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STUDY OF SMALL-POWER WIND GENERATOR WITH SINGLE-PHASE GRID-CONNECTED INVERTER

Z. Zarkov[1], V. Milenov[1], I. Garciarena Martincorena[2]

[1]Technical University of Sofia, Faculty of Electrical Engineering, 8 Kliment Ohridski, 1000 Sofia, Bulgaria
[2]Public University of Navarra, Technical School for Industrial Engineering and Telecommunications, Pamplona, Spain

Abstract: In this work the authors studied a wind generator system consisting in: three-phase synchronous generator, rectifier, voltage limiter and single-phase inverter connected to the grid. A simulation model of the electrical part of the wind generator was created in the environment of PSpice. An electronic circuit of voltage limiter with hysteresis controller was developed, simulated, manufactured and tested. An experimental study of the wind energy conversion system was also performed. The good coincidence between simulation and experimental result proves the correct operation of the developed computer model. The work was carried out in the Renewable energy sources laboratory (Electrical aspects) in the Faculty of electrical engineering of the Technical University of Sofia.

Keywords: single-phase inverter, voltage limiter, wind energy conversion, wind generator

1. Introduction

Nowadays, energy is one of the most important factors in society. There is no doubt that the way of obtaining and using this energy has a high impact on the planet, and that some of the most relevant sources which are being used now (fossil fuels) are not sustainable at all. Taking this into consideration, it is time to promote renewable sources of energy, to guarantee a future with a cleaner planet and without power limitations.

One of the most widely used renewable energy source is the wind. Wind generators are currently popular sources of electricity. At the end of 2014 the total installed capacity of wind turbines in the world reached 370GW [1]. Small-scale wind generators with capacity below 10kW are also gaining popularity [2]. It is a modern practice to connect them to the mains through single-phase inverters [3,4]. These systems are still in the beginning of their development and to advance in their study it is important to simulate the performance of the wind generators under different conditions.

The goal of the study is to create a simulation model of the electrical part of a small-power wind generator consisting in: synchronous generator, rectifier, voltage limiter and single-phase inverter connected to the grid. Experiments will be performed on a laboratory test bench where the wind turbine is replaced with a computer controlled variable speed DC motor drive.

2. System Overview

The block-diagram of the electrical part of studied wind generator is shown in Figure 1.

The studied system is composed of the following elements:

- Three-phase synchronous generator 1500 W, 400 V, 2.2 A, 1500 rpm;
- Three phase diode rectifier;
- Voltage limiter with limiting voltage level 360 V;
- Single-phase grid-connected inverter Windy Boy 1700 with nominal AC power 1550 W, nominal AC current 6.7A, AC voltage range 180-265V, and input DC voltage range 140-400V.

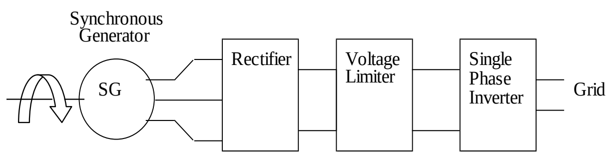

Figure 1. Block-diagram of electrical part of studied wind generator.

3. Simulation Model of the System

3.1. Synchronous generator and diode rectifier

On the basis of the above shown block-diagram an electronic circuit is designed in OrCAD/PSpice environment to simulate the behaviour of the real objects. The model of three-phase synchronous generator is built by representing each phase as an alternating voltage source with internal impedance as it is shown in Figure 2. The resistance value is obtained by direct measuring and it is 5 Ω. The internal inductance is considered constant although it changes with the saturation of the magnetic circuit

