Abstract: The paper presents the effects of severe demands on the quality of voltage that is raising the existing Serbian Technical recommendation no. 16. Possibilities of wind farm connection subject to the requirements in terms of voltage change in the transitional regime set by this document are described in details, and analyzed on the real demand of investors, which appeared in 2010. Improved Technical recommendation no. 16 whose adoption is expected, which is consistent with the application of technologically advanced wind generators and modern European standards on power quality of wind generators connected to the network, allows greater freedom of choice in terms of its possible connection to the network. Because of these facts, losses in the distribution network can be significantly smaller, with more economical electric power distribution. Conditions in terms of connecting specific wind farm were analyzed from the aspect of existing and updated recommendations, and its effects on energy efficiency are particularly emphasized.

Key-Words: Distribution Network, Wind Farm, Connection, Voltage Quality, Energy Efficiency

1 Introduction

Wind farms are specific among the renewable energy. After nearly 100 years in which the importance of wind as an energy source declined in the first years of XXI century, thanks to advances in technology of energy conversion, this clean source of energy in the ecological sense is gaining importance. By middle of 2010, according to the World Wind Energy Association, the total installed capacity of wind generators in the world amounted to 175 000 MW, which is about 16 000 MW more than at the end of 2009, and total production in 2009 was estimated at 340 million MWh [1]. The five largest producers of electricity from wind farms in 2009 (the U.S. with 22.1%, China with 16.3%, Germany with 16.2%, Spain with 11.5% and India by 6%) occupied 73% of the world's installed capacity in electricity generation from wind.

Hence, the importance of wind as an energy source is increasing in the world, and Europe. In Serbia, the wind electricity production is at the start, partly because of legislation that has not been adapted to technological progress in this area, and not completely defined and developed procedures for future producers of electricity from wind energy. Of course, a special significance for the future expansion of electricity generation from wind energy has a privileged price of 9.5 c€/kWh for a period of 12 years, which is defined in Regulation [2] of the Republic of Serbia Government.

In this paper we analyzed the specifics of the possibility of connection to the power distribution network of wind power up to 10 MW. In the first step analysis was carried out in terms of existing conditions of connecting presented in the Technical Recommendation no. 16 of Directorate for distribution of Serbian Power Utility (EPS) [3]. In the next step, analysis was carried out in terms of the changed Technical Recommendation no. 16, whose adoption is expected, which is consistent with the application of technologically advanced wind generators and modern European standards on power quality for wind generators connected to the network [4]. Voltage variations in the transitional and stationary state criteria will be the subject of analysis, but other criteria, which connected wind farm must meet in order to ensure satisfactory quality of electricity, will be presented, too.

Wind farms connected to the distribution network may have different effects on the functioning of this network. The paper will discuss the impact on the real example with significant differences regarding the impact on losses in distribution network depending on the adopted criteria.
The Technical Recommendation no. 16 of Directorate for distribution of EPS [3] and the Distribution Grid Code [5] define the main technical requirements for connection of small power plants, including wind farms, to distribution network. Criteria for wind farms connecting to the distribution network are:

- Criterion of permitted power for small power plants (Section 5.4 of [3])
- Flicker criterion (Section 5.5 of [3])
- Criterion of permissible higher harmonics currents (Section 5.6 of [3])
- Short-circuit power magnitude criterion (Section 5.7 of [3])
- Stationary state voltage change criterion (Section 4.4 a) of [3])

The criteria of flicker and allowed current harmonics can be checked only for a specific wind generator based on parameters provided by the manufacturer or an authorized independent institution, separate for each generator and power plant as a whole, based on the certificate of type testing of small power plant that has the same or similar characteristics as small power plant to be built. After completing the construction of wind farm and connecting to the distribution system, measurement must be performed to confirm the value of the parameters on which the conditions checking was performed.

The same conclusion applies to the criterion of short-circuit power magnitude. Specifically, checking of this criterion requires knowledge of the data on the synchronous reactance of the specific generators to be connected to the network.

