Impact of Large Scale Wind Power on Power System Stability

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Abstract

The amount of wind power constantly increased during recent years requiring detailed analysis about the impact of wind power on system security and system operation. Therefore several wind impact studies have been carried out recently in different countries. The findings of these studies are usually related to a superposition of different aspects of wind power, such as the fluctuating nature, distributed location of wind farms, generator technologies, generator control etc. and predict required network reinforcements, additional reserve requirements, etc.

This paper is focusing on transient stability issues and analyses the impact of various aspects like generator technology, connection points, distributed generation etc. separately for getting a thorough understanding about the impact of these aspects on transient stability.

1 Introduction

The growing importance of wind power, which can be observed in many European countries, the USA, Canada and also Australia [1] requires detailed analysis of the impact of wind power on power system stability.

Therefore, a number of studies have been carried out recently and are currently carried out for identifying required network reinforcement, reserve requirements and the impact of wind power on power system stability (e.g. [2]).

These studies are dealing with different aspects related to wind power, such as the fluctuating nature of wind power, location of wind resources, various generator technologies and generator control. The results are generally representing a superposition of various wind power aspects and predict required network reinforcements, additional reserve requirements, the impact on power system stability etc. but it is difficult to explain the reasons for encountered problems and required system upgrades from these studies because of the large variety of aspects that have been studied simultaneously.

The objective of this paper is to explain and to understand and not to calculate actual numbers and figures. The phenomenon that is subject to investigation of this paper is transient stability, especially transient stability limits on long tie-lines. Similar work is currently carried out about other phenomena, such as voltage stability, oscillatory stability and frequency stability and will be published in the near future.

In a first step, the question "why is wind power different?" needs to be answered. The main aspects having a possible impact on transient stability issues are:

1. Wind resources are usually at different locations than conventional power stations. Hence, power flows are considerable different in the presence of a high amount of wind power and power systems are typically not optimized for wind power transport. This aspect can be more or less severe in different countries. In Germany, where most wind resources can be found in the north, this aspect is extremely important [2].

2. Wind generators are usually based on different generator technologies than conventional synchronous generators. In this paper, only modern variable speed generators with low-voltage ride-through capability have been analyzed. Problems related to wind generators that disconnect on low voltages have not been considered in this paper.

3. Wind generators are usually connected to lower voltage levels than conventional power stations. Most wind farms are connected to subtransmission (e.g. 110 kV, 66 kV) or even to distribution levels (e.g. 20 kV, 10 kV) and not directly to transmission levels (> 110 kV) via big step-up transformers as in case of conventional power stations.

Other aspects, especially the fluctuating nature of wind power have not been seen to be relevant to transient stability problems because wind speed variations are too slow compared to the time frame relevant to transient stability (one to ten seconds). However, because of limited predictability of wind speed, systems with high amount of wind power usually require higher spinning reserve than conventional power systems, which adds inertia to the system that has influence on transient stability. In this sense, wind fluctuations are having an indirect influence on transient stability issues, why one case considering increased spinning reserve was analyzed additionally [3], cite2b.

The approach of this paper consists of analyzing each of the above mentioned aspects separately from each other, e.g. just the impact of modified power flows, without changing the generator technology (even if there aren't any large wind farm based on big synchronous generators...), or just replacing a number of synchronous generators by DFIGs, without modifying power flows etc.

The transmission system model used for these general studies is a virtual system having four areas interconnected by (weak) tie-lines and an overall installed capacity of 45 GW.

The paper starts by describing the wind-farm models that have been used in this paper. Conventional synchronous generators including AVR and PSS have been modelled according to international practice and IEEE recommendations [5]. The paper continues with a presentation of transient stability studies that have been carried out and finally summarizes the results and conclusions.

2 Wind Farm Modelling

For the studies carried out in this paper, all wind farms were based on the doubly-fed induction generator concepts. However, it can be shown that most conclusions are also valid for wind farms based on generators with fully-rated converters. Additionally, it is assumed that all wind-farms are equipped with low-voltage ride-through capability and reactive current support according to latest connection standards (e.g. [6]).

Even if most wind generators installed today do not comply with these requirements because they have been connected based on older grid code requirements, it is assumed that future wind generators will fulfil these requirements so that problems related to low-voltage disconnection, are just of a temporary nature.

To analyse the impact of large wind farms on transient stability of power systems, the transient behaviour of the complete wind farm has to be modelled accurately. Especially when analysing the local stability of the wind farm a detailed model of every single wind generator including mechanical components and controller devices has to be considered.