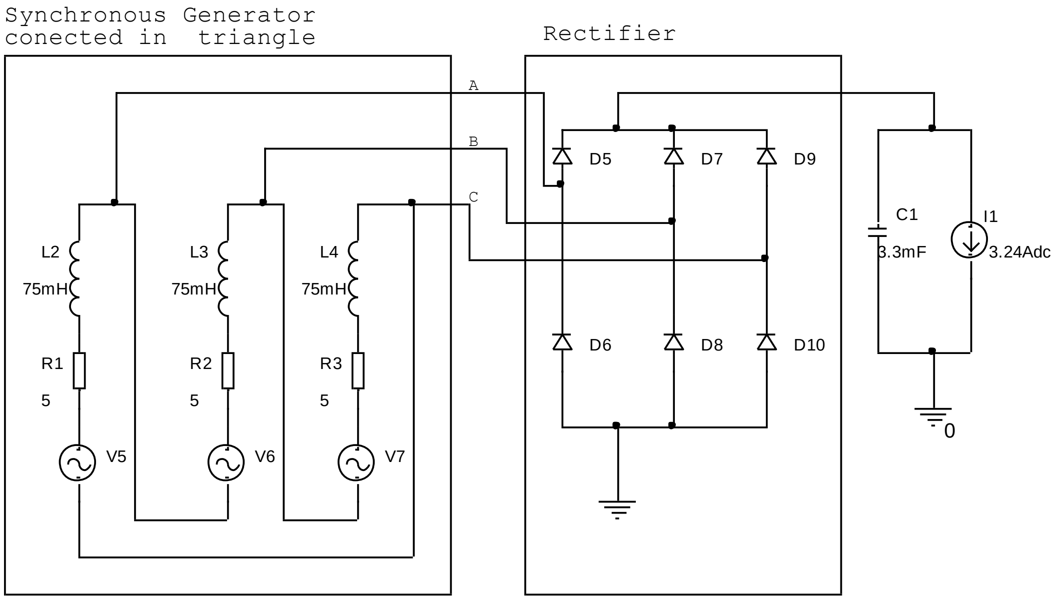

Figure 2. Complete circuit of the PSpice model of the synchronous generator and the rectifier.

of the machine. Its value is known from previous authors' work and it is 75 mH [5].

Figure 2 shows the complete circuit of the developed model of the synchronous generator and diode rectifier. The generator windings are connected in triangle in order to decrease the rectified voltage to acceptable level for the inverter.

Figure 3 shows the simulated waveforms of voltages and currents of the synchronous generator working together with the diode rectifier. The current waveform is not sinusoidal because the rectifier is a nonlinear load. Under the imposed operating conditions (speed of rotation 1500rpm and rated excitation) the rectified DC voltage is 344V at load DC current 3.24A and the total electrical power is 1115W.

3.2. Voltage limiter

At higher speeds than 1500 rpm the generator and rectifier will produce DC voltage which can exceed 400 V. This voltage is dangerous for the inverter so it has to be limited. One possible solution is to build a

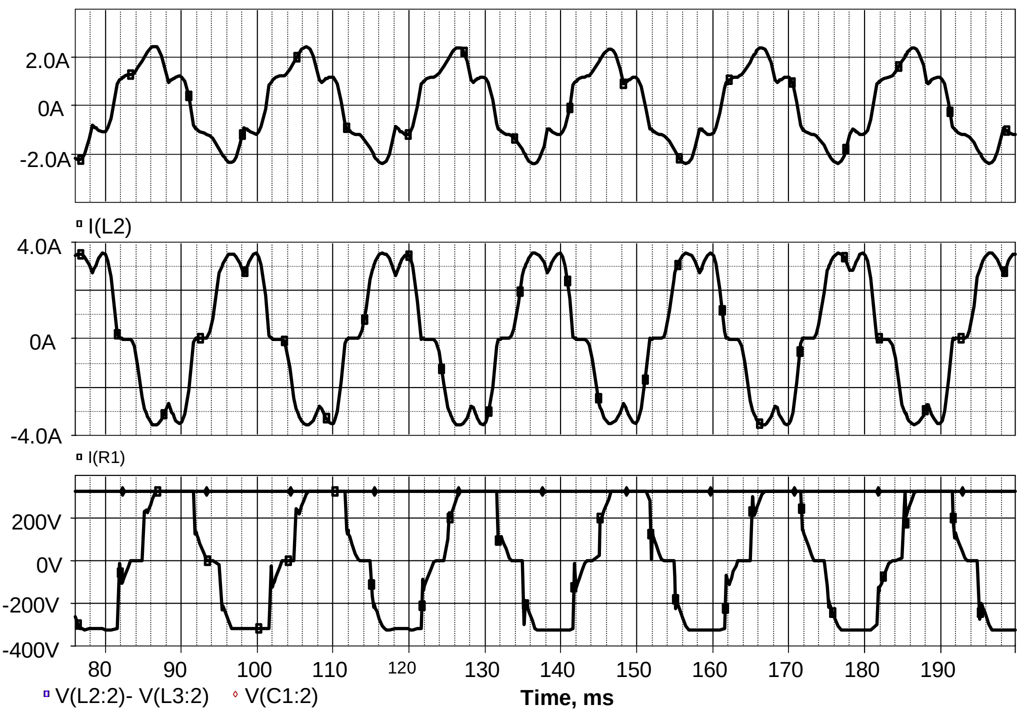

Figure 3. First plot: generator phase current. Second plot: line current. Third plot: line to line voltage (down), rectified DC voltage (up).

