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DESIGNE OF A SIMPLIFIED ACTIVE STALL FIXED SPEED WIND TURBINE SIMULATION MODEL

FIKSĒTA ĀTRUMA VĒJA TURBĪNAS VIENKĀRŠOTĀ MODEĻA MODELĒŠANA

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Keywords: active stall fixed speed wind turbine, power controller, drive train, aerodynamic model

I. Introduction

With the increasing integration of wind energy into power systems, the behavior of wind turbines and the control of wind farms will have significant effects on the power quality of both the connected power systems and the wind farms.
An essential aspect of integrating wind farms into power systems is knowledge of the transient behavior of the wind farm subject to grid faults. Grid faults may cause isolation of one wind turbine or even isolation of a large part of the wind farm from the grid. This will have a great importance in the event that the wind farm is a significant part of the power system. Thus losing part of the wind production system due to grid faults can have severe consequences on power system stability. Hence in order to design a reliable system, it is important to understand the behavior of the wind farm and to have the knowledge of wind turbines interaction with one another under grid faults.

II. Mathematical model of wind turbine

The fixed speed wind turbine, which is also called conventional wind turbine, can be characterized as follows [1]:

- Induction generator with compensation for reactive power (capacitor bank)
- Fixed rotational speed (squirrel cage induction generator)
- Power electronic devices (soft-starter) for limiting inrush current during the starting
- Active stall regulation

Figure 1 shows the block diagram of basic components of active stall fixed speed wind turbine. As depicted in Figure 1 wind energy is converted to mechanical energy through the drive strain. Then by means of induction generator mechanical power is converted to electrical power. Figure also includes characteristics that were described above, such as capacitor bank with controller, soft starter with controller and power controller for blade pitch angle control. Induction generator is connected to the HV grid through the two winding transformer.

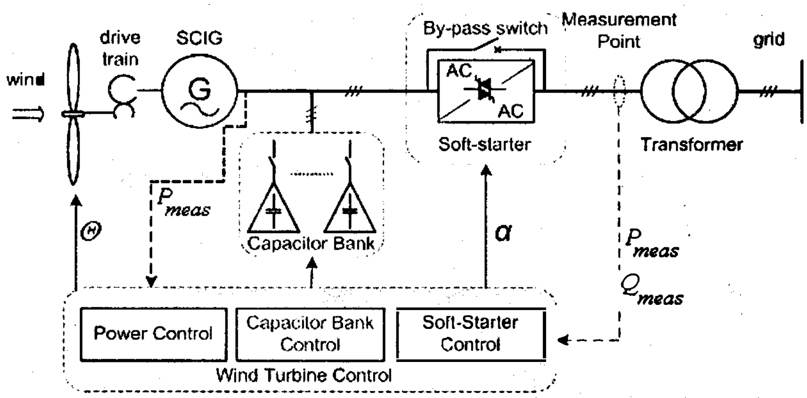


Figure 1: Block diagram of active stall fixed speed wind turbine [2]

A. Mechanical model

In the mechanical model only parts of dynamic structure of the wind turbine that contribute to the interaction with the grid are included. Thus only drive train is considered because this part of wind turbine has the most significant influence on the power fluctuations [3].

According to [4] in stability analysis, when system response to heavy disturbance is analyzed, drive train usually is approximated by two mass model. The drive train model of the wind turbine is shown in Figure 2 [5].

In Figure 2, small mass is represented by induction generator inertia J_{gen} and large mass corresponds to large turbine rotor inertia J_{rot}, representing the hub and the blades. The flexibility of low speed shaft is modeled as stiffness k and damping ratio c, however high speed shaft is assumed to be stiff. The drive train in Figure 2 also includes model of ideal gear box with the ratio (1 : n_{gear}).