However when investigating the impact of the farms onto the transmission system stability, the wind farm response at the point of common coupling (PCC) has to be modelled exactly. The complete wind farm model will consist of a large number of small wind turbines, which will result in rather long simulation times for a transmission system with several wind farms included.

Thus before starting the investigation of effects on the transient stability of large power systems, aggregation techniques for generator models are applied to model a complete wind farm by an aggregated wind park model representing an entire wind park by one equivalent wind generator [7], [8].

In this chapter the used detailed wind generator models are described and the aggregated wind farm model for the doubly-fed induction generator is validated for the usage in the transient stability analysis.

2.1 The Doubly-Fed Induction Generator Model

To obtain the exact response of a doubly-fed induction generator (DFIG), all electrical components as well as the mechanical parts and the controllers have to be considered in the model.

A doubly-fed induction machine is basically a standard, woundrotor induction machine with a frequency-converter connected to the slip-rings of the rotor. The converter is set up by two PWM converter with an intermediate DC voltage circuit.In this paper a generator with an active power output of 1.5 MW is used for building up the wind farms.

The scheme of the DFIG is shown in Figure 1.

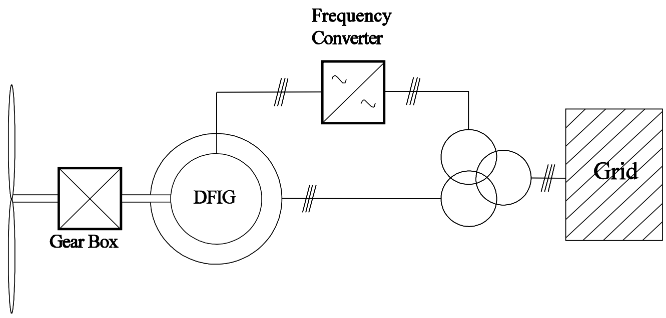

Fig. 1: Doubly-Fed Induction Generator

The main components of the DFIG are

- induction generator model with grid and generator side PWM converters
- electrical control including low voltage ride through
- mechanical parts, e.g. shaft and aerodynamics
- pitch control

Electrical Control

An inner, fast control loop controls d- and q-axis currents by adjusting the pulse width-modulation indices and hence the AC-voltages of the rotor-side- and grid-side converters. The control operates in voltage-oriented reference systems, hence, d-components correspond to active and q-components correspond to reactive currents.

An outer, slower control loop at the rotor-side converter regulates active and reactive power. Additionally to the normal operation, a reactive current boosting is implemented into the PQ controller. Corresponding to the E.ON criteria the wind turbine has to support the grid voltage by increasing the reactive current of the wind generator during low voltage conditions in the network.

During this time the magnitude of the current and thus the active current output has to be limited to ensure that the PWM converters are not thermally overloaded during the increased reactive current. Fig. 2 shows response of the wind generator to a three phase fault at the high-voltage terminals of the turbine.

The figure show the voltages at HV bus bar as well as at the generator terminal with and without activated reactive current boosting. The second plot indicates the active and reactive power at the PCC. It can be seen, that the voltage (solid curves) at the generator is higher than with deactivated boosting (dashed curve). The boosting is also clearly visible in the reactive power output of the generator.

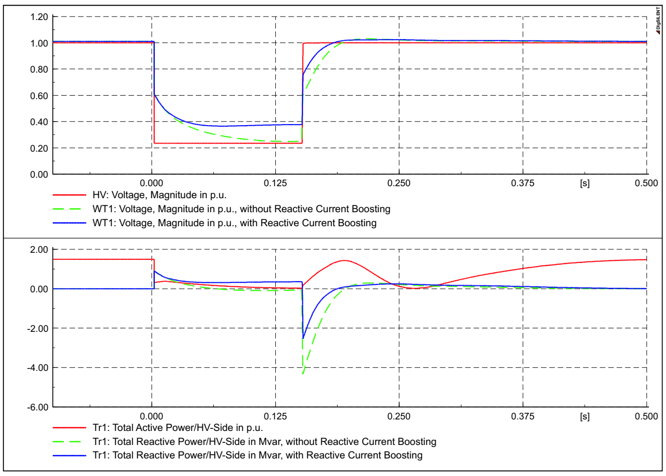

Fig. 2: Voltages, Active and Reactive Power at the PCC during a 3-phase fault with (solid) and without (dashed) reactive current boosting.

At the grid-side converter, an outer control loop regulates the voltage of the intermediate DC circuit by adjusting the d-axis-current component. The reactive current of the grid side converter can be used for sharing reactive power between the stator and the grid-side converter.

