efficiency does not change with the machine length. Even though eq. (59) definitely consist of components which depend on $l$. The reason is that both the numerator and the denominator of eq. (59) depends on $l$ in the first order. $P_{out}$ is a function of rotor volume and $P_{loss,ring}$ is a function of air gap surface area. Thus the dependancy of length is cancelled.

In terms of improving the efficiency calculation, further development of the calculation of the individual loss components is recommended.
However, though the result might be less accurate, it is still considered to be useful for mapping the trend of the efficiency change of a PMG in relation to length and diameter.

## D. Mass Estimation

It is difficult to determine the accuracy of the mass estimation in the scaling model. The power levels of commercial wind turbine generators today are not very large, thus no data for the mass of multi megawatt commercial generators was available to compare with. What can be said is that the results of the mass scaling for an example generator does resemble those of [19], which the mass scaling is based on. This is a well cited paper.

Since the calculation of the volumes and mass of all components are based on the air gap radius there are naturally errors. For a more accurate calculation, the radial distance to all active and structural elements of the stator and rotor could be been used. However, these radial distances require in depth knowledge about the internal geometry of the machine. This is not always available. The use of air gap radius is therefore considered the best approach. Especially since the relative difference between the air gap radius and the stator and rotor radius is very small.

## E. Scaling Program

The main objective of this thesis was to make an easy-to-use Scaling Program for direct drive PMGs. This objective is considered to be fulfilled. The Scaling Program lets the user estimate key parameters such as price, mass and efficiency of a reference PMG.

There are however still functionality which can be improved. The automated calculation of more comparable parameters, such as torque density, power density and heat dissipation factor. Feedback from testers of the program has said that the Scaling Interfaces can still be made more user friendly. For instance an explanation of the parameters in the program is wanted. So that it can be used independently of the thesis report. This is recommended as further work.

The philosophy of the thesis was that the user should only have to use reference data, which can be expected to be handed over by a generator supplier. At the end the Scaling Program needs the mass and efficiency of the reference generator. These are parameters which are not expected to be handed over by a generator supplier, unless the user bought the generator and got its data sheet. If the program is to be developed further, this challenge of estimating more information with less data is sent to the next developer.
MATLAB GUIDE has proven as a very efficient and useful tool for making a programmable graphical user interface. The possibility of matrix calculation makes it and effective tool for handling large amounts of data. Its versatile handling of graphical objects is especially useful. The possibilities for adding new functionality is also big, considering MATLABs wide range of toolboxes.

## XI. Conclusion

In conclusion, the objective of the thesis is deemed to have been fulfilled. The program is considered to be an easy-to-use tool for scaling direct drive PMGs. The Scaling Program also lets the user estimate key parameters such as price, mass and efficiency of a reference PMG. Though feedback from program testers implies that some more in-program explanation of the input and output parameters would be helpful. This is said to make it easier to use the program independently of the thesis report.

Regarding the scaling laws, the scaling of the output power is according to the theory. With a constant tangential stress, a larger rotor volume increases the output power.

The scaling of the losses are shown to be more crude than necessary. According to the presented theory of losses in an electrical machine, the iron losses are dependant on the angular frequency, which for a PMG is assumed to be increasing with diameter. The use of the developed ”ring-loss-method” neglects such a dependancy.

The estimated efficiency increases with diameter as expected since the theory states that the output power increases with the second power of the diameter, while the losses increase with the first power of the diameter. The estimated efficiency is independent of independent of the active length. This is thought to be due to the inaccuracies in the loss-ring-method.

The scaling of the mass results in similar characteristics as in [19], which the method is based on. This is however not considered a sufficient verification. Because mass of commercial multi megawatt PMGs are not available, it is difficult to verify the scaling law.

Matlab GUIDE is deemed as an excellent tool for creating graphical user interfaces. The possibility of matrix calculation makes it and effective tool for handling large amounts of data. Its versatile handling of graphical objects is especially useful.

## XII. Further Work

The Scaling Program is thought to be developed further by other students. Therefore much of the theory which has been looked into but not included in the Scaling Program is included in the Appendix ”Other Parameters of Interest”. A general recommendation for further work is also made. This approach is thought to help the next student have an easier start for continued development of the program.

The additional work is summed up to the following.

