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Properties of Low Speed Generator for VAWT Using Passive Spring Transmission

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Abstract- We present a novel double rotor generator with passive spring transmission (PST). Basic measurements are illustrated on a patented vertical axis wind turbine. The aim of this study is to provide low cost improvement of wind turbine run-up using a large coreless generator with the novel PST system. Since wind is inherently a changing variable, the presented measurements were performed with real wind speed data. The wind turbine was simulated via an external motor controlled by a computer and frequency changer to maintain steady conditions. In this way we imitated wind speed fluctuation by controlling RPM fluctuations. The design of the double rotor magnet generator generated approximately 100 W per phase at 160 RPM, while the passive spring transmission system captured the maximum wind energy in the low-wind-speed zone by reducing the fatigue load.

Keywords- *Vertical Axis Wind Turbine, CVT, Generator*

I. INTRODUCTION

Nowadays, wind turbines are becoming the fastest growing energy source and receive a great amount of attention due to the technological advancements in harnessing wind power [1]. Recent scientific advances have focused on large wind turbines as a well consolidated technology [e.g. 2, 3]. But there is increasing attention paid to decentralized power generation for smart cities and green buildings. This system is associated with great interest in small wind turbines [4,5].

Wind turbines are a suitable tool for generating small distributed energy, they are very attractive both in separate configurations connected to the network and with other renewable resources [e.g. 6, 7], or into the building sector [e.g. 8, 9]. Axial flux designs are becoming popular for low speed vertical axis wind turbine (VAWT) up to 10 kW because of their simple construction and modularity [10].

In this study, a new dual rotor generator with axial flux permanent magnets and a passive spring transmission design with illustrative measurements are presented. VAWT allows capturing highly unstable and turbulent wind with low noise emission, easy maintenance and compact construction. These advantages show that VAWT are more suitable for small wind projects [11, 7]. Small scale wind turbine can become a potential source of socio-economically valuable energy. It is still necessary to study and understand these yet not so popular system [5].

Normally, data from aerodynamic tunnel tests are performed with smooth flow, which, however, does not represent the actual atmospheric behavior during operation of VAWT in real conditions. Wind velocity is a highly stochastic process, wind energy is not constant and aerodynamic power is proportional to the cube of wind speed. These factors cause the output power to fluctuate [12]. Therefore, a new approach needs to be adopted. The system is powered by an AC motor controlled via frequency changer operated by computer to imitate rotation of VAWT in various wind conditions.

In our system we use a double rotor generator with axial flux permanent magnets to generate electric energy. Advantages of the axial flux coreless PMG are its simple design, low manufacturing costs, no cogging torque which facilitating the start-up of the generator at lower wind speed, low risk of demagnetization of permanent magnets, no core losses, multiphase operation can be implemented easily. Certainly, there are also disadvantages of the proposed design, e.g. maintaining a constant air gap between the rotor and stator, large amount of neodymium magnets increasing the price of the whole system, and eddy losses in copper windings [10,13–19].

Several solutions have been proposed to increase the wind turbine energy output. For example fixed transmission or capturing maximum wind energy in the low-wind-speed-zone with the Continuously Variable Transmission (CVT) are often discussed [20, 21, 22].

Zhao and Maißer presented an electrical planetary transmission controlled by speed of servo motor [23]. Idan and Lior [20] proposed a novel hybrid variable speed transmission with two planetary transmission stages in which the annulus gear speed of the second stage (three rotating shafts) was controlled by three servo motors. Hicks and Cunliffe [24] presented a transmission consisting of a single PGT with its output shaft connected to the induction generator through a bevel gear drive, and the third shaft connected to a single servo-motor generator. Hydro-viscous transmission based automatic gearbox was also presented by Yin [25]. These systems increase the cost of the whole system, mainly because of control system and servo-motor generators [26]. There is also way to vary speed operation of the wind rotor to maintained constant speed of a generator by controlling electromagnetic torque or speed of the servo motor [27]. Using these additional systems we can utilize the wind energy more efficiently, reduce mechanical stress and improve the overall system reliability [25].