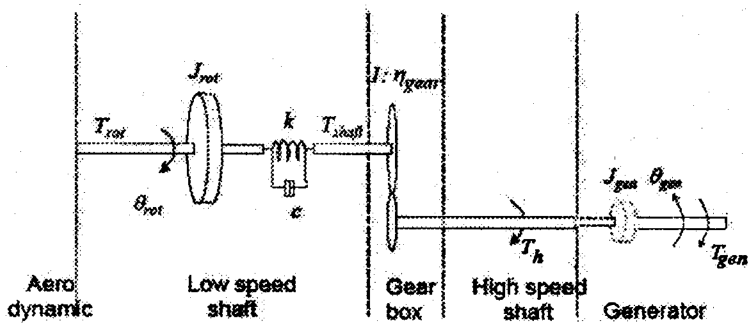


Figure 2: Two mass model of drive train

The drive train converts aerodynamic torque of the rotor T_{rot} into the torque on the low speed shaft T_{shaft}. The drive train can be described by following first order equations.

$$J_{rot}\frac{d}{dt}\omega_{rot} = T_{rot} - k\theta_k - c\omega_{rot} + c\frac{\omega_{gen}}{n_{gear}} \quad (1)$$

$$J_{gen}\frac{d}{dt}\omega_{gen} = -T_g + k\frac{-\theta_k}{n_{gear}} + c\frac{\omega_{rot}}{n_{gear}} - c\frac{\omega_{gen}}{n_{gear}^2} \quad (2)$$

$$\frac{d}{dt}\theta_k = \omega_{rto} - \frac{\omega_{gen}}{n_{gear}} \tag{3}$$

B. Aerodynamic model

Not all the power from the wind can be converted to the mechanical power. The mechanical power extracted from the wind is given by following equation.

$$P_{rot} = \frac{\rho}{2}\pi R^2 C_p\left(\theta_{pitch}, \lambda\right)v_w^3 \tag{4}$$

where $\rho = 1.225 \ \left[kg/m^3\right]$-air density, R -radius of turbine blades, v_w -wind speed.
As it can be seen from the equation 4 aerodynamic efficiency depends on pitch angle θ_{pitch} and the tip speed ratio λ. Tip speed is calculated using equation.

$$\lambda = \frac{R\omega_{rot}}{v_w} \tag{5}$$

Mechanical power of the wind turbine is also a function of a non dimensional power coefficient Cp, which however depends on a pitch angle and tip speed ratio. The typical Cp curve as a function of pitch angle and tip speed ratio is shown in Figure 3.

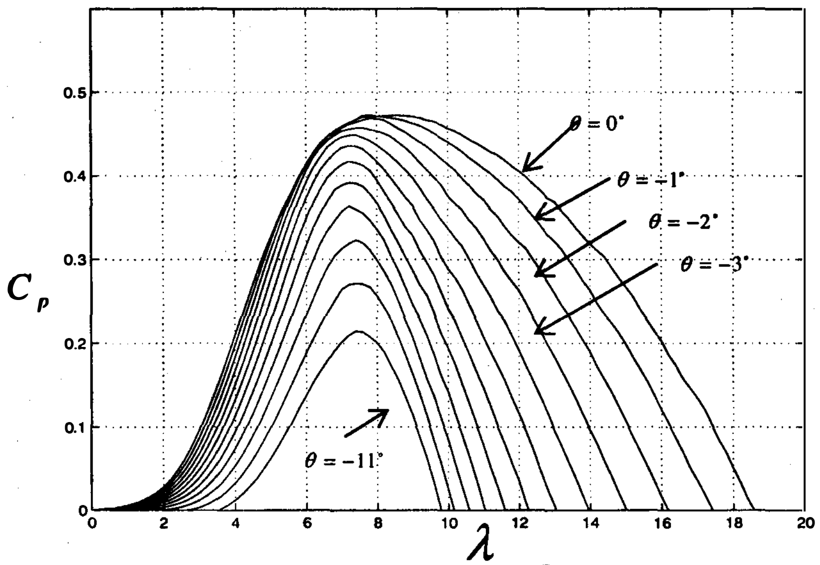


Figure 3: Wind power Cp curves

The aerodynamic torque developed on the main shaft of the wind turbine can be modeled by following equation.

$$T_{rot} = \frac{P_{rot}}{\omega_{rot}} \tag{6}$$

C. Control strategy for active stall wind turbines

Active stall wind turbines use stall effect and by varying pitch angle maximum power output from the wind turbine can be controlled to a constant value. In active stall wind turbines power captured from the wind can be divided into two stages:
First stage is power optimization where power yield is maximized between cut-in wind speed and nominal wind speed. In this stage only few fixed step are used to change pitch angle in order to extract as much power from the wind as possible [6]. In order to maximize power output for different wind speeds a corresponding values of C_p has to be found from the look up table, for a given pitch angle.