- As already discussed, the iron losses is thought to have a more complex dependancy on $D_{ag}$ than what the ”ring-loss-method” includes. A mapping of relationship between $D_{ag}$ and the angular frequency of eq. (30) is suggested as further work.
- Implementation of a division of losses in the Scaling Program as elaborated in the Appendix.
- Include thermal estimation especially temperature for windings and magnets.
- Verification of scaling model in by FEM modelling of large PMG or by scaling up a smaller reference generator to have the same geometric and power values as a known larger generator.
- Implement additional functionality to the program, such as.
  - Cost estimation for user defined reference generators.
  - Automatic calculation of power density and torque density in state of the art map.
  - Calculation of heat dissipation factor.
- Improve user-friendliness of the program by adding in-program explanation of parameters.

# XIII. APPENDICES

## CALCULATION OF COMPOUND ANNUAL GROWTH RATE (CAGR)

In the introduction the compound growth rate of wind turbine installation is mentioned. The calculation is done as follows

$$CAGR = (\frac{EV}{BV})^{\frac{1}{n}} - 1 \tag{66}$$

Where $EV$ is the ending value and $BV$ is the beginning value and $n$ is the number of years.

## THEORY OF SCALING MASS

The theory of mass scaling is based on [19] and is summarised below.

### *Scaling of Electromagnetic components*

The electromagnetic components consists of the stator yoke and teeth, the copper of the windings, the permanent magnets and the rotor yoke. To simplify the estimation of the mass of the electromagnetic components, a general formula for all components is made.

$$m_{em} = \rho_{em} V_{em} \tag{67}$$

where $m_{em}$, $\rho_{em}$ and $V_{em}$is the mass, density and volume of the electromagnetic component, respectively.

The volume of the electromagnetic component is

$$V_{em} = 2\pi R_{em} l t_{em}. \tag{68}$$

$R_{em}$ is the distance from the machine centre to the layer, $l$ is the active axial length of the machine, $t_{em}$ is the thickness of the electromagnetic layer. $R_{em}$ is assumed to be equal to the arm diameter $R_{beam}$ as defined in Figure 6. And as with the losses, $R_{beam}$ is assumed equal to $R_{ag}$ without leading to big errors. This leads to

$$m_{em} = k_{em} R_{beam} l t_{em} \rho \tag{69}$$

The specific values of the constants are not of interest. As the result of this scaling will show, the ratios between mass and power rating or aspect ratio is important. The constants term cancel each other when presented in a form of ratios.

As in [19] this model will have two scaling conditions. One where the aspect ratio is kept constant, and one where the aspect ratio is not constant.

*Constant Aspect Ratio:* In this scaling model, it is assumed that the aspect ratio, $k_{AR}$, is fixed. In other words, the ratio of the generator length to diameter is kept constant. This assumption also makes it reasonable to assume that the design will keep the same force density [19]. Now, eq. (69) can be written as

$$m_{em} = k_{em1} k_{AR} R_{beam}^2 \tag{70}$$

where $k_{em1} = 2k_{em} t_{em} \rho$. The thickness $t_{em}$ is almost a constant value for machines designed with an optimum force density [19]. And for the purpose of simplification it is considered to be constant in this thesis.

The power of the generator $P_{gen}$, is given as

$$P_{gen} = \sigma_{F,tan} 2\pi R_{beam} l v_{ag} \tag{71}$$

where both the force density, $\sigma_{F,tan}$, and air gap velocity, $v_{ag}$, are constant. The air gap velocity of the machine remains the same for machines of same aspect ratio because the wind turbine tip speed is limited to a constant value [19]. So when the wind turbine size increases, the rotational speed decreases. Eq. (71) can be reduced to

$$P_{gen} = k_{gen} k_{AR} R_{beam}^2 \tag{72}$$

where $k_{gen} = 4\pi v_{ag} \sigma_d$.

Therefore from eq. (70) and (72) the scaling law between the mass and the power rating of the machine is given as

$$\frac{m_{em1}}{m_{em2}} = \frac{P_{gen1}}{P_{gen2}} \tag{73}$$

### *Structural Beams*

Both the stator and rotor comprise of a cylindrical ring and beams to support the cylindrical ring and transfer the torque as shown in Figure 6. Both of these elements are assumed to be made of cast iron. The stator cylindrical ring holds the electromagnetic part i.e. the copper and core of the machine and the rotor ring holds the permanent magnets.