A novel passive spring transmission is presented in this paper. The annulus is attached by spring to the base of the wind turbine to act like CVT for short-time e.g. during the run-up of the wind turbine or during rapidly changing wind speed with consequent changes in rotation of the wind turbine. No additional electronic control or active servo motors are needed.

II. MATERIALS AND METHODS

One of the goals of this paper is to reduce stress load and material fatigue of gearbox and our wind turbine system with simple spring design. We constructed a vertical axis wind turbine (VAWT) and tested it with a commercial permanent magnets generator (PMG). Due to unsatisfying results, we adjusted the commercial PMG to our needs to make an axial flux permanent magnet generator with coreless coil. This design facilitates reducing the start up speed. The system was tested by simulating wind. Two operation set-ups are compared.

A. Data sources

Without access to a wind tunnel it is merely impossible to compare two systems at the same wind conditions. In our case we used a gearbox with an AC motor controlled by frequency changer witch allowed us to change revolution of AC motor with PC. The real wind speed data (2-second resolution) were provided by the Slovak Hydrometeorological Institute. The time-series covered a period of several days in April 2017. We choose four 180-second long sequences of wind (Figure 1, Figure 2, Figure 3 and Figure 4) The wind speed data were first converted to an input signal for the frequency changer to simulate the wind condition and shaft speed of our VAWT.

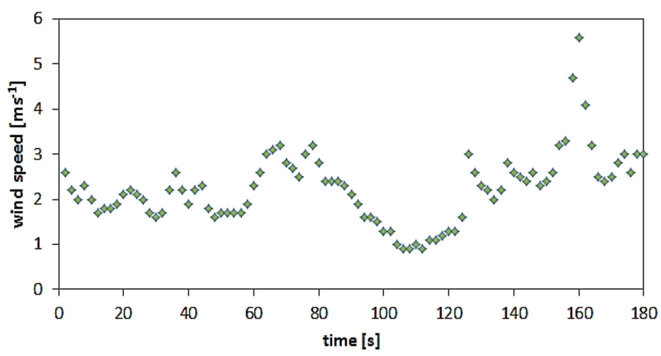

Figure 1. Situation No 1.- 180 seconds of real wind speed (April 2017)

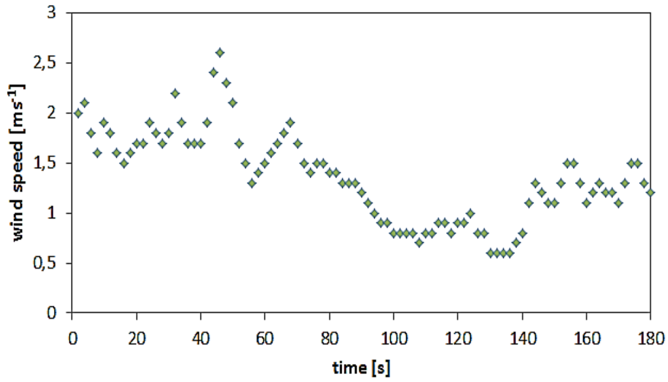

Figure 2. Situation No 2. - 180 seconds of real wind speed (April 2017)

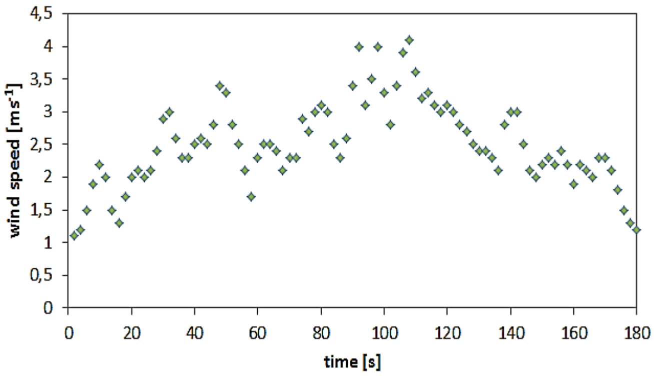

Figure 3. Situation No 3. - 180 seconds of real wind speed (April 2017)

