The Experience of Designing and Testing a 20 kW Multi Pole Permanent Magnet Generator for Wind Turbines

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1. Introduction

A wind turbine, connected to the grid through a frequency converter and designed to operate with variable rotational speed is one of the most promising concepts for the future development in the wind energy field [1,2,3,4]. This allows to obtain maximum wind rotor efficiency up to nominal wind speed. As a step forward, the use of low speed multi pole electrical generators rules out an expensive and vulnerable element of the conventional wind turbine transmission - the gearbox. It gives an opportunity to reduce the weight, dimensions and mechanical noise of the wind turbine. Moreover, combining an electrical generator with a wind turbine hub, makes the construction more simple and elegant. At the same time, one of the main tasks is an improvement of technical and economical parameters of electrical equipment, which improves the total efficiency of a wind turbine.

The solution includes the following steps:

- development of new types of multi pole generators with better output characteristics;
- development and optimisation of frequency converters and methods for their operation.

The first large scale implementation of low speed multi pole generator for wind turbines was made by ENERCON (model E-40), see Fig.1. The generator has 84 poles, 6 phases, rotor with field windings and a grid connection through a frequency converter [2].

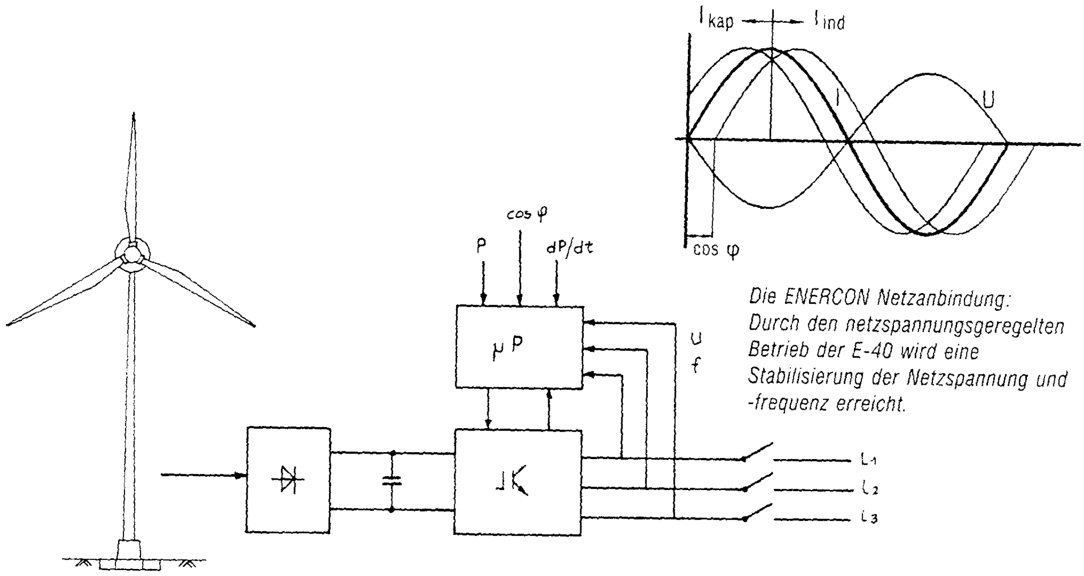

Fig. 1. Electrotechnical concept of Enercon E-40

Another technical solution is the use of multi pole generators with permanent magnets (PMG). This type of generator achieves higher efficiency and the absence of excitor coils on the rotor reduces winding losses (Fig. 2).

Advantages of using PMG as compared to traditional design of a transmission with an asynchronous generator (Fig. 2) can be summarised as follows:

- higher reliability due to absence of gearbox;
- high efficiency of wind turbine due to higher efficiency of the PMG as compared to conventional generator type and transmission;
- simple technology of manufacturing ;
- easier to carry out service and maintenance;
- reduction of mechanical noise;
- option of stand alone operation as a self-contained system.

Designing multi pole permanent magnet generators, the following requirements must be fulfilled:

- generator should have high power efficiency (equal or higher, comparing with traditional electrical generators) at a variable wind speed;
- mass and dimensions of the generator and production cost should be equal to or lower than combination of gearbox and generator for traditional wind turbines concept;
- generator should be designed for short time overloading during wind gusts;
- choosing the generator's nominal rotational speed, the acceptable aerodynamic noise level from the wind turbine must be taken into account.