The general control concept of the frequency converter is shown in Fig. 3.

Shaft System and Aerodynamics

Disturbances and active power variations of the wind generator will result in torsional oscillations of the shaft system [9]. Therefore, a two-mass shaft model is used for representing torsional oscillations [8], [10].

In dynamic impact studies, wind speed is usually assumed to be constant during the observed time frames. Hence just the turbine response to speed and pitch angle variations is essential. Thus a steady-state turbine characteristic consisting of the aerodynamic equation and a two dimensional power coefficient table is sufficient [7].

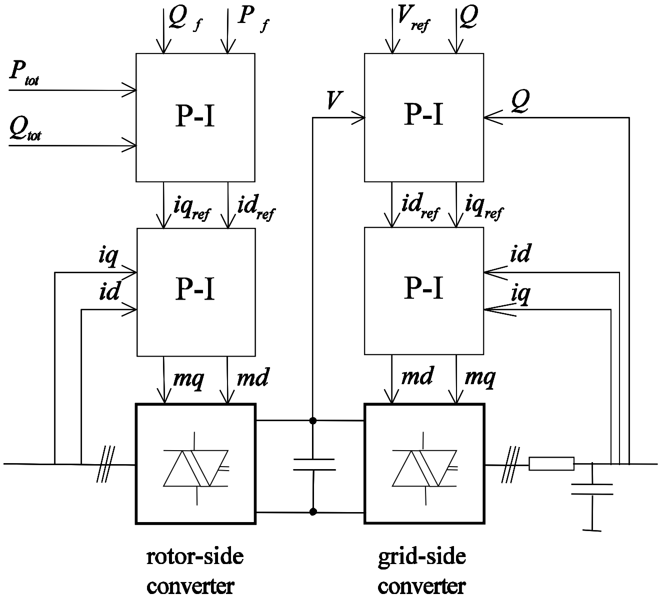

Fig. 3: Electrical Control Concept of the DFIG

Pitch Control

The pitch controller is realized by a PI controller using a first order servo model with rate-of-change limitation. The rate-of-change limit is very important, because during system faults the speed with the active power of the wind turbine can be reduced depend on this limit. The pitch rate limit is set to a standard value of 10 deg/s.

2.2 *Aggregated Wind Farm*

To reduce the calculation time of the transient simulations, the number of machines representing the wind farm can be reduced without loosing accuracy of the results for transient stability studies. This is done by using an aggregation technique [7].

For the study aggregated wind farm models where designed depending on the amount of power of conventional power plants to be substituted by DFIG wind generators. The aggregated wind farm models consist of only one equivalent wind turbine including the detailed controller models as well as the representation of the mechanical system.

The equivalent cable impedance between the aggregated machine and the connection point is defined in a way that the transient short-circuit contribution of the aggregated model at the point of common coupling is equal to the short- circuit contribution of the complete wind farm model.

For validating the approach of using equivalent wind farm models, the response of both the aggregated and the complete model to a unsymmetrical two phase to ground fault at the connection point is compared. Fig. 4 shows the active and reactive power at the PCC for the two different models assuming that each turbine of the wind farm operates under full load conditions.

- Complete wind farm model (500MW): green (grey) curve.
- Fully aggregated wind farm model (500MW): red (black) curve.

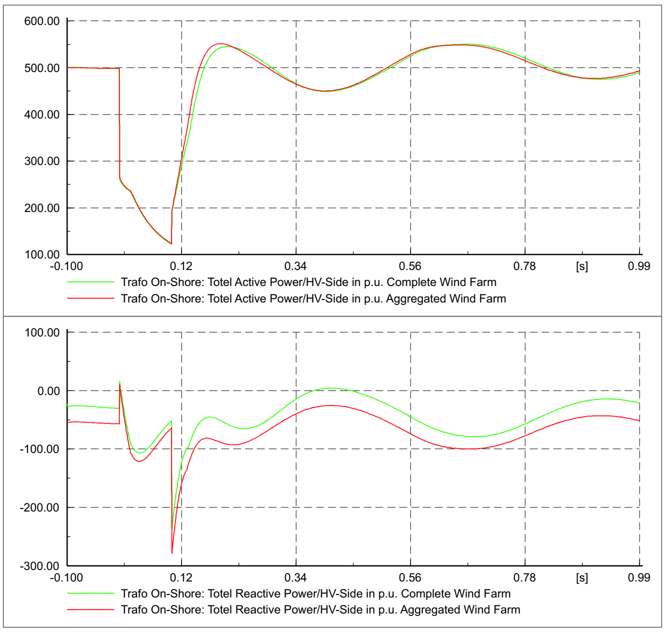

Fig. 4: Comparison of the complete wind farm to the aggregated wind farm

The graphs in Fig. 4 clearly show that the response of the fully aggregated wind farm model at the connection point is very close to the response of the complete wind farm model. The differences in the reactive power results from slightly different cable impedances of complete and aggregated model causing a different steady-state at the beginning of the simulation.

