Power quality assessment of wind turbines and comparison with conventional legal regulations: A case study in Turkey

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ABSTRACT

Renewable energy sources have been investigated for use instead of conventional fossil fuels in many areas. Among these renewable energy sources, wind energy has come into prominence owing to the fact that it is a clean, sustainable and cost-effective type of energy. However, the connection of large wind farms to the grid may cause problems in terms of power quality due to the variability of the energy extracted from the wind. The mentioned power quality problems are generally taken into consideration after the grid integration of wind farms. However, the precautions that can be taken by means of the assessments before the installation of the turbines represent an easier and more economic way. In this study, the possible effects of the grid connected wind turbines on the power quality characteristics have been defined and the MATLAB based models have been constructed so as to calculate these effects. Particularly, fast voltage variations that are difficult to model due to their relations with the human factor have been analyzed in detail. It has been aimed that the models are suitable for use in practice while utilizing various standards such as IEC 61400-21 and IEC 61000-4-15 in order to setup the models. The analyses of the implementations that represent constraints for exploiting the wind resources in Turkey have been realized in terms of production and consumption with a case study. The realized calculations present the applicability of the model to grid conditions with different characteristics. It is also presented that the wind energy penetration can be increased without deteriorating the power quality of the grid with the use of the proposed model.

1. Introduction

The rapid depletion of fossil fuel resources and the rising public awareness for environmental protection on a worldwide basis have necessitated an urgent search for alternative energy sources. Particularly, among the many types of competitive alternative sources of energy, wind power generation has experienced a very fast development in the whole world [1]. However, wind power may cause problems to the existing grid in terms of power quality [2,3]. One of the fundamental definitions to power quality problems is any power problem manifested in voltage, current or frequency deviations that results in failure or miss operation of customer equipment [4]. Power quality decrement is generally caused by many factors such as impulsive and transients, over voltage or under voltage variations, voltage imbalance, waveform distortion, such as dc offset, harmonics, notching and noise, voltage fluctuation and frequency variations. In recent years, concern over power quality has increased significantly due to economic reasons and problems that can affect the manufacturing industries and the other customers [5].

Depending on wind turbine technology, there are different effects that could damage power quality of a specific grid. Several Transmission System Operators (TSOs) have published grid codes for wind turbines. The codes require wind turbines and/or wind farms to participate in voltage regulation and frequency control. Also according to these codes, the wind power plants must be able to produce the required active and reactive power during transient grid fault to support the grid [6,7]. However in some situations, although the wind power plants provide the essential conditions, the limit values may be exceeded in terms of power quality. Thus, most of the countries have the rules such as that the wind turbines should not cause a voltage increment of more than 1% which limit the wind turbine installation to a specific grid [8,9]. Similar to that case, specifically in Turkey, a rule such as that the total wind power should not exceed 5% of the short circuit power of the grid is mostly applied [10]. Although these kinds of rules are usable for preventing the power quality problems caused by wind power in a grid, the wind power exploitation, particularly in weak grids is greatly decreased due to these rules. In order to increase the exploitation, it is quiet convenient to utilize the power quality standards for wind turbines, issued by the International Electrotechnical Commission (IEC). With utilizing the standard IEC 61400-21, which defines the power quality characteristic of grid
connected wind turbines, it is possible to make room for more wind power by assessing the likely effects of wind turbines on the power quality of the grid.

In this article, the assessment procedure is modeled in MATLAB software program in order to make use of the standard simply. Thus, the power quality characteristics can easily and rapidly be defined using the measurements obtained from the wind turbines. The modeling procedure is realized for all power quality characteristics. However, the most detailed section is devoted to fast voltage variations (voltage flicker) as the models setup for voltage flicker are more complex compared to the other power quality characteristics owing to the close relationship between the variations and human. This method can be used to know in advance whether a wind farm at a specific site could damage power quality level or not. Besides, the maximum number of wind turbines that can be connected to the grid without deteriorating the power quality limits at a given site can easily be decided by the proposed method before making investment and realizing installation.

As a consequence, the effects of different numbers of wind turbines on power quality for different grid specifications are examined in the article. Also, the steady state voltage variations as well as the flicker emissions during continuous and switching operations are evaluated. For the application, a wind farm consisting of stall controlled and directly grid connected wind turbines with induction generators is considered. It is also possible to evaluate the characteristics of a wind farm consisting of different types of wind turbines by the proposed methodology.

