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RESEARCH ARTICLE

Wind farm voltage dip measurements

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ABSTRACT

This paper is based on continuous measurements of voltages and currents from three wind farms for a period of 1 year, and the focus is on voltage dips. The purpose is to get an overview of the characteristics and rate of voltage dips, which occur in the wind farms and to study the wind turbine responses to voltage dips. In each of the wind farms there is one measurement point at a single wind turbine and one for measuring the contribution from the whole wind farm. Different wind turbine technologies are used in the three wind farms; fixed speed turbines with directly connected induction generators in wind farm 1 and variable speed turbines with power electronics converters and synchronous generators in wind farms 2 and 3. Voltage dips are evaluated according to the standard EN 50160, by considering the durations and residual voltages of the positive sequence component voltage dips. Some examples of voltage dip events with corresponding responses in active and reactive power are shown and discussed with a view to the different technologies. Copyright © 2013 John Wiley & Sons, Ltd.

KEYWORDS
measurements; fixed speed wind turbine; variable speed wind turbine; voltage dip; fault ride through

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1. INTRODUCTION

Wind power generation capacity is growing worldwide, meeting the growth in electricity demand and the political goal of increasing the amount of energy coming from renewable resources. The European Union has set a goal to have 20% renewable energy in Europe by 2020, and wind power is pointed out to provide for more than one third of the renewable electricity.[1] As the amount of wind power increases, its impact on the network also becomes more significant.

This paper focuses on voltage dips, and is based on 1 year continuous measured data from three wind farms. The wind farms are located within a geographical area of about 400 km, and have different wind turbine technologies, both fixed and variable speed. To identify the characteristics and rate of voltage dips occurring on the terminals of the different wind turbines or wind farms, a mapping of voltage dips in the measured data is carried out. Different definitions of voltage dips (voltage sags) exist,[2] but the definition given by EN 50160[3] is used in this work. According to this standard, a voltage dip is a temporary reduction of the root mean square (rms) voltage below 90% of the reference voltage (nominal or declared voltage) at a point in the electric power system, with duration from 0.01 s to 60 s. The duration is defined as the time from when the voltage goes below 90% to when it goes above 90% again.[3] The minimum value of rms voltage during the dip is named residual voltage and is expressed as a percentage of the reference voltage. A supply interruption is defined as a condition where the voltage falls below 5% of the reference voltage on all phases.[3] Interruptions lasting up to 3 min are defined as short interruptions. A voltage dip is typically associated with the occurrence of a short circuit somewhere in the electrical system, the starting of an induction motor or transformer energization. The durations of dips caused by short circuits are determined by the operation time of the protection and breakers, and are generally much shorter than dips associated with motor starting.[2] Voltage dips caused by short circuit generally have sharp recovery, whereas dips caused by motor start-up or transformer energization recover slower.[4]

Several publications have presented results of voltage dip measurements. Results from large power quality surveys in Italy and the USA are presented in[5] and[6], respectively. Both publications contain voltage dips statistics including characteristics of the measured dips, and thus provide information on which dips that can be expected to occur in the networks, without any focus on wind power. A general discussion on voltage dips on wind turbine terminals are given in Bollen *et al*. (2005).[7] A mapping of different grid fault types and their frequency, and an overview of grid connection requirements in different countries are given in Iov *et al*. (2007).[8] Present grid codes of most countries contain requirements for fault ride-through (FRT; low voltage ride-through) capabilities of wind turbines.[9] The requirements are given as voltage versus time curves, specifying the minimum voltage level and maximum duration of voltage dips for which wind turbines must remain in operation. The intention is to prevent disconnection of large amounts of wind power during system disturbances. FRT capabilities of full-rated converter wind turbines from a specific manufacturer are discussed in the study of Fischer and Schellschmidt (2011).[10] The paper also shows results from FRT tests using a special short circuit test container.