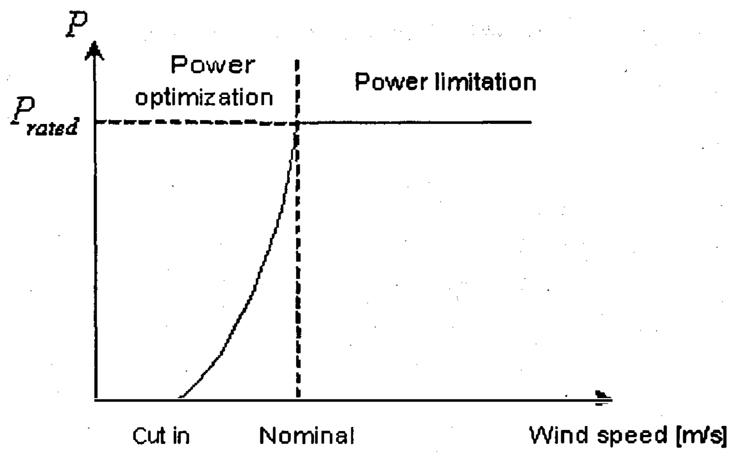


Figure 4: Power curve for active stall wind turbine

Second stage is power limitation when wind speed is between nominal speed and cut-out speed. In this stage power is limited when wind turbine power exceeds the nominal power, rotor blade angles are turned into the wind thus stall effect is increased and power is reduced. To get desired stall effect the blades have to be pitched in negative direction. Typical power curve of active stall wind turbine is shown in Figure 4.

D. Pitch angle control system

Pitch angle control system is exposed in Figure 5. It contains *PI* controller and a pitch system. First a reference power (Pref) is compared to the measured power (Pmes) and an error is sent to the *PI* controller. *PI* controller however generates appropriate reference pitch angle θ_{ref} which is further sent to the pitch system.

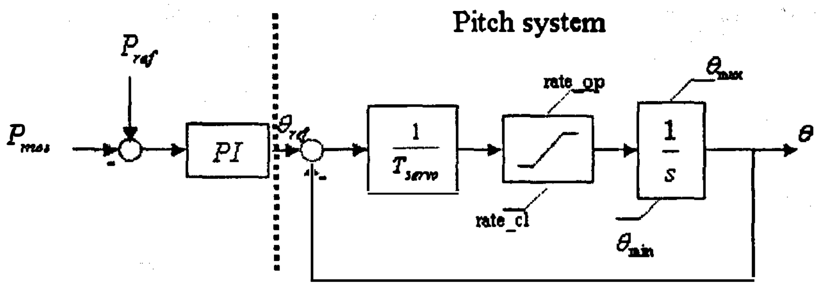


Figure 5: A block diagram a pitch actuator system

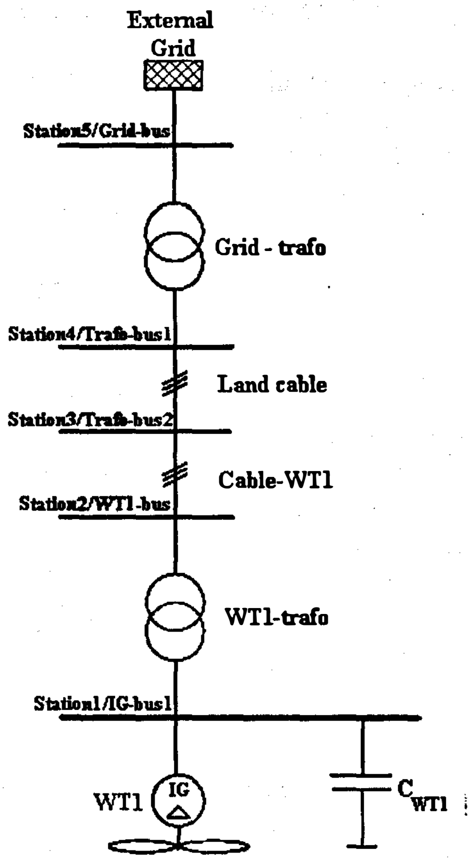
Pitch mechanisms accounts for the associate time constant (Tservo [s]) and limitation of rate of change in pitch angle (rate_op [deg/s] - opening rate, rate_cl [deg/s] – closing rate). The dynamics of the pitch system can be approximated by a first order system.

