Impact on System Stability of Different Voltage Control Schemes of Wind Power Plants Connected Through AC and VSC-HVDC Transmission

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Abstract—**Wind turbine generators have a different dynamic behavior compared to conventional synchronous generators. In power systems with a significant share of wind generation, transmission system operators require in their grid codes additional technical capabilities from wind power installations to ensure stable system operation during faults in the grid. Besides the requirement of remaining connected during severe network disturbances, wind generators shall contribute to maintaining the system voltage by reactive current injection. This contribution demonstrates the effects of voltage support by a wind park at the point of common coupling on grid stability. Three commonly formulated reactive current injection methods are examined: no voltage control, reactive power boosting, and continous voltage support. These control schemes have been tested with the help of a benchmark system thas was originally proposed by Cigré. The paper also studies the influence of a long ac cable connection on voltage control. Among other results, it is shown that the limited effectiveness of voltage support by the ac connection can be overcome by connecting the wind park through a VSC-HVDC scheme.**

I. INTRODUCTION

The increasing share of wind power in the generation mix leads to wind generation technologies no longer being neglegible in the overall dynamic behavior of power systems. To optimize their power output over a range of wind speeds, the majority of modern wind turbines has a variable speed design in which power electronics (partly) decouple the rotational speed of the wind rotor from the nearly constant grid frequency. Due to this decoupling these wind generators have a reaction to network disturbances that is almost completely determined by engineered control algorithms and not by physical reaction, as is the case for grid-coupled synchronous generators, until now the workhorse of large-scale power generation. On the other hand, power electronics enable faster algorithms for grid control that until now could not have been easily realized due to the limitations of machine physics. To ensure interoperability with conventional generation and secure operation of the power system as a whole, transmission system operators (TSO) have been enforcing stringent technical requirements to wind power plants. These requirements are laid down in grid codes. In many countries the grid code requirements for wind generators are more detailed than for conventional generators.

A requirement that is of special importance in this context is *low-voltage ride through* (LVRT), i.e. the capability of wind generators to remain connected to the grid during periods of low network voltage, mainly due to faults. In general, wind generators must remain connected minimally the same duration as a directly coupled synchronous machine of equal power rating. Furthermore, wind power plants are required to supply a reactive current during and after the period of low voltage to support restoration of the system voltage. In that period synchronous generators may draw a reactive current from the network due to the oscillations in load angle. It is considered that wind turbines can enhance system stability by supporting the voltage. However, the limited current rating of power electronic converters causes the active current to be temporarily reduced during this voltage support. This might lead to a larger active power imbalance in the system that may on the other hand adversely affect system stability. Another complicating factor with voltage support during and after faults is that large-scale wind power plants are often remotely situated and are connected to the main system through long cable connections, as is the case for offshore plants. When grid connection of these projects is realized through high-voltage ac cables of some tens of kilometers length, the capacitive nature of cables greatly impairs the effectiveness of the voltage support capability during and after faults in the main grid [1]. Wind power plants that are planned even longer distances away from the main network will probably be connected through high-voltage dc transmission based on voltage source converters (VSC-HVDC). In that case the voltage support to the main network is solely determined by the VSC interfacing with the main grid.

The objective of this contribution is to systematically assess the effectiveness of different voltage support schemes during and after LVRT to improve system stability. Although the term ‘system stability’ covers a wide range of definitions [2], here specifically the transient rotor angle stability is meant, i.e. the ability of the synchronous machines in the system to remain in synchronism during and after faults. The method used for the study is the construction of a benchmark system in a software simulation platform and to subject the model to a series of disturbances. Different wind park connection arrangements and/or different voltage support schemes can then be investigated. Simulation results will be compared on the ability to maintain stability, and on the severity (amplitude, damping) of oscillations following the disturbance. In order not to further extend the ever-growing number of test systems, the authors have tried to use an existing test system, initially developed for studying FACTS devices [3] and adopted by a Cigré working group specifically for small wind power integration studies [4]. A generalized representation of variable speed wind turbines that is independent of the actual machine type has been applied [5], as this is of lesser importance to the purpose of the study.

The paper is organized as follows. In section II, a short survey of grid code requirements concerning LVRT in general and voltage support support in particular is presented and the the required control schemes to implement these are explained. The test system, as well as the necessary adaptations to it for this study are the topic of section III. The simulation results of different voltage support schemes are systematically compared in section IV. The paper ends with conclusions.

II. GRID CODE REQUIREMENTS

To ensure stable and reliable operation of the power system, many TSOs have given special attention to wind power in their grid codes [6], [7]. Grid codes pose a wide range of technical requirements to generators concerning their interaction with the grid both during normal operation and during disturbances.