This paper consists of four chapters, in addition to the introduction in Section 1. Section 2 describes the locations and characteristics of the three wind farms, the measurement system and measurement period. Statistics of voltage dip durations and residual voltages are presented according to the standard EN 50160[3] in Section 3. Section 4 presents examples of measured voltage dip events. Section 5 contains some general discussion and conclusions.

2. MEASUREMENT LOCATION AND SET-UP

The three wind farms are located along the coastline, within a geographical area of about 400 km. Wind farms 1 and 2 are located in fairly flat terrain, whereas wind farm 3 is on top of a ridge. One wind farm has fixed speed turbines, whereas the two others have variable speed turbines. Main characteristics of the wind farms and grid connections are given in Table I.

The network short circuit capacities are for the grid as seen from the connection point of each wind farm, on the high voltage side of the transformer. The short circuit contributions of the wind farms are not included. A larger angle means a more inductive network. For wind farm 1, the short circuit capacity is found through simulations on a network model including the topology and impedances up to 132 kV transmission network level. No data for variation between summer and winter were available. For wind farms 2 and 3, the short circuit capacities were provided by the local utility companies. The values are only indicative, as they are depending on the network configuration and short circuit capacity of the transmission network, which will vary through the year. Especially in the connection point of wind farm 3, there is a very large difference between summer and winter.

The measurements are carried out using state-of-the-art instruments (Elspec G4420/G4430[11]), which continuously samples voltage and current measurements for all three phases and store all measurements to a central database. All instruments have sample rates per channel larger than 25 Hz. Instrument measurement accuracy is 0.2% for voltage and 0.5% for current. Measured data are communicated either using global system for mobile communication with global positioning system synchronization or via broadband with Simple Network Time Protocol synchronization. Processing of data is partly by the instruments and partly by post-processing accessing the measurement database. The instrument software provides power quality parameters according to EN 61000-4-30,[12] and for the post-processing both instrument software and a set of developed MATLAB[13] routines are used.

This paper considers measurements recorded from 1 January 2010 to 1 January 2011. The measurement system was in operation for the whole period, but some data are missing because of synchronization errors and others. Wind farm 1 stands out as having longer periods of missing data than the other measurement locations, and data are missing for 82 and 53% of

Table I. Wind farm and grid characteristics.

Wind farm	1	2	3
Number of turbines	24	5	15
Rated power (MW)	55.2	11.5	45.65
Rated voltage in measurement point (kV)	0.69 (turbine)66 (farm)	22 (turbine and farm)	22 (turbine)66 (farm)
Wind turbine type	fixed speed, active stall control	variable speed, pitch control, gearless	variable speed, pitch control
Generator type	Induction, squirrel cage	Multi-pole, synchronous	Permanent magnet synchronous
Grid interface	Direct connection	Full-scale power electronics converter	Full-scale power electronics converter
Reactive control	Shunt capacitors	Grid-side converter voltage controller	Grid-side converter voltage controller
Grid short circuit capacity (MVA)	$175\angle 75^\circ$	$117\angle 69^\circ$ (summer) $208\angle 65^\circ$ (winter)	$94\angle 73^\circ$ (summer) $419\angle 71^\circ$ (winter)

the time in June and July, respectively. In wind farm 2, data are missing for 7 and 5% of the time in April, for the farm and the turbine measurement points, respectively. For the rest of the measurements, there are only negligible amounts of missing data.

3. VOLTAGE DIP STATISTICS

This chapter presents some statistics of voltage dip events occurring in the wind farms and turbines during the measurement period of 1 year. Table II summarizes the counts of three-phase, two-phase and one-phase voltage dips and the corresponding number of disconnections. Disconnection means that the voltage dip is followed by a disconnection of the wind turbine and/or wind farm, so that the active power goes from a positive value before the dip to zero after the dip. Following the recommendations from EN 50160,[3] line-to-line voltages are considered, and the number of line-to-line voltages involved in each voltage dip event are detected and stored. A simple way of classifying the type of dip has been applied. A fault is classified as three-phase, two-phase or one-phase dip according to how many of the line-to-line voltages that go below 90% of the nominal voltage during the duration of the voltage dip. This means that the duration and residual voltage is not necessarily equal for all of the line-to-line voltages involved in a polyphase dip, and a three-phase dip may be unsymmetrical.