$$\frac{d}{dt} = \frac{1}{T_{servo}}\left(\theta_{ref} - \theta\right) \qquad (7)$$

The reference pitch angle set by the *PI* controller is compared with an actual pitch angle and the error is corrected by pitch mechanism. As it shown in Figure 5 blade angle for protection reasons is also limited by $\theta_{\max}$ [deg] and $\theta_{\min}$ [deg] which denotes for maximum and minimum blade angle.

III. Simulation using simple grid model

2.3 MW wind turbine WT1 is connected to the 0.69 kV busbar at station #1 (IG – bus1). The capacitor bank (CWT1) used for compensation of reactive power is also connected to the same busbar, respectively to IG – bus1. The LV/MV (0.69/33 kV) transformer (WT1 – trafo) is connected between IG – bus1 and a busbar WT1 – bus at station #2 in order to boost up voltage. Transformer WT1 – trafo is connected to the busbar Trafo – bus2 at station #3 through the 3 km long 33 kV cable (Cable – WT1). The Trafo – bus2 is connected to the grid side transformer (Grid – trafo, 33 kV/132 kV) with a 0.25 km long cable (Landcable). Further transformer Grid – trafo is connected to the external grid at stations #5 132 kV busbar.



A. Evaluation of a pitch angle controller for variable wind speed

In order to evaluate performance of a proposed pitch angle control system a simple sinusoidal wind speed with 20 Hz Gaussian noise on top was modelled in DigSilent. From simulation results observed in Figure 6 it is seen that power controller works correctly in both power optimization and power limitation modes. When wind speed is above nominal speed (12 m/s) blade angles are turned into the negative direction, however when wind speed is bellow nominal speed power controller is trying to maximize wind turbines power output.

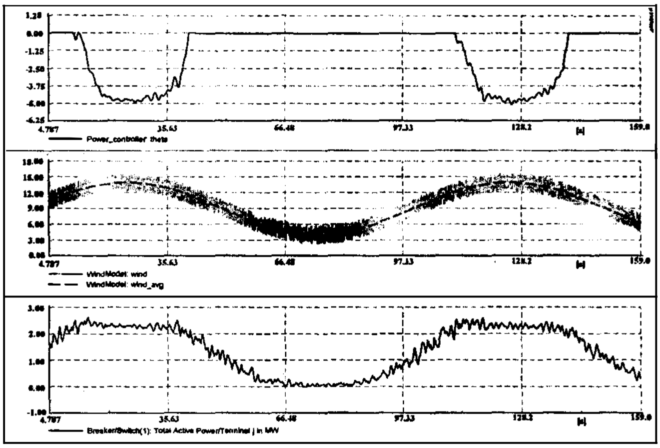


Figure 6: Pitch angle, Wind speed, Total active power

A. Simulation results under three phase fault

A symmetrical self-clearing three phase to ground fault with zero fault impedance is placed on the Station2/WT1- bus. The short circuit is activated at t = 5 sec and cleared at t = 5.1 sec. The simulation step time has been kept constant to 0.0001 sec.

