Modeling and Analysis of the AFPM Generator in a Small Wind Farm System

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Abstract. This paper reports measurements and simulations performed on the generator - matrix converter system designed for small vertical axis wind turbine. The presented coreless axial flux permanent magnet generator has 3 kW of rated power at 300 rev/min. The measurement system constructed for examination of the generator under investigation as well as the measured characteristics were presented. The system of grid connected matrix converter designed for the presented generator was simulated.

Keywords: AFPM generator · Wind farm system · Wind turbine

1 Introduction

The paper presents the design and test results of a generator dedicated especially for wind power plants. Unfortunately, wind turbines generate relatively slow speed range on the shaft. For small units, it can be several hundred revolutions per minute, for large dozen revolutions per minute. In order to match the turbine speed to the rated parameters of a classic generator, multiplicators must be used. Mechanical gears, however, worsen the overall efficiency of the power plant, increase noise and cost of structures reducing its reliability. Therefore, the search goes towards the development of a generator with a significantly low rotational speed. The magnitude of the voltage generated in fact does not depend on the angular velocity, but on the peripheral speed at the location of the winding and the magnet. In order to reduce the speed, the diameter of the machine needs to be increased to ensure sufficient linear speed. The development of neodymium magnet technology has caused a revolution in the field of electrical machines. Currently created machines based on the classic magnet-winding -movement solution are more simple and smaller designs with similar power [1]. The design of the generator shown in the paper belongs to a dedicated system for applications in wind energy, it is a flat system called the "pancake", multi-pole, three-phase with a capacity of 3 KW and rated speed of 300 1/ min.

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2 Construction of the Generator

Figure 1 shows the most important elements in the generator arrangement. The stator disc in which the flat stator windings are flooded in the perimeter part is marked with the letter “s”. The external rotor discs must at the same time ensure load transfer from the turbine profiles.

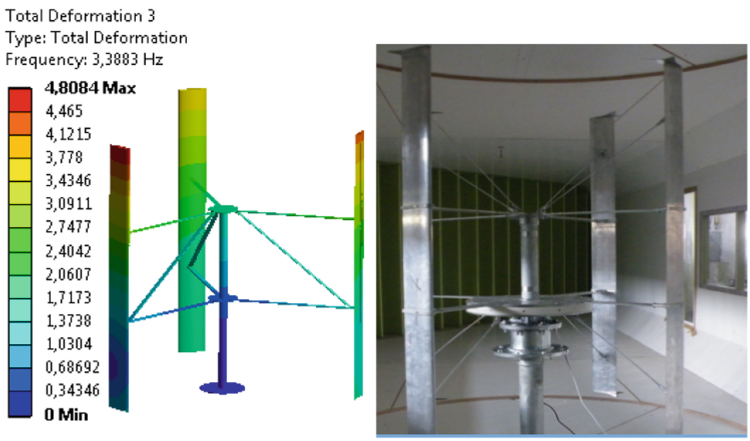

Fig. 1. Distribution of the magnetic induction vector on the cylindrical surface passing through the center of the active part of the winding and construction of the generator with wind turbine.

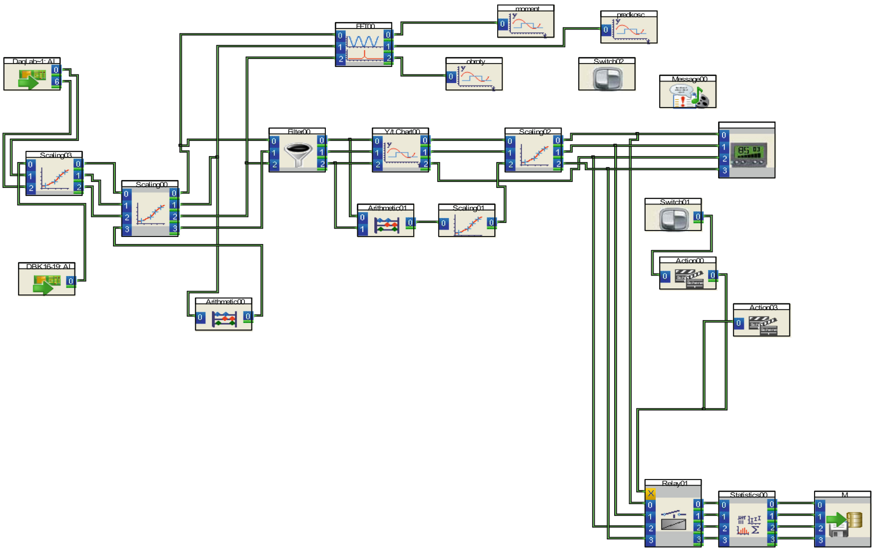

Fig. 2. Measurement system diagram created in DasyLab.

