# Voltage Dips at the Terminals of Wind Power Installations

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***Abstract*—This paper gives an overview of the kind of voltage dips or sags that can be expected at the terminals of a wind-power installation. The description is based on the study of those dips at the terminals of industrial installations. For voltage dips due to faults a classification into different types is presented. Five types appear at the terminals of sensitive equipment and thus have to be included when testing the wind-power installation against disturbances coming from the grid. Dips due to other causes are also discussed. Finally some thoughts are presented on voltage-tolerance requirements for wind-power installations.**

***Index Terms*—power quality, voltage dips (sags), electromagnetic compatibility (EMC), wind power installations.**

## I. INTRODUCTION

THE operation of wind-power installations after a disturbance in the power system is an issue of growing concern. Large wind parks at transmission level may adversely affect the stability of the transmission system. Smaller installations at distribution level may increase or decrease the reliability of the supply after a fault. An important criterion here is whether the wind-power installation will be able to operate normally immediately after the fault in the power system. The disconnection or otherwise mal-operation of wind-power installations will cause a multiple contingency with its associated high risk of supply interruptions.

For smaller wind-power installations, connected to the distribution network the impact of mal-operation of an individual installation is less severe. However a single fault at transmission level may affect all installations over a wide range of territory, such a fault may trigger the sudden loss of a substantial fraction of generation. This is again a serious threat to the security of the system.

The behaviour of the installation immediately after the fault is very much related to the behaviour during the fault. During the fault the installation experiences a voltage dip or sag: a short reduction in voltage. Thus the study of the impact of voltage dips on wind-power installations is an important part of guaranteeing the reliability of power systems with a substantial fraction of generation supplied by wind power.

Voltage dips have been widely studied in the power-quality field [1],[2] for their effect on industrial installations. The main problem of the short-duration reduction in voltage is that it leads to mal-operation of (power) electronic equipment as well as computers and control equipment [3]. More severe voltage dips even lead to stability problems for direct-driven induction and synchronous motors. The research on power quality issues during the last 15 years has resulted in a better understanding of the kind of disturbances that can be expected at the terminals of industrial installations.

In this paper we only consider disturbances that originate in the grid. The type of load connected to the grid does not significantly affect those disturbances (for a discussion on the effects on load on voltage dips, please refer to [4]). The disturbances at the terminals of a wind-power installation are of the same character as those at the terminals of an industrial installation. The effect of the load on the disturbances is much less than local variations within the system. Therefore the knowledge obtained from the study of industrial installations can be applied directly to wind-power installation.

This paper will describe the kind of voltage dips or sags that can be expected at the terminals of a wind-power installation. Section II of this paper introduces the different types of dips that occur due to earth faults and short circuits in three-phase power systems. This classification is used in Section III to discuss the testing of wind-power installations against voltage dips due to faults. A distinction is made in Section III between installations connected at transmission level and those connected at distribution level. Section IV discusses methods for obtaining information on the number of dips that can be expected at a certain location in the system. In Section V dips due to other causes are discussed and in Section VI the authors give some of their thoughts about voltage-tolerance requirements.

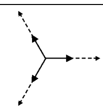
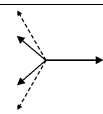
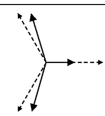
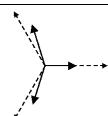
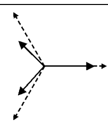
## II. SYMMETRICAL AND NON-SYMMETRICAL FAULTS

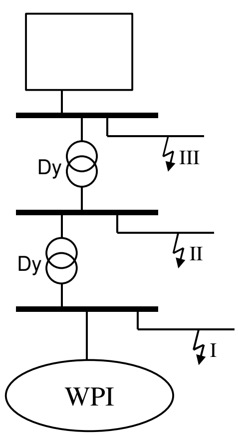
The main causes of voltage dips at the terminals of a wind-power installation are short-circuits and earth faults in the grid. The fault current causes a voltage drop over a wide part of the network. The voltage starts to recover when the protection clears the fault or when the fault clears itself in case of a self-clearing fault. However the number of self-clearing faults leading to serious voltage dips is very small.