The structural arm holds the cylinder, carries the torque from the turbine and is loaded due to self weight and point force in both axial and radial direction. Normally the radius of the direct drive machine is large. This means that the structural arms are long. It is assumed that the self weight of the arm is a dominant part of the deflection on the axial side. According to [19] this is normally true for long arms with small point force as it is the case here on the axial direction. Similarly the torque of the machine is the dominant part of deflection of the arm on the radial side.

The arm can be modelled as a cantilever beam. The beam is loaded on the radial side by the self weight, $q_g$, and the torque of the machine, $F_\tau$. Similarly the machine is loaded on the axial side by the self weight, $q_{gt}$ and the weight of the cylinder, $F_c$. The axial loading of the generator is due to the tilting of the wind turbine.

It is assumed that the air gap radius will represent the length of the arms for the stator and rotor without any significant difference.

The theory behind the scaling of the mass of the structural beam is extensive and considered to be outside of the scope of a Power Engineering Master. The interested reader is referred to [19] for further reading.

The mass of the beam is

$$m_{beam} = b_{beam} h_{beam} R_{beam} \rho \tag{74}$$

The result of the extensive theory presented in [19] leads to the following relations:

$$\frac{h_{beam,1}}{h_{beam,2}} = \frac{R_{beam1}}{R_{beam2}}. \tag{75}$$

$$\frac{b^2_{beam,1}}{b^2_{beam,2}} = \frac{R^3_{beam1}}{R^3_{beam2}} \tag{76}$$

$$\frac{P_{gen1}}{P_{gen2}} = \frac{F_{\tau 1}}{F_{\tau 2}} = \frac{R^2_{beam1}}{R^2_{beam2}} \tag{77}$$

Inserting the values of $b_{beam}$ and $h_{beam}$ from eq. (75) and (76) into (74) gives

$$m_{beam} = k_t R^{3/2}_{beam} R_{beam} R_{beam} = k_t R^{7/2}_{beam} \tag{78}$$

Therefore the scaling of the mass of the beam with respect to power can be found substituting eq. (77) into (78). This is now given by

$$\frac{m_{beam1}}{m_{beam2}} = \frac{P^{1.75}_{gen1}}{P^{1.75}_{gen2}} \tag{79}$$

This scaling law can be used over a range of beam structures. This is because a change in beam structure only changes the constants in the scaling of $h_{beam}$ and $b_{beam}$.

*Cylindrical Ring*

The cylinder is supported by the structural beam. The cylinder holds the stator and/or rotor active material. As described in Section III-B2 there is a large radial force per area, $\sigma_{rad}$ due to the interaction of magnet and iron that occur between the two cylinders of the stator and rotor. [19] Achieves a simpler relation between the mass of the cylinder as the power rating of the machine increases by assuming that the ratio of the thickness of the cylinder $t_{cy}$ and the radius of the machine is constant given as

$$k_{thick} = \frac{t_{cy}}{R_{beam}} \tag{80}$$

This leads to the deflection of the cylinder being a linear function of the radius of the beam

$$y_{cy} = k_{cy} R_{beam} \tag{81}$$

where $y_{cy}$ is the deflection of cylinder and $k_{cy}$ is a constant.

The mass of the cylinder is given as

$$m_{cy} = 2\pi R_{beam} l_{gen} t_{cy} \rho \tag{82}$$

Substituting eq. (33) and (80) in (82) gives

$$m_{cy} = 2\pi \rho k_{AR} k_{thick} R^3_{beam} = k_{mass,cy} R^3_{beam}. \tag{83}$$

Therefore the scaling of the cylinder mass with respect to power rating of the machine can be written as

$$\frac{m_{cy1}}{m_{cy2}} = \frac{P^{1.5}_{gen1}}{P^{1.5}_{gen2}}. \tag{84}$$

*Varying Aspect Ratio*

The theory behind the mass estimation with varying aspect ratio can be found in [19]. It is implemented in the Scaling program, but due to time constraints, the theory is not elaborated on.

## Other Parameters of Interest

This section is reserved for parameters of interest when scaling a PMG. They are not included in the scaling laws or in the Scaling Program, but are thought to be of interest in further work.

### *Inductance*

In any synchronous machine, the most important inductance is the synchronous inductance, $L_d = L_m + L_\sigma$, where $L_m$ is the magnetizing inductance $L_m$ and $L_\sigma$ is the leakage inductance. This is because of its impact on the maximum torque production [17].

$$L_m = \frac{mD_{ag}}{\pi p^2 \delta_{ef}} \mu_0 l (k_{ws1} N_s)^2. \tag{85}$$

where $\delta_{ef}$ is the effective air gap and $k_{ws1}N_s$ is the effective number of turns.

