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Professional paper

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EXAMPLE OF MATLAB/SIMULINK TOOL USAGE FOR EVALUATION OF WIND TURBINE OPERATION DURING VOLTAGE REGULATION AND REACTIVE POWER REGULATION

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Abstract: In this paper, the types of wind turbines are listed and described, with the emphasis on horizontal-axis wind turbines. The parts are explained in more detail, the criteria for the selection of the wind turbine generator and the methods of managing the wind turbine are defined. In the Matlab/Simulink programming environment, a model of an electric power network with a wind farm was created, and the characteristics of the operation of wind turbines under normal and fault conditions were presented.

Keywords: wind turbine, generator, Simulink

INTRODUCTION

A wind turbine is a rotating machine that first converts the kinetic energy of the wind into mechanical energy, and then uses it in an electric generator to produce electricity. Wind turbines with a vertical axis of rotation and wind turbines with a horizontal axis of rotation are distinguished according to their structural forms.

The two primary types of wind turbines with a vertical axis of rotation are derived from the Darrieus and Savonius turbines. Darrieus turbines are based on aerodynamic lift, so they can use both drag force and lift force, and as a result they have relatively higher efficiency, but they also require higher wind speeds to start working. This is why these turbines are not popular in low wind conditions [1]. Significant characteristics of the Savonius wind turbine based on aerodynamic resistance are the ability to self-start as well as lower starting speeds, but the impossibility of exploiting lift forces, i.e., unsatisfactory aerodynamic efficiency, makes them unsuitable for most applications [2].

Even if they require a mechanism to guide the blades, wind turbines with a horizontal axis of rotation, in the version with three blades, are more popular than others due to their various advantages and are therefore the subject of research in this paper. The lift force is used to create a driving torque that causes rotation [3].

The dominant technology today is wind turbines with three blades, although versions with fewer and more blades are possible. A smaller number of blades requires an additional increase in speed, which leads to an increase in noise, for the same amount of energy produced. A larger number of blades ensures a lower rotation speed, and therefore lower efficiency, so wind turbines with three blades are the best solution.

The task of this paper is the creation of a model of the power system with a wind farm and the implementation of simulations with a graphical representation of the characteristics of the operation of wind turbines during the transition processes that may occur during their operation. In order to achieve these goals, it is necessary to know the parts of the wind turbine, the reasons and method of selecting individual parts, especially the generator, as well as the ways of managing the wind turbine. Therefore, the mechanical and electrical parts of the wind turbine are described in the paper, and the emphasis is placed on the electrical parts, especially on the generator, the various versions of which are described in detail. The modes of operation of wind turbines are also described, i.e., operation with constant speed and operation with variable speed, and the selection of wind turbine generators according to the speed of rotation is defined.

After that, in the Matlab/Simulink programming environment, a scheme was created and simulations of the operation of wind turbines with variable rotation speed, equipped with double-fed induction generators, were carried out. Simulations were carried out of the operation of wind turbines with voltage regulation and with reactive power regulation under normal operating conditions and with the occurrence of a short circuit in the network. Depending on the type of regulation, the power output characteristics of

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the wind turbines as well as bus voltages are shown, and it is defined when the wind turbines will continue to operate in the event of a short circuit in the network, and when they will be turned off.

1. WIND TURBINE COMPONTENTS

In the previous part, the versions of wind turbines according to the axis of rotation were presented, and it is clearly visible that wind turbines with a horizontal axis of rotation, in the version with three blades, dominate the market due to their efficiency and practicality. In the following, the main parts of this type of wind turbine will be defined, which can be divided into mechanical and electrical components, whereby each of these categories can be further divided into primary and secondary components. Every wind turbine has primary components (Table I) and would not be able to work without them, while secondary components depend on the type of wind turbine, so the wind turbine may or may not have them.

Table I: Wind turbine components

WIND TURBINE COMPONENTS		
Mechanical compontents	Primary components	Foundation, tower, nacelle, rotor
	Secondary components	Gearbox, break
Electrical compontents	Primary components	Generator, transformer
	Secondary components	Anemometer

1.1. Mechanical components

Due to its weight and exposure to strong wind forces, the wind turbine must have a sufficiently strong foundation. Under each wind turbine there is a large and heavy concrete foundation of sufficient mass to hold the wind turbine in place and prevent it from turning, tilting, swaying, etc.

