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

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***Abstract*—The objective of Chalmers test station is to carry out research, maintain and run the wind turbine at the plant. The station is used in research projects as well as a demonstration and a 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 is focused mainly on the generator and its electrical system. An investigation of series compensation of the PM generator has been made. Theoretical studies have shown that the use of capacitors in series with the generator windings in comparison to the present parallel capacitors could increase the power output from the generator in a certain design speed interval. Both theoretical calculations and practical tests show that an increase of the power by 60 % is possible**

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

I. INTRODUCTION

THE world is seeing an very rapid increase of wind power production. The wind turbines are larger and larger and the electrical systems develop towards variable speed operation. It is also important that the costs for electric energy is keep low. This paper present one option to reduce the costs for the rectifier in a variable speed operation electrical system.

II. THE GENERATOR AND THE ELECTRICAL SYSTEM

The system consists of a permanent magnetized direct driven generator with a diode rectifier and a grid inverter. The objective is to realize a simple, reliable variable speed system with a 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 possibility 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 of the test turbine generator described below the active rectifier was ruled out since each module would have required its own active rectifier. This paper describes 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. The design was made 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 within an EU project. It was built as a pre-study of a 500 kW generator of the same design. The generator design is characterized by a modular arrangement whereby modules of a set size, for both the permanent-magnet rotor and the stator, may 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 are 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 surronds a steel tube. It's function is to support the stator module and provide cooling of the module. The tube has open ends, which allows the 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 becomes rather heavy and large related to it's rated power. The mechanical design can be seen in Figure **1**.

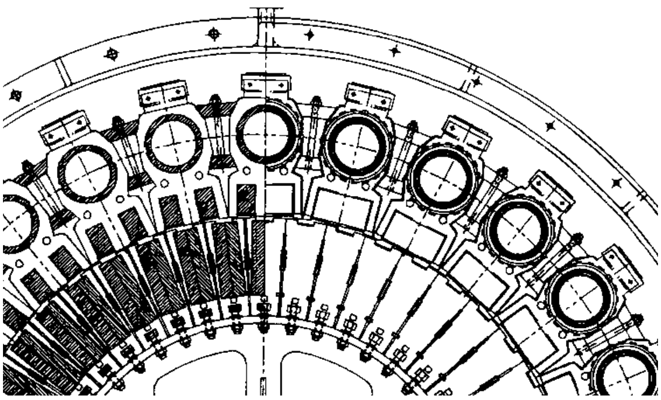

Figure 1. Mechanical design of the generator.

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 about 192 V rms at rated speed 75 rpm. To counteract the voltage drop over the relatively large inductance of about 116 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. It's objective is to reduce the turbine speed to a low value in case of an inverter or a 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 can be seen in Figure 2.

Each stator coil is represented of it's 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.

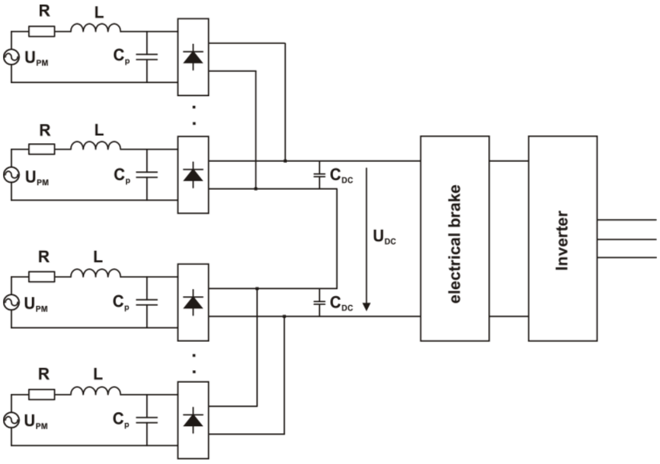

Figure 2. Chalmers test turbine generator electrical system with parallel compensation.

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. The grid current will increase and hence the losses. At full compensation no reactive power is taken from the grid.

In the case of the direct driven PM generator with a diode rectifier there is no grid that could provide reactive current 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 it will result in a substantial voltage drop which limits the output power. The voltage drop can to a large extent be counteracted if reactive power is supplied in some other way to the generator.

The test turbine generator is in it's original design equipped with capacitors connected in parallel to the stator coils of the generator. An alternative is series compensation where capacitors are connected in series with the generator coils.

