ISSN 1330-3651
UDC/UDK 621.311.245 : 621.316

INFLUENCE OF WIND POWER PLANTS ON POWER SYSTEM OPERATION – PART ONE: WIND POWER PLANT OPERATION AND NETWORK CONNECTION CRITERIA

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Subject review

For the purpose of a comprehensive review of power system operation with the connection of wind power plants, this review is presented in two articles. The first article presents the main concepts of wind power plants, technical possibilities of wind power plant operation and all requested criteria for connecting the wind power plant to the power system. In the second article the power quality after connecting wind power plant to the distribution network, energy losses in distribution network with connected wind power plant and feasibility and development of electrical energy production with wind power plants in the power system of the Republic Croatia are considered.

Keywords: *connection criteria, distribution network losses, power quality, power system, wind power plant*

Utjecaj vjetroelektrana na rad elektroenergetskog sustava – 1. dio: Pogon vjetroelektrana i kriteriji priključenja na mrežu

Pregledni rad

Zbog sveobuhvatnosti pregleda rada elektroenergetskog sustava s priključenim vjetroelektranama pregled se prikazuje u dva članka. U prvom članku prikazani su osnovni pojmovi o vjetroelektranama, tehničke mogućnosti pogona vjetroelektrana i svi zahtijevani kriteriji priključenja vjetroelektrane na elektroenergetski sustav. U drugom članku razmatra se kvaliteta električne energije nakon priključenja vjetroelektrane na distribucijsku mrežu, gubici energije u distribucijskoj mreži s priključenom vjetroelektranom, te mogućnost proizvodnje i razvoj proizvodnje električne energije s vjetroelektranama u elektroenergetskom sustavu Republike Hrvatske.

Ključne riječi: *elektroenergetski sustav, gubici u distribucijskoj mreži, kriteriji priključenja, kvaliteta energije, vjetroelektrana*

1 Introduction
Uvod

Considering the fact that the construction of wind power plants is constantly increasing in the Republic of Croatia, which is understandable regarding the increasing trend of constructing wind power plants in the world, our analysis of the power system operation with the connection of wind power plants requires a presentation of the first two constructed wind power plants in the Republic of Croatia and their main characteristics.

In 2004, the first wind power plant was installed at the Ravne site on the island of Pag [1]. The system consists of seven Vestas V52-850kW [2] wind turbines, which means the total installed power of 5,95 MW. The measurement of the average annual wind speed shows that the wind speed lies between 6 and 6,5 m/s. Furthermore, measurements have shown that Pag has 1 600 windy (operation) hours per year (from the possible 8 760 hours per year). The wind power plant is expected to annually produce 15 GWh. The tower height is 49 m, while the rotor diameter is 52 m (Fig. 1)[3].

In 2006, the second wind power plant was installed at the Trtar-Krtolin site near Šibenik. 14 wind turbines of the company WPD International GmbH i Enersys Gesellschaft für regenerative Energien mbH [4] have been installed with the nominal power of 800 kW, i.e. total installed power of 11,2 MW. Analysis has shown that Trt has about 2 000 windy (operation) hours per year. It is important to mention that the electricity generated by both wind power plants is purchased by HEP under the agreement made for the next 15 years.

After the installation of the two wind power plants, the trend to construct other wind power plants has continued on different locations. It is estimated that currently there are more than 50 wind power plants in the Republic of Croatia [3] in different phases of construction.

Figure 1 *Wind power plant Ravne on the island of Pag*
Slika 1. *Vjetroelektrana Ravne na Pagu*

2 Operation of the wind power plant
Pogon vjetroelektrane

From the engineering point of view, the most important issue to be solved is how to connect the electricity generated by wind power plants to the existing power system of the Republic of Croatia. Furthermore, the question of output values, i.e. voltage, frequency, active and reactive power has to be solved. Therefore, it is necessary to consider the operation of the first wind power plant Ravne on the Island of Pag which consists of 7 Vestas V52-850 kW wind turbines [1]. The wind turbines in question use an asynchronous doubly fed induction generator with variable speed ranging from 0,6 pu to 1,2 pu. Bearing in mind that the rotation speed is the key factor for wind power plant operation [6, 7], it is necessary to explain the classification of wind power plants which fall into two groups:

1) with constant rotation speed
2) with variable rotation speed.

The generator in wind power plants with constant rotation speed is directly connected to the power system. The frequency of the system determines the generator rotational speed, and hence the rotor speed. Gearbox increases the speed of the shaft thus transforming low rotor rotational speed to high generator rotational speed. The generator speed depends on the number of pole pairs and the network frequency.

The generator in wind power plants with variable speed is connected to the network either via an inverter system based on power electronics or via excitation windings fed from the inverter system of the external frequency. The speed of the rotating magnetic field of the generator, and thus the rotor, is separated from the frequency system. The rotor has a variable speed and adapts to wind speed.