In a three-phase power system, a number of different fault types can occur: single-phase-to-ground; phase-to-phase; two-phase-to-ground and three-phase. Different fault types lead to different dips: i.e. a different relation between the remaining voltages in the three phases. A classification commonly used is the one in seven types as shown in Table I.

Table I shows the definition of the dip type (as an expression for the complex phase voltages) together with a typical phasor diagram. In the expressions for the complex phase voltages, V is the so-called characteristic voltage of the dip, and $E_1$ is the pre-event voltage. The reader will notice that types B and E are missing. These two types include a zero-sequence component which does not have to be included when considering the impact of the dip on equipment. For a complete discussion of the classification of three-phase unbalanced dips, please refer to [5],[6],[7] or to other literature on this subject.

TABLE I: SEVEN TYPES OF THREE-PHASE UNBALANCED VOLTAGE DIPS.

| Type | Voltages | Phasors |
|---|---|---|
| A | $U_a = V$<br>$U_b = -\frac{1}{2}V - \frac{1}{2}jV\sqrt{3}$<br>$U_c = -\frac{1}{2}V + \frac{1}{2}jV\sqrt{3}$ |  |
| C | $U_a = E_1$<br>$U_b = -\frac{1}{2}E_1 - \frac{1}{2}jV\sqrt{3}$<br>$U_c = -\frac{1}{2}E_1 + \frac{1}{2}jV\sqrt{3}$ |  |
| D | $U_a = V$<br>$U_b = -\frac{1}{2}V - \frac{1}{2}jE_1\sqrt{3}$<br>$U_c = -\frac{1}{2}V + \frac{1}{2}jE_1\sqrt{3}$ |  |
| F | $U_a = V$<br>$U_b = -\frac{1}{2}V - \left(\frac{1}{3}E_1 + \frac{1}{6}V\right)j\sqrt{3}$<br>$U_c = -\frac{1}{2}V + \left(\frac{1}{3}E_1 + \frac{1}{6}V\right)j\sqrt{3}$ |  |
| G | $U_a = \frac{2}{3}E_1 + \frac{1}{3}V$<br>$U_b = -\frac{1}{3}E_1 - \frac{1}{6}V - \frac{1}{2}jV\sqrt{3}$<br>$U_c = -\frac{1}{3}E_1 - \frac{1}{6}V + \frac{1}{2}jV\sqrt{3}$ |  |




| | ϕn | ϕϕ | 2ϕn | 3ϕ |
|---|---|---|---|---|
| I | **C** | **D** | **F** | **A** |
| II | **D** | **C** | **G** | **A** |
| III | **C** | **D** | **F** | **A** |

Fig.1: Voltage dips at the interface to a wind-power installation for different types of fault in the power system.

The relation between dip types and fault types is shown in Figure 1. For example a phase-to-phase fault at location II gives a type C dip at the interface with the wind-power installation. The dips are given for equipment connected in delta, which is the most common way of connecting three-phase equipment like electrical machines and power-electronic converters. In case there are additional transformers between the interface with the system and the actual wind turbines, a similar reasoning can be used to determine the dip type at the wind-turbine terminals: a Dy-connected transformer changes type C into type D; type D into type C; type F into type G; and type G into type F. Type A is not affected by any transformer.

For study of the impact of voltage dips on wind-power installations it is sufficient to know these dip types and the values of the characteristic voltage $V$ that can be expected.

## III. VOLTAGE-TOLERANCE CURVES

The so-called voltage-tolerance curve is a useful tool to describe the way in which equipment copes with voltage dips at its terminals. When testing existing equipment against tolerance requirements it is not needed to obtain the complete curve, but during the design and development stage the voltage-tolerance curve is a good tool to describe the actual performance. A hypothetical example of a voltage-tolerance curve is shown in Figure 2. The underlying assumptions of this way of presenting the performance of equipment are as follows:

- Voltage dips can be characterised by one retained voltage and one duration.
- Any increase in duration and any decrease in retained voltage will make the event more severe.
- Two dips with the same retained voltage and the same duration have the same effect on the equipment.