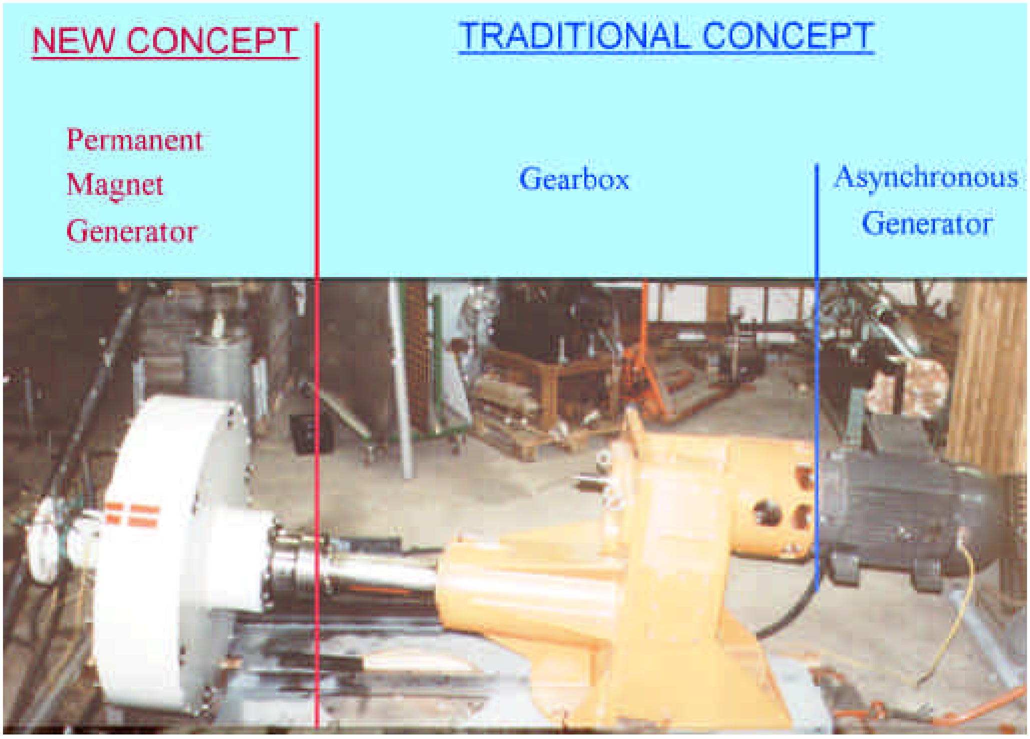

Fig. 2.: Multi pole generator with permanent magnets (PMG)

The present machine is designed to be driven directly from a wind turbine without gearbox with the main objective to find a solution with increased energy efficiency of the whole system.

The present 20 kW PMG project was carried out in Denmark as the first phase of the research in the field of designing multi pole direct driven permanent magnet generators for medium scale wind turbines. The main purpose of the research is to estimate efficiency of the PMG as compared to conventional electrical generators, to design, test and optimise the machine and provide recommendations for manufacturers.

This work is a result from co-operation between the Danish project parties Folkecenter for Renewable Energy, A/S De Smithske and Berendsen Teknik A/S. Furthermore the following parties have been involved in the project as subcontractors: TM-Consult, Cetec, Stockholm University, Islef+Hagen, and Berendsen System Teknik.

Below are given some aspects on the design, the choice of materials, specifications of the machine, and the test results. Developing the test prototype of the 20 kW PMG, requirements, mentioned above were taken into account.