2.1 Criterion of permitted power for small power plants

2.1.1 Existing Criterion and its Consequences

Bearing everything previously stated in mind, the basis for checking the technical conditions for connection of small power plant is the criterion of permitted power of small power plant. This criterion guarantees that, in transient regimes, the change in voltage at the connection point to the distribution network will not exceed the value of $\Delta u_m = 2\%$.

According to [3], small power plant can be connected to the distribution network subjected to the criterion of permitted power if the following condition is fulfilled:

$$S_{NGM} \leq \frac{S_{k}}{50 \cdot k} \quad (1)$$

Where:

- $S_{NGM}$ - Power of the biggest generator unit in a small power plant, or total power of several generators when connected simultaneously to the distribution network, in MVA
- $S_k$ - The actual value of three-phase short-circuit power at the point of connection to the distribution network, in MVA
- $k = I_p/I_n$ - Coefficient determined by the quotient of maximum starting current $I_p$ (inrush current) and rated current of generator $I_n$, and has a value:
  - $k = 1$ for synchronous generators and inverters
  - $k = 2$ for asynchronous generators
  - $k = 8$ for the case when there is no known data on the starting current $I_p$.

In small power plants with multiple generators, connecting the next generator to the distribution network is allowed to be performed at least two minutes after connecting the previous generator. Otherwise, these generators should be treated as if they are connected simultaneously. According to [3], another criterion is cited for the (simultaneous) connection of small power plants to the distribution network:

$$S_{MEL} = \sum S_{NG} \leq \frac{S_{k}}{500} \quad (2)$$

Where with $S_{MEL}$ is the indicated the total installed capacity of all generators in a small power plant.

Possibilities for connection of small power plants to the distribution network are usually analyzed under the assumption that there is the possibility for individual generators connection to the distribution network in all considered small power plants. Therefore, criterion (2) will not be taken into account, as it is much stricter than criterion (1).

Consequences of set criteria implementation can be viewed if you analyze optimal (but also real) cases from the standpoint of short-circuit power value applied to synchronous wind generator ($k = 1$):

The maximum permitted short-circuit current in 110 kV network is about 24 kA, which means that short-circuit power is about 5000 MVA (110 kV equipment in some 110/X kV substation in Serbia is dimensioned to this value).

If the wind farm connects to 35 kV busbar at the 110/35 kV substation with two 31.5 MVA transformers (although during criterion check a...
single transformer is taken into account), the maximum generator size is over 5.8 MVA. If the short-circuit current values correspond to the lowest in the network in Serbia (about 3 kA), maximum generator unit that can be attached is about 4.3 MVA, and if at least one 110/35 kV transformer of 20 MVA is installed, maximum size of generator would drop to about 3.15 MVA.

Since wind farms are located to suburban areas, it is possible to connect to 35 kV line, either to 35 kV side of a 35/10 kV substation, either to existing or newly formed 35 kV plant (RP). Usually, the 35 kV overhead line supplies substation or RP. The most common cross-section of 35 kV line in the distribution networks of Serbia is AlFe 95 mm$^2$, and the first kilometer of this line reduces the size of generator unit that can be connected for 140 kVA. The tenth kilometer of line reduces unit size to about 3.1 MVA in the best case ($I_{KS} = 24$ kA, $S_{TR} = 31.5$ MVA).

The greatest reduction in allowable generator size brings the transformer 35/10 kV. E.g., 8 MVA transformer in the previously analyzed case decreases the maximum power of wind generators to only 1.5 MVA, and if the supplying line is only 1 km long, to about 1.9 MVA. Conventional wind generators that are cost-effective for use in Serbia range from 1.5 to 3 MVA, so it is clear that it is difficult to expect the possibility to connect these units to the medium voltage network, and that they meet the set criteria. If there is a connection point only one kilometer along the 10 kV line AlFe 50 mm$^2$ away from the 35/10 kV substation with the 8 MVA transformer, which is supplied by 1 km long 35 kV line, the size of unit that can be attached to network falls to just 1.3 MVA.