It can be seen from Table II that much fewer voltage dips are registered in wind farm 3 than in the two other wind farms. The highest number of voltage dips is seen in wind farm 1, with a high number of three-phase dips, and a very high number of single phase dips at the wind farm measurement point. At wind turbine 1 however, only few single phase dips are registered. Wind farm 2 has approximately half the number of three-phase dips compared with wind farm 1. Most dips in wind farm 2 are single-phase dips. For all measurement locations except wind turbine 1, the majority of the voltage dips are single phase. For all measurement locations, the numbers of three-phase dips are larger than the number of two-phase dips.

For all measurement locations, very few of the dips led to disconnection of the wind turbines. However, the low numbers of disconnections due to voltage dips are a bit misleading, as in many cases the wind turbines were not generating power when the dips occurred. Reasons for this could be low wind speeds or maintenance. This applies to about 45% of the dips in wind farm 1, about 13% of the dips in wind farm 2 and about 25% of the dips in wind farm 3. Most of the disconnections occurred after three-phase dips. Only one interruption lead to disconnection for wind farm 2. For the other interruptions, the wind turbine or farm was already disconnected before the interruptions happened. For location 1 the number of interruptions is larger for the wind turbine than the farm, but data are missing for the wind farm for periods when interruptions were registered in the turbine.

3.1. Classification of voltage dips according to positive sequence

EN 50160[3] suggests that some polyphase aggregation is applied for the evaluation of voltage dips. This means that an equivalent dip with a single duration and single residual voltage is defined for the polyphase dip. The standard also specifies categories to be used for voltage dip statistics. In the following, polyphase aggregation is applied by considering the positive sequence component of the voltage, and the voltage dips are classified according to the duration and residual voltage of the positive sequence component. This choice is in accordance with CENELEC (2008).[13]

Table II. Number of voltage dips and disconnections for each of the measurement locations.

	Wind farm location:					
Number of:	WF 1	WT 1	WF 2	WT 2	WF 3	WT 3
Three-phase[a] dips	26	25	14	13	5	4
Disconnections after three-phase dips	1	2	0	1	1	1
Two-phase[a] dips	11	17	1	3	2	4
Disconnections after two-phase dips	1	0	0	0	0	1
One-phase[a] dips	36	3	22	20	12	13
Disconnections after one-phase dips	0	0	0	0	0	1
Interruptions	1	7	4	4	0	0
Disconnections after interruptions	0	0	1	0	0	0

WF = wind farm measurement point; WT = single wind turbine measurement point.

[a] Three-phase, two-phase and one-phase dips refer to the number of line-to-line voltages involved in the dip.

Figures 1–3 show positive sequence voltages for the six measurement locations classified according to the minimum residual voltages and the duration of the dips.

Looking at the positive sequence voltage, a total number of 48 voltage dips are found in WF 1 and 37 dips in WT 1. This is less than the total number line-to-line voltage dips of 73 for WF 1 and 45 for WT 1. Thus, even if an event is classified as a dip considering the line-to-line voltage, the corresponding positive sequence voltage may not go low enough to be a dip. This is especially valid for single-phase dips. All dips measured in wind farm 1 have residual voltages between 0.7 and 0.9 pu, except two dips at the wind farm measurement point (WF1) with residual voltages between 0.4 and 0.7 pu. Three dips with duration longer than 5 s are found in WF 1, and none in WT 1. Four dips with duration 1–5 s are found in WT 1, and none in WF 1. The rest of the dips have durations between 0.01 and 1 s.

