# Fault Ride-through Requirements for Onshore Wind Power Plants in Europe: the Needs of the Power System

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***Abstract*—Wind power plants show different behavior than conventional (synchronous) generators. As the traditional power systems mainly consisted of centralized generation by synchronous machines feeding passive loads, it was well-understood how the system reacted in normal operation as well as during disturbances. As wind power plants are foreseen to increase in size and the amount of installed wind power will grow, the relative contribution of equipment not exhibiting this common behavior increases. At the same time power electronics offer opportunities for additional features to stabilize the power system. Transmission system operators impose requirements on the (dynamic) capabilities of connected new generation resources (including wind power plants) which are specified in grid codes.**

**In this paper, the importance of such requirements is explained by looking at the needs of the power system and by showing simulation results for a test network. The paper facilitates a detailed understanding of the underlying phenomena related to grid code requirements with a focus on low-voltage ride-through and voltage support by reactive current boosting.**

***Index Terms*—Power systems, transient stability, grid code requirements, wind power, low-voltage ride-through, voltage support**

## I. INTRODUCTION

### A. Historical development of wind power in Europe

Wind power has become the largest source for new power plants in Europe in recent years: 39% of all new capacity installed in 2009 was wind power [1]. In the 1990s this development began in Denmark, Germany and Spain. One important characteristic of these early years of wind power development is that wind power plants (WPPs) were distributed power plants with small installed capacities and, therefore, were connected to the medium voltage (MV) distribution system. Only after the year 2000 were larger WPPs increasingly connected to the high-voltage (HV) sub-transmission systems (typically 110/150 kV).

With WPPs becoming larger in size and being more frequently connected to the HV sub-transmission systems, grid operators changed their paradigm for considering WPPs in network operation: MV-connected WPPs were considered as "negative loads" and had to disconnect during any network faults in the past, whereas now both these and HV-connected WPPs have to remain connected. The reasons for this change are detailed in subsection C.

The fact that the increasing connection of WPPs alters the system performance and requires revised planning and operation concepts for the power system has been shown by various studies in the recent years, e.g. [2], [3].

### B. Challenges and mitigation measures

A concern that remains today in Europe is how to mitigate the negative impact of older WPPs that disconnect during faults and potentially reduce power system stability. Some countries, e.g. Germany and Spain, follow a two-level strategy:

- Retrofitting of old WPPs (either voluntarily, incentivized or obligatory)
- Requirement and application of extended capabilities of new WPPs during faults, i.e. voltage support by reactive current boosting during faults.

The first level induces unexpected extra costs for existing WPPs but its technical benefits are widely accepted. The effectiveness of the second level, however, has scarcely been analyzed on a power system level with the exception of [4].

The possibility to support the voltage during a network fault by making WPPs feed a reactive current into the network is widely acknowledged [5], [6]. The question that remains to be addressed is whether only WPP at 400 kV extra-high-voltage (EHV) and 220 kV transmission system (if any) and 110 kV sub-transmission system should have and activate this feature or whether also WPP in the MV networks can effectively prevent old, non-retrofitted, WPP in their (electrical) neighborhood from disconnecting during faults. This question is investigated in this paper by a qualitative discussion of technical requirements for WPPs in section II and by presentation of simulation results in sections III and IV.

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### *C. Necessity of fault ride-through requirements*

Power system disturbances can arise from short-circuits at branch elements or busbars, or the loss of a large generator. Protection acts to temporarily isolate different parts of the power system as a result. Further tripping of lines or generators can occur during or after the fault. After the event, a new mixture of generation and load may prevail. If a power imbalance then holds, frequency deviations will occur, and sufficient reserve capacity must be activated to prevent frequency collapse. During the fault the characteristics of the network, loads and generators (together with their controller settings) determine how voltages and angles in the system change. Even if load and generation match before and after the event, the transient stability of the system [7] may not be guaranteed.

Previous to and during a short-circuit, some synchronous generators may be more heavily loaded than others. Thus, their internal voltage angles may differ significantly from that of a reference machine or group of machines. Upon clearance of the short circuit, all connected generators engage in oscillations, and the internal voltage angles of some may exceed the stability limit and result in loss of synchronism. Busbar voltages are maintained during and after a fault because most synchronous generators are equipped with automatic voltage regulators and always contribute a short-circuit current in the sub-transient and transient time-frame. The design of protections, regulator settings, and generator power-frequency droops are all based on well-known physical phenomena and respective dynamics of synchronous machines.

