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Citation for the original published paper (version of record):
Carlson, O., Hylander, J., Tsiolis, S. (1986). Variable speed AC-generators applied in WECS.
European Wind and Energy Association Conference and Exibition, 1: 685-690

European Wind Energy Association
Conference and Exhibition
7-9 October 1986, Rome - Italy.

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VARIABLE SPEED AC-GENERATORS APPLIED IN WECS

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SUMMARY

Constant speed operation is at present the most common way of operating wind turbines. This method, however, results in a stiff coupling between the generator speed and grid frequency. To overcome this stiffness, adjustable speed ac drives can be used. Variable speed drives allow the wind turbine to operate at optimal tip-speed ratio and smooth out the torque transients in the drive train.

This paper describes two variable speed ac-drives, the synchronous generator with frequency convertor for large speed range and the rotor cascade induction generator for small variations of speed. Results obtained with transient state calculations using computer models and verifying laboratory tests were performed for the electrical systems. In the synchronous generator system, a frequency convertor with a dc-link is installed between the grid and the generator. In the rotor cascade induction generator system, the generator is a standard wound rotor induction machine which rotor circuit is connected to a 6-pulse rectifier. The rectified slip-power can be recovered by feeding it back to the grid via an inverter and a transformer.

A 40 kW, three-bladed, variable pitch wind-turbine is used as the test machine at Chalmers Test Station for Windmills. The system with synchronous generator and frequency convertor together with a digital control system has been tested on the windmill.

1. INTRODUCTION

Work on electrical systems applied in WECS has been carried out at the department, during the last ten years. The work included investigations of the switching and short circuit behaviour of induction and synchcronous machines in windpower plants with constant speed operation. [1],[2].

Several experiments and calculations on different variable speed systems have lately been carried out.[3],[4]. Variable speed drives, allow the wind turbine to operate at optimal tip-speed ratio, and smooth out the torque transients in the drive train. As a result of these characteristics, the number of variable speed generators in WECS has increased in recent years.

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2. VARIABLE SPEED AC-GENERATORS

The use of variable speed ac-motors and generators in industrial applications has rapidly increased during the last decade. This fast development has its background in the "continuously" increasing power handling capability of the semiconductor devices, especially the power transistors.

During the design of an adjustable speed drive for windmills, it is important to consider the following points; speed range, time constant of control system, torque pulsations in the rotating machine, injection of harmonic currents into the utility grid, voltage level, reactive power, efficiency, space and weight of electrical equipment.

Recent research on variable speed drives has been concentrated on three different electrical variable speed systems; induction generator with rotor convertor cascade, synchronous generator with frequency convertor and induction generator with frequency convertor.

The induction generator with rotor convertor cascade system is shown in Fig. 1. This consists of a slip-ring induction generator, machine-side rectifier, dc-coil, line-side inverter and a transformer.