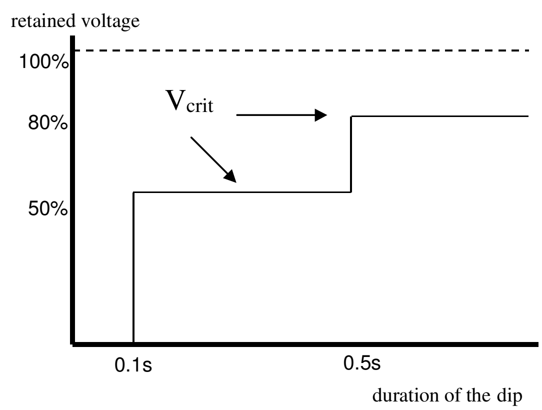



Fig. 2: Hypothetical example of a voltage-tolerance curve.

Under the first assumption, every dip corresponds to one point in the retained-voltage-duration plane in Figure 2. Every dip that ends up below the curve will lead to mal-operation of the equipment; every dip above the curve will not. The voltage-tolerance curve is obtained by applying voltage dips of different retained voltage and duration until the position of the curve is known with the required accuracy.

As we saw in the previous section the third assumption may not be true for voltage dips due to faults. A dip of type A may affect equipment in a completely different way from a dip of type C, even if they have the same retained voltage and duration. The consequences of this for the testing will be discussed in more detail below, where a distinction is made between installations connected to the transmission grid and those connected to the distribution grid.

### A. *Transmission Grid*

Any installation connected to the transmission grid will almost exclusively experience voltage dips due to faults in the transmission grid. Faults at lower voltage levels than where the installation is connected only cause shallow dips that are normally not of concern.

For voltage dips due to faults at transmission level, the characteristic voltage is a real number: i.e. there is no phase-angle jump in the characteristic voltage. The voltage-dip can thus be described by only two parameters: retained voltage and duration. For completeness a voltage-tolerance curve has to be obtained for each of the five types of dips in Table 1. This does not mean that the tests will always result in five distinctly different curves, but the different types do have to be all considered. Knowledge of the equipment may help in merge dip types. For a directly-connected induction machines it can be easily understood that types C and D give similar behavior (so do types F and G). However for a adjustable-speed drive the effect of types C and D is distinctly different [3].

### B. Distribution Grid

Installations connected to the distribution grid also experience voltage dips due to faults at distribution voltage levels. An important characteristic of those dips is that they are associated with a jump in characteristic phase angle: i.e. the characteristic voltage $V$ becomes complex:

$$\underline{V} = Ve^{j\varphi}$$

where $V$ now stands for the absolute value of the characteristic voltage (the characteristic retained voltage) and $\varphi$ for its phase angle (the characteristic phase-angle jump). To find a relation between the retained voltage and the phase-angle jump, the so-called "impedance angle" has been introduced in [2].

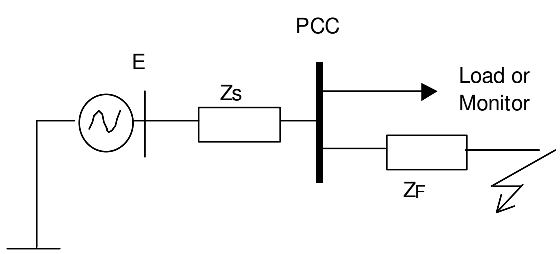



Fig. 3: Voltage divider model for voltage dip: the fault position is to the right, the source feeding the fault to the left.

The complex voltage at the point-of-common coupling (PCC) between the fault and the load (or monitor) is found from:

$$U_{PCC} = E\frac{Z_F}{Z_F + Z_S} \qquad (2)$$

with $E$ the pre-fault voltage, $Z_F$ the impedance between the PCC and the fault and $Z_S$ the source impedance at the PCC. As both impedances are complex numbers, the resulting voltage $U_{PCC}$ will show a magnitude drop and a change in phase angle compared to the pre-fault voltage $E$. In transmission systems, both $Z_F$ and $Z_S$ are formed mainly by transmission lines, so that the phase angle jump will be small. In distribution systems, $Z_S$ is typically formed by a transformer with a rather large X/R ratio, whereas $Z_F$ is formed by lines or cables with a much smaller X/R ratio. This will lead to a significant change in phase angle, especially for cable faults.