A. Low-Voltage Ride Through

First-generation wind turbines were mainly fixed-speed designs based on directly coupled induction generators. During and directly after faults these machines draw a large reactive current from the grid and may eventually become unstable [8]. To prevent this from happening, usually an undervoltage protection was installed that tripped the machine as soon as a low voltage was detected. With the limited penetration of wind generation at that time, the effect of this disconnection on the total power balance in the grid was negligible. Now wind is becoming significant, the effect of losing a large amount of generation due to a fault is no longer tolerable and wind generators are therefore forced to remain connected. Moreover, they often specify a minimum speed (ramp rate) at which power production has to be restored once the fault is cleared.

Most grid codes specify the required LVRT capability as a predefined voltage profile, such as shown in Fig. 1. As long as the actual terminal voltage remains above the gray area the unit has to remain connected, if the voltage falls below it is allowed to disconnect. A common misunderstanding in the interpretation of LVRT voltage profiles like the one showed, is that the skew part of the curve (t_1–t_2) can be expected in reality. It must be reminded that the idea behind the curve is to summarize many voltage profiles resulting from a range of faults, both deep and shallow. One interpretation is that nearby faults, resulting in deep voltage sags, are expected to be cleared by the network protection without delay, typically within the first $150\,\mathrm{ms}$ (0–t_1). Remote faults lead to a shallower voltage dip, but the unit must remain connected even if the primary protection fails and the fault is cleared by the backup protection [9], which is usually after 500 to $700\,\mathrm{ms}$ or even longer (t_1–t_2). This is done to restrict the geographical impact of the fault on the active power balance in the system. Another explanation is that in networks where synchronous generators are dominantly present, voltage restoration after fault clearance might be delayed because of oscillations in reactive power caused by the machines speeding up during faults. Wind turbines that are installed at such locations must also be able to survive voltage profiles like these.

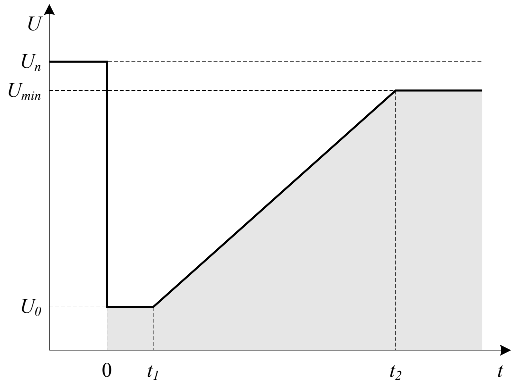

Fig. 1. Exemplary low-voltage ride through curve

LVRT requirements are typically specified for three-phase symmetric faults only, as these are expected to have the most significant impact on system stability. Most codes simply require the response for unsymmetric faults not to be worse than for the symmetric case, although in future revisions—as the knowledge about this topic grows—more detailed requirements are expected. In this contribution we limit ourselves to three-phase symmetrical disturbances, to keep the analysis simple.

Modern variable-speed wind turbines have developed over the past years to comply to the most stringent LVRT requirements. Power electronic converters have hardly any current overload capability and therefore must be carefully protected not to damage from faults. Thanks to their fast controllability it is possible to quickly reduce the output power, thereby storing the excess incoming wind power in the rotating mass of the rotor for a short period.

For wind parks that are to be connected through a VSC-HVDC link the situation is different. Since LVRT will be required on the side of the main grid, it are mainly the power electronics of the link itself that determine how the wind turbines are affected. Much attention has to be paid to how the active power balance accross the link is kept during the fault. Different solutions for can be identified [10], [11], ranging from dissipation of the incoming wind power during the fault to fast reduction of the generated power itself.

B. Voltage Support During Grid Disturbances

During a fault in the grid a funnel-shaped voltage profile will result. The voltage can be supported by injecting a reactive current during and after the fault, which will also minimize the geographical impact of the dip. Large synchronous machines equipped with exciters will naturally show such a reaction during faults, but after voltage restoration the rotor speed deviation generally causes a reactive consumption that might delay voltage restoration. TSOs have started to require voltage support during and after faults from wind generators as well. An additional advantage of the controllability of variable speed wind turbines is that they can inject reactive current immediately after voltage restoration. This is considered to be beneficial for improving the stability of nearby synchronous generators.

Variable speed wind turbines are able to deliver this reactive current contribution within the current limit of the power electronic converter. As the power electronics have no overcurrent capability, this limit must be maintained at all times. Some TSOs require a reactive current injection as high as the rated current of the wind unit, and hence the active current injection needs to be temporarily reduced. Different current limiting strategies can be selected, giving precedence to either active or reactive current, or proportional limiting.

