Electric Power Generation and Storage Using a High Voltage Approach

BJÖRN BOLUND
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Abstract

Production and consumption of electricity have grown enormously during the last century. No mater what the primary source of energy is, almost all generation of electricity comes from conversion of a rotational movement in a generator. The aim of this thesis is to see how high voltage technology influence production and storage of electricity. Power flow in the generators used to convert mechanical movement to electric energy is analyzed using Poynting’s vector. The impact of new generator technology for efficient extraction of hydroelectric power is shown. Simulation of a large permanent magnet turbo generator is presented. A flywheel storage system for electric vehicles utilizing high voltage technology is also presented. In pulsed power applications, a cheap method for intermediate storage of energy during milliseconds, which enables an inductive primary storage is presented and experimentally tested.

Keywords: Flywheel, Generation, Generator, High Voltage, Power flow, Poynting

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List of Publications

Most of the content in this dissertation is based on the work described in the following journals and conference reports. Capital letters refer to appendices in this report.


B. B. Bolund, M. Leijon, U. Lundin ‘Poynting Theory for Cable Wound Generators’ submitted to IEEE Transactions on Dielectrics and Electrical Insulation

C. M. Leijon, B. Bolund, U. Lundin, ‘High Voltage Generators; Ideas Behind them and Operation Data’, Invited and refereed conference paper to International Conference on Conditioning Monitoring and Diagnostics, Korea in April 2006


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<th>SI Unit</th>
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<tr>
<td>$A$</td>
<td>Tm</td>
<td>Magnetic vector potential</td>
</tr>
<tr>
<td>$B$</td>
<td>T=Vs/m²</td>
<td>Magnetic flux density</td>
</tr>
<tr>
<td>$C$</td>
<td>F</td>
<td>Capacitance</td>
</tr>
<tr>
<td>$D$</td>
<td>C/m²</td>
<td>Electric displacement field</td>
</tr>
<tr>
<td>$E$</td>
<td>V/m</td>
<td>Electric field strength</td>
</tr>
<tr>
<td>$e$</td>
<td>J/m³</td>
<td>Energy density</td>
</tr>
<tr>
<td>$f$</td>
<td>Hz</td>
<td>Frequency</td>
</tr>
<tr>
<td>$H$</td>
<td>A/m</td>
<td>Magnetizing field</td>
</tr>
<tr>
<td>$I$</td>
<td>A</td>
<td>Current</td>
</tr>
<tr>
<td>$I$</td>
<td>kg/m²</td>
<td>Moment of inertia</td>
</tr>
<tr>
<td>$J$</td>
<td>A/m²</td>
<td>Surface current density</td>
</tr>
<tr>
<td>$j$</td>
<td>A/m²</td>
<td>Free current density</td>
</tr>
<tr>
<td>$K_w$</td>
<td>-</td>
<td>Dissociation constant</td>
</tr>
<tr>
<td>$L$</td>
<td>H=Vs</td>
<td>Inductance</td>
</tr>
<tr>
<td>$M$</td>
<td>A/m</td>
<td>Magnetization</td>
</tr>
<tr>
<td>$p$</td>
<td>-</td>
<td>Number of poles</td>
</tr>
<tr>
<td>$r$</td>
<td>m</td>
<td>Radius</td>
</tr>
<tr>
<td>$T$</td>
<td>K</td>
<td>Temperature</td>
</tr>
<tr>
<td>$V$</td>
<td>V</td>
<td>Electric scalar potential</td>
</tr>
<tr>
<td>$\delta_{\text{skin}}$</td>
<td>m</td>
<td>Skin depth</td>
</tr>
<tr>
<td>$\varepsilon_r$</td>
<td>-</td>
<td>Relative permittivity</td>
</tr>
<tr>
<td>$\varepsilon_0$</td>
<td>As/Vm</td>
<td>Permittivity</td>
</tr>
<tr>
<td>$\eta$</td>
<td>-</td>
<td>Efficiency</td>
</tr>
<tr>
<td>$\mu_r$</td>
<td>-</td>
<td>Relative permeability</td>
</tr>
<tr>
<td>$\mu_0$</td>
<td>Vs/Am</td>
<td>Permeability</td>
</tr>
<tr>
<td>$\nu$</td>
<td>-</td>
<td>Poisson ratio</td>
</tr>
<tr>
<td>$\rho$</td>
<td>kg/m³</td>
<td>Density</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>A/Vm</td>
<td>Conductivity</td>
</tr>
<tr>
<td>$\tau$</td>
<td>s</td>
<td>Intrinsic time constant</td>
</tr>
<tr>
<td>$\omega$</td>
<td>rad/s</td>
<td>Angular frequency</td>
</tr>
</tbody>
</table>
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAES</td>
<td>Compressed Air Energy Storage</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined Heat And Power</td>
</tr>
<tr>
<td>SMES</td>
<td>Superconducting Magnetic Energy Storage</td>
</tr>
<tr>
<td>AFPM</td>
<td>Axial flux Permanent Magnet machine</td>
</tr>
<tr>
<td>RFPM</td>
<td>Radial Flux Permanent Magnet machine</td>
</tr>
</tbody>
</table>
Although universities have conducted research on electromagnetism, there has rarely been a basic physical approach that has led to new technological steps and applications. As a consequence of the distance between industry and the academic world, there have been very few inventions with infrastructural impact from the universities and, due to commercial pressure, an inability of the industry to challenge the limits. Therefore, during the last decades, no new renewable power sources and very few new means of power storage have been presented. Except for hydropower, existing renewable power sources struggle with subsidies. Apart from pumped hydro and compressed air energy storage, existing means of power storage are far too expensive for commercial use. The idea at the department is to explore new ways of thinking and to try to create solutions where technical, economical and environmental concerns are accounted for already at the design stage.

During the last six months of my undergraduate studies my diploma work was carried out at the department for electricity and lightning research. The work I did on energy storage in water capacitors aroused an interest in the storage of electricity. I was able to continue working with water capacitors in the beginning of my PhD studies. After experiments with pulsed power and high power handling, their applications for other power storage media became interesting. Founding from FOI, FMV and Uppsala University led to investigation of the flywheel energy storage concept, which combine both energy storage and power storage with the use of generators. It was found that there existed a large potential for improving flywheel generators. However founding from Eskilstuna Energi & Miljö and STEM combined with a temporary lack of founding for continued research on flywheels, redirected the research to high voltage turbo generators. Both turbo generators and generators used in flywheel storages rotates very fast. There are a lot of similarities between and they face some of the same problems. During the same period founding from Vattenfall led to a study where traditional generators in hydropower where compared to high voltage generators. Over the last year founding from Uppsala University and STEM turned the focus to working with power flow in generators by using Poynting vector and Finite Element Method simulations. New founding from FOI also allowed for continued work with the flywheel energy storage concept.
When facing a problem, the easy way out and also the common thing to do is to fall back on and depend upon already working solutions. This path, if taken, results in a danger of getting stuck in development. Universities provide the means to let individuals think freely and thereby allow for testing the boundaries of new ideas. Over time this may give rise to new technologies that in this area can lead to a change in the use and utilization of energy. It is therefore always good to challenge existing systems with new solutions, to see what new knowledge can bring forth. Nowadays, computer simulation methods can be an important tool in that development. It is a tool that, if handled correctly, is reliable and far cheaper than actual experimental tests.

During my PhD studies I have come to realize how important it is with good colleagues and friends. I believe that to continue ones personal development you must be open and willing to listen to critics, good and bad. Afterwards, you can decide whether or not to hold on to the critics.
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Mr Ulf Ring is gratefully acknowledged for his construction work.

Special thanks to Dr. Urban Lundin for work regarding Poynting’s vector.

Last, but not least, I would like to express my sincere gratitude to my lunchpals for interesting discussions and other friends and colleagues at the division of Electricity and Lightning Research for their support, exchange of ideas and for making it a fun workplace.

I express my deepest gratitude to my wife, my mother and father and to my brother and sisters who have always supported encouraged and believed in me.
1. Introduction and Aim of the Thesis

The use of energy has grown enormously during the last century and it continues to increase. The availability of large resources and fossil fuels, combined with a disregard of environmental consequences, resulted in the production of cheap energy and an exploitation of the available reserves. Today, with supply reaching its limit and with growing environmental concern, energy needs to be more efficiently extracted and better managed.

There are many kinds of different energy forms: electric energy, chemical energy, kinetic and potential energy, mechanical energy, work, heat, etc. Energy is continuously converted from one form to another. While you are reading this thesis, chemical energy in the food that you have eaten, is turned into heat used for electrical impulses, transformed into kinetic and potential energy and so on. One of the most versatile forms of energy is electricity, which can be converted into almost any other form of energy. The use of electricity has grown enormously during the last 100 years and is now an integral part of everyday life. There are a number of different ways for large scale production of electricity, of which many include conversion from mechanical movement. The most widespread way to produce electricity is by rotating turbines attached to generators. Some form of intermediate energy carrier like steam, water, wind or some other fluid drives turbines. Fossil fuel power plants or nuclear plants use steam to drive the turbine and in hydropower water is used. Heat and electricity can be generated and used simultaneously as in combined heat and power plants where steam is used to generate electricity and the excess heat in the steam is used for warming water. Co-generation gas turbines generate power directly by combustion of natural gas and use the residual heat to generate electricity from steam. Smaller generators are often powered by diesel engines.

Other types of electric generation, such as Photovoltaic generation and some types of fuel cells are so far mostly used for low energy and low power applications. In this thesis, electricity generation from two energy sources is investigated: hydropower and combined heat and power (CHP). New high voltage generators for five of the largest hydropower stations in Sweden have been designed and simulated, with the aim of increasing the overall conversion efficiency in the plants. The CHP plant studied used the only high voltage turbo generator in the world. The aim was to compare measured efficiency with simulated data and use the same simulation tool to investigate the possibility of more effective turbo generators.
Unlike chemical energy, which can easily be stored and used when desired, electric energy is difficult to store and is ideally produced and consumed simultaneously. In a country’s electric grid that is often the case and the electricity production is closely matched to the consumption. Nowadays, when emphasis on developing renewable sources for production of electricity increases, the intermittent nature of most renewables will create a discrepancy in correlation between production and consumption. To handle such a situation, the produced electricity can be stored intermediately. At present, there is no universal large-scale technology for energy storage, although there are several promising techniques such as, pumped hydro, CAES (Compressed Air Energy Storage), SMES (Superconducting Magnetic Energy Storage), batteries, super capacitors and flywheels. Pumped hydro is a commercial technique used worldwide. However it needs geologically special sites and has large environmental impact. CAES is used in combination with gas turbines (yields a clean and efficient operation). The other techniques are currently not viable for large-scale installations. Apart from these large-scale electric networks required to maintain a working infrastructure, energy storage is also crucial for the growing area of small electrical devices. The growing need for electric vehicles also constitutes a huge potential market. The storing unit has to possess different attributes, depending on the application. Properties that need to be optimized are energy density, power density, working efficiency, response time and lifetime. In this thesis, two ways of storing energy are investigated: flywheel energy storage and water capacitors. For flywheels, the motor/generator has been studied, especially the use of axial flux permanent magnet machines. A water-capacitor storing unit does not contain a generator; it is a purely electric form of storage. Water capacitors are predominantly applied where very high power and low energy is required. The nature of water capacitors makes them suitable for power storage on millisecond or shorter time-scales. For water capacitors the aim was to test the storage capability when a new dielectric medium is used.

The link between producing electricity with hydropower or CHP and storing energy with flywheels is in the energy conversion unit, the generator. Most of the work in this thesis has been carried out with the purpose of analyzing and improving the generator. The goals have been to adapt the generator to the physical conditions of the energy source or storing unit and thereby find a generator with a better performance. To achieve that, the background physics and working conditions for both the generator and the energy source or storing unit must be known. The situation in many power plants today is a sub-optimized solution, e.g. where a standard generator is fitted to the energy source and surrounding environment using devices such as gearboxes and transformers. If the physics is well known, possible improvements can be identified and the overall performance of a system can be enhanced.
In a generator mechanical power from the rotor is transmitted to the stator via electromagnetic fields and converted into electric power. The basic laws of electricity and magnetism formulated in Maxwell's equations [1-2] combined with Poynting’s vector [3] and modern finite element computer programs allow for studying the power flow in generators from a field perspective. Power flow in the air gap and into the stator cables for a synchronous three-phase generator operating at different loads has been simulated. The aim is to get insight in how energy flows in a generator.

The work with analyzing generators has been carried out through an extensive literature study and simulations at Uppsala University and by experimental work at Eskilstuna Energi & Miljö. The new generators are calculated and simulated in the way described under section mathematical models. The performed work on energy storage in water-capacitors includes both a theoretical description and an experimental verification.
2. Theory

2.1 Mathematical model of the generator

When a generator is simulated, a two-dimensional model of the generator cross-section geometry is created, similar to Figure 1. The geometry is based on straight lines and circular arcs. The geometric domains are assigned a material with corresponding material properties such as resistivity, permeability, coercivity, sheet thickness, price etc. Voltages and currents can be coupled to circuit equations; thermal sources can be given as scalars.