This article is organized as follows. Section 2 describes the modeling procedure of the proposed methodology. Section 3 presents the results derived from the proposed methodology for a case study in Turkey. Finally, the overall study is discussed and conclusions are presented in Section 4.

2. Models for assessment of power quality characteristics of grid connected wind turbines

Power quality problems which are caused by wind power, especially in weak grids may represent technical constraints for exploiting the wind resources. As mentioned before, the purpose of the proposed methodology based on IEC standards is to enable an assessment of expected power quality of one or more wind turbines. The details of the proposed methodology are given in the following subsections.

2.1. Steady state voltage

Operation of a wind turbine may affect the steady state voltage in the network. It is generally needed that load-flow calculation should be performed to assess this effect.

If \( \cos(\psi_k + \phi) > 0.1 \), the change of steady state voltage should be given by:

\[
d = \frac{S_{60}}{S_k} |\cos(\psi_k + \phi)|
\]

Steady state voltage model developed by assuming that the above given criterion is supplied is shown in Fig. 1.

2.2. Voltage fluctuations

One of the most important problems associated with the wind turbines is voltage fluctuations. Luminance variations of light sources due to the fluctuation of voltage in a frequency range from 0.05 Hz to 35 Hz are referred as “voltage flicker”. The effects of flicker to people depend on many parameters. The degree of annoyance caused by flicker may be increased with respect to these parameters; even some symptoms, such as dizziness, fatigue and headaches appear in the people who are subjected to light from a lamp fed by a voltage with variations visible by the human eye for a long time. Also some loads are adversely affected by voltage flicker (e.g. speed changing for motors, undesired control actions for control systems acting on the voltage angle and impairment of electronic equipment subjected to the fluctuation of the supply voltage, for example computers and components for telecommunication) [11,12].

For the wind turbines, flickers may be caused by the switching operations and by the fluctuations of active and/or reactive power in the continuous operation. The latter are mainly due to the influences of turbulence intensity, tower shadow, blade pitching error, yaw misalignment, wind shear, tower oscillation and the fluctuations of wind speed [13]. Flicker emissions caused by wind turbines must be evaluated both for continuous and switching
operations separately and these evaluations are presented as follows.

2.2.1. Continuous operation

The measurement and assessment procedures for flicker during continuous operation are shown in Fig. 2. The procedures shown in Fig. 2 are explained in clauses below:

(a) For wind turbines, the aim of a flicker measurement is a test result which is independent of the grid conditions at the test site. Therefore, a measurement with the developed flickermeters for wind turbines is not feasible. According to the IEC 61400-21 standard, it is necessary to use a method that simulates a fictitious grid which contains only voltage fluctuations of the tested wind turbine to accomplish the grid-independent flicker measurement. The phase diagram of the fictitious grid is shown in Fig. 3.

The fictitious grid is represented by an ideal phase to neutral voltage source with the instantaneous value \( u_0(t) \) and a grid impedance consisting of a resistance \( R_{\text{fic}} \) in series with an inductance \( L_{\text{fic}} \). The wind turbine is represented by the current generator \( i_m(t) \), which is the measured instantaneous value of the line current. As a consequence, a simulated voltage with the instantaneous value \( u_{\text{fic}}(t) \) should be defined as:

\[
u_{\text{fic}}(t) = u_0(t) + R_{\text{fic}} \cdot i_m(t) + L_{\text{fic}} \frac{di_m(t)}{dt}
\]  

(2)

The model of the fictitious grid is fundamentally formed by the \( d-q \) conversion as shown in Fig. 4. The parameters \( R_{\text{fic}} \) and \( L_{\text{fic}} \) must be calculated for each grid impedance angle value owing to the fact that power quality characteristics are defined for four different angles.

(b) Each simulated instantaneous voltage time-series are used as inputs to the voltage flicker algorithm described in IEC 61000-4-15 to generate the flicker emission value \( P_{\text{st,fic}} \). Therefore a flickermeter model is setup in the MATLAB by simulating the blocks of IEC flickermeter in order to use in analysis of the power systems with wind turbines. The flickermeter as described in IEC 61000-4-15 consists of five blocks (Fig. 5). While the blocks 2, 3 and 4 perform the simulation of the response of the lamp–eye–brain chain to voltage fluctuations, statistical analysis of the flicker signal is performed by block 5. The details of the mentioned blocks are given as follows:

Block 1 – input voltage adaptor and calibration checking circuit:
This block contains a voltage adapting circuit and a signal generator. The voltage adapting circuit is used to match the input signal to the limited range of the analogue flickermeter. Hence it is not necessary to use a voltage adaptor in the simulation model. The aim of the signal generator is to check the proper operation of the flickermeter on site. Here, two different calibration signals, sinusoidal and rectangular respectively, are utilized to verify the accuracy of the model developed as follows [14]:

![Fig. 1. The model of the calculation of the steady state voltage change.](image)

![Fig. 2. Measurement and assessment procedures for flicker during continuous operation of the wind turbine.](image)

![Fig. 3. Fictitious grid for simulation of fictitious voltage.](image)
Block 2 – square law demodulator: Block 2 consists of a quadratic demodulator that recovers the percentage voltage fluctuation by squaring of the scaled input voltage, simulating the behavior of the lamp.