The presented generator is adapted to cooperate with small vertical turbines, in principle it creates an inseparable whole structure of the head. It is also possible to use it for a system with a horizontal axis. The disc form allows it to be embedded in the flow area [2]. It should be noted here that the generator shown has a very small starting torque, no latching torque and better smoothness of operation at very low rpm. Low power units work in a varying rotating system, so in order to cooperate with the network, an inverter is required. The quality of generated energy returned to the network depends only on the quality of the inverter (Fig. 2).

3 Results

The tests were carried out on a research site, where the generator was driven by an asynchronous motor controlled by an inverter in order to remove the some features of the generator. Then, a rotation reduction adapted to the generator was applied. Between the gearbox and the generator, a dynamometer was set up to measure the mechanical torque. In addition, the rotational speed of the generator was optically measured. The output of the generator was connected to a three-phase rectifier with filtration, obtaining a constant component, in order to more conveniently measure the electrical parameters of the generator [3]. The power was determined based on the measurement of the load current and the output voltage on the regulated active load. All results were recorded using a 16-bit USB-231 measurement system, operated from the DasyLab measurement software. The developed program carried out all the required measurements, calculated the necessary quantities like the power generated and the mechanical power supplied. On this basis, it determined the efficiency of the generator in real time. In addition, it carried out the spectral analysis of signals measured using Fourier fast transformation module. All parameters were measured, calculated, recorded in instantaneous values, as well as averaged samples in files separately.

The tests were carried out for two combinations of stator pole winding connections. One in serial mode giving a nominal voltage of 680 V (RMS) and the other being a parallel combination generating a nominal voltage of 340 V (RMS). Figure 3 shows the graph of changes in the output voltage in an unloaded system for both combinations of stator winding combinations (U and Ur lines), and the power of mechanical and aerodynamic losses of the generator itself. A characteristic feature of this solution are very small mechanical and aerodynamic losses, especially for low rotational speed.

Figure 4 shows the family of load characteristics for constant rotational speeds. The load curves are linear in nature, the characteristic feature is that the generator can be used in very wide limits of rotational speed variation. Useful speed is already 60 revolutions per minute. In the case of using an inverter, the generator can be used effectively within 60–300 or more of the rotational speed. It translates into a large range of wind speed variation.

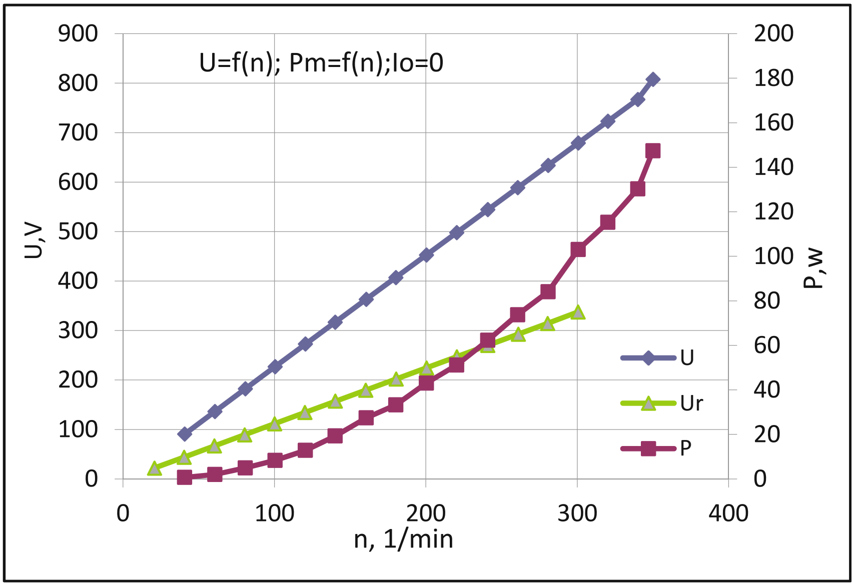

Fig. 3. Idle voltage characteristics and the power of mechanical losses.