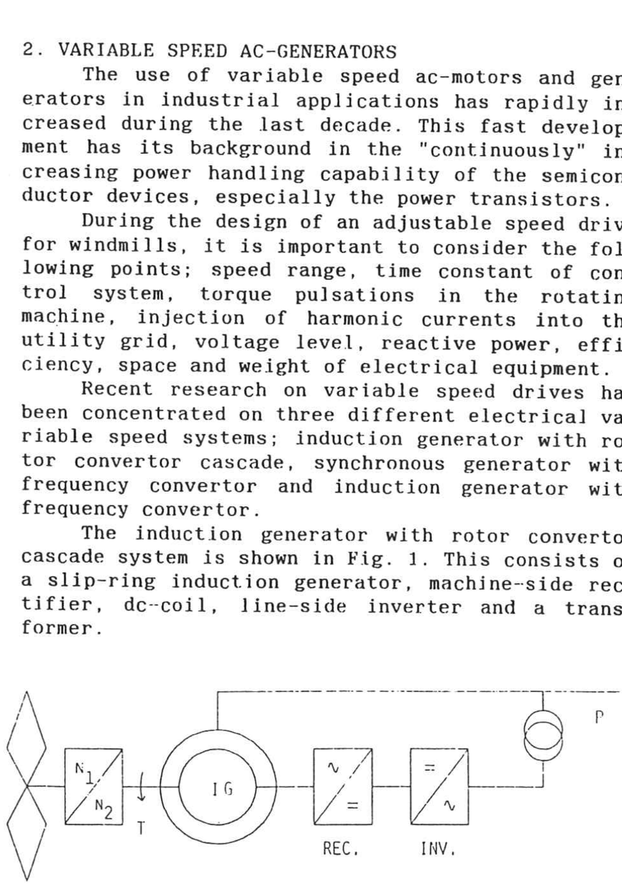

Fig. 1. Induction generator with rotor convertor cascade

In this system only a part of the output power is passing through the convertor. This part is proportional to the slip of the system (Eq. 1.)

$$P_{conv} = (n - n_s)*P_{gen}/n_s \quad (1)$$

where: P_{conv} is the power of the convertor
P_{gen} is the power of the generator
n is the speed
n_s is the synchronous speed

Due to the presence of the rectifier in the rotor circuit, the only possible power flow is from the generator, resulting in speeds above the synchronous speed. The inverter controls the current in the rotor cascade and consequently also the torque in the system (Fig. 2). By this control it is possible to reduce torque transients in the drive train due to windgusts. Torque transients due to windgusts can be reduced if the speed range is small, (about 20% of the synchronous speed). As this small speed range is not enough to make the turbine operate at optimal tip-speed ratio, no significant impact on the amount of produced energy will occur.

This system has been tested by Hydro-Quebec, Canada [1], SERI Wind Energy Research Center, USA and NASA Lewis Research Center, USA.

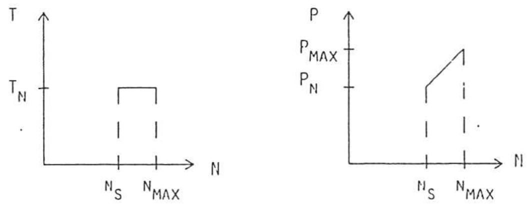

Fig. 2. Torque and power range for the rotor cascade

A variable speed system with a synchronous generator consists of, besides the generator, a three-phase machine-side rectifier, dc-coil, three-phase line-side inverter and (if needed) transformer with filter.

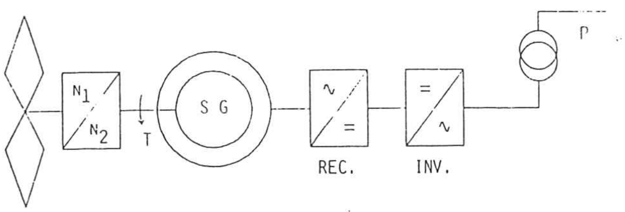

Fig. 3. Synchronous generator with convertor

With this system it is possible to have full control of the torque in the speed range 0.2-1.2 times the synchronous speed. The power is linear with the speed (Fig. 4.). All the power passes through the convertor and due to this, the rated power is the same as maximum power.

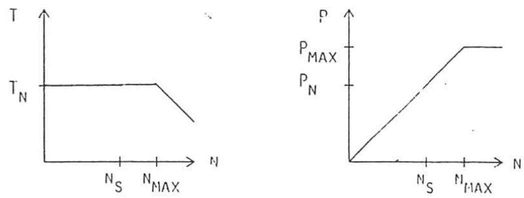

Fig. 4. Torque and power range for the synchronous generator system

The system of induction generator with frequency convertor consists of a cage induction generator and two force-commutated convertors.

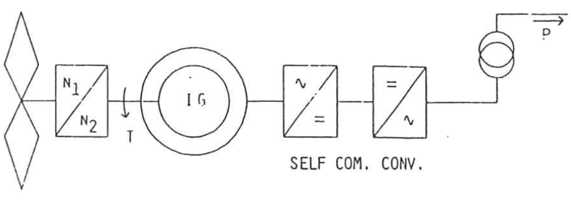

Fig. 5. Induction generator with convertor

The machine-side convertor is operated as a rectifier when the machine is generating and as an inverter when the machine is motoring. During both modes of operation the convertor produces reactive power for the machine. The line-side convertor is, on the contrary, operated as an inverter when the machine is generating and as a rectifier when it is motoring. The convertors are manufactured by power transistors. With this equipment it is therefore possible to operate the machine as a motor or generator in the whole speed range, and control the reactive power.