Parallel compensation has it's main advantage compared to series compensation in that it allows a relatively high power output from the generator at a rotor speed lower than the rated speed. The disadvantages are a relatively low maximum output power, a high no load voltage at rated speed and a relatively high current flowing 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 of reactive power from the generator wich instead is load dependent. With series compensation the reactive power produced by the capacitor follows the variations in the generator's reactive power consumption, as the generator current changes. The no load voltage will be 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. Figure 3 shows the equivalent circuit of one stator coil, parallel capacitor and a load. The stator coil equivalent circuit consists of the induced voltage, coil resistance and coil inductance.

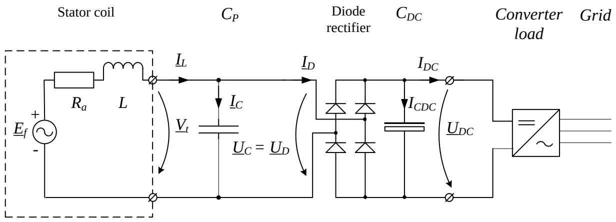

Figure 3. Parallel compensation, E_f : Induced voltage in the coil, R_a: coil resistance, L: coil inductance, C_p: parallel compensation capacitor.

It can be shown that the optimal parallel capacitance for maximum power output is

$$C_p = \frac{1}{2\omega^2 L} \tag{1}$$

where

ω stator current angular frequency

For the Chalmers generator the optimal parallel capacitance at rated speed would be about 121 µF. Due to restrictions in the no load voltage level and 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

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

To overcome these drawbacks series compensation has been investigated. The level of compensation is not dependent on the size of the load, but just on the speed. To obtain maximum output power from the circuit, the series compensation capacitor should have the same capacitive reactance as the generator coil inductive reactance. The 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

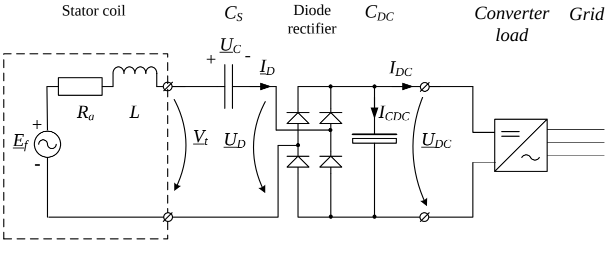

Figure 4. Series compensation, E_f : Induced voltage in the coil, R_a: coil resistance, L: coil inductance, C_s: series compensation capacitor.

The series capacitance for full compensation can be calculated as

$$C_S = \frac{1}{\omega^2 L} \tag{2}$$

Full compensation is acheived for one angular frequency only. Since the angular frequency is related to the rotor speed, the compensation must be tuned to one particular rotor speed. One drawback with series compensation is the relatively low power at lower speed.

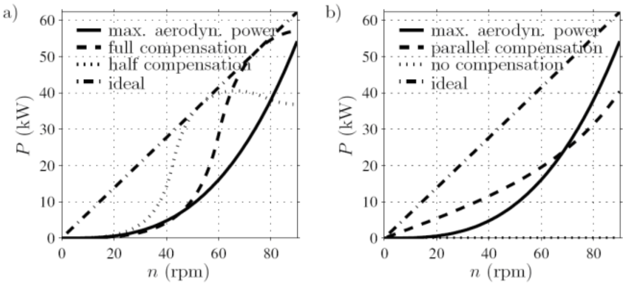

Figure 5. Analytical calculation of the maximum mechanical power as a function of the rotor speed with a limited current of 10 A. a) series compensation, b) parallel compensation and no compensation

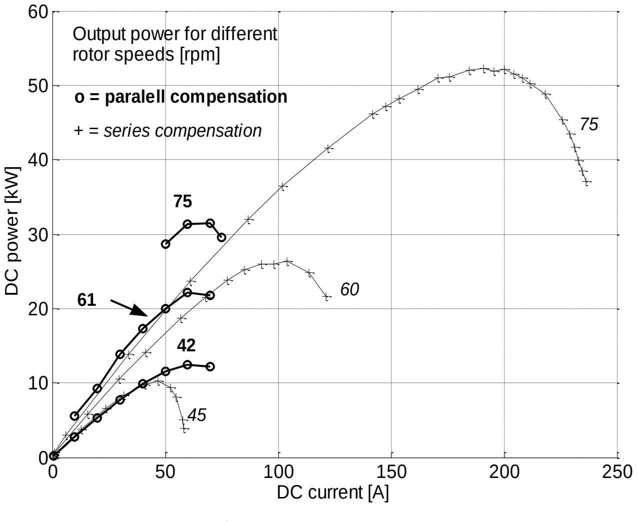

Figure 6. Comparison of maximum output power with series compensation and parallel compensation at different rotor speeds. The series capacitor is optimized for 75 rpm.