Common conditions in the network were significantly worse than analyzed, and under the terms of a criterion 5.4 in the [3], one can not expect that wind farm economically adjusted to wind in Serbian conditions, satisfies the conditions of connection to the 10 kV network and, even to 35 kV network.

2.1.2 Changed Criterion and its Consequences

On the other hand, technological advance enabled the application of induction generators as wind generators, which are connected to the network via the AC-DC-AC converter (generators with full conversion - Fig. 1), making variations of voltage at switch minimized. More about the possibilities of this kind of generator is given in [6].

![Fig. 1: Full converter wind-generator scheme](image)

Namely, presented criterion of permitted power for small power plants comes from the need to limit the voltage change in the course of transition process during the generator start-up. Transition process is a consequence of the generator's synchronization to the grid. In fact, it is estimated that power plants are connected to the network while there is still generator's frequency, voltage and phase angle deviations of values dictated by the network at the connection point. In the case of connecting generators with full conversion to network, there is no galvanic contact between
Because of differences among generators and possibilities to measure their response in terms of change voltage at startup, the standard IEC 61400-21 [4] defines the maximum expected change in voltage at the connection point due to starting of wind generators as:

\[
d_{\text{max}} = 100 \cdot \frac{\Delta U_{\text{max}}}{U_n} = 100 \cdot k_u \cdot \frac{S_{\text{nom}}}{S_k}
\]  

(3)

From which one simply goes into the formula (1) defined in [3].

Factor \( k_u \) in the formula is defined as the voltage change factor corresponding to \( k_u \) in [3], and depends on value of the phase angle of short-circuit impedance which a generator "sees" at the connection point. Other units in the formula are:

- \( d_{\text{max}} \) - maximum expected change in voltage at the connection point due to wind generator's start-up, in \( \% \),
- \( \Delta U_{\text{max}} \) - maximum expected change in voltage at the connection point due to wind generator's start-up, in kV,
- \( U_{\text{nom}} \) - rated network voltage at the connection point, in kV,
- \( S_k \) - three-phase short-circuit power value at connection point, in MVA,
- \( S_{\text{nom}} \) - generator apparent rated power in the wind-farm that parallels simultaneously with distribution network, in MVA,
- \( \psi_k \) - short-circuit impedance phase angle at connection point, in degrees:

\[
\psi_k = \arg(Z_{ks}) = \arctan\left(\frac{X_{ks}}{R_{ks}}\right)
\]  

(4)

- \( Z_{ks} \) - complex value of short-circuit impedance at connection point reduced to rated network voltage at connection point, in \( \Omega \),
- \( X_{ks} \) - reactive part of short-circuit impedance at connection point reduced to rated network voltage at connection point, in \( \Omega \),
- \( R_{ks} \) - active part of short-circuit impedance at connection point reduced to rated network voltage at connection point, in \( \Omega \).

It is clear that, with defined value of maximal expected change of voltage at connection point because of wind-turbine start-up, it is possible to calculate easily maximal permitted wind-generator rated power that can be connected to network simultaneously. Standard [4] defines conditions for voltage change factor \( k_u(\psi_k) \) measurement and angle \( \psi_k \) value as measurement parameter. Therefore, \( k_u(\psi_k) \) value will not be adopted for generators with known characteristics (as it is the case in [3]), but it will be measured under predefined conditions. Measured values will be used for connection to real network possibility analysis.

The consequences of criteria changes can be seen when analyzing cases mentioned in section 2.1.1, from the standpoint of short-circuit power value and network parameters. The estimated parameter values (that go to the side of safety) of one 3 MVA generator have been adopted for the analysis (Fig. 2).