The tower keeps the other parts in the air (Figure 1), so it must be able to withstand the weight of the components it holds and the wind forces that disrupt its operation. The trend in wind turbines is to increase their size in order to increase energy efficiency [4]. In addition to the gravitational loads of the wind turbine, i.e., the own weight of the structural elements, which affect the tower, there is also the rotating load of the blades and the wind pressure load [5].

The rotor represents the rotating mechanical parts of the wind turbine, and consists of three blades and a hub. The

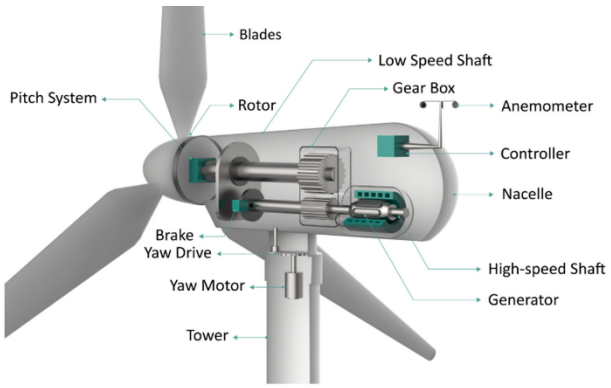


Figure 1: Wind turbine components

parts of the wind turbine that collect wind energy are the blades, and the wind forces in the three blades create a torque on the shaft and turn it. The rotor of the wind turbine not only greatly affects the total costs, but also has a direct impact on energy production and mechanical loads. Therefore, the optimization of the rotor design has a great influence on the operation of wind turbines [6].

The nacelle, which is located between the rotor and the tower, does not rotate with the rotor, but rotates in relation to the tower. In order for the wind turbine to be directed into the wind, a jawing system is needed. The main shaft, which connects the rotor and the generator, transfers mechanical energy to the generator, which then converts it into electrical energy. In most cases, with wind turbines, this transmission is not direct, but there is a transmission between the low-speed shaft, i.e., the rotor output, and the high-speed shaft, i.e., the generator input. Therefore, components and equipment such as gearbox, generators, heating and cooling systems, brakes, motors and gears for rotation, systems for measuring wind speed and direction and other equipment necessary for the operation of wind turbines are located inside the nacelle.

In the case of wind turbines, the speed of rotation must match the speed of the generator. In order to achieve this, if it is not a direct drive technology, a wind turbine gearbox is needed. Wind turbines represent an exceptional case where the speed of rotation of the driving element is lower than the speed of the generator. The transmission, therefore, must increase the speed of the rotor to become suitable for the generator. Most often, the speed of generators is between 900 and 1800 revolutions per minute, while rotors have a speed in the range of 12 to 24 revolutions per minute, which means that the transmission of the wind turbine must therefore increase the speed by a ratio of about 75 times.

There are frequent situations when the wind turbine needs to be stopped, such as certain maintenance work, extremely strong wind, failure of certain components and so on. The pitch system is responsible for keeping the

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wind turbine operating within normal speed conditions, but it also works as the primary brake system by pitching the blades out of the wind. However, in certain cases, the wind turbine is required to have a mechanical brake that will prevent the rotor from turning.

1.2. Electrical components

The main electrical components of the wind turbine, as already mentioned, are the generator and the transformer. Also, the wind turbine has numerous other electrical components needed for various functions, such as motors, sensors, heaters, lighting, and so on. Also, the management system of modern wind turbines uses various electrical, electromechanical and electronic equipment.

1.2.1. Generator

An electric generator or simply a generator (Figure 2) converts mechanical energy into electricity. Versions in different sizes are possible, and the size of the generator is proportional to the power. In general, a generator is actually an electrical machine that has the same structure as a motor, and each generator can work as a motor, and the motor as a generator. However, for practical and constructive reasons, electric machines are designed either as a generator or as a motor, and less often it can work as both a generator and a motor.



Figure 2: A typical wind turbine generator

There are two types of generators used in wind turbines: synchronous generators and asynchronous generators, which are also known as induction generators. The main difference in operation between a synchronous generator and an induction generator is that a synchronous generator must have a constant speed. In all power plants that operate on hydro, nuclear and fossil fuel energy, only synchronous generators are used. Wind turbines are the only exception. Synchronous generators work in sync with the frequency of the power system, and they can be connected to the grid using converters that enable synchronous generators to work at different speeds. Induction generators produce electricity when the rotation speed is higher than that of synchronous generators.