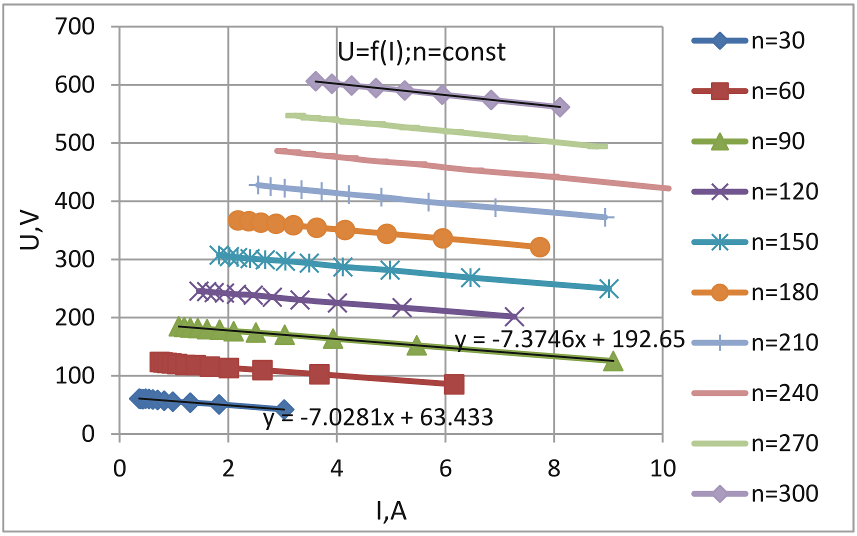

Fig. 4. External characteristics of the generator for the series winding combination.

Figure 5 shows the family of load characteristics in the case of parallel connection of stator windings. As we can see the voltage has fallen by a half, but the current efficiency is greater. The coefficients at the approximation function are three times smaller than the configuration from Fig. 4. Such a system is less sensitive to the voltage drop on the windings at higher loads. These two operating modes allow for more flexible adaptation to the inverter and turbine.

Figure 6 shows the variability curve of the generator efficiency as a function of the rotational speed at a constant resistive load. The efficiency of the presented machines is very high and reaches 95%. It is flat in most of the working range.

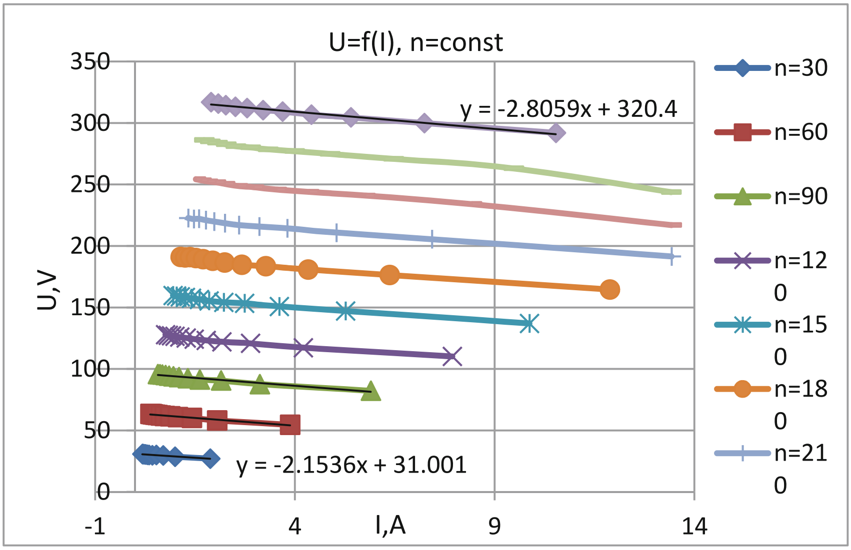

Fig. 5. Load characteristics for parallel combination of stator windings.

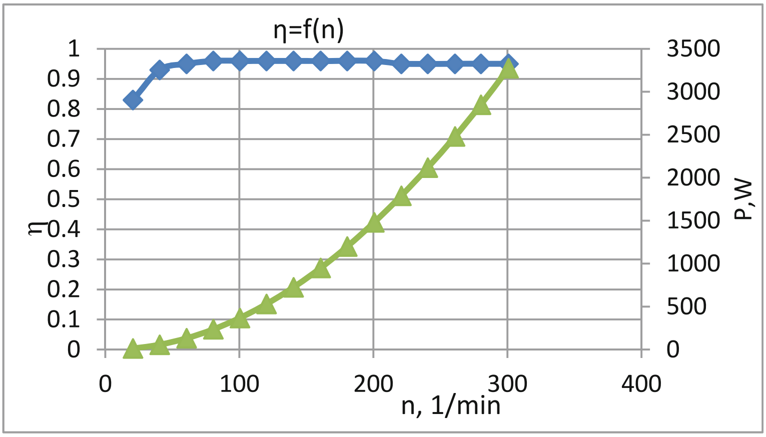

Fig. 6. The graph of generator efficiency as a function of the variability of the speed at constant active load.