Equation (2) can be rewritten as follows:

$$\frac{U_{PCC}}{E} = \frac{\lambda e^{j\alpha}}{1+\lambda e^{j\alpha}} \qquad (3)$$

with $\frac{Z_F}{Z_S} = \lambda e^{j\alpha}$. The value of $\lambda$ depends on the distance to the fault, whereas $\alpha$ is the angle between source impedance and the feeder impedance, which is constant for any feeder/source combination. This angle is referred to as the "impedance angle" in [2]. The phase-angle jump is the argument (angle) of (3):

$$\Delta\phi = \arg\left(\frac{\lambda e^{j\alpha}}{1+\lambda e^{j\alpha}}\right) \qquad (4)$$

For any given impedance angle, there is a unique relation between voltage dip magnitude and phase-angle jump. A network operator often uses the same types of cables and lines and the same types or transformers throughout their network, so that a limited number of impedance angle values results.

The result of these calculations is shown in Figure 4. Note that the term "magnitude" is used instead of retained voltage. For a given retained voltage and a given impedance angle the phase-angle jump can be obtained from the figure.

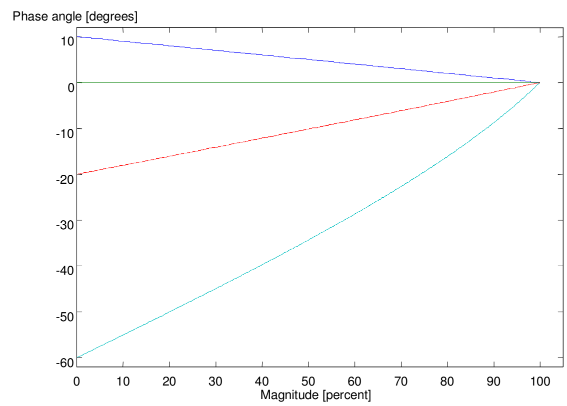



Fig. 4: Relation between retained voltage and phase angle for voltage dips due to three-phase, two-phase-to-ground and phase-to-phase faults. The curves are given for impedance angles of (top-to-bottom) +10°, 0, -20° and -60°.

The above expressions only hold for voltage dips due to two and three-phase faults, not for voltage dips due to single-phase faults. The effect of a single-phase fault depends on the type of system-earthing used. In a high-impedance earthed system, single-phase faults do not cause any significant voltage dips at all. They do cause a zero-sequence voltage but this does not affect end-user equipment so there is no need to consider them as voltage dips. In solidly-earthed system single-phase faults do lead to voltage dips but less severe ones than those due to the other types of faults. Not even is the retained voltage higher, also the phase-angle jump is less severe. The resulting characteristics are shown in Figure 5 for a solidly-earthed system where it has been assumed that positive and zero-sequence source impedance are the same, which is a reasonable assumption for distribution systems.

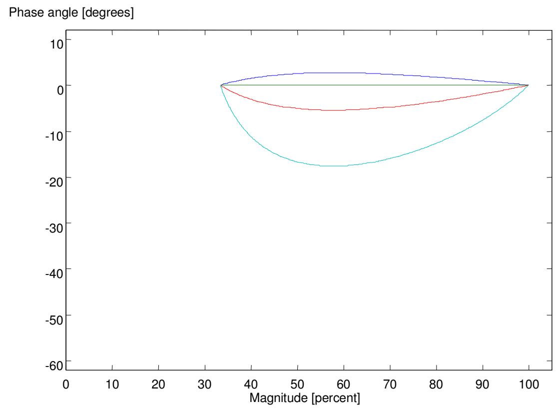



Fig. 5: Relation between retained voltage and phase angle for voltage dips due to single-phase faults. The curves are given for impedance angles of (top-to-bottom) +10°, 0, -20° and -60°.

For equipment connected to the distribution grid, the phase-angle jump has to be included when assessing its tolerance against voltage dips. This can be done by determining different voltage-tolerance curves for each dip type. For types C and D the difference between dips due to single-phase and those due to phase-to-phase dips has to be considered as well. The exact implementation of this depends on the application.

