A control procedure for permanent magnet variable-speed wind turbine

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Abstract. In this paper a prototype of the electrical part of a variable speed wind turbine is considered, equipped with a permanent magnet synchronous generator. The modelling of the generator and power electronics interface is checked with measurements realised in the prototype under both steady state and dynamic conditions. Measurements as well as control functions are performed by using a microprocessor. The outcome of the simulation and experimental work are actually utilised in the development of a 25 kW wind turbine, in the frame of a research project.

Key words

Dynamic response, microprocessor based control, permanent magnet, synchronous generator, wind turbine.

1. Introduction

The control of wind turbine systems is a complicated task due to the stochastic nature of available energy by the wind. Moreover often conflicting requirements are involved, such as the low cost and reduced stresses [14], on the one hand, and the good output power quality and dynamic characteristics on the other [9],[10]. In this paper variable speed wind turbines are considered, equipped with permanent magnet generators [7],[8]. The examined wind turbines are multi-polar in order to avoid switch-gears, exhibiting the well-known weight and reliability problems [6].

In order to achieve variable speed operation, a power electronics converter stage is necessary to connect the generator to the grid [1],[2]. The system analysis in such cases involves models for the generator [3],[4],[5], the static converter [2],[12] and the grid [9].

In this paper a 2 kW prototype of the electrical part of such a variable speed wind turbine is considered, equipped with a 24 pole permanent magnet synchronous generator. The modelling of the generator and power electronics interface is presented and checked with measurements realised in the prototype, both in the steady state and in dynamic conditions. Measurements as well as control functions are performed by a microprocessor.

The outcome of the simulation and experimental work are actually utilised in the development of a low cost 25 kW wind turbine, in the frame of a research project funded by the Greek Secretariat for Research and Technology.

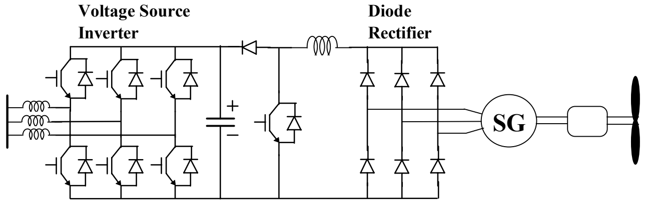


Fig. 1. Subsystems of the electrical part of a typical permanent magnet generator variable speed wind turbine system

2. Subsystems and Modelling

The basic components of a variable speed wind turbine system are shown in Fig. 1. In this figure, it may be noted that there is no gearbox to increase the speed of the generator rotor. This is due to the machine multiple pole structure, in order to achieve reasonable electrical frequencies for low rotor speed. In the case considered 100 poles are needed (100 rpm) for the 25 kW sized machine while 24 poles (400rpm) were adopted for the prototype.

The static converter shown in Fig. 1 consists of an uncontrolled 3-phase diode rectifier, a DC/DC boost converter, a 3-phase PWM voltage source inverter and possibly a step-up transformer.

A. Aerodynamic part and control reference

Aerodynamic analysis of the wind turbine blades provided the characteristics shown in Fig.2. The continuous curves show variations of the rotor torque with rotor speed, for a given wind speed.

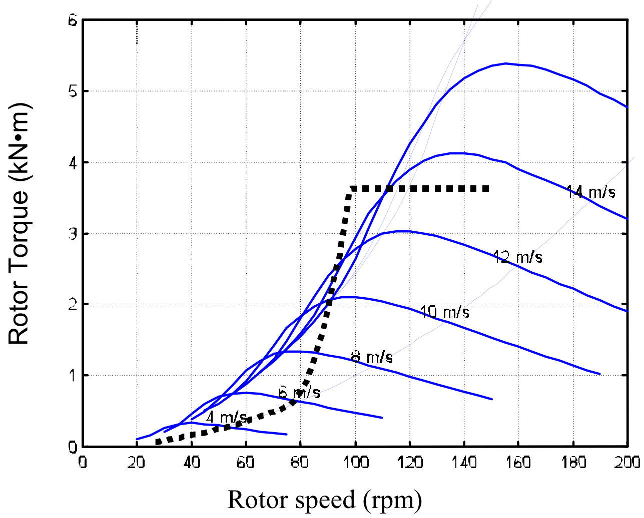


Fig. 2. Aerodynamic part torque-speed characteristics for different wind speeds and proposed control reference

