Network Fault Response of Transmission Systems with Active Distribution Systems during Reverse Power Flows

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***Abstract*—Some transmission areas have such high amounts of wind power connected to the sub-transmission and distribution systems that reverse power flows (RPF) occur. Power electronics used by the modern variable speed wind turbines in wind power plants (WPP) can change the characteristic response of a power system to network faults in undesired ways.**

This paper deals with the effects of RPF on transient stability of transmission systems. This is examined by comparison of the critical clearing time (CCT) for a transmission system fault for one non-RPF and three RPF load flow cases in a Cigré benchmark system. The CCT results suggest that transient stability may be decreased during times of RPF if no mitigation measures are taken.

Finally the effects of the reactive current boosting feature of WPPs, connected either at sub-transmission or distribution level, are qualitatively discussed.

***Index Terms*—Transient stability, grid code requirements, low-voltage ride-through, voltage support, reverse power flows**

I. Introduction

Wind power has become a major contributor to the renewable energy mix over the past decades. In the 1990s the major deployment of wind power began, most prominently in Denmark, Germany and Spain. Characteristic for these early years of wind power development was that wind power plants (WPP) were distributed and had small installed capacities, for which a MV network connection was most suitable. With WPPs becoming larger in size and being more frequently connected to the HV systems, grid operators changed their paradigm for considering WPPs in network operation: e.g. the MV-connected WPPs were considered as "negative loads" and had to disconnect during any network faults in the past, whereas now both these and the HV-connected WPPs are required to remain connected, as described by grid codes.

The increased penetration of wind power alters the system performance and requires revised planning and operation concepts for the power system [1, 2]. The wind penetration may become so high in certain areas that reverse power flows (RPF) occur regularly [3], making re-dispatching and sometimes de-commitment of conventional generators on transmission level necessary. The effects of RPF on the transient stability of power systems having large amounts of converter-interfaced generators in the distribution system are not fully understood. Such understanding will be crucial to make well-reasoned grid code requirements for future deployment of wind turbines.

This paper studies the interaction between WPPs connected at lower voltage levels and synchronous generators connected at transmission level under reverse power flow conditions. The main focus of the paper is on transient stability, which manifests itself by the critical clearing time (CCT), which is the maximum fault-clearing time that can be tolerated while keeping all syncrhonous generators synchronized. One non-RPF and three realistic RPF scenarios are studied through time-domain simulations using an adaptation of the benchmark system introduced by Cigré [4].

Of particular interest are system-wide effects of the reactive current boosting (RCB) feature of WPPs, connected either at sub-transmission or distribution level. A qualitative discussion on possible effects of this support method is provided in the paper.

The remainder of this paper is organized as follows. First, the description of the simulation setup (i.e. the power system model used, the scenarios, the study cases and the sensitivities analyzed) is described in Section II. Section III presents and explains the study results. Section IV discusses qualitatively the impact of reactive current boosting during RPF while conclusions about the main findings and an outlook for further research are given in Section V.

II. Description of the Study

A. Generation Scenarios

The impact of RPF on transient stability can be best analyzed by time-domain simulations of transmission system

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faults using a realistic power system model where some synchronous generators or loads are replaced by distributed generation. Fig. 1 shows a schematic representation of the power system model used, which is more elaborately described by us in [5]. In order to create a realistic RPF condition, the capacities of WPPs within the sub-transmission and distribution networks have been increased relative to the benchmark system. The level of wind generation has been chosen not only to replace the generation level (500 MW) of one synchronous generator in area 1 close to the distribution system considered (as marked in Fig. 1.), but also to compensate for all additional active power losses. This has the effect of leaving active power flows and dispatches of remaining synchronous generators unchanged at the transmission level (top cloud in Fig. 1). In addition, reactive compensation (i.e. shunt capacitor) has been added in area 1 to keep reactive power flows the same in all scenarios. Finally, uprating of certain lines at sub-transmission and distribution level as well as reinforcement of 220/110 kV and 110/20 kV substations by adding a second transformer kept voltages and power flows within acceptable limits in the initial steady-state.

The following set of generation scenarios are defined:

- Base Scenario: Original scenario with no reverse power flows and an installed capacity of WPP, unit commitment, and dispatch according to the adapted Cigré benchmark system [5]
- Scenario 1: Insertion of additional WPP capacity, all connected to the sub-transmission network;
- Scenario 2: Insertion of additional WPP capacity, half connected to the sub-transmission network and half connected to the distribution networks;
- Scenario 3: Insertion of additional WPP capacity, all connected to the distribution networks.

To better reflect future scenarios, the inertia constant of the most critical synchronous generator for the fault studied (see subsection B) is decreased from 3 s. to 2 s. This results in CCT values in line with primary protection settings (approx. 300 – 400 ms.) while not changing the overall system performance.

B. *Simulation setup*

A solid three-phase fault is studied as it is most severe from a system perspective. This allows limiting the simulation and all models to consider only the positive-sequence network representation. The fault occurs on one circuit of a 400 kV double circuit line in area 1, close to the bus where the sub-transmission and distribution systems are connected (i.e. within 1% of the length of the 400 kV line). In order to determine the impact of RPF on transient stability of the power system, the CCT of the least stable generator for this particular fault is calculated; protection relays and automatic reclosers have not been considered. The fault is cleared by disconnection of the faulted line for the remainder of the simulation. The total simulation time is set to 1 s, since we are interested in transient stability aspects.

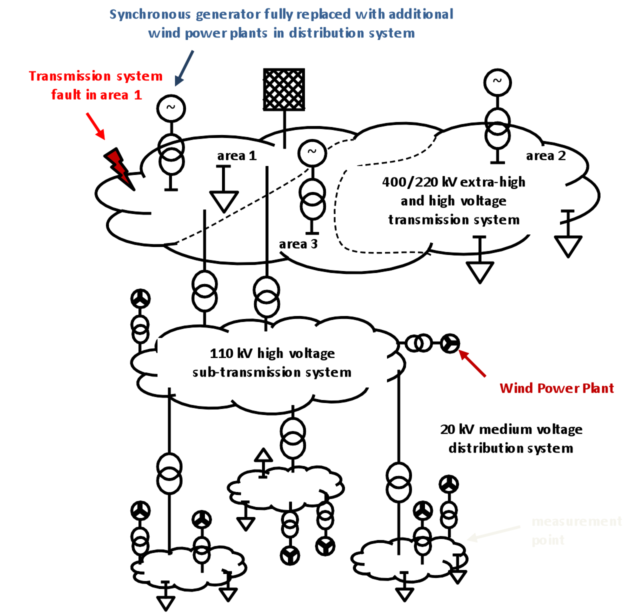

Fig. 1. Schematic representation of power system model used in the simulations.

The WPP models used in this paper are based on generic models for DFIG WPPs presented in [6]. The WPPs can operate in three different control modes with respect to network disturbances. An overview of these operating modes is shown in Table I. Only new WPPs can operate in mode B (with LVRT) and mode C (with LVRT plus reactive current boosting). For the simulations performed in this paper only control modes A and B are involved. Studies including control mode C are under investigation. Section IV discusses the impact of this control strategy on a qualitative basis. Table II shows the particular control modes adapted per voltage level and the fraction of WPPs chosen to have LVRT capability. This distribution approximately reflects the historical deployment of WPPs in Europe. The synchronous generators are all equipped with standard exciter and governor models.

TABLE I
WIND POWER PLANT CONTROL MODES

Mode	Old / non-LVRT WPP	New WPP	Description
A	x		▪ No specific controls (WPP installed before 2006)
B		x	▪ LVRT (WPP installed in 2006 or later)
C		x	▪ LVRT ▪ reactive current boosting, prioritised before active current (WPP installed in 2008 or later)

TABLE II
CONTROL MODES PER VOLTAGE LEVEL

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

III. Study Results

The study results in terms of critical clearing times are presented in Table III for the four generation scenarios, each of which uses the same control modes for WPPs based on where they are connected, as given in Table II.

TABLE III
CCT VALUES FOR EACH SCENARIO

Base Scenario	381 ms.
Scenario 1: (additional WPP in sub-transmission network only)	346 ms.
Scenario 2: (additional WPP in sub-transmission and distribution networks)	339 ms.
Scenario 3: (additional WPP in distribution network only)	318 ms.

The highest CCT value is observed in the base scenario where no RPF occurs. In the order of scenarios 1, 2, and 3 the CCT value decreases. A lower CCT value indicates that the system is less stable. Therefore, the results suggest that the transient stability of the transmission system is best in the base scenario and is reduced in any of scenarios 1-3 in which RPF occurs. Comparing scenarios 1-3 with each other reveals that transient stability is decreasing as additional WPP capacity is connected to the medium voltage distribution system instead of the high-voltage sub-transmission system.

Overall, the results suggest that transient stability may be decreased during RPF if no mitigation measures are taken. A closer look in the time-domain results reveals that the synchronous generator in area 2 of the transmission system is always the least stable generator. Therefore, the angle excursion of the area 2 machine during and after network faults relative to the reference machine determines in every scenario the overall transient stability of the transmission system.

Although the system studied has four generators, meshed connections and a detailed distribution network, it is still useful to consider these results in light of some basic principles of transient stability. The swing equation for a synchronous generator is [7].

$$H_s \frac{d^2\delta^i}{dt^2} = P_m^i - \sum_{j \neq i} P_e^{ij} \tag{1}$$

where H_s is the inertia constant, δ^i is the internal voltage angle of generator i, P_m^i is its mechanical power, and ΣP_e^{ij} is the electrical power delivered by generator *i*, flowing into the network to a set of nodes *j* directly connected to *i*. During a fault, due to voltage depression, the electrical power that can be exported from the machine is a fraction of the normal level, and the rotor of a synchronous machine experiences a large accelerating torque. Whether the rotor angle δ^i will be sufficiently decellerated to a stable post-fault oscillation depends on the duration of the fault and on the factors in (1), i.e. inertia and operating point of the machine. In particular, instability is more likely when the post-fault impedances between generators are large, as will be explained below.

Where possible, the simulation configurations were selected to control most factors in (1) to be the same in each scenario. The inertia constant H_s for each synchronous generator is, naturally, the same in all scenarios. The careful selection of generation dispatch and added WPP capacity (as outlined in Section II.A) has the effect that P_m^i also remains the same for all generators over the various scenarios. The fault location, type, clearing time, and clearing method were also the same. Thus these factors need not be considered when interpreting the results in Table III.

The power flowing out of a chosen synchronous generator *i* and into another directly connected node j (be it another synchronous machine, a converter interfaced distributed generator, or a load) is in general given by

$$\begin{aligned} P_e^{ij} = & \frac{1}{1+\left(\frac{R_{ij}}{X_{ij}}\right)^2} \frac{|V_i||V_j|}{X_{ij}} \sin\left(\delta^j - \delta^i\right) \\ & - \frac{1}{1+\left(\frac{X_{ij}}{R_{ij}}\right)^2} \frac{|V_j|^2}{R_{ij}} \left(1 - \frac{|V_i|}{|V_j|}\cos\left(\delta^j - \delta^i\right)\right) \end{aligned} \tag{2}$$

where $|V_i|$ and δ^i denote the magnitude and angle of the internal voltage of the synchronous machine of interest, $|V_j|$ and δ^j denote the magnitude and angle of a node voltage, and X_{ij} and R_{ij} denote the line reactance and resistance respectively between the nodes. In transmission networks, the ratio X_{ij}/R_{ij} is very large, due to small resistance R_{ij}. As a result, the second term of (2) becomes negligibly small and the power received at node *j* can be approximated by the first term. In contrast, for the network of lines and cables connecting the WPP to the transmission network, both terms are significant due to a higher line resistance, and the impedances are also in general larger.

In the simulation study, the initial values for voltage magnitudes and angles at the transmission level change little between the scenarios, but they change substantially within the sub-transmission and distribution levels as WPP are added in different parts of the network. While in the base case a synchronous generator provided power, in the other scenarios it is replaced by a voltage dependent reactive power source (fixed shunt capacitor) and WPPs connected at successively lower voltage levels, with the lower X_{ij}/R_{ij} ratio and larger impedance typical of such networks. The distributed generation of the WPPs provides the same active and reactive power in all scenarios, but must overcome the active power losses represented by the second term of (2), and through a larger impedance. The voltage and angle differences are necessarily larger and therefore closer to stability limits and component limits. This effect partly explains the reduction in critical clearing time between the scenarios. Dynamically, the current and voltage feedback controls of the WPPs and the excitation control of the synchronous machines also complicate the behaviour of these voltage and angles, and are currently being further investigated via time-domain simulation.

IV. Voltage Support by WPPs

Unlike older WPPs, power-converter interfaced WPPs can remain connected during faults, providing short-circuit current and controlling voltage at their point of common coupling. This can in some cases also achieve the effect of preventing older WPPs from disconnecting during faults [5]. Requirements on reactive current boosting (RCB) call for further exploitation of this capability.

The latest requirements regarding RCB of the German and draft Spanish grid codes ([8, 9]) as well as an ENTSO-E working draft currently under consultation ([10]) are shown in Fig. 2. With RCB the individual wind turbines quickly switch to another control mode in which an *additional* reactive current in-feed is defined, adding to the reactive current in-feed resulting from the averaged pre-fault reactive power set-point of the WPP according to

$$I_{reactive} = I_{reactive,av} + \Delta I_{reactive} \tag{3}$$

with

$$I_{reactive,\,av} = \frac{1}{\tau}\int_{t-\tau}^{t} I_{reactive}\; dt \tag{4}$$

and

$$\Delta I_{reactive} = \begin{cases} 0 & |\Delta U_r| < U_{deadband} \\ k(\Delta U_r - U_{deadband}) & \Delta U_r > U_{deadband} \\ k(\Delta U_r + U_{deadband}) & \Delta U_r < -U_{deadband} \end{cases} \tag{5}$$

in which k is a reactive current gain,

$$\Delta U_r = U - U_{av} \tag{6}$$

and

$$U_{av} = \frac{1}{\tau}\int_{t-\tau}^{t} U\; dt\,. \tag{7}$$

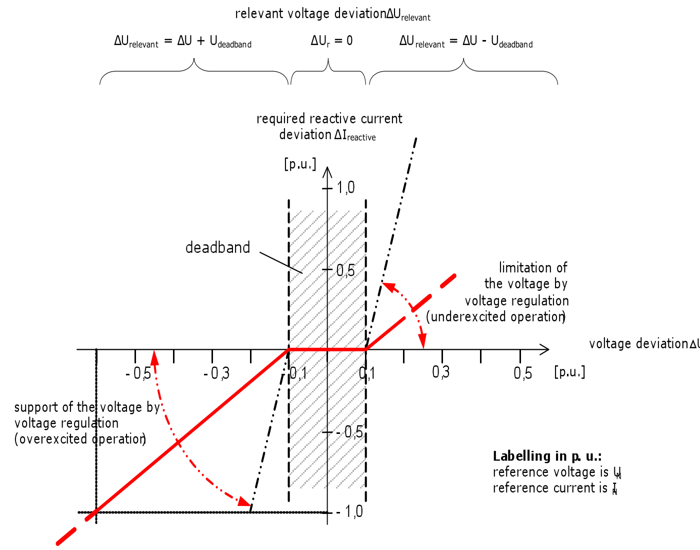

Fig. 2. Additional reactive current boosting in case of deviations of the voltage at the LV side of the wind turbine machine transformer (generation convention) [8].

With respect to the study of this paper, the RCB can be of relevance because it may influence the short-circuit power of the transmission system. However, following aspects must be considered cautiously:

1. Equivalent impedance between WPP and transmission system,
2. Load behavior for voltage-sensitive loads, and
3. Prioritization of reactive over active current injection at the power electronics interface.

A relatively high equivalent impedance influences the effectiveness of current boosting. Suppose a given level of reactive current must be delivered through the meshed grid to affect a transmission system node voltage. The larger the impedance, the larger is the voltage at the terminals of the WPP resulting from the required current. WPPs "deep" enough in the distribution system may reach their over-voltage protection limits. High equivalent impedance also introduces the complication that the observed voltage dip at the WPP connection point is smaller than at points electrically close to the fault location. Without a location-dependent adjustment of the reactive current gain *k,* higher impedances would mean smaller ΔU_r during the fault and thereby also a smaller reactive current contribution $\Delta I_{reactive}$. Moreover, additional losses are incurred when reactive power is transported to the transmission network from the sub-transmission and distribution levels.

In addition, load characteristics may considerably influence the behavior of the system during and after faults. WPPs connected at distribution level support the voltage at transmission level differently compared to the case when there are no reverse power flows. This has consequences for voltage-sensitive loads with respect to the power drawn, and therefore should also influence CCT.

Another notable feature of RCB as a voltage support method is the necessity of implementing current limits at the WPP. When the limit is reached, a control scheme can prioritize either the active or the reactive part of the current. This behaviour constitutes a significant departure from typical machine response during a transient event. The normal response of a synchronous generator to a network fault is determined by its pre-fault loading (rotor angle), its internal reactance, and the distance to the fault (i.e. impedance between generator and fault). Due to the electro-mechanical coupling between generator and network, a "natural" response and energy balance is always maintained by machine physics. In contrast, the controlled reduction of active current in order to prioritize reactive current boosting from a WPP differs from this natural response, and also involves significant nonlinearity due to current-limiting and over-voltage protection of its converters. It remains unclear to what effects this could lead, especially when considering the low X/R ratio of the distribution system.

V. Summary and Conclusions

This paper studied the effects of reverse power flows (RPF) on the transient stability of transmission systems. The comparison of CCT values suggested that transient stability may be decreased during RPF if no mitigation measures are taken. Through a succession of scenarios, the results further showed that the transient stability decreases even further when WPP capacity is added in the medium-voltage distribution system instead of in the sub-transmission system. Some relevant factors influencing transient stability were kept constant between the scenarios by careful selection of the simulation configuration and operating points. This allowed the hypothesis that the observed deterioration in transient stability can be partly explained by a reduction in short-circuit power at transmission level and increased equivalent impedances between the transmission network and the WPPs connected deeper into the sub-transmission and distribution networks. A qualitative discussion of voltage support by reactive current boosting (RCB) from WPPs revealed that further studies are necessary to analyze the trade-off between positive and possibly negative impacts of this control capability on overall system performance.

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