Block 3 – weighting filters: Block 3 is composed of two cascade filters and a measuring range selector. The first filter eliminates the dc component and the ripple at network double frequency from the output voltage of the quadratic demodulator. According to the standard [15], the filter consist of a first order high-pass filter centered at 8.8 Hz that simulates the frequency response to sinusoidal voltage fluctuation of a coiled filament gas filled lamp (60 W–230 V) followed with the human eye. A suitable transfer function for this weighting filter, which is taken from [15], is shown in Eq. (7):

$$ F(s) = \frac{k w_1 s}{s^2 + 2 \lambda s + w_1^2} \frac{1}{(1 + s/w_2)(1 + s/w_3)} \quad (7) $$

in which indicative values of the parameters are considered as follows:

$$ k = 1.74802 \quad \lambda = 2 \pi 4.05981 \quad w_1 = 2 \pi 9.15494 \quad w_2 = 2 \pi 2.27979 \quad w_3 = 2 \pi 1.22535 \quad w_4 = 2 \pi 21.9 $$

The frequency response of the weighting filter centered at 8.8 Hz is shown in Fig. 6.

The range selector determines the sensitivity of the instrument by varying the gain as a function of the voltage fluctuation amplitude to be measured. Here, a range selector is not required since the adequate sensitivity is realized by the number of the flickermeter model classes.

Block 4 – squaring and smoothing: This block contains a squaring multiplier that simulates non-linear eye–brain perception and a first order low-pass filter with 0.3 s time constant that simulates the build-up time of the brain. The output of that block represents the instantaneous flicker level, $P(t)$. The transfer function of the first order filter is below:

$$ P(t) = \frac{k w_1 s}{s^2 + 2 \lambda s + w_1^2} \frac{1}{(1 + s/w_2)(1 + s/w_3)(1 + s/w_4)} \quad (7) $$
Averaging

Normalization

The values defined in Eqs. (10)–(13) are used to calculate the minimum and maximum RMS values, \( U_{\text{fic,min}} \) and \( U_{\text{fic,max}} \) as shown in Fig. 8. Each \( P_{\text{st,fic}} \) value is normalized to a flicker step factor and each voltage change \( (U_{\text{fic,min}} - U_{\text{fic,max}}) \) is normalized to a voltage change factor. Then these factors are averaged for each network impedance phase angle.

(c) Flicker emission and voltage changes are estimated according to Eqs. (16)–(18) as follows:

\[
P_{\text{st}} = \frac{18}{S_k} \left( \sum_{i=1}^{N_{10i}} \left( k_{fi}(\psi_k) \cdot S_{ni} \right)^{0.31} \right) \]

\[
P_{\text{st}} = \frac{8}{S_k} \left( \sum_{i=1}^{N_{120i}} \left( k_{fi}(\psi_k) \cdot S_{ni} \right)^{0.31} \right) \]

\[
d = 100 \cdot k_u(\psi_k) \cdot \frac{S_u}{S_k} \]

2.3. Harmonics

The measurement and assessment procedures of flicker for switching operations are shown in Fig. 7. The procedures shown in Fig. 7 are explained in clauses below [16]:

(a) The instantaneous voltage time-series, obtained as in the continuous operation, are used to generate the flicker emission value and used to calculate the maximum and minimum RMS values, \( U_{\text{fic,min}} \) and \( U_{\text{fic,max}} \) as shown in Fig. 8.

(b) Each \( P_{\text{st,fic}} \) value is normalized to a flicker step factor and each voltage change \( (U_{\text{fic,min}} - U_{\text{fic,max}}) \) is normalized to a voltage change factor. Then these factors are averaged for each network impedance phase angle.

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\[
d = 100 \cdot k_u(\psi_k) \cdot \frac{S_u}{S_k} \]

2.3. Harmonics

Wind turbines equipped with induction or synchronous generator directly connected to the electrical system cause limited harmonic currents. Thus, only wind turbines using power electronics have to be examined in terms of harmonics. Thyristor-based converters may influence the harmonic voltages. However, the

\[
c(\psi_k) = P_{\text{st,fic}} \cdot \frac{S_{k,\text{fic}}}{S_0} \]

(d) For each network impedance phase angle, the weighted accumulated distribution functions of the flicker coefficients \( P_{\text{st}(\omega_j)} \) are calculated for four different wind speed distributions. Finally, the 99th percentile of the flicker coefficient is reported for each distribution and an assessment table is created by replacing these values [16].

(e) For assessment procedure, firstly, the flicker coefficient is determined with respect to the annual average wind speed and the network impedance phase angle of the site. Then, the flicker emission is calculated from the following equation:

\[
P_{\text{st}} = \frac{1}{S_k} \sum_{i=1}^{N_{10i}} \left( c(\psi_k) \cdot v_u \cdot S_{ni} \right)^2 \]

2.2. Switching Operation

The measurement and assessment procedures for voltage changes and flicker during switching operations of the wind turbine.
transistor-based converters are operated at switching frequencies above 3 kHz. Therefore, the impact of such converters on the voltage waveform should be negligible.

3. Test and results

In order to determine the power quality characteristics of wind turbines, the following wind turbine specifications are utilized:

Type of wind turbine: Stall controlled, equipped with induction generator directly connected to the grid
Rated power: 2400 kW
Rated apparent power: 2445 kVA
Rated voltage: 690 V

The effects of the wind turbine on the power quality characteristics are checked for different sites and grids concerning steady state voltage, continuous operations and switching operations.

3.1. Steady state voltage

For the evaluation of wind turbine characteristics during steady state operation, steady state voltage change is calculated as 0.7% while substituting the short circuit power of the grid and the grid impedance angle with 120 MVA and 60°, respectively on the model. Thus, it is convenient to connect three wind turbines to the grid for the countries in which the maximum permitted steady state voltage change by wind turbines is 2% of nominal voltage. The voltage change could be reduced if the short circuit power is increased. For instance, the limit values are not exceeded for the same impedance phase angle and voltage change limit in the case of four wind turbines are connected to the grid which has a short circuit power of 200 MVA.

The grid impedance angle is the most effective parameter on determining the number of the turbines regarding steady state voltage change. In the first case in which the short circuit power is 120 MVA, the voltage change will be 0.9% for the impedance phase angle of 55° and in this way, the number of the turbines will increase. In the higher angle cases, number of the wind turbines will begin to decrease owing to the fact that voltage dips will occur with the connection of more turbines.

3.2. Voltage fluctuations

The simulations carried out for voltage fluctuations are explained under two subtitles as continuous operation and switching operation as follows.

3.2.1. Continuous operation

Flicker coefficients calculated as a function of wind speed for the network impedance phase angle of 50° for the wind turbine mentioned above are shown in Fig. 9. The flicker coefficients belonging to the other impedance phase angles and the values obtained from these coefficients are not showed in order to avoid repeating.

Firstly, flicker coefficients are classified in 1 m/s bins of the wind speed and the number of measurements is determined in each wind speed bin. The wind speed bins, the number of measurements of each bin, the relative occurrence frequency of measured flicker coefficients for each wind speed bin and the Rayleigh
distribution for four different annual average wind speeds (6 m/s, 7.5 m/s, 8.5 m/s and 10 m/s) are reported. Then, the weighting factors and the sum of the weighting factors for each wind speed bin are calculated. The measurements are sorted according to the flicker coefficients. The upper row gives the maximum value of all of the flicker coefficients in the wind speed range from 3 m/s to 15 m/s. Subsequent rows of table are completed by subtracting the weighting factor for the relevant measurement divided by the total sum of weighting factors from the figure in the previous row. The 99th percentiles give the flicker coefficients for the network impedance phase angle of 50°. Table 1 is completed after the same procedure is realized for the other impedance phase angles. Thanks to Table 1, the power quality characteristics of the considered wind turbine may be calculated for a given site. In the first case, the short term flicker severity is estimated as 0.14 for a single wind turbine at a site where the annual average wind speed is 8.4 m/s. Also, it is assumed that nominal voltage of the grid is 34.5 kV and the maximum permitted steady state voltage change by wind turbines is 3% of nominal voltage. The calculated short term flicker severity is equal to the long term flicker severity for the continuous operation. The flicker severity of the whole wind farm is square root of the number of turbines times higher than that of a single wind turbine if the wind farm consists of the same type wind turbines. Thus, the number of the turbines that can be connected to the grid without exceeding the flicker emission limit is calculated as four. The most important parameter that could affect this value is the short circuit power of the grid. If this power is selected as 200 MVA, the number of turbine is calculated as twelve and selected as 60 MVA, it is calculated as only one. The remaining parameters that could change the number of turbines are grid impedance phase angle and annual average wind speed of the site. The number of turbines that can be connected to the grid will be maximum for impedance phase angle and annual average wind speed of the site. The number of turbines that can be connected to the grid will be maximum for impedance phase angle of 79° as in the steady state voltage change. The effect of annual average wind speed could increase the number of turbines by one at most even in extreme cases. However, for the case that the turbulence density is out of the limits defined in the standard, the effects of wind speed on the flicker severities may be significant.

### 3.2.2. Switching operation

In the switching operation, flicker severities and relative voltage change are determined. For the flicker calculation, only the values belonging to $\ell_1$ phase are utilized and two different states are regarded as follows: wind turbine start-up at cut-in wind speed and at rated wind speed. The acquired measurements for both types are shown Table 2. Besides, the minimum and maximum RMS values of the fictitious grid are calculated for both of the switching types as well and reported in Table 3. Flicker step and voltage change factors are calculated by applying the values acquired from the measurements in Tables 2 and 3, respectively as inputs to the related models. In the calculation of the flicker step factor, transient time period of a switching operation is assumed as three seconds so that the transient effects in MATLAB are ensured to be abated. Finally, acquired flicker step and voltage change factors are averaged. Herein, the short circuit power of the fictitious grid is assumed as 40 MVA in the calculations.

The effects of a given wind turbine on power quality could be estimated for a specific site in terms of switching operations thanks to Table 4. For instance, short term and long term flicker severities are calculated as 0.21 and 0.25, respectively for a wind turbine while substituting the short circuit power of the grid and the grid impedance angle with 120 MVA and 60°. Thus, the number of turbines that can be connected to the grid without exceeding the limit values becomes two regarding the switching operations.

The number of turbines is proportional to the short circuit power of the grid as in the continuous operation. For example, without affecting the power quality, eight wind turbines may be connected to the grid whose short circuit power is 200 MVA. The other parameter that affects the number of wind turbines is the number of the switching operations. It may be ensured that the number of turbines increases to 2–3 times higher for the same short circuit power while restricting the number of switching operations in 10 min and 2 h with a control system. The effects of the grid impedance phase angle on the flicker severities during the switching operations could be negligible.

For the wind turbines, relative voltage change is independent from the number of the turbines unless two of the turbines will perform a switching operation at the same time. Therefore, the parameters that are effective on the voltage change caused by a switching operation are short circuit power of the grid and grid impedance phase angle. The voltage change is calculated as 0.98 for the short circuit power of 120 MVA and as 0.59 for the short circuit power of 200 MVA for the given turbine. The impedance phase angle values for both of the short circuit power do not cause the voltage change to exceed the limit values. Hence, the voltage change occurring during the switching operations is not a constraint for the number of turbines considering the given turbine. However, if the limits determined for the relative voltage changes are under the value of 2%, the miniscule and majuscule values could be a problem in terms of power quality.

As mentioned before, the wind farm power is determined in Turkey considering a rule such that the total wind power should not exceed 5% of the short circuit power of the grid. In order to evaluate the feasibility and applicability of that rule, the calculations realized by considering the power quality characteristics of the given wind turbine for different regions and grids and the calculations for the conventional 5% rule are presented in Table 5.

Due to the fact that wind speed do not have a significant effect on flicker calculations during continuous operation, the annual average wind speed is considered as constant as 7.5 m/s in Table 5. Besides for the flicker calculation during switching operation, the number of switching operations is also considered as constant as they are assumed to be taken from the manufacturer.

Here, as the only parameter that can significantly change the calculations obtained by the 5% rule is the short circuit power of the grid, the number of turbines increases directly proportional to short circuit power. However due to IEC 61400-21, it has been observed that the general rules like 5% rule of Turkey redundantly limit the number of turbines that can be integrated with the grid.
such rules cannot prosperously protect the grid from power quality decrement in some cases. As an example, for the case that the short circuit power of the grid is 60 MVA, the number of wind turbines calculated due to 5% rule has similarities with the calculations realized by considering IEC standard for steady state voltage and continuous operation flickers. However, due to the power quality problems occurring during switching operation, integrating the mentioned 2.4 MW wind turbine into a grid with 60 MVA short circuit power will cause to exceed the limits of flicker and relative voltage change. Thus, even as it is considered as riskless by the conventional 5% rule, the wind turbine with those specifications is calculated due to 5% rule as shown in Table 5. For 200 MVA short circuit power, only lower numbers of wind turbines are obtained. Besides, the infinite value of relative voltage change for this short circuit power is caused by the fact that this value is independent from the number of wind turbines.