![Figure 1 Two dimensional picture of the cross section geometry for one generator pole.](image)

A two-dimensional finite element method (FEM) is used in the calculations. To ensure high accuracy and fast computations, the mesh is made more detailed in areas where the divergence of electromagnetic fields is large, such as in the air-gap and in the stator teeth and coarser in the yoke and the rotor rim. The base-functions used in the FEM solver can be chosen to be of first, second or third order. To account for three-dimensional effects like coil-end reactance’s and resistances, analytical expressions similar to those developed by Lagerkvist [4] are used for conventional generators. For
high voltage generators a 3-d FEM simulation is used to calculate reactance’s.

The steady state field simulation neglects time derivatives and rotation is accomplished by simulation at a number of discrete rotor positions, giving a fast estimation of the fields and currents. The transient simulation carried out as a function of time gives a more accurate description of the magnetic fields in the generator.

When calculating the induction in the stator, the displacement current $\mathcal{D}/\mathcal{t}$ can be neglected. This is because of the low frequencies and because displacement current is directed in radial direction in the insulating dielectric material surrounding the stator cables. It will therefore not contribute to any induction.

Without the displacement current, Ampere’s law can be written as:

$$\nabla \times \mathbf{H} = j$$  \hspace{1cm} (1)

where $\mathbf{H}$ is the magnetizing field and $j$ represents the free current density. The constitutive relations $\mathbf{B} = \mu_0 \mu_r \mathbf{H}$ and $j = \sigma \mathbf{E}$ relate fields to material properties, where $\mu_0 \mu_r$ is the magnetic permeability, $\mathbf{B}$ is the magnetic flux, $\sigma$ is the conductivity and $\mathbf{E}$ is the electric field. The $\mathbf{B}$-field can be expressed by the vector potential, $\mathbf{A}$,

$$\mathbf{B} = \nabla \times \mathbf{A}$$  \hspace{1cm} (2)

Combining (1) and (2) with the constitutive relations gives:

$$\nabla \times \left( \frac{1}{\mu_0 \mu_r} \nabla \times \mathbf{A} \right) = \sigma \mathbf{E}$$  \hspace{1cm} (3)

Faradays law $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$ in combination with (2) and Helmholtz’ theorem gives:

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} - \nabla V$$  \hspace{1cm} (4)

where $V$ is the scalar potential. By modeling the generator in two dimensions, the vector potential is expressed as $\mathbf{A} = A_z(r, \phi, t)\hat{z}$ which together with (3) and (4) results in:

$$\sigma \frac{\partial A_z}{\partial t} = \nabla \cdot \left( \frac{1}{\mu_0 \mu_r} \nabla A_z \right) - \sigma \frac{\partial V}{\partial z}$$  \hspace{1cm} (5)
The term $\partial V/\partial \hat{z}$ is traditionally called applied potential and couples to e.g. the field winding. $\sigma \partial A_j/\partial t$ is a source term connected to currents in the stator winding, eddy currents etc. A current source representation of (5) can be written as

$$\nabla \times \frac{1}{\mu} \nabla \times A = J + J_m$$

(6)

where $J$ is the source current density and the current density $J_m$ is represented if there are permanent magnets in the model. When representing a permanent magnet with thin current sheets the equivalent current density takes a constant value in a small part of the permanent magnet [5]. The current term $I_m$ caused by the equivalent current density is given by the remanence magnetization $B_r$, the recoil permeability $\mu_r$, and the length of the permanent magnets $h_{pm}$ according to (7).

$$I_m = \frac{B_r h_{pm}}{\mu_0 \mu_r}$$

(7)

In the simulation tool (6) is solved for a number of different discrete rotor positions under transient conditions, where the distance between those positions is given by the rotor speed. The rotor and stator mesh are connected along a line in the air gap using varying boundary conditions (explained further under section method for time stepping). For non-eccentric rotors and for most types of slots per phase relationships, symmetries in both geometry and electromagnetic field enables the generator to be presented by a two dimensional unit cell with periodical boundary conditions. Depending on the stator slot pitch, the unit cell can include one or more rotor poles.

Fick’s law and the continuity equation for heat determine the thermal distribution in the generator:

$$k \nabla^2 T - \frac{\partial T}{\partial t} = -J_{\text{heat}}$$

(8)

where $k$ is the diffusion coefficient and $J_{\text{heat}}$ is a heat source i.e. ohmic current losses, magnetic losses and external cooling. In addition to the field equations appropriate initial, boundary and jump conditions should be added. The values in the magnetization curves, BH-curves, for all materials have been experimentally derived by the Epstein method [6].
2.2 Losses in a generator

The time derivative of the vector potential in (5) is related to the penetration of a magnetic field in a material, also called the skin effect. The skin depth in a material, \( \delta_{\text{skin}} \), is given by:

\[
\delta_{\text{skin}} \approx \frac{1}{\sqrt{f \mu_0 \sigma}} \tag{9}
\]

where \( f \) is the electric frequency of the generator.

Electromagnetic losses in the generator consist of copper losses and iron losses. Copper losses occur in the stator and rotor windings and consist of ohmic losses and eddy current losses. Iron losses occur in the stator steel and in the rotor pole and are defined as:

\[
p^{Fe} = k_f k_h B_{\text{max}}^2 f + k_f k_{\text{eddy}} (B_{\text{max}} f)^2 + k_f k_e (B_{\text{max}} f)^{1.5} 8.67 \tag{10}
\]

where \( p^{Fe} \) is the iron losses, and the right hand term represent the hysteresis-, eddy current- and excess losses respectively. Excess losses originate from the movement of magnetic domain walls as the domain structure changes under the action of an applied field over the steel. The excess losses are neglect ably small. The term \( k_f \) is the stacking factor, \( k_h \) and \( k_e \) are coefficients for hysteresis- and excess loss respectively. The coefficient for eddy current loss, \( k_{\text{eddy}} \), is dependent on steel sheet geometry [7].

Overall the losses that occur in a generator are given in Table 1.

<table>
<thead>
<tr>
<th>Where</th>
<th>Why</th>
<th>How to compute</th>
</tr>
</thead>
<tbody>
<tr>
<td>In the Stator core</td>
<td>The hysteresis loss is always present when exposing a ferromagnetic material to magnetic flux [8]. Plotting ( B ) for various ( H ), the remanence and coercivity of a ferromagnetic material give rise to a hysteresis loop. The area enclosed by the hysteresis loop represents the energy needed to reverse the magnetization in the material.</td>
<td>Area enclosed by hysteresis loop ( W_H = \int H \cdot dB )</td>
</tr>
<tr>
<td>Hysteresis losses in the iron core</td>
<td></td>
<td>Power dissipated in a volume ( V ) exposed to an alternating magnetic field with frequency ( f ) ( P_H = V f \int H \cdot dB )</td>
</tr>
<tr>
<td>Eddy currents in the iron core</td>
<td>Faraday’s law shows that currents are induced in a conducting material exposed to varying magnetic field. The stator sheets, that build up the stator core are subjected to an alternating magnetic field from the rotor poles and currents are induced in the sheets. Sheets are made thin and with low conductivity to reduce eddy-currents.</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td></td>
</tr>
</tbody>
</table>
| **Power loss per unit volume for a thin sheet** | With induced eddy current \( \mathbf{J} \) and associated electric field \( \mathbf{E} \) :
\[
W_{ee} = \frac{1}{hd} \iint_{S} \mathbf{J} \cdot \mathbf{E} \, dldd
\]
h=height \( d \)=width
|
| **Power dissipated in a volume \( V \) of laminated iron core with resistivity \( \rho \) :** |
| \[
P_{ee} = V \frac{1}{12 \rho} \int_{0}^{\frac{T}{2}} \left( \frac{dB}{dt} \right)^2 \, dt
\]
For a sinusoidal magnetic field with \( m \) harmonics |
| \[
P_{ee} = V \frac{d^2 \omega \alpha^2}{24 \rho} \sum_{l=1}^{m} l^2 B_{\max}^2
\]
| **Power dissipated in cables** |
| Power dissipated in a single conductor with resistivity \( \rho \), diameter \( d \), and length \( l \):
\[
P_{ee} = \frac{ld^2}{64 \rho} \frac{1}{T} \int_{0}^{\frac{T}{2}} \left( \frac{dB}{dt} \right)^2 \, dt \, dS
\] For a sinusoidal homogenous magnetic field with \( m \) harmonics [9] |
| \[
P_{ee} = \frac{\pi dd^4 \omega \alpha^2}{128 \rho} \sum_{l=1}^{m} l^2 B_{\max}^2
\] |
| **Resistive losses in the stator cable** | Due to finite conductivity \( \sigma \neq \infty \) of the stator cables, Ohm’s law means that there will be a voltage drop over the stator cables and power will be dissipated as heat |
| **Power dissipated in cables** |
| \[
P_{\Omega} = RI^2
\] For a conductor with diameter \( d \), length \( l \) and resistivity \( \rho \)
\[
P_{\Omega} = \frac{4l}{\pi d^2} \rho l^2
\] |
In the PM Rotor

Eddy currents in the rotor and magnets

If the rotor and magnets are constructed of a conducting material eddy currents will be induced due to the harmonics in the magnetic field coming from the currents in the stator cables.

The power dissipation in a magnet with induced eddy current \( J \) is

\[ W_{ec} = \int_{V} \rho J^2 \, dV \]

for a magnet with width \( w \) and, length \( l \) and thickness \( t \)

\[ P_{ec} = \int \int \int_{V} \frac{d^2 w^2}{4 \rho (d + w)^2} \left( \frac{dB}{dt} \right)^2 \, dv \, dl \, dt \]

In a rotor with field winding

Eddy currents occur and can be calculated in the same manner as eddy currents in the stator. The B-field is given by the harmonics from the stator cable. Resistive loss occur for the same reason as resistive losses in the stator cable.

Power dissipated in cables

\[ P_{\Omega} = RI^2 \]

for a square conductor with length \( I \) and cross section area \( A \).

\[ P_{\Omega} = \frac{4I}{A} \rho I^2 \]

Analytical expressions for eddy current losses in surface mounted permanent magnets are given in [10-11]. For surface mounted permanent magnet machines, expressions for \( B \) and for stator losses can be found in [12].

2.3 FEM- Background

In 1976 Hanalla and Macdonald [13] computed the operation of a synchronous machine with stationary rotor and open circuit armature. At the beginning of the transient the field winding was short circuited. Field equations were derived by the use of Ampere’s law. Induced current in the damper windings depended only on the time derivative of the vector potential and the impedances of the end windings were not taken into account. A uniformly distributed current was assumed in the field winding and the effects of end winding regions were not modeled.

In 1981 Konrad [14] derived an integro-differential formulation for the skin effect (current distribution in conductors) containing only the magnetic vector potential and the total current in the conductors (11).

\[
\left( \nabla \cdot \frac{1}{\mu} \nabla \right) A - j \omega A + j \omega \frac{\sigma}{S_{area}} \iint A \cdot dS = - \frac{J}{S_{area}} \quad (11)
\]
where $S_{area}$ is the area of the conductor cross section. This formulation is suitable for calculations of generators with a given output voltage and power, as in that case the current is determined and can be used as an input parameter.

In 1983 Potter and Cambrell [15] combined the voltage equations of windings made of thin separate conductors, with the field equations. A squirrel cage induction motor was simulated in time domain, using an iterative treatment of material non-linearity and a conductor current expressed by the conductivity and time derivative of the vector potential.

In 1985 Belforte et al. [16] developed a procedure to calculate the electromagnetic field both when voltage sources are given and when the current in the conductors is given. Field equations were derived where the effect of eddy currents are taken into account.

In 1985 Strangas [17] made a time domain computation for the operation of an induction motor. The stator windings are modeled using current as an input source and the rotor cage is modeled with a constant value of the voltage, similar to (5). The time stepping method used is based on changing the air-gap mesh for every time-step, not by the use of periodical boundary conditions.

In 1985 Konrad [18] presented a survey of numerical methods for eddy current field computation. The criteria and constraints valid for different conductor setups are discussed and examples are given for transformers and motors.

In 1993 Tsukerman et al. [19] made a comparison of accuracy and time consumption for different numerical methods when used to compute eddy current problems. Numerical examples are given for 2D solutions.

In 2004 Yamazaki et al. [20] presented a method for eddy current analysis using moving coordinate systems and adaptive finite element meshing. Accurate results are obtained with a small number of finite elements.