The dotted line is the proposed reference for the control system and can be divided into three main parts associated to different control operations: the leftmost part, with low inclination, corresponds to the maximum power points for every wind speed. The median part, with high inclination, prevents the turbine from over-speed, thus protecting it by using the stall effect. The rightmost part corresponds to the situation that the machine cannot deliver more torque, so an external braking system is needed for shutting down the system. Obviously, the control action should avoid such a situation, that is why the paper is devoted to the implementation of the first two parts of the reference.

The characteristics shown in Fig. 2 are static corresponding to the steady state of the aerodynamic part. The wind speed is practically never steady. In fact, it is quite variable, depending on the wind characteristics of the specific place. So it is very important both in the design and implementation of the control system to consider the dynamic behaviour.

B. Electrical part

The actual configuration used in the laboratory did not include the shown in Fig. 1. In our case the generator's inductance was used for voltage boosting and filtering. Moreover, the voltage source inverter and the grid have been represented by a convenient resistive load controlled by a chopper.

The rectified output of the generator prototype is quite similar to the ones of a direct current machine. This is shown in Fig. 3 comparing the theoretical prediction of such a characteristic by using finite element simulation [8]. This form of behaviour involves simple calculations for representation of the boost converter.

The generator model used in the electric circuit analysis considered sinusoidal electromotive forces. This provides acceptable accuracy for the generator representation while necessitating reduced calculation means [7].

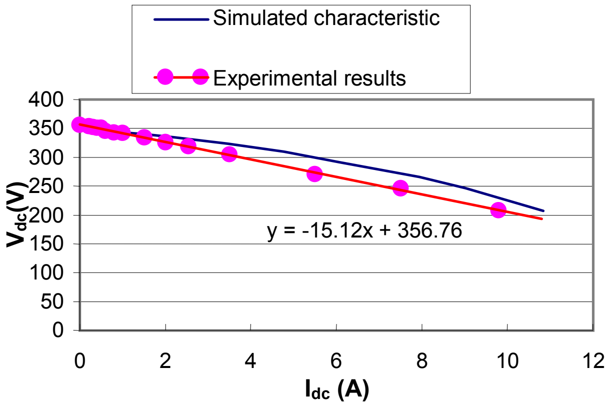


Fig. 3. I-V characteristics of the rectified output of the synchronous permanent magnet generator

To ensure accuracy, a three phase equivalent circuit has been used together with a rectifier and a resistive load, and both measured and simulated waveforms have been compared. The circuit illustrated in Fig. 4 allowed for both fundamental and higher harmonics analysis.

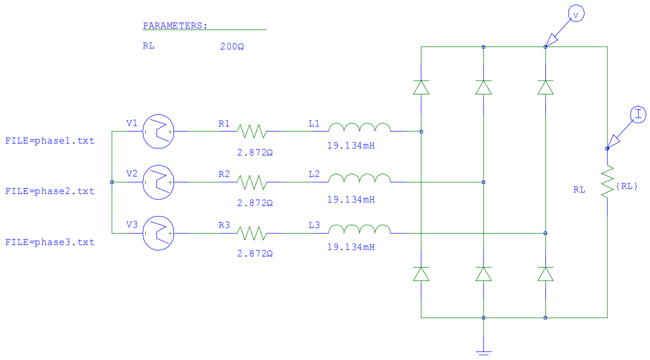


Fig. 4. Three phase equivalent circuit used in all simulations of the permanent magnet synchronous generator

The case of low load condition has been simulated and the computed results by the different models are compared to measurements. The measured time variations of the phase current and voltage are shown in figures 6c and 7c, respectively. Both current and voltage waveforms are distorted due to the reactive power effect of the rectifier.

The simulated results by the fundamental component model for the phase current and voltage in the machine in this case are shown in figures 6a and 7a, respectively.

