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WIND TURBINE WTH CONTINUAL VARIATION OF TRANSMISSION RATIO – DESIGN AND TESTING METHODOLOGY –

Sanja VASIN, Milosav OGNJANOVIĆ, Marko MILOŠ

University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade, Serbia
E-mail: vasinsanja@gmail.com

Wind speed variation presents the main problem for electricity production in wind power industry. Although wind is all around us, it is impossible to control its stochastic nature. As a result, existing wind turbines produce electricity with variable frequency, which demands synchronization with electric net. Synchronization process implies frequency conversion, which generates significant power losses in the system. Present researches mainly focus on reduction of power losses and efficiency increase of WT's through speed control and maintain of electric generator speed at the same level. In this work as a backbone of wind power plants innovation, authors present a new design of WT gear train with variable transmission ratio according to wind speed variation, providing direct synchronization to electric net – a hybrid gearbox that consists of mechanical, electro-electronic and software system. Mechanical system contains one specific planetary gearbox, with total transmission ratio i=1/25 and one planetary gear set for continual variation of overall transmission ratio. Electro-electronic system consists of motor-generator for transmission ratio variation and of electronic components for closed loop speed control. Software system provides control system variation and variation of components characteristics based on process identification and predictive control model decision. Concepts of software and control systems are presented and discussed in this work. For each of these systems, testing methodology is developed, with proposal of new closed power loop test rig design. The new design of testing rig provides testing of load capacity of complete WT drivetrain and verification of the system operation quality.

Key words: planetary gear unit, hybrid system, wind turbines, CVT, experiments.

1. INTRODUCTION

Existing wind turbines (WT) produce electricity with variable frequency, which has to be synchronized with electric net. Synchronization process demands continuous rectification of frequency, which leads to overall power losses. The leading edge of this work is an idea to develop a new type of WT gearbox with constant output rotation speed which will power the generator with ability of direct synchronization to electric net. For constant gearbox output speed, transmission ratio will be continuously varied according to variation of wind power and speed. Present gearboxes do not have capability to change transmission ratio. Design is oriented to gearbox mass and size reduction, good load distribution between planetary gears, reduction of bearing reaction forces, gain of maximal torque and transmission ratio and in combination with CVT hydraulic converter, with all designs having fixed transmission ratio. The insight of mentioned designs is given in the work of Höhn [1]. For validation of functional requirements fulfillment and verification of systems behavior in different operating conditions, experimental testing of WT drivetrain is crucial. Beside development process and design of new WT gearbox, it is necessary to develop a proper testing methodology for experimental investigation of gearbox prototype. Since it is a hybrid gearbox consisting of mechanical, electro-electronic and software system, testing methodology can be divided on testing processes of each of this systems. For testing of complete, mechanical, electric-electronic and software system, specific design of closed power loop test rig is presented and discussed in this work. Test installation provides possibility to test load carrying capacity of complete drivetrain with simulation of continuous variation of torque and input rotation speed, according to wind speed variation. Simulation is based on torque load spectrum and on wide range of wind speeds. This methodology is different comparing to approach presented in [2] where gearbox prototype tested to determine load distribution of each gearbox component. The main principle of power

circulation in developed test rig is based on FZG principle with hydraulic load (torque) continual variation presented in [3]. Control of load and speed variation according to load spectrum is the software task. The goal of this work is to develop testing methodology for the new hybrid WT drivetrain, which comprehends the synergy of mechanical, electro-electronic and software system. The task of developed methodology is validation and verification of WT drivetrain under wide range of operating conditions.