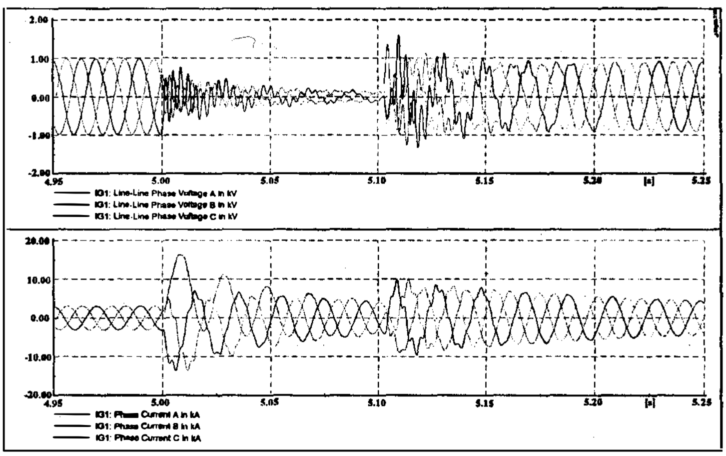


Figure 7: Simulation results under three phase to ground fault
a) Line-to-line voltages [kV] b) Phase currents [kA]

Figure 5.5a shows three phase line-to-line voltages in kV. Also three phase currents are shown in Figure 5.5b. The measurements are taken on the generator terminals.

As it is observed from Figure 7b the phase currents are increased approximately to 5 times of the nominal currents. In Figure 7a it is seen that the oscillation frequency of generator line-to-line voltages has significant increased right after the short circuit happens and as well as after the short circuit is cleared.

In Figure 8 powers and torques are observed during three phase to ground fault. From graphic 8a it is seen that no active power is transferred to the grid anymore. Hence as seen in Figure 8b no electrical torque is produced.

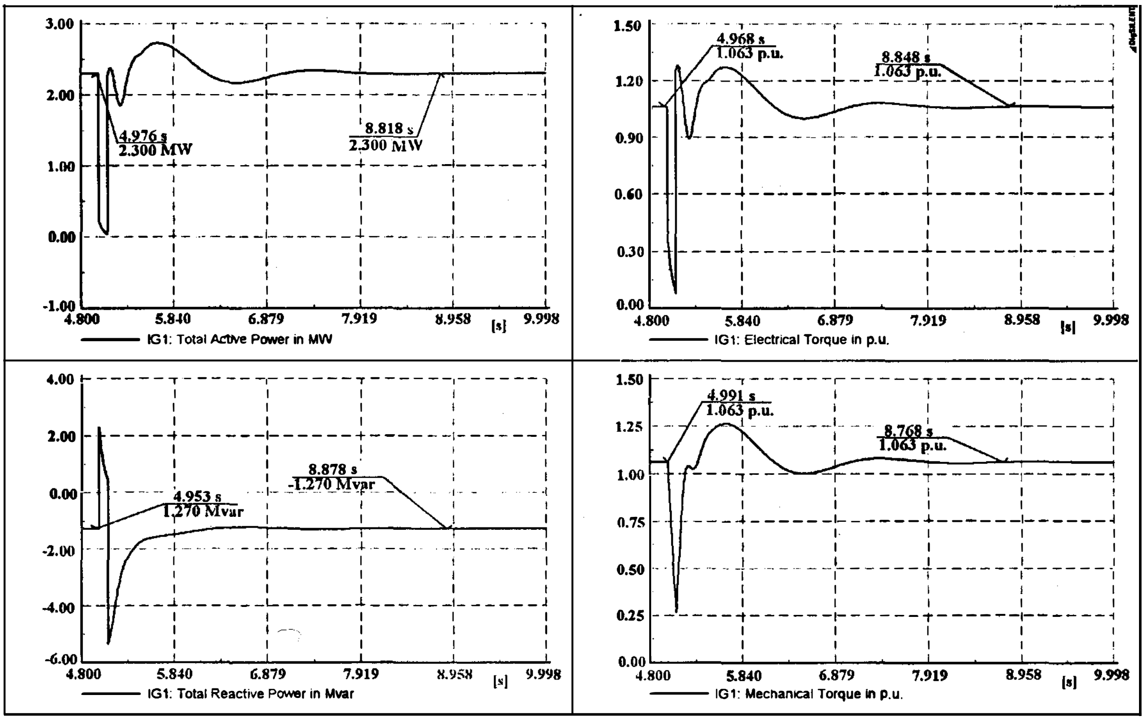


Figure 8: Simulation results under three phase to ground fault:
a) Total active power [MW] b) Electrical torque of the generator [p.u.]
c) Total reactive power [Mvar] d) Mechanical torque of the generator [p.u.]

