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Analysis of DC Converters for Wind Generators

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Abstract: The present paper investigates the system behavior of a rectifier and a DC-boost converter used in a wind generator with variable speed. In many cases a combination of diode rectifier and a DC boost converter is used as interface between the generator and the inverter in order to match the requirements for the DC bus voltage. Different models of the converters have been developed in Malab/Simulink and PSPICE environments. Comparison between the simulations and experiments is shown. The power losses are also discussed.

Keywords: Boost converter, wind generator, renewable energy.

1 Introduction

IN recent years the development of the Wind Energy Conversion Systems (WECS) is significant. However, their widespread system integration is often associated with energy quality deterioration in view of the stochastic nature of the wind. Thus, the extensive research of the WECS, i.e. primary energy extraction, mechanical conversion, electrical conversion and power generation and network integration, is needed to improve the quality of "green" energy production.

Different configurations of WECS exist, some of them using DC-DC converters [1]. These converters adjust the varying input voltage of the system compared to desired output voltage. In many cases a combination of diode rectifier and a DC boost converter is used as interface between the generator and the inverter in order to match the requirements for the DC bus voltage - Figure 1. The present paper deals with a diode rectifier and a DC-boost converter used in a wind generator

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with variable speed. Converters models have been developed in Malab/Simulink and PSPICE environments. Two simple and accurate models of the boost chopper have been designed using the software MATLAB/Simulink. The first method uses the dynamic mathematical equations of the converter for building Simulink representation. This method allows the subsequent easy control design and implementation. Two control loops: inner feed forward current control loop and outer voltage control closed loop are modeled. The second method is based on the SimPowerSystems® library of Simulink for building the model using directly the converter electrical circuit. Thus, the electrical signals such as currents and voltages might be correct simulated and observed. PSPICE model of the converter and the control circuit is also elaborated to improve and facilitate the hardware implementation. Comparisons between different models simulations and experiments are shown. The power losses it the converter and the generator are also discussed.

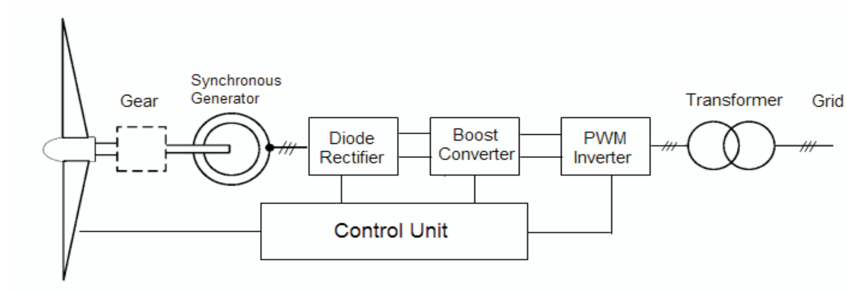

Fig. 1. Wind generator with diode rectifier, DC boost converter and inverter.

1.1 Boost converter model

The dynamics of the converter in the continuous current mode (CCM) can be described using the Kirchoffs equations for the circuit depicted in Figure 2 [2, 3].

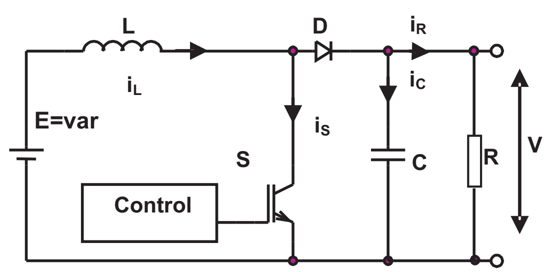

Fig. 2. Boost converter electrical circuit.

The state variables are the current through the inductance L and the DC voltage V. The control manipulates the duty ratio in way to boost the rectifier DC voltage, while keeping a constant near unity power ratio. The inductor current is

$$\frac{\mathrm{d}i_l}{\mathrm{d}t} = -(1-u)\frac{V}{L} + \frac{E}{L} \tag{1}$$

where E can be any input DC voltage (ex. from rectifier or battery) and V is the output DC voltage. Normally, for the boost operation V is at least equal or superior to E. The capacitor voltage equation becomes

$$\frac{\mathrm{d}V}{\mathrm{d}t} = -(1-u)\frac{i_L}{C} - \frac{V}{RC} \tag{2}$$

The Simulink implementation of these equations is presented in Figure 3.