Nowadays, the application of wind power plants having variable speed wind turbines is on the increase, and the size of the wind turbines in question is constantly growing. The main goal of the variable speed wind turbines is to maximize utilization of available wind energy. The variable speed drive can be achieved by using appropriate combinations of generator and power electronic converter.

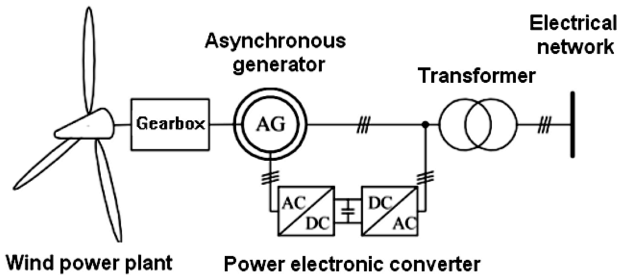

Figure 2 *Doubly fed induction generator - DFIG*
Slika 2. *Dvostrano napajani indukcijski generator - DFIG*

The advantages of asynchronous DFIG based wind power plants are as follows:

- a relatively wide area of change of rotor speed ranging from 50 % to 130 % of synchronous speed
- low power of the semiconductor converter (up to 30 % of the generator nominal power)
- total regulation of active and reactive power output of the generator.

The asynchronous DFIG must have contact rings and brushes which represents the main disadvantage of this type of generator [8]. The electric power of the asynchronous DFIG injected into the power system depends on the wind speed which can be seen in Fig. 3 for any variable speed wind power plant [9].

The upper part of the curve lying between the nominal wind speed and wind speed output presented for the asynchronous DFIG based wind power plants utilizing variable speed technology, can be maintained linear according to equal amount of nominal generator power. At wind speeds below the rated speed, the pitch control enables us to obtain larger output power compared with the basic type of constant speed wind turbine and constant frequency. Moreover, aerodynamic efficiency is optimized through the speed control system for DFIG wind turbines by exploiting the highest available power at every wind speed.

Figure 4 shows the power of DFIG which depends on

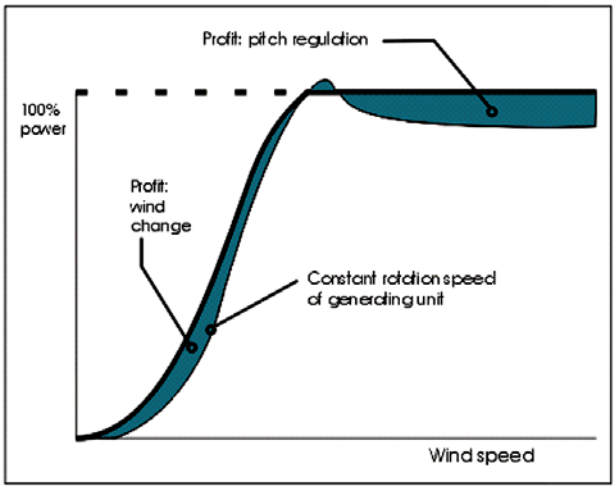

Figure 3 *Power of variable speed wind power plant depending on wind speed*
Slika 3. *Snaga vjetroelektrane s promjenjivom brzinom vrtnje u ovisnosti o brzini vjetra*

the wind turbine speed. The bold line connects the power curve relative to optimal operation points with regard to different wind speeds. In low wind-speed conditions, power curve values are monitored in order to determine the maximum energy output of wind turbines. At higher wind speeds, operation limitations regarding mechanical speed, rated torque and system power occur. Then, the pitch regulation system is employed to set the generator momentum to nominal value.

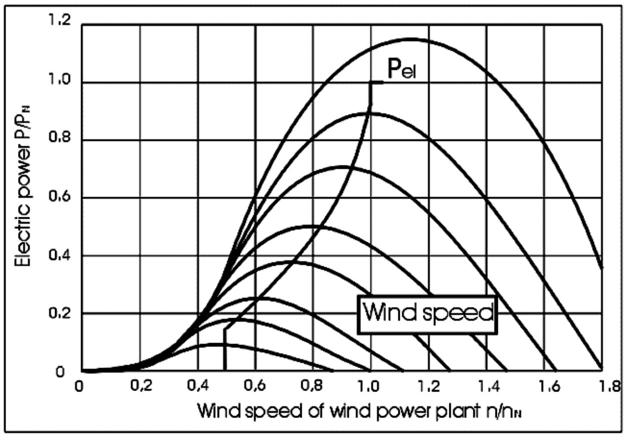

Figure 4 *Power of DFIG depending on rotation speed of wind turbine*
Slika 4. *Snaga DFIG u ovisnosti o brzini vrtnje vjetroturbine*

The wind power plant can operate at four different types of wind speed changes:

1) Linear change of wind speed
2) Noise change of wind speed
3) Gust change of wind speed
4) Continuous change of wind speed.