IV. FEM-ANALYSIS APPLIED ON THE GENERATOR OF CHALMERS TEST WIND TURBINE

The Finite Element Method 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 is adapted into a total system solution. This is done by matching the results of adjacent elements to each other (e.g. connect adjacent element to each other).

One important field 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 has been performed to increase the theoretical knowledge about some important electromagnetic phenomena e.g.

- demagnetization of the permanent magnets (to evaluate possibilities of increasing the active power by increasing the coil current)
- the air gap (between stator and rotor poles) dependence on the induced voltage
- the harmonic properties of the induced voltage
- the coil inductance and its dependence of the relative position between stator and rotor poles

For more detailed information of the realized project see [1], appendix B.

A. FEM-analysis. Basics

See [1], appendix B, chapter 3.

The configuration of the device is shown in Figure 1 and Figure 7. The first approximation will be to handle the generator as a symmetric design. This is not quite correct (there are 24 × 2 rotor poles and 27 stator E-cores). It is important to remember this approximation when using the model. This approximation makes it for example impossible to study the field in more than **one** stator E-core at the same time (same rotor position), and to compare the results).

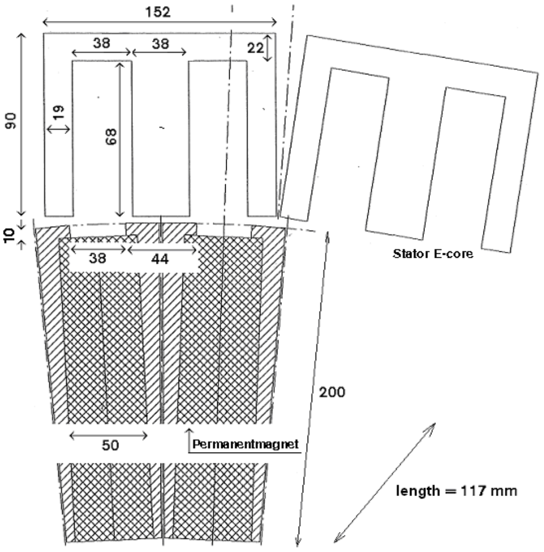

Figure 7. The stator- and rotor modules. Dimensions in mm.

In the FEM-calculations the following materials have been used:

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 is assumed to 165 mm, see Figure 8. The air gap between rotor and stator is 2 mm, nominal value.

Figure 8 illustrates the geometry of the model that has been used in the FEM-analysis. Figure 9 shows a part of the geometric model with an example of 20 mm shift (x-shift) from the symmetric position between a stator pole (E-leg) and a rotor pole. Calculations are performed with different x-shifts in the interval 0 to 82.5 mm. As the distance between two equivalent points of stator modules is assumed to 165 mm we have symmetry around a shift of 82.5 mm, 165mm + 82.5mm, 2 × 165mm + 82.5mm, ….., and so on. Figure 10 gives the calculated flux image corresponding to Figure 9.