1.2.2. Transformer

The wind turbine transformer is a transformer (Figure 3) that increases the output voltage and connects the wind turbine to the wind farm connection. It is performed as a three-phase dry or oil transformer, and it can be located at the bottom of the wind turbine tower (inside or outside) or inside the wind turbine nacelle.



Figure 3: The transformer located inside the tower of the wind turbine

Currently, conventional distribution transformers are very often used as wind turbine transformers, where transformer manufacturers and operators are often not familiar with the limitations of wind turbine transformers and as a result, the use of conventional distribution transformers as wind turbine transformers reduces the level of reliability [7]. The main source of wind turbine transformer challenges is the variable nature of the wind, which causes the transformer to frequently operate from low load to high load (several times a day) causing high thermal and mechanical stresses. In addition, these constant changes require the transformer to be repeatedly connected and disconnected resulting in repetitive overvoltage transients that impose dielectric stress and repetitive inrush currents that cause the aforementioned mechanical and thermal stress on the transformer. Therefore, the wind turbine transformer is under greater electrical, mechanical and thermal stress than a conventional distribution transformer, although a wind turbine transformer is expected to be much more reliable and robust than a conventional distribution transformer. The first reason is that the transformer is placed near wind turbines, i.e., near a very expensive structure, and therefore it should have a higher fire safety characteristic considering the oil in the transformer [8]. Second, the electricity production of the wind turbine should not be interrupted by the failure of its transformer, which is static equipment with less risk and lower cost. In addition, any repair or replacement of the transformer in case of failure, due to the most remote location of wind turbines, would be expensive. Therefore, the design of the wind turbine

transformer should have a high level of reliability because its failure would lead to large economic losses [9].

2. SELECTION OF WIND TURBINE GENERATOR

In general, a wind turbine can have any type of three-phase generator. The need for grid-compatible electricity can be provided by connecting frequency converters, regardless of whether the generator provides variable frequency alternating or direct current. The most popular electric machines in the wind industry are synchronous and asynchronous machines and their variants [10].

The system for generating electricity from the wind can work at a constant or variable speed, depending on the configuration of the wind turbine [11]. Constant speed operation ensures a simple electrical system, greater reliability, lower cost and no need for a power electronics system. On the other hand, variable speed operation increases energy efficiency, reduces torque oscillations in the drive unit, reduces the resulting forces on the drive unit, and provides better quality electricity.

2.1. Induction generator

The principle of operation of an induction generator is quite different from the principle of operation of a synchronous generator, although both operate on the basis of a rotating magnetic field. The difference is in the way of inducing the magnetic field of the rotor. In this sense, the structure of the stator is the same, and only the rotors differ from each other. This means that, in principle, the rotors of two similar (by size and power) synchronous and induction generators can be replaced. In general, an induction generator has more advantages compared to conventional direct current and synchronous generators, such as lower cost, robustness, possible brushless design (in a cage structure), smaller dimensions, easy maintenance, self-protection against strong overloads and short circuits, better dynamic response and the ability to generate power at different speeds, but requires the reactive power required for the magnetizing current [12].

If the rotor rotates at a speed greater than the synchronous speed, the relative motion (slip) between the rotor and the rotating field of the stator induces an electric field, which causes a current in the rotor windings. The interaction of the associated rotor magnetic field with the stator field results in a torque acting on the rotor. The rotor of an induction generator can be made as a cage rotor or as a wound rotor, so there are Squirrel Cage Induction Generator and Wound Rotor Induction Generator.

2.1.1. Wound Rotor Induction Generator - Doubly fed induction generator

In the case of a wound rotor induction generator, it is possible to control the electrical characteristics of the rotor externally, and thus the rotor voltage. The windings of the wound rotor can be connected externally via slip rings and brushes or by power electronics, which may or may not require slip rings and brushes.