This is presented in the following sections [9].

2.1 Linear change of wind speed
Linearna promjena brzine vjetra

The linear change of wind speed, which is shown in Fig. 5, enables the wind turbine to inject power into a network from minimum to maximum power of the wind turbine [9]. In the dynamic model of an asynchronous DFIG, reactive power Q_G control systems are applied.

Reactive power regulation of generator stator is carried out by controlling the power factor between 0,98 cap and 0,95 ind. The wind turbine speed can also be controlled through the voltage in generator rotor (Fig. 7). Regarding the voltage in the connection point of the wind power plant, it is important to mention that the voltage in the connection point depends both on the reactive power of the wind power plant and the type of connection to the distribution system, i.e. place of connection.

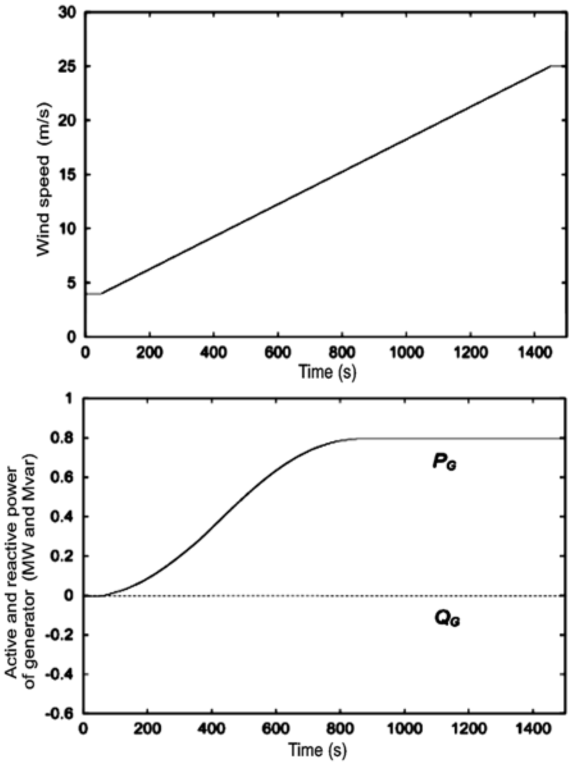

Figure 5 *Linear change of wind speed and the influence on active and reactive power of DFIG*
Slika 5. *Linearna promjena brzine vjetra i utjecaj na djelatnu i jalovu snagu DFIG*

Accordingly, there are two possibilities to connect the wind power plant Ravne on the island of Pag to the distribution system, and these are connection point 1 – node TS Kiršina 10 kV and connection point 2 – node Čve 10 kV (Fig. 7).

In the inductive operation of the wind power plant, the voltage increase in the connection point is considerably higher if compared with capacitive operation. Discrepancies due to different types of connections are significant. Moreover, voltage deviations/changes in the connection point are present in the case when the wind power plant is connected to the node Čve which lets us conclude that the connection point 2 has lower voltage stiffness than connection point 1.

2.2 Noise change of wind power
Šumna promjena brzine vjetra

Noise change of wind speed (Fig. 8) illustrates capability of the DFIG based wind power plant to regulate the reactive power exchange with the network.

Noise change of wind speed causes fluctuations of output power which can be seen in Fig. 9.

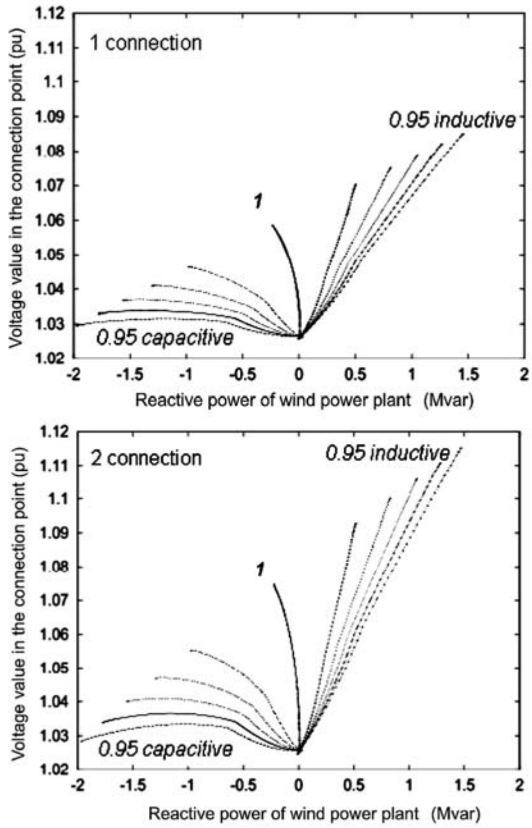

Figure 6 *Voltage in a connection point depending on reactive power of the wind power plant (connection 1-Kiršina, connection 2-Čve) (voltage/reactive power)*
Slika 6. *Napon u čvorištu priključenja u ovisnosti o jalovoj snazi vjetroelektrane (priključak 1.- Kiršina, priključak 2.- Čve)*