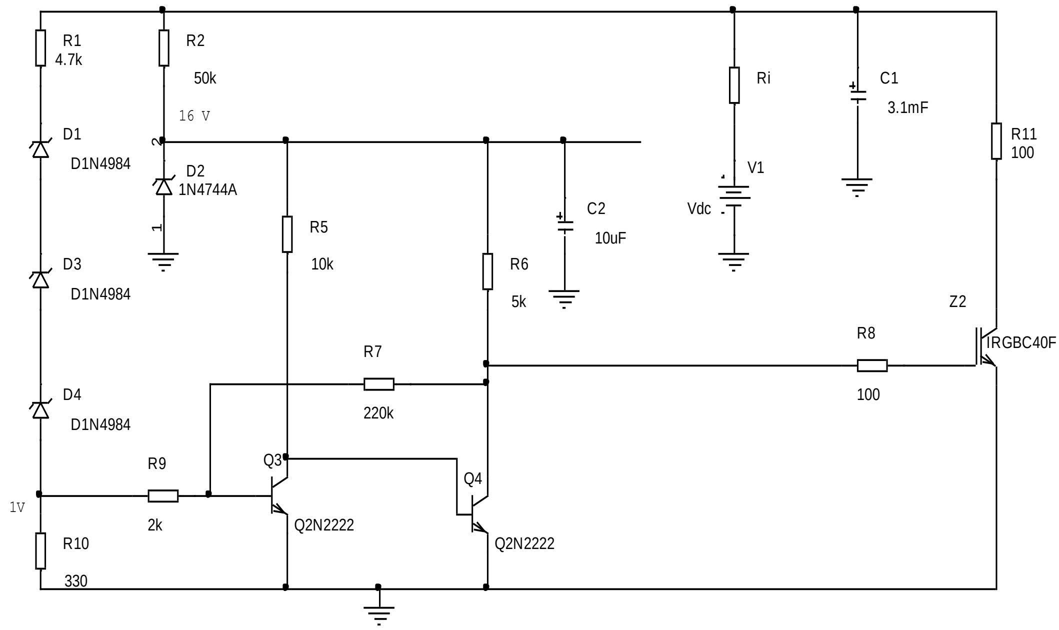

Figure 4. Voltage limiter with hysteresis controller.

voltage limiter that dumps the generator power into an external resistive load. The voltage limiter operates as a regulator that keeps the DC voltage at a predefined value when the input voltage exceeds it.

In this work the adopted solution for the described problem is a hysteresis controller that follows the DC voltage and controls the power transistor. The transistor turns on and off a dump resistor, which dissipates the extra power.

Figure 4 presents the developed simulation circuit of voltage limiter with hysteresis control. The hysteresis controller is a Schmitt trigger built of