WPPs alter the behavior of a power system during disturbances due to the different characteristics of the prime-mover and of the generators with their power electronics interfaces. Three main types of wind turbine generators have been widely used:

- Squirrel-cage induction generators (SCIG),
- Doubly-fed induction generators (DFIG), and
- Full-converter wind turbine generators (FCWTG).

All of them respond to faults differently from a synchronous machine. SCIGs draw large and uncontrolled reactive currents during a fault, and can depress busbar voltages significantly [8]. By contrast, DFIGs employ back-to-back voltage source converters in the rotor circuit that can control the reactive current, and thus support the voltage, but to a limited degree due to the relatively small rating of the converter. The ability of DFIGs to control the reactive current is further decreased if a crow-bar is used because it may be triggered during or after a short-circuit to protect the power electronics in the rotor circuit.

Latest DFIGs use choppers to prevent unacceptably high voltages in the DC-link of the converters in the rotor circuit. Choppers allow for more flexible operation than a crow-bar while the latter is still used as a backup protection. However, only few WPPs with DFIG currently use chopper technology in Europe.

FCWTGs can support voltage during faults similarly to a synchronous machine, but still cannot over-contribute that much due to converter's limited overloading capability.

When WPP penetrations were still low, network operators preferred disconnection of WPPs when faults occurred. When the amount of load supplied by WPPs begins to approach values in the magnitude of a power system's spinning reserves, this approach is no longer feasible: once disconnected, staggered reconnection of turbines within the WPP may occur, taking several minutes.

For system-wide active power balancing reasons, WPPs are presently required to ride through faults and remain connected until a fault is cleared and the power system voltage has fully recovered. Beyond fault ride-through requirements, additional requirements have been introduced which make use of the special controllability of wind turbine generators for the benefits of the power system.

## II. TECHNICAL REQUIREMENTS FOR WIND POWER PLANTS

### *A. Low-voltage ride-through*

Fault ride-through requirements are specified using low-voltage ride-through (LVRT) curves that define the voltage region above which turbines must stay connected. Fig. 1 shows LVRT curves in effect in some European countries [9].

From Fig. 1 it can be seen that the described voltage curves differ per country. This is a result of their specific historical development, the particular network operator's approach, the respective power system characteristics (system dynamics, short-circuit power, network protection), location of relevant faults in relation to WPPs, and whether the curves refer to the voltage at the point of common coupling (PCC) or any other reference node. An analysis of the origins of LVRT requirements and a systematic clarification of their interpretation is presented in [10].

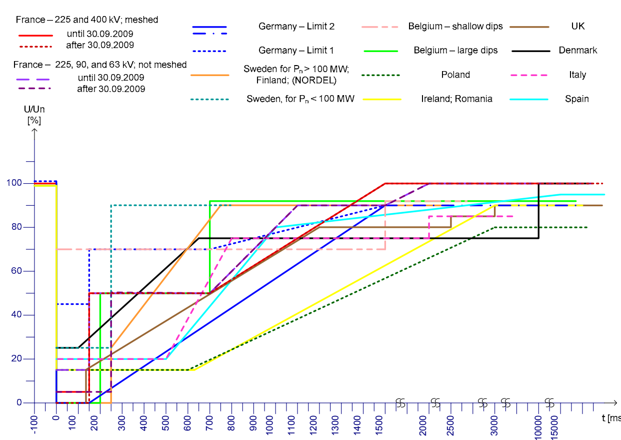


Fig. 1. Comparison of low-voltage fault ride-through curves [9]

In short, the particular shape of LVRT curves are determined by

- relevant combinations of voltage dip depth and length that may occur for typical faults and that depend on the particular network protection, and

- the lower boundary of the post-fault voltage oscillations throughout the network.

For a better understanding of the second point, two parts within the ride-through curves can be distinguished: a deep rectangular region immediately after the short-circuit and a skew part after fault clearing, stretching from the fault recovery voltage level to the nominal value over a much longer period. A typical voltage response of a synchronous generator to a three-phase to ground fault is shown in Fig. 2. The fault is cleared after 200 ms by the protection. During the fault the stator flux quickly increases and the rotor accelerates. After fault clearance the stator flux restores and interacts with the rotor flux, oscillating to a new operating point. These dynamics are reflected in the voltage behavior in the network and may take a few seconds to damp out.

To fulfill the requirement of remaining connected, a WPP must therefore be able to withstand both the initial voltage dip *and* the post-fault voltage oscillations. The bottom boundary of the deep rectangular region is based on the expected voltage level and fault location whereas the duration is based on the critical clearing time (CCT) of the connected generators. The skew part can be interpreted as the lower boundary of the post-fault voltage oscillations in the network (solid line in Fig. 2).