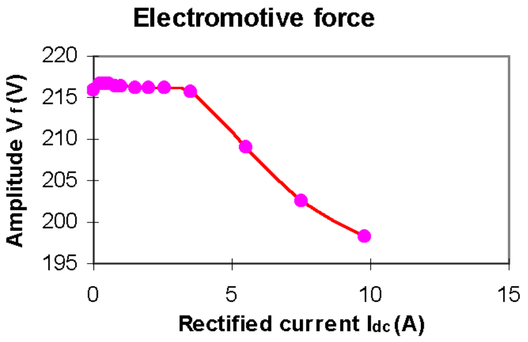
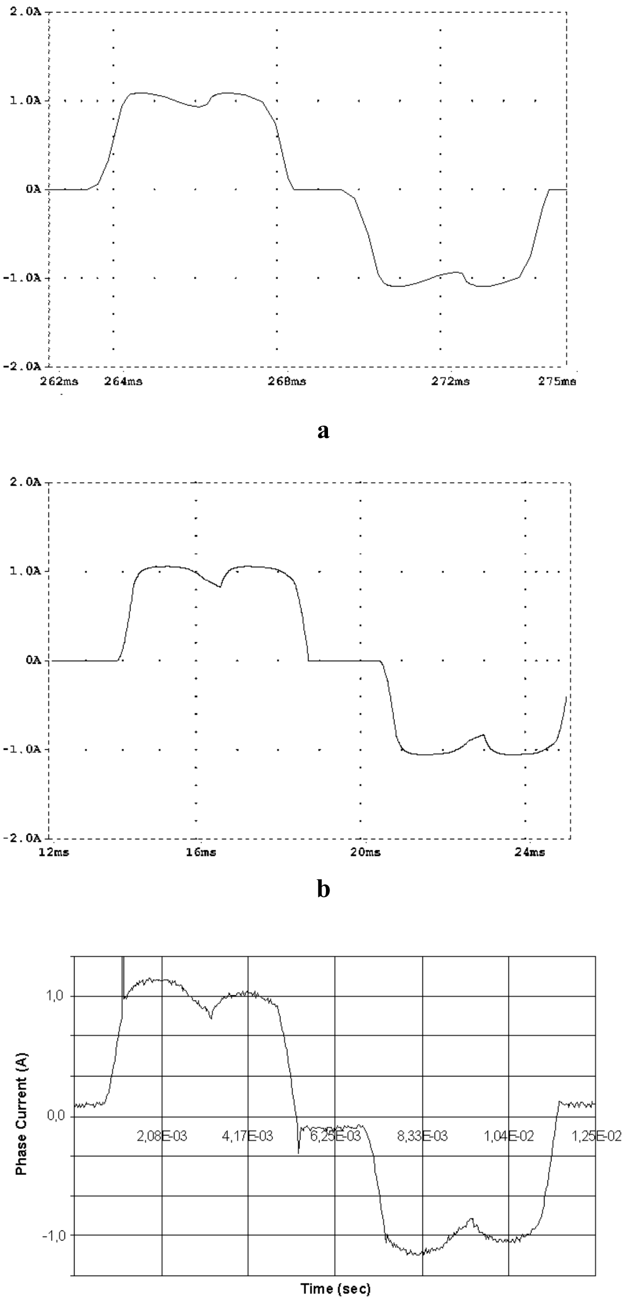


Fig. 5. Reduction of fundamental electromotive force to match rms electrical values in fundamental component model