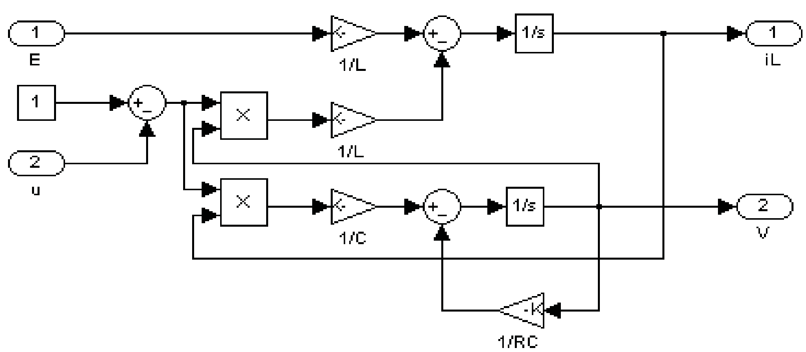

Fig. 3. Simulink realisation of the boost converter mathematical model.

1.2 SimPowerSystem model of the diode rectifier-boost chopper wind energy system

SimPowerSystems® is a supplement library of MATLAB/Simulink. It adds the functionality of power electronics and electrical machinery simulations in a simple way. Instead of signal connections, SimPowerSystems® uses the electrical ports. The ports manage both voltages and currents and the circuit is derived directly from the real pattern. The model is constructed using different blocks from the Matlab/Simulink library SimPowerSystem and it is shown in Figure 4.

1.3 Control circuit models

The boost converter control circuit is designed on the basis of the converter Bode characteristics for current mode control [4]. The compensator is designed to ful-

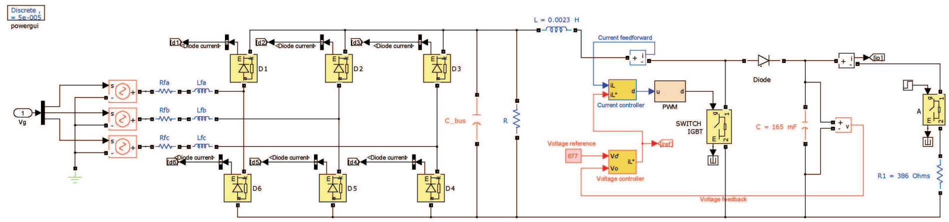

Fig. 4. SimPowerSystems diode rectifier-boost chopper conversion system.

fill the following requirements open system crossover frequency of 400Hz, and 20dB/dec slope in the whole range of the Bode plot. Thus, the stability of the closed-loop system is ensured, nevertheless the parameters variations. Consequently, the compensator s-function Tc(s) should have a pole at the origin (integrator) in order to give high accuracy in steady-state mode, followed by a zero at 16Hz to compensate the main pole and another pole at 803Hz to compensate the zero due to the capacitor ESR. The DC gain in the middle has to be 26dB in order to put the crossover frequency at 400Hz.

2 Simulation and Experimental Results

The simulation results obtained from the developed models are shown below. Besides the described converter modeling, some experiments have been also carried out. The test bench for the generator consists of a DC motor drive with variable speed and synchronous generator with electromagnetic excitation. The main generator data are: rated power 1.5kW, rated voltage 400V, rated current 2.2A, rated speed 1500rpm.

The simulation results for a load current step change for the PSPICE and SimPowerSystems® model are shown in Figure 5.

Oscillograms of the regulator response to load current step change are shown in Figure 7. The conditions are the same as in the simulations. It can be seen that there is a very good coincidence with the simulation results. The regulator has very good performance with relatively small voltage drop (3%) and fast recovery time after the step change of the load current.

Simulation results for the boost converter operation obtained with Simulink and SimPowerSystems® models are shown in Figure 6. In the graphs, the collector voltage of the switching transistor and the inductor current are shown.