2.4 Method for time stepping

Transient analysis of a rotating generator can be a time consuming process. Techniques previously used include, for every time step, either remeshing of the whole generator (rotor, stator and air gap) or, if separate coordinate systems are used for the rotor and stator, changing the mesh in the air-gap. A more time efficient method is to use so-called periodical boundary conditions, where the equations for stator and rotor are written in their own coordinate systems. All mesh-nodes in the air gap are placed with equal distance, in the tangential direction, between all nodes. Rotation of the rotor is achieved by shifting the conditions for one node to the neighboring node. In every step the vector potential is calculated by solving a minimization (variation) problem using the Newton method with field equations and circuits.
connected. An extended Matrix equation is then solved. For this to work, the magnetization curves must be strictly growing. Figure 2 illustrates the principle, where the entire mesh can be seen to the left and an enlarged picture of the mesh in the air gap is shown in the top right figure. For a rotor turning counter-clockwise, the first time step is illustrated in the bottom right figure. Note the equal distance between the nodes where the solutions are matched.

![Figure 2 Left) Mesh generated by the FEM solver. Top right) Enlarged picture of the mesh in the air-gap. Bottom right) The mesh after one time step.](image)

### 2.5 Power flow and Poynting’s theorem

Electromagnetic circuits can be modeled and interpreted in different ways. The two most common ways are circuit analysis and field analysis. In circuit analysis voltages, currents and impedances are used to model and analyze the electromagnetic behavior of a circuit. The power flow can be calculated by the well known equation $P = UI$. In field analysis electric and
magnetic fields are studied and used to calculate power flow. Already in 1884 electric and magnetic fields was connected to a power flow by Poynting’s theorem. A few articles have been written where Poynting’s theorem are used on rotating machines [21-26]. The background theory for Poynting’s theorem is explained very well by Ferreira [27] and is derived in paper H. In Poynting’s theorem

\[\frac{\delta}{\delta t} (E \times H) \cdot da + \oint_j E \cdot d\tau = -\frac{\delta}{\delta t} \int \left( \frac{1}{2\mu} B^2 + \frac{1}{2\varepsilon} E^2 \right) d\tau + \oint_j E \cdot E d\tau \quad (12)\]

the right hand side is the applied electric power and the total change of electromagnetic energy within the volume, \(V\). The left hand side represent the heat dissipation, \(\int j \cdot E d\tau\), and the power transported to or from the volume.

Poynting’s vector is defined as:

\[S = E \times H\]

and gives the flow of electromagnetic power per unit area. Surface integration over the Poynting vector gives the total flow of electromagnetic power, to or from the volume, in the direction perpendicular to the \(E\) and the \(H\) fields. Figure 3 shows the fields in a conductor carrying a current \(I\).

\[\frac{\delta}{\delta t} (E \times H) \cdot da + \oint_j E \cdot d\tau = -\frac{\delta}{\delta t} \int \left( \frac{1}{2\mu} B^2 + \frac{1}{2\varepsilon} E^2 \right) d\tau + \oint_j E \cdot E d\tau \quad (12)\]

For the heat dissipation equation, \(E_z\) is the only electric field component that will give a non-zero value. It means that the heat dissipated is given by the voltage drop over and the current passing through the conductor.

As can be seen from Poynting’s vector (13) the power flowing axially out from the cable is determined both by the radial electric field, \(E_r\), and the tangential magnetizing field, \(H_\theta\). Ampere’s law gives the relationship between the \(H\)-field and the current, \(I\):

\[\oint H dr = I \quad (14)\]

To maximize the power flow in a cable both the \(E_r\) and \(H_\theta\)-field should be designed to be as high as possible, i.e. the cable should be designed for as high voltage and current as possible.
All types of generators need cables in the stator winding. When rated power output increase, current and voltage handling becomes important. During the 1940s when methods for on site assembly of generators were developed, generator size grew and stator cables were made square or rectangular for easy mounting. Even today conventional generators use rectangular conductors in the stator winding. One of the benefits of a square shape conductor is the high copper-filling factor that is achieved in the stator slot.

Due to the skin effect, $\delta_{\text{skin}}$, a conductor is built up by several small rectangular conductors, in order to maintain a somewhat uniform current distribution. The stator winding build up is thoroughly described on pages 51-58 in [28]. The drawback is that a square conductor shape results in local enhancements of the electric field at the corners of the conductor, see Figure 4. In that way the insulation is unevenly stressed, a problem addressed already in 1929 [29-30] and shown by simulations in Paper H. The electric field is also further enhanced where the end winding bars are bent. Figure 5 shows a typical end winding for a conventional generator. The corners of the cables are usually rounded off to reduce the local electric field enhancements.

![Figure 4](image1.png)

**Figure 4** Equipotential electric field lines for square shaped conductors, paper H.

![Figure 5](image2.png)

**Figure 5** Traditional stator coil end.

The predominant insulation material is Glass-mica tape impregnated with epoxy-resin to cover cavities. The square shape of the conductor combined with the insulation materials used, sets an upper electric stress limit of 3
kV/mm on conventional generators. In practice, conventional generators are built with an upper voltage limit of around 30kV. It means that previously, the only way to increase the power flow in the generators was to increase the current.

The resistive, or Ohmic, losses in a stator cable depend on the resistance in the cable and the current passing through the cable according to, \( P_{\text{loss}} = RI^2 \). Since the resistance in a cable increase with higher temperature, a high current in the cable must be followed by an increased conductor area and effective heat cooling to decrease resistance and get rid of excessive heat.

The magnetic field produced by a square cable carrying a current is shown in Figure 6.

![EQUIPOTENTIAL LINES](Image)

Figure 6 Magnetic field lines for a square conductor carrying a current.

The means for building high voltage generators without square shaped conductors has existed for a long time. Parsons and Rosen presented for instance a high voltage generator with circular windings in 1929 [29]. Polymer insulated cables was introduced in the 1960s. But it took until 1998 before the first commercial high voltage generator was built [31-32] High voltage generators nowadays use insulated circular conductors [33-35]. In a Powerformer\textsuperscript{TM} [36], the circular conductors consist of high voltage extruded solid dielectric cables [37] with PEX (cross-linked polyethylene) as insulation material. A condition for the use of high voltage insulation materials is low temperature in the stator, for PEX \(< 90\, ^{\circ}\text{C}.\) Axial water-cooling is therefore a necessity for the large high voltage generators used today [38]. Other insulation materials that can be used at low stator temperatures are EPDM-rubber, silicon rubber and other polymers. A circular conductor shape combined with an inner and outer semi-conducting layer on the cable gives a
smooth electric and magnetic field distribution, see Figure 7. It also creates a good thermal coupling for copper and isolation.

![EQUIPOTENTIAL LINES](image)

*Figure 7 Electric and magnetic field equipotential lines for a circular conductor*

A comparison of the voltage and current design conditions valid for traditional and high voltage generators are given in Table 2.

**Table 2 Design limitations for electric field in the insulation and current in the stator conductor. The last column shows the power density in the conductor.**

<table>
<thead>
<tr>
<th></th>
<th>$E$ (kV/mm)</th>
<th>$I$ (A/mm$^2$)</th>
<th>Power density (kVA/mm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional</td>
<td>2 - 3</td>
<td>3.5 - 4.5</td>
<td>7 – 13.5</td>
</tr>
<tr>
<td>High voltage</td>
<td>10 - 15</td>
<td>1.5 - 3</td>
<td>15 - 45</td>
</tr>
</tbody>
</table>

The last column in Table 2 shows the power density (product of electric field and current) in the stator conductor. A higher power density means a better utilization of the stator slot in terms of power flow capability. As can be seen from Poynting’s vector and the design limitations, both the copper filling-factor and the insulation filling-factor are important for power flow in a cable.
3. Power Generation

3.1 CHP

3.1.1 CHP background

The principals of power and CHP (combined heat and power) generation have been well known since the time of Carnot. Technologies are and have been widely available which have led to a major expansion of the electric industry. Yet the worldwide development of CHP has not kept pace with energy business in general. In some countries CHP has been a topic, while in others no attention has been paid to it what so ever. Industrial history reveals that CHP is not a technical issue, but one of economics and energy policy. A CHP plant generates both electricity and heat and the overall conversion of energy is generally high. It is however important to distinguish between the two different energy products, electric power and heat. Electric power is a very high quality output as it is convertible to almost any other form of energy. The quality and usefulness of heat depends on its temperature level. The different nature of power and heat ought to be considered continuously to give a correct picture of the efficiency in a CHP-plant.

A CHP can be characterized by its fuel-type, overall energy conversion efficiency and heat/power ratio. The benefit of a CHP plant depends strongly on the heat/power ratio [39].

As discussed earlier, the power grid electricity demand is fluctuating and a CHP plant can only meet such a fluctuating load demand by modulating the process. If there is no other generation source available that is capable of stabilizing the grid, the choice of CHP technology must be made with respect to the particular application since storage of energy is a well-known technical problem. In all industrialized nations transport and distribution of electricity is well projected with losses in the power grid network ranging from 5 to 10 percent [40]. The scene is different for transportation of heat, where the transport of steam over long distances requires huge investments and/or leads to big losses. Likewise, the network for transportation of hot water needs to be expanded which, over long distances, also imposes unacceptably high losses. The extent of the heat market is therefore limited which has been a major drawback for large-scale extension of CHP in many countries. Another issue is how the price for CHP fuel and subsidies in form of
green certificates relates to prices for fuel and subsidies given to other means of power production, such as nuclear and hydropower.

In principal, any solid, liquid or gaseous fuel can be used for CHP. The main applications for CHP have historically been in industrial applications such as oil refining, chemicals, food and drink, paper, board, iron and steel. Over the last 20 years technological changes have transformed the CHP scene to also include community heating, buildings, sewage treatment and landfill sites, which can be seen for instance in the UK [41]. One of the main applications for waste-fired CHP has been in sewage treatment works. As methane is far more potent as a greenhouse gas then carbon dioxide, it is important to make use of the methane rich sewage gas, produced by anaerobic digestion of sewage. In the year 2000, the electricity production from CHP-plants in Sweden amounted to 8.5 TWh and in the EU it was 248 TWh [42].

3.1.2 CHP in Sweden and the plant in Eskilstuna

As a result of the oil crisis in 1973 and 1979, the Swedish government policy concentrated on reducing the country’s dependence on oil. Instead the use of domestically produced fuels, such as biofuels was encouraged and subsidies were and are given to ecologically beneficial actions. The taxation of carbon dioxide from fossil fuels, for instance, has contributed strongly to the move towards more biofuel.

In 1968, the building of a district heating system in Eskilstuna began which, together with the government energy policy, has resulted in the city having the newest and most efficient CHP system in Sweden, at least until recently. The district heating system supplied 90 % of the heat demand in Eskilstuna and its suburbs. The biomass fueled CHP plant in Eskilstuna, *Figure 8* and *Figure 9*, had a rating of 42 MVA (38.7 MW) electric and 71 MW thermal energy. The boiler is of the bubbling fluidized bed type, with a steam data of 139 Bar at 540°C. One high pressure and one low pressure steam turbine are mounted on either side of the generator, which previously was a 3000 rpm two pole turbo Powerformer.
The turbo Powerformer previously installed in Eskilstuna was rated at 42 MVA /136 kV and is the only high voltage turbogenerator that has ever been in use. During over excitation it was successfully operated at 177 kV [43]. Figure 10 shows a sketch of the generator.
Transportation of electricity over long distances is done using high voltage to minimize ohmic losses in the grid cables. A transformer is normally used to raise the voltage from the generator to that of the grid. Transformers are costly and introduce extra losses. Direct generation of high voltage, at the voltage-level of the surrounding grid, reduces the losses from and the need for a step-up transformer, resulting in an overall more efficient system.

3.1.3 Tests performed in Eskilstuna

Two tests were performed at the turbo generator in Eskilstunna. The first test involved measuring the power input to the generator and power output from the generator at different loads. The aim was to determine the working efficiency of the generator. The second test included measuring vibrations on the generator.

**Generator efficiency**

To try and measure the working efficiency of the generator the power output from the generator was logged during almost two hours. In the meantime, temperatures, flows and pressures were measured in the entire CHP plant. During the two hours, the load was changed with discrete intervals and a plot of the output power is given in *Figure 11*. 
When analyzing the data it was found that the accuracy in flow and temperature readings was inadequate. Since the total power input to the generator is between 18-40 MW and the losses in the generator (from previous tests) are 500-700 kW, a small error in the measurement is devastating to the analysis. Measured values for the efficiency of the generator could therefore not be extracted. The measured losses were to be compared to simulated losses. The simulations were still carried out at different loads and the result is given in Figure 12.

In the left figure the conversion efficiency for the generator (electric, ventilation and friction losses are accounted for) is given as a function of load when operating at a power factor of 0.93. In the right figure the resistive and eddy current losses for the stator winding is given at different loads. Due to failure at the CHP plant, no new measurements of the generator efficiency could be carried out.
Vibrations

Vibrations in the generator frame were measured in two ways. First, using accelerometers\(^1\) and then using high frequency probes\(^2\) to isolate the source of the vibrations.