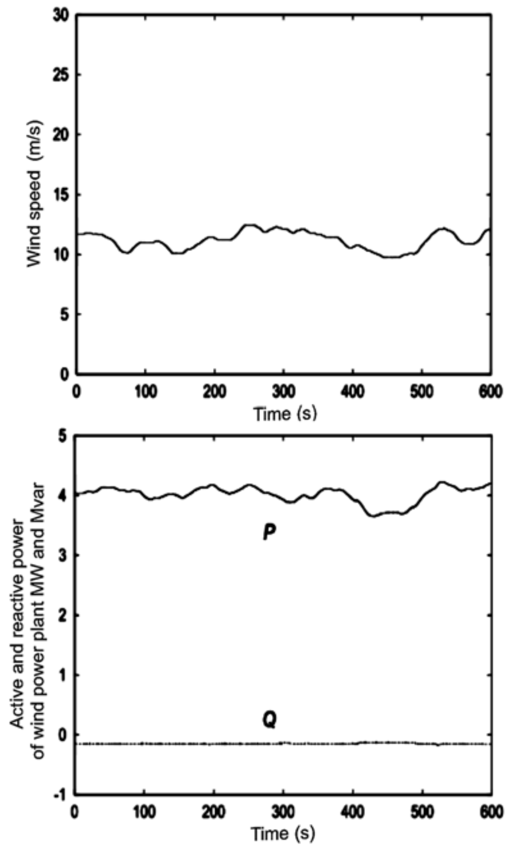

Figure *7 Noise change of wind speed and influence on active and reactive power of wind power plant*
Slika 7. *Šumna promjena brzine vjetra i utjecaj na djelatnu i jalovu snagu vjetroelektrane*

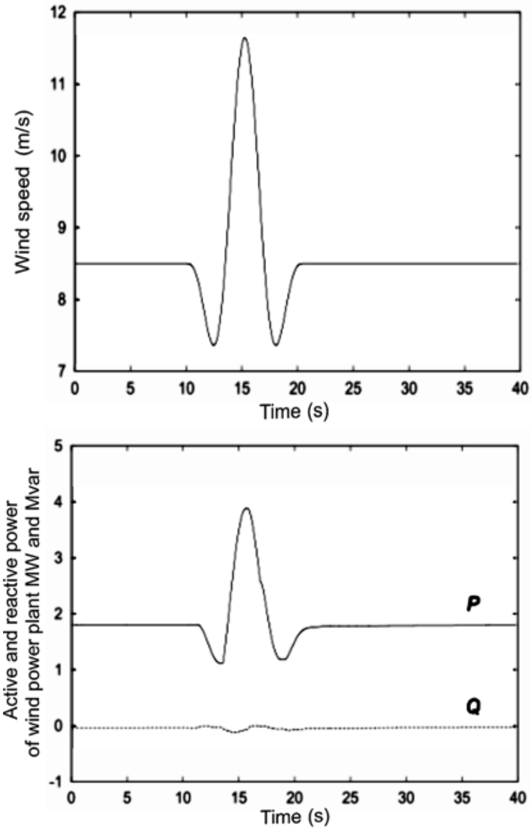

Figure 8 Gust change of the wind speed and the influence on active and reactive power of the wind power plant
Slika 8. Udarna promjena brzine vjetra i utjecaj na djelatnu i jalovu snagu vjetroelektrane

The active power generated by the wind power plant depends on wind speed changes, while reactive power is kept at the initial value by regulating the unity power factor of generator stator through rotor voltage V_{rd}.

2.3 Gust change of wind power
Udarna promjena brzine vjetra

At gust change of wind speed, fast fluctuations of active P and reactive power Q occur (Fig. 8). At the initial and final value of wind speed of 8,5 m/s, the wind power plant injects approximately 1,8 MW of active power while the reactive power is totally compensated. In variable wind speed conditions, the wind turbine generates variable reactive power ranging from 1,1 MW to 4,0 MW. Furthermore, due to the applied control system the reactive power generated by DFIG based wind power plants is kept at approximately zero value during gust change of wind speed.

Output power fluctuations due to gust change of wind speed cause the occurrence of voltage fluctuations. The reference and real rotation speed of the wind turbine ($n\omega_T^{REF}$ and $n\omega_T$) vary between 0,8 pu and 1,28 pu (Fig. 9).