As it can be seen from Figure 6, the Simulink model cannot show the transistor

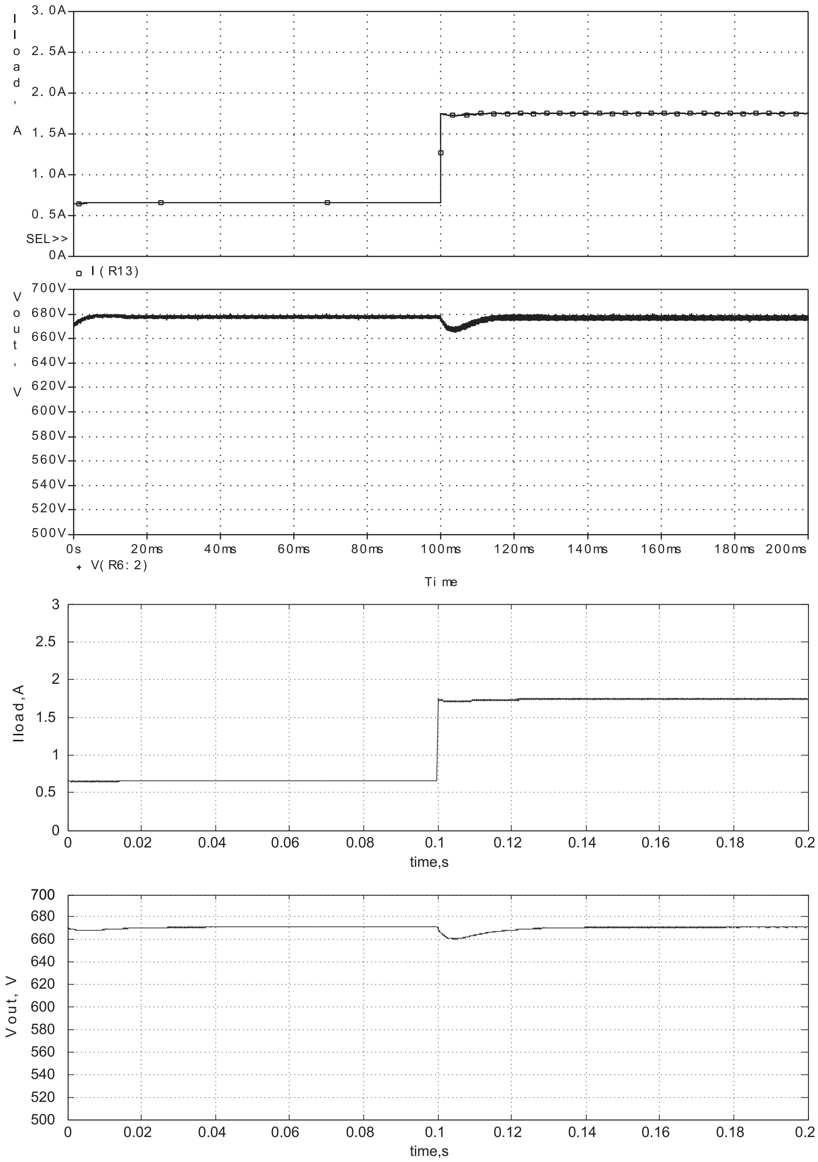

Fig. 5. The output voltage at load current step change simulated with PSPICE (up) and SimPowerSystems® model (down).

collector voltage behavior in discontinuous current mode while the SimPowerSystems model correctly calculates the voltage waveform. The experimental waveforms of the transistor voltage and inductor current are shown in Figure 8.

Simulated waveforms of the generator phase voltage and phase current are

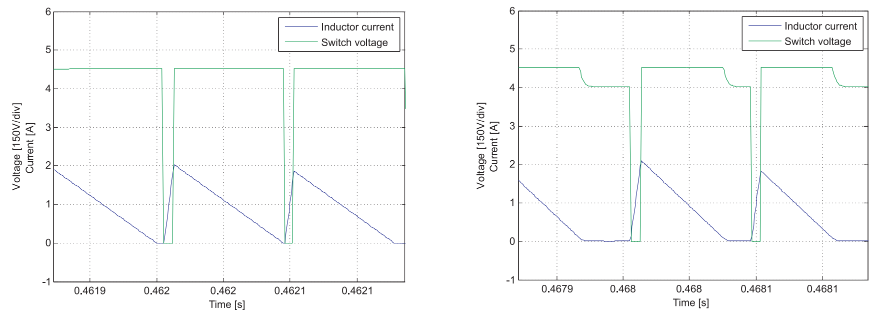

Fig. 6. Simulated waveforms of the collector voltage and inductor current: Simulink (left) and SimPowerSystems® (right).