2. The choice of magnetic circuit materials

2.1 The choice of magnets

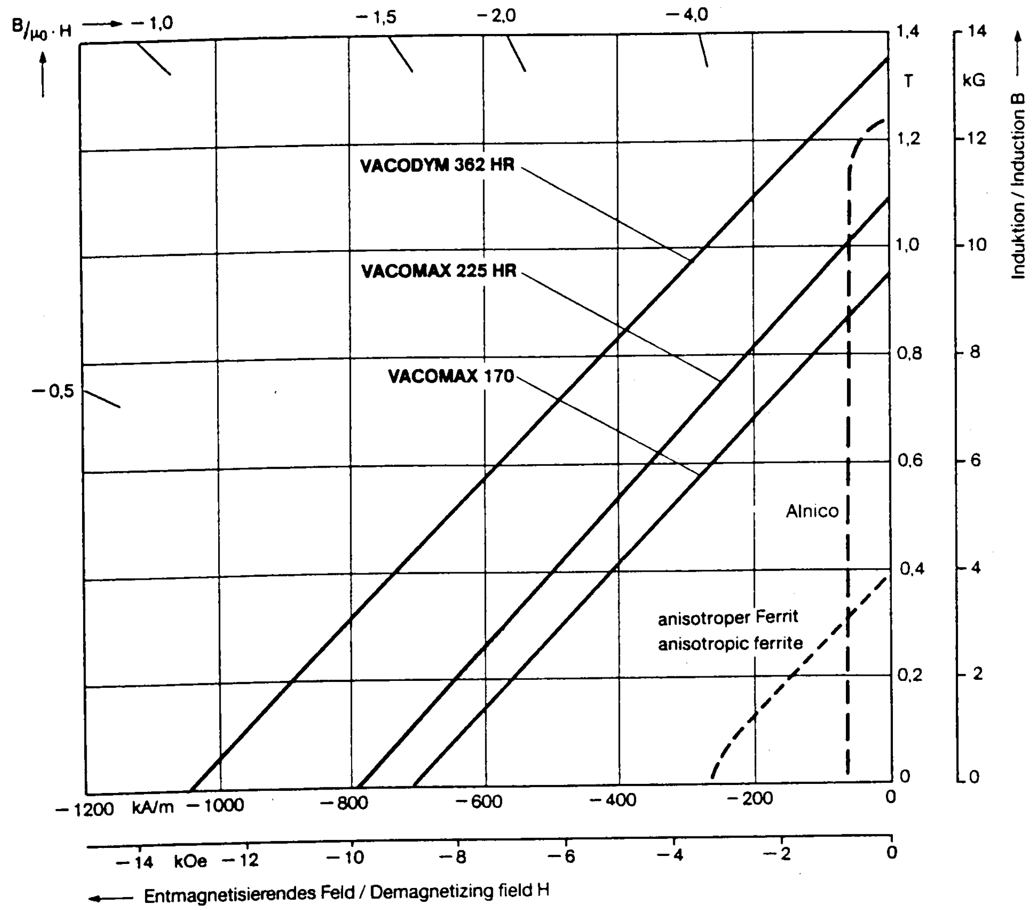

Fig. 3: Characteristics of magnets, provided by VACuumschmelze GmbH.

As shown in Fig. 3, the Nd-Fe-B (VACODYM) type of magnet has superior characteristics because it has maximum values for residual induction B_r and coercive force H_{cb}. Depending of the magnet specification, those values are: B_r is between 1.0 - 1.35 T and H_{cb} is between 760 and 1020 kA/m. The maximum specific magnet energy ($(BH)_{max}$) is about 190-320 kJ/m^3. For the same temperature conditions SmCo group of magnets (VACOMAX) have lower values for B_r (0.9 -1.1 T), H_{cb} (660 - 820 kA/m) and $(BH)_{max}$ (160 - 225 kJ/m^3). It is obvious, that these magnets with the same geometry and similar conditions generate less magnetic flux in the air gap comparing with VACODYM type.

For anisotropic solid ferrites the following values apply: B_r is 0.33 - 0.4 T, H_{cb} is 150 - 260 kA/m and $(BH)_{max}$ is 14.3 - 29.5 kJ/m^3, e.g. ferrites have lower residual induction and coercive force comparing with rare earth magnets. As a result, achieved $(BH)_{max}$ is 10 - 11 times lower. It means, that for generators with similar characteristics (nominal power output, efficiency, etc.) and optimised magnet system (e.g. magnets are used near the point, corresponding to $(BH)_{max}$), required volume of ferrites increases accordingly, compared to required volume of rare earth magnets. Total weight of the generator with ferrites significantly increases due to larger rotor dimensions. Moreover, low value of residual induction (0.4 T) requires special magnet system design with tangentially placed magnets in order to concentrate magnetic flux in the air gap.
The main disadvantage of AlNiCo magnet is low coercive force H_{cb}=35 - 150 kA/m, with Br=0.8-1.35 T and $(BH)_{max}$=36-80 kJ/m^3. Comparing with rare earth magnets, maximum special magnetic energy,

generated by AlNiCo is 4-9 times lower. To create the same magnetic flux in the air gap, as VACODYM magnets, AlNiCo magnets also must have larger dimensions, mainly height.