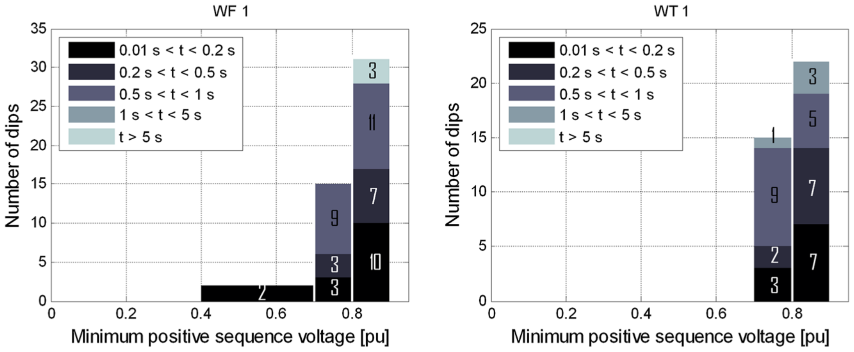

Figure 1. Voltage dips in wind farm 1 by positive sequence dip duration and residual value.

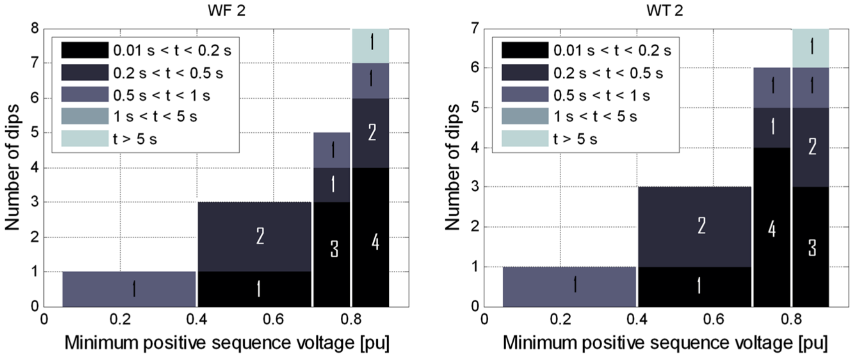

Figure 2. Voltage dips in wind farm 2 by positive sequence dip duration and residual value.

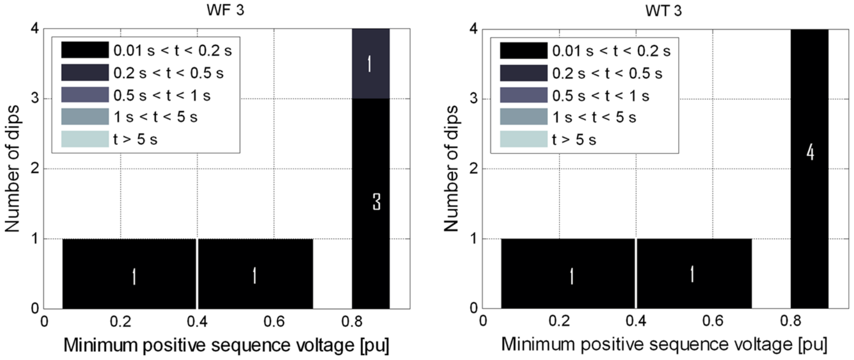

Figure 3. Voltage dips in wind farm location 3 by positive sequence dip duration and residual value.

One positive sequence voltage dip leads to disconnection of both WF 1 and WT 1. The residual voltages were between 0.7 and 0.8 pu in both measurement points. This event is further discussed in Section 4.2. In addition one disconnection was seen in WF 1 after a dip with residual voltage between 0.7 and 0.8 pu, and one in WT 1 with residual voltage between 0.8 and 0.9 pu. In all cases, the dips had durations from 0.5 to 1 s.

Looking at the positive sequence voltage, a total number of 17 voltage dips are found in both measurement points in wind farm 2. The total numbers of dips in the line-to-line voltages were 37 for the wind farm measurement point (WF 2) and 36 for the wind turbine measurement point (WT 2), which are more than double of the number of positive sequence dips. The majority of the dips have residual voltages between 0.7 and 0.9 pu. In both WF 2 and WT 2, there is one dip with duration longer than 5 s, whereas the remaining dips have durations from 1 to 0.2 s. One positive sequence dip leads to disconnection of WT 2. The duration of the dip was between 0.5 and 1 s, and the residual voltage was between 0.05 and 0.4 pu, and thus it was a very large dip.