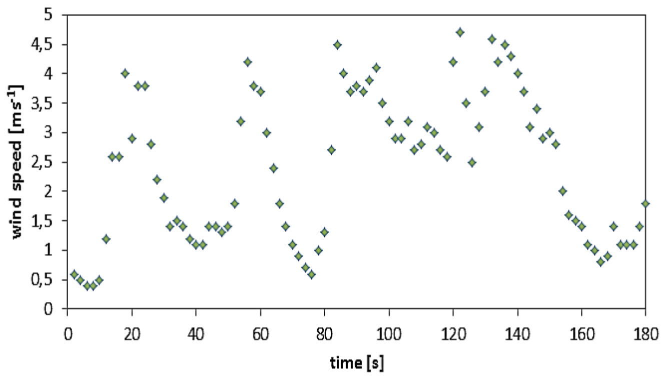

Figure 4. Situation No 4. - 180 seconds of real wind speed (April 2017)

B. Generator

The double rotors axial flux permanent magnet generator shown in Figure 5. was designed and manufactured as a new patented WAVT. To ensure the highest circumferential speed the generator has extraordinary large stator diameter.

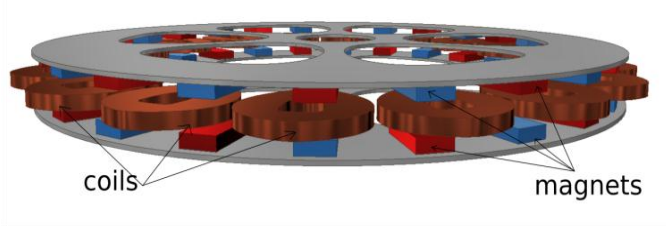

Figure 5. Generator. Magnets are shown in blue and red depending on the pole orientation. Stator coils are shown in brown and rotor in grey.

Two rotors made of 3-mm thick martensitic stainless steels provide support for the magnets. Martensitic steel and stainless steel have ferromagnetic properties [28] which helps arrange the magnetic flux. Twenty four strong neodymium magnets are placed in block geometry (50 x 25 x 10 mm). Magnets are placed in a circle array around the end of the rotor. Illustrations of alternate orientations of the magnets and magnetic flux paths are shown in Figure 6. This type of arrangement provides almost linear induction flow between the magnets. The air gap between the magnets is 20 mm. The flux density between magnets in 20 mm air gap was approximately 0.45 T.

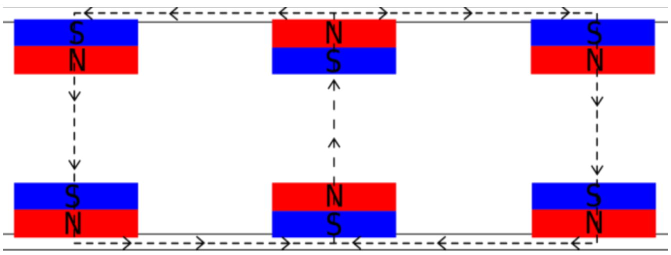

Figure 6. Appearance of arrangement of the magnets and magnetic flux paths

The stator of the PMG is composed of 18 coils with 120 windings of wire with a diameter of 1.3 mm. The diameter of the stator is 640 mm. The coil is 10 mm thick and the working width of the coil is 30 mm. The hole in the coil is 25 mm wide which represents the width of the magnet. The coils are arranges into three phase, with 6 coil in each (Figure 7). These phases are mutually independent and have separate outputs. This configuration allows connecting a phase separately. Although this configuration may not be appropriate for the power grid, it appears to be suitable for off-grid heating using resistance wires. A sequential connection of the individual phases allows reducing the start-up load, which leads to smoother functioning of the wind turbine at low wind speeds. One phase was constantly connected and other two phases were controlled by a computer and switch on by relays.

Figure 7. Arrangement of coils in the stator.

A description of the rotor and stator is given in Table 1. The final manufacturing design is shown in Figure 8. The power- RPM diagram was created for the generator Figure 9.