Further to the requirement to stay connected to the network during and after faults, grid codes set specific requirements for the active power recovery after fault clearance. Depending on system size this requirement can range from 1s [11] to 5s [12].

The active power recovery of WPPs also depends on the voltage support strategy followed during network disturbances: if priority is given to reactive current instead of active current, the active power can only be increased after the reactive current that was necessary for voltage support has been sufficiently decreased. Voltage support is implemented by a so-called reactive current boosting during (and in some cases also after) disturbances as explained in the following section.

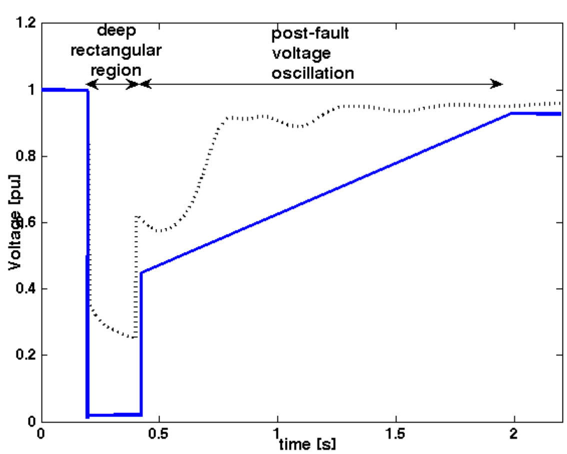


Fig. 2. Example low-voltage ride-through curve and actual voltage at PCC. The real representative voltage response of the network is bounded by a polygonal curve to define a representative voltage boundary to WPPs.

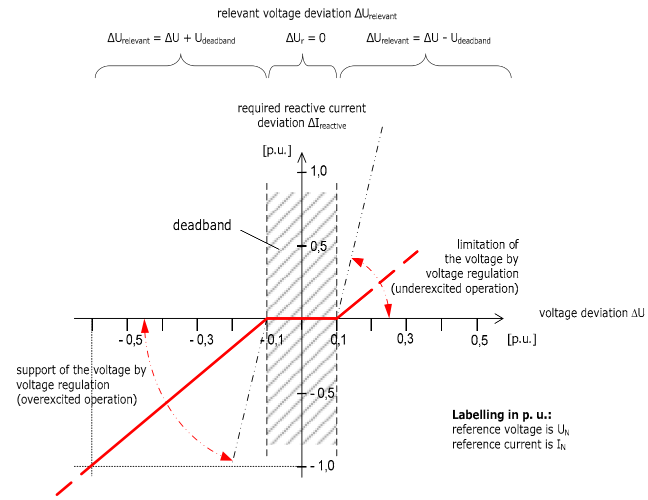


Fig. 3. Additional reactive current boosting in case of deviations of the voltage at the LV side of the wind turbine machine transformer (generation convention) [16]

## B. Voltage support during faults

The principle of reactive current boosting during and after faults aims at supporting the grid voltage for the purpose of enabling non-LVRT compliant WPPs[1] and other decentralized generators to stay connected. Furthermore, it helps the WPPs themselves to ride through network faults, since the voltage at the low-voltage (LV) terminal of the wind turbine generator is raised in proportion to the impedances between the terminals and the fault location and the magnitude of the reactive current boosting [6].

The latest requirements regarding reactive current boosting of the German and draft Spanish grid codes [13], [14] as well as an ENTSO-E working draft currently under consultation [15] are shown in Fig. 3 [16].

It is important to note that the reactive current boosting is an *additional* reactive current in-feed, adding to the reactive current in-feed resulting from the pre-fault steady-state reactive power set-point of the WPP. This means that in those situations, for instance when a WPP is supplying a positive[2] reactive current (e.g. in order to reduce the voltage at PCC), the reactive current boosting may actually decrease the magnitude of the reactive current. In the other cases, when the WPP supplies a negative reactive current to the network (e.g. in order to supply inductive loads in the neighborhood), the reactive current boosting actually increases the magnitude of the reactive current during and after the fault to further support the depressed grid voltage.

The controller for the reactive current boosting is implemented at wind turbine level with a proportional gain which can be set to any value $k$ between 0–10 p.u., as desired by the respective network operator. Therefore, the magnitude

[1] The term "non-LVRT" refers to WPP that are not able to ride-through faults but disconnect within e.g. 200ms if the voltage drops below e.g. 0.8p.u. in practice. Protection settings used in the presented simulations may differ.