A total number of six positive sequence voltage dips are found in both measurement points in wind farm 3. The total number of dips in the line-to-line voltages was 19 for WF 3 and 21 for WT 3. This is more than triple of the number of positive sequence dips. All dips except one have durations between 0.01 and 0.2 s. In both measurement points, there are one dip with residual voltage of 0.05–0.5 pu and one dip with residual voltage of 0.4–0.7 pu. The remaining dips have residual voltages between 0.8 and 0.9 pu. One positive sequence voltage dip leads to disconnection of both WF 3 and WT 3. This dip had a duration of 0.01–0.2 s and residual voltage between 0.05 and 0.4 pu in both measurement points, thus it was a short but large dip.

4. EXAMPLES OF VOLTAGE DIPS AND DYNAMIC RESPONSES

In the following subchapters, examples of voltage dip events that occurred during the measurement period are shown, together with corresponding dynamic responses in active and reactive power. Some examples of dips followed by disconnection are also given. Only measurements from the single turbine in each of the three wind farms are shown.

4.1. Dynamic responses to small voltage dips

As seen in the previous section, a majority of the voltage dips were small, i.e. with relatively high minimum residual voltage and short duration and did not lead to disconnection of the wind turbines. Examples of such events are shown in Figures 4 and 5. The dips had short duration and sharp drop and rise, and were probably caused by short circuits. The relatively high residual voltage indicates that the fault locations were far away from the wind farms, somewhere in the

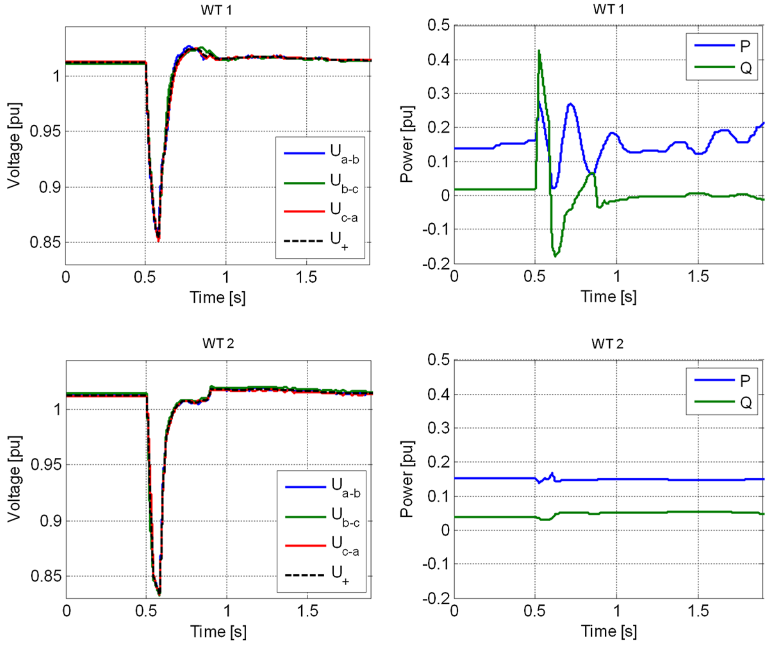

Figure 4. Measured responses of wind turbines 1 and 2 for a three-phase voltage dip, visible from both wind farms.

