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Testing of a direct drive Generator for Wind Turbines

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Abstract

The normal drive train of a wind turbine consists a gearbox and a 4 to 8 poles asynchronous generator. The gearbox is an expensive and unreliable components and this paper deals with testing of a direct drive synchronous generator for a gearless wind turbine. The danish company Belt Electric has constructed and manufactured a 27 kW prototype radial flux PM-generator (DD600). They have used cheap hard ferrite magnets in the rotor of this PM-generator. This generator has been tested at Risø and the test results are investigated and analyzed in this paper. The tests have been done with three different load types (1: resistance; 2: diode rectifier, DC-capacitor, resistance; 3: AC-capacitor, diode rectifier, DC-capacitor, resistance).

1. Technical data for the generator

The main data for the direct drive PM-generator is draw up in table 1.

Table 1. Technical data for the direct drive PM-generator (DD600)

Outside diameter	1200 mm	Bearing lubrication	Grease
Outside length	450 mm	Number of phases	3
Number of pair of poles p	25	Thermal protection system	1 Pt 100 + 3 klixon
Nominal rotation speed n_N	68.0 rpm	Connection	Star
Nominal frequency f_N	28.3 Hz	Cooling	Natural wind
Magnet type	Hard ferrit	Insulation class	F (155 °C)
Weight of electro-magnetic	570	Degree of protection	IP65
Bearing types	Spherical roller	Ambient temperature	-15 °C ... +40 °C

The generator is designed for a 27 kW gearless wind turbine.

2. Measurements

The equipment for testing of the generator are described. The PM-generator is connected mechanical to a asynchronous motor by a gearbox. The asynchronous motor is fed by a three phase frequency inverter and the rotation speed of the PM-generator can be change from zero to 68 rpm. Moreover is the PM-generator electrical connected to a load through a three phase power analyzer (VOLTECH PM3000A). The torque at the generator shaft is measured with a calibrated force transducer (DYNAFOR 2T).

The equipment for testing of the PM-generator is outlined in figure 1.

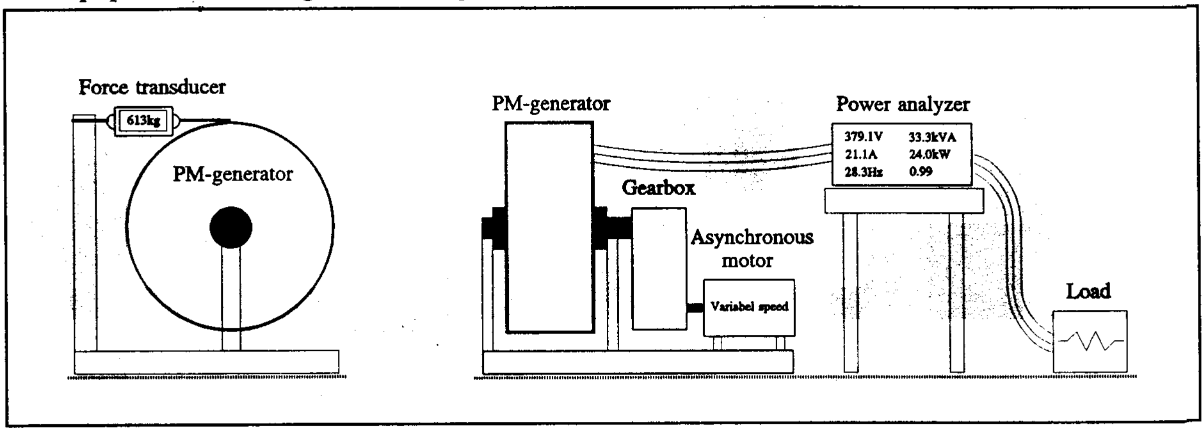

Figure 1. Equipment for testing of the PM-generator

All tests are made at stationary conditions and all the electrical parameters are only valid for a star coupled machine.

2.1. Equivalent diagram for the PM-generator

The equivalent diagram (line to zero) for a star coupled PM-generator is shown in figure 2.

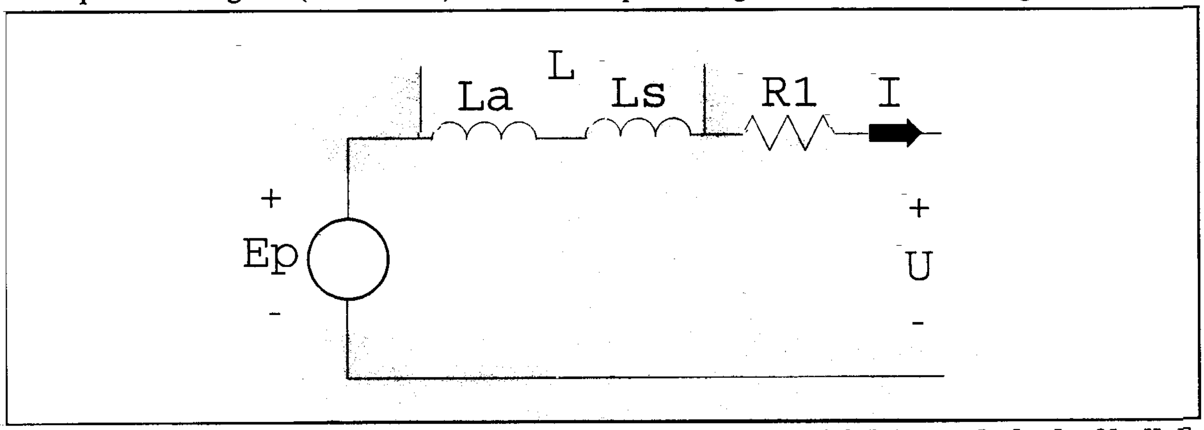

Figure 2. Equivalent diagram (line to zero) for the PM-generator. Resistance R_1=2.23 Ω, Inductance $L=L_a+L_s$=85 mH, E_p = Electromotive force, U = voltage and I = current

2.2. Testing of the generator without an electrical load

It is assumed that the sum of the mechanical loss such as the friction loss and the cooling loss is much smaller than the sum of the copper loss and the iron loss for a direct drive PM-generator.

Therefore at no electrical load is the power given by:

$$P_m = m_d \omega_r = P_e + P_{loss} \approx P_e + P_{cu} + P_{fe} \tag{1}$$

$$\textit{No load: } P_e = 0 \Rightarrow P_{cu} \approx 0 \Rightarrow P_m \approx P_{fe}$$

where: m_d = torque, ω_r = angular velocity, P_e = electrical power, P_m = mechanical power, P_{loss} = loss, P_{cu} = copper loss, P_{fe} = iron loss.

The iron loss and the electromotive force are measured when the load is disconnected from the PM-generator. The measurement results are draw up in table 2.

Table 2. The electromotive force E_p, the mechanical torque m_d and the iron loss P_{fe} as function of the speed n

n [rpm]	E_p [V]	m_d [Nm]	P_{fe} [W]
0.0	0.0	59	0.0
16.9	130.4	96	169
21.8	168.6	96	219
29.0	223.5	96	291
33.8	260.5	96	340
43.3	333.2	96	435
57.2	441.8	102	611
68.4	528.8	102	731

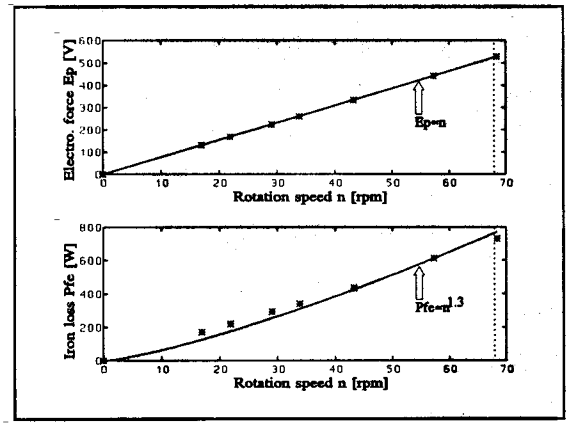

Figure 3. The electromotive force and the iron loss are measured as a function of the speed. (The nominal speed is indicated with a dash line)

The same results are also graphic illustrated in figure 3. Firstly, the electromotive force E_p increase linearly with the speed n. Secondly, the iron loss is less than 800 W which is under 3 % of the nominal power. Finally, the standstill torque is only 59 Nm which is less than 2 % of the nominal torque.

2.3. Testing of the generator with a resistance load

Three 25.6 Ω resistances were connected to the PM-generator in this test. The load diagram is outline in figure 4.

The electrical power and the mechanical power for the PM-generator are measured as function of the rotation speed. It is possible from this measurement to calculated the efficiency of the PM-generator. The results are shown in table 3 and in figure 5.

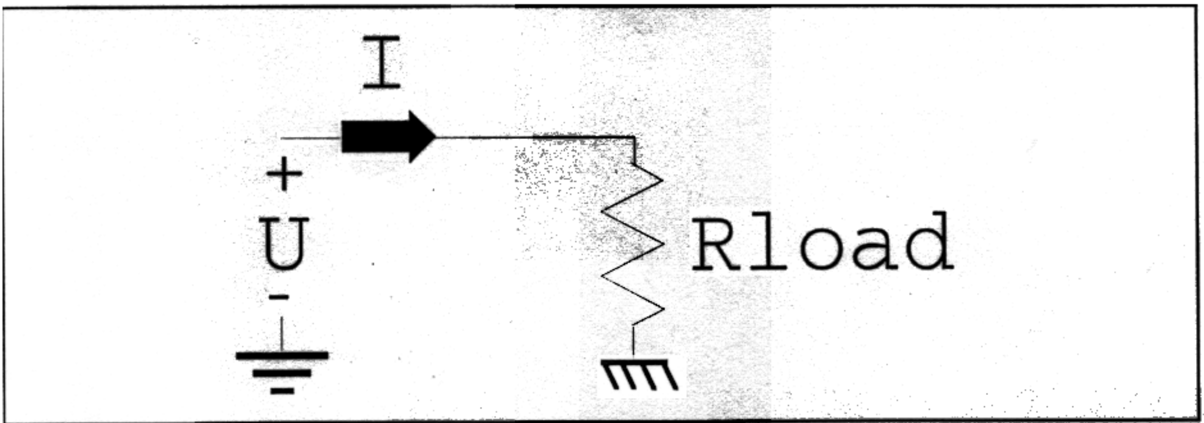

Figure 4. Diagram of the (line to zero) load. The load is a standard resistance (25.6 Ω)

Table 3. Measurement of the mechanical and the electrical power for the PM-generator when the load is a resistance

n [rpm]	U [V]	I [A]	P_e [kW]	P_m [kW]	η [%]
13.1	93.3	3.63	1.01	1.3	80.0
21.6	152.3	5.87	2.68	3.2	84.3
29.2	203.7	7.87	4.81	5.6	85.7
35.4	244.0	9.45	6.92	8.0	86.4
43.0	291.5	11.3	9.90	11.4	86.7
50.2	334.9	13.0	13.1	15.1	87.0
57.3	375.3	14.7	16.5	19.0	87.0
68.6	434.7	17.0	22.2	25.4	87.1

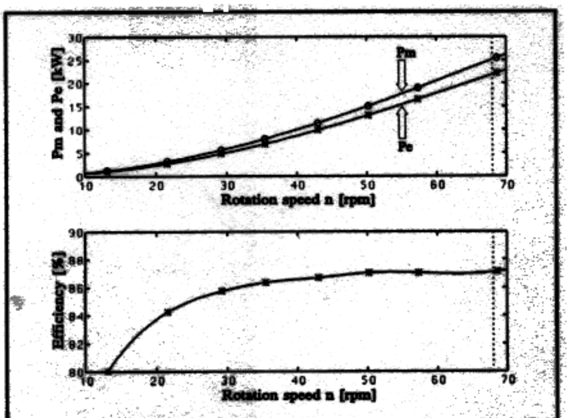

Figure 5. The mechanical power, the electrical power and the efficiency are measured as a function of the speed. (The nominal speed is indicated with a dash line)

The efficiency for the PM-generator is greater than 80 % when the electrical power P_e is higher than 1 kW.

2.4. Testing of the generator connected to a diode rectifier, a DC-capacitor and a resistance

The resistance load is change to a three phase diode rectifier (SKD60/08, 800 V/60 A) connected to a DC-capacitor (367 μF, 900 V) and a resistance (10.5 Ω), see figure 6.

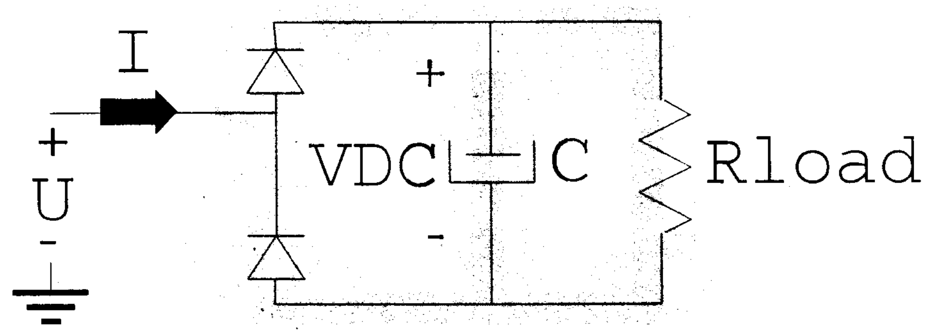

Figure 6. Diagram of the (line to zero) load. The load is a diode rectifier, a DC-capacitor (367 μF) and a resistance (10.5 Ω)

The diode rectifier and the DC-capacitor have to simulated an AC/DC-converter in a normally frequency inverter which will be connected to the PM-generator when it is used in a wind turbine. Table 4 and figure 7 shows the test results.

Table 4. Measurement of the mechanical and the electrical power for the PM-generatoren when the load is a diode rectifier, a DC-capacitor (367 μF) and a resistance (10.5 Ω)

n [rpm]	U [V]	I [A]	P_e [kW]	P_m [kW]	η [%]
14.6	98.9	5.46	1.52	1.9	80.1
22.1	147.1	7.93	3.29	4.0	82.1
36.3	231.9	12.2	7.96	9.6	83.3
43.5	270.6	14.1	10.7	12.8	83.7
50.6	307.2	15.8	13.7	16.3	83.9
57.9	342.4	17.4	16.8	20.0	84.0
67.7	384.4	19.6	21.3	25.4	83.8

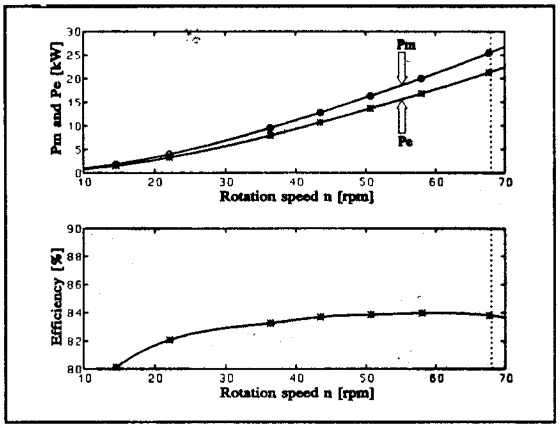

Figure 7. The mechanical power, the electrical power and the efficiency are measured as a function of the speed. (The nominal speed is indicated with a dash line)

The efficiency for the PM-generator at nominal power and speed is reduced 3 % from 87 % to 84 % when the load is change from a resistance to a diode rectifier plus a DC-capacitor and a resistance, see table 3 and table 4.

The efficiency decreased because a diode rectifier together with a DC-capacitor generate harmonics in the phase current which is increasing the copper loss in the stator windings.

3. Optimizing of the AC-capacitor

A three phase AC-capacitor (68 μF) is connected parallel with the load in chapter 2.4 for increasing the DC-link voltage (V_{DC} in figure 6 and figure 8), the nominal electrical power and the efficiency of the PM-generator, see figure 8.