The actual research activities directed to prediction of overall system behavior contain various analyses of WT drive trains components and complete systems. In the area of components analysis, dominate stress-strain distribution and natural frequencies identification by applying of Finite Elements Method. Analysis of complete WT drivetrain include non-linear, dynamic, frequency, fatigue and thermal analysis of gearbox detailed model, where each component, especially bearings, gears and shafts, is presented as 3D nonlinear model comprising all possible interactions between components. In the work [4], with advanced simulation tool WT drivetrain dynamic loads have been computed, including Sensitivity analysis and Misuse maneuvers. Article [5] contains application of advanced gear analysis for reliable prediction of gear service life, excitation behavior analysis of gear pair and identification of possible failure modes, transmission errors, gear stiffness, tooth root stresses, gear teeth flanks pressure, effects of deviation due manufacturing or assembly errors. Structural elasticity of gearbox, [6] must be taken in consideration during modeling. If neglected, it can lead to underestimation of gear mesh misalignment and inaccurate prediction of gear teeth load distribution, especially prediction of gear life service. Complex interactions in planetary gearbox demand accurate modeling for system overall analysis [7]. Any change in WT drivetrain performance and operating conditions can be captured with continuous online system monitoring based on signal measurements providing early detection of possible failures and their causes. A systematic overview of present condition monitoring techniques for wind power systems and their applications are given in the work [8, 9, 10]. The influence of wind speed and power variation on electricity production process is most important and till nowadays-unresolved problem. Power losses due to inability of system to transform stochastic nature of wind into electricity with constant frequency for the need of public electric net are significant and present the core of scientific research and world's industry interest. With new drivetrain, presented in this work, direct synchronization with electric net is provided, based on capability of gearbox to vary the transmission ratio according to wind speed variation giving all the time constant output rotation speed to power the generator for generation of electricity with constant frequency. During gearbox testing, influence of wind speed variation can be simulated with application of torque load spectrum [11], as load pattern in back-to-back test rig, where vertical axis presents torque value and horizontal axis presents the wind speed. Simulation of WT drivetrain input and output relationship, given in the work [12], can be determined through modeling and creation of load and power spectrum. For certain frequency range [13], power spectrum as system output, can be simulated based on Discrete Fourier transformation. In the work [14], Auto-regressive (AR), method is used to characterize wind speed field for generation of time-varying load spectrum. In the article [15], it is also defined testing methodology of complex professional electronic systems based on Functionality, Stress and Robustness testing, with goal to fully automate testing process to gain maximal testing reliability, minimal testing time and minimal human interference. For complete understanding and control of system behavior during testing, measurement of static and dynamic characteristics of testing equipment, [16] can be valuable information. On-line real-time digital simulation of whole power electronics system can be performed with Hardware-in-the-loop (HIL) Simulation. HIL Simulation permits repetition and variation of tests on actual product or prototype without any risk for people or system, [17]. To be able to control new WT drivetrain during testing process and exploitation, concepts of two software systems are defined in this work. For testing process, software system will provide simulation of torque and transmission ratio continuous variation. Once placed in the field, drivetrain will be controlled with software system providing continuous identification of system parameters for optimal system performance. To verify software quality and reliability, proper testing methodology is developed and presented. In the work [18] is given the classification of software testing techniques and strategies. State-of-the-practice shows that for development process of high quality software it is necessary to investigate the relationship of testing process and reliability, [19]. Testing of software risk [20], presents estimation of probability that the software will fail after deployment. To avoid system power losses during implementation, in the work [21] is presented application of FDD (Fault Detection and Diagnostic) method for fault detection and isolation in power system.

2. DESIGN OF HYBRID GEAR TRAIN TRANSMISSION SYSTEM

In Fig., 1a design solution of new WT drivetrain schematically is presented with marked positions of components vital for realization of gearbox operating principle. It consists of one specific planetary gearbox with total transmission ratio i=1/25 (g_1-g_3) and of one additional planetary gear set which can provide continual variation of transmission ratio. In Fig.1b is presented 3D model of mechanical part of WT drive train unit. Housing of the unit and planetary gear carriers are welded design structures. From left side on its entrance, gearbox is connected to rotor shaft with elastic coupling. The input shaft of gearbox is supported with cylindrical roller bearing, which is placed inside gearbox housing. Another cylindrical roller bearing is placed inside right end of gearbox shaft, to support planet carrier. Main gearbox, (i=1/25) contains two inside toothed ring gears, where one ring gear is input (drive) gear (g_1) and the other one (g_3) is fixed, without rotation. Both ring gears are in mesh, with the sets of five planet gears (g_2), giving the total transmission ratio, i=1/25. Input ring gear is connected to main shaft of gearbox with rotation speed 10–18 rpm, by means of ring gear carrier. A pair of spherical roller bearings is placed inside each of five-planet gear complete (g_2). Applied design concept provides reduction of dimensions and increase of system reliability. Planetary gear set for the total transmission ratio variation, is connected by spline joint and supported with pair of cylindrical roller bearings. The ring of planetary gear set for transmission ratio variation is toothed on both sides (g_6) and can rotate around bearing support. Internal teeth system is in mesh with the three planet gears (g_4) supported with planet carrier directly connected to the main gearbox (i = 1/25). In the center of gear set is sun (output) gear (g_5) placed on the end of output shaft, which is connected to electric generator with elastic coupling. Outside teeth system of the ring (g_6) is in mesh with additional gear (g_7) connected to motor-generator with reverse rotation, which provides variation of transmission ratio according to wind speed in order to supply constant speed of output shaft. The ring gear (g_6) is connected to carrier supported on cylindrical roller bearings placed in the central wall of housing. When wind speed is low, gear (g_7) speed-up the planetary gear set, and when wind speed is high, the gear (g_7) slows down the ring (g_6), providing variation of this planetary gear set in the range of i=1/(3,3…6). Together with gearbox with i=1/25, total transmission ratio is i=1/(83…150) which provides constant generator speed of 1500 rpm for wind rotor speed variation 18…10 rpm.