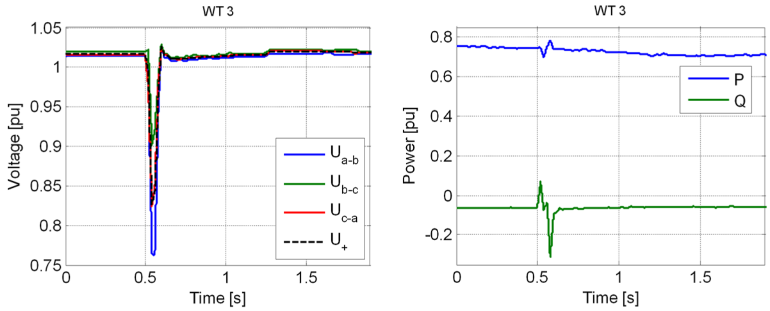

Figure 5. Measured responses of wind turbine 3 for an unsymmetrical voltage dip not followed by disconnection.

central or regional grid. Figure 4 shows symmetrical three-phase voltage dips and corresponding active and reactive power responses measured at the same time for the turbines in wind farms 1 and 2. Thus the same event was visible from both locations. Both turbines were generating about 0.15 pu of active power in the pre-fault state. Minimum residual voltage was 0.85 pu for turbine 1 and 0.84 pu for turbine 2. None of the turbines were disconnected because of the fault.

The turbine in wind farm 1 is a directly connected induction generator, and the active power response is determined by both generator and shaft dynamics. Reactive power response is mainly determined by the induction generator, but the shunt capacitors installed for reactive compensation also has some impact. Without reactive compensation, the reactive power would have been negative in steady state, and the first swing during the dip would have been towards zero. The basic shape of the response is kept with reactive compensation, but the whole curve is lifted. The shunt capacitor batteries can be connected in steps, but the control is probably not fast enough to react during the voltage dip. However, the third reactive power swing up to about 0.08 pu may be due to switching on and off an additional capacitor step, and this can also be causing the overshoot observed in the voltage before reaching steady state.

The turbine in wind farm 2 is connected to the network through a full-scale frequency converter, and active and reactive power transient responses are determined by the power electronics converter with corresponding controllers. The dynamic response of the wind turbine and generator is of less importance because of the decoupling effect of the back-to-back converter. Both active and reactive powers are kept quite constant by the converter controller during the fault. The converter appears to have constant reactive power or power factor control rather than voltage control since the reactive power is not increased during the dip. The voltage is at a slightly lower value for a short period after the fault before reaching steady state. The step-up to steady-state voltage is not caused by the wind turbine, but rather due to some voltage control action somewhere in the system, for instance a tap changing in a transformer.

The same event was also visible from the turbine in wind farm 3, as a step change in the voltage. However, the step change was small, and the voltage did not go below 0.9 pu. Events that could be observed from all three locations occurred a few times during the measurement period. However, these events caused voltage dips in only one or two of the locations and a smaller voltage change in the remaining location(s). No events caused simultaneous voltage dips in all three locations. Figure 5 shows the response of wind turbine 3 to an unsymmetrical voltage dip. Wind turbine 3 has a full power converter interface, such as turbine 2, and the dynamic response appears more similar to wind turbine 2 than turbine 1.

4.2. Examples of severe voltage dips

Figure 6 shows a nearly symmetrical voltage dip which leads to disconnection of wind turbine 1.

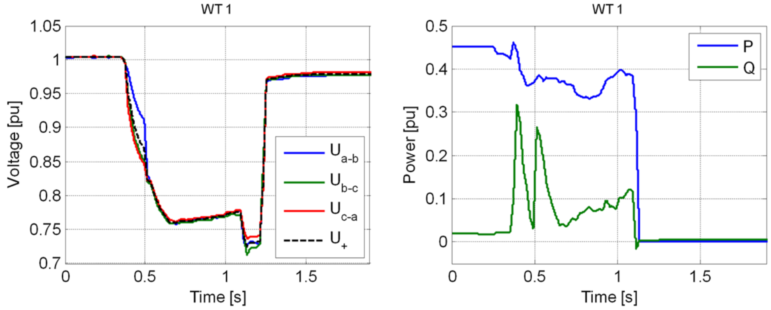

Figure 6. Measured voltage dip and response of wind turbine 1 for three-phase dip followed by disconnection.