[2] The authors follow the generation convention, i.e. a positive WPP reactive current withdraws reactive power from the network and a negative WPP reactive current injects reactive power into the network.

of the additional reactive current supplied to the network is proportional to the deviation of the voltage at the LV terminals of the wind turbines in the WPP from the pre-disturbance value and the gain *k*. In Germany, the standard value is *k* =2 p.u. However, most distribution system operators currently require a *k* =0 p.u., i.e. a deactivation of reactive current boosting, due to complications with existing distribution system protection schemes. In terms of magnitude, individual wind turbines must be able to inject a total reactive current of at least 1.0 p.u.. Even higher values are welcomed in most cases by transmission system operators.

The desired time performance of the reactive current boosting is determined by the protection of the network and of connected generators that are not LVRT compliant. While a short rise time is needed to selectively activate the distance protection of a faulted line, a short settling time is required to support the grid voltage sufficiently as soon as possible; otherwise non-LVRT WPP will disconnect or activate the crow-bar in the rotor circuit of their DFIGs. [13] requires, for example, a rise time of 30 ms and a settling time of 60 ms.

The rise time requirement poses challenges to FCWTG mainly because a fast recognition of voltage dips is necessary. For DFIG, the uncontrolled sub-transient short circuit current enables them to comply with the required rise time. However, they are challenged by the settling time requirement because a fast reactive current control is needed and the rating of the rotor circuit converter only allows for injection of a fraction of the DFIG nominal current. It must also be noted that protection measures like short-term converter blocking (in the order of some milliseconds, depending on the manufacturer) can complicate compliance with the desired rise time.

### *C. High-voltage ride-through*

Over-voltages may arise in a power system due to load shedding or unbalanced faults [17]. Nodes behind long radial lines or cables show a higher risk for over-voltages than nodes in meshed networks. The impact of over-voltages on wind turbines and related high-voltage ride-through (HVRT) features of WPPs have been discussed in detail [17]. Over-voltages may lead to the reversal of the power flow in the line-side converter (LSC) of DFIGs which eventually may increase the dc-link voltage in the rotor circuit to an unacceptable value. Therefore, HVRT requirements are becoming more important.

A detailed discussion of HVRT is out of the scope of this paper. However, HVRT becomes very important when offshore WPPs are connected by long ac cables and transmission lines to an onshore power system. In order to prevent the loss of large amounts of generation, dedicated HVRT requirements will be necessary for offshore WPPs.