In addition, ferrites and AlNiCo type of magnets have non-linear characteristics and may demagnetise during life time. That will reduce magnetic energy and will further increase magnet volume by 30 - 40 %. The analysis shows, that the Nd-Fe-B magnet system is best by dimension and weight criterions. It reduces volume and mass of magnets and rotor fittings and improves the technology of the manufacturing process.

There are different optimising criterions for electrical generators, related to purpose of use and special requirements. For example, special purpose generators for aircrafts and ships are designed by minimising their masses and dimensions. General purpose generators are normally designed, by minimising the production cost. A wind turbine generator is considered a general purpose machine, and the cost of the generator is taken as the main factor. The production cost analysis for PMG - 20 kW is given below. Table 1 consists of market wholesale prices per cubic centimetre and per gram for different types of magnets.

MAGNET TYPE	PRICE ,DKK/cm^3	RICE, DKK/g
Nd-Fe-B	4,52	0,60 *)
$SmCo_5$; Sm_2Co_{17}	19,30 - 33,60	2,30 - 4,00
Ferrites	0,30 - 0,44	0,06 - 0,09
AlNiCo	5,00 - 6,30	0,70 - 0,90

*) *For the last two years the price for rare earth magnets has been going down due to developing of new technologies for their production. According to figures, given by Risø National Laboratory, Denmark [4], the price for Nd-Fe-B in 1995 was around 0,6 DKK/g.*

Tab. 1: Specific prices for different types of magnets

As mentioned above, it is necessary to consider specific magnet energy in order to estimate magnet volume.The magnet system for PMG - 20 kW was calculated, using data for VACODYM 383 HR. The total volume of the magnet system is 1260 cubic centimetres. The wholesale price of magnets is approximately 5700 DKK.

The total magnetic energy, estimated by $(BH)_{max}$ = 310 kJ/m^3 is 0.391 kJ. For comparison, the volumes and prices for alternative magnet systems are given in Table 2. Calculations have been made, assuming that the magnet systems are optimised by $(BH)_{max}$ and hold the same magnetic energy.

MAGNET TYPE	VOLUME, cm^3	PRICE, DKK
Nd-Fe-B	1260	5700 *)
$SmCo_5$; Sm_2Co_{17}	1740 - 2445	33580 - 82150
Ferrites	13250 - 27340	4000 - 12030
AlNiCo	4890 - 10860	24450 - 68400

*) *The material is chosen for prototype of the PMG -20 kW. The total price for magnetic system has been estimated on the basis of market price for Nd-Fe-B (around 0,6 DKK/g).*

Tab. 2: Volumes and prices for different magnets

These data show, that the cost is within the range of a ferrite magnet system. Moreover, the volume of the ferrite system is, in average, 16 times larger, than the volume of the Nd-Fe-B type. At the same time, production cost and hence the total cost are higher.
Technical parameters and prices for other magnet systems (SmCo and AlNiCo) inhibit their use for PMG. Therefore, ferrite and Nd-Fe-B (best performance, low weight and small dimensions) magnetic systems can be considered for PMG. Larger volume of the magnetic system makes the rotor heavier due to increased weight of magnets and fittings. For PMG - 20 kW with ferrite magnet system, the weight of the active part of the rotor would be increased by 150 - 200 kg compared to VACODYM magnet system. In addition, the manufacturing process becomes much more complicated for ferrite magnetic system.

Taking into account the fact, that the market price of rare earth magnets is going down [4], it is reasonable to minimise the mass of the generator by choosing a magnetic system based on Nd-Fe-B type of magnets (VACODYM 383 HR). It is also important to notice, that the chosen magnetic system is demagnetisation proof.

2.2 The choice of electrical steel

Basically, there are three types of electrical steel: ordinary steel, plate magnetic steel and cobalt steel. Cobalt steel has higher magnetic permeability and its saturation induction is about 2.0 - 2.2 T (depending of the type), with very low magnetising force. Among the products are: PERMENDUR 49, PERMENDUR 24, RETELLOY, RETELLOY 45, HISAT 50, HISAT 35 with plate thickness from 0.05 to 0.5 mm. High content of cobalt (from 24 to 50 %) makes these types of steel very expensive (about 700 - 800 DKK/kg) and comparable by the price with rare earth magnets. Therefore it is justified to use them only in electrical machines for special purposes, for example in aviation.