## IV. Predicting Voltage-Dip Statistics

The retained voltage during the event is used to classify the total number of dips experienced by a given load. In order to distinguish between severe dips and shallow ones a classification of these in terms of retained voltage is useful.

From the point of view of a sensitive wind power installation, what matters is the expected number of severe dips (i.e. retained voltages below the critical voltages) because all these dips will expose the installation to a potential disconnection or mal-operation. A suitable way to present this information is the cumulative histogram of retained voltages (dips).

How often severe dips occur at a given location depends on several factors, the number of faults occurring in the "electrical neighbourhood" being the most important one. This "electrical neighbourhood" is called exposed area and contains all buses and line segments at which faults cause dips more severe than a given critical value. An analogue concept in radial systems is the critical distance that is the length of feeders in which faults cause severe dips at a given observation bus.

Predicting dip frequency requires an accurate model of the network and reliability data for all the components. The magnitude of a dip caused by a fault at a bus $f$ of the system can be determined applying short circuit theory. How often one of these dips occurs at terminal of a wind power installation in a given bus $k$ depends on the reliability of the bus $f$ or more precisely on the fault rate of the fault position $f$. If the fault rate of the fault position $f$ is $\lambda_f$, the particular dip caused by this fault will be seen $\lambda_f$ times per year.

Expected frequency of dips can be calculated combining during fault voltages (retained voltages) and the fault rate corresponding to the fault positions. Two methods have been extensively discussed in the literature: Method of critical distance and method of fault positions.

### A. Method of Critical Distance (Approximate Expressions)

The method uses the voltage divider model shown in Figure 3 to estimate dips due to short circuit faults in distribution feeders. To estimate the critical distance and the expected number of severe dips, the critical voltage $V_{crit}$ of Figure 2, is used.

From (2) and expressing the feeder impedance $Z_F$ in terms of the length of the feeder measured from the PCC to the fault point and assuming that the X/R ratios of source and feeder are equal, we find an approximate expression for the critical distance.

$$L_{crit} = \frac{V_{crit} \cdot Z_S}{(1 - V_{crit}) \cdot z_F} \tag{5}$$

where $z_F$ is the feeder impedance per kilometer.

If the fault rate in the segment of the feeder between the PCC and the critical point is γ fault per km-year, then the expected number of trips due to dips is:

$$Fdip_{crit} = \frac{V_{crit} \cdot Z_S}{(1 - V_{crit}) \cdot z_F} \cdot \gamma \tag{6}$$

Equation (6) does not give the total number of dips expected at PCC but the critical ones, i.e. those that may cause equipment trips. To fully describe the PCC in terms of voltage dips it is necessary to segment the dip range and estimate the frequency in each range. Equation (6) is also useful for that. We make $V_{crit}$ variable and plot $F_{dip}$ versus V. Figure 6 shows that relation in qualitative terms.

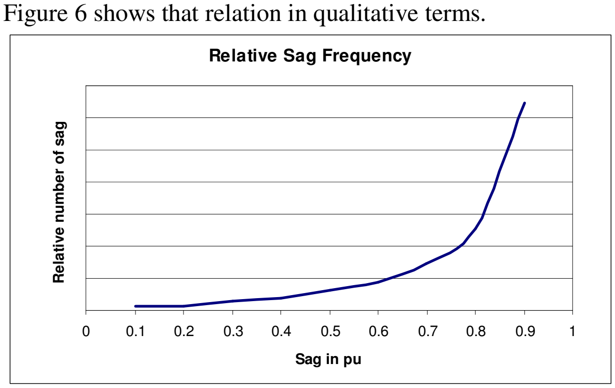



Fig. 6. Relative voltage dip frequency

### B. Method of Fault Positions

The Method of Fault Positions is a straightforward but more time-consuming way to determine the expected number of dips and their characteristics. Basically, the method applies short circuits faults (symmetrical and un symmetrical) in a number of positions along lines and busses throughout (part of) the system.

Retained voltages are calculated from system-fault performance for each bus of interest. The short-circuit frequency at each position is calculated using the fault rates. Combining dip characteristics with frequency of occurrence probabilistic information about dips and their characteristics is obtained.

Consider a network with N+1 nodes and its impedance matrix **Z**. The reference node is named zero and is chosen to be the common generator node. Among the remaining N nodes are the created nodes on lines needed to simulate faults at the chosen fault positions. If the voltages before the fault are assumed 1 pu everywhere in the network, from standard fault analysis we find that the retained voltage at node *k* due to a three-phase fault at node *f* is:

$$v_{kf} = 1 - \frac{z_{kf}}{z_{ff}} \tag{7}$$

where $z_{ff}$ is the impedance seen looking into the network at faulted node *f* and $z_{kf}$ is the transfer impedance between node *k* and *f*. Equation (7) can also be expressed in matrix form.

$$V_{dip} = 1 - \left[diag(Z)\right]^{-1} \cdot Z \tag{8}$$

where *diag(Z)* is the matrix corresponding to the diagonal of the impedance matrix **Z**.

$V_{dip}$ is called dip-matrix and contains all the retained voltages for every bus of the system and for faults at every fault position. The dip-matrix contains more nodes than the physical buses because includes several fault positions on lines. Nodes corresponding to physical buses of the system have a fault rate given by the actual fault rate of the bus. Fault positions on lines have a fault rate that is a fraction of the actual line fault rate. If more than one fault position is considered on the line and faults are uniformly distributed along the line the actual fault rate need to be divided by the number of fault positions in order to calculate the frequency of the resulting dips. If only one fault position is considered on a given line, then the actual fault rate is taken.

Once the fault rate for all fault positions is determined the expected number of dips and their characteristics can be determined by combining the dip-matrix and the fault rates.

Let λ be the vector containing the corresponding fault rate of each one of the Fp fault positions.

$$\boldsymbol{\lambda} = \left(\lambda_1 \ldots, \lambda_k \ldots, \lambda_N \ldots, \lambda_{Fp}\right) \tag{9}$$

Each fault will cause a drop in voltage for all buses but only part of these fault-caused events will be counted as dips at load buses (the ones for which $v_{kf} < 0.9$ pu). A large part of these events will result in retained voltages above 0.9 pu. The vector λ contains the yearly event rate (voltage drops) caused by faults and can be used to estimate dips frequency. To illustrate this consider an arbitrary observation bus *k* at which a sensitive wind installation may be connected. Table II shows row *k* (transposed) of the dip matrix and vector λ.

TABLE II: AN ARBITRARY ROW OF THE DIP MATRIX AND THE CORRESPONDING FAULT RATE.

| Magnitude of dips at bus *k* ($v_{kf}$) | Frequency (λ) |
|---|---|
| $v_{k1}$ | $\lambda_1$ |
| $v_{k2}$ | $\lambda_2$ |
| … | … |
| $v_{kN}$ | $\lambda_N$ |
| … | … |
| $v_{kFp}$ | $\lambda_{Fp}$ |

To build the cumulative histogram the during-fault voltages contained in Table II need to be grouped according to the dip magnitude (retained voltage) of interest. For example if we take the bins shown in the first column of Table III then the second column would be the data table for building the cumulative histogram.

Finally, in order to take into account the different fault types, the procedure described needs to be performed for each one of the dip-matrices corresponding to unsymmetrical faults and the resulting frequencies combined according to the probability distribution of fault types.

TABLE III: CUMULATIVE DIP FREQUENCY FOR A GENERAL BUS *k*:

| Dip Magnitude bins (pu) | Frequency (events/year) |
|---|---|
| $0 - 0.55$ | $\sum_i \lambda_i : v_{ki} \le 0.55$ |
| $0.55 - 0.6$ | $\sum_i \lambda_i : 0.55 < v_{ki} \le 0.6$ |
| $0.6 - 0.65$ | $\sum_i \lambda_i : 0.6 < v_{ki} \le 0.65$ |
| : | : |
| $0.85 - 0.9$ | $\sum_i \lambda_i : 0.85 < v_{ki} \le 0.9$ |
| $0.9 - 0.95$ | $\sum_i \lambda_i : 0.9 < v_{ki} \le 0.95$ |

## V. OTHER DIP TYPES

Not only faults lead to voltage dips: any short-duration overcurrent gives a voltage dip elsewhere in the grid. The most severe overcurrents, apart from faults, are associated with motor starting, transformer energizing [8], and capacitor energizing. Even thought the resulting voltage disturbances are less severe than those due to faults, their different characteristics require special attention.