Reducing active current in favor of reactive current during and after faults means that less active power can be delivered. To secure system stability after faults system operators will generally try to restore the active power balance as fast as possible. This is a conflicting requirement to injecting reactive current. The question can therefore be asked whether for maintaining system stability it is better to prioritize voltage support or to give precedence to active current injection for restoring the active power balance.

In general, three different methods for voltage support can be distinguished: no voltage support, reactive power boosting, or continuous voltage support.

1) No Voltage Support: Grid codes that have no specific provisions for voltage support during faults implicitly adhere to the strategy of prioritizing active power balancing.

2) Reactive Power Boosting: Reactive power boosting refers to injecting a reactive current proporional to the voltage deviation. This is for instance required in Germany [12], [13]. A typical curve is shown in Fig. 2. A typical value for the proportional gain is 2, meaning that at a 50% voltage depression the rated reactive current is injected. Moreover, a dead band is frequently added to the control characteristic to prevent unnecessary control actions caused by small voltage variations. The reactive current given by this control is additional to the pre-fault reactive current.

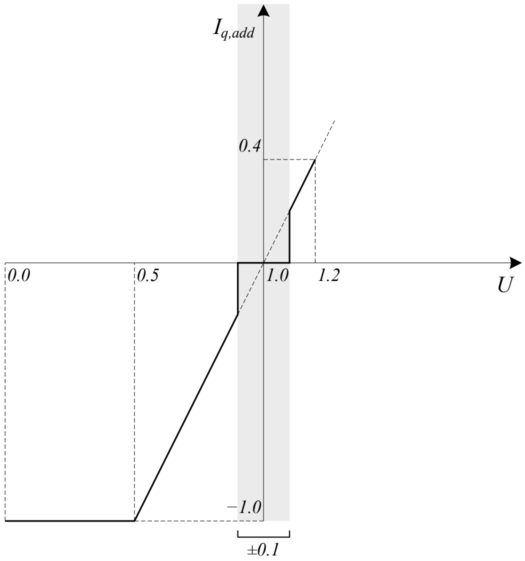

Fig. 2. Reactive power boosting characteristic

3) Continous Voltage Control: Other grid codes require wind parks to participate in voltage control already during normal system operation. This is for instance the case in the United Kingdom [14]. This control employs a reactive droop of between 2% and 7%, which means that the full reactive current is delivered already at the end of the normal operating voltage range. During faults, this control therefore injects more reactive current faster than the reactive power boosting method described above.

III. TEST SYSTEM

A. Network Model

To test the different voltage control schemes a test sytem is needed. The main requirements are: a relatively compact system, a realistic structure comparing to a typical high-voltage and extra high-voltage network, and relatively weak at the PCC to let voltage support have a noticable impact.

In order not to develop yet another test system, the authors have used an existing benchmark model. In this respect, the efforts of Cigré Working Group B4.39 have been carefully followed, and their benchmark model has been initially adapted for this study [4]. The system, however, origins from an earlier IEEE publication [3] aimed at testing FACTS devices. System topology and main parameters are shown in Fig. 3. For furter parameters the reader is referred to the original Cigré publication [4].

After careful investigation, it was concluded that the system needed some further adaptation. The long double-circuit line between nodes N7 and N8 was very ligtly loaded in the Cigré system, and showed a high sensitivity to small voltage variations. To alleviate this problem, the load at node N3 has been increased from $-320-\mathrm{j}240\,\mathrm{MVA}$ to $-600-\mathrm{j}200\,\mathrm{MVA}$. This lowers the sensitivity. Although the results presented in this paper are based on this benchmark system, the authors