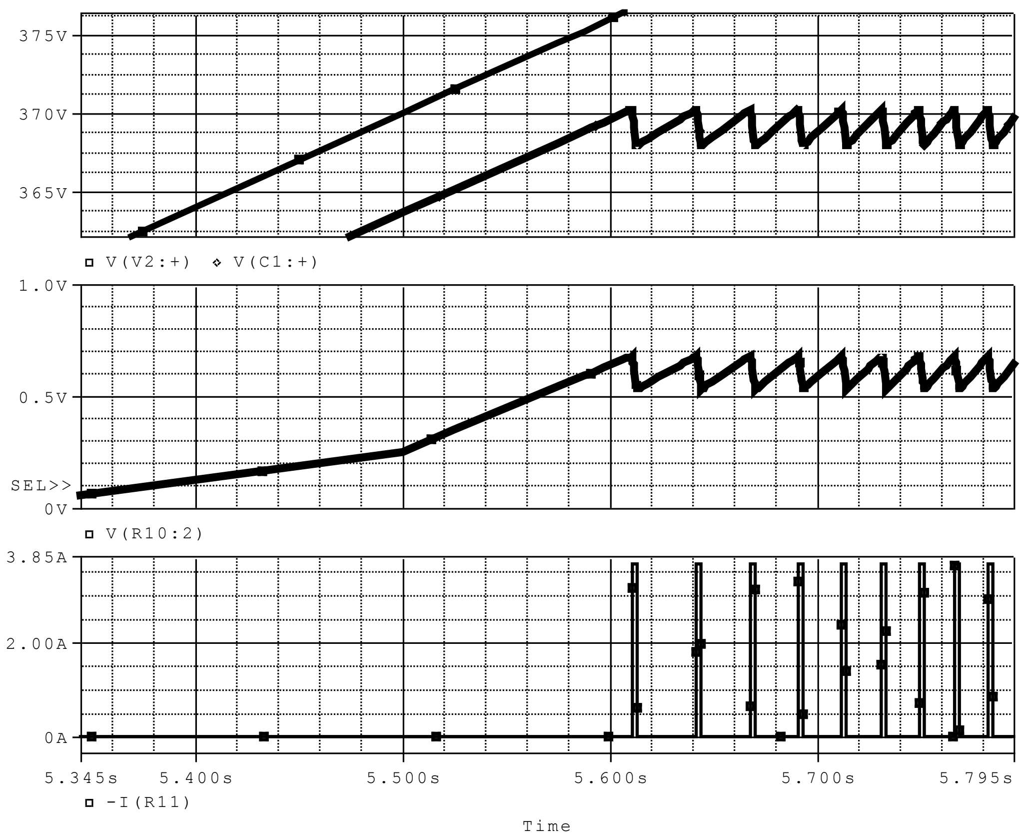

Figure 5. Voltage limiter simulation: First plot: V1 source voltage (up), DC voltage (down). Second plot: R10 voltage. Third plot: dump resistor (R11) current.

the transistors Q3 and Q4 and the resistors R5, R6, R7 and R9. The voltage detector consists of R1, zeners D1, D3, D4 and R10.

Some results from the simulation of the designed voltage limiter with hysteresis controller are shown in Figure 5.

As it can be seen from simulated waveforms, the operation of the designed hysteresis controller and voltage limiter is correct. The DC voltage is limited to a value 368V which is well close to the desired value of 360V. Voltage ripples caused by the hysteresis controller are very small and they are considered not to affect the inverter operation.

3.3. Inverter

Windy Boy is a single-phase grid-connected inverter with built-in low-frequency transformer at the output and full-bridge configuration. The transformer is necessary for electrical isolation of the whole system from the grid, to avoid safety problems. Besides, it gives the possibility to increase the voltage from the transistor bridge to the value that is required by the grid, in this case 230Vac. The used inverter has the possibility to operate with 140V input DC voltage when the grid voltage is 230Vac. The transformer is step up and the voltage in the secondary winding has double value than in the primary.

The inverter with the transformer output is simulated using the circuit from Figure 6.

The output voltage of the H-bridge is filtered by a LCL filter consisting of L1, C1 and L2. R22 is a dumping resistor that suppresses the oscillations in the filter.

The purpose of the resistance R26 is not to let the secondary winding of the transformer floating this is a requirement of the simulator software. The voltage source V2 represents the grid.

The aim of a pulse-width modulator is to create a pulse sequence that controls the transistors in the bridge of the inverter in order to create a sinusoidal

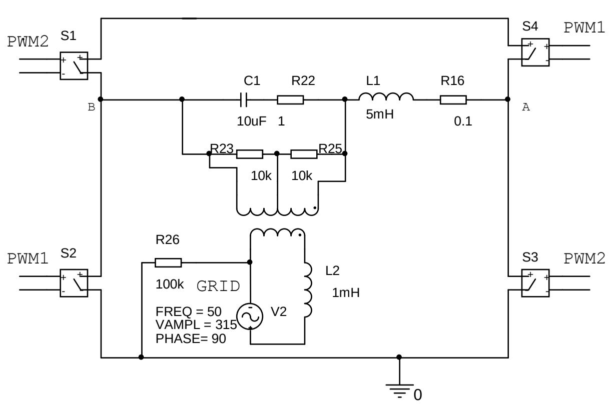

Figure 6. Inverter and transformer connected to the grid.