Plate electrical steel is widely used in different electrical generators for general purpose. Magnetic permeability of this type is lower, comparing with cobalt steel and saturation induction is about 1.5 - 1.6 T. Obviously, the mass of magnetic conductor, made from it, is 1.5 - 2.0 times higher, comparing, for example, with magnetic conductor made from PERMENDUR 49, having similar magnetic flux resistance. It is also important to take into account essentially low cost of e.g. V 470-50 A (13-15 DKK/kg). Therefore, using cobalt steel for magnetic conductor in the stator of PMG does not provide many advantages by reducing its mass, but significantly increases the production cost.

Consequently, V 470 - 50 A was chosen for both stator and rotor. There are less requirements for the steel, used in magnetic conductors, placed in constant magnetic fields (inductor of the generator). Usually, ordinary steel with low magnetic permeability is used for their production. Naturally, the rotor dimensions are increased in that case. However, considering the large diameter of multi pole generator, and the fact, that manufacturing process for the PMG rotor, using magnetic steel, is more expensive, it is reasonable in future to manufacture rotor from ordinary steel in one piece (casting). This also provides a possibility to combine the magnetic conductor of the rotor with its rim and even use it as a hub for the wind turbine.

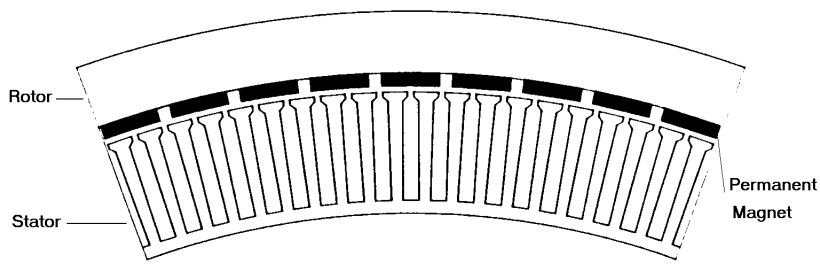

Fig. 4: A proposed design of PMG - 20 kW magnetic circuit

3. Requirements for the winding

3.1 Stator winding

Designing the stator winding, the following requirements must be fulfilled:

- in order to achieve sinusoidal voltage form, winding factor K_{01} for the first harmonic should be maximised, minimising at the same time winding factors for high harmonic components of the voltage form;
- the number of slots must be reasonably minimised in order to ease the manufacturing process of the stator and work on the winding;
- the number of slots/pole/phase (q) must be chosen with consideration of starting moment of the generator.

3.2 Damper winding

In synchronous generators the damper winding of conventional type fulfils the following functions [3]:

- attenuation of synchronous field feedback when asynchronous load occurs;
- damping of rotor vibration, which occurs due to different perturbations in the electrical grid;
- prevention of dynamic over voltage in cases of asymmetrical short circuits;
- amplitude reduction for harmonic components of the voltage form, related to the stator geometry.

PMG - 20 kW is designed to be connected with the electrical grid through DC link and frequency converter. For these conditions the functions of the damper winding are:

- reduction of voltage pulsation in the output stage of the rectifier;
- prevention of the dynamic over voltage, occurring due to non-sinusoidal current in the stator circuit, when the generator is connected with electrical grid through rectifier and frequency converter;
- reduction of dynamic deflections during wind gusts [5].

4. Test results of PMG - 20 kW

Testing of PMG - 20 kW was carried out at the Folkecenter in October - November 1995 (see Fig. 2). Basic test results are given below.

4.1 Open circuit test and voltage diagram

Calculated and experimental curves for open circuit test are given on Fig. 5. The solid line shows calculated open-circuit voltage curve U_{ph}, obtained earlier, and given by

$$U_{ph} = 3.242\ n \qquad (1)$$

where n is number of rotations per minute.

Experimental open-circuit characteristics are slightly higher. The difference between calculated and experimental data is about 2.5 - 3 %. The results, therefore, are correlated with the calculation uncertainty of the magnetic flux $\Phi\delta$ in the air gap, which is also about 2.5 - 3 %.

Analysis of voltage quality shows, that the non-sinusoidal factor is 1.27 % for the open circuit operation and 1.093 % for nominal active load of the generator, e.g. the design requirements for electrical machines, directly connected to the grid, are fulfilled [3, 6].