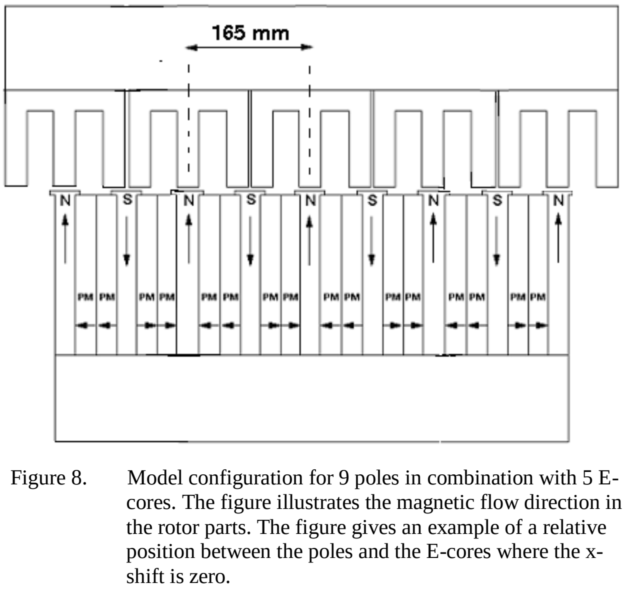

Figure 8. Model configuration for 9 poles in combination with 5 E-cores. The figure illustrates the magnetic flow direction in the rotor parts. The figure gives an example of a relative position between the poles and the E-cores where the x-shift is zero.

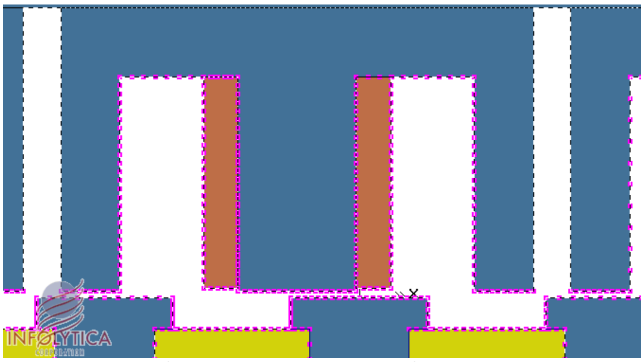

Figure 9 Part of the geometric model. X-shift in this example 20 mm. The coil is wired around the middle E-core.

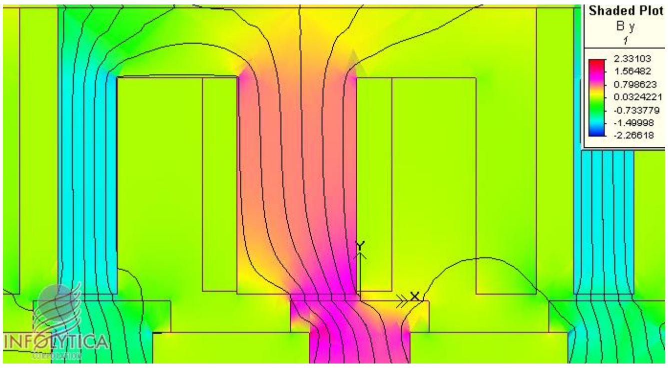

Figure 10 Calculated flux image corresponding to Figure 9.

Figure 11 is a plot of how the flux linkage varies when the shift is alternated.

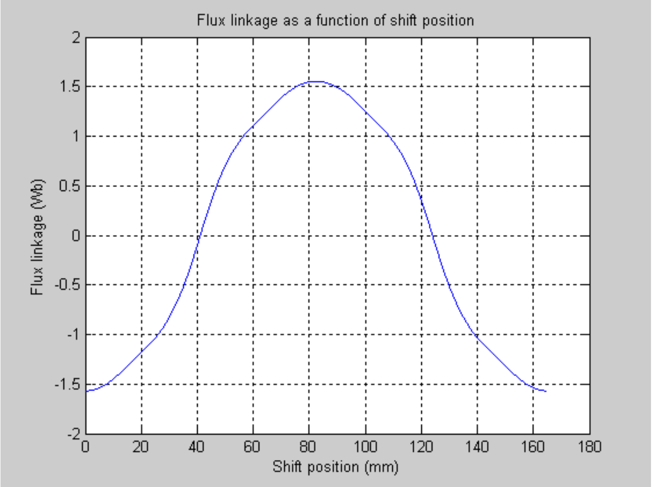

Figure 11. Flux linkage for a coil (323 turns) vs shift position.

The position dependent flux linkage according to Figure 11 could be divided into a DC-component, a fundamental frequency and a number of harmonics. Fourier analysis (chapter D) points out the fairness to approximate 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. Suppose the following generator parameters:

A: amplidue 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)
u(t): induced voltage in the coil (V)

this results in the following equations:

$$\phi(t) = A \cdot \sin\left(\frac{Vrot \cdot P}{60} 2\pi \cdot t\right) \tag{1}$$

$$\begin{aligned} u(t) &= (-)\frac{d\phi(t)}{dt} \\ &= (-)A \cdot \frac{Vrot \cdot P}{60} 2\pi \cdot \cos\left(\frac{Vrot \cdot P}{60} 2\pi \cdot t\right) \end{aligned} \tag{2}$$

Figure 12 gives the equivalent electrical circuit of a single stator module.