Currently, the world market is dominated by variable speed wind turbine technology based on induction generator with double feed [13]. This is due to many advantages over constant speed induction generators or variable speed synchronous generators with full-range electronic power converters, including variable speed operation for maximum power tracking, separate active and reactive power management, lower converter cost, and reduced power loss [14]. Better dynamic performance in comparison to other types of wind turbines comes from the fact that they have the ability to perform dynamically at subsynchronous and supersynchronous speeds and the ability to generate a constant frequency of active power [15]. Also, the advantage of this technology is that it requires a power electronics converter with reduced capacity (30% of full capacity) as a converter connected to the rotor circuit instead of the stator circuit. However, the main disadvantage of this type of wind turbine is the need for a gearbox that requires regular maintenance and suffers from occasional errors and breakdowns [16].

As shown in Figure 4, a doubly fed induction generator is a wound-rotor induction generator in which the stator windings are directly connected to a three-phase constant-frequency network, while the rotor windings are mounted on a bidirectional IGBT converter with a voltage source. “Doubly fed” means that the voltage to the stator is supplied from the grid, while the voltage to the rotor is induced by the electronic power converter. The converter actually compensates for the difference between the resulting mechanical and electrical frequency by injecting a variable frequency current into the rotor.

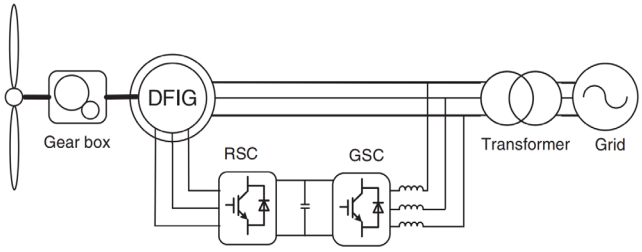


Figure 4: Configuration of variable speed system with doubly fed induction generator

As shown, the stator of the generator is directly connected to the grid. The rotor side of the generator is controlled by converters called rotor side converter (RSC) and grid side converter (GSC). If the rotor current is controlled with the help of a converter on the rotor side, it is possible to control the output power, torque and rotor speed of the generator at synchronous speed. Considering that the rated power of the inverter is usually only 30% of the rated power of the generator, this concept is attractive in terms of costs. The main disadvantage of this concept

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is its sensitivity to mains voltage disturbances, such as mains faults, mains harmonic distortions and unbalance.

3. WIND FARM MODEL IN SIMULINK

As already mentioned, the electricity produced by each wind turbine, in order to be transmitted to the large electricity grid, is usually centralized in wind farms. The introduction of a system for the production of electricity from wind energy will significantly affect the power system and disturbances in the power system, such as faults in the network and voltage imbalances, and the distortions created in the network will have a great impact on the operation of wind turbines, especially on wind turbines that use doubly fed induction generator. Therefore, it is necessary to investigate changes in the output parameters of wind turbines under conditions of sudden wind changes during normal occurrences in the network and when a short circuit occurs.

In order to achieve these goals, a scheme was created (Figure 5) and simulations of wind turbine operation were carried out in the Matlab/Simulink programming environment. Six wind turbines were used, which make up one wind farm, with variable rotation speed equipped with doubly fed induction generators. The nominal output power of each wind turbine is 1.5 MW, and the total power of the wind farm is 6×1.5 MW. The connection of this wind farm to the grid, as shown in the following picture, was achieved with a 0.69/20 kV transformer, and the entire system consists of a total of three voltage levels, namely 690 V, 20 kV and 110 kV.

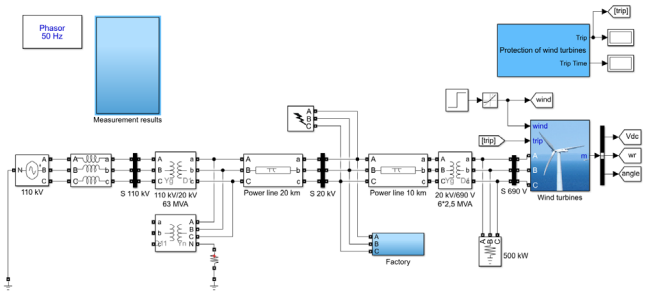


Figure 5: Power grid model with wind farm

The wind farm exports electricity to the 110 kV network via the 20 kV distribution system. Therefore, in relation to the standard 110/35/10(20) kV transformer stations, the transition from the transmission network to the 20 kV voltage level was carried out and thus one transformation was reduced. By eliminating one transformation, instead of the four-voltage distribution system 110/35/10/0.4 kV, in addition to the three-voltage 110/20/0.4 kV, it is possible to reduce electricity losses, reduce the space occupied by a larger number of locations and routes of transmission lines and cables, and facilitate plant maintenance. In the 20 kV network, a significant consumer, a factory, with a squirrel cage induction motor with a power of 1.68 MW and a power factor of 0.93, is supplied with its own 20/2.3 kV transformer station. Significant consumers of reactive power in this model of the power system are the induction motor, transformers and lines.