Embodiment design of WT drive train is carried out for the next function requirements. Input speed of gearbox is equal to operating wind rotor speed of 12 rpm, output speed 1500 rpm, and input torque 1200kNm. These data correspond to transmission of 1.5 MW mechanical powers in the course of all operating life. Due to the wind and rotor speed vary transmitted power also vary in relation 0.4…2.5 MW. Material selection together with gear teeth thermal treatment (surface carbonized and grinded teeth), is chosen with the objective to obtain maximal load capacity with minimum of gearbox dimension. Design parameters are selected using robust design methodology, which includes possible stochastic operation conditions, and stochastic failure probability of gear teeth flanks. Desired gear drive reliability and service life duration of gear drive unit were the main constraints in design parameters definition.

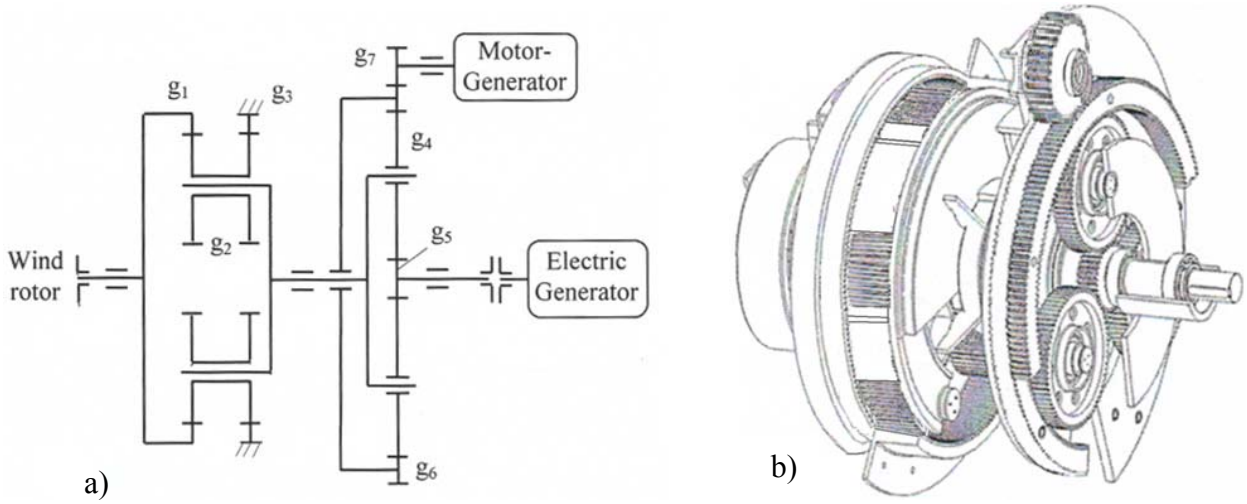

Fig.1 – Schematic representation (a) and 3D model (b) of new WT gearbox with continual variation of gear train transmission ratio.

In order to provide permanently constant speed 1500 rpm of output shaft and 3-phase AC generator, permanent variation of transmission ratio is essential. This function carry out gear (g_7) connected to gear ring (g_6) – Figs. 1a and 2. The gear (g_7) is driven by PM-SM servo motor-generator (Fig. 2). Electric current produced by 3-phase generator is under monitoring of power monitoring system (PM). The power level, frequency and other characteristics are permanently monitored and produced power after voltage transformation is transferred into public electric net (PEN). Digital signal processor (DSP) processes information about variation of current frequency and sends signals for pulse width modulation (PWM) and control of motor-generator. Motor-generator has very important function, alternatively change of direction and speed of rotation, to consume and produce electricity. The speeds of rotation are relative small and very often with speed equal to zero (standing position). These are very strong operating conditions for motor-generator which has to be equipped by additional electronic for protection. In addition, control and reaction of motor-generator control system has to be very fast in order to kip current frequency in the process of random variation of the wind. Software for wind turbine control (SWTC) adapts DSP and PWM functional characteristics. This process is in interaction with power monitoring operators, or can perform automatically by corresponding algorithmic procedure presented in Fig. 2.