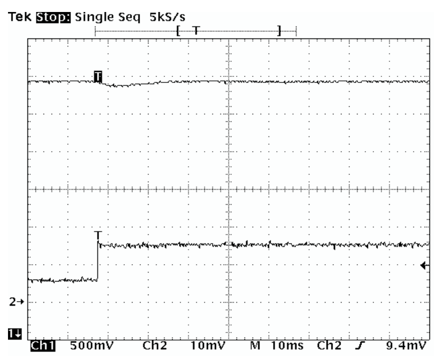

Fig. 7. Oscillograms of the output voltage of the boost converter at load current step change (100V/div, 1A/div).

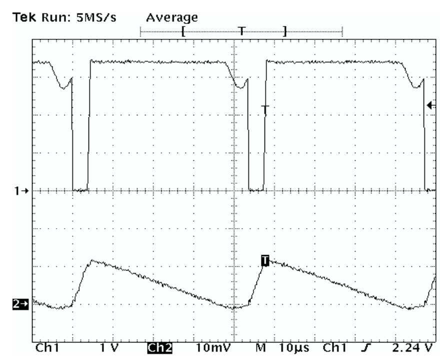

Fig. 8. Oscillograms of the collector voltage of the transistor and the inductor current (200V/div, 1A/div).

shown in Figure 9. Here, the generator is loaded with diode rectifier and boost converter. The simulation is performed with the SimPowerSystems® model. Oscillograms of the phase voltage and current at the same conditions are shown in Figure 10.

An analysis of the harmonic content of the generator current and voltage has been carried out using power quality analyzer VA6200. The result of the current harmonic content is shown in Figure 11.

2.1 Power losses in the converter

The converter power losses are calculated using producer datasheets of the electronic components and experimental data. The switching losses in the power transistor and diode are calculated using experimental waveforms of the current and

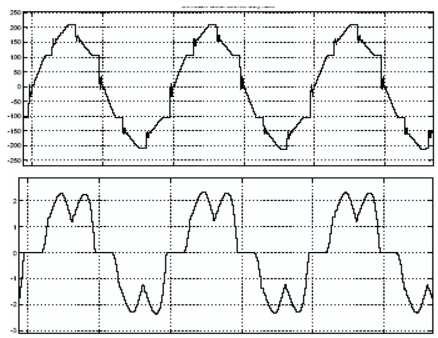

Fig. 9. Simulated waveforms of the phase voltage (upper) and current of the generator.

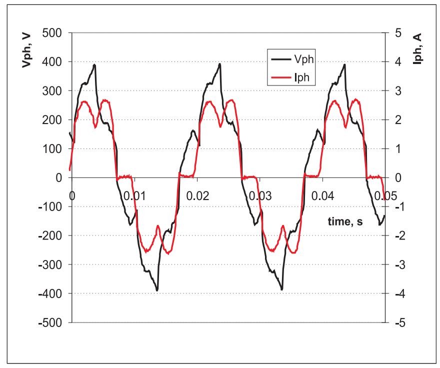

Fig. 10. Oscillogram of the phase voltage and phase current of the generator.

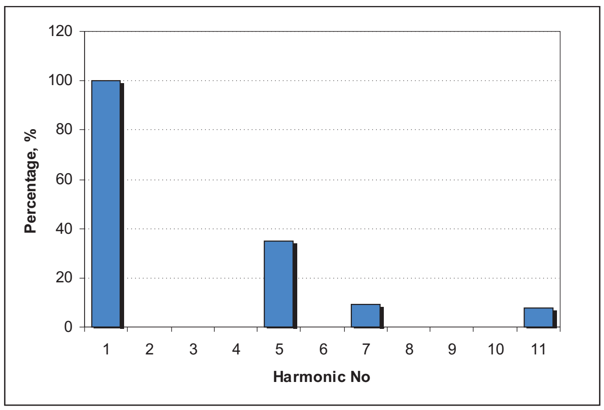

Fig. 11. Harmonic content of the generator current loaded with diode rectifier.