According to the already presented model of the electric power system with a wind farm, simulations of the operation of wind turbines with voltage regulation and reactive power regulation were carried out, the way of reaction of wind turbines to changes in wind speed during normal operation and during a single phase-to-ground fault short circuit at a voltage level of 20 kV was investigated. The results show that the change in wind speed in normal operation, as well as in the event of short circuits, affects the operation of the wind farm differently depending on the method of regulation.

All the following simulations are observed through the operation of the system for 50 seconds, the initial wind speed is set to 8 m/s, and then at time t = 5 s, the wind speed is suddenly increased to 14 m/s. By starting the simulation with changes in the wind speed, the turbine speed, the pitch angle, the active and reactive power and bus voltages are monitored.

3.1. Voltage regulation

First, a simulation of the operation of the wind turbine with voltage regulation was carried out, where the voltage of the reference bus, i.e., the bus to which the wind turbine is connected, is to be maintained at a value of 1 pu, i.e., 690 V, and the characteristics of the rotor of the wind turbine are shown in Figure 6 to Figure 8.

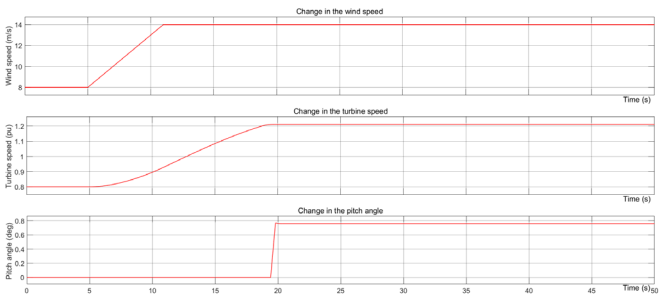


Figure 6: Changes in the turbine speed and the pitch angle with a change in the wind speed (voltage regulation)

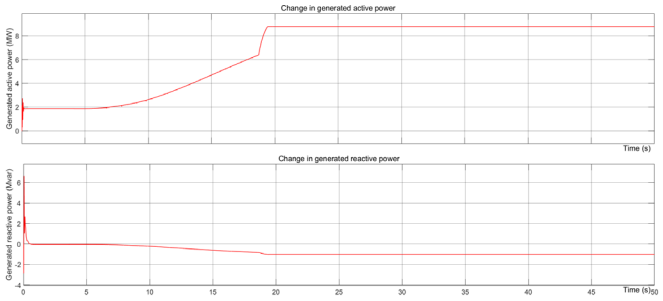


Figure 7: Changes in generated power with a change in the wind speed (voltage regulation)

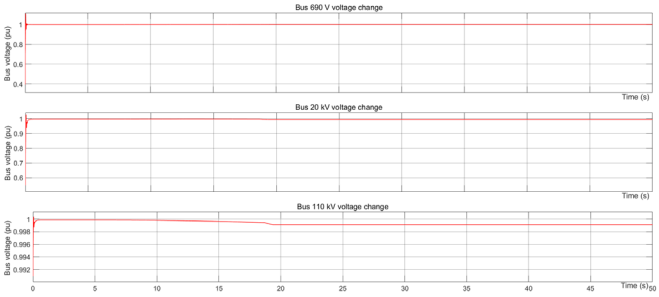


Figure 8: Bus voltage changes (voltage regulation)

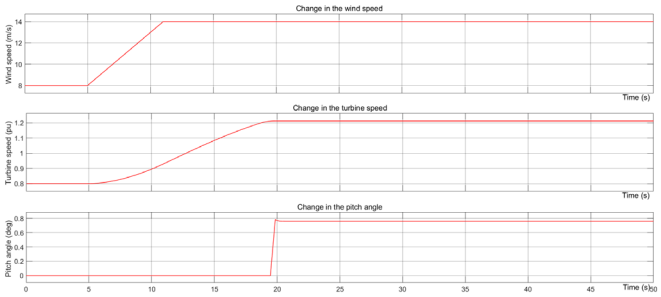


Figure 9: Changes in the turbine speed and the pitch angle with a change in the wind speed (reactive power regulation)

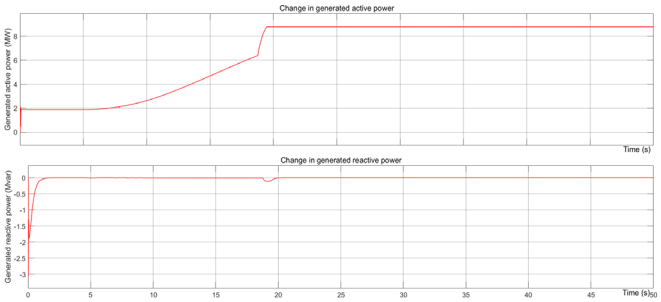


Figure 10: Changes in generated power with a change in the wind speed (reactive power regulation)

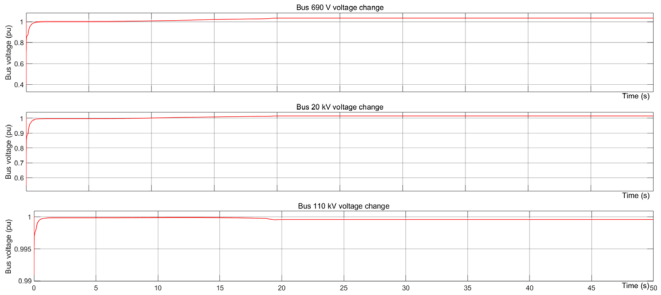


Figure 11: Bus voltage changes (reactive power regulation)

Along with the increase in wind speed, there is also an increase in the rotation speed of the turbine, and therefore the generated active power increases until it reaches its approximately nominal value of 9 MW. During this time, the rotor speed will increase from 0.8 pu to 1.21 pu. Initially, the blades do not need to be rotated, then the blade angle is increased from 0 degrees to 0.76 degrees to limit the power output. Considering that it is voltage regulation, the bus voltage of 690 V is approximately 1 pu, and in order to achieve this, the wind turbine needs to generate a certain amount of reactive power. For this purpose, at nominal power, the wind turbines generates Q = -0.86 Mvar, that is, it absorbs Q = 0.86 Mvar from the network.

Unlike active power, reactive power cannot be efficiently transmitted over long distances, so it is regulated locally in order to support the transmission of active power and maintain the appropriate quality of voltage at hubs. However, the unmanageable withdrawal of reactive power from the grid by the wind farm can cause a decrease in the amount of voltage in the surrounding part of the grid.

The centralized regulator of the wind power plant is the one that controls the generated, i.e., absorbed active and reactive power into the network towards the bus in accordance with the network rules of the electric power system. In order to achieve centralized control, efficient communication between the centralized wind farm controller and each of the wind turbines is required at all times. So, while each wind turbine reports to the centralized controller of the wind farm its active and reactive power that it can deliver at any time, during this time the centralized controller of the wind farm gives each of the wind turbines references of active and reactive power.

3.2. Reactive power regulation

In the next simulation (Figure 9 to Figure 11), the operation of wind turbines with reactive power regulation is shown, during which the wind turbine should neither generate nor absorb reactive power from the network.

Like the previous simulations, even now, with the regulation of reactive power, there is no difference in the operation of the wind turbine and the angle of rotation of the blades. The wind farm generates again approximately 9 MW of power in the same way with a change in wind speed as with voltage regulation. The difference is that now the wind farm does not generate, that is, it does not absorb reactive power from the network. As a result, on the 690 V bus, to which the wind turbines are connected, the voltage increases, and at the nominal output power of the wind power plant it is approximately 1.032 pu.

An increase in voltage is also visible on the 20 kV and 110 kV busbars, due to more reactive power in the network compared to the previous case. In general, the consumption of reactive power reduces the voltage levels in the system hubs, while its production increases them. Wind farms, like this one, are often installed in remote areas from the rest of the grid, so the flows of reactive power, which cannot be efficiently transmitted over long distances, will lead to power losses and low voltages through long and often radial lines, therefore the ability to provide services is required from wind farms reactive power regulation. The unmanageable production of

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reactive power of the wind power plant will additionally affect the increase of local voltages.

3.3. Voltage regulation with short circuit

In order to show the characteristics and transient processes that can occur in the wind power plant, simulations of the operation of wind turbines with a single phase-to-ground fault short circuit were carried out (Figure 12 to Figure 14). A short circuit occurs in the fifth second of the simulation with a duration of 9/50 seconds, on a 20 kV line, next to a 20 kV busbar. As a result of short circuits in the entire network, there is a decrease in voltage, which has a particularly unfavourable effect on consumers.

Important data in conducting simulations refers to the protection, which, under certain conditions, will give an order to stop the operation of the wind turbine generator. The stop is programmed for a voltage drop greater than 25% and its duration longer than 0.1 second. Simulations of the operation of wind turbines in the event of a single phase-to-ground fault short circuit on the 20 kV line, with voltage regulation, are shown in the following graphs.

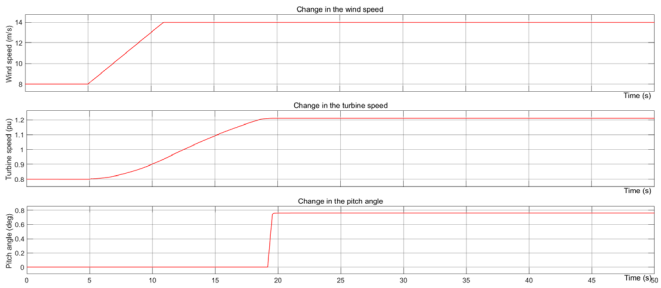


Figure 12: Changes in the turbine speed and the pitch angle with a change in the wind speed (voltage regulation with short circuit)

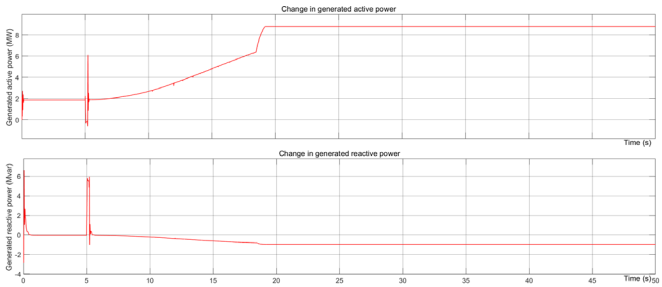


Figure 13: Changes in generated power with a change in the wind speed (voltage regulation with short circuit)

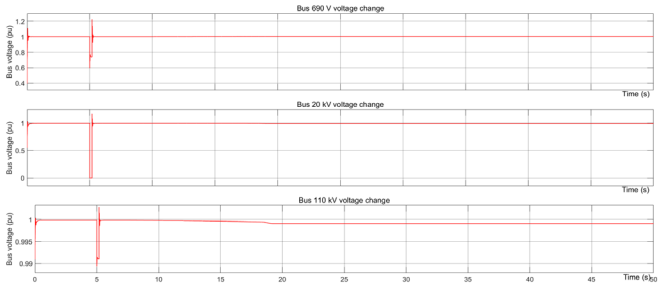


Figure 14: Bus voltage changes (voltage regulation with short circuit)

Again, there are no changes related to the operation of the wind turbine and the angle of rotation of the blades. Disruption of the output active power, as well as the absorbed reactive power, occurs during the duration of the short circuit, after which the output power of the wind power plant increases according to the nominal value. Also, voltage disturbances on the buses occur during the duration of the short circuit, after which the voltages assume a constant value. At the moment of the short circuit, the voltage of the affected phase drops by 38%, but for a duration shorter than 0.1 second, so the wind turbines continue to work, given that the voltage drop of the affected phase during the rest of the short circuit time is 24%, i.e., it is 0.76 pu, which is above the undervoltage protection threshold. Therefore, thanks to the absorbed reactive power, the wind farm remains in operation.

3.4. Reactive power regulation with short circuit

The simulations were carried out again, this time with reactive power regulation when a short circuit occurs. The simulation results are show in Figure 15 to Figure 17.

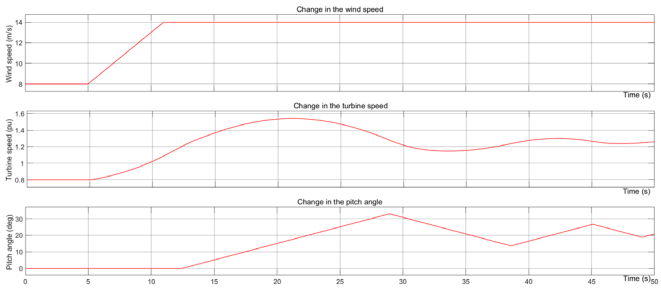


Figure 15: Changes in the turbine speed and the pitch angle with a change in the wind speed (reactive power regulation with short circuit)

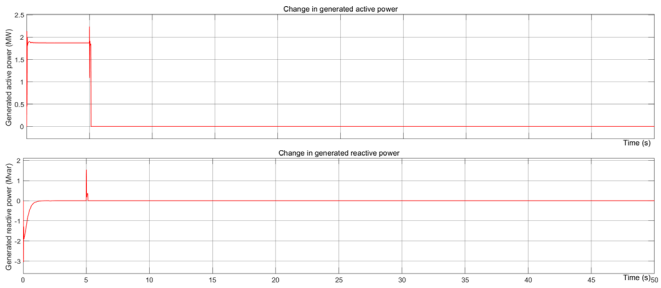


Figure 16: Changes in generated power with a change in the wind speed (reactive power regulation with short circuit)

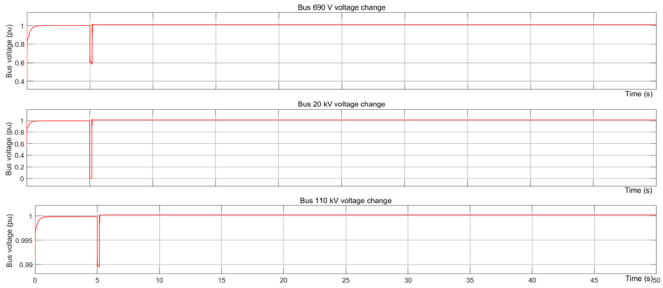


Figure 17: Bus voltage changes (reactive power regulation with short circuit)

In this case, during reactive power regulation, the bus voltage of 690 V drops by 40%, amounts to 0.6 *pu* in a period longer than 0.1 second, and there is a condition for stopping the operation of the wind turbine. The reason for the significant drop in voltage, along with the appearance of a short circuit, is the inability to absorb reactive power from the grid, because wind turbines operate under reactive power control. Consequently, by stopping the wind turbine, no active power is generated to the network, and with a high wind speed, the wind turbine cannot be stopped instantly, so with a constant change in the rotation angle of the blades, its speed slows down slightly. The reason for stopping the rotation of the rotor in this way stems from the fact that an additional increase in the rotation angle of the blades or maintenance at a large angle would lead to a greater mechanical load on the blades, and this could lead to damage or failure of the wind turbine during a long period of time under load.

4. CONCLUSION

By analysing the operation and obtained output characteristics of a variable speed wind turbine based on a doubly fed induction generator, it is possible to draw certain conclusions. With normal operating conditions and voltage regulation, wind turbines draw reactive power from the network in order to maintain the nominal voltage of the bus to which they are connected. In this way, the available thermal load of the connection lines for the transmission of the produced active power is reduced. By switching to reactive power regulation, the wind turbines no longer consume reactive power from the network, so there is an increase in the voltage on the bus since there is now more reactive power in the network. A higher amount of reactive power implies higher losses in the network, i.e., the flow of reactive power contributes to losses of active power in the system, therefore, in order to minimize losses, it is necessary to reduce the flows of reactive power by network elements. When a single phase-to-ground fault short circuit occurs in the network, there is a voltage drop, and the voltage drop with voltage regulation is significantly smaller, so that the wind turbines continue to work, compared to the regulation of reactive power, during which the wind turbines are turned off. Therefore, if the wind power plant actively regulates the amount of voltage on its connectors, then during transient failures this can significantly contribute to an easier and faster passage through the failure state. Therefore, regardless of the type of wind turbine, in accordance with its technical characteristics, in order to preserve the voltage quality, wind power plants are required to possess certain reactive power management capabilities. Along with automatic regulation of voltage and reactive power and the ability to pass through a fault condition, wind farms would also be enabled to participate in the reactive power market.

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