To keep the constant generator speed of rotation 1500 rpm, when wind speed is high, *i.e.* wind rotor speed 18 rpm and for output power 2.5 MW, motor-generator rotates in one direction providing the total transmission ratio i=1/83. For these conditions, the ring (g_6) has to rotate with 500 rpm in direction (a), and motor-generator with 3000 rpm. In this condition, motor-generator is acting as electricity generator and brakes (inhibits) ring (g_6) and produces maximal power of 0.6 MW. This is extreme condition when hurricane wind appears. When wind speed is low, wind rotor rotates with 10 rpm, and motor-generator has to accelerate ring (g_6 – speed direction – b) by power consumption. For this condition output power of WT is 0.4MW, motor-generator rotates providing the total transmission ratio i = 1/150 at speed of motor-generator 420 rpm (ring g_6 speed 70 rpm) with maximal power consumption of 0.1MW.

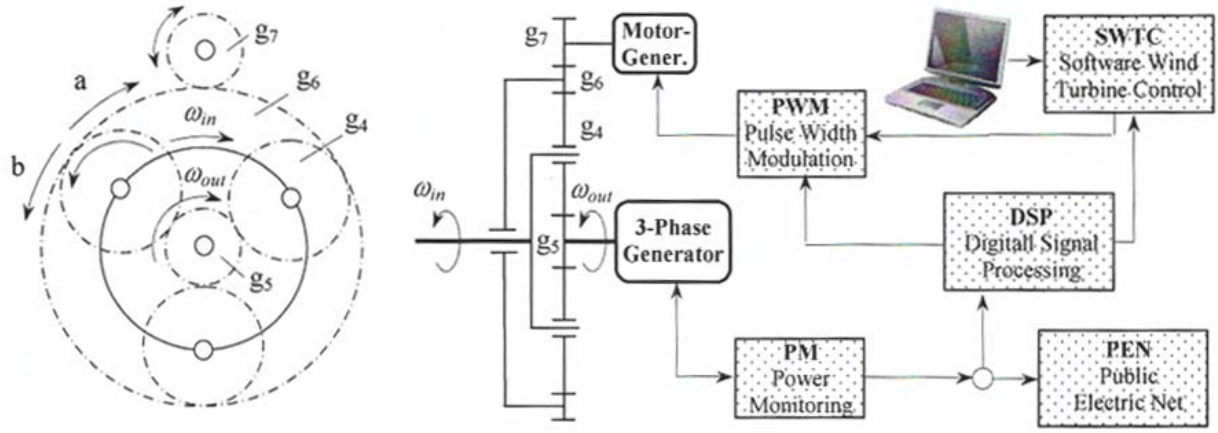

Fig. 2 – Concept of control system.

Comparing to WT drive trains with defined (constant) transmission ratio, proposed WT drive train provides significant advantages, especially in the area of efficient wind power transformation into electricity. Frequency transformation of electric current using special transformers with significant loses, in the new solution is eliminated. The power production significantly increases including power produced by motor-generator. Power consumption when motor-generator is acting, as motor is very low. The range of wind speed *i.e.* maximal wind speed, which can be used in exploitation, can be significantly bigger. These are the reasons for significant increase of power production efficiency. Mentioned advantages will prove testing and verify operating properties and quality.