As seen in Figure 9c due to the change in electrical and mechanical torques the induction machine starts to accelerate by reaching speed that is roughly 3 % higher than nominal speed. Due to the drop in voltage during short circuit no flux in the generator is produced consequently no reactive power will be consumed by the generator and hence capacitor is discharged through the short circuit path. This fact can be seen in Figure 8c where the reactive power is measured on the bus IG-bus1.

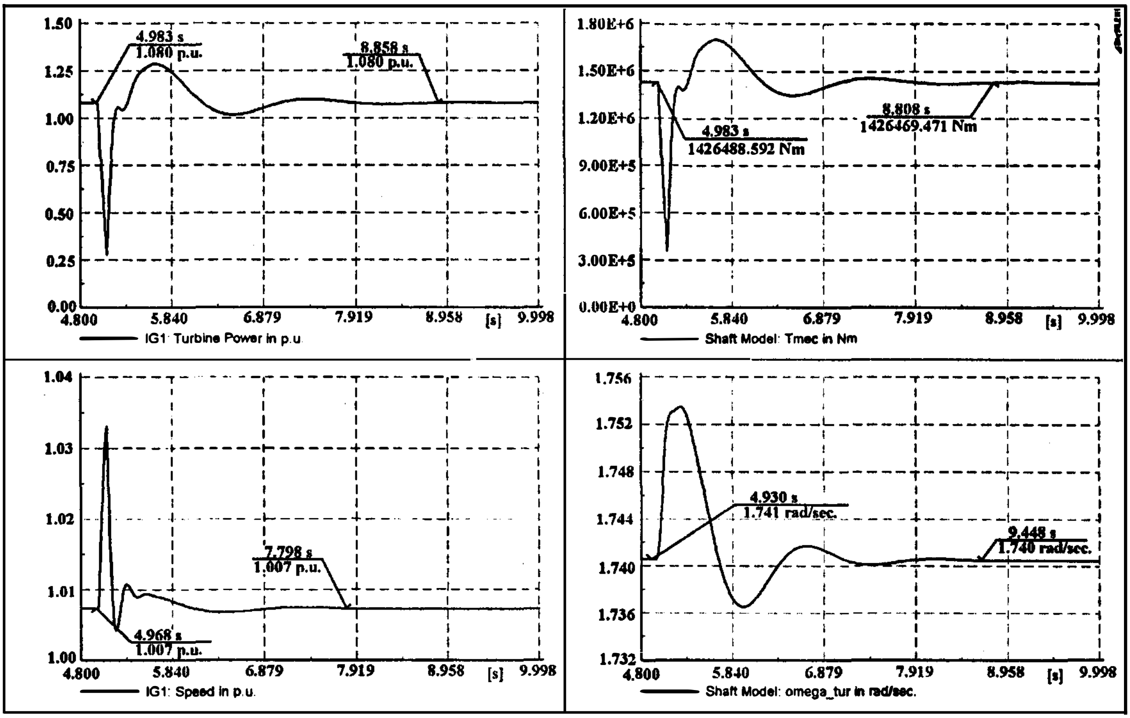


Figure 9: Simulation results under three phase to ground fault
a) Generator mechanical power [p.u.] b) Torque on the low speed shaft [Nm]
c) Generator speed [p.u.] d) Angular velocity of the low speed shaft [rad/s]

The same behavior is observed on the low speed shaft in Figure 9d where the turbine speed has increased. As the pitch angle and the wind speed is kept constant the turbine is forced to operate at higher tip speed ratio. This corresponds to lower power coefficient as seen in Figure 3. Thus turbines power is reduced as seen in Figure 9a.
After clearing short circuit it is see that generator consumes a lot of reactive power from the grid, around -5 Mvar (Figure 8c) that is due to the fact that generator is trying to establish flux required to bring back induction generator to steady state operation point. After clearing short circuit it takes 4 seconds for the system to return to the nominal operation condition.