As part of our wind energy program, the department is, at present, engaged in the design and construction of two new convertors. The convertors together with a generator will be tested in the laboratory this autumn and on a windmill next year.

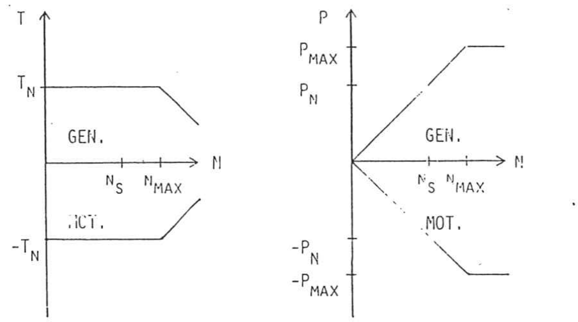

Fig. 6. Torque and power range for the induction generator system

3. INDUCTION GENERATOR WITH ROTOR CONVERTOR CASCADES.

The induction machine with a static slip power recovery system can be used only in wind power plants where a limited variation of speed is needed [6]. The system consists of a slip-ring induction generator, a three-phase inverter and usually also a transformer (Fig. 7).

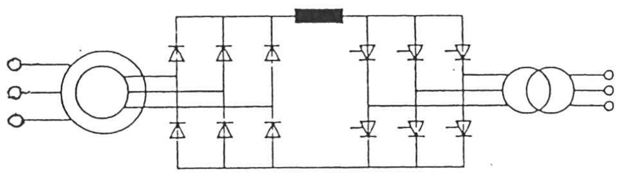

Fig. 7. An induction generator with a slip power recovery system.

The operating range for the speed is oversynchronous at generator operation. The desired torque and speed are obtained by controlling the current in the dc-link, which can be done with the inverter connected to the grid.

3.1 Current harmonics and torque pulsations

The static rectifier connected to the slip-rings of the induction machine creates slip-frequency-dependent stator current harmonics and torque pulsations. If the fundamental rotor frequency is $\omega_2(1)$, the harmonics of the rotor currents will be:

$$\omega_2(n) = (6k + 1)\ \omega_2(1) \qquad k = \pm 1, \pm 2, .. \qquad (2)$$

$$n = |6k + 1|$$

The amplitudes of the rotor current harmonics can be approximated as:

$$I_2(n) = \frac{\sqrt{6}\ Id}{|6k + 1|\pi} \qquad (3)$$

if the dc-link current I_d is completely smoothed and commutations are neglected. The frequencies of the stator current harmonics created by the rotor current harmonics are:

$$\omega_1(n) = (1 + s6k)\ \omega_1(1) \qquad (4)$$

where s is the slip and $\omega_1(1)$ the fundamental stator frequency. The amplitudes of the stator harmonics depend on the stator and rotor winding relation and on the magnetizing part of these harmonics, which usually can be neglected.

If the commutations are neglected and the flux is assumed to be created only by the fundamental stator current, the electrodynamic torque can be approximated as:

$$t_{el} = - p\psi_r I_2(1)\ \{\ \sin\Theta - \sum_k \frac{2\ \sin 6k\omega_2(1)t}{(6k+1)(6k-1)}\ \} \qquad (5)$$

where p is the pole pair number and ψ_r the fundamental rotor flux with the angle Θ between the flux and the current. Equation (5) show that the electrodynamic torque contains harmonics of six times the rotor frequency. These harmonics may excite natural frequencies of the drive, which can cause severe vibration problems.

3.2 Computer model

In order to investigate above mentioned harmonics a computer model has been developed [3]. The model consists of eleven coupled differential equations describing an induction machine currents, rotational speed and angle with a rectifier connected to the rotor circuit, Fig. 8.

The results from a calculation on a 22 kW induction machine are presented below. The parameters of the machine presented in the appendix is used.

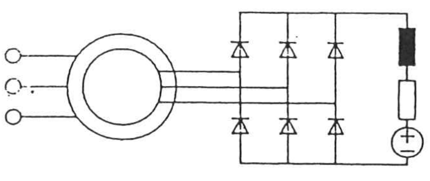

Fig. 8 The rotor cascade computer model.