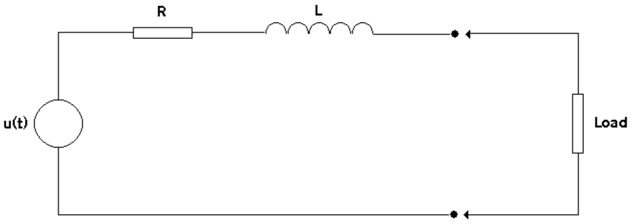

Figure 12 Equivalent circuit of the stator module.

Where R is the coil resistance (Ω) and L is the coil inductance (H). R and L have been measured to:

R = 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 chapter D) has been calculated to 1.615 Wb.

B. No load calculations

See [1], appendix B, chapter 4.1.

Table 1 gives some examples of no load voltages (RMS), calculated by (2), for a stator module when the rotor speed is varied.

TABLE 1 SOME EXAMPLES OF NO LOAD VOLTAGES (RMS) FOR THE STATOR MODULE FOR DIFFERENT ROTATING SPEEDS

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

C. *Load calculations*

See [1], appendix B, chapter 4.1.

To calculate load currents and load voltages a special kind of simulation tool called "PLECS" (Piecewise Linear Electrical Circuit Simulation) have been used. The circuit according to Figure 13 corresponds to the circuit in Figure 12 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.

Figure 14 - Figure 17 illustrate results based on measurements and simulations for a rotor speed of 80 rpm and a total power of 20 kW.

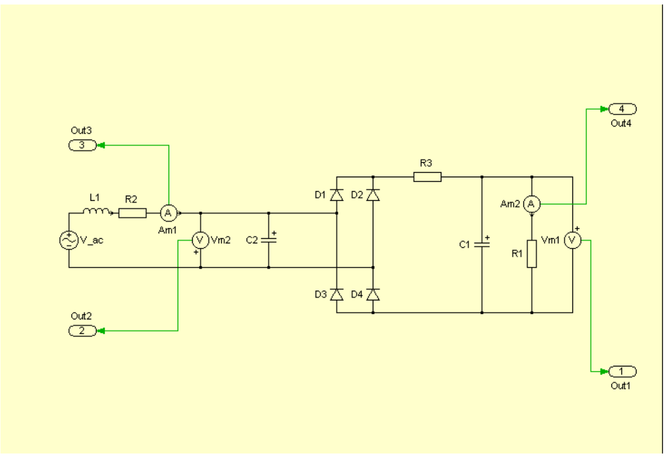

Figure 13. Used PLECS circuit for simulation.

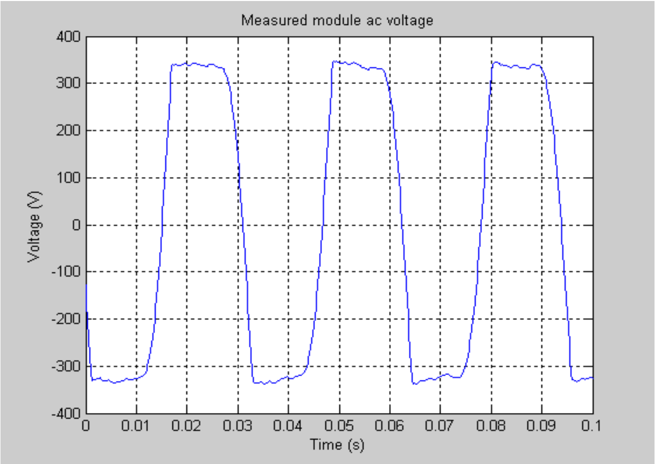

Figure 14. Measured module voltage. Rotor speed 80 rpm. Power 20 kW.

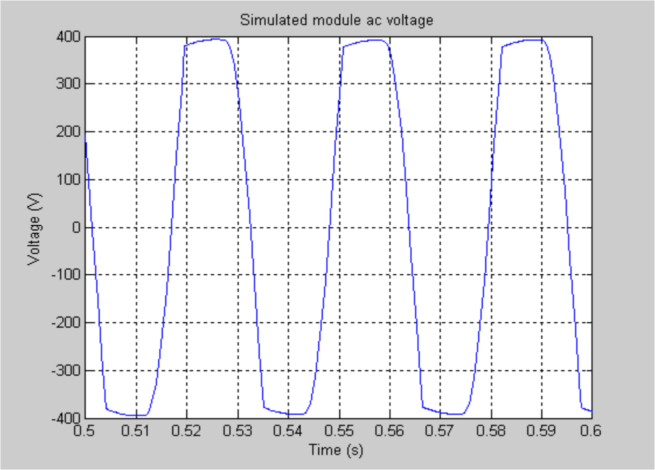

Figure 15. Simulated module voltage. Rotor speed 80 rpm. Power 20 kW.

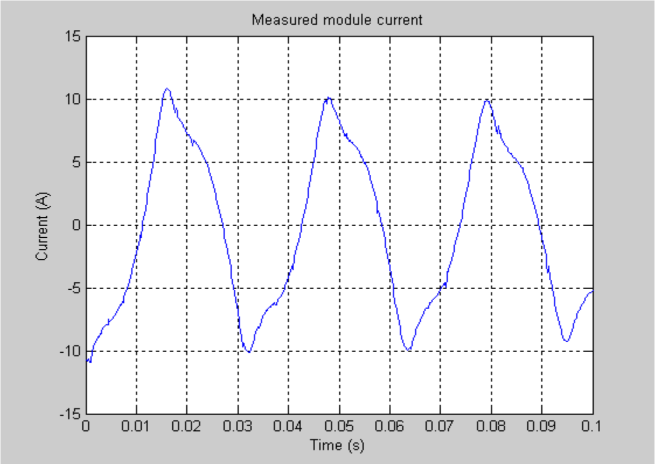

Figure 16. Measured module current. Rotor speed 80 rpm. Power 20 kW.

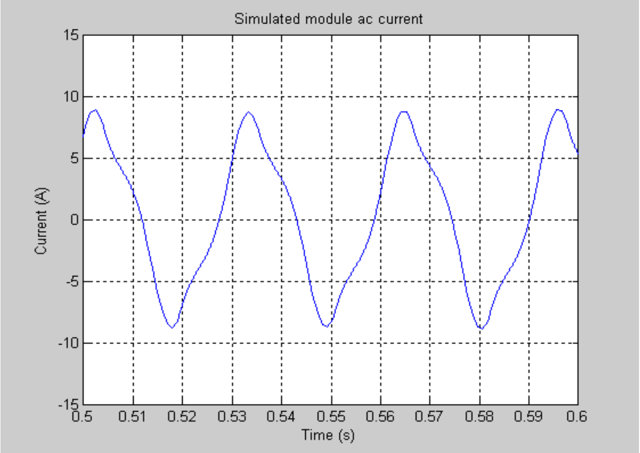

Figure 17. Simulated module current. Rotor speed 80 rpm. Power 20 kW.

D. Fourieranalysis

See [1], appendix B, chapter 5.

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

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

$A_1 = 1.6166$

$A_3 = 0.1076$

$A_5 = 0.0696$

$\omega_1 = 2\pi \cdot 0.4 \cdot \Omega \cdot 1$

$\omega_3 = 2\pi \cdot 0.4 \cdot \Omega \cdot 3$

$\omega_5 = 2\pi \cdot 0.4 \cdot \Omega \cdot 5$

$\alpha_1 = \pi$

$\alpha_3 = 0$

$\alpha_5 = \pi$

Ω is the rotor speed (rpm)

This function (with 3 terms) is given in Figure 18.

If only the first term is used (i.e.: $\phi(t) = A_1 \cdot \cos(\omega_1 t + \alpha_1)$) the result according to Figure 19 is on hand. As is illustrated this results is a fair good approximation.