3. TEST RIG DESIGN

There are a few reasons that it is necessary to perform testing process of complete hybrid structure of WT drive train. Operating properties such as time of control system reaction and quality of current frequency control, acceptable range of turbine rotor speed, carrying capacity (maximal power), operating lifetime, is possible to verify by extensive laboratory testing under load in conditions close to exploitation. For the purpose of long duration of testing until components failure under the full load, the closed principle of power circulation provides very efficient approach. Based on this principle in the Fig. 3 testing installation for WT drive trains with variable transmission ratio are presented. Output shafts for connection to 3-phase AC generator are connected to asynchronous electric motor with constant speed of rotation 1500 rpm. Input gear unit shafts for turbine rotors, are connected between each other by the two gear units with transmission ratio $i = 1$ and by additional shaft. This shaft together with gear units has the speed of rotation, which corresponds, to the speed of WT rotor. The load of closed system provides hydraulic device at connecting shaft, by torques at the shaft ends in opposite directions (action and reaction – quasi-static system). For the purpose of overall transmission ratio $i = 1/(83…150)$ variation and wind rotor shaft speed variation the motor-generator together with bevel gear unit is anticipated. Variation of transmission ratio (speed of input shafts – Wind rotor shafts) and load of these shafts variation during the testing process is controlled by software for testing SHGT (Software for Hybrid Gear unit Testing) which manages operation of the unit PWM (Pulls Width Modulation) and HSLC (Hydraulic System Load Control). The first one modulates direction and speed of rotation motor-generator, and another one makes control of hydraulic system for continual variation of the system load according to load spectrum presented in the next section.

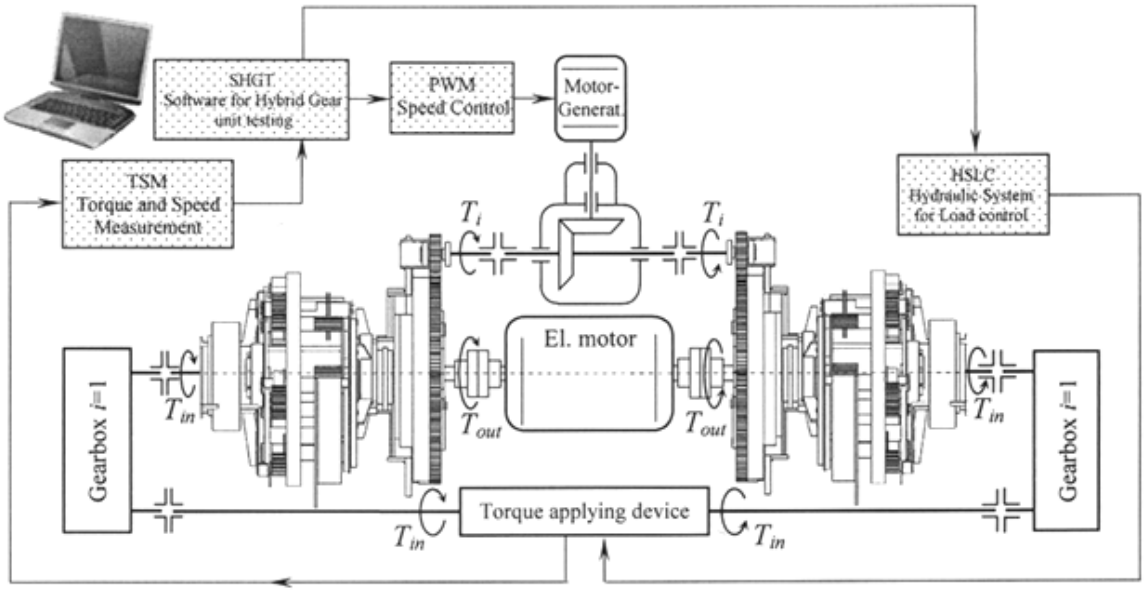

Fig. 3 – Closed power loop test rig for testing of complete WT gear units.

The role of electric motor placed in the center of test rig has function to connect the two tested units in back-to-back principle, to provide permanent speed of rotation equal to 1500 rpm, which is equal to electric generator speed in exploitation conditions, and to provide torque for prevailing of friction resistances inside of gear units in the closed system. This is about 20% of the power which circulates inside of the system, *i.e.* 0.3…0.5 MW.

The role of torque applying device is to provide the torque load in closed system of power circulation and its variation of according to load spectrum in relation of speed of rotation (Fig. 5). This is hydraulic device placed at the shaft with low speed of rotation. The low speed 10…18 rpm provides easier supply of oil under controlled pressure. At this place is provided the space for corresponding device dimensions which corresponds to necessary torque in the range of 0.15…1.3 kNm. The oil pressure is under software control according to load spectrum in Fig. 5.