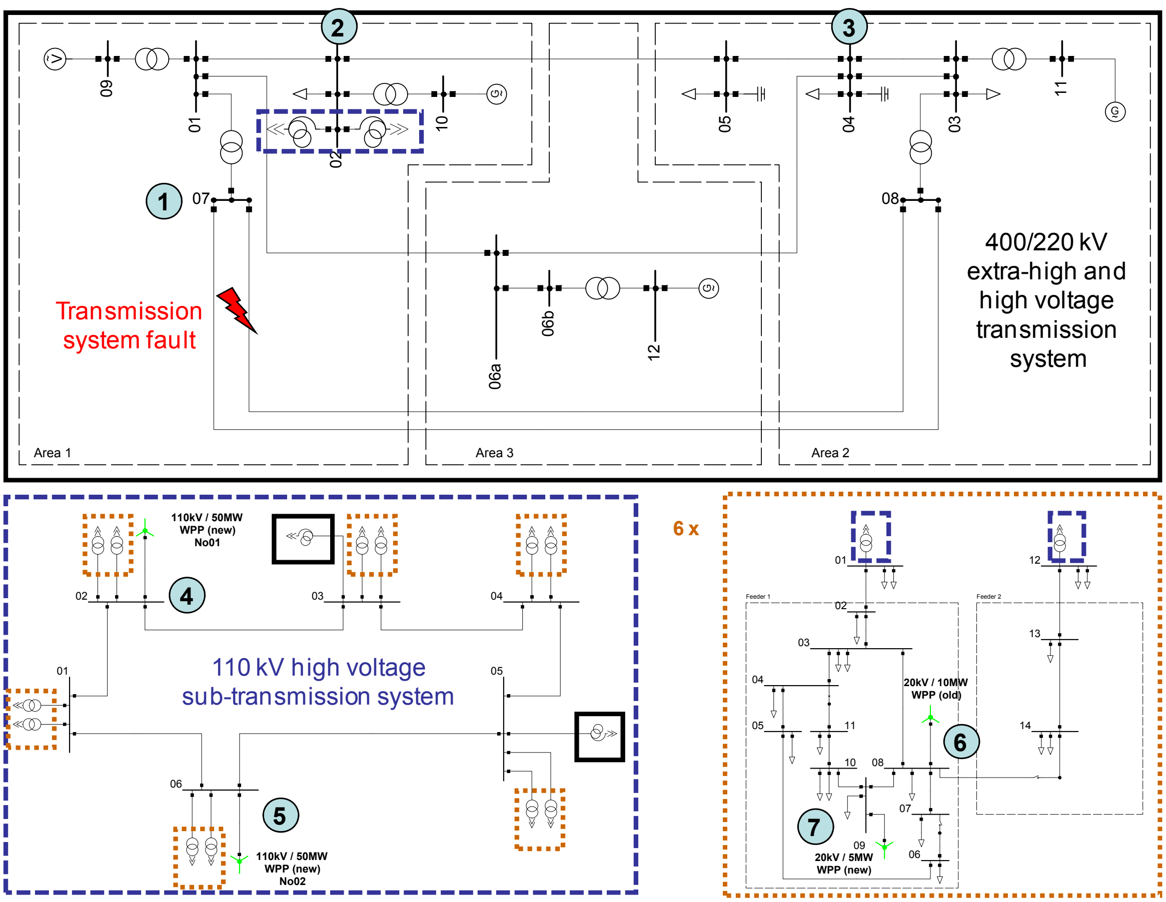


Fig. 4. 400/220 kV transmission test system (top), 110 kV sub-transmission test system with HV connected wind power plants in green (bottom left); one of the six 20 kV distribution test systems with MV connected WPPs (bottom right). Circles with numbers ①–⑦ indicate measurement points.

## III. Description of the Studies

The necessity of the previously described technical requirements for wind power plants can be better appreciated by consideration of the simulations of faults presented in the following by use of a realistic power system model.

### A. Studies carried out

A balanced fault at the extra-high voltage level is studied as it is most severe from a system perspective. A solid three-phase transmission system fault occurs on one line of the double circuit system at 10% of the distance from the 400 kV nodes 7 to 8. The fault is cleared after 100 ms; protection relays and automatic reclosers have not been considered.

### B. Description of the study network

Fig. 4 gives an overview on the complete test system including measurement points ①–⑦ (these are referred to in the figures showing simulation results). A 400/220 kV transmission test system was used according to [18]. Node 1 is an infinite bus modeled as a stiff ac voltage source behind a transformer. At this voltage level, no WPPs are connected. Loads are modeled as static constant impedances. Part of the load at node 2 (②) was replaced with a more detailed representation of the connected 110/20 kV sub-transmission and distribution test systems (see bottom frames in Fig. 4).

The 110 kV ring sub-transmission test system was implemented according to the structure presented in [19] and [20] with reasonable assumptions for line parameters. The system is connected to the 400/220 kV transmission test system in the 110 kV nodes 3 and 5. Two new WPPs of 50 MW each are connected at the 110 kV nodes 2 and 6 (measurement point ④ and ⑤). The 110 kV test system feeds six 20 kV medium voltage networks taken from [21] (lower right frames in Fig. 4). Each of these MV networks contains a non-LVRT compliant 10 MW WPP at the 20 kV node 8 (measurement point ⑥) and a (new) 5 MW WPP at the 20 kV node 9 (measurement point ⑦).

The total amount of 20 kV connected WPPs is 60 MW of non-LVRT WPPs and 30 MW of new WPPs. A total of 190 MW of WPPs is installed in area 1 of the 400/220 kV transmission test system. This amount was chosen for area 1 under the consideration of realistic operational criteria for the given transmission system [22]. The decisive factor is the allocated primary reserve per area (108 MW for area 1). The maximum capacity of wind power allowed for each area was defined such that the active power lost due to a disconnection of non-LVRT WPPs during or after network faults, would not exceed the allocated primary reserve for that area.

Table I shows the distribution of WPPs among the voltage levels as well as their technology split (SCIG, DFIG, and FCWTG) which is representative for the wind power currently installed in Germany [23]. About 2/3 of total installed wind power are old WPPs without FRT capability while 1/3 are new WPPs with FRT capability and (potentially) reactive current boosting ability.