a

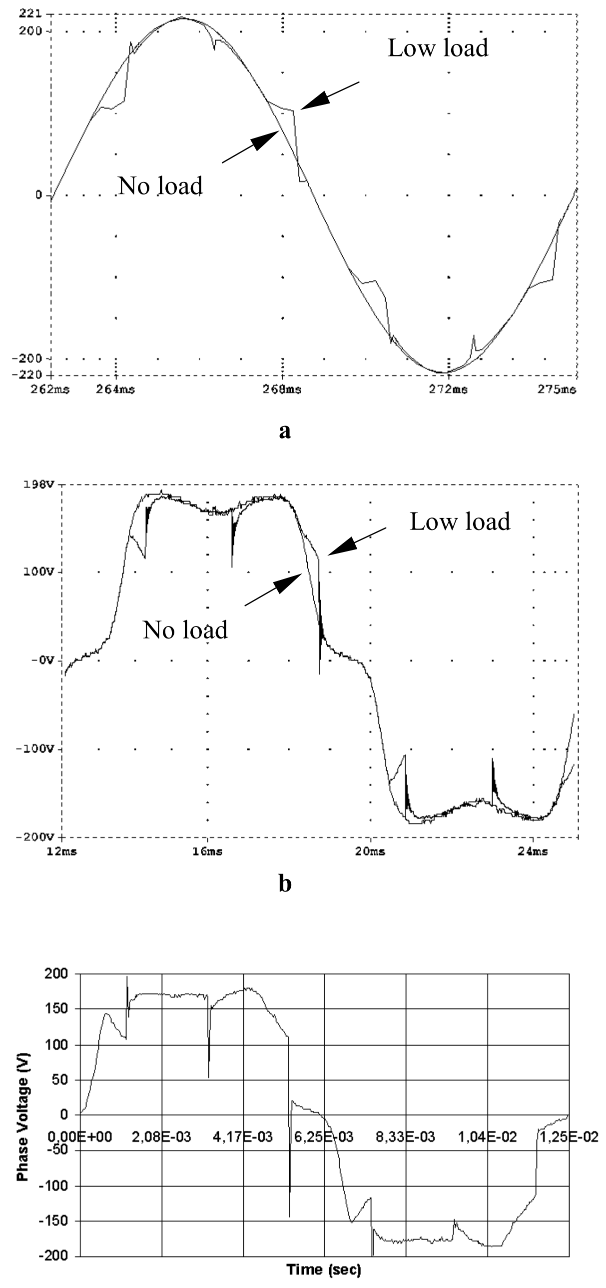
b

c

Fig. 6: Phase current of the permanent magnet synchronous machine at low load conditions
a: simulated by the fundamental component model
b: simulated by the higher harmonics model
c: measured

While the simulated current is in very good agreement with the measured one by using this model, the voltage is not represented properly. This implies that fundamental component model cannot be very accurate in voltage prediction as it neglects the higher harmonics.

Higher harmonics model is in very good agreement with the measured waveforms for both phase current (figure 6b) and voltage (figure 7b). In these figures, even the spikes due to diode recovery are efficiently represented. At high load conditions the current has less higher harmonic content but the voltage is even more distorted.



a

b

c

Fig. 7: Phase voltage of the permanent magnet synchronous machine at low load conditions
a: simulated by the fundamental component model
b: simulated by the higher harmonics model
c: measured

Higher harmonics model provides simulated waveforms, which are almost identical to the measured ones. Furthermore, this model needs no adjustment of electromotive force's amplitude to represent efficiently rms values, and can be easily used for lower machine speeds.

On the contrary the results in fundamental analysis showed the need for reduction of electromotive force to match rms electrical values. Fig. 5 shows the amount of reduction in full speed operation.

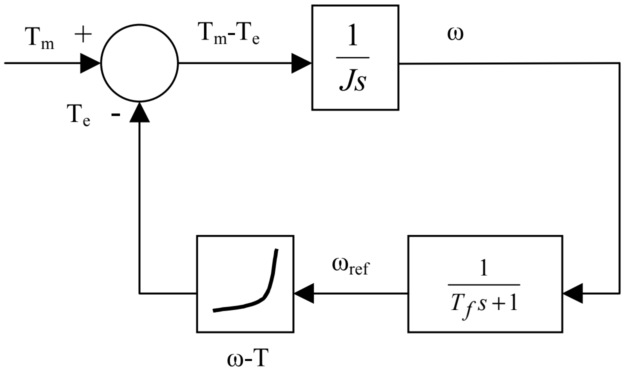


Fig. 8. Speed control system block diagram

B. Mechanical part

In the case of the simpler representation of the mechanical part by a concentrated mass with moment of inertia J rotating at angular velocity ω_r, the governing equation is:

$$T_m - T_e = J\left(\frac{2}{P}\right)\frac{d\omega_r}{dt} \tag{1}$$

where P is the number of poles, T_m is the mechanical torque on the shaft and T_e the electromagnetic torque

In order to obtain a control without oscillations, a low-pass filter must be included in the rotor speed feedback path of the control, as shown in Fig. 8. Its purpose is to attenuate speed oscillations, which otherwise would be reflected on the generator torque, degrading the output power quality and contributing to the variability of the mechanical torque. Thus a convenient selection of T_f is very important [7].