Figure 7 presents the dependencies of variability of generator output voltage for two different cases of active load. Changing of the load for nominal conditions by 100% results in a small change in the output voltage of the generator, which proves its high stiffness, i.e. low relative dynamic resistance.

Figure 8 shows the distribution of the magnetic induction vector on the cylindrical surface passing through the center of the active part of the winding. This distribution confirms the correct the magnets magnetizing and the correct definition of boundary conditions of the Master/ Slave type.

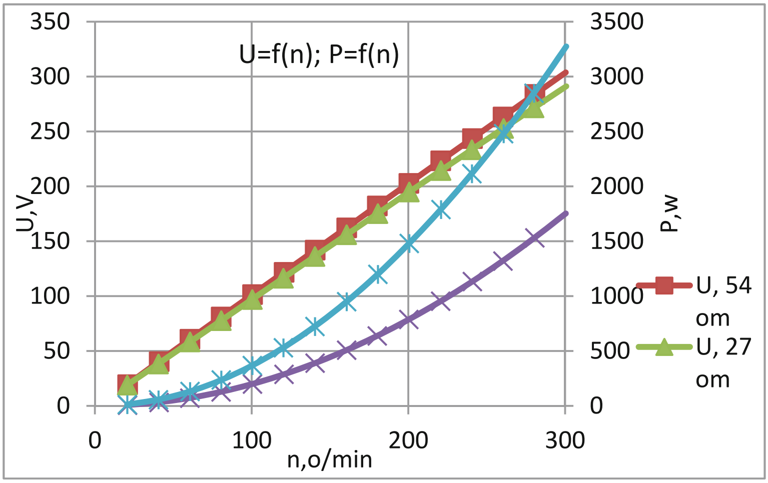

Fig. 7. The graph of voltage and power variation for two different constant active loads.

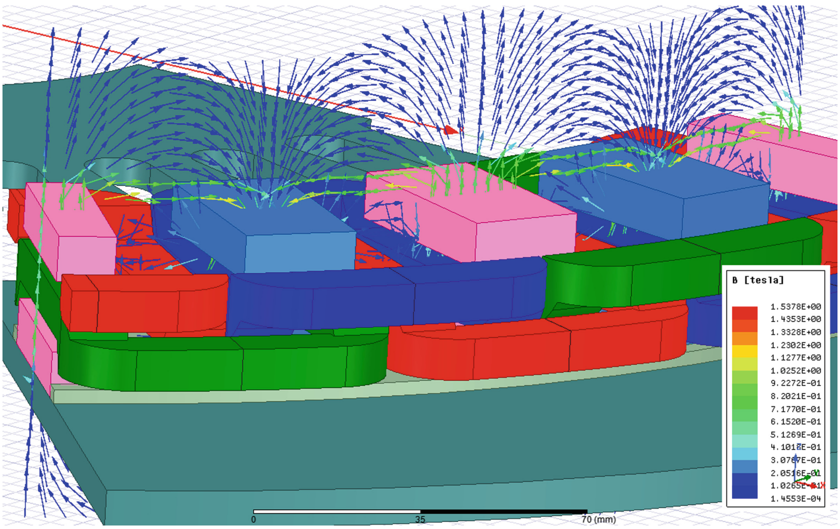

Fig. 8. Distribution of the magnetic induction vector on the cylindrical surface passing through the center of the active part of the winding.

4 Turbine-Generator System Powered by Power Grid via a Matrix Converter

The matrix converter is designed to connect generator phases directly to grid voltages. It is assumed that the grid is sufficiently rigid, and proper switching on is to ensure proper generator voltage for maintaining the set speed *w0_zad*. This speed results from the conditions of cooperation with a turbine and therefore the moment loading the generator from the side of the turbine *mobc* should be taken into account [4].