2.4 Continuous change of wind speed
Stalna promjena brzine vrtnje

The total amount of active P and reactive power Q were measured in the in-feed point at the 10 kV side during 48-hour period (Fig. 10) depending on constant and continuous variable wind speed.

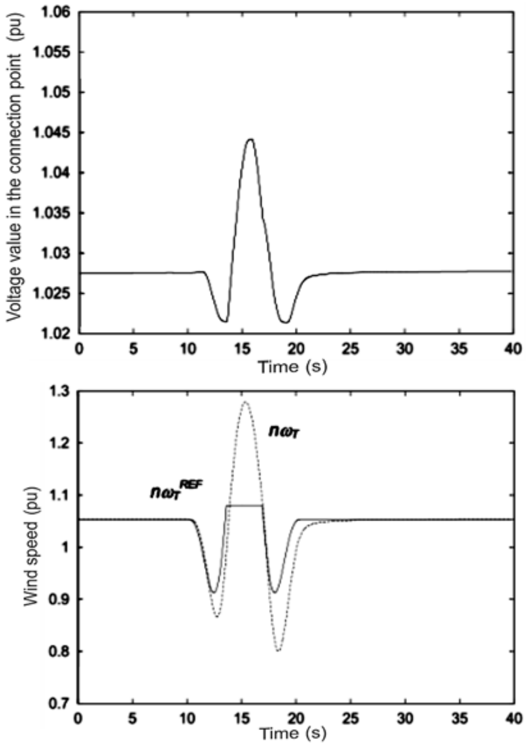

Figure 9 Influence of reference and real speed of the WPP on voltage value in a connection point
Slika 9. Utjecaj referentne i stvarne brzine vrtnje VE na iznos napona u čvorištu priključenja

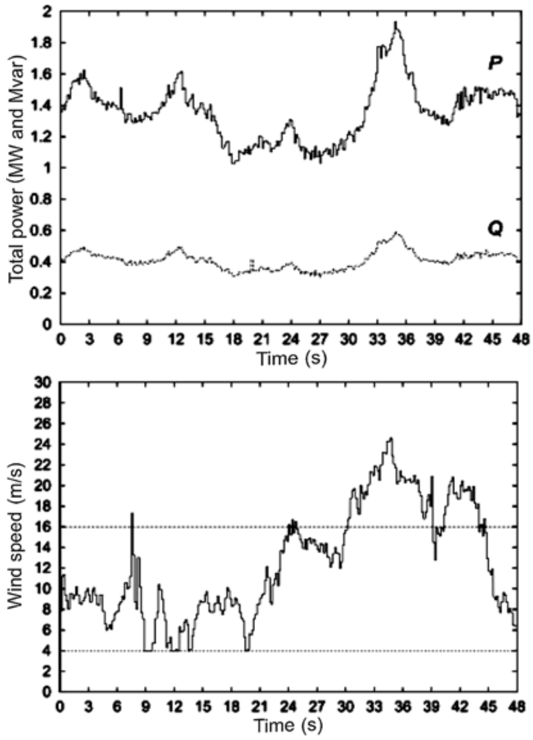

Figure 10 Total active and reactive power depending on constant and continuous variable wind speed
Slika 10. Ukupna djelatna i jalova snaga u ovisnosti o stalnoj i stalno promjenjivoj brzini vjetra

The influence of two constant speeds (4 and 16 m/s) and one continuous variable speed (4 - 25 m/s) have been analysed. The defined wind speeds cause variability of active and reactive power that the wind power plant injects into the 10 kV network (Fig. 11). The wind power plant injects a variable amount of active power into the network, while the reactive power of the asynchronous generator is compensated through a continuous control system. The reference value – rotation speed of the wind turbine ($n\omega_T^{REF}$) is variable and depends on the wind speed.

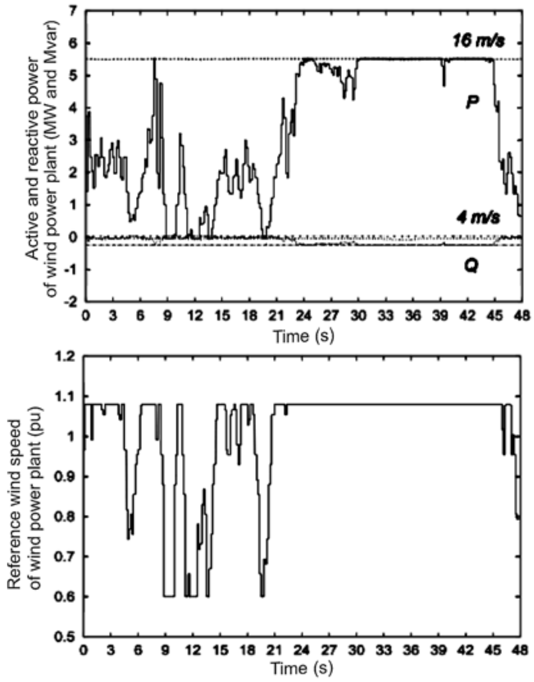

Figure 11 Total active and reactive power depending on reference speed of the wind power plant
Slika 11. Ukupna djelatna i jalova snaga u ovisnosti o referentnoj brzini vjetroturbine