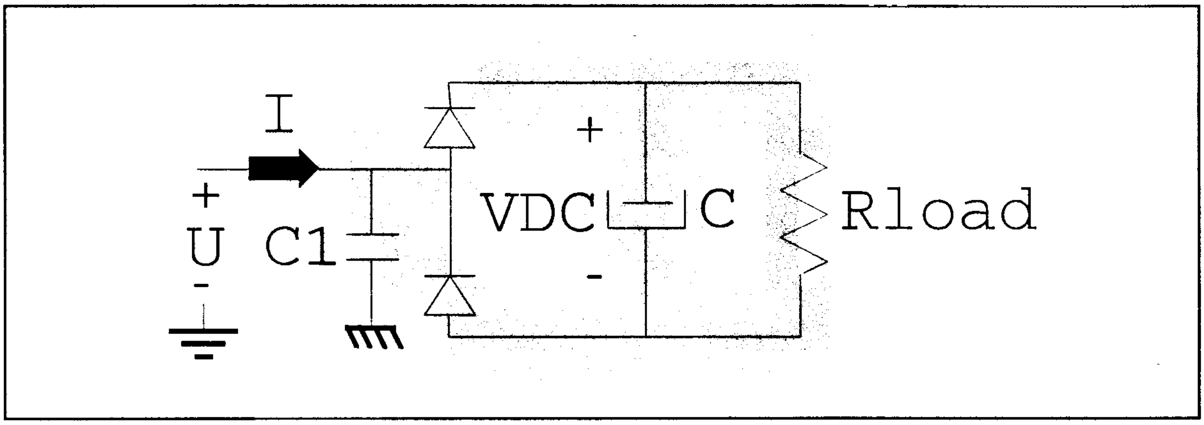

Figure 8. Diagram of the (line to zero) load. A three phase AC-capacitor (68 μF) in parallel with a diode rectifier, a DC-capacitor (367 μF) and a resistance

The test results with and without a three phase AC-capacitor are shown in table 5.

Table 5. Testing of the PM-generator with and without a three phase AC-capacitor (C_1=68 μF) when the electrical power P_e is 20.1 kW. Top: Without C_1, Bottom: With C_1

n [rpm]	U [V]	V_{DC} [V]	I [A]	P_m [kW]	η [%]
63.9	356.8	753	19.9	24.0	83.6
63.9	508.5	1126	15.6	23.1	87.1

The effect of the AC-capacitor is radically because the DC-link voltage V_{DC} increase from 753 V to 1126 V and the efficiency of the PM-generator rise from 83 % to 87 %. A simulation program for optimization of the AC-capacitor is developed. The load resistance in the simulation is choose so the electrical power is proportional with the rotation speed in third because it looks like the power characteristic for a wind turbine. The calculations proved that 68 μF is close to a optimum value for the AC-capacitor, see figure 9.

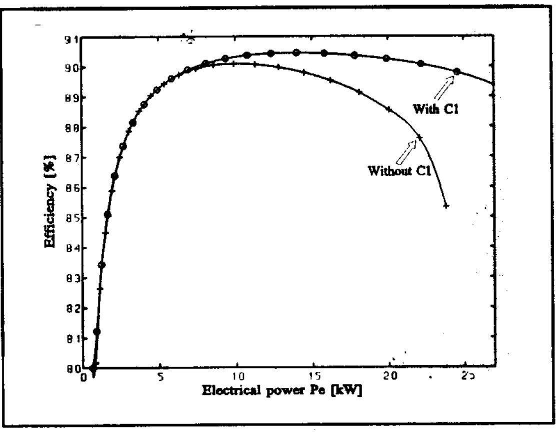

Figure 9. Efficiency for the PM-generator with and without a three phase AC-capacitor (C_1=68 μF) as function of the electrical power

The nominal electrical power and the nominal current at nominal speed can be calculated when a three phase AC-capacitor is connected to the PM-generator.

The calculation is given by:

$$I_N = 21.1A \ , \ E_p = 525.5V$$
$$P_{e,N} = 28.0kW \ , \ P_{m,N} = 31.6kW \quad (2)$$
$$\Rightarrow \ \eta = 88.6\%$$

The rated electrical power for the PM-generator increase more than 19 % from ***23.6 kW*** to ***28.0 kW*** because of the three phase AC-capacitor.

4. Conclusion

The measurements has indicated that this 27 kW prototype PM-generator works properly. The main test results are:

1: The losses at no load are less than 3 % of the nominal electrical power,
2: The torque at standstill is less than 2 % of the nominal torque,
3: The efficiency is greater than 82 % (without AC-capacitor) when the electrical power is over 8 % of the nominal electrical power.
4: The maximal efficiency is better than 90 % when a three phase AC-capacitor is used.

The direct drive PM-generator is suitable for wind turbines because at low load is the efficiency relative high compere to a standard drive train with a gearbox and an asynchronous generator.

Acknowledgments

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References

Søndergaard L., Testing of a Direct Drive Generator BELT DD600 for Wind Turbines, July 1995, Risø-I-908