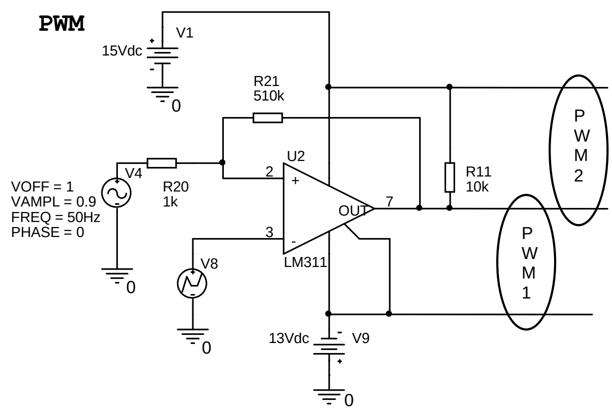

Figure 7. Pulse width modulation circuit.

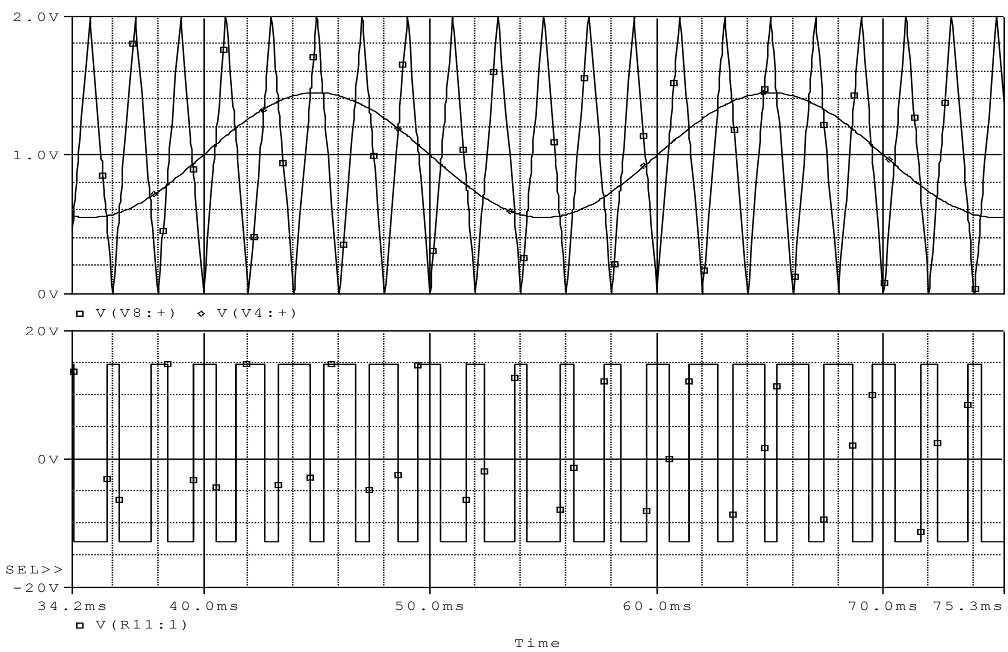

Figure 8. First plot: comparator inputs. Second plot: comparator output voltage control signal PWM1. (Here the frequency of the carrier signal is 500 Hz instead of 10 kHz to clarify the view).