Figures 9, 10, 11 presents the results of simulation of dynamic states of the axial generator when powered from a matrix converter. The necessary voltages at the

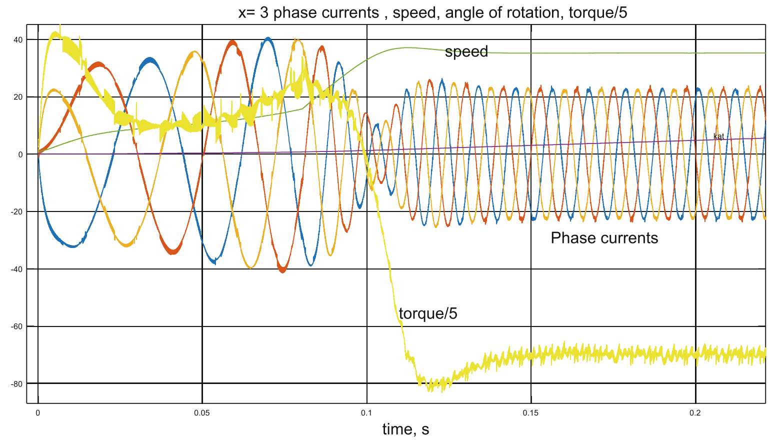

Fig. 9. The waveforms of phase currents, rotational speed, mechanical angle of rotation and electric torque (/5) at the set speed *w0_ad* = 31.4 [rad/s] and load moment *mobc* = −350 Nm.

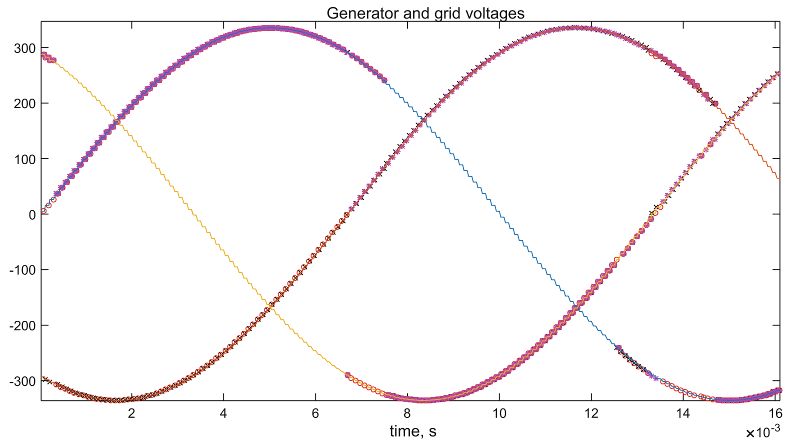

Fig. 10. The sequence of grid voltages (solid line) and the way of connecting the generator phases to these voltages: generator phase A - red o, phase B - black x, phase C - magenta *.

generator phases are calculated using the prediction method. These voltages are obtained by directly connecting the generator phases to the mains voltage via a matrix converter. Figure 9 shows start-up of the generator to the set speed w0_zad = 31.4 rad/s. Driving torque from the wind turbine was assumed as mobc = −350 Nm. Figure 10 shows how the phases of the generator are connected to the mains phases during the start-up. Figure 11 shows the waveforms of voltages obtained in this way on the phases of the generator.

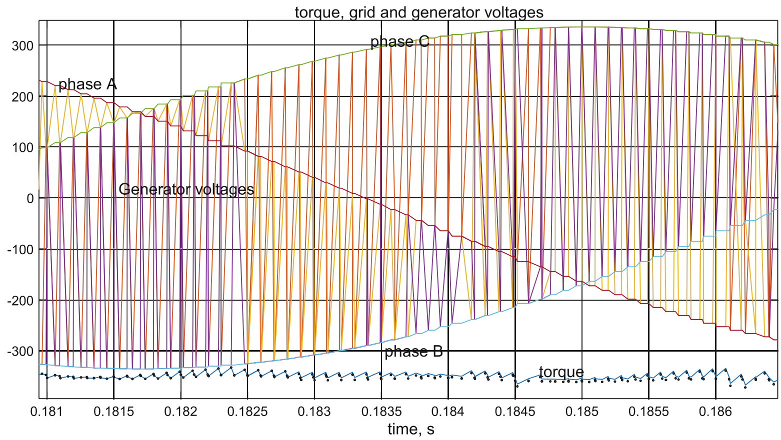

Fig. 11. The sequence of grid voltages of the phase A, B, C generator voltages based on grid voltages through a matrix converter and electromagnetic torque.

5 Conclusion

The coreless Axial flux permanent magnet generator of 3 kW rated power was presented. This generator was designed to work in the small wind turbine - matrix converter system. The properties of the discussed generator such as big ratio of machine diameter to its axial length, high efficiency, low rotational speed, lack of cogging torque makes it especially suitable for proposed application. The measurement system created for the investigated generator was presented [5]. The idle and load characteristic measured for two windings arrangements proved the generator design and its suitability for the intended application. Further investigation of the generator working in the grid connected matrix converter system was carried out by means of simulation. Those investigations showed very good performance of the designed system.

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