Conclusion

The main aim of this paper has been to design a model of a wind turbine that is valid for the investigation of grid faults. Thus a model of an active stall fixed speed wind turbine was designed and simulated. Given paper describes mathematical model of a wind turbine, as well as proposes a control strategy for active stall fixed speed wind turbines. Simulation tool used for this paper in order to verify power controller as well as to see the performance of the wind turbine under three-phase short circuit is fault is DigSilent.
For simulations idealized model of wind farms was used, with one 2.3MW active stall fixed speed wind turbine. Simulation results proved that proposed power controller works correctly. However given power controller can be used only for study purpose, because a lot of improvement is needed before such power controller can be implemented in real life. Idealized model was also placed under three-phase short circuit and clearly it was observed

that given simulation model works correctly. Thus it is concluded that proposed simulation model is valid for investigation of turbines performance under the different grid faults.

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Bērziņš M., Ribickis L., Fiksēta ātruma vēja turbīnas vienkāršotā modeļa modelēšana.
Pēdējos gados vējfermu pieslēgšana elektriskajiem tīkliem ir būtiski pieaugusi. Tāpēc, pirms integrēt vējfermu elektriskajā sistēma ir nepieciešams izveidot dotās sistēmas simulācijas modeli, lai zinātu kā dažādi īsslēgumi elektriskajā sistēmā ietekmēs vējfermu.
Dotajā darbā tiek apskatīts vēja turbīnas matemātiskais modelis No dažādām pieejamām vēja turbīnu topoloģijām, šajā projektā tiek pētīta fiksēta ātruma vēja turbīna.
Lai novērotu vējfermas sniegumu, konkrētā sistēma ir projektēta un simulēta lietojot DIgSILENT Power Factory datora programmu. Simulācijas tika veiktas izmantojot idealizēto vēja turbīnas modeli. Dotā jaudas kontroliera

darbība tika verificēta. Trīsfāzu īsslēgumu iespaids uz vēja turbīnu tika pētīts izmantojot idealizēto modeli, kas satur tikai vienu vēja turbīnu.

Berzins M., Ribickis L., Design of a simplified active stall fixed speed wind turbine simulation model.

In recent years integration of wind farms into power systems has been rapidly developed. Thus before such integration takes place, it is necessary to create a simulation model of given wind farm in order to see how system will perform under different grid faults.

In this paper mathematical model of a wind turbine is explored. From the various wind turbine topologies available, this paper focuses on the performance of the active stall fixed speed wind turbine topology.

To observe the performance of a wind turbine, the wind turbine is designed and simulated using DIgSILENT Power Factory simulation software. The simulations are carried out on idealized model. The performance of a proposed power controller is verified. An idealized model of one wind turbine is used to see the effect of a three-phase fault on wind turbine dynamic performance.

Берзиньш М., Рибицкис Л., Моделирование фиксированной скорости в упрощенной модели ветровой турбины.

За последние годы интеграция ветровых ферм в электросети значительно возросла. В связи с этим появилась необходимость в создании экспериментальной модели ветровой фермы, с помощью которой, возможно отслеживать и изучить влияние коротких сетевых замыканий на ветровую ферму.

В данной работе рассмотрена математическая модель ветровой турбины. При наличии различных и доступных топологий ветровой турбины, в проекте особое внимание уделено фиксированной скорости ветровой турбины.

Чтобы наблюдать за работой ветровой турбины, в определенной системе была спроектирована и промоделирована с помощью программного обеспечения DIgSILENT Power Factory ветровая турбина. Эксперименты производились, используя модель идеализированной ветровой турбины. При этом была определена работа соответствующего контролера мощности. Влияние короткого трехфазного замыкания на ветровую турбину было изучено посредством идеализированной модели, содержащей только одну ветровую турбину.