For a surface mounted PM generator

$$\delta_{ef} \approx \delta_e + \frac{h_{PM}}{\mu_r} \tag{86}$$

and $\delta_e = k_C \delta$ with the Carter coefficient, $k_C$, taking into account the longer distance travelled by the air gap flux because of slotting. [7] gives $k_C \approx 1 - 1.1$, depending on the slot fraction $\alpha_s = \frac{w_s}{\tau_s}$.

$L_\sigma$ consists of multiple elements. [17] lists the main contributors as leakage inductance in air gap $L_\delta$, slot $L_u$, tooth tip $L_{dt}$, and end winding $L_w$:

$$L_\delta = \sum_{\substack{V=-\infty \\ V\neq 1}}^{V=+\infty} \left( \frac{k_\mathrm{w}}{V k_\mathrm{w1}} \right)^2 L_m \tag{87}$$

$$L_\mathrm{u} = \frac{4m}{Q} \mu_0 l' N^2 \lambda_{p,u} \tag{88}$$

$$L_\mathrm{dt} = \frac{4m}{Q} \mu_0 l' N^2 \lambda_{p,dt} \tag{89}$$

$$L_\mathrm{w} = \frac{4m}{Q} \mu_0 q N^2 l_\mathrm{w} \lambda_{p,w} = \frac{2}{p} \mu_0 N^2 l_\mathrm{w} \lambda_{p,w}. \tag{90}$$

where $\lambda_p$ are permeance coefficients and $l_w$ the winding length. For a large air gap machine, such as the ones in this thesis, the importance of $L_\delta$ is small. This is because it is directly proportional to $L_m$ and thus inversely proportional to $p^2$. On the other hand, $L_u$, $L_{dt}$ and $L_w$ are proportional to the square of winding turns $N$. From the relation of $N$ in a synchronous machine

$$N = \frac{E_\mathrm{m}\sqrt{2}}{\omega k_\mathrm{w} \hat{\Phi}_\mathrm{m}} = \frac{E_\mathrm{m}\sqrt{2}}{\omega k_\mathrm{w} \alpha_\mathrm{i} \hat{B}_\delta \tau_\mathrm{p} l'} = \frac{E_\mathrm{m} 2\sqrt{2} p}{\omega k_\mathrm{w} \alpha_\mathrm{i} \hat{B}_\delta \pi D l'} \tag{91}$$

One can see that $L_u$ and $L_{dt}$ are proportional to $p^2$ and $L_w$ to $p$. [17] claims that despite the moderating effect of Q and D, the leakage inductance tends to increase in high pole pair machines.

The maximum torque of a PM synchronous machine is given by

$$\tau_{max} = p \frac{E_{PM} U_s}{\omega^2 L_d} \tag{92}$$

In permanent magnet machines with induced per unit voltage $E_{PM,pu} = 1$ and terminal voltage $U_{s,pu} = 1$ the synchronous inductance must be small to produce enough peak torque. [17] recommends an $L_{d,max,pu} \approx 0.6 - 0.7$.

### *Temperature Rise*

The temperature rise of a machine would be very interesting to investigate. And compare the value to the standards if the IEC. As can be seen in Table VII

### *Windings and Insulation Thickness*

In terms of the windings, a one layer, concentrated, full pitch winding is assumed. This is a standard winding topology for low-speed PM Synchronous machines. The low speed also results in a low electrical frequency, see eq. (25), this in turn lowers the need for avoiding losses due to skin effect or circulating currents. Thus normal wires are assumed. Had the rotational speed been higher, Litz wire windings should have been implemented to minimise losses from skin effect and circulating currents. The number of phases, $m$ is assumed to be 3 and the number of slots per pole and phase, $q$, is assumed to be 1. According to [17] this is a good choice, despite some high air gap harmonics. Mainly because of the fundamental winding factor ending up at $k_{W1} = 1$. Another valid choice could have been factional slot winding with $q = 0.4 - 0.5$. Though this would lower the harmonic contents, the fundamental winding factor would also decrease to $k_{W1} = 0.933 - 0.966$ (for q=0.4, but depending on winding type) [17].