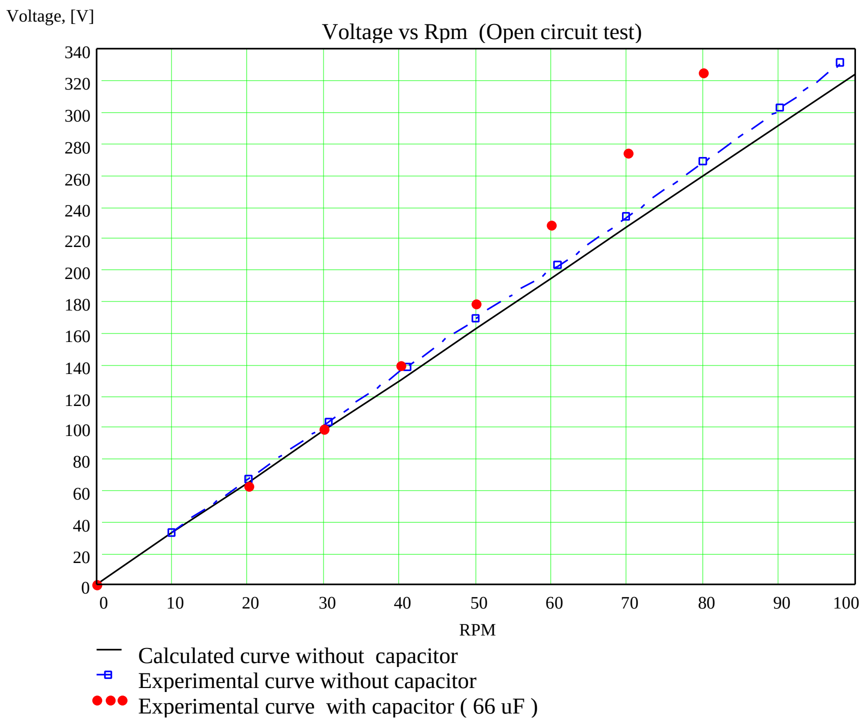

Fig 5. Calculated and experimental curves for open circuit tests

4.2 Output characteristics of the PMG - 20 kW

Output characteristic of the generator with permanent magnets is the voltage (U) as a function of current (I) with correct power factor (cos φ). Rotor poles of the synchronous generator with permanent magnets are clearly defined. Therefore the work process can be described precisely using voltage diagram. In addition, as a part of the magnetic conductor, the magnets have high reluctance to the armature reactive fluxes in lengthwise (Φad) and transverse (Φaq) directions. Therefore they are forced to close in the directions of stray fluxes and, as a result of it, inductances Xad and Xaq are significantly lower than stator inductance Xs. Calculation results show, that it is possible to achieve rather precise description of output characteristics (uncertainty does not exceed 2-3 %), assuming that

$$Xd = Xq = Xs. \quad (2)$$

The main equations, used for output characteristics calculations are:

$$U \cos(\psi-\varphi) = Eq - I\,Rph \cos\psi - I\,Xs \sin\psi \quad (3)$$

$$U \sin(\psi-\varphi) = I\,Xs \cos\psi - I\,Rph \sin\psi \quad (4)$$

where:

U - voltage output,
Eq - electromotive force (e.m.f.) of the open-circuit regime,
I - current in stator windings,
Rph - winding phase ohmic resistance,
Xs - stray inductance,
φ - angle between voltage and current,
ψ - angle between e.m.f. Eq and current of the generator.

This non-linear equation system has two unknown parameters: the voltage U and the angle ψ between e.m.f. Eq and the current I. Taking into account the variable rotational speed of the generator, the following corrections are applied:

$$Eq = Eqnom\ (n/nnom) \qquad (5)$$

$$Xs = Xsnom\ (n/nnom) \qquad (6)$$

where:

nnom - nominal RPM of the generator,
n - current RPM of the generator,
Eqnom - nominal e.m.f. of open-circuit regime and nominal RPM,
Xsnom - nominal stray inductance for nominal RPM.

Fig. 6 shows calculated and experimental characteristics of PMG - 20 kW for cos φ =1. Power output of 20 kW was reached with 74 revolutions per minute and 34.3 A current. In case of optimal voltage stabilisation by capacitors (with the same rotational speed and power output of the generator), phase current has been reduced down to 30.3 A. Reduction of phase current by 4 A has decreased main winding losses by 0.6 kW, e.g. approximately by 20 % and, therefore, has raised efficiency of PMG - 20 kW up to 91 %, from 86 % without voltage stabilisation. The maximum power output, obtained in these conditions was 22.5 kW.