Motor-generator variants the transmission ratio of connected gear units and speed of rotation of slow (input) shaft with Torque applying device, in the range 10…18 rpm. According to Fig. 2, motor-generator has to provide torque at the ring (g_6) for the two connected gear units. The torques in tested gear units are in opposite directions (Fig. 3). This is the reason that the torques for transmission ratio control T_i also has to be in opposite directions. The motor-generator has function to provide motion with minimal power enough to prevail friction resistance, no higher than 0.1 MW.

4. LOAD SPECTRUM DEFINITION

Existing WT's have defined range of wind speeds or so-called cut-in speeds approximately 3.5m/s and cut-out speeds 20÷30m/s of WT operating range. With new gearbox design it is possible to capture the wind even at lower wind speeds 0.5m/s – light breeze and especially at higher wind speeds 32.7 m/s and more – strong winds. In Fig. 4a are presented testing results of existing WT with maximal power (capacity) of 1.5 MW [21]. With wind speed increase the WT's power increases and maximal level of 1.5 MW is fulfilled with 12 m/s. The same research shows that lover wind speeds are much more frequent than higher. The diagram in Fig. 4b shows that low speeds are four times more frequent than middle and higher are the two times more frequent than middle wind speeds. However, the speed of rotation of WT rotor is not in direct relation to the wind speed. In order to optimize air-streaming efficiency, the rotor blades vary angle and change efficient surface exposed to air stream. To the low wind speed corresponds higher efficient surface and to higher speed lover surface. Results presented in Fig. 4 include this effect.

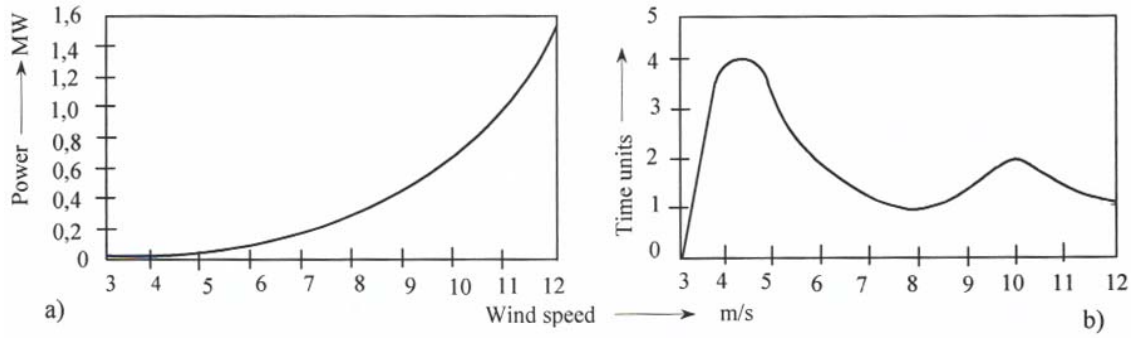

Fig. 4 – Relation between wind speed, absorbed power and time participation.

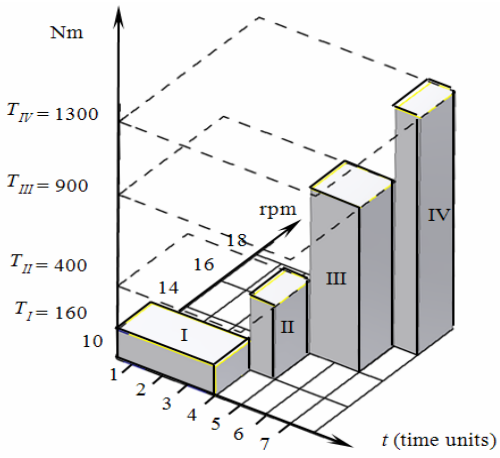

Fig. 5 – Average rotor speed a load spectrum for laboratory testing.

These results can be base for the load spectrum identification for WT drive train testing using testing rig presented in Fig. 3. For this purpose in Fig. 5 is presented torque load spectrum in the form of four blocks which corresponds to rotor and wind speeds and to average time of this conditions. The first block is created for low wind speed (5 m/s) *i.e.* rotor speed (12 rpm) and to four time units. According to diagram in Fig. 4a for these conditions, absorbed power is 200 kW and input (rotor) torque 160 kNm. The second block corresponds to wind speed of 8m/s (rotor speed 14 rpm), to one time unit and to absorb power of 600 kW which corresponding to rotor torque of 400 kNm. The third block covers the two time units and corresponding to high wind speed of 10 m/s (16 rpm) and power of 1.5 MW (torque 900 kNm). Higher wind speeds, until to 30 m/s has very small participation in the total time of testing, less than one time unit. This also means that rotor speed can be 18 rpm, no higher than 20 rpm. By blade

angle, control of the rotation speed and absorbed power do not increase in the same relation with the wind speed increase. These conditions in the testing process are involved by forth load block with torque of 1300 kNm which corresponding to 2.5 MW.