TABLE I
Distribution of Wind Generator Types over Voltage Levels
(Country: Germany; left: proportions; right: absolute in MW)

| type | location<br>TS (EHV/HV) | Sub-TS (HV) | DS (MV) | TOTAL |
|---|---|---|---|---|
| SCIG | 0% / 0 | 0% / 0 | 22% / 40 | 22% / 40 |
| DFIG | 0% / 0 | 26% / 48 | 13% / 24 | 39% / 72 |
| FCWTG | 0% / 0 | 26% / 48 | 13% / 24 | 39% / 72 |
| **TOTAL** | 0% / 0 | 52% / 96 | 48% / 88 | 100% / 184 |
| Number of WPP | 0 | 2 | 6 | |
| Capacity of WPP | 0 | 48 | 15 | |

### C. Wind Power Plant Models and Control Modes

The WPP models used in this paper are based on generic models presented in [24]. The WPP can operate in three different control modes with respect to network disturbances. An overview of these operating modes is shown in Table II. Only new WPPs can operate in mode B (with LVRT) and mode C (with LVRT plus reactive current boosting). It is important to note that in mode C the maximum reactive current during boosting is limited to 1.0 p.u. while higher values might be possible temporarily. Non-LVRT WPPs always operate in mode A and disconnect if the voltage drops below 80% of nominal voltage for more than 40 ms. Steady-state reactive power control was set to a fixed power factor.

TABLE II
Wind Power Plant Control Modes

| mode | Old / non-LVRT WPP | New WPP | Description |
|---|---|---|---|
| A | x | | No controls for reactive power, nor LVRT, nor reactive current boosting during disturbances, *(WTG installed before 2006)* |
| B | | x | Control for reactive power + LVRT. *(WTG installed in 2006 or later)* |
| C | | x | Controls for reactive power + LVRT + reactive current boosting during fault. *(WTG installed in 2008 or later)* |

### D. Study Cases

The study cases comprise various combinations of the control modes for the HV and MV connected WPPs as shown in Table III. In the Base Case, it is assumed that all old WPPs disconnect during faults and all new WPP remain connected but do not provide to transient voltage support.

Case 1 assumes that new WPPs at HV level not only stay connected during faults but also support the voltage by feeding a reactive current. To show the maximum possible voltage support the reactive current gain has been chosen as $k$=10 p.u.). Non-LVRT WPP continue to disconnect during faults if the voltage drops below 80% of nominal voltage for more than 40ms.

Case 2 assumes that, in addition to new WPPs at high-voltage level, also new WPPs at medium voltage level support the voltage by feeding a reactive current (again with $k$=10 p.u.).

TABLE III
STUDY CASES

| case | location TS (EHV /HV) | Sub-TS (HV) | DS (MV) | Remarks |
|---|---|---|---|---|
| Base Case | no WPP | B | A+B | 66% of WPP (old ones) without LVRT, 33% of WPP (new ones) with LVRT |
| Case 1 | no WPP | C | A+B | As above, but all new WPP that are connected to the HV network have reactive current boosting besides LVRT |
| Case 2 | no WPP | C | A+C | As above, but all new WPP that are connected to the MV network have reactive current boosting besides LVRT |

## IV. STUDY RESULTS

The plots in Fig. 5 to Fig. 7 show the voltages at different nodes in the test networks and the active and reactive power of selected WPPs. The Base Case plots are shown in red, the Case 1 plots in green and the Case 2 plots in blue.

The plots of the transmission system voltages are shown in Fig. 5. The voltage at the 400 kV busbar in node 7 (①) drops in all Cases to about 0.25 p.u. and the voltage at the 220 kV busbar in node 4 (③) stays close to 0.5 p.u. due to the impedances of the 400/220 kV transformer. Although located closer to the fault, the voltage at the 220 kV busbar in node 2 (②) stays at about 0.7 p.u.; this shows the high short circuit power provided by the infinite network that is connected to node 1. The effectiveness of voltage support by WPP in the 110 kV and 20 kV networks on the 400 kV and 220 kV networks remains insignificant. No post-fault voltage oscillations are observed because of the infinite grid at node 1.

The plots of the distribution system voltages are shown in Fig. 6. The voltage at PCC of the 110 kV 50 MW new WPP (④) drops in the Base Case to significantly less than 0.8 p.u. while it remains closer to 0.8 p.u. in Cases 1 and 2. The voltage at the PCC of the 20 kV 10 MW non-LVRT WPP (⑥) drops in the Base Case to significantly less than 0.8 p.u. while it remains close to (Case 1) or even above (Case 2) 0.8 p.u. in the other Cases.

The voltage at the PCC of the 20 kV 10 MW non-LVRT WPP (⑥) suddenly drops shortly before the fault clearance in the Base Case (red line) because these non-LVRT WPPs are disconnected by their under-voltage protection and a total of about 6 x 10 MW of generation in the MV distribution networks is lost. As a consequence, the power flows from the transmission to the distribution network(s) increase respectively and result in a voltage drop over the impedances between the transmission and distribution nodes. Since the non-LVRT WPPs stay disconnected after the fault, the voltage does not fully recover post-fault.