3. Control System and Measurements

After constructing the circuits and predicting the electrical behaviour, a control program is needed to evaluate the data measured and act as necessary to bring the system to the desired working point [11]. In our case two loops are working: A current control loop associating the reference torque-speed characteristic to a convenient generator current - speed characteristic as shown in Fig. 9 has been introduced.

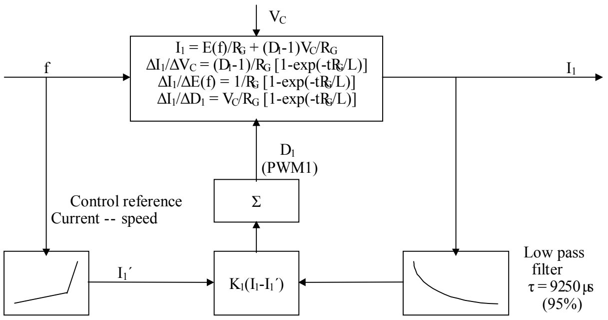


Fig. 9. Schematic diagram of synchronous generator current -speed control subsystem

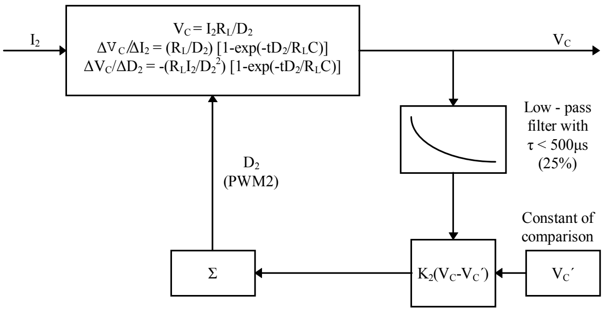


Fig. 10. Schematic diagram of capacitor voltage -loading control subsystem

Moreover a voltage - loading control loop has been adopted illustrated in Fig. 10.

The current control loop draws monitors the electrical power from the generator in order to achieve the correct combination of power and electrical frequency corresponding to the optimum operation of the aerodynamic part (reference in Fig. 2). It is a PI controller with a low pass filter and a non-linear reference.

The power drawn from the generator charges the filtering capacitors. The voltage control loop takes care of monitoring the accumulated power in the capacitors to the load.

As the capacitors are charged, their voltage increases. This PI controller shown in Fig. 10 filters the measurement and compares the result with a pre-defined constant. Then capacitors are discharged through the load adjusted by a PWM controlled IGBT.

The program consists of two branches as shown in Fig. 11: the main program and automatic control. In the main program the user may review measurements and alter state variables.