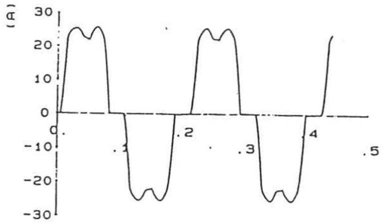

Fig. 9 Calculated rotor current.

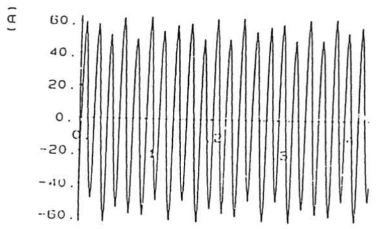

Fig. 10 Calculated stator current.

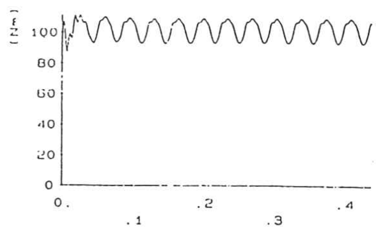

Fig. 11 Calculated electrodynamic torque.

3.3 Measurements

To verify the computer calculations, measurements were made on the 22 kW induction machine, which was used during the calculations. The slip-ringed induction machine was coupled by a torque transducer to a 31 kW dc machine, acting as a wind turbine. The slip rings of the induction machine were connected to a six-pulse diode bridge rectifier. The dc-side of the rectifier was loaded with an inductance and a resistance. The stator and rotor currents as well as the torque were measured with a computer-based measurement system. The results from the measurements agree well with the calculations (Fig. 12 ... 14).

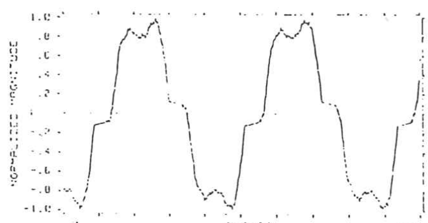

Fig. 12 Measured rotor current.

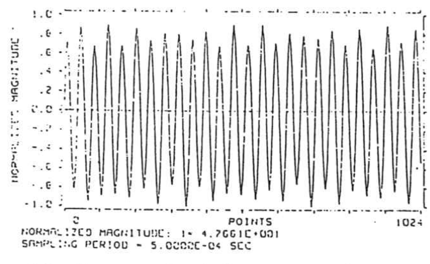

Fig. 13 Measured stator current.

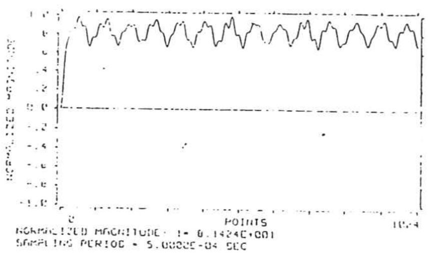

Fig. 14 Measured electrodynamic torque.

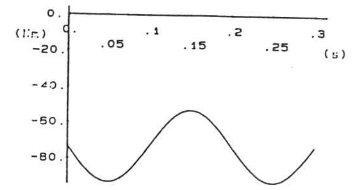

Fig. 17 Applied mechanical torque.

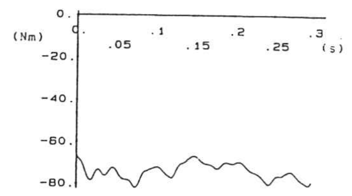

Fig. 18 Calculated electrodynamic torque.

3.4 Reduction of current harmonics and torque pulsations.

The harmonics in the rotor currents, which creates the torque pulsations, can be reduced if a twelve-pulse rectifier is used. Two alternatives are here possible; either an external D/DY transformer (Fig. 15) or a modified rotor winding with two three-phase groups separated 30 electrical degrees. Both calculations and measurements have been made [7] on these two systems.

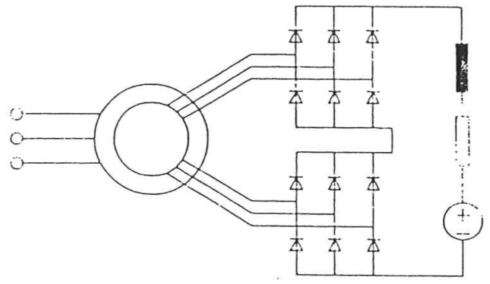

Fig. 15 A twelve-pulse rotor cascade.