Fig. 7 shows the active and reactive power of the 110 kV 50 MW new WPPs (④, ⑤), the 20 kV 10 MW non-LVRT WPP (⑥) and 5 MW new WPP (⑦) at the respective PCCs. As expected, the active power is reduced during the fault period while the reactive power is proportional to the reactive current boosting and the retained LV machine voltages in the WPP. If enabled, all WPPs support the grid voltage during the fault according to the aforementioned reactive current boosting settings, with a rise time of 30 ms and a settling time of 60 ms.

Note that the active power of the 20 kV 10 MW non-LVRT WPP (⑥) drops to zero in the Base Case because the voltage drop at the PCC of this WPP as shown in Fig. 6 triggers the under-voltage protection of the WPP. In Cases 1 and 2 the non-LVRT WPP in the MV networks are not lost during or after a transmission system fault.

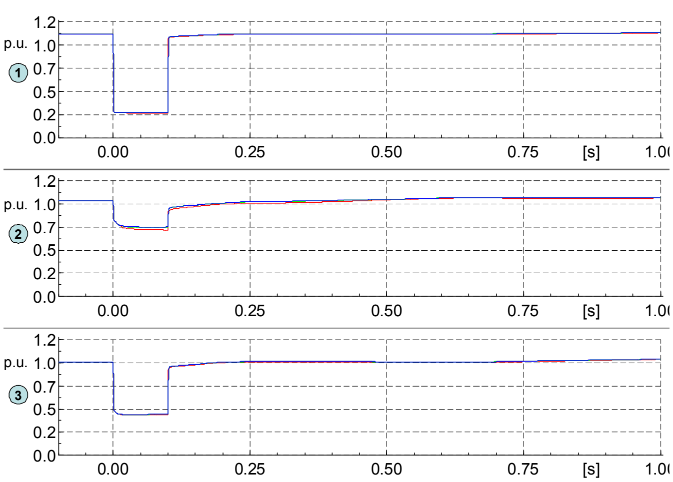


Fig. 5. 400 kV voltage at node 7 (top ①) and 220 kV voltages at node 2 (middle ②) and node 4 (bottom ③) during and after the fault for the different study cases (red – Base Case; green – Case 1; blue – Case 2)

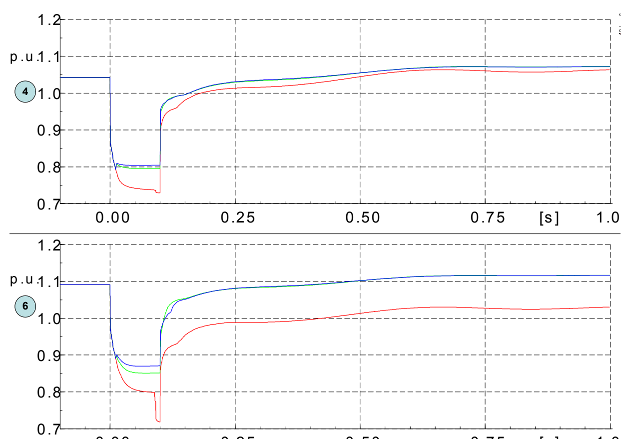


Fig. 6. 110 kV voltage at PCC of 50 MW new WPP (top ④) and 20 kV voltage at PCCs of 10 MW non-LVRT WPP (bottom ⑥) during the fault for the different study cases (red – Base Case; green – Case 1; blue – Case 2)