TABLE I. PARAMETERS OF PMG

Parameters	Values
Stator diameter	640 mm
Stator material	Fiber glass and epoxy
Number of coils	18 (6 per phase)
Number of windings	120
Coil thickness	10 mm
Coil wire diameter	1,3 mm
Rotor diameter	565 mm
Rotor material	martensitic stainless steels
Rotor thickness	3 mm
Number of magnets	24 each rotor
Dimension of magnets	50 x 25 x 10 mm
Magnet material	N38H
Gap between magnets	20 mm

Figure 8. Axial flux PMG with 2 rotors

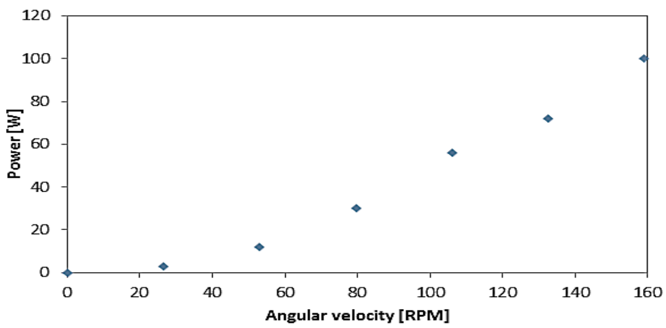

Figure 9. Power chart of the double rotor with axial flux generator, per phase.

A new patented prototype of the vertical axis wind turbine (VAWT) was created (patent no. 3214303) with a goal to achieve a low cost, durable, simple construction wind turbine, as shown in Figure 10Error! Reference source not found.. The height of the turbine is 2.75 meters and the length of wings is 0.85 m. The VAWT rotates at a rate of up to 25 RPM. Compare with other systems, it is very slow, yet the torque is high. High RPM are necessary to generate electricity from the PMG. Therefore, the primary goal is to omit gearbox and compensate it with a large diameter rotor for high circumferential speeds. The power of the generator is proportional to the second power of the angular velocity, which is the only parameter controllable by a gearbox and is not defined by design and material of the PMG.

Figure 10. Prototype of the new VAWT

C. Transmission

To increase revolution of the generator a planetary gearbox (Figure 11.) was added to our system with a gear ratio 1:5.3. The main problem of our gearbox was its fixed ratio, which is not a good option for dynamically varying wind speeds. Hence, using a transmission with several ratios seems to be a better option. To improve a smooth running of the VAWT we could use CVT to guarantee constant generator shaft speed over an entire range of wind speeds [21]. Idan and Lior [20] present a hybrid variable speed transmission with two planetary transmission stages in which the annulus was controlled by three servo-motor generators to maintain the optimal rotor speed for a given wind speed, while the speed of the conventional asynchronous generator coupled with the sun gear was held constant.

Figure 11. Planetary gearbox, on the left description of the components source: http://commons.wikimedia.org/wiki/File:Planetengetriebe_Prinzip.jpg on the right used planetary gear box

In our case we used springs to smooth run up of wind turbine to avoid bump effect during strong gust wind. We have used planetary gear box where the outer annulus is connected to base of the VAWT (Figure 12.) by springs which provide change of gear ratio during run up from continuously from 1:0 to 1:5,3 gear ratio but just in short time period during the stretching of the springs. These two boundary conditions are when the annulus is free to move input shaft rotates a planet carrier which care pinions subsequently runs annulus but output sun gear stays still thus the generator is not rotating at all although the wind turbine is running. This first condition represents gear ratio 1:0. The second boundary condition is when the annulus is fixed to base. Input shaft rotates planet carrier, but now the annulus is fixed therefore the sun gear is running but with designed maximum ratio 1:5,3. Springs allows changing gear ratio between these two extreme conditions via rotations of annulus during stretching the springs which react to load of input power during run-up of the wind turbine because of change of the wind speed. We called this system with abbreviation: PST (Passive Spring Transmission).

Dissipative energy is used to stretch the springs, but the smoother running of the generator appears to have positive effect of fatigue load for the system. The stiffness of the spring was 0.27 N/m ± 0,02 N/m. This new PST system improves rotation of the wind turbine at low wind speeds. Wind turbine with PST system start to rotate generator with torque approximately 26 Nm. Without the system it was necessary to achieved torque round 35 Nm.