When measuring with the accelerometers one accelerometer was placed at point 1 in Figure 13 and used as reference, the other accelerometer was moved around. Using point 1 as reference, the phase difference is given in Figure 13 along with the axial, tangential and radial moving pattern.

\[\text{Figure 13} \quad \text{Generator vibration pattern. The arrows show the moving direction and in the top figure is the measured phase difference (using point 1 as reference) given. Low pressure turbine is located to the right and high pressure turbine is located to the left.}
\]

\[\text{Figure 14} \quad \text{shows the peak to peak amplitude in millimeters.}
\]

\(^1\) The accelerometers came from Bruel & Kjaer (no. 4381 and 4391) the amplifiers came from Bruel & Kjaer and Kistler
\(^2\) The high frequency probes came from Physical acoustics (RD 150 and WD) along with the amplifier.
High frequency probes were used to target the source of the vibrations. Measurements were made at 128 point evenly distributed on the generator frame. Figure 15a shows the measurement points where the color represents how clear the signal was and the size of the dot indicate the amplitude of the signal. A large black dot means a strong clear signal and a small bright dot means a blurry weak signal. Figure 15b shows the points where the strongest axial and radial signals were measured. Figure 15c shows the injection points to the frame that cause the radial movements.
Figure 15 High frequency measurements on the generator frame. A big dark dot means a strong signal whereas a small bright dot means a weak signal.
3.2 The turbogenerator

A turbo generator is a generator constructed with two or four poles. To produce electricity for the 50 Hz grid network it needs to rotate at speeds of 3000 rpm or 1500 rpm respectively, for a 60 Hz grid the rotation speed is 3600 rpm or 1800 rpm respectively. Traditionally a turbogenerator consist of an electro magnetized rotor, and a stator with concentric or diamond wound armature with two bars per slot. The concentric winding can be of either a two- or three plane winding type and the diamond winding can be of lap or wave winding type [44]. Turbogenerator design, construction and operation can be found in [28].

3.2.1 Cooling

The way to deal with losses in a generator is to cool off the excessive heat. The equipment needed for cooling and ventilation is therefore essential but, in a normal generator, also very expensive. Nowadays air, water or hydrogen can be used for cooling of both the rotor and the stator. Table 3 summarizes the most common cooling methods.

Table 3. Different ways of generator cooling.

<table>
<thead>
<tr>
<th>Type of cooling</th>
<th>Traditional methods</th>
<th>Methods used in high voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>Stator air-cooled</td>
<td>Stator hydrogen-cooled, rotor hydrogen-cooled, rotor air-cooled</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>Stator hydrogen-cooled, rotor hydrogen or air-cooled</td>
<td>Stator hydrogen-cooled, rotor water-cooled, rotor air-cooled</td>
</tr>
<tr>
<td>Water</td>
<td>Stator air-cooled, rotor water-cooled</td>
<td>Stator hydrogen-cooled, rotor water-cooled, rotor air-cooled</td>
</tr>
<tr>
<td>Hydrogen-water</td>
<td>Stator and rotor air-cooled</td>
<td>Stator water-cooled, rotor air-cooled</td>
</tr>
<tr>
<td>Air</td>
<td>Stator hydrogen-cooled, rotor hydrogen or air-cooled</td>
<td>Stator hydrogen-cooled, rotor water-cooled, rotor air-cooled</td>
</tr>
<tr>
<td>Water</td>
<td>Stator air-cooled, rotor water-cooled</td>
<td>Stator and rotor air-cooled</td>
</tr>
</tbody>
</table>

In general air-cooling is mostly used for turbo generators up to 500 MW and hydrogen cooling is used in the middle region 300-550 MW. Water-cooled generators are manufactured up to 800 MW and hydrogen-water-cooled turbogenerators can be found with ratings up to 1200 MW (for two-pole) and 1700 MW (for four-pole). [45-46]. One technique, in air-cooling, is to have an axial fan fitted to each end of the rotor. The fan circulates a part of the air in hollow copper conductors in the rotor, the other part of the air is pressed through the rotor-stator air-gap. Operating experience from generators with that configuration reveals that friction and ventilation amounts to 45 % of the total loss, at full load. For partial load the loss-percentage from
friction and ventilation is higher [47]. As can be seen, just running the ventilation system consumes a lot of energy. Due to the possible potential gain associated with improving the cooling system, especially for air-cooled generators, a lot of development is being done on various new techniques for generator cooling. Measures looked into previously include optimization of fan efficiency and improvement of part load efficiency. Introducing water-cooling lowers the losses for ventilation and cooling.

Generators can be constructed either with an induction rotor or with the use of a permanent magnet rotor. The field winding in a rotor will give rise to ohmic losses that needs to be controlled. In fast rotating generators it is complicated to get an even airflow through the rotor for cooling. If permanent magnets are used instead of electromagnets the only losses in the rotor pole are induced eddy-currents in the permanent magnets. An increase in overall efficiency for a motor stator has been observed when the rotor is changed from a standard induction rotor to a permanent magnet rotor. The losses are about 50 % lower [48]. Few large permanent magnet generators have been built commercially. One of the largest is a 1.6 MW direct driven permanent magnet machine for wind power [49]. The slow rotational speed in wind turbines makes the generators large and heavy. For faster rotating machines the research field is still open, even though there will be difficulties with the mounting and handling of magnets for large generators.

3.3 Hydropower

3.3.1 History

The first hydropower stations in Sweden where built in the 1880’s. In the beginning they were often situated where there had been directly driven machinery for mills, saws etc. The first stations were small and essentially intended for electricity production to industries and communities in the vicinity. As techniques of transferring power over long distances were developed in the early 1900’s larger and more remote rivers became exploited. Until 1967 the power supply in Sweden was based almost entirely on hydropower, which at that time played the role of both basic power supply and power regulation [50]. With the introduction of Nuclear power as basic power supply, the role for hydropower as power regulator grew in importance. Today, when more intermittent renewable energy such as wind and Photovoltaic are introduced, hydropower’s ability to balance the power in the grid is even more valuable [51]. Figure 16 shows the yearly hydropower production in Sweden during 1965-2004 and Figure 17 shows the total consumption of hydroelectric energy per year in the world during the same period.
3.3.2 Hydropower generators

Hydropower generators are built up in different ways depending mainly on desired power output and speed. Before 1940 the generator size was limited by transportation restrictions. In the late 1940’s a method for on-site assembly of rotors was developed and a few years later a 105 MVA machine was built in Harsprånget. A decade later a 225 MVA generator was taken into service in Seitevare and in the 1980’s a 500 MVA machine was built in Harsprånget. The rated power determines the physical size of the machine and the speed affects the number of poles in the rotor. The rotational speed for different hydropower stations usually varies from around 80 rpm to approximately 600 rpm. In 2005 Perers et al. made a good review of generator
development in Swedish hydropower [53]. Figure 18 shows a hydropower generator.

![Hydropower generator](image)

*Figure 18* A hydropower generator wounded with high voltage cables.

Just as for turbogenerators, effective cooling of hydropower generators is essential. To reach a uniform stator temperature distribution, the rotor acts as a fan pressing air through radial ducts in the stator. By making use of high voltage technology, less cooling is needed. High voltage machines have already been successfully installed and operated at six sites, Table 4.

<table>
<thead>
<tr>
<th>Location</th>
<th>Commissioning</th>
<th>Type</th>
<th>Voltage (kV)</th>
<th>Rating (MVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porjus</td>
<td>1998</td>
<td>Hydro</td>
<td>45</td>
<td>11</td>
</tr>
<tr>
<td>Eskilstuna</td>
<td>2000</td>
<td>Turbo</td>
<td>136</td>
<td>42</td>
</tr>
<tr>
<td>Porsi</td>
<td>2001</td>
<td>Hydro</td>
<td>155</td>
<td>75</td>
</tr>
<tr>
<td>Höljebro</td>
<td>2001</td>
<td>Hydro</td>
<td>78</td>
<td>25</td>
</tr>
<tr>
<td>Miller Creek</td>
<td>2002</td>
<td>Hydro</td>
<td>25</td>
<td>33</td>
</tr>
<tr>
<td>Katzurazawa</td>
<td>2003</td>
<td>Hydro</td>
<td>66</td>
<td>9</td>
</tr>
</tbody>
</table>

### 3.3.3 Upgrading hydropower in Sweden

The project with hydropower involved investigation of the upgrade potential for Swedish hydropower. The study was focused on five stations located in four rivers, Lule River, Ångerman River, Ljusnan and Åtran. Since hydropower generation is a complex system, the entire conversion process was examined. The inner and outer water courses along with the turbine were
studied by Luleå University. The generator and grid connection were investigated at Uppsala University. The aim with the project was to investigate how much more energy that can be extracted from each single station if state of the art technology are used. For the generators it meant design and simulation of high voltage generators, directly generating electricity at the surrounding grid voltage. Thereby losses are decreased and more energy is produced.

Background data from the hydropower stations was collected and the existing generators was reconstructed and simulated in MAGIC$^3$. Those generators were compared to new generators. The new generators was designed and modeled with the following attributes under consideration.

- Same rotation speed as the previous generator
- Geometrical dimensions must not exceed those of the existing foundation
- Voltage is set by surrounding grid
- Power is set by the power from the turbine

For each new generator a first design was modeled, simulated and evaluated. The main evaluation criteria’s where

- Lower overall losses (iron and copper losses, cooling losses)
- Load angle under $30^\circ$
- No harmonics with an amplitude larger than 3% of the fundamental frequency

Stator and rotor build-up was altered until a satisfying generator design was made. Approximately 50 different designs were simulated for each generator.

---

$^3$ MAGIC is a simulation tool for rotating electric machines using finite element technique. It is explained more in detail under the THEORY section.
4. Power Flow in Generators

4.1 Aim with simulating power flow in generators

In a generator, kinetic energy in the rotor is transmitted via a magnetic field across the air gap into the stator. The magnetic field in the stator induces an electric field in the stator cables and electric energy can be extracted from the end terminals. Figure 19 is a schematic picture of the power flow in a three-phase synchronous generator.

![Figure 19 Power flow in a three-phase generator](image)

In papers G-I the electric and magnetic fields in a generator have been used to create a picture of the power flowing across the air gap and into the stator cables.
4.2 How were the simulations done

The following procedure was used to determine the power flow in the air gap and into the stator cables.

Two models of a generator were created in the computer program for rotating electric machines called MAGIC. The generators created were three-phase synchronous generators with one slot per pole and phase, two cables per slot and no coil pitch. Properties of the 8-pole generator is given in Table 5.

Table 5 Properties for the designed generators.

<table>
<thead>
<tr>
<th>Property</th>
<th>8 pole generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed [rpm]</td>
<td>750</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>1700</td>
</tr>
<tr>
<td>Stator inner radius [mm]</td>
<td>1000</td>
</tr>
<tr>
<td>Stator outer radius [mm]</td>
<td>1450</td>
</tr>
<tr>
<td>Air gap width [mm]</td>
<td>15</td>
</tr>
<tr>
<td>No. slots per pole and phase</td>
<td>1</td>
</tr>
<tr>
<td>No. cables per slot</td>
<td>2</td>
</tr>
<tr>
<td>Coil pitch</td>
<td>3</td>
</tr>
<tr>
<td>Designed voltage [kV]</td>
<td>1</td>
</tr>
<tr>
<td>Power</td>
<td>500 kW at a loadangle of 4.7°</td>
</tr>
</tbody>
</table>

The two dimensional geometry and material properties were extracted from the generators created in MAGIC, along with information about the magnetizing current and the generated power at different loads. In the generator geometry, fictive lines were placed in the air gap and around each of the stator cables. The fictive circles had a circumference of 0.06 m and the air gap line was 0.4 meters long for the 8-pole generator and 0.63 meters long for the 10-pole generator. Each stator cable was given a number and a mesh grid was generated Figure 20a and b shows the geometry and the mesh.
The steady state magnetic field for this geometry (with material properties and magnetizing current) was solved in the commercial program Ace\textsuperscript{4}. $A$ and $H$ were extracted at the mesh grid nodes along the fictive line in the air gap and on the fictive circle around each of the stator cables. The rotor was then rotated 2 electric degrees (corresponds to 0.5 mechanical degrees) at a time until the rotor had rotated one half electric period. In the mean while the magnetizing current was kept constant and $A$ and $H$ were extracted along the fictive lines and circles.

The power flowing across the air gap and into the stator cables can be obtained by calculating Poynting’s vector on the fictive line in the air gap and for the fictive circles around each of the stator cables. This problem has been solved in cylindrical co-ordinates and Poynting’s vector in the air gap and around the cables can be found in Table 6.

\textsuperscript{4} Ace is a simulation tool based on FEM technique for calculation and simulation of magnetic and electric properties for different geometries.
Table 6 Calculation of Poynting’s vector in the air gap and around the stator cables

<table>
<thead>
<tr>
<th>Radial power flow in the air gap</th>
<th>For the $E$ and $B$ field $B = B_r \hat{r} + B_\theta \hat{\theta}$ The radial poynting vector becomes: $S_r = E_z \hat{z} \times H_\theta \hat{\theta} = -\frac{E_z B_\theta}{\mu} \hat{r}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tangential power flow in the air gap</td>
<td>For the $E$ and $B$ field $B = B_r \hat{r} + B_\theta \hat{\theta}$ The tangential poynting vector becomes: $S_\theta = E_z \hat{z} \times H_r \hat{r} = -\frac{E_z B_r}{\mu} \hat{\theta}$</td>
</tr>
<tr>
<td>Radial power flow around the cables</td>
<td>For the $E$ and $B$ field $B = B_r \hat{r} + B_\theta \hat{\theta}$ The radial poynting vector becomes: $S_r = E_z \hat{z} \times H_\theta \hat{\theta} = -\frac{E_z B_\theta}{\mu} \hat{r}$</td>
</tr>
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</tr>
</tbody>
</table>

One way to get hold of $E$ would be to use the equation for Lorentz force $F = q(E + v \times B)$, thus $E = v \times B$. But when the magnetic vector potential, $A$, and the rotor speed is known Maxwells equation $\nabla \times E = -\partial / \partial t B$ can be combined with the vector identity $B = \nabla \times A$ and the electric field, $E$, can then be expressed as $E = -\partial / \partial t A$. The generator is simulated for 90 discrete rotor positions, with a distance of two electric degrees between two positions. At each rotor position the electric field is calculated from the two nearest rotor positions i.e. for the $i$:th rotor position the electric field on the nodes of the fictive lines and circles is given by:

$$E_i = \frac{A_{i+1} - A_{i-1}}{t_{i+1} - t_{i-1}} \quad (15)$$

*Figure 21* illustrates the procedure.
The time step is proportional to the rotor speed, \textit{rpm}, number of poles, \textit{p}, and the angle between the rotor positions, \( \Delta \phi \). To ensure a small enough time step, the time derivative of \( A \) along the fictive line in the air gap was derived for three different lengths of the rotor step 4, 0.4 and 0.08 electric degrees. Table 7 gives the positions of the rotor at which the generator is simulated. \textit{Figure} 22 shows the derivative of \( A \) and it can be concluded that its behavior is rather insensitive to the time step length and that rotor positions 2 degrees apart result in a sufficiently small time step.

\textbf{Table 7} The different rotor positions used when comparing \( \partial_t \vec{A} \).

\begin{tabular}{|c|c|}
\hline
\textbf{Difference in electric degrees} & \textbf{Rotor position} \\
\hline \( \Delta \phi=4^\circ \) & \( \phi_{i-1}=13^\circ \) \\ & \( \phi_i=17^\circ \) \\ & \( \phi_{i+1}=21^\circ \) \\
\hline \( \Delta \phi=0.4^\circ \) & \( \phi_{i-1}=16.6^\circ \) \\ & \( \phi_i=17.0^\circ \) \\ & \( \phi_{i+1}=17.4^\circ \) \\
\hline \( \Delta \phi=0.08^\circ \) & \( \phi_{i-1}=16.92^\circ \) \\ & \( \phi_i=17.00^\circ \) \\ & \( \phi_{i+1}=17.08^\circ \) \\
\hline
\end{tabular}
4.3 What does the power flow look like

Derivation of Poynting’s vector in the air gap and around the stator cables creates a picture of the power flow occurring in a generator. Starting in the air gap, this simple generator design has a high degree of cogging. An effect of this can clearly be seen when plotting the power flux across the air gap at a very low load angle, see Figure 23.
The magnetic field is drawn to the teeth, minimizing its path in the air and thereby creating a magnetic field component in the tangential direction (giving rise to the radial energy transfer). The tangential magnetic field, resulting from minimization of the flux path, is added to the tangential magnetic field coming from the load of the machine. It is this field which gives the torque production and the active power. At no-load, energy still flows across the air gap although it integrates to zero. At heavier load, the tangential field coming from the load dominates and the energy flow across the air gap becomes unidirectional. This is shown in the bottom graph of *Figure 24* where the power flow in the air gap (power as a function of arc length) is plotted for no load and at a load angle of 24°. The radial and tangential magnetic field in the air gap are plotted in the top two graphs. Comparing the first and third graph, the similarities between $H_r$ and $-\partial_r \vec{A}$ can be seen, as should be the case since the electric field can be expressed as $E = -\partial_r A_z = v \times B = R \omega B_r$.

---

*Figure 24* Power flow as a function of arc length in the air gap at no-load and, at a load angle of 24° (10-pole generator). The rotor is located directly in front of a stator slot. The top two graphs show $H_r$ and $H_\phi$. $P_r = -\partial_r \vec{A} \cdot H_\phi$ and $-\partial \vec{A}$ can be related to $H_r$, which can be seen in the graphs above. The bottom graph shows $P_r$.

Power flow into and out of the stator cables are given in *Figure 25* and *Figure 26* where *Figure 25* gives the power flow in cable 3 and *Figure 26* gives the power flow in cable 4 (cables 3 and 4 can be found in *Figure 20*).
It can be seen that power flows both into and out of the cable closest to the rotor. Most of the power flows in from the side of the cable closest to the rotor, some of the power traverses the cable and flows into the next cable in the slot. No power flows in from the side of the cable closest to the yoke.

The power input to the cables for all three phases as a function of the rotors mechanical angle, $\varphi_m$, as well as the current power relationship, for 360 electrical degrees is given in Figure 27. The top graph in Figure 27 shows the power influx for the six cables in front of one pole as a function of me-
chanical angle. The inset graph shows that the energy influx is very similar for both cables in one slot. In Figure 28 the total power influx to the cables has been plotted, that is the power given by Poynting’s vector has been added for all three phases. Once again the effect of cogging is clearly visible.

Figure 27 The top graph show the power influx to the cables versus mechanical angle for the six cables of one pole. The inset graph shows the flux to the two cables in a slot, we see that the power influx is the same for both cables. The lower graph show the power input to the cables as a function of the current running in the cables (10-pole generator).
Figure 28 The total power output for all three phases given by Poynting’s vector (8-pole generator).
5. Energy and Power Storage

5.1 Flywheel basics

5.1.1 Flywheel energy storage

The basic principle of storing energy in a flywheel is that a rotating wheel represents stored kinetic energy. More than a hundred years ago pure mechanical flywheels where used solely to keep machines running smoothly from cycle to cycle, thereby rendering the industrial revolution possible. During that time, several shapes and designs where implemented, but it took until the early 20th century before flywheel rotor shapes and rotational stress were thoroughly analyzed [55]. Later, in the 1970s, flywheel energy storage was proposed as a primary objective for electric vehicles and stationary power backup. At the same time fiber composite rotors where built, and in the 1980s magnetic bearings started to appear [56].

One of the key issues for making flywheel energy storage units a competitive energy and power storage, are the recent improvements in material, magnetic bearings and power electronics. Progress in power electronics, IGBTs and FETs, makes it possible to operate flywheel at high power, with a power electronics unit comparable in size to the flywheel itself or smaller. The use of composite materials enables high rotational velocity, with power densities comparable to that of chemical batteries. Experimental tests of the energy density for different rotor configurations shows energy storage capabilities (in the flywheel only) of 79-244 Wh/kg [57]. Magnetic bearings offer very low friction and high stiffness, enabling low internal losses during long-term storage [58-61].

Some of the primary attributes that make flywheels useful for applications where other storing units are currently being used include high power density, large number of repetitive deep discharge cycles without capacity degradation, virtually maintenance free and environmentally friendly materials. The ability to handle high power levels is one of the major advantages of flywheels and is a desirable quality in e.g. a vehicle, where a large peak power is necessary during acceleration. It is equally and advantage when electrical breaks are used, since a large amount of power is generated for a
short while when breaking. The field of hybrid electric vehicles is an expanding research area where the target is a more efficient and environmentally friendly use of energy [62]. A very good review of the field of hybrid electric vehicle along with modeling of permanent magnet machines for flywheel energy storages was done by Holm [63]. Two other interesting application areas for flywheels are as uninterruptible power supplies (UPS) and in space applications. Individual flywheels are so far capable of storing more than 1 GJ and peak power ranges from kilowatts to hundreds of megawatts, with the higher powers aimed at pulsed power applications [64-65].

5.1.2 High voltage

When striving to reduce overall losses and increase the power output a necessary step is to increase the voltage. One of the highest voltages attained so far is a 10-pole permanent magnet machine with a continuous voltage of 6.7 kV and a peak voltage of 10 kV constructed in 2001 [66]. In fusion research tokamaks, utilize flywheels capable of generating 10.5 kV [64]. Today true high voltage applications require a transformer, introducing more unwanted losses.

5.1.3 Build-up and limitations

A flywheel stores energy in a rotating mass. Depending on the inertia and speed of the rotating mass, a given amount of kinetic energy is stored as rotational energy. The flywheel is placed inside a vacuum or gas filled container to eliminate friction-loss from the air and is suspended with bearings for a stable operation. Kinetic energy is transferred in and out of the flywheel with an electrical machine that can function either as a motor or generator depending on the load angle. When acting as a motor, electric energy supplied to the stator winding is converted to torque and applied to the rotor, causing it to spin faster and gain kinetic energy. In generator mode, kinetic energy stored in the rotor applies a torque, which is converted to electric energy. Figure 29 shows the basic layout of a flywheel energy storage system. Apart from the flywheel, additional power electronics are required to control the power input and output, speed, frequency etc.
The kinetic energy stored in a flywheel is proportional to the mass and to the square of its rotational speed according to (16).

\[ E_k = \frac{1}{2} I \omega^2 \]  \hspace{1cm} (16)

where \( E_k \) is kinetic energy stored in the flywheel, \( I \) is the moment of inertia and \( \omega \) is the angular velocity of the flywheel. The moment of inertia for any object is a function of its shape and mass. One of the more dominating shapes is a hollow circular cylinder, approximating a composite or steel rim attached to a shaft with a web, which leads to an inertia of

\[ I = \frac{1}{4} m (r_o^2 + r_i^2) = \frac{1}{4} \pi \rho a (r_o^4 - r_i^4) \]

where \( r_o \) and \( r_i \) are the outer and inner radius, \( a \) is the height of the rim and \( \rho \) is the density. Equation 16 shows that the most efficient way to increase the stored energy is to speed up the flywheel.

The speed limit is set by the stress developed within the wheel due to inertial loads, called tensile strength \( \sigma \). Lighter materials develop lower inertial loads at a given speed therefore composite materials, with low density and high tensile strength, are excellent for storing kinetic energy [68]. The maximum energy density with respect to volume and mass respectively is:

\[ e_v = K \sigma \]
\[ e_m = K \sigma / \rho \]  \hspace{1cm} (17)
where \( e_v \) and \( e_m \) are kinetic energy per unit volume or mass respectively, \( K \) is the shape-factor depending on the flywheel shape, \( \sigma \) is maximum stress in the flywheel and \( \rho \) is mass density.

In a three-dimensional object there will be three-dimensional interaction of material stresses. For a rotor constructed with a non-isotropic material, like fiber-reinforced composite, that stress interaction will limit the practical dimensions possible. In short hollow cylinder designs, the two stresses of primary concern are the radial stress and the hoop stress (Figure 30). For an isotropic material the radial stress is expressed by (18).

\[
\sigma_r = \frac{3 + v}{8} \rho \omega^2 \left( r_0^2 + r_i^2 - \frac{r_0^2 r_i^2}{r^2} - r^2 \right) \tag{18}
\]

where \( \rho \) is the mass density, \( \omega \) is the rotor speed, \( v \) represents the Poisson ratio, \( r_0 \) is the outer radius of the rotor, \( r_i \) is the inner radius of the rotor and \( r \) represents any radius within the rotor.

The hoop stress is expressed by (19)

\[
\sigma_v = \frac{3 + v}{8} \rho \omega^2 \left( r_0^2 + r_i^2 + \frac{r_0^2 r_i^2}{r^2} - \frac{1 + 3v}{3 + v} r^2 \right) \tag{19}
\]

![Figure 30](image-url) Radial- and hoop stress in a short hollow cylinder rotating about its axis with angular velocity \( \omega \).

Table 8 presents characteristics for common rotor materials.
Table 8 Data for different rotor materials [69]

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>Tensile strength (Mpa)</th>
<th>Max energy density (for 1kg)</th>
<th>Cost ($/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monolithic material 4340 Steel</td>
<td>7700</td>
<td>1520</td>
<td>0.19 MJ/kg = 0.05 kWh/kg</td>
<td>1</td>
</tr>
<tr>
<td>Composites</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E-glass</td>
<td>2000</td>
<td>100</td>
<td>0.05 MJ/kg = 0.014 kWh/kg</td>
<td>11.0</td>
</tr>
<tr>
<td>S2-glass</td>
<td>1920</td>
<td>1470</td>
<td>0.76 MJ/kg = 0.21 kWh/kg</td>
<td>24.6</td>
</tr>
<tr>
<td>Carbon T1000</td>
<td>1520</td>
<td>1950</td>
<td>1.28 MJ/kg = 0.35 kWh/kg</td>
<td>101.8</td>
</tr>
<tr>
<td>Carbon AS4C</td>
<td>1510</td>
<td>1650</td>
<td>1.1 MJ/kg = 0.30 kWh/kg</td>
<td>31.3</td>
</tr>
</tbody>
</table>

In most designs the eigenfrequencies are designed to appear for low speeds. To avoid going through the eigenfrequencies and to maintain a high conversion efficiency, the depth of discharge is usually between 75 and 95 percent. Tests with composite rotors show that in case of failure the composite rotor can be turned into small dustlike particles [57]. Overall, the flywheel geometry and speed determine the energy storage capability, whilst the motor/generator and power electronics determine the power capabilities.

5.1.4 Magnetic bearings

Mechanical bearings used in the past cannot, due to the high friction and short life, be adapted to modern high-speed flywheels. Instead various types of hybrid magnetic bearing systems are utilized. Electropermanent magnetic bearings do not have any contact with the shaft, have no moving parts, experience little wear and require no lubrication. They consists of permanent magnets, which support the weight of the flywheel by repelling forces. Electromagnets are used to stabilize the flywheel, although it requires a complex guiding system. Another way to stabilize the flywheel is to use mechanical bearings at the ends of the flywheel axle and use permanent magnets to levitate and stabilize the flywheel [70-71]. The best performing bearing is the high-temperature super-conducting (HTS) magnetic bearing combined with permanent magnets and in some cases mechanical bearings. It can situate the flywheel automatically without need of electricity or a positioning control system [72-73]. However, HTS magnets require cryogenic cooling by liquid nitrogen [69].
5.2 Flywheel technical considerations

5.2.1 Permanent magnets and steel

High-field permanent magnet materials allow designs with customary values of the flux density in the magnetic circuit [74]. For fast rotating permanent magnet machines, the mounting of magnets on the rotor is an important issue. It is essential that the rotational forces acting on the magnets, thereby causing radial and hoop stress, does not exceed the magnets tensile strength. However, it is equally important to mount the magnet in a way that it does not break under the strong centrifugal forces, sending the whole magnet-pole flying. One of the more common mounting types is surface mounted neodymium-iron-boron magnets, Nd$_2$Fe$_{14}$B, [75]. A design study of different mounting types for low speed applications can be found in ref [76]. For high-speed applications, magnets can for instance be mounted inside a non magnetic tube, or surface mounted magnets can be surrounded by an epoxy layer.

Magnetic saturation starts to occur at magnetic field-strengths of 1.8 T. Development of grain oriented steel has led to thinner, more exactly oriented, and domain controlled sheets. For motor/generator applications steels are also becoming thinner, sheet thickness down to 0.12 mm is commercially available. The development of high purity and low loss alloys is described by Beckley [77-78].

5.2.2 Motor/generator

The motor/generator, used to feed and extract energy to and from the flywheel, can in theory be of any type. For the large fairly slow rotating flywheels, standard induction generators can be used. For the smaller and faster rotating flywheel energy storages, the high rotation speed prohibits contact between the rotor and stator, making permanent magnet motor/generators ideal for these environments. The permanent magnet motor/generators that are used can be categorized into three groups.

- Axial- Flux Permanent Magnet machines (AFPM)
- Radial- Flux Permanent Magnet machines (RFPM)
- Dipole Halbach array machines

There are numerous alternatives for the design of an AFPM machine such as internal rotor, internal stator, multidisc, slotted or slot-less stator, ironless stator or rotors with interior or surface-mounted magnets [79-82]. Unlike radial machines, axial machines can have two working surfaces. Either two rotors combined with one stator or one rotor combined with two stators. The benefit of using a two surface working machine is the increase
in power output [81, 83]. The axial machines have a few advantages over the radial ones, such as a planar adjustable air gap, low external leakage of magnetic field for ironless stator configurations, easy cooling arrangements which are important when working under low-pressure conditions [84]. An example of the rotor for a radial flux machine is given in Figure 31 and example of a three phase air-wound stator is given in Figure 32.

![Figure 31 Example of an axial flux rotor with trapezoid-shaped magnets.](image1)

![Figure 32 Example of a three phase air-wound stator for an AF machine.](image2)

Much attention has been directed towards optimizing radial gap machines [85-87]. In a RFPM machine the magnets can be surface mounted on the rotor axle surrounded by the stator, or mounted in a ring enclosing the stator. The radial flux machine is used mostly in small-scale high-speed machines, where the tensile strength of the permanent magnets demands placing close to the rotating axle. Figure 33 shows a cross section slice of a radial flux machine.
In the internal-dipole Halbach-type magnet arrays, permanent magnets rotate with the flywheel and are arranged to produce a uniform flux distribution that interacts with a set of stationary coils to produce torque, Figure 34. The magnetic flux is given by

\[ B = B_{\text{rem}} \kappa \log \left[ \frac{r_2}{r_1} \right] \] (20)

where \( \kappa = \sin \left( \frac{2\pi}{m} \right) \left/ \frac{2\pi}{m} \right. \) and \( m \) is the number of magnets used to create the internal dipole. Two major advantages with this configuration are the low external magnetic field produced (especially if a steel rim is placed outside the magnets) and that the positions of the stator windings inside the field do not affect the conversion efficiency. Johnson et. al. describes a flywheel storage system utilizing magnetic bearing vacuum enclosure and a Halbach type motor/generator[88]. Machines with operating voltage in the range of 70-400 V have been built [89-90].
Figure 34 Internal dipole Halbach type array made with permanent magnets. Inside the magnets stationary coils are placed.

Apart from the PM motor/generator used in almost all flywheels there is also the possibility of using a Synchronous Reluctance Motor/Generator. In 1996 a 60kW flywheel, utilizing this motor, was developed [91].

5.2.3 Power electronics

A brushless permanent magnet generator (in a flywheel) produces variable frequency AC current. In most applications though, the load requires a constant frequency making it necessary to first rectify the current and then convert it back to AC. Power converters for energy storage systems are based on SCR, GTO or IGBT switches. In an early stage of energy storage utility development, SCRs were the most mature and least expensive semiconductor suitable for power conversion. SCRs can handle voltages up to 5 kV, currents up to 3000 A and switching frequencies up to 500 Hz. Due to the need of an energized power line to provide the external on/off signal to those switches, they were replaced with GTOs, which do not depend on an energized line to function. The GTO device can handle voltages up to 6 kV, currents up to 2000 A and switching frequencies up to 1 kHz. In recent years IGBTs have emerged. The IGBT is a solid-state switch device with ability to handle voltages up to 6.5 kV, currents up to 2.4 kA and most important high switching frequencies [92-93].

The technique used to produce AC current from DC is called Pulse-Width Modulation (PWM). Pulses of different length are applied to the IGBTs in the inverter, causing the DC current to be delayed by the inductive load and
a sine wave is modulated [94]. A fast switching frequency in the power converter improves emulation of a sine wave mainly by eliminating some of the higher order harmonics. To reduce the harmonic content even further, a filter consisting of capacitors and inductors can be connected on the AC side of the output.

5.2.4 Magnetic flux

The air-gap between rotor and stator is preferably as small as possible and its minimum distance is determined by mechanical considerations. The presence of an air gap will reduce average flux density \( B_{av} \) to

\[
B_{av} = \frac{l_g}{1 + \frac{d_m}{l_g}} B_{\text{magnet}}
\]

(21)

where \( d_m \) is the thickness of the magnet and \( l_g \) is the effective radial distance from the stator teeth to the rotor. Equation 21 is valid for configurations where the permanent magnet is surface mounted.

5.2.5 Work done to date

Small-scale

Small-scale flywheel energy storage systems have relatively low specific energy figures once volume and weight of containment is comprised. But the high specific power possible, constrained only by the electrical machine and the power converter interface, makes this technology more suited for buffer storage applications. Development of alternative dual power source electric vehicle systems that combine a flywheel peak power buffer with a battery energy source has been undertaken [82, 95].

Peak power buffers

The uses of a flywheel as power buffer in an electric vehicle can significantly reduce the peak currents drawn from the ordinary storing supply e.g. battery. Elimination of the peak currents will prolong the battery life [95].

Wind-diesel generator with a flywheel energy storage system

In 2000 a simulation of a Wind-Diesel generation plant together with a kinetic energy storage unit was presented and its construction was started. The goal of this system is a unit where the regular wind oscillations are compensated by the diesel generator and the flywheel. The 0.6 kWh, 50 kW flywheel is able to supply active and reactive power to compensate both
frequency and voltage of the network. The unit is designed to supply total power during a period of 1.8 minutes with a rated voltage 750 V and a maximum current of 102 A [96].

Flywheel for photovoltaic system

A doubly salient permanent magnet (DSPM) motor flywheel energy storage for a building integrated photovoltaic (BIPV) system was simulated in 2001. By adding a flywheel to a BIPV equipped building situated in Hong Kong, the load supply time could be prolonged from 9am-3pm to 8am-beyond 6pm [97].

Harmonics

Different flywheel systems for compensating harmonics in low voltage (~400 V) power networks have been compared and analyzed. Up to the eleventh harmonic a decrease of about 50% was accomplished [98].

Flywheel in distribution network

A 10 MJ flywheel energy storage system, used to maintain high quality electric power and guarantee a reliable power supply from the distribution network, was tested in the year 2000. The FES was able to keep the voltage in the distribution network within 98-102% and had the capability of supplying 10 kW of power for 15 minutes [99].

High power UPS system

A 50 MW/650 MJ storage, based on 25 industry established flywheels, was investigated in 2001. Possible applications are energy supply for plasma experiments, accelerations of heavy masses (aircraft catapults on aircraft carriers, pre-acceleration of spacecraft) and large UPS systems. The 50 MW peak power can be supplied for about 13 s, with an overall efficiency of 91-95%. The flywheels are connected in parallel to a 1200 V DC-link. Similar PM flywheels have previously been tested in urban traffic busses and rail systems with a resulting energy save of up to 40% [100].

UPS system

A Case study on an existing medium voltage network has been carried out, in which different disturbance scenarios have been simulated (voltage dips, start-up etc). The idea was to connect four 1.6 MVA flywheel based dynamic UPS systems combined with a diesel generator to the 20 kV distribution network, thereby improving the power quality. The simulation results indicate that the approach is feasible, and show a significant improvement in power quality. Typically, the voltage dips are divided by a factor 3 even in the worst cases. A transformer is required between the flywheel storage system and the medium voltage network [101].
Storage system with magnetic bearings

A complete kinetic energy storage system using a Halbach array motor and hybrid magnetic bearings was modeled, simulated and constructed with off the shelf components. Interesting is the magnetic bearing system utilizing two ring magnets for radial stability and a hard ball on top of a hard flat plate for axial support [72].

Flywheel and air friction

The idling energy loss in a conventional flywheel UPS system enclosed in an air-tight container has been investigated. Air has been replaced by helium and it was found that a mixture of 75% helium reduced losses by over 70%. The article shows clear derivations of analytical equations describing flywheel rotation and losses. The flywheel storage system was also tested as a back-up power supply for short time voltage fluctuations where it was found that 740 W loads was protected for 0.2 s sags [102].

Flywheels in trains

A version of the Alstom Light Innovative Regional Express (LIREX) with flywheels as complementary energy storage has been constructed. The Research Center of Deutsche BAHN AG carried out simulations of the operation of such a train. According to that simulation, about 11% energy can be saved, for normal traffic conditions, by using flywheels to capture energy while breaking [103].

Aerospace applications

A two pole, three-phase PM synchronous motor/generator coupled to a flywheel has been simulated. The flywheel storage unit is intended to replace a battery storage unit onboard the International Space Station. The motor is rated to 7kVA, 80 V and 50 A and 1000 Hz. A comparison between flywheel and NiH2 battery systems for an EOS-AMI type spacecraft has shown that a flywheel system would be 35% lighter and 55% smaller in volume [104].

High voltage stator

A 10 pole PM machine with a continuous voltage of 6.7 kV and peak voltage of 10 kV was constructed in 2001, for use in hybrid electric combat systems. The 25 MJ flywheel is to produce a continuous power of 350 kW (loss 2.4 kW) as well as intermittent 5MW pulses, the idling loss is calculated to be around 250 W. To handle the heat produced, the stator is cooled by 70 °C or 90 °C oil. The insulation on the cables is constituted of filler epoxy (type 1) and FEP tubes surrounded by epoxy (type 2) see Figure 35. The overall size and weight of the system is 0.28 m³ and 519 kg [66].
Figure 35 Cross section of the 6.7 kV Stator [66].

**Of the shelf systems**

The operating voltages of three available flywheel systems from different companies can be found in Table 9.

<table>
<thead>
<tr>
<th>Developed by:</th>
<th>Energy (kWh)</th>
<th>Power (kW)</th>
<th>Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCM -EMAFER</td>
<td>4</td>
<td>325</td>
<td>750</td>
</tr>
<tr>
<td>Magnet Motor</td>
<td>2</td>
<td>150</td>
<td>300-700</td>
</tr>
<tr>
<td>Magnet motor</td>
<td>22</td>
<td>5000</td>
<td>--</td>
</tr>
<tr>
<td>URENCO</td>
<td>2</td>
<td>100</td>
<td>450-800</td>
</tr>
</tbody>
</table>

**Table 9 Operating voltage of three different flywheel systems [105-107].**

5.2.6 Losses

Apart from the mechanical losses (friction from bearing and air) in a flywheel system there are also electric losses in the integrated motor/generator.

For radial flux machines an iron stator is necessary and all of the losses previously described under section 2.2 will occur. For generators constructed with rare earth high field permanent magnets flux densities are high enough to allow axial flux machines with air-gap windings, without a magnetic stator core[108]. Absence of stator material eliminates iron losses, and gives a machine with lower stand by (or no-load) losses. Without hysteresis loss, the stand-by losses are given by the leak eddy currents in the stator cables, bearing losses and air friction.

The low tensile strength of the magnets compared to that of the composite flywheel limits their placing to the vicinity of the hub. As a consequence the number of poles, and therefore the rate of change of magnetic flux, must be
carefully selected in order to achieve the desired voltage. Table 10 shows the tensile strength for common magnetic materials.

Table 10 Data for different magnetic materials [109].

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>Tensile strength (Mpa)</th>
<th>Remanence (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sintered Neodymium-Iron-Boron (Nd-Fe-B)</td>
<td>7400-7600</td>
<td>80</td>
<td>1.08-1.36</td>
</tr>
<tr>
<td>Sintered Samarium-Cobalt</td>
<td>8000-8500</td>
<td>60</td>
<td>0.75-1.2</td>
</tr>
<tr>
<td>Sintered Ferrite</td>
<td>4800-5000</td>
<td>9</td>
<td>0.2-0.43</td>
</tr>
<tr>
<td>Injection molded composite (Nd-Fe-B)</td>
<td>4200-5630</td>
<td>35-59</td>
<td>0.40-0.67</td>
</tr>
<tr>
<td>Compression molded composite (Nd-Fe-B)</td>
<td>6000</td>
<td>40</td>
<td>0.63-0.69</td>
</tr>
<tr>
<td>Injection molded composite Ferrite</td>
<td>2420-3840</td>
<td>39-78</td>
<td>0.07-0.30</td>
</tr>
</tbody>
</table>

5.2.7 External gyroscopic aspects

For flywheels situated in a vehicle, satellite or space station, the gyroscopic forces are important. In a satellite it is possible to make use of the gyroscopic force from a flywheel by letting it provide torque to the spacecraft for altitude control, thereby diminishing the overall weight and increase the effective use of energy. In space stations and vehicles, the flywheel batteries can be controlled as pairs and situated to rotate in opposite direction, so as not to produce any net torque [110-111].

5.3 Water capacitors

5.3.1 High power Pulses

Generation of high power pulses is usually done by building up the pulse in two steps. Energy from a primary storage is transferred to a secondary storage, which in its turn delivers its energy the load. Traditionally the idea has been to charge the primary storage to the energy needed, which often takes a relatively long time since the power initially available is fairly low. When a sufficient amount of energy is reached, the primary storage transfers its energy into the secondary storage in a few microseconds. Already at this stage the power of the pulse leaving the primary storage has gained several orders of magnitude compared to the power it was initially charged with. The energy is held in the secondary storage a short while before it is dis-
charged through the load. Ideally all the energy in the primary storage should be delivered to the load in an extremely short period of time, giving a pulse with high power. Today it is not unusual to have an increase in power of thirteen orders of magnitude [112].

The primary storage usually consists of a Marx-bank. A Marx-bank has two good properties: it can discharge all its energy in a few microseconds and it also magnifies the voltage. If the primary storage is a Marx-bank, then a pure water capacitor can be used as a secondary storage. A pure water capacitor can store the energy for about 15 microseconds, which is long enough. For large pulse generators it would be desirable to replace the Marx-bank (capacitive storing of energy) with a coil (inductive storing of energy), as it is a cheaper and more efficient way of storing energy. One of the key parameters when transferring energy is the intrinsic time-constant given by:

$$\tau = \sqrt{LC}$$  \hspace{1cm} (22)

Switching from capacitive to inductive primary storage will increase the intrinsic time-constant to millisecond level, which means that the secondary storage needs to be able to store the energy for several milliseconds. Figure 36 shows an electric schedule of a pulsed power machine.

![Figure 36 Pulsed power machine with inductive primary storage.](image)

5.3.2 Water capacitor

A capacitor using water as a dielectric medium is called a water capacitor. Using water has a few obvious advantages like being cheap and environmentally friendly. The price is very important when it comes to scaling up the capacitor [113].

In pulsed power applications it is important to have a secondary storage that can discharge fast. Assume a "parallel plate capacitor", Figure 37.
The capacitor cannot be discharged faster than the charge can leave the capacitor i.e. the time it takes for the electrons furthest away from the connections to travel to the connections. Looking at the picture, that time is represented by the time it takes for an electron at “a” to get to “b”. This means that the capacitor should be small to get a quick discharge. In order to store much energy in a small capacitor a dielectric with high $\varepsilon_r$ and/or a big $E_{\text{max}}$ is needed.

At room temperature pure water has a dielectric constant of 82. Many other traditionally used materials (polymers etc) have an $\varepsilon_r$ of about 2-5. The dielectric constant of water is also increasing with decreasing temperature. This makes water very interesting as a dielectric medium, although its conductivity, $\sigma$, causes problems. It will, if used as a dielectric medium, cause the capacitor to discharge continuously (self discharge). The conductivity of water is due to two things. One is ions solved in the water, the other is the auto-ionization process of water itself [114].

$$\text{HOH} \Rightarrow H^+ + OH^- \quad (23)$$

Model

The self-discharge of a water capacitor, due to the conductivity of water, can as a first approximation, be modeled as a simple RC-circuit according to Figure 38.

Figure 38 RC-circuit.

R is inversely proportional to the conductivity of the water that is used. The ability to model the water capacitor in this way has been shown previously in [115]. The discharge of a capacitor in a RC-circuit is exponential and given by:
\[ U = U_0 e^{-t/\tau} \] (24)

The product \( RC \) is called intrinsic time constant and symbolized by \( \tau \). From (24) it follows that when \( t = \tau = RC \) about 37% of the initial stress over the capacitor remains. \( \tau \) can also be calculated in the following manner

\[
\tau = RC = \left[ \frac{\varepsilon e^{-\frac{d}{\epsilon}}}{\mu_A^2} \right] = \varepsilon \rho \frac{A}{d} \frac{d}{A} = \varepsilon \rho = \varepsilon_i \rho \] (25)

where \( A \) is the area and \( \rho \) is the density. Thus the intrinsic time constant of the water capacitor (how long it keeps the energy) is ideally only dependent on the properties of the water that is used.

5.3.3 Water/methanol

In the set-up used, the water in the capacitor passes continuously through an ion-exchange filter in order to decrease the conductivity. This removes all the ions and thus diminishes the conductivity. However, due to the auto-ionization process the conductivity is still too large. Lowering the temperature slows the auto-ionization process. Mixing the water with methanol enables temperature depression below 0°C. Depending on the concentration of methanol in the water the freezing temperature varies [116], \( \text{Figure 39} \).

![Figure 39 Freezing point for different concentrations of methanol.](67)
Mixing water with methanol also affects the dielectric constant. The dielectric constant for different water/alcohol-mixtures has been investigated in [117]. The dielectric constant for different water/methanol concentrations is given in Figure 40.

![Figure 40](image)

Figure 40 $\varepsilon_r$ as a function of temperature for different water/methanol concentrations.

The mixing of methanol will lower the dielectric constant. Fortunately $\varepsilon_r$ increases for lower temperature and approaches 80 near the freezing point of the mixtures. Thus at the freezing temperature the dielectric constant will only be lowered a few percent.

Waters ability to solve ions is expressed by the dissociation constant $K_w$. For water in room temperature [116]

$$pK_{w,H,O} \approx 14$$  \hspace{1cm} \text{(26)}

where $pK_w = \log_{10} K_w$. For methanol in room temperature

$$pK_{w,\text{met}} \approx 16$$  \hspace{1cm} \text{(27)}

$K_w$ is proportional to the concentration of hydrogen ions. This gives the following relationship between $[H^+]$ and $H_2O$ for water

$$\frac{[H^+]_{H_2O}}{[H_2O]} = 10^{pK_{w,\text{met}}} \approx 10^{-14}$$  \hspace{1cm} \text{(28)}
and the relationship between \([H^+]\) and CH\(_3\)OH for methanol to

\[
\frac{[H^+]}{[CH_3OH]} = 10^{\text{pK}_w_{\text{water}}} \approx 10^{-16}
\]  

(29)

It is clear that mixing water with methanol reduces the total amount of ions in the dielectric. The concentration of ions decreases exponentially with temperature [114] since

\[
\ln K_w \sim \frac{1}{T}
\]

(30)

A liquid dielectric is also self-healing. It means that if the stress over the water capacitor is so high that it creates an electrical breakdown (a spark between the electrodes) the dielectric is not destroyed, which is usually the case for solid dielectrics. Assuming the spark does not damage the electrodes, the capacitor can survive several electrical breakdowns.
6. Summary of Papers

These papers are the outcome of this research work. The first three papers A-C have the simulation of power flows in generators in common. The next three papers D-F are concerned with the design and evaluation of generators using the design and simulation tool described in chapter 2.1. Paper G is mostly experimental work on pulsed power energy storage. Paper H is a review of flywheel energy storage.

Paper A: Poynting vector analysis of synchronous generators using field simulations

There are different ways to describe and model power flows in a generator. This article is the first and also the more mathematical of two articles describing how the power flows in a generator using field theory. This article describes

- The power flow across the rotor-stator air gap
- The power flow into and around the stator cables

A three phase synchronous generator has been simulated for no load, light load and heavy load. The power flow has been calculated from the electric and magnetic fields using a Poynting vector approach. Detailed pictures showing the magnitude and direction of power flow are presented and it is interesting to notice how the cogging contributes to a bi-directional power flow in the air gap at no load and light load.

This article came partly from initiative by me. About half of the theoretical work, simulations and writing have been carried out by me.

Submitted to IEEE Transactions on Magnetics in February 2006.

Paper B: Poynting theorem for cable wound generators

This, the second paper describing power flows in generators using field theory, focuses on connecting the different expressions in Poynting’s theorem to a three phase synchronous generator. The result is linked to design
considerations and the power flow distribution in two different types of stator cables is compared. The outcome of this article shows why high voltage generators can be beneficially used in high power applications if insulation material properties are combined with the knowledge of how the cable geometry connects to electromagnetic field distributions. All of the simulations and most of the theoretical work and writing were carried out by myself.

Submitted to IEEE transactions on Dielectrics and Electrical Insulation in February 2006.

Paper C: High voltage generators; ideas behind them and operation data

A conference paper, presenting the basic theory for designing a high voltage generator and followed up by operation data from the Powerformer generator at the Porsi hydropower station in Sweden. Part of the writing and the power flow simulations was done by me.

Invited and refereed conference paper to the International Conference on Conditioning Monitoring and Diagnostics, Korea in April 2006.

Paper D: Rotor configuration impact on generator ventilation needs

Turbogenerators are widely used the world over and produce a large portion of all electricity. The standard operating voltage for turbogenerators is around 20 kV. This article compares three 20 MW/20 kV turbogenerators. One is a conventional design, the second uses a stator with the Powerformer concept and the third generator uses a permanent magnet rotor combined with a Powerformer stator.

It is shown that a 20 MW/20 kV permanent magnet generator can be designed and that losses can be cut down by up to 69% as compared to a conventional design, due to less heat development in the rotor, smaller iron losses and water-cooling instead of air-cooling. This paper was carried out fully by myself.