Based on the analysis and considering different wind speed conditions as well as different connection points, it can be concluded that the output values of the same wind power plant at different voltage level connection locations vary considerably. In other words, electrical conditions in the network can limit the quality of wind power plant operation regardless of its high technological design. Five main criteria to be fulfilled with the aim of connecting wind power plants to the distribution system are as follows:

1) Requests with respect to frequency
2) Requests with respect to voltage
3) Requests with respect to fault ride-through capability
4) Requests with respect to quality of delivered energy
5) Requests with respect to signals, communications and control.

3 Criteria for connection of a wind power plant to the transmission system

Kriteriji priključenja vjetroelektrane na prijenosni sustav

For the purpose of connecting a wind power plant to the transmission system technical criteria are considered which ensure a quality connection of larger wind power plants (≥ 50 MW) to a high voltage transmission system (110 kV). Due to a sudden change of the wind power plant output power according to the change of wind speed, it is important to analyze dynamic properties of the system that also depend on the technology of wind power plant design and an interaction of adjacent synchronous generators connected to the same voltage level. The purpose of technical criteria and general Network rules is to preserve the most important properties of the power system, such as security of power supply, power reliability and quality for a short-term and long-term period [3, 10, 11, 12].

3.1 Requests with respect to frequency

Zahtjevi s obzirom na frekvenciju

Important factors under consideration with respect to connection of a wind power plant to the transmission system are as follows:

- Frequency range in the system during normal and disturbed operating conditions;
- Wind power plant characteristics within the whole system frequency range;
- Participation of a wind power plant in frequency regulation and active power control;
- Speed change referring to wind power production;
- Ensurance of spare power by the wind power plant.

Table 1 shows frequency ranges regulating conditions of the expected wind power plant operation in certain European power systems in which there exist Network rules for wind power plants [3, 10, 11, 12]. Table 2 gives requests with respect to participation of wind power plants in frequency regulation and active power production in some European systems.

On the basis of these data it can be stated that frequency response of a wind power plant is required in most of the European countries, i.e. participation of a wind power plant in frequency regulation in the distribution network. According to Croatian requests [12], WPP power must be regulated according to frequencies based upon a characteristic given in Figure 12.

Table 1 Requests of some European systems with respect to the range of frequency
Tablica 1. Zahtjevi nekih europskih sustava s obzirom na raspon frekvencije

Country	England / Wales	Scotland	Ireland	Denmark	The Netherlands
Frequency range	47,0-47,5 Hz during 20 sec 47,5-52 Hz always	47,0-47,5 Hz during 20 sec, 47,5-50,4 Hz always, 50,4-52 Hz power decreases with min. speed of 2 % of WPP output power with 0,1 Hz frequency deviation above 50,4 Hz	47-47,5 Hz during 20 sec, 47,5-52 Hz during 60 min, 49,5-50,5 Hz always power must remain unchanged during the frequency change of 0,5 Hz/s	47-47,5 Hz during 10 sec, 47,5-48 Hz during 5 min, 48-49 Hz during 25 min, 49-50,3 Hz always, 50,3-51 Hz during 1 min, above 53 Hz disconnection	48-51 Hz always

***Table 2** Requests of some European systems for participation of wind power plants in frequency and active power regulation in Europe*
***Tablica 2.** Zahtjevi nekih europskih sustava za sudjelovanje vjetroelektrana u regulaciji frekvencije i djelatne snage u Europi*

Country	England / Wales	Scotland	Ireland	Denmark	The Netherlands
Frequency range	Limited frequency-dependent WPP operation. Complete ability of frequency response is required after 1 January 2006	Ability of frequency response WPP>100 MW now WPP 30-100 MW July 2004 For frequencies above 50,5 Hz output power must be reduced with statics of 10 %	Ability of frequency response is required with respect to a decrease of active power production as well as regulation power and frequency of WPP within categories >5MW and >10 MW.	Ability of frequency response of WPP is required. In conditions of island operation, the possibility of participating in frequency regulation is required.	Contribution of WPP to primary frequency regulation is required with limitations set by control strategy and wind conditions.