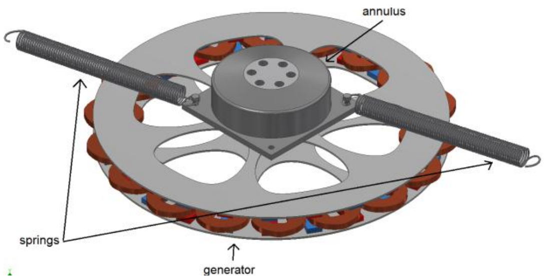

Figure 12. Appearance of the passive spring transmission. One end of the spring is attached to annulus, the other one to the base of VAWT.

D. *Set up*

A three phase 1.1 kW motor plus a robust gear box with a gear ratio 30:1 creates a system which represents the VAWT. The behavior of the shaft rotation in various wind conditions was simulated (Figure 13.). The revolutions of the motor are given by frequency changer VYBO Electric E550-4T0030B. A program sends signal simulating wind conditions for four different scenarios. The program was calibrated by comparing RPM of the real VAWT for certain wind speeds and frequencies of the signal and RPM.

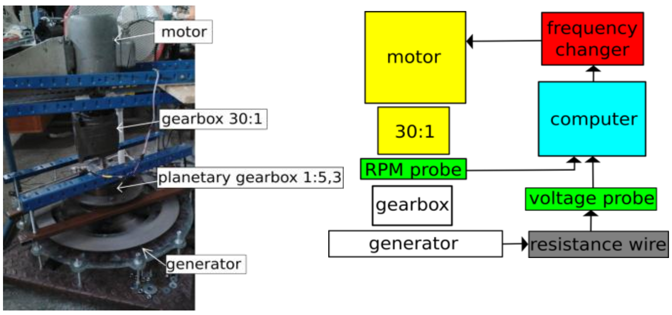

Figure 13. Left- Experimental setup of the system. Right- diagram of the system. Imitation of VAWT in yellow, measure probes in green, frequency changer in red, control system in blue, gearbox and generator in white and final electrical appliance in grey

The generated electricity was converted to heat by resistance wire with resistance 4 Ohm. The maximum output power was measured with this resistor. The voltage was measured by a simple voltage probes placed on the resistance wire.

III. RESULTS

Four 180-second sequences of wind speed data with 2-second resolution were acquired from the Slovak Hydrometeorological Institute. To simulate rotation of the turbine, the wind speed data were used to control the input signal of the frequency changer that powered a 1.1 kW motor through a gearbox with the gear ration 30:1. The same wind conditions were simulated and compared in two setups:

A. Fixed gearbox - normal state using fix gear ratio 1:5.3– blue line in Figure 14.- Figure 17.

B. Passive spring transmission (PST) – red line in Figure 14.- Figure17.

Five measurements for each situation were conducted. The averages of the measured values are presented below.

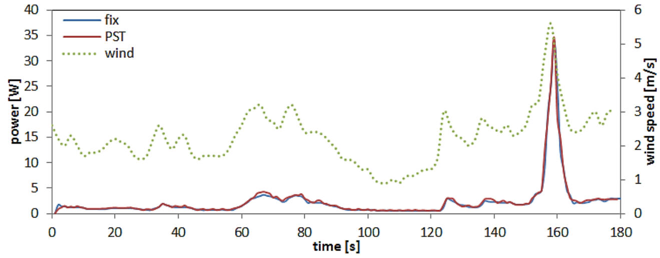

Figure 14. Power- time plot for 1. wind condition blue- normal situation using fixed gearbox with fix gear ratio, red- using PST setup, green- wind speed

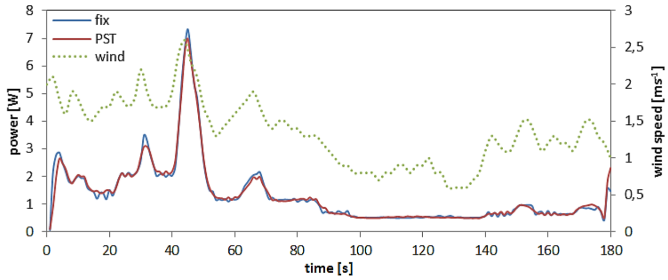

Figure 15. Power- time plot for 2. wind condition blue- normal situation using fixed gearbox with fix gear ratio, red- using PST setup, green- wind speed