Calculations show, that it is possible to optimise voltage stabilisation for different wind conditions and minimise the generator current for power outputs lower than nominal, raising the generator efficiency. Power, current and efficiency data are given in Table 3.

Power output of the generator [kW]	**Parameters of the PMG - 20 kW without voltage stabilisation**		**Parameters of the PMG - 20 kW with optimal voltage stabilisation**	
	current [A]	**efficiency [%]**	**current [A]**	**efficiency [%]**
20	34.3	86	30.3	90 - 91.5
18	29	87	26.7	90.1 - 92.4
16	24.6	90	23.5	91 - 93.1
14	21.3	91	20.3	92 - 93.7
12	17.8	92.5	17.2	92.7 - 94.2
10	14.4	93	14.2	93.4 - 94.5
5	7	94	7	94 - 94.5

Tab. 3: Current and efficiency data of PMG - 20 kW with and without voltage stabilisation

In contrast to an asynchronous generator with gearbox, the efficiency of PMG - 20 kW increases with decreasing load as far down as quarter load before it drops. Voltage stabilisation increases and tends to even out the the efficiency, the largest improvement being at full load. It is important to notice, that the same voltage stabilisation effect may be achieved by programming the frequency converter for sinusoidal current and appropriate phase angle between current and voltage on the generator side. For PMG - 20 kW, the capacitor current phase angle is between 0^o and 23^o for variable power output from 0 to 20 kW accordingly.

With the above difference in characteristics, a PMG has a great advantage over the traditional asynchronous generator and gearbox. Partial loads being predominant in wind turbine applications, the use of PMG - 20 would improve the annual energy production by more than 10 % as compared to the traditional solution with asynchronous generator and gearbox.

In Table 4, the PMG - 20 kW is compared to a traditional solution based upon quality products under like conditions, i.e. with full advantage of the frequency converter. A typical 20 kW wind turbine will operate approximately 2/3 of the time with an average power output of 10 kW. As it appears, the corresponding weighting results in a 12.9 % improvement of the average efficiency and hence the annual energy production.

Power output of the generator		Efficiency of PMG-20 kW with voltage stabilisation	Efficiency of traditional 20 kW solution	Relative superiority of the PMG- 20 kW	Weighting
kW	%	%	%	%	
20	100	91	86	5.8	1 / 7
15	75	92.5	86	7.6	1 / 7
10	50	94	83.5	12.6	2 / 7
5	25	94.5	80.5	17.4	3 / 7
Average values:		93.6	82.9	12.9	

Tab. 4: Comparison of the efficiency of PMG - 20 kW to a traditional 20 kW solution

When PMG - 20 kW is compared to a traditional solution without frequency converter, the efficiency of the latter drops to 76.5% at 25% load, so that the superiority of PMG - 20 increases to 23.5%. With the same weighting as in Table 4, the resulting improvement of the average efficiency is 15.3%. The losses in the frequency converter is more, than outbalanced by optimisation of the rotational speed, and hence the annual energy production is improved by at least 15.3%. In addition, the optimised rotational speed reduces loads and noise.