- Wind generator unit capacity of 10 MVA, with the characteristics shown in Fig. 2, could be connected to 35 kV busbar of any 110/35 kV substation. In the most unfavorable case of connection to the 35 kV side of 110/35 kV transformer 1x20 MVA of installed power, and short-circuit current at 110 kV side of 3 kA, the \( d_{\text{max}} \) reached 1.7%, which is less than permitted 2%.
- 35 kV line, type AlFe 95 mm², 10 km long, limits the power generator unit, with the characteristics as in Fig. 2, at about 5 MVA.
- The greatest reduction in allowable generator size brings the transformer 35/10 kV. E.g., 8 MVA transformer in the previously analyzed case decreases the maximum power of wind generators to 3.3 MVA, and if the supplying line is only 1 km long, to about 5.7 MVA. If there is a connection point only one kilometer along the 10 kV line AlFe 50 mm² away from the 35/10 kV substation with the 8 MVA transformer, which is supplied by 1 km long 35 kV line, the size of unit that can be attached to network falls to 4.1 MVA.

<table>
<thead>
<tr>
<th>Case of switching operation</th>
<th>Start-up at rated wind speed or higher</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. number of switching operations, ( N_{\text{sw}} )</td>
<td>3</td>
</tr>
<tr>
<td>Max. number of switching operations, ( N_{\text{sw}} )</td>
<td>35</td>
</tr>
<tr>
<td>Network impedance phase angle, ( \psi_k [\degree] )</td>
<td>30°</td>
</tr>
<tr>
<td>Flicker step factor, ( k_f(\psi_k) )</td>
<td>0.4</td>
</tr>
<tr>
<td>Voltage change factor, ( k_u(\psi_k) )</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Fig. 2: Estimated Parameter Values of Wind Generator
Adoption of new criterion of permitted power, for the analysis of possibilities of wind farms connection to distribution network, provides a significantly larger generator unit connection. In some cases, this will mean the possibility of connecting wind farms to the medium voltage network (10 kV), if it is near wind farms and is relatively close to the 35/10 kV supplying substation. For all common situations in a 35 kV network, wind farm with the usual power generator unit (1.5 - 3 MVA) will be connected to the nearest point in the 35 kV network, which, using the current criterion, is not always possible. The main criterion that limits the connection of wind farms will no longer be a limit of voltage variations in the transient, but, probably, the voltage change in stationary state (above all, in states with minimal network load and the maximum engagement of wind farms).

3 Functioning of Generators in Stationary States

3.1 Voltage Variations in the Stationary States Criterion
As recommended in [3], in steady state, the highest allowed voltage deviation at the connection point in relation to the rated voltage is \( \Delta U_m = \pm 5\% \), if the small power plant connected to the medium voltage network, or \( \Delta U_m = \pm 5\% \) - \(-10\%\), if the small power plant is connected to low voltage network. Checking this criterion is not easy because terms of steady state are not defined in terms of voltage at supplying point of distribution network and network loading.

To overcome problems related to verification of this criterion it is proposed to define a broader range of allowable values of voltages in the stationary mode, at the connection point, for any mode of network operation. This range is related to the voltage limit when planning a network, defined by [5] and is given in the table below.

### Table 1: Voltage Limits for Planning Purposes

<table>
<thead>
<tr>
<th>Rated Network Voltage</th>
<th>Minimal Network Voltage at Normal Network Operation</th>
<th>Maximal Network Voltage at Normal Network Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>35 kV</td>
<td>31.5 kV</td>
<td>38 kV</td>
</tr>
<tr>
<td>20 kV</td>
<td>19 kV</td>
<td>21.4 kV</td>
</tr>
<tr>
<td>10 kV</td>
<td>9.5 kV</td>
<td>10.7 kV</td>
</tr>
</tbody>
</table>

Of course, the network operation in the stationary regime depends on voltages at the threshold of distribution network (e.g. at 35 kV side in 110/35 kV substation), which can vary within a relatively broad range, and load level and its disposition. It is appropriate to analyze the variation of voltages at the supplying point within reasonable limits, because it is impossible to expect that any wind farm (or other small power plant) adjusts at voltage variation at this point in the widest extent possible (e.g. in the range of 31.5-38 kV). On the other hand, considering voltages, the wind farm must be adapted to all levels of load in the network.