### A. *Motor Starting*

Voltage dips due to motor starting are shallow: the retained voltage is rarely below 80% of nominal but may be of long duration. They are not a concern at most locations in public grids. An appropriate way of testing is to study the ability of the installation to operate for a longer duration (e.g. 1 minute) at an rms voltage of 80 to 85% of nominal. For large installations such a demand may exist anyway to prevent the installation from aggravating voltage-stability problems.

### B. *Transformer Energising*

Voltage dips due to transformer energising have similar magnitude and duration range as dips due to motor starting. However transformer-energising voltage dips are associated with a large amount of even-harmonic distortion which could lead to interference with the control of power-electronic converters. In such a case transformer saturation after a voltage dip may also cause interference. Testing against these disturbances may consist of applying bursts of second and fourth harmonic distortion with amplitudes up to 10% of nominal and duration up to several seconds.

### C. Capacitor Energising

Capacitor energising gives a voltage disturbance that is normally not referred to as voltage dip but as a voltage transient. But like a voltage dip its consequence is an increased risk of mal-operation of electronic equipment. Therefore its inclusion in this paper is justified. A set of tests may consist of a voltage drop down to zero, followed by a recovery in the form of a damped sinewave. The frequency of the damped sinewave can be between 250 Hz and 1 kHz, with damping time constants up to 1 cycle of the power-system frequency.

## VI. Voltage-Tolerance Requirements

When designing a wind-power installation it is important to consider all the voltage disturbances mentioned in this paper. When this is done at an early stage, e.g. when designing protection and control of the power-electronics interface with the grid, it is easy to simulate a wide range of cases.

The actual voltage-tolerance requirements of the installation are outside of the scope of this paper. They will be dictated by the security and reliability demands of the grid and of the wind-power installation. However some important general comments can be made, with reference to the discussion on designing industrial power systems in [9].

i. It is obvious that wind-power installations, like all other equipment will have to tolerate normal operating conditions as defined e.g. in EN 50160. Examples of these are rms voltages between 85% and 110% of nominal and THD up to 8%. These ranges may be different for different locations and for different voltage levels.

ii. The installation should also be tolerant for "normal events" like motor starting, transformer energising and capacitor energising. These events are part of the normal operation of the power system and should not lead to operational problems or equipment failure. Note that this philosophy does not rule out improvements in the grid like synchronised switching. For large installations the voltage-tolerance requirements may be based on the local environment. This poses the risk however of future interference problems due to changes in the grid. For smaller "off-the-shelf" equipment it is recommended to pursuit voltage-tolerance requirements based on the before-mentioned worst-case tests.

iii. The tolerance of equipment against disturbances due to faults in the grid (dips and interruptions) can only be determined from a discussion on security and reliability. Several network operators have started to define voltage-tolerance curves, albeit without distinguishing between different dip types. The above-mentioned methods for predicting the dip frequency should be used to come to local and overall voltage-tolerance requirements.

## VII. Conclusion

Any installation connected to the power grid experiences a range of disturbances. The number of disturbances is strongly dependent on the location, but the type of disturbances is similar for every location.

Faults in three-phase system lead to five types of voltage dips at the terminals of wind-power installations. The wind-power installation is not different from any other installation in that respect. When assessing the tolerance of wind-power installations against voltage disturbances these five types should be considered. For installations connected to distribution systems, also the phase-angle jump should be considered.

Also motor starting, transformer energising and capacitor energising lead to voltage disturbances that may pose a threat to the correct operation of the installation. The installation should be immune to these "normal operation events" as well as to variations of rms voltage, frequency, distortion, etc. during normal operation. Standard requirements and tests have to be developed for this.

For voltage dips due to faults, well-defined voltage-tolerance requirements have to be developed. These have to consider the different dip types, should be accompanied by a clear testing protocol, and be based on the security and reliability requirements of the system. Different requirements and testing protocols may be developed from the viewpoint of the reliability of the wind-power installation.

With any of these requirements and protocols knowledge obtained from the study of industrial installations can be used.

## Acknowledgment

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