# Series and Parallel Compensation for the Permanent Magnet Synchronous Generator at the Chalmers Test Wind Turbine

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***Abstract*—The objective of the work at Chalmers test station is to carry out research, maintain and run the wind turbine at the plant. The station is used for research projects and as a demonstration and lab facility. The turbine is equipped with a permanent magnet direct-driven generator and an electrical system with a DC link suited for variable speed operation. Research focuses mainly on the generator and its electrical system. Series compensation of the PM generator is investigated. Theoretical studies show that the use of capacitors in series with generator windings in comparison to the present parallel capacitors can increase power output from the generator at a certain design speed interval. Both theoretical calculations and practical tests show that an increase in power by 60 % is possible.**

***Index Terms*—Compensation, PM generator, parallel, series, wind turbine.**

## I. INTRODUCTION

THE world is seeing a rapid increase in wind power production. Wind turbines are becoming larger and electrical systems are developing towards variable speed operation. Direct-driven permanent magnet generators have been introduced. Their qualities make it likely that they will have a growing share of the wind turbine market. Direct-driven PM generators in wind turbines always need some kind of power electronics to allow for variable speed and adapt to grid frequency. Because of the high inductance in direct-driven PM generators, reactive power compensation must be provided by the power electronics. This paper studies one option for designing a simple, efficient and cost effective electrical system to maximize electrical output utilizing a simple diode rectifier. Practical tests have been conducted on the Chalmers wind turbine generator. Measurements are compared to theoretical calculations.

## II. THE GENERATOR AND THE ELECTRICAL SYSTEM

The system in the Chalmers wind turbine consists of a permanent magnetized direct-driven generator with a diode rectifier and a grid inverter. The objective is to obtain a simple, reliable variable speed system with high efficiency. It is a challenge to design a simple yet effective electrical system for this kind of generator since it has a large reactance and there is no potential to vary the field strength because of the permanent magnets. To compensate for the voltage drop over the reactance, different methods can be used. If an active rectifier is used it could provide reactive power to compensate for the voltage drop. Another method is to use capacitors connected to the generator either in parallel or in series with the generator coils. Because of the large number of modules on the test turbine generator described below, an active rectifier was ruled out since each module would have required its own active rectifier. This paper investigates the advantages and drawbacks of parallel and series capacitors.

### *A. The Generator*

The Chalmers test turbine is equipped with a permanent magnetized direct-driven synchronous generator. It was designed in 1996 in England and was built as an experimental machine with a rated power of about 40 kW at a rated speed of 75 rpm. The objective was to develop a direct-driven generator adopted for wind power. The generator was designed and built as part of an EU project. It was built as a pre-study for a 500 kW generator of the same design. The generator design is characterized by a modular arrangement [2] whereby modules of a set size, for both the permanent-magnet rotor and the stator, can be assembled to produce a machine of any required rating within a wide range. The dimensions of the modules of the 40 kW experimental machine have been optimized for the 500 kW design. By reducing the number of modules and the length of the machine, the size was reduced to 40 kW. The stator consists of 27 modules. Each module consists of an E-core of laminated iron with a concentric coil on the center leg of the E-core. The laminated iron core surrounds a steel tube. Its function is to support the stator module and provide cooling for the module. The tube has open ends, which allows ambient air to flow through the tube. The rotor has 48 modules arranged to give 24 pole pairs. The rotor uses ferrite magnets and flux concentrators of laminated iron. The rotor diameter is 1287 mm and the air gap is about 3.25 mm. The active length of the modules was set to 100 mm. Mechanically, the generator was designed to include all bearings necessary to carry the turbine mounted upwind on the shaft. This resulted in an overall diameter of 2110 mm, and length (not including the rear-end bearing) of 712 mm with a total mass of 4500 kg. Since the modules are optimized for a 500 kW generator size, the 40 kW generator became rather heavy and large related to its rated power. The mechanical design is shown in Fig. 1.

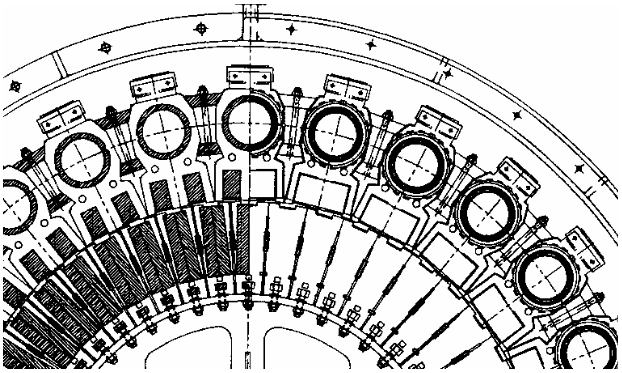

Fig. 1. Mechanical design of the generator.

### B. *The electrical system*

The AC voltages from each of the 27 stator coils are rectified separately in one diode rectifier each. The rectified voltage is then connected to a common DC link. The DC link is then connected to a grid inverter. The generator torque is controlled by the DC current taken by the grid inverter. Each stator coil gives an open circuit voltage of 192 V rms and a frequency of 30 Hz at rated speed 75 rpm. To counteract the voltage drop over the relatively large inductance of about 112 mH in the coil, a capacitor is placed in parallel with each coil so as to achieve a higher power output into the DC-link. Maximum power is reached at a stator coil AC current of about 7.5 A rms. The stator coil short circuit current is about 8.1 A rms. An electrical brake is mounted on the DC link. Its objective is to reduce turbine speed to a low value in case of inverter or grid failure. The efficiency of the generator and diode rectifier with parallel compensation is about 85% at maximum power and rated speed. The electrical layout is shown in Fig. 2

Each stator coil is represented with its equivalent schematic ($U_{pm}$, R, L). The upper branch consists of 14, and the lower branch of 13 modules. The modules in both branches are internally connected in parallel to each other on the DC side of the diode rectifier. The branches, in turn, are connected in series with each other to produce a voltage and current level more suitable for the existing grid inverter. The smoothing capacitors $C_{DC}$ are 3300 μF each. The parallel compensation capacitors $C_p$ are 60 μF each.

## III. PARALLEL VERSUS SERIES COMPENSATION

Capacitors are often used to compensate for reactive power consumption in an inductive load. Normally, the capacitors are connected in parallel to the load. One example is the capacitor used in a fluorescent tube armature, where it compensates for the inductance in the choke coil used for limiting the current through the fluorescent tube. Without the capacitor, reactive power will be taken from the grid. Grid current will increase as well as the losses. At full compensation, no reactive power is taken from the grid.