3.5 Control of the torque.

If the mechanical torque is measured, calculations [3], have shown that it is also possible to control the torque pulsations (and of course also the loading torque of the generator) by controlling the dc-link current with the grid-side inverter. By controlling the torque of the generator, in order to keep the loading torque at a constant level, the speed will vary.

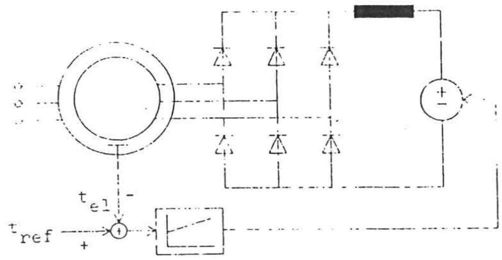

Fig. 16 Calculation model with torque control.

Calculations have been made with an applied low frequency sinusoidally varying mechanical torque with a dc-level. The control, which is performed with a PI-regulator controlling a voltage source connected to the dc-link (Fig. 16), uses the difference between the actual electrodynamic torque in the generator, t_{el}, and a reference torque, t_{ref}. The calculations on the 22 kW induction machine indicate that this method can be used to reduce both external torque disturbances and torque harmonics created from the power electronics. The method used is straightforward and uncomplicated, though difficulties can occur estimating the electrical torque.

4. SYNCHRONOUS GENERATOR WITH FREQUENCY CONVERTOR

The reasons for choosing to start with testing and evaluating the synchronous generator system are the simplicity and availability of standard, well tested component parts and that the equipment offers a wide range of speed below synchronous speed. This can be compared with the rotor cascade system, which can only operate above the synchronous speed. The control of the inverter is also well tested on dc-drive systems for industrial applications. The inverter controls the current and thereby the electrical torque in the generator.

The objective of the control of this system is to have the turbine running at optimal tip-speed ratio up to the rated torque [8]. For higher winds the torque will be constant and the speed will change due to the wind gusts. When the speed reaches its upper limit, the blades will feather to decrease the power from the wind.

The generator which has been used (see appendix) in the calculations and laboratory tests is a slip-ring induction generator. The windmill (Section 4.3) has a generator of the same type but with twice the rating. By feeding a dc-current through the rotor windings, the generator will act as a synchronous one. The machine has, however, to be derated by 40 % due to overheating in the rotor windings.

4.1 Theoretical analysis

Theoretical analysis is carried out by a circuit analysis program that can handle transient models of electrical machines [9]. In the model, the generator is represented by seven differential equations, three for the stator windings, three for the rotor windings and one for the mechanical behaviour. The three-phase rectifier is repesented by six differential equations. In order to reduce the model, the inverter is represented by a small resistance and a controlled dc-source.

To show the control and dynamics of the system calculations are carried out at a constant speed and torque operating point, and from this constant point, driving torque step is applied (Fig.19.). As a response to this step, the generator will start to accelerate while the control of the torque, via the current, will keep the electrical torque in the generator constant (Fig.19).

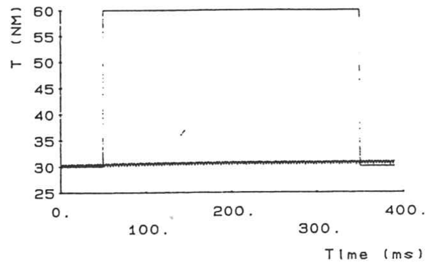

Fig 19. Applied and electrical torque.

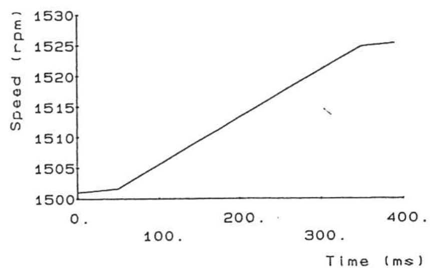

Fig.20. Speed of the generator

For comparison, calculations have been carried out with the generator working as a cage induction generator under similar conditions. The generator will operate in the slip-dependent speed-range, about 1 % for machines of mega-watt size and 3-4 % for small machines like the one used here. Figure 22 shows how the speed rises to its new value and figure 21 shows how the electrical torque follows the applied one.