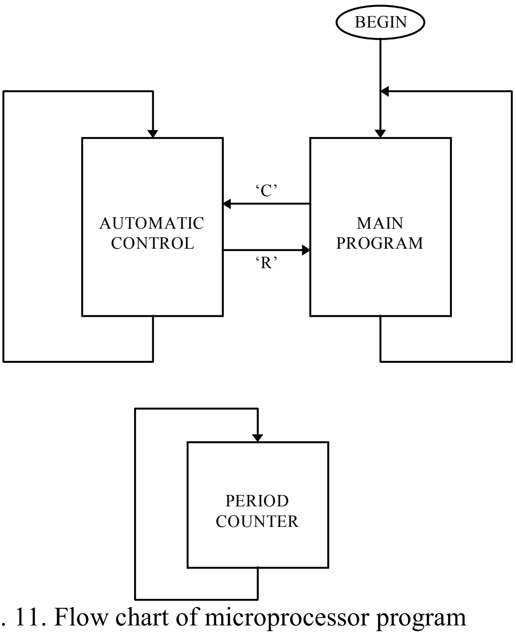


Fig. 11. Flow chart of microprocessor program

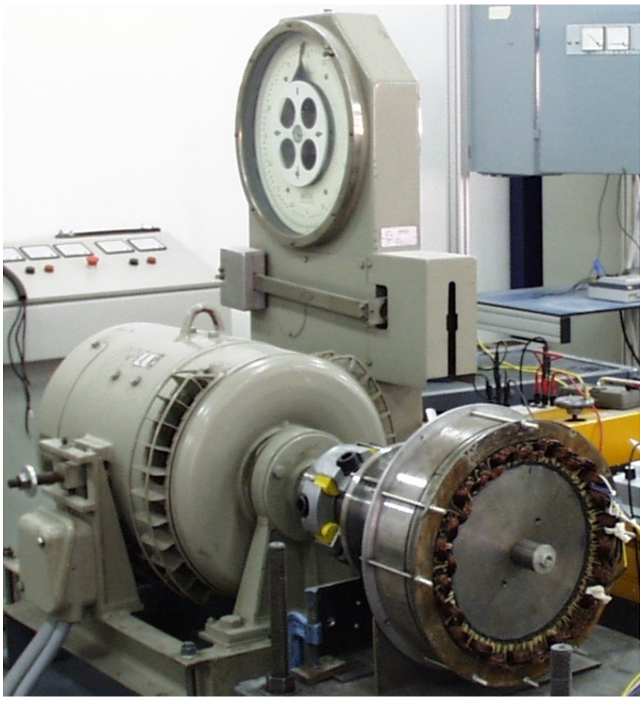


Fig. 12. Experimental set-up showing the 2 kW permanent magnet synchronous machine prototype.

By pressing the ‘C’ key on the PC keyboard one may start the automatic control, where the two aforementioned loops cooperate and monitoring is disabled due to speed problems. Special care is taken at extreme circumstances, i.e. in case of an over-voltage condition.

4. Results and Discussion

The experimental set-up comprises the permanent magnet synchronous generator prototype consisted of 24 poles, illustrated in Fig. 12. The shaft torque is controlled by using a dc machine torque-meter simulating the aerodynamic part of the wind- turbine. The maximum rotating speed adopted for the experiments was 400 rpm.

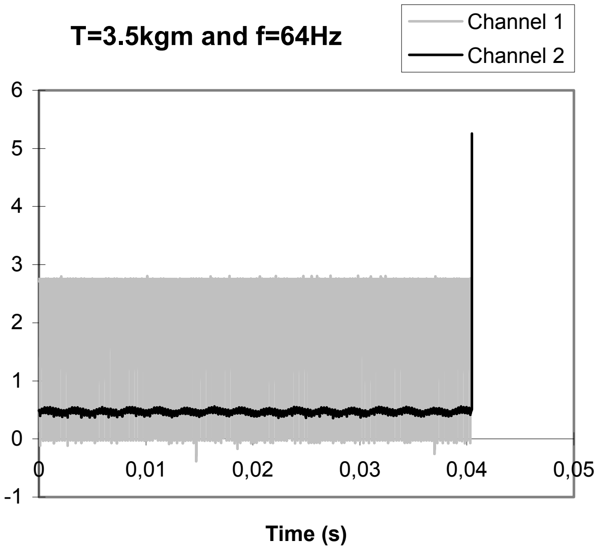


Fig. 13. Measured steady state system ripples (capacitor voltage and generator current for 3.5 kg.m torque and 64 Hz frequency)