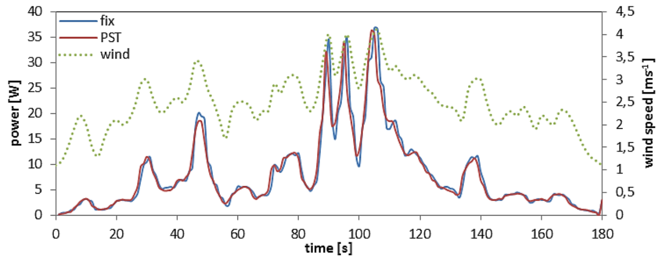

Figure 16. Power- time plot for 3. wind condition blue- normal situation using fixed gearbox with fix gear ratio, red- using PST setup, green- wind speed

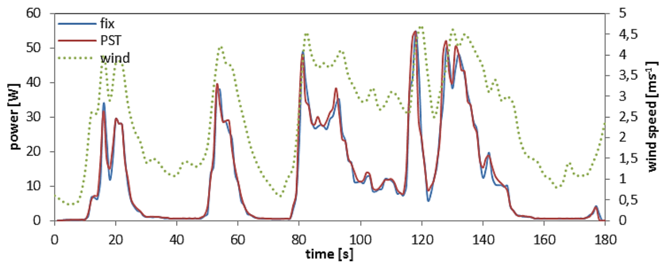

Figure 17. Power- time plot for 4. wind condition blue- normal situation using fixed gearbox with fix gear ratio, red- using PST setup, green- wind speed

Figure14.-17. show visible differences between the fixed setup and our PST setup. A smooth run without sharp peaks is noticeable. The maximum peaks were generated mostly in the fix mode. The sum of the generated energy is presented in Table 2. Where it is calculated as average difference to 3,08 % .

TABLE II. SUM OF ENERGY IN WS USING 2 MODES IN 4 WIND CONDITIONS.

	Fix [Ws]	PST [Ws]	Difference in %
1.	412,93	428,62	3,80
2.	229,63	237,8	3,56
3.	1469,29	1447,6	-1,48
4.	2164,61	2240,02	3,48

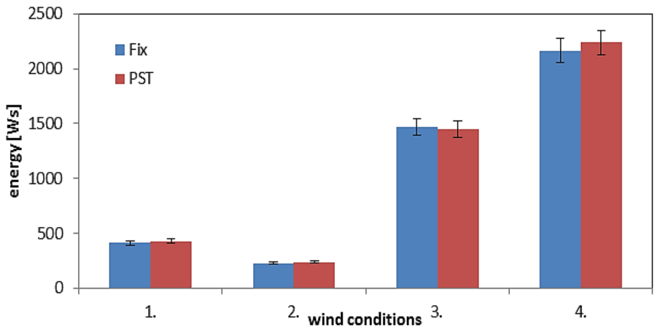

Figure 18. Sum of energy in 2 modes fixed and PST in 4 wind conditions

IV. CONCLUSIONS AND DISCUSSION

In this study a new double rotor axial flux coreless permanent magnet generator and passive spring transmission design and prototype are presented. The generator can generate electrical energy at various wind speed, even at low wind speed without cogging torque. The output power of 356 W was achieved at as low as 160 PRM.

Two setups: A) fixed gear ratio and B) new Passive Spring Transmission (PST).

A modified type of adaptive planetary gearbox (PST) was created. This system uses the springs with stiffness 0.27 N/m to continuously change the gear ratio for a short time, which reduces the torque required to run-up the turbine and generator from 35 to 26 Nm.

To compare the effect of the PST we created a system consisting of a computer, frequency controller, and motor to simulate various wind conditions. This guaranteed repeatability of the measurements and a sufficient amount of data for statistical processing.

Table 2. shows that there is no significant increase in output energy and that the increase is within the error tolerance of the measuring equipment. Dissipation of energy due to stretching of the springs was utilized. But the main contribution of the PST system is in decreasing the run-up torque from 35 Nm to 26 Nm and reducing the stress load, reducing material fatigue of wind turbine construction by smoothing the operation of the generator shown without using expensive electronic add-ons.

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