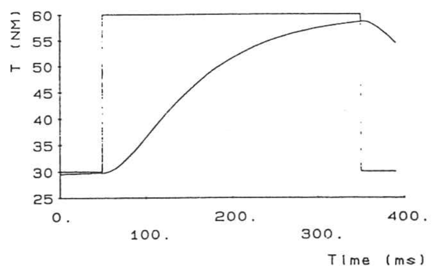

Fig. 21. Applied and electrical torque at the cage generator

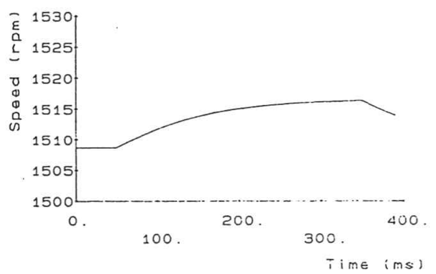

Fig. 22. Speed of the cage generator

4.2 Laboratory experiment

During the laboratory tests, the generator was connected to a dc-motor. To control the torque of the dc-motor, a current-controlled rectifier was used. The control signal to this rectifier is here similar to the applied torque (Fig. 23.).

The conditions for the laboratory tests are similar to those in the calculations. The results from the measurements show good agreement with theoretical analysis. Figure 25 shows how the speed increases. The electrical torque, however, remains constant (Fig. 23.). The mechanical torque is measured on the shaft between the dc-motor and the generator. In this way, there will be an increase in the mechanical torque during acceleration due to the rotor inertia of the generator (Fig. 24.).

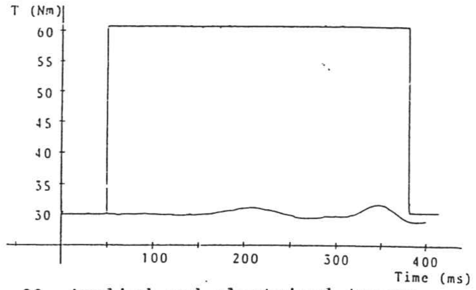

Fig. 23. Applied and electrical torque

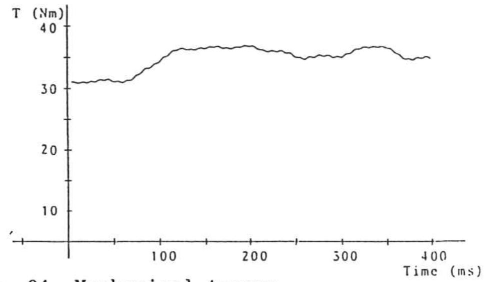

Fig. 24. Mechanical torque

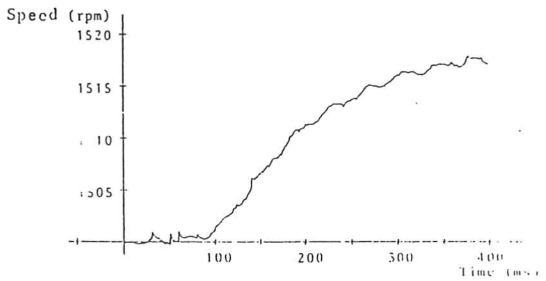

Fig. 25. Speed of the generator

Measurements on a cage induction generator have also been carried out. The machine is not controlled and the mechanical torque rises due to the applied one (Fig. 26.). The speed rises to its new constant torque dependent value (Fig. 27.).

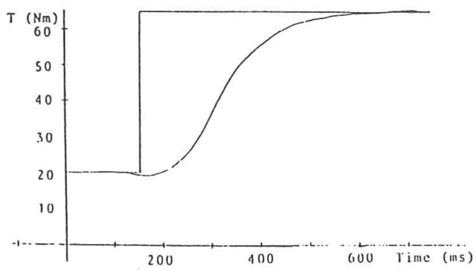

Fig. 26. Applied and mechanical torque in constant speed operation.