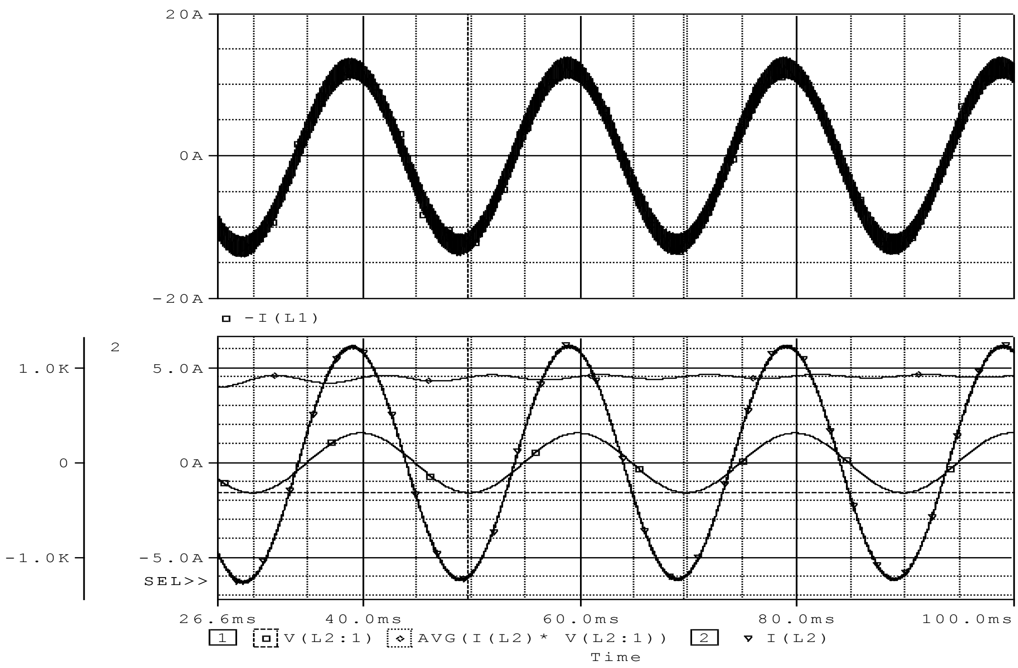

Figure 9. First plot: current in the inductance L1. Second plot: voltage, current and power flowing to the grid.

output voltage. The PW Modulator in this project is built with a comparator LM311 and two voltage sources representing the modulating sinusoidal signal with 50Hz frequency and the carrier triangle signal with 10 kHz frequency. The simulation circuit of the modulator is shown in Figure 7.

The resistances R20 and R21 are added to make a small hysteresis that makes the switching faster and more reliable.

The comparator receives two input signals: modulating and carrier, as it is shown in Figure 8. It produces two inversed control signals PWM1 and PWM2 for the two couples of switches in the bridge. It is clear to see that the comparator output varies between two values: 14 V and -13 V.

The magnitude of the first harmonic of the inverter output voltage is controlled by the modulation index. In the case shown in Figure 8 this modulation index is equal to 0.45.

Figure 9 shows an example of simulated current and voltage waveforms in the inverter circuit. The magnitude of the output AC current is 6.05A and the active power is $P = 810$ W. The current at the bridge output (L1) has relatively big high-frequency ripples, but after the second stage of the filter (C1 and L2) the current is very smooth and purely sinusoidal as it can be seen in the second plot of Figure 9.

4. Experimental Study

A general view of the test bench used for experiments is shown in Figure 10.

The generator and the rectifier were tested together by measuring the DC voltage at the rectifier output with different load currents obtaining in this way the dependence $V_{dc} - I_{dc}$. The speed of rotation of the generator was 1500 rpm. Figure 11 shows the curves $V_{dc} - I_{dc}$ in the real circuit and in the simulated one shown in Figure 2.

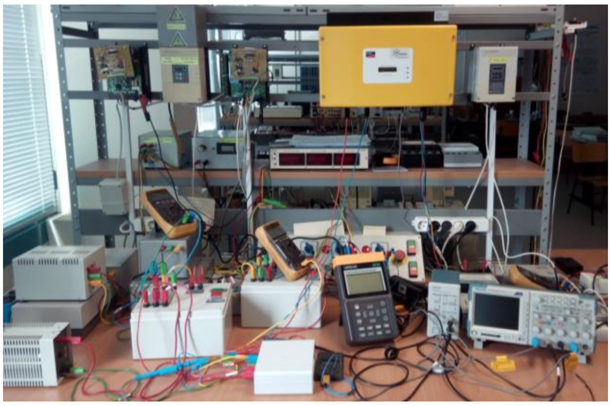

Figure 10. Image of the test bench.

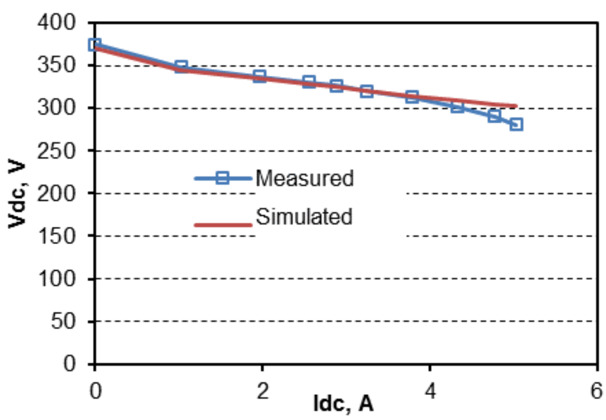

Figure 11. $V_{dc} - I_{dc}$ dependance from the simulation and from the measurements.