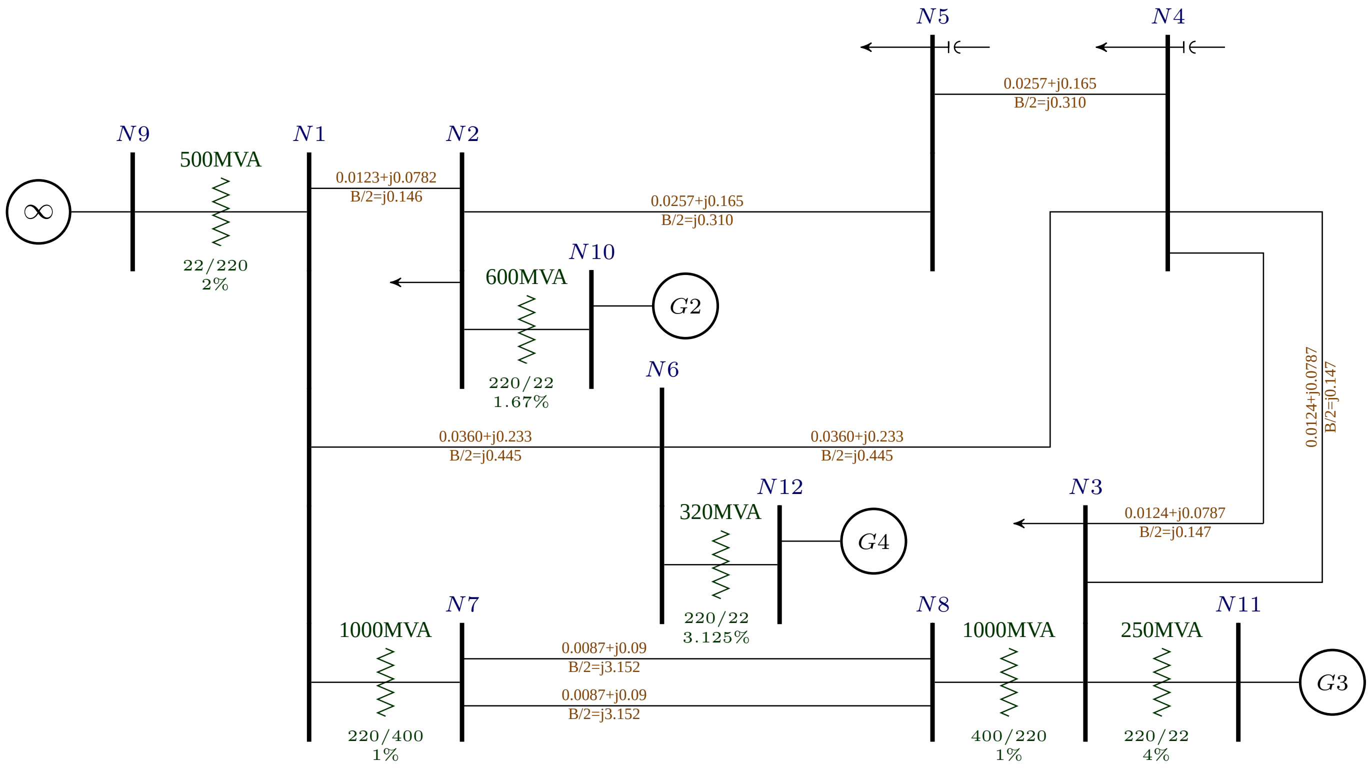

Fig. 3. Cigré Benchmark system, circuit parameters. Impedances are in per unit on 100 MVA base. Transformer impedances u_k are in per cent on 100 MVA base. Rated bus voltages correspond to the indicated transformer ratios.

believe more testing is required before the Cigré benchmark system can be universally applied for wind integration studies.

The initial load flow of the system is shown in Fig. 4. All bus voltages are within the range of 0.95–$1.05\,\mathrm{pu}$.

B. Wind Park Model

For studying the performance of the different voltage support schemes a wind park is connected to node N6. The wind park is aggregatedly represented as a single turbine, scaled to the power rating of the complete park.

The objective of this research is to study the voltage support schemes for variable-speed wind turbines independent of the actual design. The results should be generally valid for wind generators based on a synchronous or induction generator behind a full-rated power converter, as well as those based on a doubly-fed induction generator (DFIG). Therefore, a generalized model had been applied [5], in which the wind turbine is treated as a controlled current source. The validity of this model is only guaranteed when keeping in mind several important assumptions. First, it is considered that the power electronic converter of the wind turbine and its controller have no significant time delay, i.e. they instantaneously reach their reference values. This is generally true within the typical bandwidth of interest for stability phenomena (0.1–$10\,\mathrm{Hz}$). Second, at terminal voltages near rated voltage the wind generator can be regarded as a controlled power source, and during low network voltages as a controlled current source, within the current rating. Third, the wind rotor is used as an energy storage element for all power imbalances. This means that only faults of a relatively short duration can be investigated, as the rotational speed is not allowed to violate a limit.

IV. COMPARISON OF VOLTAGE CONTROL SCHEMES

A. Base Case

As a disturbance scenario the network of Fig. 3 was subjected to a three-phase bolted short-circuit in the center of the upper line between N7 and N8. The fault is detected and isolated after $100\,\mathrm{ms}$ by opening the breakers at both ends of the line. No auto-reclosure was applied. Despite the fact that this disturbance entails a relatively shallow voltage sag at the PCC N6, it can be considered an interesting case for studying the influence of voltage support schemes at system stability. As this connection is $N-1$ safe, its disconnection will have only a limited influence on system topology. Contrary, a bolted fault at N6, for example, would pose a much more severe voltage dip to the wind park, but is of limited interest here since it is located directly at the interface under study. The voltage support scheme would have less influence in this case.

In the base case a synchronous generator behind a step-up transformer has been connected to N6. The rating of this machine has been selected $320\,\mathrm{MVA}$, and in the steady state active power production amounted $300\,\mathrm{MW}$. Simplified speed governor and excitor models have been used, identical to those

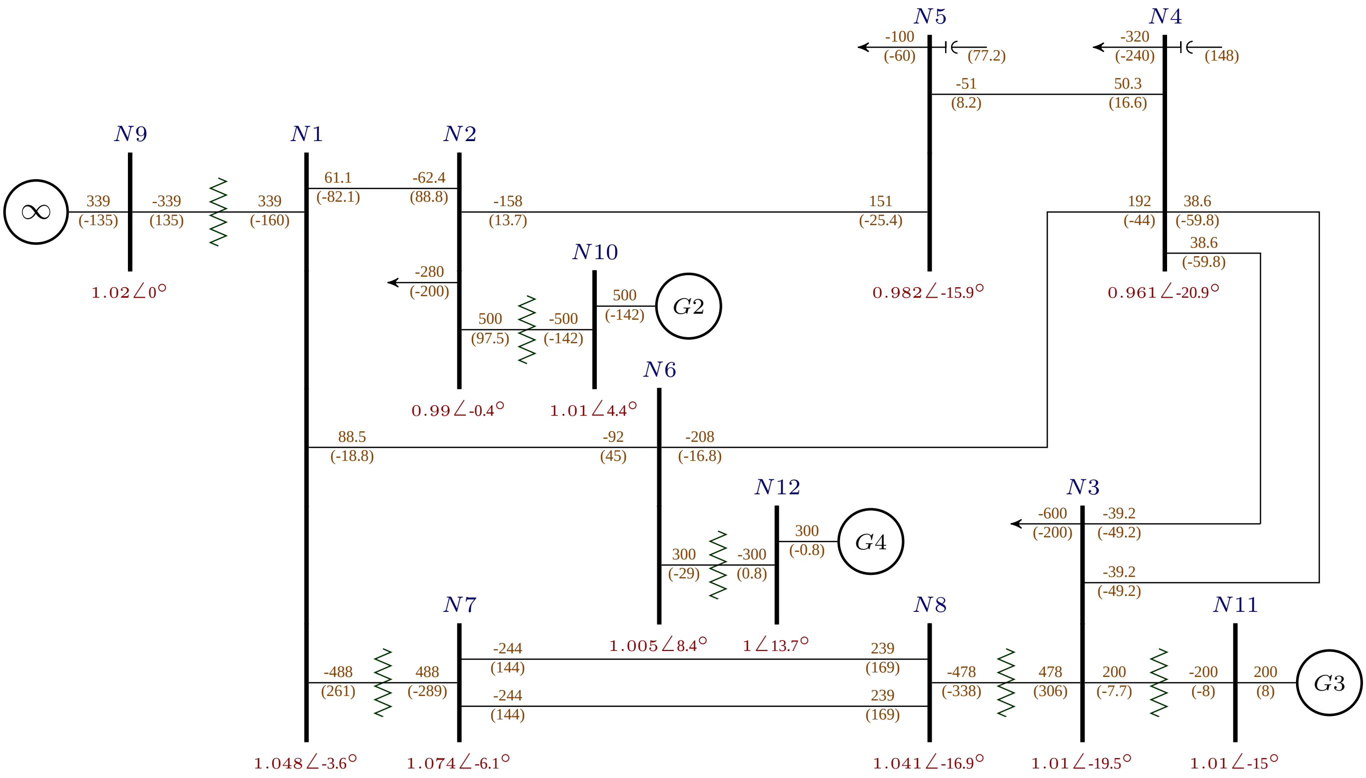

Fig. 4. Cigré benchmark system, base case load flow results. Voltages are in per unit on rated bus voltage base, active and reactive power are in MW and MVAr (in parentheses), respectively.

for generators G2 and G3. When subjected to the described disturbance the system remains stable (Fig. 5a). The voltage at the PCC (N6) reaches a minimum value of $0.81\,\mathrm{pu}$. It can also be seen that due to the rotor speed deviation, it takes about $1\,\mathrm{s}$ after fault clearance before the steady-state voltage at this node is restored. The bottom graph shows the active power through the line in which the fault occurs. It can be seen that the system settles in a new operating point, as the total impedance between N7 and N8 is changed by the disconnection.

B. *Wind Park Without Voltage Control*

Now generator G4 at N12 is replaced by a wind park of equal rated power. The step-up transformer remains connected between N6 and N12. In all studied cases, a current limit of $1.1\,\mathrm{pu}$ has been selected with q-axis priority limitation, i.e. reactive current is given precedence all the time.

Fig. 5b shows the results of the system in which the wind park does not contribute to voltage control: The reactive current i_q remains zero throughout the simulation. Nevertheless, at fault inception and fault clearance a quickly decaying peak in the reactive power is observable that is caused by the fact that the alignment of the internal dq-reference system of the wind park model is slightly delayed with respect to the network solution, for numerical stability reasons. This can be considered a realistic behavior however, since real wind turbines will have a phase-locked loop (PLL) that is responsible for this alignment. A PLL will show a delayed time response as well.

The minimum value of the voltage at the PCC (N6) during the fault is $0.22\,\mathrm{pu}$, which is considerably lower compared to the base case of a synchronous generator. It can therefore be concluded that the geographical impact of the fault is much more widespread if no voltage support measures are taken. The voltage restoration now takes more than $5\,\mathrm{s}$. Also, the maximum value of the first swing of the load angle of generator G3 is larger ($21.1°$) than in the base case ($17.8°$). Comparing load angle deviation between these cases is not entirely fair, however, since the total amount of inertia in the system is reduced and larger oscillations can be expected anyhow.

C. *Reactive Power Boosting*

Fig. 6a shows the response to the described disturbance in case reactive power boosting is applied. As in the case of no control, the wind park is operating at unity power factor before the fault. A dead band of $\pm 10\%$ is included in the control, implying the controller gets only activated after the voltage has dropped below $0.9\,\mathrm{pu}$.

It can be seen that due to the additional reactive current fed during the fault the terminal voltage is kept at a higher level of $0.61\,\mathrm{pu}$. Comparing to the case of no voltage control directly shows the benefit of the injection of reactive current during the fault. The voltage restoration process is equally slow, it takes longer than $5\,\mathrm{s}$ before the voltage is restored. This is due to

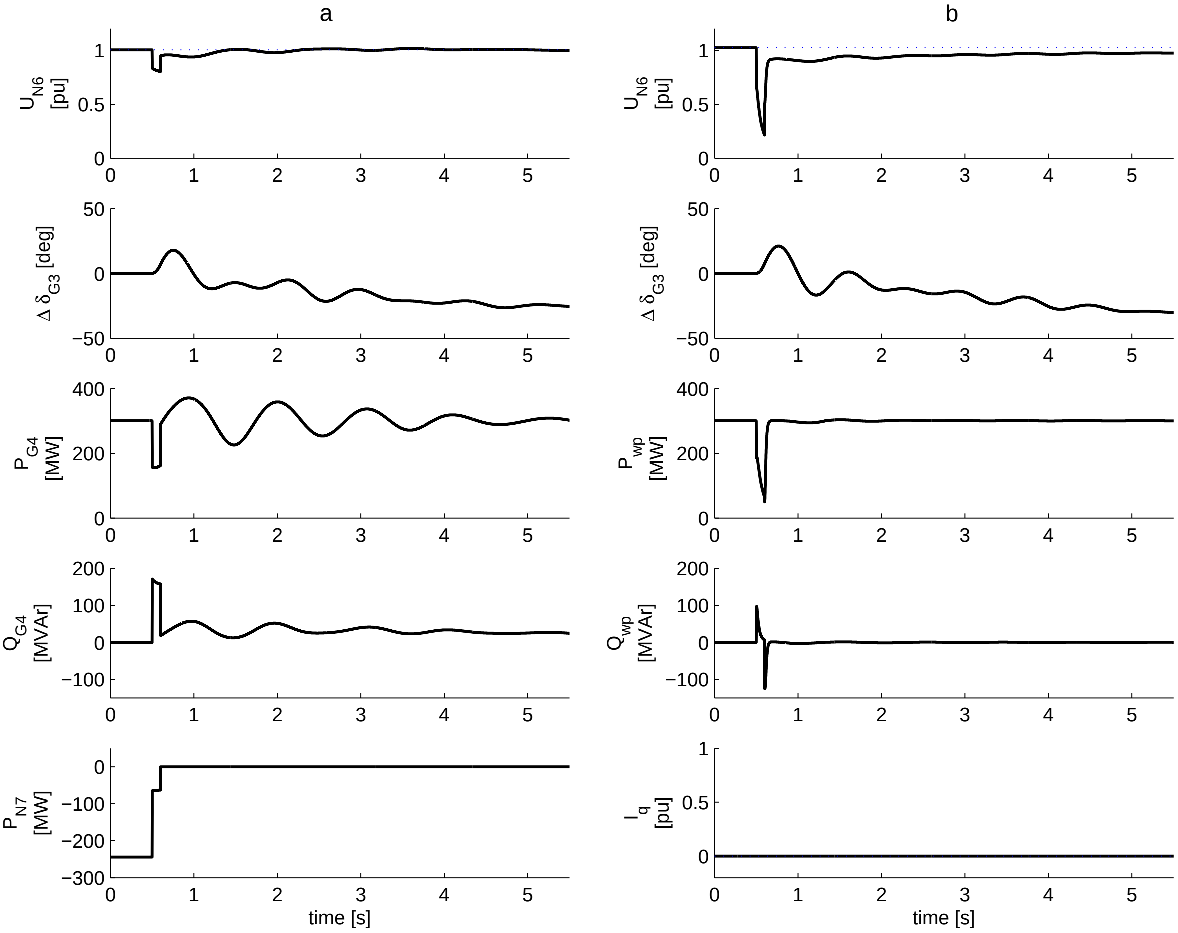

Fig. 5. Simulation results for the base case with a synchronous generator behind a step-up transformer connected to N6 (left), and a wind park without voltage control (right). Pre-fault voltages are shown in dashed lines to aid comparison.

the fact that as soon as the terminal voltage returns into the dead band the control is disabled. The maximum load angle deviation of generator G2 is $21.3°$, which is comparable to the the case without control. Again, this is due to the fact that for terminal voltages above $0.9\,\mathrm{pu}$ the controller is disabled. The reactive capability of the wind park is not fully exploited however, the maximum reactive power fed during the fault is about $0.5\,\mathrm{pu}$.

D. Continous Voltage Control

Now the wind park is equipped with a continously acting proportional-integral voltage control. The solid lines in Fig. 6b show the response for this control scheme. It can be observed that the voltage drops to $0.62\,\mathrm{pu}$ during the fault, which is similar to the results acquired with the reactive power boosting method. The most significant difference between the previously adapted voltage control schemes is that the voltage at the PCC (N6) is much more rapidly restored after fault clearance. The effect of the integrator part of the voltage controller is clearly noticable. The effect of the improved voltage profile is reflected at the maximum load angle deviation of generator G2, which slighly lower compared to the previous cases and equals $19.7°$.

The main purpose of this simulation was to show the response of a wind park directly coupled to the PCC (N6). However, the same behavior will be exemplary for a wind park that is connected through a VSC-HVDC link. As the power electronics of the grid-side VSC will have a similar control structure to a scaled wind turbine, the response will be almost identical. This supports the observation that the actual length of the cable for a wind park connected through VSC-HVDC is of minor influence on the interaction with the grid.

E. Influence of a Long AC Cable vs. VSC-HVDC

Next, an ac cable of $100\,\mathrm{km}$ length is added between the wind park and the PCC. Typical parameters for a $220\,\mathrm{kV}$ submarine cable have been selected: $R = 0.05\,\Omega/\mathrm{km}$, $X = 0.15\,\Omega/\mathrm{km}$, and $C = 175\,\mathrm{nF}/\mathrm{km}$. The cable has been no-load

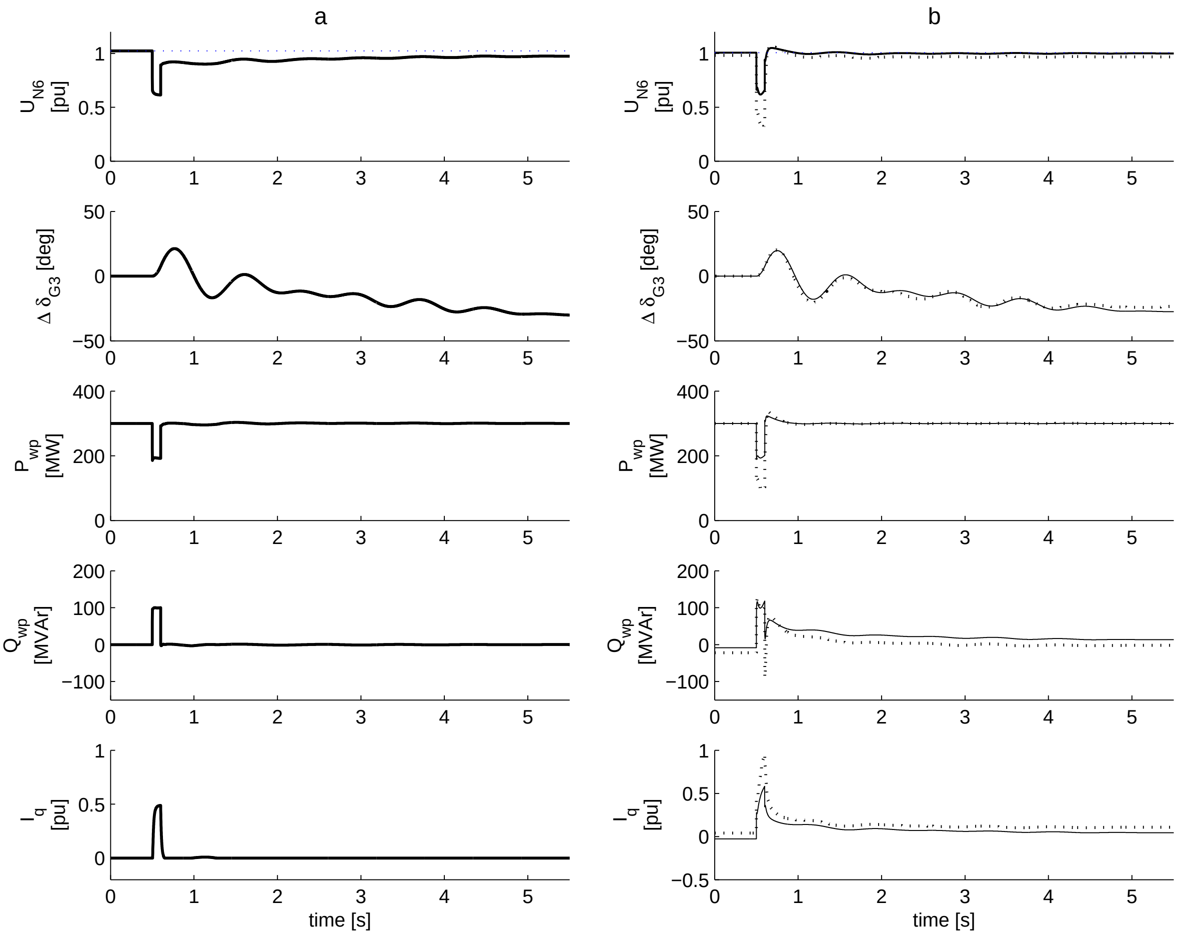

Fig. 6. Simulation results for the case of a wind park with reactive power boosting with a ±10% dead band (left), with continous voltage control (right, solid lines), and continuous voltage support behind a long cable (right, dashed).

compensated by selecting appropriately sized shunt reactors at both ends of the link. The same continous voltage control scheme as in the previous experiment has been applied, regulating the voltage at the wind park terminals.

Results are shown in Fig. 6b as well. It can be seen that during the fault the wind park injects the maximum reactive current of $1\,\mathrm{pu}$. The effect of supporting the voltage at the PCC is limited in this case, as the voltage drops to a value of $0.31\,\mathrm{pu}$ during the fault. The high impedance of the cable clearly limits the effectiveness of the wind park supporting the grid voltage at the PCC. The maximum load angle deviation equals $20.2°$, which is comparable to the results obtained with the VSC-connected wind park.

V. CONCLUSION

This paper presented the results of an investigation into the effectiveness of different voltage support schemes for wind power plants. Grid codes require different contributions from wind generators, ranging from no contribution, through reactive power boosting, to continuous voltage control. The influence on the grid of these schemes has been tested on a test system. A benchmark model taken from Cigré has been applied, but proved difficult to use without some adaptations.

Simulation results have proven the effectiveness of wind power plants contributing in voltage support. The voltage at the PCC is kept at a higher level if the wind power plant injects a reactive current during and after a fault in the grid. This certainly improves the geographical impact of voltage dips, as the funnel-shaped voltage profile is flattened. Comparing the reactive power boosting and continuous voltage control methods, it can be concluded that the latter better helps in quickly restoring the voltage profile. This is mainly to be attributed to the dead band that is often additionally required for reactive power boosting control. Intended to prevent unnecessary control actions, it completely disables the control system as soon as the voltage returns into the dead band thereby not supporting the voltage restoration at all. Especially in weak systems the effectiveness of this method has to be challenged. The continuous voltage control also supports the voltage after the fault, leading to a much faster restoration to pre-fault values.

Finally, the influence of a long ac cable on the effectiveness of voltage support has been studied. The results clearly show that ability to maintain the voltage at the PCC is rather limited, even if the wind park injects its rated reactive current. Therefore, it is advisable to consider additional equipment that can support the voltage directly at the PCC and not to rely on the wind park's control ability alone. Remote wind parks that are connected through VSC-HVDC do not have this problem, as the grid-side VSC will have a comparable control performance to the wind park itself, thanks to the fact control possibilities of the power electronic front end.

The research will be continued to investigate more in depth the effectiveness of voltage control method. Especially, the sensitivity of the obtained results to variations in converter current limit and control settings needs to be thoroughly tested.

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