voltage [4]. The results are summarized in Table 1 and shown as graph in Figure 12. In this table P_{gen} is the measured output generator power, P_{rect} diode rectifier power losses, P_{boost} boost converter power losses, P_{supply} power losses in the module supplying the converter, P_{tot} total power losses in the DC converter. The efficiency η is

$$\eta = \frac{P_{gen} - P_{tot}}{P_{gen}}. \tag{3}$$

2.2 Power losses in the generator

Here, the power losses in the synchronous generator are subject to experimental study. In order to study the power losses in the synchronous generator, two mea-

Table 1. Power losses in the converter.

P_{gen}, W	P_{rect}, W	P_{boost}, W	P_{supply},W	P_{tot}, W	Efficiency η
20	0	4.26	16.6	20.9	0
648	1.8	13.19	14.9	29.9	0.954
960	2.9	22.39	14.2	39.5	0.959
1326	4.3	35.55	13.1	53.0	0.960

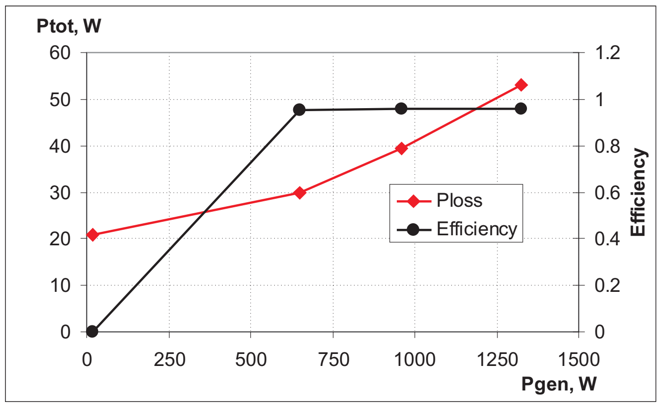

Fig. 12. The total power losses and efficiency of the converter.

surements were performed. First during normal operation with active load and sinusoidal currents, and second when the generator was loaded only with diode rectifier. The generator output power in the two cases was kept the same - 1300W. The mechanical power transferred from the motor to the generator was also measured with torque meter. The results for the power measurements in the motor-generator set are shown in Table 2.

Table 2. Generator power losses

	DC motor values						
	V_a, V	I_a, A	P_a, W	p_{Ra}, W	P_{mech}, W	P_{21}, W	P_{dc}, W
Active load	230.6	8.15	1879	242	1504	1300	
Diode rectifier	234	8.45	1977	260	1581		1302
Difference			98	18	77		

In Table 1: $P_a = V_a$. I_a is the electrical power consumed by the DC motor,

$p_{R_a} = I_a^2 R_a$ motor armature power losses, P_{mech} the input generator mechanical power, P_{21} the generator output power with active load, P_{dc} - the generator output power with rectifier.

The rectifier losses are included in P_{dc}. Because they are relatively small they are neglected in the calculations.

As it can be seen, in the with diode rectifier case, the necessary input power of the generator increases due to the increased interior power losses. The extra power, measured by mechanical interface, is $P_{ex} = 77$W. On the other hand, this extra power can be calculated from input electrical power Pa of the DC-motor driving the generator. The increase of P_a is 98W. Increase of the armature resistance power losses is 18W and consequently the extra power is $P_{ex} = 98 - 18 = 80$W. This value is close to those calculated from the mechanical power. Thus, we can consider that the total power losses in the synchronous generator are increased by some 78.5W which is 5.2% of the input mechanical power and 6% of the output power. The efficiency of the generator is decreased by 4% from 86.4 to 82.4%.

3 Conclusions

Models of a diode rectifier and a DC-boost converter used in a wind generator with variable speed have been developed in Malab/Simulink and PSPICE environments. Two simple and accurate boost chopper models have been designed using the Simulink software. The modelled converters were realized and an experimental study was carried out. Comparisons between different models simulations and experiments are shown. The converters and generators power losses are measured and calculated as so system efficiency was evaluated. Due to the harmonics in the generator current, the converter with diode rectifier leads to increased losses in the generator and decreases the system efficiency.

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