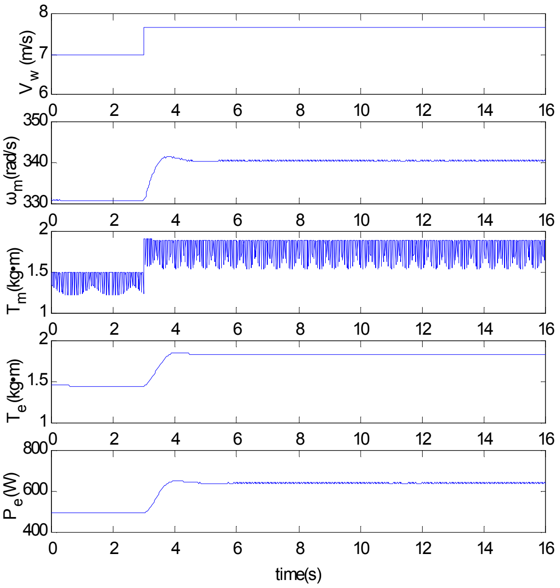


Fig. 14. Simulated electromechanical time response for step up wind speed variation

This system enables also dynamic analysis by applying convenient torque steps through appropriate control of the four quadrant converter supplying the dc torque-meter.

Figure 13 shows the capacitor voltage (Channel 1 - 550V) and generator rectified current ripples (Channel 2 - 5A) at steady state. This figure illustrates the very good steady state characteristics of the system.

The dynamic behaviour of the system is of equally great importance. The simulated time responses for the rotor angular velocity ω_m, mechanical torque T_m, electrical Torque T_e and generated power P_e, in case of a step up in wind speed V_w are shown in Fig. 14. This figure shows that the time constant involved is approximately 2 seconds, which is in good agreement with the time responses of the measured capacitor voltage and generator current for a step increase in rotor torque, given in Fig. 15.

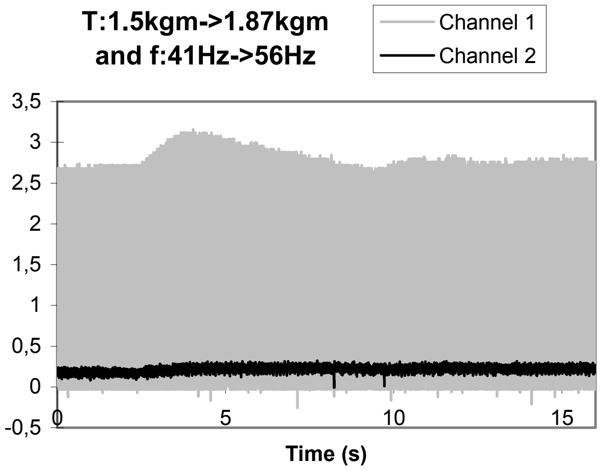


Fig. 15. Measured system time response for step up torque (capacitor voltage and generator current time variations)

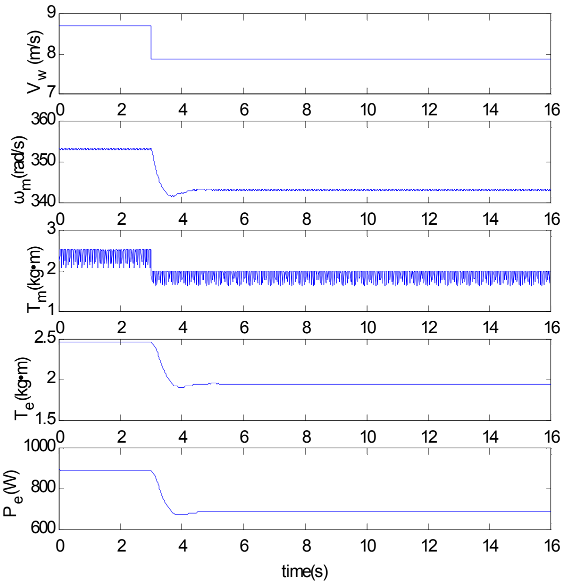


Fig. 16. Simulated electromechanical time response for step down wind speed variation

The agreement between simulated and measured time responses can be observed in Figs. 16 and 17 showing the same results in case of step down wind speed variation.

5. Conclusion

The design, construction and testing of a control system for synchronous permanent magnet generator wind turbines has been presented. This system ensures produced power optimization as well as overspeed protection in case of high wind speeds. Its performance has been checked by means of a 2 kW experimental set-up. The proposed system provides excellent steady state characteristics and adequate time response to step torque variations.