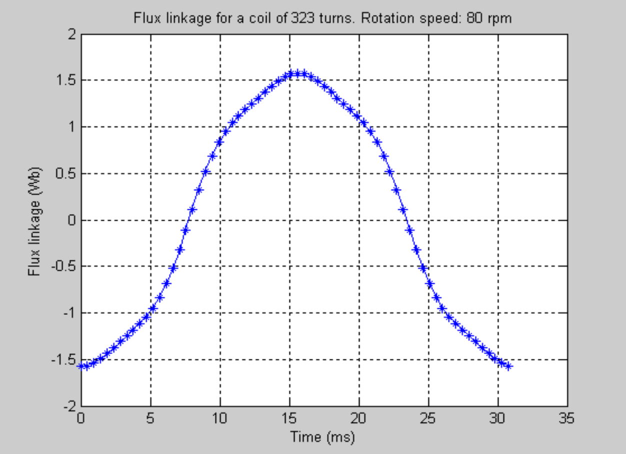

Figure 18 Flux linkage for a coil of 323 turns vs time. Rotation speed: 80 rpm, _ : original function, **: 3 sine functions (1st , 3rd and 5th harmonics)

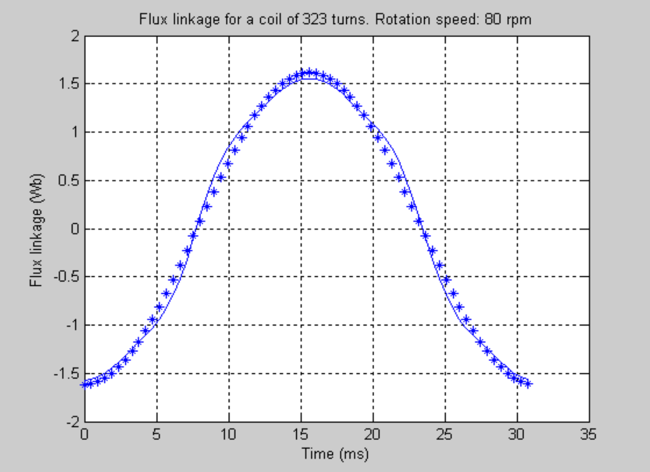

Figure 19. Flux linkage for a coil of 323 turns vs time. Rotation speed: 80 rpm, __ : original function, **: 1 sine function (1st harmonic)

E. Coil inductance

See [1], appendix B, chapter 4.3.

The coil inductance has been calculated (FEM-analysis) as a function of relative position between stator and rotor. The result is given in Figure 20.

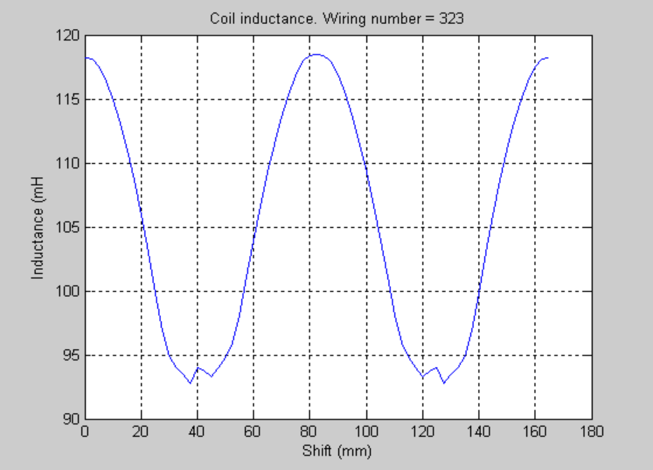

Figure 20. Calculated inductance as a function of relative position between stator and rotor

F. The air gap between stator and rotor

See [1], appendix B, chapter 4.5.

The air gap between rotor and stator has been assumed to 2 mm as a nominal value. As a result of mechanical imperfections this value varies during the rotation motion. This variation causes on the other hand a variation regarding the resulting flux linkage of the coil and thereby also a variation of the induced voltage.

Calculations based on FEM-analysis regarding the effect of varying air gaps have been performed. In Figure 21 the relative flux linkage (relative to the flux linkage value when the air gap is 2mm) is illustrated.

Figure 22 illustrates an example of measured “no load voltage and current” for the stator modules. The variation of the different modules is understood as an effect of varying air gap between stator and rotor vs rotor position.