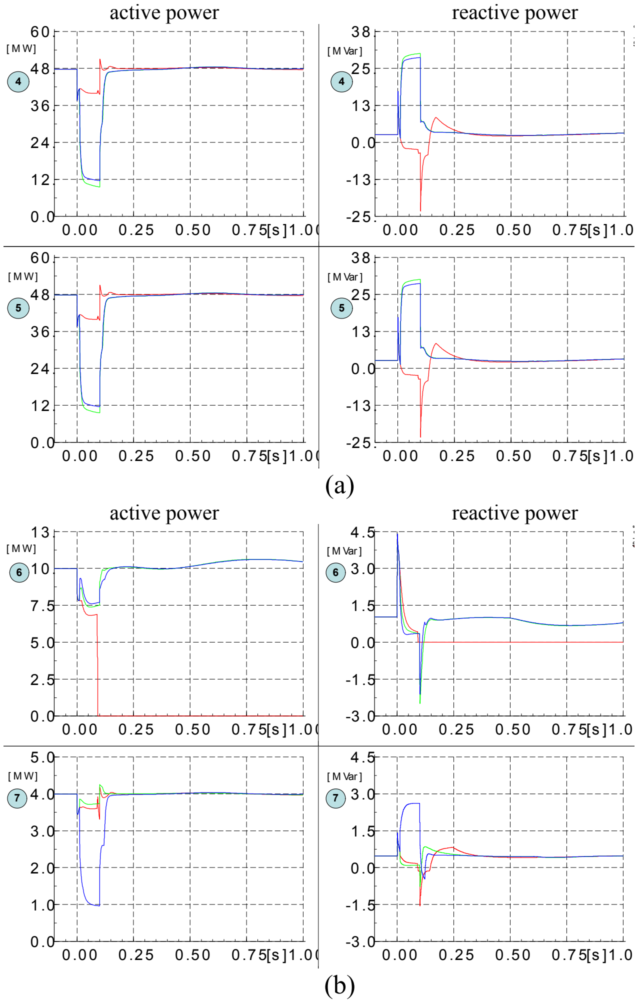


Fig. 7. Active power (left column) and reactive power (right column) of (a) the two 110 kV 50 MW new WPPs (top ④ and bottom ⑤) and (b) one of the six 20 kV 10 MW non-LVRT WPPs (top ⑥) and one of the 5 MW new WPPs (bottom ⑦) during the fault for the different study cases (red – Base Case; green – Case 1; blue – Case 2)

Interestingly the differences between Cases 1 and 2 are small. A comparison of the results leads to the conclusion that reactive current boosting from new 110 kV connected WPPs is very effective in keeping non-LVRT WPP in these (particular) MV distribution systems online during and after faults. This can be explained with the much lower power ratings of 20 kV connected WPP compared to 110 kV connected WPP and also the transformer impedances between 20 kV connected WPP in distribution systems that are supplied by different feeders.

For further understanding, an additional case was studied (though not presented in the figures) where the 20 kV connected new WPPs in half of the MV distribution systems supported grid voltage through reactive current boosting.

It was found that reactive current boosting by new WPPs at the MV level helped only those WPPs in their own MV distribution system, due to transformer impedances of the HV/MV substation. However, the reactive current boosting also resulted in improved ability of the new WPPs themselves to stay connected at even deeper voltage dips, an effect recently studied for different network conditions in [6].

## V. Summary and Conclusions

Low-voltage ride-through of wind power plants has become a standard requirement in recent years. However, many older WPPs are not able to ride through faults and will, therefore, disconnect if the voltage at the machine terminals falls below about 80% of nominal voltage for a certain time.

Power system stability simulations as performed in this paper under realistic assumptions for the distribution of WPPs among the respective voltage levels in Europe lead to the following conclusions:

1. The more WPPs are able to ride through faults the better post-fault active power balance and hence the power system stability in general.
2. In networks that contain many WPPs which are not able to ride through faults, voltage support of other WPPs by reactive current boosting during the fault has the potential to keep some of the non-LVRT WPPs in the electrical vicinity online during and after faults.
3. WPPs connected to 110kV voltage levels and above are especially effective for keeping non-LVRT WPPs in lower voltage levels online.
4. Deciding on a general requirement for WPPs connected at MV level (e.g. 20 kV) is not trivial: their effectiveness for voltage support by reactive current boosting is limited while this requirement might trigger additional costs for design and hardware.

Finally, the authors would like to raise awareness of the fact that deep dip ride-through may only be required for WPP connected to 110 kV levels or above. Such a feature is relevant for transmission faults that are close to the PCC of the respective WPP. For 20 kV connected WPP this would involve a fault located in the distribution system with negligible impact on the overall system operation.

## VI. Outlook

The results presented in this paper depend to a certain extent on the particular network topology and are, moreover, only applicable for the chosen WPP penetration levels, though this was a realistic study example. The paper only studied balanced transmission system faults. In addition, the models used did not model protection in full detail, neglected some possibly relevant short-term effects like converter blocking and assumed a conservative reactive current limit of 1.0 p.u. for both DFIG and FCWTG during faults.

Therefore, the effectiveness of voltage support by reactive current boosting during faults provided by medium voltage connected WPPs needs further investigation. The obviously related positive effect on the PCC voltage – which helps these WPPs to ride through faults themselves – is important and should be taken into account. Special attention should be given to several distribution system related protection issues that may arise around this feature as shown in [25].

Further investigations should also study unbalanced faults and faults in the 110 kV and 20 kV networks. Unbalanced faults can introduce challenging complications for WPP component ratings. And when reactive current boosting is enabled for unbalanced faults, mitigation strategies for riding through over-voltages in the healthy phases might become necessary, depending on network conditions.

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