For this reason, the test criteria for connecting generator to network should be analyzed under two condition sets: 1) state with a minimum load, maximum expected voltage at the threshold of distribution network and maximum generators' engagement, 2) state with a maximum load, minimum expected voltage at the threshold of distribution network and disengaged plant. These rules are usually applied for stationary state voltage change criterion check. If in both states at all points in the network voltages are inside limits defined in Table 1, where it is possible to use a dispatch action (seasonal change of transformer ratio, or seasonal exclusion of unloaded transformer), it is considered that wind farm (or other small power plant) meets the conditions in the stationary regime.

3.2 Study Case of Wind Farm Influence to Distribution Network Losses Considering Criteria Modification
One cannot make a general conclusion about the impact of wind farms to the losses in distribution network. Losses depend on the disposition of the load through time, the voltage at the threshold of distribution network, the network configuration to which the operation of wind farms can have an impact, the position of wind farms in the network and of course wind farm's production in a given time.

Experience suggests that one can expect increase rather than reduction of losses for several reasons. On the one hand, it is cost-effective to build wind farms close to maximal power, and in areas where wind allows operation in the regime of maximum generation in the long term. On the other hand, wind farms are usually located in unpopulated areas, i.e. areas with low load density, and low total consumption. Therefore, wind farm usually returns power to the power supply point for the distribution network instead of reducing the power flow in feeder lines.
Wind farm in the area of Danube basin in Serbia, the power of about 9 MW, shows, however, that the impact may be positive. Nevertheless, this effect depends on the connection (direction of generated power), which is related with criteria to be applied for the connection (existing or altered). Namely, in case of the application of existing criterion, it is possible to connect the wind farm with a unit generator power of 1.8 MW, where wind farm, consisting of five generators, should generate power toward 110/35 kV substation Požarevac (Fig. 3). In this way, losses in the network would reduce for about 100 kW in maximal regime. Half of generated power would supply 35/10 kV substation Bratinac, and the other half would flow toward supplying 110/35 kV substation Požarevac. Load flows by 35 kV lines would not reduce, but increase after wind farm connection to network.

In case of modified criteria application, the unit generators in the wind farms can have larger capacity (we adopted four 2.3 MW units), where the power flows toward other 110/35 kV substation Veliko Gradište. In the second case, the operating losses are reduced by almost 600 kW in maximal regime. The reduction is consequence of almost complete annulation of load flow on 35 kV line Veliko Gradište - Češijeva Bara.

If the equivalent time of engaging the maximum power of wind farm is about 2000 hours (for small wind farms should be larger to be cost effective for build), the expected savings in procurement of electricity per year would be higher than 15 000 €. Thus, the revised criterion provides flexibility in choice of connection that enables you to choose solutions that best fit the work of distribution network in stationary regime.

4 Conclusion
The rigidity of the existing recommendations [3] creates significant difficulties for the possibility of connecting wind farms to the distribution network. Certain conservatism, concerning the protection of the distribution network operation, must exist, but current recommendations do not appreciate the technological advancement of wind generators, which by itself provide a stable network operation.

European standards (e.g. [4]) covered these technological improvements through the possibility that the parameters, which were previously computationally checked, are measured in the laboratory. On that basis, one can make conclusions about the possibility of meeting the existing criteria. Amendment recommendation [3] goes in that direction and we have analyzed the consequences of changes applied to the real example.

It is shown that the altered recommendation application provides connection of significantly larger units to the network from the standpoint of the voltage variations in transition period criterion, so that the criterion of wind farm functioning in the stationary regime, and flicker criterion become the decisive for selection how to connect the wind farm.

On the other hand, by applying modified criteria more flexibility in connection is provided, so there is a possibility of significant improvement of distribution network operation in some situations that would not be possible through the application of existing criteria of connection. The presented example shows that the application of modified criteria for choice of connection may provide the reduction of losses by nearly 600 kW at full load, which makes a significant positive financial effect to distribution company.

References: