

International Review of Grid Connection Requirements related with Voltage Dips for Wind Farms

J. A. Fuentes, M. Cañas, A. Molina, E. Gómez, F. Jiménez

Abstract—In this work, the Spanish grid code is compared to other recently approved —or proposals published or under revision— international regulations for connection of wind turbines to the network. More specifically, it highlights their main characteristics.

Index Terms—Voltage dips, wind turbines, grid codes

I. INTRODUCTION

Over the last few years the installed capacity of wind power has undergone an outstanding growth around the world. Special mention should be given to Europe, in particular Germany and Spain, where the production of clean energy reaches a considerable percentage of their energy supply. Due to the policies and incentives offered in these countries, the industry has developed a technology that allows large wind farms to be considered as a serious alternative to traditional power plants. The more relevant advances in this field have been based in the Double Fed Induction Generator and the power electronics that allows the wind turbine accomplish with the code of each country for a safe operation of the electric grid.

The stability and reliability of the power system depends strongly on the penetration of wind farms in such systems. Consequently the Operators have modified their Grid Codes in the last years to improve the integration of the large wind farms to the grid. Wind farms must maintain uninterrupted generation throughout power system disturbances, supporting the network voltage and frequency, and therefore, extending features such as low voltage ride through, or reactive an active power capabilities. Low voltage ride through is particularly important to maintain the voltage stability, specially in areas with high concentration of wind power generation. If the wind turbine is not designed to achieve these requirements and disconnects from the grid during a power system disturbance, this may result in severe stability failures in the grid, which in turn could amplify the disturbance, [1], [2].

Among power system disturbances, voltage dips are mainly due to short-circuits and earth faults in the grid, [2], i.e. they are the disturbances involved in low voltage ride through

studies. A voltage dip is a sudden voltage reduction (between 10% and 90%) at a specific location in the electrical system, which lasts for half a cycle to 1 min, [3].

Nevertheless, several national network codes have been approved or are under investigation nowadays to avoid explicitly the disconnection of the electrical generation units, when submitted to voltage dips related to correctly cleared short-circuits, [4] due to the notable increase in the demand as well as in the installed wind power capacity,. The disconnection of wind farms can cause a multiple contingency with its associated high risk of supply interruptions, [2]. Furthermore, it is necessary that wind farms supply reactive power depending on the network demands and the corresponding voltage levels. Obviously, these grid codes specified by the transmission system operators are responsible for maintaining the power system stability and power quality and they impose the requirements regarding wind turbine integration to the network. In [5]–[8] the grid connection requirements corresponding to Denmark, Germany, Ireland, Sweden, Scotland and Spain have been studied as shown in figure 1 summarizes their requirements related with undervoltage and overvoltage protection and requirements for islanding, [7], [8].

The REE requirements have been discussed below, including government-based and other national grid codes (Germany, Ferc and Hydro-Québec).

II. REE REQUIREMENTS RELATED TO VOLTAGE DIPS

REE grid code, recently published, specifies that the wind farm must support voltage dips, at the point of interconnection with the transmission network, without tripping. The voltage-time curve that limits the magnitude and duration of the voltage dips, produced by single-phase-to-ground, two-phase-to-ground and three-phase short-circuits, is shown in figure 1. In the case of phase-to-phase short-circuits, the maximum voltage drop is 0.6 pu, instead of 0.2 pu as plotted.

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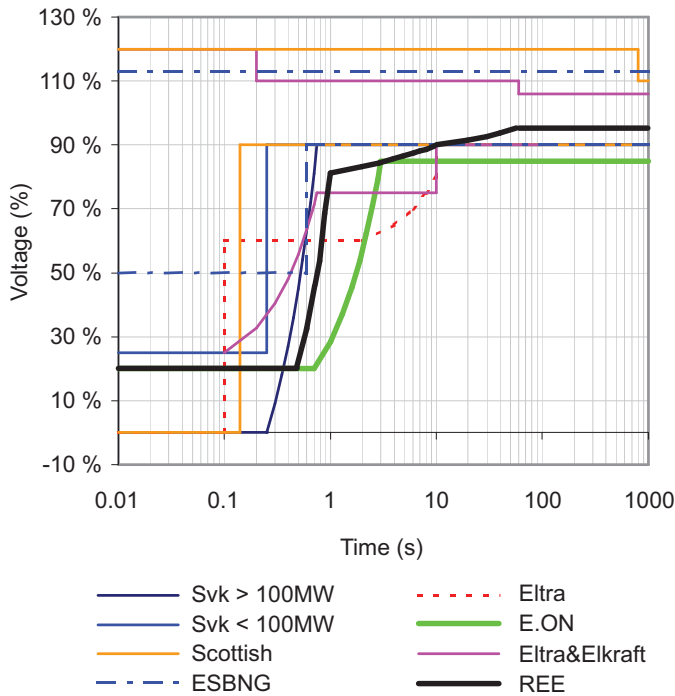


Fig. 1. Requirements for voltage operating range, [7]

A. Balanced three-phase faults

Wind farms will not absorb reactive power during either balanced three-phase faults, or the voltage recovery period after the clearance of the fault. Nonetheless, reactive power absorptions may occur during a period of 150 ms after the beginning of the fault, and also 150 ms after the clearance of the fault, although the following requirements must be met:

- The net reactive power consumption of the wind farm during the 150 ms interval after the beginning of the fault, in 20 ms cycles, must not exceed 60% of its rated power.
- The net reactive energy consumption of the wind farm after the clearance of the fault must not exceed 60% of its rated power, and the reactive current, in 20 ms cycles, must not exceed 1.5 times the rated current.

The constraints of the reactive power are imposed to avoid the absorption of a large amount of reactive power, during faults and post-faults periods, when the generator is allowed to remain connected to the grid. This absorption of a large amount of the reactive power may induce instability on the line, especially for large-scale wind parks, [9]. A more detailed study about the power system stability in case of large-scale wind farms can be found in [10].

In terms of active power, the wind farm at the grid connection point must not absorb active power during the fault or the voltage recovery period after the clearance of the fault. On the other hand, absorption of active power is accepted for 150 ms after the beginning of the fault and further 150 ms after the clearance of the fault, figure 2. During the rest of the fault, the active power consumptions are additionally may take place up to a 10% of the wind farm rated power.

Regarding currents, wind farm must provide the maximum generation of reactive current to the electrical network at the

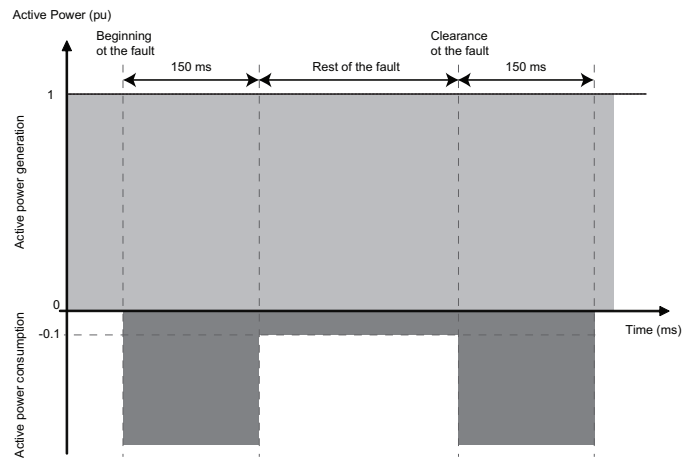


Fig. 2. REE Grid Code requirements for active power (balanced three-phase faults)

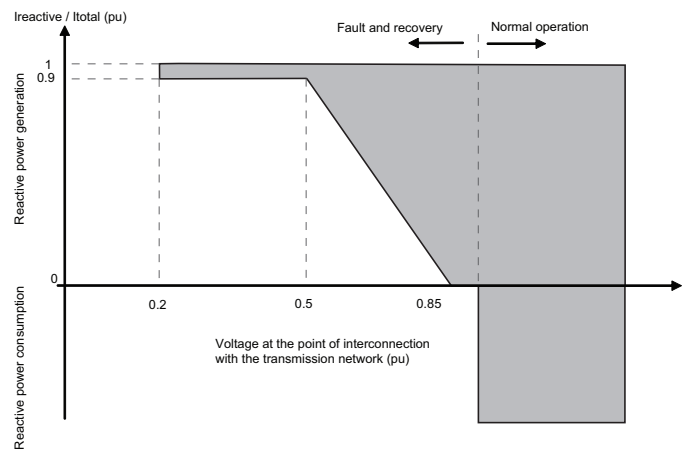


Fig. 3. REE Grid Code requirements for current and reactive power (balanced three-phase faults)

grid connection point during the fault and later in the voltage recovery period. In any case, this current must be located in the shaded area in figure 3, within 150 ms after the beginning of the fault or after the clearance of the fault. Therefore, the wind farm must generate reactive current with voltages below 0.85 pu, and it must not consume reactive power between 0.85 pu and the minimum admissible voltage for average operation of the electrical network.

B. Unbalanced two-phase and single-phase faults

During unbalanced two-phase and single-phase faults, as well as in the voltage recovery period after the clearance of the fault, wind farms must not absorb reactive power at the grid connection point.

Nonetheless, reactive power absorptions are admitted during a period of 150 ms after the beginning of the fault and a period of 150 ms after the clearance of the fault, with two constraints:

- The net reactive power consumption of the wind farm, during the 150 ms interval after the beginning of the fault, will not exceed the 40% of its rated power during a period of 100 ms.

- The net reactive power consumption of the wind farm after the fault clearance, in 20 ms cycles, will not exceed the 40% of its rated power.

Additionally, transitory consumption is allowed during the rest of the fault with two constraints:

- The net active consumption must not exceed the 45% of the equivalent rated active energy of the installation during a period of 100 ms.
- The consumption of active power, in cycles of 20 ms, must not exceed the 30% of its rated active power.

III. EON REQUIREMENTS RELATED TO VOLTAGE DIPS

In Germany, the first Grid Code for wind farms was introduced in 2003. In 2005 and due to the accumulated experience and considering the positive results derived from the application of the Code, the German transmission grid operators (E.O.N. among them) in addition to several German research institutes and wind turbine manufacturers performed an extensive technical study about the viability of wind power utilisation. This study was called 'dena-study', [11], and was carried out by DENA (Deutsche Energie-Agentur - the German Energy Agency). In this study, the consequences of wind power utilisation on the system stability and operation of the German grid were analysed. They concluded that the transport and distribution of wind power could alter the power flow along the structure of the German transport grid, causing new congestions. To avoid such congestions, new transport lines were necessary to ensure that the electricity generated in wind parks can be distributed with a certain quality level imposed by the Grid Code, [12].

The importance of these Grid codes lies on the installed wind turbine capacity (18 GW). This means that if the wind power generation falls down during a fault and is disconnected from the grid, the whole system will become unstable and the risk of a total black-out increases significantly. This certainly explains why the wind farms can not be disconnected during a non-severe grid fault. In a near future, by the year 2020, it is expected a total wind power capacity installed of nearly 50GW, which in percentage means a large wind power penetration in the system and hence the role of wind farms will be far more relevant on the stability and operation of the German grid.

A wind farm connected to the German grid must be capable to work with the following conditions during a grid fault:

- Zero voltage for about 150 ms at the grid connection point.
- The total duration of the low voltage period referred in the Grid Code is 1.5 s.
- Short-Term Interruption is introduced and always required when low voltage occurs for less than 1.5s and the Fault Ride Through (FRT) should not take place without tripping.
- The wind turbines must ensure that the power generation after FRT continues within the shortest possible time. To achieve this, the required minimum power gradients must be previously defined.

In the future, large offshore wind farms equipped with 3-5 MW wind turbines will have an important role in the continuous voltage control of the grid. This requires the design of

voltage controllers taking into account power system stability aspects as occurs in conventional synchronous generators. A fast continuous voltage control, e.g. rise time ≤ 20 ms, is necessary to ensure variable voltage support during normal operation of the grid. This type of control helps to ensure the availability of reactive current in-feed during faults. A reactive current of 1.0 p.u. will be supplied at voltages below 50% of the initial, whereas the minimum reactive current/voltage gain required is 2.0 p.u. according to the new Eon Grid Code. A voltage support is required when there is a dead band of 10% around the current voltage operation point at the grid connection. If the voltage drops below 85% of the grid rated voltage at the connection point and the reactive power flow is directed to the wind farm, the wind turbines must be disconnected after 0.5 s delay. The disconnection should be done at the wind turbines directly in order to ensure a quick restoration.

IV. FERC REQUIREMENTS RELATED TO VOLTAGE DIPS

The Federal Energy Regulatory Commission (FERC) of the US issued the Order No. 661-A on December 12, 2005. This Order specified the standard procedures and revised the agreements for the interconnection of large wind farms established in Order No. 661. In Order No. 661-A. The FERC revised the low voltage ride-through (LVRT) standards to adopt the LVRT provisions jointly proposed on September 19, 2005, by the North American Reliability Council (NERC) and the American Wind Energy Association (AWEA). Specifically, FERC imposed standards for LVRT, supervisory control and data acquisition (SCADA) and power factor requirements. In Order No. 661 FERC had required all public utilities to revise their open access transmission tariffs to adopt the FERC standard procedures and the technical requirements for the interconnection of large wind generating facilities.

An aspect related to power factor requirements caused a partial disagreement from Order No. 661-A as the FERC declined to revise the power factor requirements for a wind farm, i.e. a wind farm has to maintain the same power factor as other generators only if the Transmission Provider demonstrates in a System Impact Study that reactive power is necessary to ensure the safety or reliability of the transmission system. The decision to exempt wind generators from compliance with the same power factor standards as synchronous generators results in an excessive preference for wind generators and creates an uncertainty for the wind industry. A further consequence is that the stability of the grid is not ensured.

Basically, the Order No. 661-A imposes that wind farms shall be able to remain connected during voltage disturbances if these are not severe and the Transmission Providers System Impact Study shows that low voltage ride-through capability is required from the wind plant to ensure a good operation of the grid. Before time 0.0 s, the voltage at the grid connection point is the rated voltage. At time 0.0 s, the voltage drops. If the voltage remains at a level greater than 15 percent of the rated voltage for a period that does not exceed 0.625 s, the wind farm shall stay connected. Further, if the voltage returns to 90 percent of the rated voltage within 3 s of the beginning

of the voltage drop, the wind farm shall be still connected. A wind generating plant must be able to operate continuously at 90 % of the rated line voltage, measured at the high voltage side of the wind plant substation transformer.

If the Transmission Providers System Impact Study shows that a voltage ride-through capability is required to ensure safety or reliability, the wind farm shall maintain a power factor within the range of 0.95 leading to 0.95 lagging measured at the point of interconnection. To accomplish these requirements, the wind farm must be equipped with power electronic converters designed to supply such level of reactive capability or fixed and switched capacitors if agreed with the Transmission Provider, or a combination of the two. Wind farms shall also be able to provide sufficient dynamic voltage support for system safety or reliability and helping to asynchronous generators with the automatic voltage regulation to maintain an adequate voltage level.

V. HYDRO QUÉBEC REQUIREMENTS RELATED TO VOLTAGE DIPS

Today, only 110MW of wind power are installed in Québec. However, Québec has a very good wind potential and Hydro-Québec expects to integrate 1530MW of wind power in its grid over the next years. These large wind farms must be integrated with the requirements to ensure system reliability [13]. Hydro-Québec's system has a number of features that make stability, voltage control and frequency control critical issues in the design of its transmission system. The Hydro-Québec transmission system (with no synchronous link with neighboring systems, Hydro-Québec relies only on its own inertia to control its frequency) is isolated with the large distances between generation and load centres and the concentration of generation at large hydroelectric sites. Therefore, generating facilities connected to Hydro-Québec transmission system should remain in service without tripping as long as possible during severe events that cause large voltage or frequency variations. The reason for this requirement is, on one hand, not to interfere with the automatic controls in use on the system, and on the other hand, to help restoring or maintaining voltage and frequency. For wind farms equipped with asynchronous generators capable of voltage regulation (such as wind turbines equipped with double-fed asynchronous generators or those equipped with a converter), the generator facilities must be designed to supply or absorb at the generating unit outlet (system side) the reactive power that corresponds to an overexcited or under excited rated power factor equal to or less than 0.95. The reactive power must be available over the entire active power generation range.

Facilities that use power electronics must remain operational throughout the entire voltage range except for voltage levels greater than 1.25 p.u. where temporary blocking is allowed and must deblock as soon as the voltage goes under 1.25 p.u..

The minimum periods of time when wind farms must remain in service without any tripping during voltage variation are these: one should note that the voltage is the positive sequence voltage at rated frequency.

For the first 0.015 s the wind farm must support, without tripping, a voltage level of 0 p.u.. During the first second,



Fig. 4. Voltage dip generator system

if the voltage level is above 0.25 p.u. the wind farm must be operational. The same occurs for the first 2 seconds, the wind farm must be operational if the voltage level is over 0.50 p.u.. During the first 3 seconds, the voltage level must be over 0.85 p.u., otherwise the wind farm can be disconnected of the grid. Voltage protection with a threshold set to operate in the voltage zone ($0.85 \leq V \leq 90$) should have a minimum time-lag of 300 seconds.

VI. FIELD TESTS AND RESULTS

To compare the requirements imposed by the chosen grid codes, a voltage dip field test—an unbalanced phase-to-phase voltage dip—to a Gamesa G80 wind turbine is applied and the results obtained according to the REE grid code evaluated.

The test has been carried out with a special installation, developed by Gamesa, in medium voltage in order to generate voltage dips and test wind turbines. This equipment can generate all kind of balanced and unbalanced faults while the network electrical conditions in the rest of the wind farm, and external grid, remain unchanged. The Gamesa medium voltage dip generator is connected between the wind farm 20 kV grid and the point of wind turbine connection, figure 4.

A. Unbalanced phase-to-phase voltage dip

In figure 5(b), the amplitude of the voltage space vector of a phase-to-phase voltage dip and the time intervals, along with the intervals between the beginning of the dip and 150 ms, and the end of the dip and 150 ms, considered by the REE grid code are represented. It is also represented the 0.85 pu level, which marks the beginning of the dip when is crossed by the voltage. It represents the evolution of the line voltages during the voltage dip in a compact form, [8], with the line voltages defined in figure 5(a).

Figure 5(d) represents the instantaneous reactive power. In [8] is presented a detailed study about the computation of reactive power using different well-known definitions. Table I summarizes the differences obtained for the calculated generated reactive energy through the time intervals defined in the



Fig. 5. Phase-to-phase voltage dip test

TABLE I
GENERATED REACTIVE ENERGY IN PU DURING THE TIME INTERVALS FOR THE PHASE-TO-PHASE VOLTAGE DIP

Time interval	$[dip, dip+150ms]$	$[clear, clear+150ms]$	$[dip+150ms, clear]$
Reactive energy (pu)	-0.0038	-0.0086	-0.0354

REE grid code for the phase-phase voltage dips, taking into account the results shown in figure 5(d).

VII. CONCLUSIONS

This paper adds to the previous bibliography regarding the regulations for the interconnection of wind farms with the power system, following the Spanish REE grid code.

Field tests have been performed to study the behavior of the Gamesa G80 wind turbines when they are submitted to a range of voltage dips. To generate such dips, a specially designed equipment has been used, which allows the generation of

all kind of balanced and unbalanced faults required by the different national grid codes.

To take advantage of the voltage dip records —where instantaneous voltages and currents were measured in the tests—, reactive power and reactive energy have been calculated according to the methodology specified by the REE grid code. These tests have been done to a Gamesa G80 wind turbine checking that fulfils the REE grid code voltage dips requirements for existing wind turbines, not being representative its results to new ones.

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