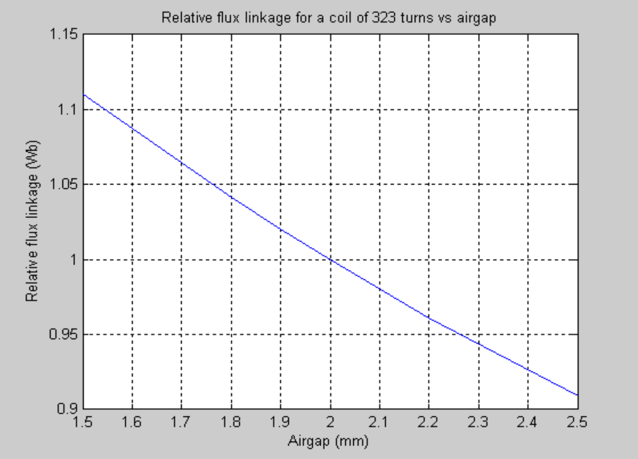

Figure 21. The relative flux linkage vs airgap. The reference is airgap = 2 mm.

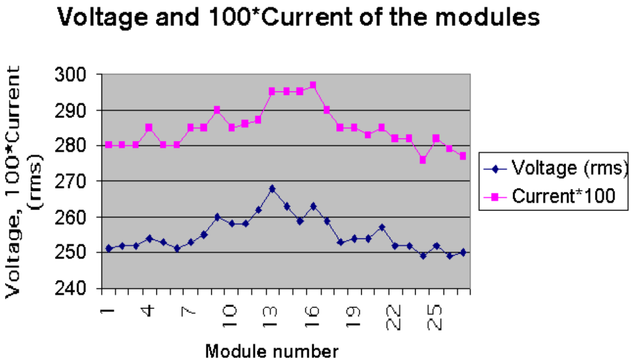

Figure 22. No load voltage and current of the modules. The voltage and current variations could be explained as a result of air gap variations. An air gap variation of about ± 0,15 mm gives according to calculations this effect.

It is not only the induced voltage that is dependent on the air gap in question. Also the coil inductance will vary for alternating air gaps. Figure 23 illustrates the calculated coil inductance vs the air gap.

Figure 23. The coil inductance is dependent on the air gap.

As a consequence of the discussion above two parameters, the induced voltage and the coil inductance is take into account when analyzing the resulting effect of air gap variations.

G. Demagnetization current

See [1], appendix B, chapter 4.2.

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 reduction of the 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 “Hönö” generator the permanent magnets in the rotor poles are exposed to a reversed field from the stator poles. The size of reversed field depends on the coil current and the load angle. FEM-calculations point out that for a coil current exceeding about 17 A amplitude, (i.e. an rms value of about 12 A) and a load angle of 90° (inductive load) there is a risk that permanent demagnetization effects on the magnets could be on hand. Further studies regarding these questions will be performed.

V. REFERENCES

Number citations consecutively in square brackets [1]. The sentence punctuation follows the brackets [2]. Multiple references [2], [3] are each numbered with separate brackets [1]–[3]. When citing a section in a book, please give the relevant page numbers [2]. In sentences, refer simply to the reference number, as in [3]. Do not use “Ref. [3]” or “reference [3]” except at the beginning of a sentence: “Reference [3] shows ... .” Type the reference list at the end of the paper using the “References” style.

VI. CONCLUSION

The analysis regarding reactive power compensation shows that it is possible to increase the active output power by a factor of more than 1.5 when using series compensation in stead of parallel compensation. This implies that the rotor speed is in between a certain specified interval. If this presumption is not fulfilled there is a risk for decreased active output power.

The FEM-analysis has increased the theoretical knowledge about different parameters and phenomenas in the electromagnetic field:

- The analysis results in a good correlationen between measured and calculated output voltage/current values. This is a good contribution to the validation process of the model
- The Fourier analysis shows that the induced voltage is rather free from harmonics
- The analysis shows that there is a considerable variation of coil inductance when the relative position between stator and rotor poles is altered. This will influence the induced voltage. Further studies will be performed regarding this phenomena
- It has been possible to give an explanation about the air gap variation between the stator and rotor poles and its influence regarding the induced voltage. The analysis shows that even very small air gap variations will result in significant voltage differences
- The analysis has resulted in a good feeling about the size of stator current, that could be accepted without risk for permanent demagnetization of the rotor magnets. This question will be further studied in order to increase the possibility to recommend an upper current limit as a function of load angle

APPENDIX

Appendixes, if needed, appear before the acknowledgment.

ACKNOWLEDGMENT

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