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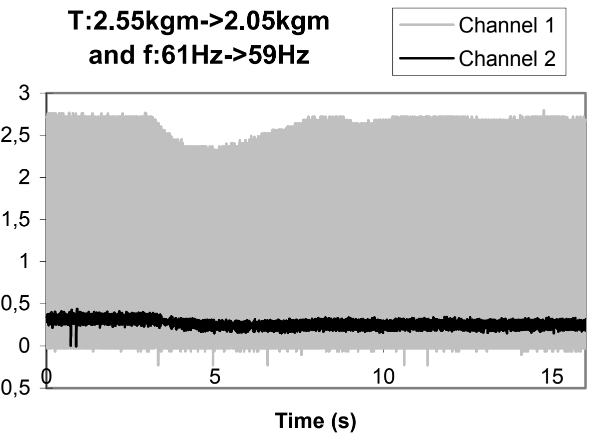

Fig. 17. Measured system time response for step down torque (capacitor voltage and generator current time variations)

References

[1] T. M. Jahns, "Motion control with permanent magnet AC machines", IEEE Proceedings, Vol. 82, No 8, 1994, pp. 1241-1252.

[2] N. Mohan, T. M. Undeland, W. P. Robbins, Power Electronics-Converters, Applications and Design, Wiley, 1995.

[3] M.A. Alhamadi, N. A. Demerdash, "Modeling and experimental verification of the performance of a skew mounted permanent magnet brushless dc motor drive with parameters computed from 3D-FE magnetic field solutions", IEEE Trans. on Energy Conversion, Vol. 9, no 1, 1994, pp. 26-35.

[4] Marchand C., Ren Z., Razek, A., " Torque optimization of a buried permanent magnet synchronous machine by geometric modification using FEM", EMF'94 International Conference, Leuven, Belgium, 1994, pp. 53-56.

[5] T. Higuchi, J. Oyama, E. Yamada, E. Chiricozzi, F. Parasiliti, M. Villani, "Optimization procedure of surface permanent magnet synchronous motors", IEEE Trans. on Magnetics, Vol. 33, no 2, 1997, pp. 1943-6.

[6] Kladas A., Papadopoulos M., Tegopoulos J., "Multipole permanent magnet generator design for gearless wind power applications", ICEM'98, Istanbul, Turkey, 1998, pp. 2055-9.

[7] Aliprantis D., Papathanassiou S., Papadopoulos M., Kladas A., "Modeling and control of a variable-speed wind turbine equipped with permanent magnet synchronous generator", ICEM'2000, Helsinki, Finland, August 2000, pp. 558-562.

[8] G. Tsekouras , S. Kiartzis , A. Kladas, J. Tegopoulos, "Neural Network Approach compared to Sensitivity Analysis based on Finite Element Technique for Optimization of Permanent Magnet Generators", IEEE Trans. on Magnetics, Vol. 37, no 5/1, 2001, pp. 3618-3621.

[9] S. Heier, Grid Integration of Wind Energy Conversion Systems, Wiley, 1998.

[10] A. J. G. Westlake, J. R. Burnby, E. Spooner, "Damping of power-angle oscillations of a permanent magnet synchronous generator with particular reference to wind power applications", IEE Proceedings - Electric Power Applications, Vol. 143, No 3, 1996, pp. 269-280.

[11] B. C. Kuo,Automatic Control Systems", 7th Edition, Prentice Hall International Editions.

[12] D. J. Leith, W. E. Leithead, "Implementation of wind-turbine controllers", Int. Journal on Control, Vol. 66, no 3, 1997, pp. 349-380.

[13] M. G. Simoes, B. K. Bose, R. J. Spiegel, "Design and performance evaluation of a fuzzy-logic-based variable-speed wind generation system", IEEE Trans. on Industry Applications, Vol. 33, no 4, 1997, pp. 956-965.

[14] S. Papathanassiou, M. Papadopoulos, "Dynamic Behavior of Variable Speed Wind Turbines under Stochastic Wind", IEEE Trans. on Energy Conversion, Vol. 14, No. 4, Dec. 1999, pp. 1617-1623.