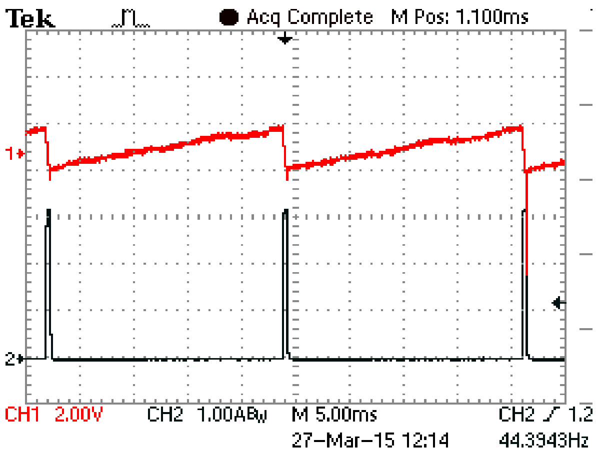

Figure 12. Voltage limiter test. AC component of the DC voltage (up); current in the dump resistor (low).

The two curves have good coincidence, so the created model represents very well the real objects.

A prototype of the voltage limiter was also manufactured and tested. The external dump resistance was a rheostat with value of 100 Ω and dissipation power 800 W.

Figure 12 demonstrates the operation of the voltage limiter. The oscillogram shows the DC voltage variations caused by the hysteresis controller. The hysteresis is around 2 V from peak to peak and the measured limiting voltage level is 358 V, which is very close to the desired value of 360 V.

The whole system was connected to the grid and tested at different rotational speeds of the generator. During the test, the voltages, currents and powers in the circuit were measured and registered.

Figure 13 shows the waveforms of the grid voltage and inverter output current at the generator speed of rotation 1500 rpm. The current is 5.43 A (RMS) and the active power injected to the mains is 1276 W.

The current waveform is almost sinusoidal and the value of total harmonic distortions (THD) is 5.73% what shows that the quality of the produced electrical energy is good enough to be supplied to the grid.

5. Conclusion

In this work a simulation model of the electrical part of a small wind generator was developed in the environment of PSpice.

An electronic circuit of voltage limiter with hysteresis controller was developed, simulated, manufactured and tested.

The results from the experimental study show the correct operation of every single part and of the complete wind energy conversion system. The comparison between simulation and experimental result proves the correct operation of the developed computer model.

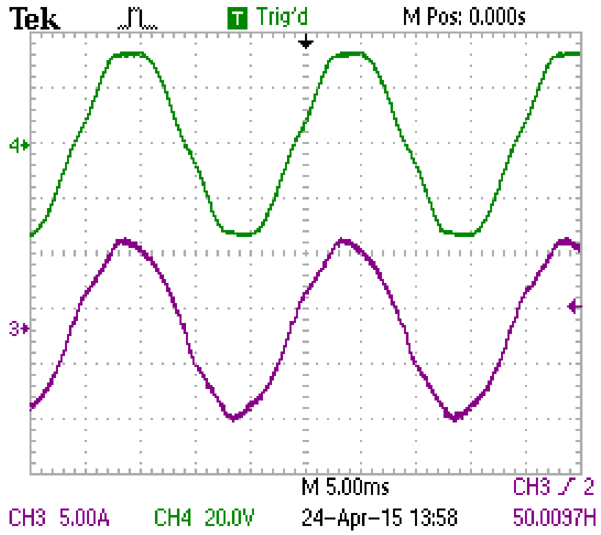

Figure 13. Inverter output voltage (up) and current (down) at n = 1500 rpm and P_{ac} = 1276 W.

This work will help to complete a laboratory test bench for physical modelling of small wind generators in the Renewable energy sources laboratory in the Faculty of electrical engineering of the Technical University of Sofia.

This research can be developed by the creation of a model of the whole energy conversion system in Matlab/Simulink. It will bring the possibility of modelling the control of the inverter.

Acknowledgement

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