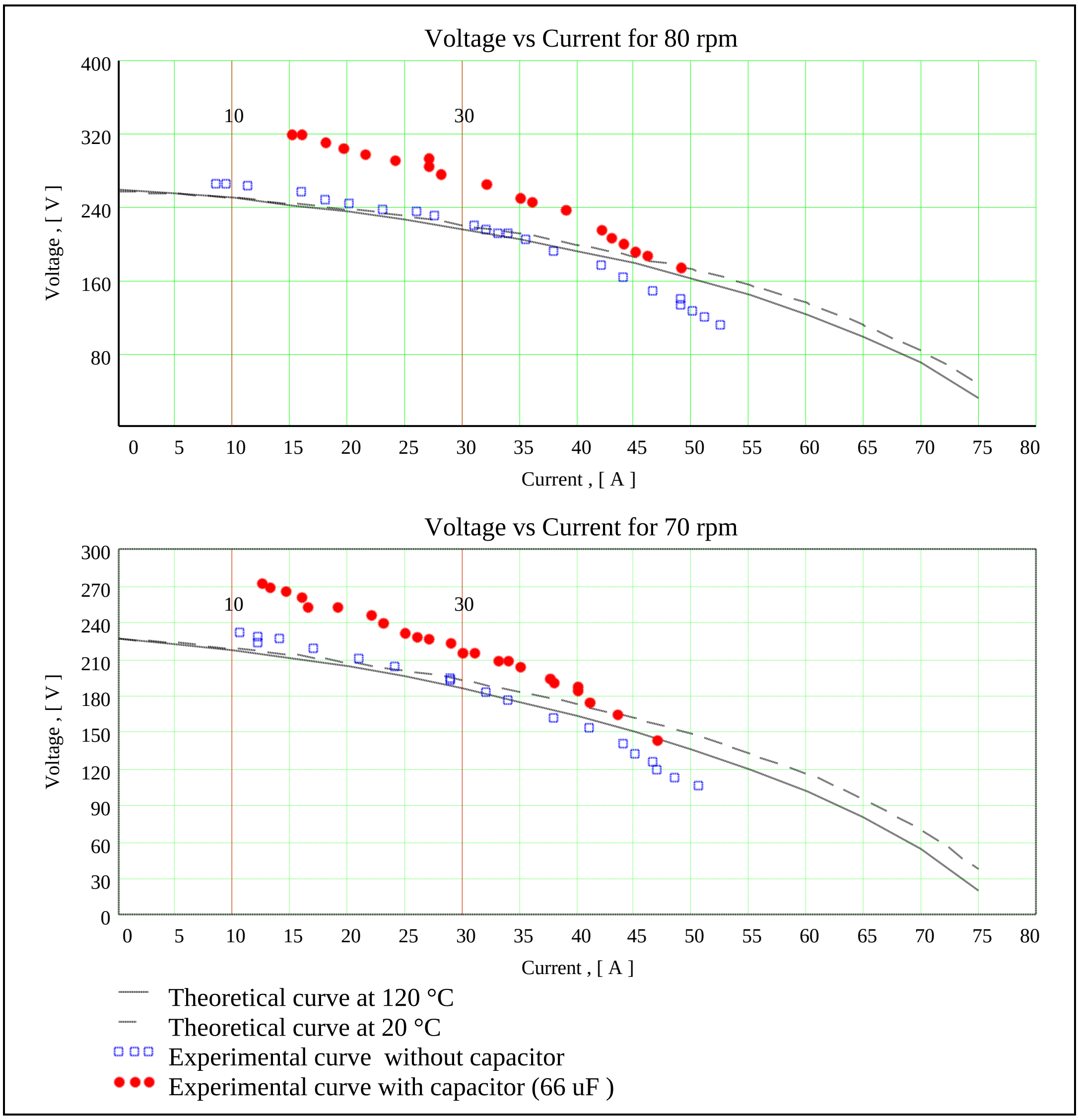

Fig. 6. Calculated and experimental characteristics of PMG - 20 kW for cos j =1

5. Conclusions

- Designed permanent magnet generator (PMG - 20 kW) possesses a number of advantages:
  - it may operate as a self-contained stand alone system;
  - it replaces the gearbox, the generator and possibly the hub of the wind turbine by combining wind rotor with external rotor of the generator;
  - the use of the PMG for wind turbines increases the reliability of the construction during the life time as compared to the conventional design (gearbox, asynchronous generator).
- The use of rare earth magnets Nd-Fe-B reduces mass, dimensions and price of the generator;
- The test of the PMG -20 kW confirms that the design method, developed for calculation of multi pole permanent magnet generators is correct in general and meets engineering requirements. The calculation uncertainty of the magnetic system and output characteristics does not exceed 2-3 %.
- Designing permanent magnet generator, it is recommended to use voltage stabilisation (capacitance or programming of the frequency converter). Efficiency is higher, while mass and production cost of the generator can be reduced by 15 - 20 %.
- The frequency converter may be used not only for control of rotational speed, but also to obtain sinusoidal capacitive current on the generator side. For PMG - 20 kW the angle between voltage and current should be within the range 0 - 23°;
- The use of the PMG - 20 for wind turbines improves the annual energy production by more than 10 % as compared to the conventional design (gearbox, asynchronous generator) based upon quality products under like conditions, i.e. with full advantage of a frequency converter. As compared to a conventional design without frequency converter, the annual energy production is improved by more than 15 %.

6. References

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