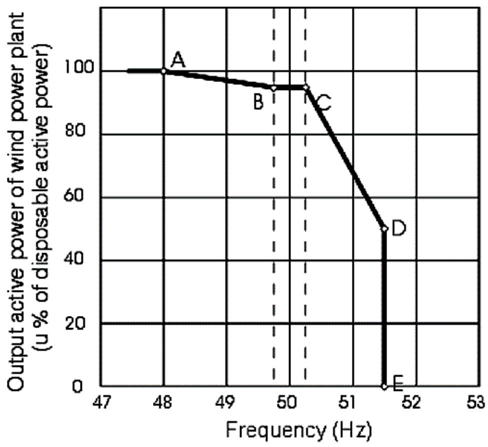

***Figure 12.** Characteristic of output power of a wind power plant according to frequency change (active power/frequency)*
***Slika 12.** Karakteristika izlazne snage vjetroelektrane prema promjeni frekvencije*

According to the technical regulation given in Figure 12, disconnection of a wind generator is conditioned if the value of frequency increases above 51,5 Hz, and the wind generator can be connected to the system again if the value of frequency decreases below 50,5 Hz.

3.2 Requests with respect to voltage
Zahtjevi s obzirom na napon

Principal requests in relation to voltage in the transmission system to which a wind power plant is connected refer to voltage ranges and its change, automatic voltage regulation and the ability of reactive power production. Two requests are considered. These are voltage range that has to be maintained in the connection of a wind power plant to the transmission system and a certain level of reactive power compensation, i.e. its exchange with the system [3, 10, 11, 12]. Table 3 shows requests set for individual European systems.

In Table 3 power factor is defined either only by the registered capacity of the wind power plant or within the overall production power range. Mutual comparison of requests with respect to reactive power shows a tendency to have wind power plants resemble conventional power plants as much as possible in terms of great construction and connection to the transmission system operating at the greatest power factor range possible.

3.3 Requests with respect to fault ride-through capability
Zahtjevi s obzirom na prolaz kroz stanje kvara

In case of power failures or faults in the system, connections between the power system and a wind power plant prove to be very significant, so that it is necessary to know the influence of a connection of large wind power plants to the transmission system and their response during power failures like short circuits in the system. Since the size of wind power plants is constantly increasing, the ability of wind power plants to overcome power failure conditions becomes more and more important, because this is linked to the overall stability of the power system [3, 10, 11, 12]. Requests of individual European systems regarding the ability of a wind power plant to overcome a power failure (the fault ride-through capability) are shown in Table 4.

According to the given data, it can be concluded that system requests are rather difficult, which actually implies that every system is unique as to its attitudes referring to states of faults. According to Croatian requests [12], every wind power plant must be capable of standing voltage dips to the level of 15 % of the nominal voltage in the period of 625 ms without disconnecting the connection. If the voltage value in the connection point decreases quasi-stationary (it does not change faster than 5 % per minute) to the level below 90 % of the nominal voltage. A wind power plant must be disconnected in 3 seconds at the earliest, Figure 13.

***Table 3** Requests for power factor range of wind power plants in some European systems*
***Tablica 3.** Zahtjevi za rasponom faktora snage vjetroelektrana europskih sustava*

Country	England/Wales	Scotland	Ireland	Denmark	The Netherlands
Power factor range	Single power factor in the connection point on a public network. 0,95 cap – 0,95 ind in the connection point after 1 January 2006.	On generator poles 0,96 cap - 0,98 ind (now >100 MW) 0,95 cap - 0,9 ind (now >100 MW) (as of July 2003 for <100 MW) 0,95 cap – 0,85 ind (as of January 2007 for all design values).	The same Mvar value of production and consumption of reactive power between the minimum and maximum load, rather than limitation on the basis of cap/ind power factor.	Neutral with respect to reactive power in the connection point (zero change of reactive power).	0,8 cap – 0,85 ind (assumed to be in the connection point)

Table 4 *Requests of some European systems for WPP fault ride-through capability*
Tablica 4. *Zahtjevi pojedinih europskih sustava za sposobnost prolaza VE kroz stanje kvara*

Country	England / Wales	Scotland	Ireland	Denmark	The Netherlands
Ability of overcoming a power failure	WPP must remain connected in conditions of a hard three-pole short circuit in 400 kV and 275 kV transmission levels throughout the fault up to 140 ms. Production power losses must not occur.	WPP must stand faults in transfer (132 kV and more) which make voltage dips: 0 % as of July 2005 (<30 MW) January 2004 (>30 MW) 15 % as of January 2004 (<30 MW) and now (>30 MW)	WPP must be able to maintain the operation at a lower voltage of 15 % lasting for at least 625 ms, and stay above the voltage recovery line for up to 3,000 ms.	WPP must remain connected in condition of a temporary three-pole short circuit, and a two-pole short circuit with unsuccessful re-connection of a power line for the state of failure.	WPP must not be disconnected for voltage dips on 0 % for duration of 100 ms. A 200 ms period of voltage value transient recovery is allowed.