5. TESTING METHODOLOGY

Laboratory testing of complete WT drive train have to be carried out with a few objectives. The first one is to check functionality and controllability of the system. The next one is to identify service life and to check service reliability of the system components exposed to the representative load spectrum. Testing of various properties of the system such as vibration and noise generation, effects of lubrication heating, cooling etc. In Fig. 3 is presented test rig and in the Fig. 5 load spectrum, which represents service conditions of the system. For the chosen time unit, for example 10 hours in continual test, all four load blocks shell be simulated and then all process repeated. The number of repetition is covering expected operating life of WT drive train.

Mechanical components are gears and bearings together with planetary gear carriers (cages), shafts, spline and other connections. Operating life of gears is limited by various flank failures of the teeth. Bearings are also components with limited operating life. In addition, various kinds of joints have to be tested in order to identify failure trends and quality of operation. Possibility of cracks occurrence in some of components is also advent, which has to be checked by laboratory testing. Mechanical structure as the rule is sources of vibration and noise. Measurement and frequency analysis in the course of the test will be permanently performed.

Similar to mechanical, electric components, especially servo motor-generator is exposed to the strong conditions of operation process. Variation of speed level and direction of rotation, including standing position without rotation, and change reaction in the short time, has to be performed frequently and in the course of all service life. Ability of servo motor-generator to satisfy this regime of exploitation has to be tested by extensive laboratory testing. Together with this executive electric component, testing rig in Fig. 3 provides possibility for testing of electronic components for servo motor-generator control, which are incorporated in the module PWM (Pulls Width Modulation). This test contains functionality testing, the range of output variation and reaction at the software signals, and stability of action including effects of temperature, humidity and others in exploitation environment. For these and other characteristics, it is necessary to perform robustness of electronic components in order to reduce delays in exploitation.

Software blocks presented in Fig. 2 (design of control structure in exploitation) and in Fig. 3 (test rig) are very similar and testing by testing process control contains conditions in exploitation process. Software is based on algorithms for processing of sensors signals and creation signals for adaption of electronic components characteristics, which will provide correct functionality according to operation conditions and environment. Software for testing rig (Fig. 3) is equipped with additional module for simulation of load spectrum (Fig. 5). Algorithm for this purpose prepares signals for hydraulic system control and provision of corresponding level of torque. Simultaneously, by action of servo motor-generator action, stimulated by software signal according to logarithm, vary transmission ratio and keeps the speed of rotation of loaded (connecting) shaft at the necessary level (Fig. 5). The speed and torque of this shaft presents speed and load of turbine rotor in service conditions. Software for testing process also has to be equipped by algorithm for fast variation of torque and speed of rotation for the testing functionality and fast reaction of electro-electronic components in maintaining of electric generator speed at 1500 rpm. The main software testing is the testing of functionality, which contains execution of mentioned functions by generation of corresponding output signals for electronic components action. If this action is not correct instead of software testing in the form of “black box”, testing in the form of “white box” has to be applied and find out the reasons for invalid signals action. Testing rig correct and wind turbine correct action needs reliable functionality of control software.

6. CONCLUSION

Presented design and testing methodology contains promotion of the new approach in the wind turbines development and exploitation, which provides significant advantages in comparing to existing solutions. The article contains (a) the new design of WT drive train with continual variation of transmission ratio controlled by software according to the wind speed, (b) the new design of testing rig which provides long term testing in order to operation reliability proof, and (c) the new testing methodology based on load spectrum created according to real exploitation conditions. Both designs, WT drive train and test rig, are hybrid designs which contains mechanical, electric-electronic and software components, which provides high level of operating quality, robustness of action and modern approach in technical systems design. The main advantages of the new WT drive trains are (a) efficient energy transformation without transformation of electric current frequency in order to synchronize to public electric net (b) increase of the level of transformed energy by significant increase of the WT rotor speed range and without braking in order to keep rotor speed in the narrow range speeds of rotation and (c) more efficient software control of WT's system. To this it necessary to add efficient testing process and WT drive train operation quality and reliability verification.

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