The thickness of the insulation depends on the rated voltage of the machine and the breakdown strength of the insulation material. The breakdown strength decreases with temperature, so the breakdown strength at the expected working temperature of the machine should be used as the dimensioning value. The insulation also has to withstand spikes in temperature during transient operation.

Estimation of the insulation thickness can be done by the following equation

$$h_i = \frac{U}{E_{max}} \tag{93}$$

Where $U$ is the voltage over the insulation and $E_{max}$ is the breakdown strength, i.e. the highest allowed field strength in the insulation material. Mica is a standard insulation material for high voltage generators [36]. It is usually mixed with a binder to fine tune its properties such as temperature resistance and breakdown strength. Most mica insulators have a breakdown strength of around 20 kV/mm [12]. In practice however, the insulation system also consist of a layer of resin to minimise air pockets and the effective field strength is therefore usually 2-3 $kV/mm$ [17].

According to IEC standard for rotating electrical machines [11], the insulation should be tested with an AC voltage at a frequency of 50 or 60 Hz. For machines above 1 kW, the test voltage, $U_{test}$, must be

TABLE VII
THERMAL CLASSES ACCORDING TO IEC [11]

| **IEC Thermal Class** | **130 (B)** | **155 (F)** | **180 (H)** |
|---|---|---|---|
| **Max Ambient Temperature [C]** | 40 | 40 | 40 |
| **Permissable Temperature Rise [K]** | 80 | 105 | 125 |
| **Hotspot Temperature Margin [K]** | 10 | 10 | 10 |

$$U_{test} = 2U_N + 1kV \tag{94}$$

With $U_N$ being the rated line-to-line voltage. For a machine with $U_N = 1kV$ and an insulation with a breakdown strength of $2.5kV/mm$, the machine needs a $h_i = 2mm$.

The insulation also has to withstand an impulse wave as well as be dimensioned for ageing effects due to partial discharges. Since the impulse test is not carried out on new machines it is not covered in this thesis. The ageing dimensioning can be done by assuring that the partial discharge level of the insulation system is kept low. This can be tested with a tan $\delta$ measurement.

*Implementation of Loss division factors*

The function of the loss division factors are to be able to make a more detailed estimate of the losses, as opposed to the very general ring-loss of Section IV-E. In the Scaling Program the total losses of the reference generator are calculated using the reference efficiency as elaborated in Section VII-C. The losses can further be divided using the loss division factors as follows:

$$P_{(cu+fe),ref} = \frac{P_{loss,ref}}{1+k_{ad}} \tag{95}$$

$$P_{cu,ref} = \frac{P_{(cu+fe),ref}}{1+k_{fc}} \tag{96}$$

$$P_{fe,ref} = P_{(cu+fe),ref} - P_{cu} \tag{97}$$

$$P_{ad,ref} = P_{loss,ref} - P_{(cu+fe),ref}; \tag{98}$$

Where $k_{ad}$ is the ratio of additional losses over resistive and iron losses. $k_{fc}$ is the ratio of iron losses over resistive losses. The method is dependant on an estimated division of each individual loss component. In Table VIII $k_{ad} = \frac{P_{ad}}{P_{Cu,s}+P_{Fe}}$ for the induction machine. For the PMG, however, $P_{ad}$ was not given but rather included in the $P_{pm}$, therefore $k_{ad} = \frac{P_{pm}}{P_{Cu,s}+P_{Fe}}$ for the PMG. $k_{fc} = \frac{P_{Fe}}{P_{Cu,s}}$ for both the IG and the PMG.

TABLE VIII
DIVISION OF LOSSES IN IG AND PMG AT RATED LOAD. LOSSES IN % OF $P_{tot}$. INCLUDING LOSS DIVISION FACTORS $k_{ad}$ AND $k_{fc}$

| **Loss** | **4 kW IG [12]** | **50 kW PMG [33]** | **Scaled PMG** |
|---|---|---|---|
| $P_{Cu,s}$ | 6.9 | 6.0 | - |
| $P_{Cu,r}$ | 4.7 | N/A | - |
| $P_{pm}$ | N/A | 1.4 | - |
| $P_{Fe}$ | 1.9 | 1.0 | - |
| $P_{ad}$ | 1.5 | - | - |
| $k_{ad}$ | 0.17 | 0.2 | 0.22 |
| $k_{fc}$ | 0.275 | 0.167 | 0.167 |

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