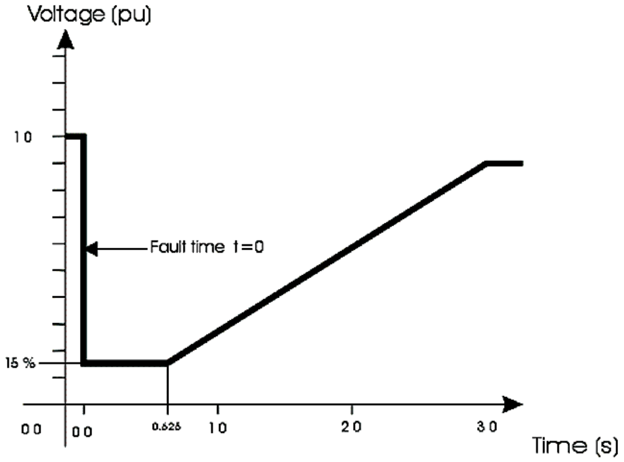

Figure 13 *A wind power plant fault ride-through capability*
Slika 13. *Sposobnost prolaza vjetroelektrane kroz stanje kvara u sustavu*

3.4
Requests with respect to the quality of distributed electrical power
Zahtjevi s obzirom na kvalitetu električne energije

When it comes to the quality of electrical power, it must be taken into consideration that by means of the generated electrical power wind power plants might affect other users in the system, especially those ones located in their vicinity, i.e. it is necessary to define the procedure by whose application aggravation of the quality in the transmission system upon connection of a wind power plant could be avoided. Estimation of the distributed electrical power quality is carried out on the basis of the following factors:

- Flicker emissions – voltage disturbances in the area of low frequencies;
- Fast voltage changes, single fast changes of effective voltage values, whereby voltage changes have a certain duration (e.g. they occur by circuit operations of wind turbine generators);
- Harmonics – periodic voltage or power disturbances with frequencies $n \times 50$ Hz (n is an integer).

This might be exemplified by Scottish and Danish rules setting requests with respect to the quality in 50-60 kV systems according to which voltage changes should be less than 3 % of the nominal voltage in the point where a wind power plant is connected to the system. Denmark sets additional requests with respect to fast voltage changes as to the rate of changes (from the rate of 10 times per hour <2,5 % to the rate of 100 times per hour <1,5 %).

In addition, definition of special requests with respect to flicker emissions and harmonics in a long-term and a short-term period is also required.

In addition to the electrical power quality, implementation of IEC regulations is proposed for all measurements, e.g. measurements of flickers, harmonics, peak power, power factor, etc. [3, 10, 11, 12].

3.5
Requests with respect to signals, communications and control
Zahtjevi s obzirom na signale, komunikacije i upravljanje

System of communications must be designed for every wind power plant that is built for every single wind generator. The owner of a wind power plant is responsible for getting signals indispensable to the control of power system operation. In addition to active and reactive production power, other signals might be requested as well, such as the status of a wind power plant and wind speed on the location where it is built.

Fundamental data for connection of a wind power plant to the transmission system are as follows:

- Information signals from the wind power plant towards the system operator;
- Control signals from the system operator towards the wind power plant;
- Prediction of production active power and power declaration.
-

All European system regulations require availability of voltage signals, active power, reactive power and the operation status of a wind power plant.

Some European systems individually require the following as well:

- Availability of the wind speed signal;
- Wind speed, temperature and pressure signal in real time;
- Frequency regulation status (on/off) and information on disturbances causing shutdown and restarting of a wind power plant within 15 minutes;
- Information on regulation abilities;
- Information on the position of a transmission ratio switch of a transformer by means of which a wind power plant is connected to the transmission system;
- Ability of controlling a wind power plant from outside.

E.g. for a wind power plant larger than 20 MW Sweden requires functional ability of local manual control or remote control 15 minutes after a fault occurs for the purpose of separation from the system, connection to the system, and control of active and reactive power, while Denmark requires the possibility of connecting and separating a wind power plant from the system outside.

It can be said for all technical criteria referring to connection of wind power plants that they are necessary for connection of wind power plants to the power system, and they are generally referred to as Network rules for wind power plants [3, 10, 11, 12].

4 Conclusion
Zaključak

Based upon the aforementioned, it is obvious that building wind power plants in the Republic of Croatia has been encouraged in recent times. For future development of building it is important to be familiar with all technical aspects of wind power plant operation that are key to selecting a wind power plant type on a certain location, since every location has a special regime of wind speed change. After harmonization of wind power plants with the present state of regime of wind speed change on some location it is necessary to satisfy all criteria as to connection of a wind power plant to a distribution network, such as frequency, voltage, overcoming the state of failure, quality of the delivered electrical power, signals, communications and control. On the basis of that a conclusion can be drawn that the selection of a wind power plant and its connection to the distribution network is a rather complex procedure.

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