A symmetric dip might indicate that the short circuit is located within a busbar or switchgear rather than on an overhead line. The long duration of the dip can mean that the fault is located in a distribution grid with long disconnection time, or that it is disconnected by backup protection. Since the residual voltage is not lower than about 0.7–0.75 pu, the disconnection of the wind turbine is most likely due to the relatively long duration of the dip. The wind turbine manages to operate during the first 0.7 s of the voltage dip before it is disconnected, which leads to a further dip in the voltage. The turbine is not far from operating through the fault, as the dip is over short time after the disconnection. Measurements from the wind farm connection point show that all production in the wind farm is shut down because of this fault.

Figure 7 shows examples of large voltage dips in wind turbines 2 and 3, occurring at different dates. Wind turbine 2 is able to operate through the dip, which have a minimum residual voltage of less than 0.2 pu. The dip is symmetrical for about 0.2 s before two of the phases are close to restored. The voltage dip in wind farm 3 leads to disconnection of the turbine. The dip is symmetrical with minimum residual voltage around 0.24 pu.

The power in wind turbine 2 is increasing again shortly after the dip, and therefore this appears to be a successful case of FRT. The turbine type used is supposed to have FRT capability, and the dip shown in Figure 7 seems to confirm this kind of capability. The power production of the wind farm does not go to zero, so the power is not equally reduced in all turbines.

The disconnection of the wind turbine 3 is most likely due to low residual voltage rather than long duration of the voltage dip. The pre-dip active power production was 1 pu for the wind turbine and a bit higher than 0.7 pu for the whole wind farm. The turbine is not connected again within the time frame shown in Figure 7. The same applies to the wind farm as a whole. Compared with the voltage dip in wind farm 2, shown in Figure 7, this dip is less severe both in residual voltage and duration. The turbine in wind farm 2 was capable of riding through the fault, whereas the turbine in wind farm 3 is not.

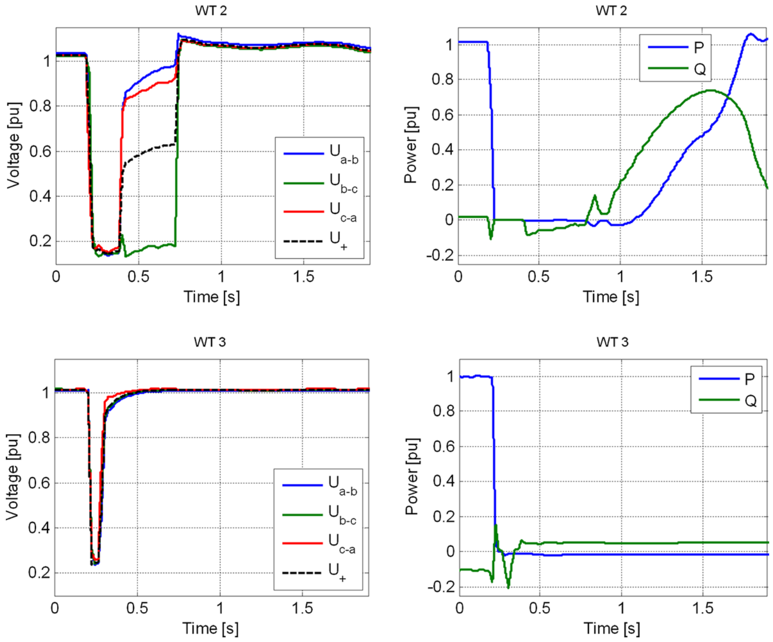

Figure 7. Measured voltage dip and response of wind farm 2 for three-phase voltage dip followed by disconnection.