Lastly, the grid with 200 MVA short circuit power is considered as shown in Table 5. For 200 MVA short circuit power, only steady state voltage among the power quality characteristics has a limiting effect on the number of wind turbines. The calculations realized for the other power quality characteristics result in a greater number of wind turbines than the conventional 5% rule. However, since the grids generally have high values of steady state voltage, the limiting effect of steady state voltage reduces. Thus, the number of wind turbines that can be integrated with the grid is higher than the level determined by the conventional 5% rule. Due to this reason, the utilization ratio of wind power is lower than its maximum possible value especially for the grids with high values of short circuit power. Thus, the wind power cannot efficiently be utilized for countries having such conventional rules which in turn may result in several kinds of negatively economical, political, environmental etc. effects on the future of the country.

<table>
<thead>
<tr>
<th>Grid short circuit power (MVA)</th>
<th>Grid impedance phase angle (°)</th>
<th>Number of wind turbines that could be connected to grid without deteriorating the power quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>50</td>
<td>3</td>
</tr>
<tr>
<td>55</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>65</td>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>120</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>65</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>55</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>65</td>
<td>46</td>
<td></td>
</tr>
</tbody>
</table>

Table 3
The minimum and maximum values of $U_{\text{fic}}$ for phase L1 in the switching operations.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>$U_{\text{fic,max}}$</th>
<th>$U_{\text{fic,min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>325.09</td>
<td>339.02</td>
</tr>
<tr>
<td>2</td>
<td>327.11</td>
<td>337.43</td>
</tr>
<tr>
<td>3</td>
<td>326.95</td>
<td>339.11</td>
</tr>
<tr>
<td>4</td>
<td>327.44</td>
<td>337.27</td>
</tr>
<tr>
<td>5</td>
<td>326.53</td>
<td>338.87</td>
</tr>
</tbody>
</table>

Table 4
Flicker severities and the relative voltage change in the switching operations.

<table>
<thead>
<tr>
<th>Case of switching operation</th>
<th>Wind turbine start-up at cut-in wind speed</th>
<th>Wind turbine start-up at rated wind speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$U_{\text{fic,min}}$</td>
<td>$U_{\text{fic,max}}$</td>
</tr>
<tr>
<td>Measurement 1</td>
<td>0.22</td>
<td>0.23</td>
</tr>
<tr>
<td>Measurement 2</td>
<td>0.50</td>
<td>0.51</td>
</tr>
<tr>
<td>Measurement 3</td>
<td>0.17</td>
<td>0.18</td>
</tr>
<tr>
<td>Measurement 4</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>Measurement 5</td>
<td>1.01</td>
<td>1.02</td>
</tr>
</tbody>
</table>

Table 5
The number of the wind turbines that could be connected to the grid without deteriorating the power quality.
4. Conclusions

In this study, an application of a complete assessment procedure modeling for evaluating the power quality characteristics of wind turbines is realized. As the result of the evaluations, it has clearly been observed that the available wind potential cannot sufficiently be utilized in many cases in Turkey. One of the most important reasons for this issue is the regional conventional rules. Besides, in some cases it is observed that the power quality limits of the grid are exceeded with the application of conventional regulations. Thus, it is clearly presented that conventional regulations limit the wider and efficient use of wind power and replacement with such new assessment procedures should be considered.

Utilizing the proposed methodology, even transient voltage variations with small amplitudes can effectively be calculated and the effects of such situations on grid can be evaluated. The overall model can also be utilized for the test of the devices such as filters, etc. that are used for improving the power quality of the grid. Moreover, the proposed methodology has a quite suitable structure for adapting the upcoming changes in the regulations of wind power area. Some of the mentioned power quality problems can be solved by utilizing “Flexible AC Transmission System (FACTS)” devices such as SVC and STATCOM, particularly in weak grids. The analysis of employing such devices in wind power systems provides the future study of the authors.

Acknowledgements

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[10] Turkish electric transmission system supply reliability and quality regulations; 2004 [in Turkish].