In the case of a direct-driven PM generator with a diode rectifier, there was no grid that could provide reactive current

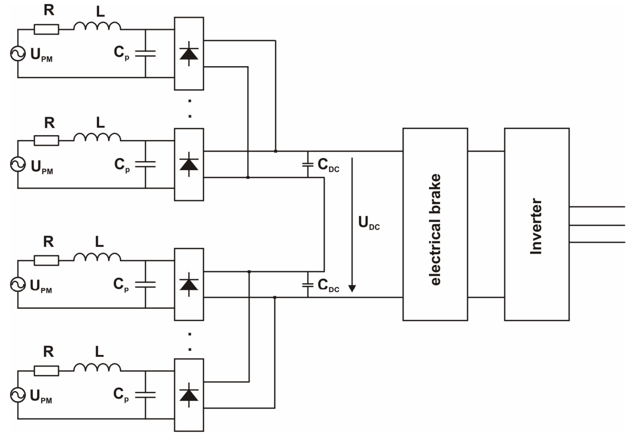


Fig. 2. Chalmers test turbine generator electrical system with parallel compensation.

to compensate for the reactive power consumption in the stator inductance. If the system is loaded so that active power is produced by the generator, the result will be a substantial voltage drop limiting output power. A voltage drop can, to a large extent, be counteracted if reactive power is supplied in some other way to the generator.

In its original design, the test turbine generator is equipped with capacitors connected in parallel to the stator coils of the generator [3]. An alternative is series compensation where capacitors are connected in series with the generator coils [4]. Series compensation of generators has been described as early as 1933 [ 5].

Parallel compensation has one main advantage compared to series compensation in that it allows for relatively high power output from the generator at a rotor speed lower than rated speed. Some disadvantages are a relatively low maximum output power, a high no load voltage at rated speed and a relatively high current flow between the coil and the capacitor even at no load. The reactive power produced by the parallel capacitors is frequency-dependent and hence rotor speed dependent. However, it does not follow the demand for reactive power from the generator which instead is load dependent. With series compensation, the reactive power produced by the capacitor follows variations in the generator's reactive power consumption, as the generator current changes. The no load voltage is of the same value as the generator coil open circuit voltage since there is no current through the series capacitor and hence no voltage over it.

### A. *Parallel compensation*

Parallel compensation means that a capacitor is placed across the terminals of the stator coil. Fig. 3 shows the equivalent circuit of one stator coil, a parallel capacitor and a load. The stator coil equivalent circuit consists of induced voltage, coil resistance and coil inductance.

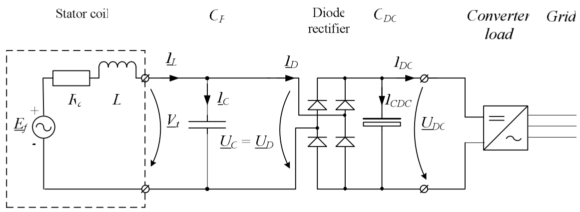


Fig. 3. Parallel compensation, $E_f$ : Induced voltage in the coil, $R_a$: coil resistance, L: coil inductance, $C_p$: parallel compensation capacitor.

It can be seen [1], that the optimal parallel capacitance for maximum power output is

$$C_p = \frac{1}{2\omega^2 L} \quad (1)$$

where

ω stator current angular frequency

For the Chalmers test turbine generator the optimal parallel capacitance at rated speed is about 121 µF. Due to restrictions on the no load voltage level and in order to reduce losses from the reactive currents flowing between the coil and the capacitor even at no or low load, a capacitor value of 60 µF was chosen.

### B. Series compensation

One general drawback of parallel compensation is the high reactive power at low load and that compensation decreases with increasing load which leads to a relatively low peak power output. Another drawback of parallel compensation is the high no load voltage. At the Chalmers test turbine, the DC voltage has to be limited with a special voltage controller which increases the DC current if the voltage gets too high. This takes the turbine out of optimal control, which lowers overall energy production.

To overcome these drawbacks, series compensation has been investigated. The circuit is shown in Fig. 4. The level of compensation is not dependent on the size of the load, but only on speed/frequency. To obtain maximum output power from the circuit, the series compensation capacitor should have the same capacitive reactance as the generator coil inductive reactance. Voltage drops over the inductance and the capacitor then cancel each other out, and the stator current will be in phase with the induced voltage, $E_f$. This is called full compensation.

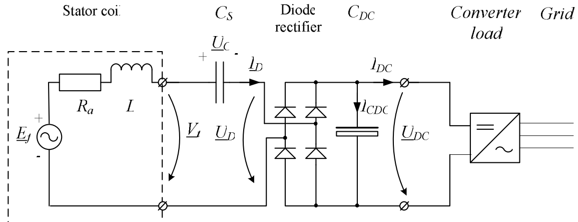


Fig. 4. Series compensation, $E_f$ : Induced voltage in the coil, $R_a$: coil resistance, L: coil inductance, $C_s$: series compensation capacitor.

The series capacitance for full compensation can be calculated as

$$C_S = \frac{1}{\omega^2 L} \quad (2)$$

Full compensation is achieved for one angular frequency only. Since the angular frequency is related to rotor speed, compensation must be tuned to one particular rotor speed. To obtain the most power from the generator with series compensation, full compensation should be tuned for the highest generator speed normally used, e.g. rated speed. For the Chalmers turbine $C_{Sfull}$ is about 251 µF at rated speed. One drawback with series compensation is the relatively low power at lower speed. If more power is required at lower speed, half compensation at rated speed can be used. Half compensation means that half the voltage drop over the inductance is compensated.

$$C_{Shalf} = 2C_{Sfull} \quad (3)$$

When the speed drops, the generator becomes fully compensated at a speed below rated speed, and the maximum achievable power at that speed is achieved. The drawback is lower peak power and that more capacitors are needed.

### C. Maximum power

Calculations of power as a function of rotor speed have been conducted for the Chalmers turbine generator for some different situations, and are also compared to measurements. The stator coil resistance, $R_a$, was neglected in the calculations. An inductance value, L = 112 mH and the induced voltage $E_f$ = 192 V, 30 Hz at 75 rpm were used in the model.

In Fig. 5, calculations of the maximum achievable rectifier power as a function of generator speed is plotted. Diagram a), shows full and half series compensation at rated speed, and diagram b), shows parallel compensation. The parallel capacitance used in the calculations is $C_P$ = 60 µF.

Both graphs also show maximum power with the ideal rectifier (sinusoidal current, $I_D$, in phase with the induced voltage, $E_f$) and maximum power with no compensation.

A generator coil current limit of 13.75 A affected calculations of half- and full-series compensation, as well as ideal cases. Without a current limit, the theoretical peak power would be infinite with the equivalent circuit shown in Fig. 4, when $R_a$ is neglected. The current limit was set to the value that was shown to produce the highest power output for full-series compensation at rated speed, according to measurements (Fig. 7).

In the no compensation case, a generator coil current of 6.45 A rms gave the maximum power output for all rotor speeds.

Measurements with series compensation were conducted for one single module. The series compensation capacitance, $C_S$, was 250 µF. The total DC current and DC power was calculated with

$$I_{DC} = 13{,}5\, I_{DC\ single\ phase} \quad (4)$$

and

$$P_{DC} = 27\, I_{DC\ single\ phase}\, U_{DC\ single\ phase} \quad (5)$$

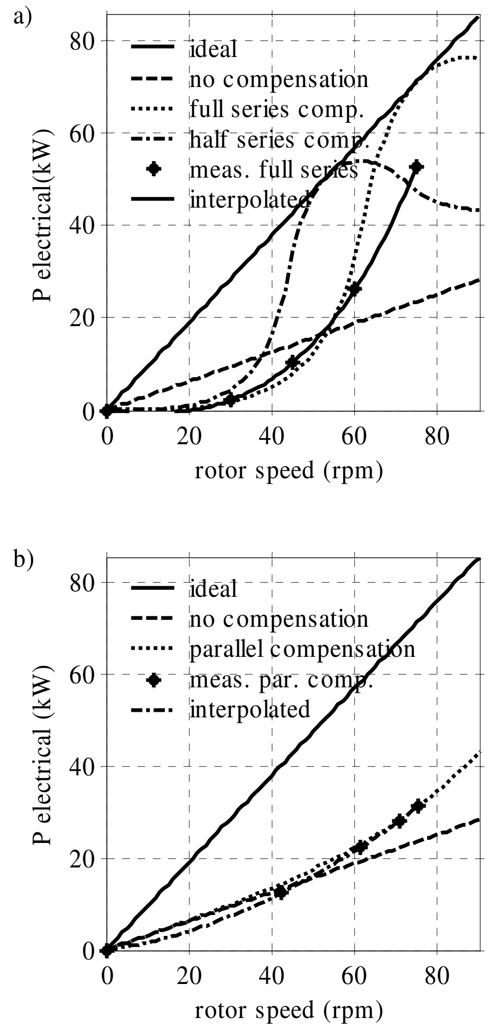


Fig. 5. Analytical calculation and measured values of the maximum electrical power as a function of the rotor speed with a generator coil current limit of 13,75 A rms. a) Ideal-, no-, full series-, half series-compensation and measured values for full series compensation. b) Ideal-, no-, parallel- compensation and measured values for parallel compensation. $C_p$ = 60 µF.

The diagram in Fig. 5,. shows that the use of series compensation results in higher power output near rated speed than parallel compensation. In the lower speed range parallel or even no compensation results in a higher power output. Half series compensation gives a higher power in the low speed range than full compensation. The measurements show a good agreement with the calculated values for parallel compensation. For series compensation the agreement is good in the lower speed range. The measured value at 75 rpm shows a significantly lower power than the calculated value. The reason for this is mainly that the generator iron becomes saturated when the current increases. This led to a lower coil inductance which in turn affected the degree of compensation. Another reason was the resistive losses which increased quadratic with the increase in current.

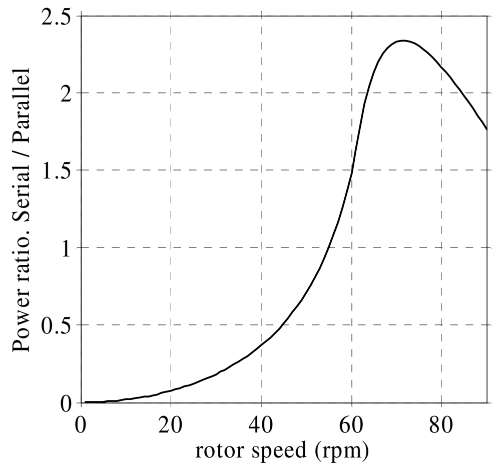


Fig. 6. Ratio between calculated electrical power for full-series compensation and parallel compensation as plotted in Fig. 5 a) and b) as a function of rotor speed.

The relation between the calculated electrical power of full series compensation and the parallel compensation as a function of rotor speed was plotted in Fig. 6. Above 55 rpm, series compensation produced a higher power output.

In Fig. 7, using the same measurements as in Fig. 5, the measured power for series and parallel compensation was plotted as a function of the DC link current at different rotor speeds.

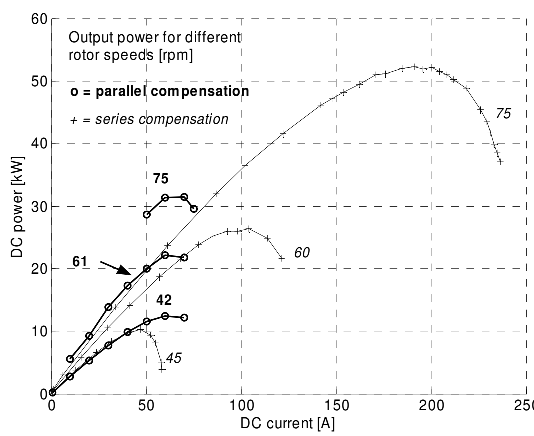


Fig. 7. Measurements of maximum output power with parallel compensation, $C_p$ = 60 µF, and series compensation, $C_S$, = 250 µF, at different rotor speeds.

Measurements show a maximum power of about 32 kW for parallel compensation and about 53 kW for series compensation. For the Chalmers test turbine generator, the increase in power output was about 60% achieved by using series instead of parallel compensation. At full power with series compensation and 75 rpm, the generator iron was partly saturated. This affected the coil inductance. It might be possible to increase the maximum power output a bit by tuning the series capacitor more accurately to the actual coil inductance. However, the magnetic flux capability of the generator put a physical limit on the maximum power output.

At the Chalmers test turbine, the increased losses in the generator when using series compensation at full power did not seem to cause overheating according to measurements and calculations [1]. This was primarily because of the relatively large physical size of the experimental generator in relation to its rated output power. For a commercial design, cooling capabilities could be a limiting factor on continuous rated power.

### D. *Generator power versus aero dynamic power*

When the generator is used in a wind turbine application, the demand on the generator is such it can absorb all the power that the turbine can produce throughout the entire speed range. In Fig. 8, a graph describing the maximum possible shaft power for the Chalmers turbine blades in any wind speed is compared to the maximum mechanical power of the generator. The Chalmers turbine is two-bladed and has a fixed pitch. Turbine power is stall controlled. This means that the only way to limit power from the turbine is to limit rotational speed. The generator mechanical power was calculated using the electrical power in Fig. 5 and an efficiency of 85 %. The actual efficiency (for parallel compensation) varies between 85 % at full load and 90% at partial load, App F. in [1])

The diagram in Fig. 8 b) shows that the rotor speed must not exceed 75 rpm for parallel compensation. At lower speeds the available generator power was greater than the maximum turbine power.

For series compensation, Fig. 8 a), it can be noted that a higher speed and output power could be allowed both for full and half compensation. Problems may arise in controlling speed below 40 rpm at full compensation. For the Chalmers turbine, the lowest turbine speed in normal operation is 40 rpm. One drawback with full series compensation in the Chalmers turbine could be the limited ability to bring the speed down from 40 rpm to almost standstill by generator braking, which is presently used when the turbine is parked. By using half compensation instead, the generator power at low speed is increased.

Nevertheless, the Chalmers turbine has a mechanical emergency brake that can be used to stop the turbine. If a generator of a similar type with series compensation is used in a commercial turbine, a variable pitch turbine is recommended.

If variable pitch blades are used, the blade angle can be held optimal over a wider wind speed range than for fixed pitch, and more power can be extracted from the wind. Induction generators commonly used in wind turbines can absorb twice the rated power, or even more, for a short while. Low speed PM-generators have a low peak power related to the rated power. For the Chalmers turbine generator, the peak power is equal to the rated power. If variable pitch is used, this is an advantage, since it can be used to more accurately adapt the maximum turbine power to the rated power of the generator at high wind speeds. If fixed pitch is used instead, the maximum power from the turbine blades must be somewhat lower than the generator rated power to prevent a runaway, and the generator capacity will not be fully used.

Variable pitch and series compensation will result in the highest energy capture.

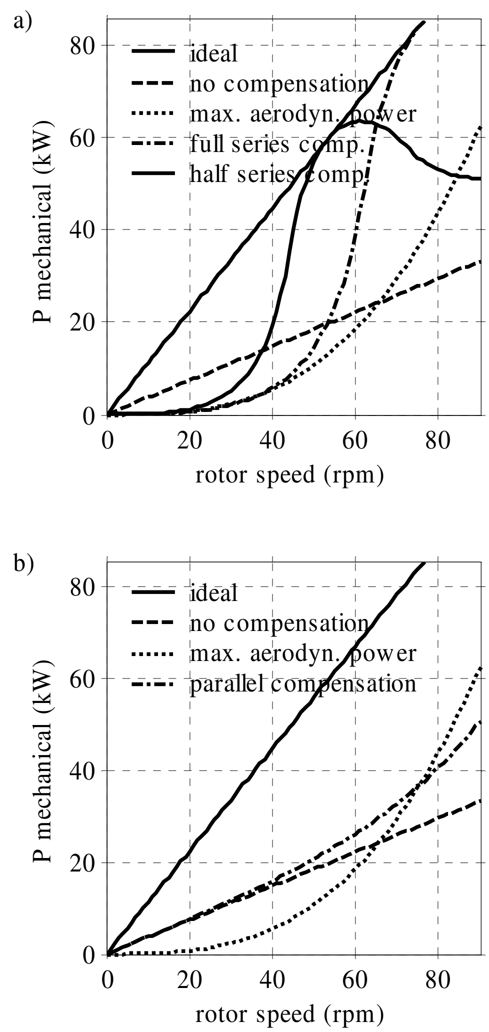


Fig. 8. Analytical calculation of the maximum generator shaft power as a function of rotor speed with a generator coil current limit of 13,75 A rms compared to the maximum aero dynamic power. a) Ideal-, no-, full series-, half series-compensation. b) Ideal-, no-, parallel-compensation. $C_p$ = 60 μF.

## IV. FEM-ANALYSIS APPLIED TO THE CHALMERS TEST WIND TURBINE GENERATOR

The Finite Element Method (FEM) is a numerical analysis method for solving (partial) differential equations. The method is very useful in combination with complex geometry. The geometry in question is here divided into a mesh of elements consisting of triangles in 2D and tetrahedrons in 3D. The analysis is then performed separately for every single element. The result of this analysis is modeled as polynomials (one polynomial for each element) in the spatial coordinates, e.g. x, y. The finite element analysis is the solution of the set of equations for the unknown coefficients in all polynomials. By a system analysis the results from the single elements are adapted into a total system solution. This is done by matching the results of adjacent elements to each other, e.g. connecting adjacent elements to each other.

One important use for FEM is to solve electromagnetic problems. In the present case, it is of interest to solve problems in the low frequency region. This is when the electromagnetic wavelength ($\lambda = c/f$) is much larger than the geometrical dimensions.

FEM analysis was, in this project, performed to obtain more theoretical knowledge about some important electromagnetic phenomena, e.g.

- demagnetization of the permanent magnets
- the air gap (between stator and rotor poles) dependence on induced voltage
- the harmonic properties of induced voltage
- coil inductance and its dependence on the relative position between stator and rotor poles

For more detailed information on the FEM analysis in the current project see [1], Appendix B.

### *A. Basics*

The configuration of the device is shown in Fig. 1. and Fig. 9. The first approximation was to handle the generator as a symmetric design. This was not quite correct (there are 24 × 2 rotor poles and 27 stator E-cores). It is important to keep this approximation in mind when using the model. For example, this approximation made it impossible to study the field in more than **one** stator E-core at the same time (same rotor position), and to compare results.

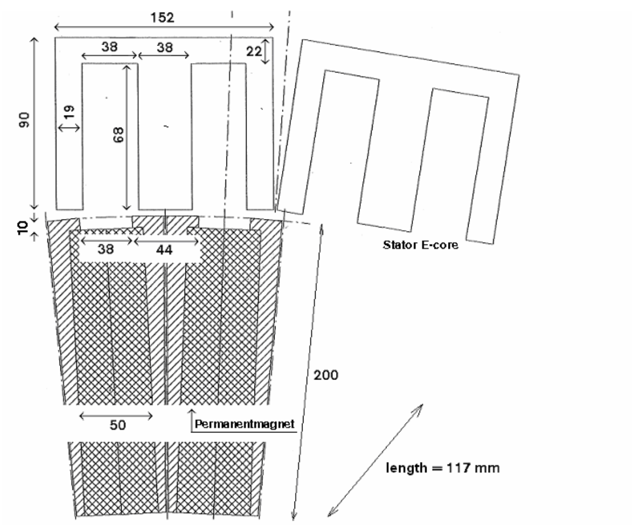


Fig. 9. The stator- and rotor modules. Dimensions in mm.

The following materials were used in the FEM calculations:

A permanent magnet: Ceramic ferrite with B-Max: 0.4 T and Hc: $-2.7{\cdot}10^5$ A/m

Other components: Cold rolled 1010 steel with B-Max: 2.15 T, Hc: 0

The distance between two equivalent points of stator modules was assumed to be 165 mm, see Fig. 10 The air gap between rotor and stator was 2 mm, nominal value. Fig. 10 illustrates the geometry of the model that was used in the FEM analysis. Fig. 11 shows a part of the geometric model with an example of a 20 mm shift (x-shift) from the symmetric position between a stator pole (E-leg) and a rotor pole. Calculations were performed with different x-shifts at intervals of 0 to 82.5 mm. As the distance between two equivalent points of stator modules was assumed to be 165 mm, we obtained a symmetry around a shift of 82.5 mm, 165mm + 82.5mm, 2 × 165mm + 82.5mm, ….., and so on. Fig. 12 shows the calculated flux image corresponding to Fig. 11.

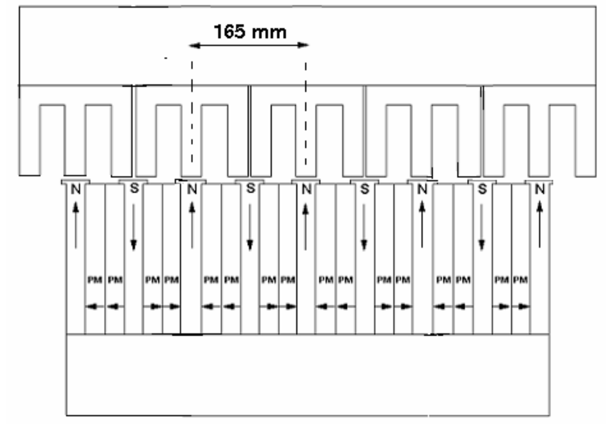


Fig. 10. Model configuration for 9 poles in combination with 5 E-cores. The figure illustrates the magnetic flow direction in the rotor parts. The figure shows an example of a relative position between the poles and the E-cores where the x-shift is zero.

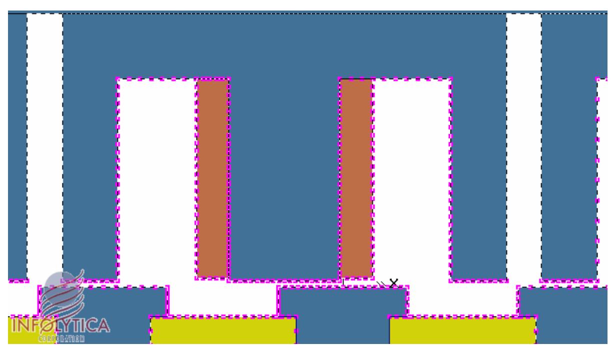


Fig. 11. Part of the geometric model. X-shift in this example is 20 mm. The coil is wired around the middle E-core.

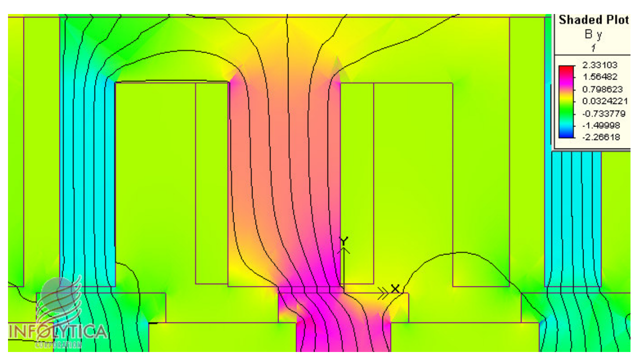


Fig. 12. Calculated flux image corresponding to Fig. 11.

Fig. 13 shows a plot of how flux linkage varies when the shift is alternated.

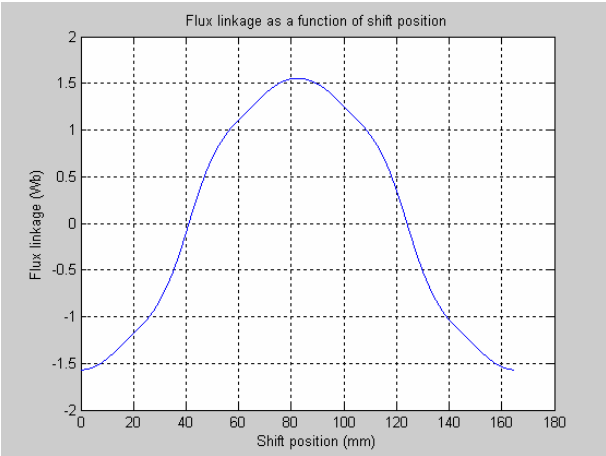


Fig. 13. Flux linkage for a coil (323 turns) vs. shift position.

The position dependent flux linkage, according to Fig. 13 could be divided into a DC-component, a fundamental frequency and a number of harmonics. Fourier analysis (Section D) justifies the approximation of the flux variation with a single sinusoidal function based on the fundamental frequency. This results in a simple expression for the corresponding induced voltage in the coil if we suppose a flux linkage variation as a result of ordinary relative movement between the rotor and the stator. Assume the following generator parameters:

A: amplitude of the fundamental regarding flux linkage (Wb)

$V_{rot}$: generator rotating speed (rpm)
P: number of pole pairs in the rotor
$\phi(t)$: flux linkage (Wb)
$e_f(t)$: induced voltage in the coil (V)

This results in the following equations:

$$\phi(t) = A \cdot \sin(\frac{Vrot \cdot P}{60} 2\pi \cdot t) \quad (6)$$

$$e_f(t) = (-)\frac{d\phi(t)}{dt} = (-)A \cdot \frac{Vrot \cdot P}{60} 2\pi \cdot \cos(\frac{Vrot \cdot P}{60} 2\pi \cdot t) \quad (7)$$

The equivalent electrical circuit of a single stator module is given as a part of Fig. 3. $R_a$ is the coil resistance (Ω) and L is the coil inductance (H). The following values were used in the simulations:

$R_a$ = 1.0 Ω (20 °C)
L = 106 mH (mean value 20 °C)
P = 24

The fundamental amplitude A, based on FEM analysis and Fourier analysis (according to Section D) was calculated to be 1.615 Wb.

For more detailed information around the appropriate FEM analysis, see [1], Appendix B, Section 3.

## B. No load calculations

Table 1 shows some examples of no load voltages (rms), calculated using (7), for a stator module when the rotor speed is varied.

Table 1 Some examples of no load voltages (rms) for the stator module at different rotating speeds

| Rotor speed (rpm) | No load voltage, (V rms) |
|---|---|
| 50 | 144 |
| 70 | 201 |
| 80 | 230 |

For more detailed information about the no load calculations, see [1], Appendix B, Section 4.1.

## C. Load calculations

To calculate load currents and load voltages a special kind of simulation tool called “PLECS” (Piecewise Linear Electrical Circuit Simulation) was used. The circuit according to Fig. 14 corresponds to the circuit in Fig. 3 with a load consisting of the ordinary “load circuit” (capacitor (C2) for reactive power compensation, diode bridge (D1 – D4), capacitor (C1) in parallel with a resistor (R1) representing the loaded DC-AC converter) for a stator module. Fig. 15 - Fig. 18 shows results of measurements and simulations of a rotor speed of 80 rpm and a total power of 20 kW.

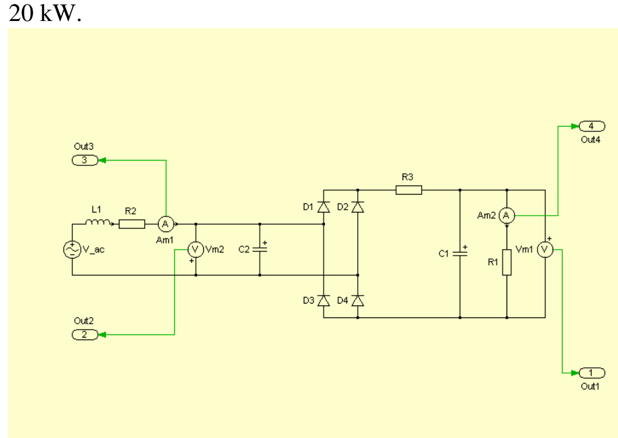


Fig. 14. PLECS circuit used for simulation.

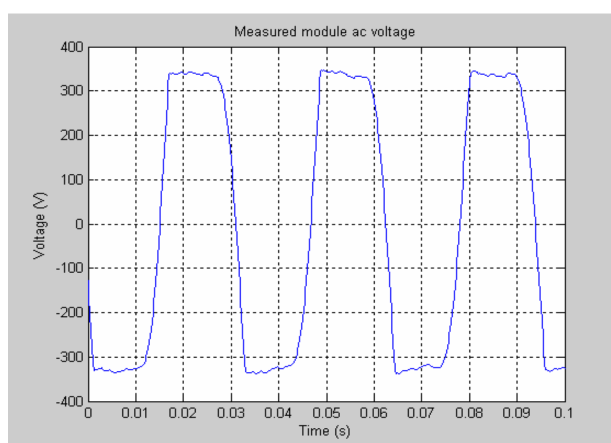


Fig. 15. Measured module voltage. Rotor speed 80 rpm. Power 20 kW.

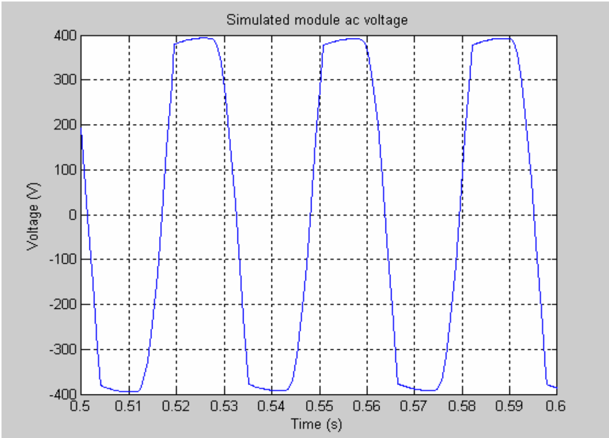


Fig. 16. Simulated module voltage. Rotor speed 80 rpm. Power 20 kW.

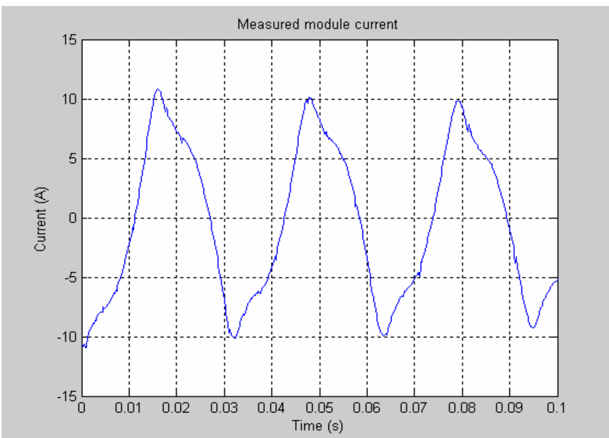


Fig. 17. Measured module current. Rotor speed 80 rpm. Power 20 kW.

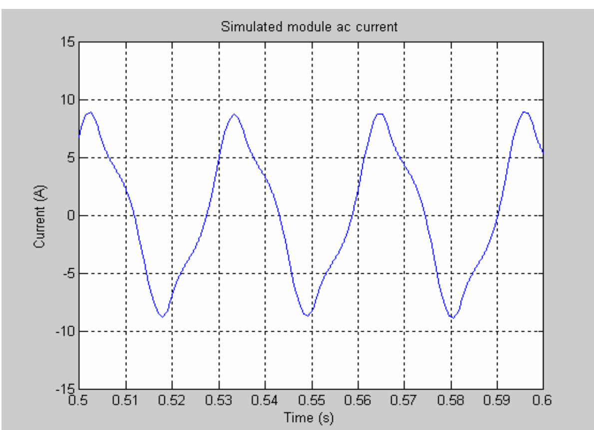


Fig. 18. Simulated module current. Rotor speed 80 rpm. Power 20 kW.

When comparing Fig. 15 (measured voltage) with Fig. 16 (simulated voltage) it can be noted that curve shapes are similar. The same similarity is found when comparing Fig. 17 (measured current) with Fig. 18 (simulated current). A corresponding comparison regarding the levels in question will give a voltage difference of about 14% higher top level for the simulated case than in the measured one and a current difference of about 20 % lower top level for the simulated case than in the measured one. However, as there are some uncertainties, especially regarding the stator coil inductance and the width of the air gap, a better agreement between simulated and measured results can not be expected. The stator coil inductance and the air gap is treated in section E and F.

For more detailed information about the load calculations, see [1], appendix B, Section 4.1.

*D. Fourier analysis*

According to the Fourier analysis of the calculated flux function, flux vs. time can be described by using 3 sine functions with frequencies corresponding to 1st , 3rd and 5th harmonics:

$$\phi(t) = A_1 \cdot \cos(\omega_1 t + \alpha_1) + A_3 \cdot \cos(\omega_3 t + \alpha_3) + A_5 \cdot \cos(\omega_5 t + \alpha_5)$$

$A_1 = 1.6166$
$A_3 = 0.1076$
$A_5 = 0.0696$

$\omega_1 = 2\pi \cdot 0.4 \cdot V_{rot} \cdot 1$

$\omega_3 = 2\pi \cdot 0.4 \cdot V_{rot} \cdot 3$

$\omega_5 = 2\pi \cdot 0.4 \cdot V_{rot} \cdot 5$

$\alpha_1 = \pi$
$\alpha_3 = 0$
$\alpha_5 = \pi$

$V_{rot}$ is the rotor speed (rpm). This function (with 3 terms) is shown in Fig. 19

If only the first term is used (i.e.: $\phi(t) = A_1 \cdot \cos(\omega_1 t + \alpha_1)$) the result according to Fig. 20 is on hand. As is illustrated, this results in a fairly good approximation.

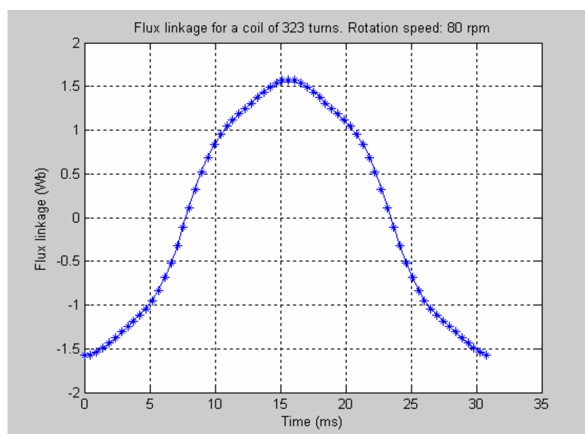


Fig. 19. Flux linkage for a coil of 323 turns vs. time. Rotation speed: 80 rpm, _ : original function, **: 3 sine functions (1st , 3rd and 5th harmonics)

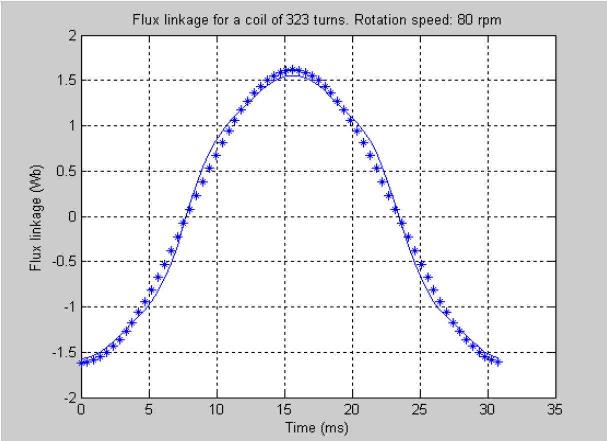


Fig. 20. Flux linkage for a coil of 323 turns vs. time. Rotation speed: 80 rpm, __ : original function, **: 1 sine function (1st harmonic)

For more detailed information about the Fourier analysis see [1], appendix B, Section 5.

### *E. Coil inductance*

Coil inductance was calculated (FEM analysis) as a function of the relative position between stator and rotor. The result is shown in Fig. 21.

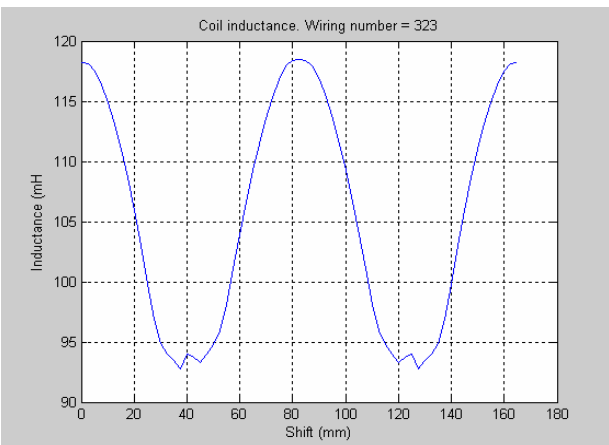


Fig. 21. Calculated inductance as a function of relative position between stator and rotor.

The variation in coil inductance will influence the induced voltage. Further studies will be conducted regarding this phenomenon. For more detailed information about the Coil inductance see [1], appendix B, Section 4.3.

### *F. The air gap between stator and rotor*

The air gap between rotor and stator was, in the simulations, assumed to be 2 mm as a nominal value. As a result of mechanical imperfections this value varied during the rotation motion. This variation caused, on the other hand, a variation in the resulting flux linkage of the coil and thereby also a variation in the induced voltage.

Calculations based on FEM analysis regarding the effect of varying air gaps were performed. Fig. 22 illustrates the relative flux linkage (relative to the flux linkage value when the air gap is 2mm).

Fig. 23 illustrates an example of measured "no load voltage and current" for the stator modules. The variation of voltage in the different modules is understood as an effect of varying air gaps between stator and rotor vs. rotor position. An air gap variation of about $\pm 0.15$ mm gives this effect, according to calculations.

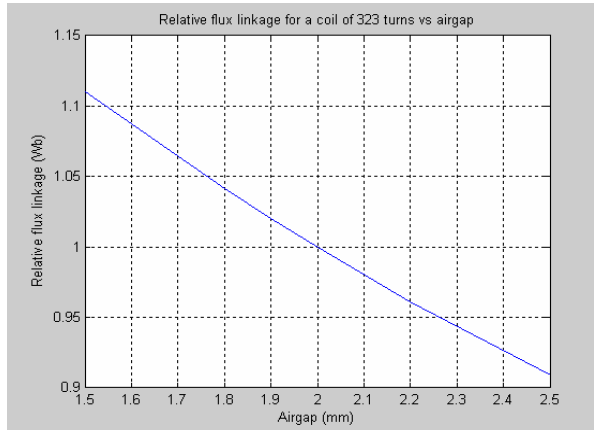


Fig. 22. The relative flux linkage vs. air gap. The reference is air gap = 2 mm.

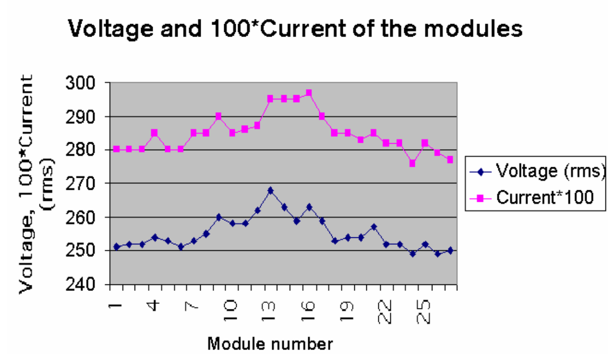


Fig. 23. No load voltage and current of the modules with parallel capacitors, $C_p$ = 60 µF connected. Rotor speed was 75 rpm.

Not only induced voltage is dependent on the air gap, even coil inductance varies with alternating air gaps. Fig. 24 illustrates calculated coil inductance vs. air gap.

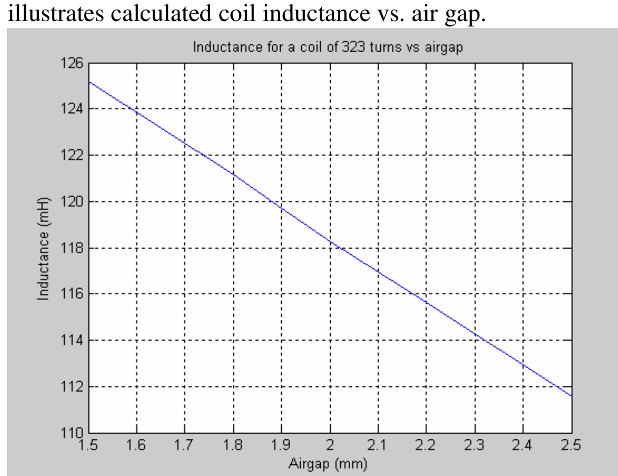


Fig. 24. The coil inductance is dependent on the air gap.

As a consequence of the discussion above, two parameters; induced voltage and coil inductance were taken into account when analyzing the resulting effect of air gap variations.
For more detailed information about the air gap between

stator and rotor see [1], Appendix B, Section 4.5.

### G. Demagnetization current

If a permanent magnet is exposed to an external magnetic field that is reversed to its own direction and that exceeds a certain limit, there is a risk for a reduction in permanent magnet capacity due to demagnetization. The size of this permanent demagnetization depends on the material in question and on the size of the reversed magnetic field. In the Chalmers test turbine generator, the permanent magnets in the rotor poles are exposed to a field from the stator poles that weaken the permanent magnet field, when the voltage drop over the stator coil inductance is not fully compensated. The worst case is when the stator winding is short circuited. The field from the stator poles does then have a value near the size of the rotor field, and the rotor- and stator fields have an almost opposing direction. [1], section 2.6.3. The steady state short circuit current has been measured to about 8.1 A rms. FEM calculations have shown a risk of demagnetization at a stator current of about 12 A rms. If a short circuit is applied to a stator coil when the generator is running, transient currents larger than 12 A rms easily can occur. The reversed field from a short circuit current that suddenly appears on a stator coil during operation is likely to partly damage some of the rotor magnets. On the other hand, at full compensation, the load current, and therefore the stator field, is displaced by 90° to the rotor field. High currents at full compensation are not likely to damage the rotor magnets. Measurements showed that the rotor magnets were not harmed by a stator current of about 17 A rms for the series compensation case. Further studies of the magnetic field at different load conditions and transient conditions will be performed.

For more detailed information about demagnetization current see [1], Appendix B, Section 4.2.

## V. Conclusion

The analysis of reactive power compensation showed that it is possible to increase active output power by a factor of more than 2 when using series compensation instead of parallel compensation. The measurements on the Chalmers turbine generator showed an increase of output power by a factor of only 1.6. The reason for this was mainly that the generator iron became saturated when the current increased. For low rotor speeds, below about 55 rpm for the Chalmers generator, parallel compensation, or even no compensation resulted in a higher output power than series compensation.

A FEM analysis gave more theoretical knowledge about different parameters and phenomena in the electromagnetic field:

- The analysis resulted in good correlation between measured and calculated output voltage/current values.
- A Fourier analysis showed that induced voltage is rather free from harmonics.
- The analysis showed that there was considerable variation in coil inductance when the relative position between stator and rotor poles was altered. This will influence induced voltage.
- It was possible to explain the air gap variation between the stator and rotor poles and its influence on induced voltage. The analysis showed that even very small air gap variations result in significant voltage differences.
- The analysis resulted in good understanding of the size of the stator current, which could be accepted without risk for permanent demagnetization of rotor magnets at short circuit conditions.

## Acknowledgments

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