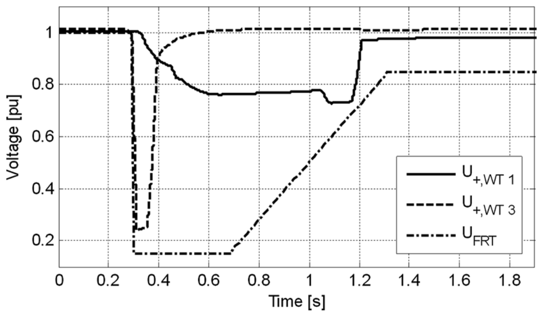

Figure 8. Three-phase voltage dips at wind farms 1 and 3 leading to disconnection and current fault ride-through curve.[14]

This indicates that the turbines in wind farm 3 have less FRT capability than the turbines in wind farm 2. With many existing grid codes, wind turbines are expected to be capable of operating through a dip as the one shown for wind turbine 1 in Figure 6 and for wind turbine 3 in Figure 7. The voltage dips are repeated in Figure 8, together with the current FRT curve for the country where the wind farms are located.[15] However, such grid codes had not been introduced at the time these wind farms were set into operation, and thus the requirements do not apply in these cases.

5. DISCUSSION AND CONCLUSIONS

Voltage dips occurred relatively frequent in the measurement period. For all measurement locations, except the single turbine in wind farm 1, the majority of the dips were single phase. For all measurement locations, the number of three-phase dips was larger than the number of two-phase dips. However, a three-phase dip is not necessarily symmetrical. For all measurement locations, very few of the dips led to disconnection of the wind turbines, but the low number of disconnections is somehow misleading, as many of the dips occurred when the wind turbines were not in operation (due to low wind speeds, maintenance, etc.). EN 50160[3] suggests that polyphase aggregation is applied for the evaluation of voltage dips, and the positive sequence voltage component has been used in this work. As expected, fewer dips were seen in the positive sequence components than in the line-to-line voltages. Especially for single-phase voltage dips, the corresponding positive sequence component might not go low enough to be classified as a voltage dip. Most dips were relatively small, and a large share of the dips (47–67%) had minimum residual voltages above 0.8 pu. A 0–1 dip with residual voltage of 0.02 to 0.4 pu occurred in each of the measurement points. A majority (51–100%) of all dips had durations less than 0.5 s. Of dips with duration longer than 1 s, 3–4 dips were seen in wind farm 1 and 1 dip in wind farm 2. In wind farm 3, all dips had durations less than 0.5 s.

The examples of recorded voltage dip events cover both voltage dips where the turbines maintained operation during the dip and more severe dips leading to disconnection of the turbines. The selection of examples is not optimal with regard to comparing responses of different wind turbines, as it is limited by the dips that actually occurred during the measurement period. During the 1 year measurement period, a few disturbances in the grid led to simultaneous voltage dips at two wind farms, but these dips were generally not severe. No voltage dips occurred simultaneously in all three wind farms. Thus a situation where many wind farms are disconnected at the same time due to a grid disturbance is not very likely to occur.

For wind turbines connected to the network through full-scale frequency converters (wind farms 2 and 3), the active and reactive power transient responses are determined by the power electronics converters with corresponding controllers, and the characteristics of the generators are of less significance for the transient responses. The amplitudes of the transient power swings are much smaller in wind farms 2 and 3 than in wind farm 1 with directly connected induction generators. Most present grid codes contain FRT capability requirements for wind turbines. Measurement shows that the turbine in wind farm 1 has been disconnected because of a symmetrical voltage dip with residual voltage not lower than 0.7 pu, but with relatively long duration. The turbine in wind farm 2 operated through a severe dip with residual voltage a bit below 0.2 pu without being disconnected, and it can be concluded that it has good FRT capability. The turbine appeared to be operated in a zero power mode during the voltage dip. The turbine in wind farm 3 is disconnected for a dip with a bit higher residual voltage and shorter duration than in the example from wind farm 2 and thus seem to have poorer FRT capability. FRT requirements in present grid codes are not met by the turbines in wind farms 1 and 3, but the requirements were introduced after the wind farms were set into operation, and therefore do not apply. If an improved FRT capability is required for the wind turbines, this could be achieved by installing reactive compensation unit, i.e. static synchronous compensator (STATCOM) or static var compensator (SVC),[15] which can provide voltage support during dips.

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