Refereed conference paper accepted for oral presentation.
Paper E: Upgrading generators with new tools and high voltage technology

Hydropower is the largest renewable energy source used in the world today. In Sweden alone, approximately 70 TWh/year is produced by hydropower plants that have been built mainly during 1940s-1960s. In this paper five high voltage generators of different sizes have been calculated and simulated. Losses and overall efficiency for the new generators have been compared with those for five existing hydropower generators in Sweden. The outcome shows it possible to reduce the losses in the generators if the new generators are adapted to the existing surrounding grid. My contribution to this article was calculation and simulations of 3 of the generators, some of the writing and the final touch of the paper outlay.

Published in Hydropower & Dams.

Paper F: Rotor concept comparison for underwater power generation

Generators with a different rotor but with an identical stator were simulated. Two of the generators had rotors with permanent magnets, one with pole shoes and ferrite magnets and one with surface mounted neodymium-iron-boron magnets. The third generator had an electromagnetized rotor. The simulations showed it possible to design generators with similar properties independent of the rotor.

Both permanent magnets and induction rotors have benefits and drawbacks. However for applications where maintenance is believed to be expensive, a permanent magnet offers a high reliability. At the time of this paper the simulation tool was not fully developed and it was not possible to extract the rotor losses. My contribution to this paper was very small.

Non-refereed paper, oral presentation.

Paper G: Dielectric study of Water/methanol mixtures for use in pulsed power water capacitors

To enable an inductive primary storage in a pulsed power system, the secondary storage needs to store energy for a few microseconds. For that purpose a water capacitor using a mixture of water and methanol was built and experimentally tested.
The ability to store energy for mixtures with 34 % and 51 % methanol by mass was investigated in the paper. Storing times of 3.4 milliseconds at an electric stress of 12 MV/m was measured. Experimental work and writing was carried out mostly by myself.

Published in Journal of Applied Physics.

Paper H: Flywheel energy and power storage systems

Storage of energy in flywheels has a long history. In earlier days it was used to smooth various types of operations. Today material and electronic development opens the area for flywheel energy storage and it can be used in vehicles or as a power backup storage. In this review article, an overview of flywheel technology and previous studies are presented. Simulations are carried out for a 200 kW, 1 kV axial flux motor/generator intended for use in a flywheel. The outcome of the article is that losses play an important role for flywheel storage and that the motor/generator part shows a great development potential. Literature review and writing was done by myself. Simulations were done partly by myself.


Patent I: System for storage of power

To achieve a fuel efficient vehicle manufacturers strive towards an efficient onboard power distribution and struggle to keep the overall weight down. The low voltage systems used in electric vehicles today convey difficulties to handle high power transfers and the thick copper wires needed for current transport introduce extra weight.

The patent comprises a flywheel power storage unit primarily intended for use in vehicles. The unique feature is that the flywheel motor/generator is provided with two stator windings, one low voltage and one high voltage winding. The power storage unit can transmit power to and from an electric apparatus as well as store energy transmitted from an electric apparatus.

I was involved in producing the idea for this patent.

Published international pct. Granted in Sweden.
Paper J: Rotating and linear synchronous generators for renewable electric energy conversion - an update of the ongoing research projects at Uppsala University

This conference article presents a survey of the research areas performed at this department. A description of the areas, an update of the research and future goals are given within the renewable and pulsed power areas.
Non-refereed paper, oral presentation by myself.
7. Summary of Results and Discussion

Generators

Large generators with production capabilities exceeding 1 MW have been around for more than 100 years. Meanwhile, technological advances have been implemented and accompanied by a rise in generator efficiency. Thinner sheets in the stator steel, different ventilation techniques and on site mounting are some of the steps towards better generators. Still, generators are not perfect, new ways of thinking and yet undiscovered applications may lead the generator development into different directions. A scenario where each generator used is individually designed to match the energy source and the load would be ideal, but hardly economically feasible. The technical performance of new designs can only, and also needs to, be matched against the existing solutions for efficiency validation.

Papers A to C shows that power flow in generators can be simulated using a Poynting vector approach. One of the issues scientists struggle with today is to develop a method where the divergence of Poynting’s vector is used to calculate losses in the stator steel. Simulations were made for generators with no losses but it is a first step and the model can be enhanced further. In paper A it is shown Figure 41 that, for a generator operating under no-load energy still traverse the air gap although it integrates to zero (losses not included). At heavier load and increased load angle, energy flow becomes more unidirectional as is shown in Figure 42 and Figure 43.
Figure 41 Radial part of the energy flow in the air gap and for the six cables at no-load for one pole-pitch. All power flow integrates to zero (losses not included), the flow is nonzero due to the flux paths being drawn to the teeth, i.e., cogging. The flow around the cables is not drawn according to scale.

Figure 42 Detail of radial flow of energy near the pole at 0 degree rot, for a machine with at normal load. The energy flow is largest in front of the stator slots where the cables pick up the power. The load angle shifts the flow towards one side of the pole (the rotor is moving counter clockwise).
The articles also show the equal importance of both electric and magnetic fields needed to create a power flow. They also show that previously much attention was directed to maximize the current and thus the magnetic field. In Paper B simulation of the power flux in terms of Poynting’s vector for round and rectangular cables Figure 44 shows the effect of field enhancements at the conductor edges. It is clear that designs with no sharp edges allows for a higher electric field.

To decrease losses and increase working efficiency, high power/high speed generators can be beneficially designed and optimized with respect to electric field rather than magnetic field i.e. high voltage and low current.
Generation of electricity

From an electromagnetic point of view, a generator is made more efficient with higher rotor speed and with a higher voltage. Hydropower generators are direct driven by a turbine and rotate much slower than a turbo generator. In Paper E it was found that theoretically and design wise, new hydropower generators, incorporating high voltage technology with surrounding electric equipment, can due to lower losses be made to produce up to 1% more energy than the existing system. Looking only at the electromagnetic losses in the generator, Figure 45 shows the losses in kW per generated MW for different sizes of conventional generators and simulated high voltage generators. It is clear that the difference in losses is substantial.

![Figure 45 Power loss per generated MW for different sizes of conventional and high voltage generators.](image)

It has also been found that large permanent magnet generators can be constructed using new rare-earth metals (Paper D). For a 20 MW machine 1500 kg of magnets had to be used and even though it can theoretically function, two major issues still needs to be examined. First, eddy currents in the rotor magnets and its influence on the overall performance. Second, the mounting of permanent magnets.

Overall the generators presented possess the following:

- A permanent magnet rotor implies a less complex design with lower losses in the rotor and an overall higher efficiency.
- For direct driven generators, when the gearbox is excluded, the need for maintenance is decreased and the reliability increases.
- Fast rotating generators can, for a given power, be made smaller which is associated with lower losses and less weight.
Turbogenerators and generators in flywheel power storages rotate very fast. Fast rotation is ideal for high voltage generation. There exists a possibility to deviate from direct generation of 50 Hz and instead make use of the fast rotation speed; thereby obtaining a smaller generator. One of the limiting factors will then be the induced eddy current in the rotor poles, in the stator steel and in the stator conductors. Rotor eddy currents are most crucial if permanent magnets are used, since they will heat the magnet and decrease the remanence.

Energy Storage

From Paper H on flywheels it can be seen that most flywheels rotate with speeds between 10 000 – 100 000 rpm. The motor/generator part of the flywheel should therefore ideally be built for high voltage if the surrounding equipment benefits from that. XLPE insulation offers the possibility to construct motor/generators with operating voltages far above the nominal. With the Powerformer™ technology it is theoretically possible to construct flywheels for direct generation of high voltages. In electric vehicles equipped with both an energy source and a power source, a flywheel combining high and low voltage can be used as power storage unit (Paper J). It has also been concluded that one of the major problems for flywheels constructed with neodymium-iron-boron permanent magnets is their high conductivity which will give rise to induced eddy currents on the magnet. One method for decreasing the eddy currents is to construct the magnet pole with several thin magnet-sheets, in the same manner as the stator steel. Problems with induced eddy currents in the rotor magnets are also present for turbo generators due to their large rotor poles.

Water capacitors using a mixture of water and methanol show ability to store energy longer than other water/alcohol mixtures do (Paper G). Lowering the temperature can hamper the self-discharge to levels where energy can be kept for several milliseconds without too much loss, Table 11.
Table 11 **Electrical breakdown strength, $E_{\text{max}}$, intrinsic time constant, $\tau$, and effective stress time, $t_{\text{eff}}$, for water/methanol mixture in a cylindrical capacitor.** $X$ is the percentage by mass methanol, $E_{\text{max}}$ is the highest electric field before breakdown (in the cylindrical capacitor).

<table>
<thead>
<tr>
<th>$X$ (%)</th>
<th>$T$ (°C)</th>
<th>$\tau$ (ms)</th>
<th>$t_{\text{eff}}$ (ms)</th>
<th>$E_{\text{max}}$ (MV/m)</th>
<th>$\varepsilon_e$</th>
<th>$W_{\text{max}}$ (kJ/m$^3$)</th>
<th>$A$ (Js/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>34</td>
<td>+18</td>
<td>0.42</td>
<td>0.19</td>
<td>5.9</td>
<td>61</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>34</td>
<td>+12</td>
<td>0.61</td>
<td>0.25</td>
<td>5.9</td>
<td>63</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>34</td>
<td>0</td>
<td>1.26</td>
<td>0.58</td>
<td>9.8</td>
<td>67</td>
<td>28</td>
<td>17</td>
</tr>
<tr>
<td>34</td>
<td>-6</td>
<td>1.8</td>
<td>0.85</td>
<td>9.7</td>
<td>69</td>
<td>29</td>
<td>24</td>
</tr>
<tr>
<td>34</td>
<td>-13</td>
<td>2.23</td>
<td>1.05</td>
<td>12.1</td>
<td>71</td>
<td>46</td>
<td>48</td>
</tr>
<tr>
<td>34</td>
<td>-19</td>
<td>3.25</td>
<td>1.45</td>
<td>10.5</td>
<td>74</td>
<td>36</td>
<td>52</td>
</tr>
<tr>
<td>34</td>
<td>-20</td>
<td>3.37</td>
<td>1.44</td>
<td>12.2</td>
<td>75</td>
<td>49</td>
<td>71</td>
</tr>
<tr>
<td>34</td>
<td>-22</td>
<td>3.71</td>
<td>1.59</td>
<td>11.8</td>
<td>76</td>
<td>47</td>
<td>74</td>
</tr>
</tbody>
</table>

This type of water capacitors is geometrically small, due to the large permeability of the dielectric, which makes them ideal for fast discharges, something that is necessary for components in a pulsed power setup.
8. Conclusions

High voltage solid extruded dielectric cables can be used beneficially both for generators used in power generation and in flywheel power storages. The large freedom in stator outline enables the design of new types of powerful permanent magnet generators. For some applications, the surrounding transmission grid and the energy source both favor a high voltage generator. It has been concluded that high voltage generators in practice and according to the Poynting vector give rise to an efficient electricity generation. The possibility to use surface mounted permanent magnets for high power machines has been theoretically manifested. Rotating power storages comprising high and low voltage windings can be used for energy transfer at high power levels.
9. Future Work

The next step in simulation of power flow in generators is to simulate the power flow when stator core losses are accounted for and calculated using the divergence of the Poynting vector. Another step would be to develop the simulation code and implement it for transient simulations.

Flywheel storage units utilizing higher voltages and multiple stator windings, for simultaneous input and output of energy, can be developed and tested for pulsed power applications.


I samarbete med Eskilstuna Energi och Miljö AB var målet att studera verkningsgrad och vibrationer hos en turbo Powerformer™. Generatorns
beteende vid olika laster skulle jämföras med simulerade data. Mättekniska
problem gjorde dock att verkningsgrader inte kunde fastställas. Simulering-
arna utfördes dock. Vibrationsmönstret hos generatorn mättes med accele-
rometrar och med högfrekvensgivare. Amplitud och fas på vibrationerna
togs fram och vibrationsmönstret fastställdes. De områden på generatorn där
vibrationerna forplantade sig över till generatorkapseln lokaliserades.

I en generator överförs moment i rotorn genom magnetfält över till statorn
där spänning induceras i statorkablarna vilket i sin tur ger upphov till en
strömn. Under de senaste åren på projektet var målet att undersöka hur effek-
ten flödar från rotorn, över luftgapet, in i statorn och vidare längs statorkab-
larna. Detta gjordes genom att simulera en generator i ett program för ro-
terande maskiner som basarar sig på Finit Element Metod. Vid simulering av
generatorn räknades elektriska och magnetiska fält ut i luftgapet och runt
statorledarna. Genom att använda sig av Poynting’s vektor kunde effektflö-
det räknas fram och en bild av hur effektflödet ser ut när rotorn roterar kunde
skapas. Bilder av effektflödet skapades både för en generator i tomgång
(utan last) och för en generator med stor last.
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A doctoral dissertation from the Faculty of Science and Technology, Uppsala University, is usually a summary of a number of papers. A few copies of the complete dissertation are kept at major Swedish research libraries, while the summary alone is distributed internationally through the series Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology. (Prior to January, 2005, the series was published under the title “Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology”.)