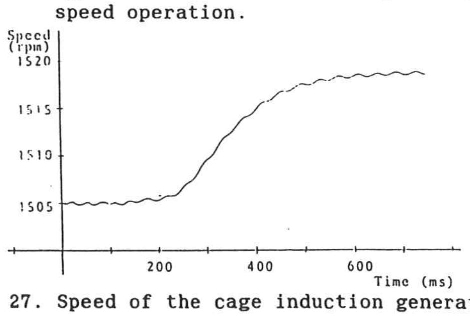

Fig. 27. Speed of the cage induction generator

4.3 Installation of the synchronous generator system on a windmill.

At Chalmers Test Station for Windmills a 40 kW, three-bladed, variable pitch wind turbine is used as a test machine. The purpose of the research on the windmill is the development and evaluation of electrical variable speed systems for large wind turbines.

After testing the system with a synchronous generator and frequency convertor in the laboratory, the equipment was moved and installed at the windmill together with a digital control system.

The results from running the system are good and the system behaves as described in the beginning of Section 4. It is always hard to find similar conditions in calculations, in laboratory testing and especially on the windmill. The measurements which are shown here were taken when a wind gust was acting on the turbine (Fig. 28.), compared with the step in calculations and laboratory tests, and the response this gust gives on speed (Fig. 30.) and electrical torque (Fig. 29.). As can be seen the torque is constant and the dynamics of the system are as expected.

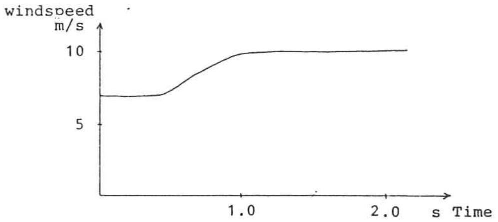

Fig. 28. A wind gust acting on the wind turbine

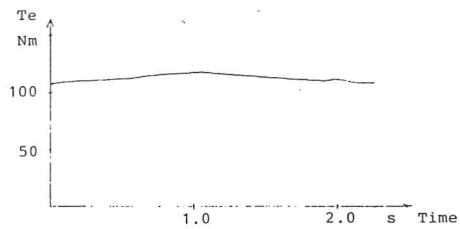

Fig. 29. Electrical torque in the generator

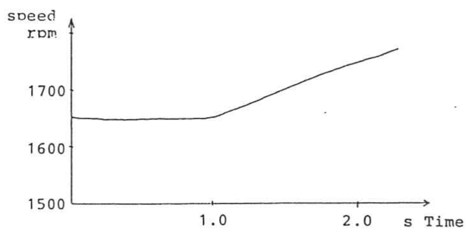

Fig. 30. Generator speed of the windturbine

5. CONCLUSION

Two variable speed constant frequency systems have been tested in the laboratory and transient calculations have been carried out. With the induction generator rotor cascade system the currents and torques have been analysed. The results show slip-dependent harmonics in currents and torques. Methods to reduce these harmonics are presented. For the synchronous generator with frequency convertor, the behaviour of the system when a driving torque step is applied is presented. The results show how the control keeps the electrical torque constant while the generator starts to accelerate.

The synchronous generator system has been installed at a windmill. The experiencies from the tests agree well with the calculations and laboratory results. The torque in the windmill remains constant when a wind gust acts on the turbine, while the speed rises.

6. ACKNOWLEDGEMENTS

The authors would like to express their thanks to Prof. Em. S. von Zweygbergk for his enthusiastic and valuable discussions and support, T. Svensson for his advice on control of synchronous machines and G. Johansson and R. Almarsoomi for their work on the measurements for Section 4. Financial support given by the Swedish Energy Administration is also gratefully acknowledged.

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APPENDIX: Ratings and data of induction machine.

P=22	kW	R_1 =0.1245	ohm/phase
n=1461	rpm	R_2 =0.1366	ohm/phase (ref. to stator)
f=50	Hz	$X_{1\lambda}$=0.358	ohm/phase
U=380	V	$X_{2\lambda}$=0.582	ohm/phase (ref. to stator)
J=0.33	kgm^2	X_m =12.5	ohm/phase (ref. to stator)