Thus Fig. 4 validates the approach of using a reduced wind farm model for transmission impact studies, in the case that all turbines operate under full load conditions.

In reality not all wind turbines will operate under full load conditions, but there will be variations of wind speed distributed over the area of the wind farm. Further detailed simulations have shown, that also during part load conditions with different wind speeds at the single wind generators, the response of the fully aggregated model to a disturbance is very similar to the complete wind farm model and an aggregated model can be used for stability simulations.

3 The Transmission System

The studies have been carried out using a system structure according to Fig. 5. It consists of four areas that are interconnected by a number of tie lines. Area 0, 2 and 3 have the same installed generation capacity of $P = 13\,\text{GW}$.

Area 1 has a lower installed capacity of around 5.5 GW and also just about half of the load as the other areas.

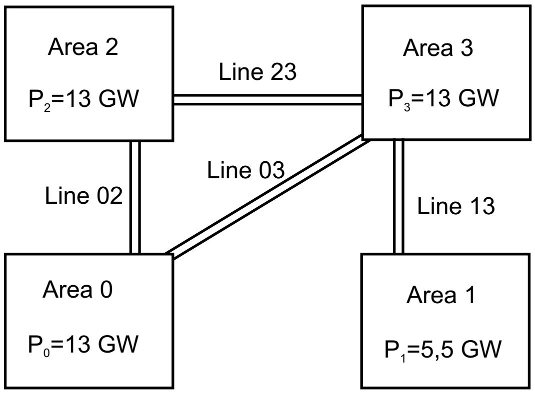

Fig. 5: The schematic power system

For each area, a simple topology according to Fig. 6 was chosen.

Most generators are equipped with typical voltage controllers and power system stabilizers so that all local modes are well damped. Governors have not been modelled because there influence on transient stability issues is of minor importance.

Fig. 6 shows the single-line diagram of one of the four interconnected areas.

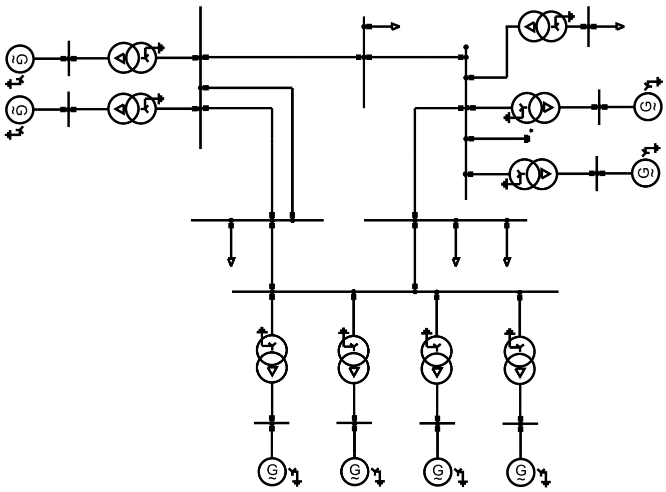

Fig. 6: The power system of the areas

4 Transient Stability Analysis

In the base case scenario, Area 1 imports about 550 MW via the tie lines from Area 3. Also Area 2 is exporting 800 MW to Area 0. The power transfer on the other tie lines is nearly zero.

The base case scenario will be modified subsequently and transient stability indices, such as critical fault clearing times or stability constrained tie-line flows are analyzed.

The different scenarios investigated are:

Base Case Import of 550 MW into Area 1. All generators are conventional synchronous generators directly connected to the transmission system. Transient stability is characterized by critical fault clearing times.

Case 1 - Changed Location of Generation: It is assumed that there are large wind resources in Area 1 and the overall generator dispatch in the entire system is purely made according to merit order fully using tie-line flow capacities. In the resulting dispatch scenario, the production in Area 1 is increased by 5000 MW by connecting additional generators to Area 1 and disconnecting generators in other areas. The generator technology remains unchanged (synchronous generators) so that only the influence of redirected load flows is analysed (Aspect 1, see Introduction).

Case 2 - DFIG Technology: In contrast to Case 1, the additional generation is now assumed to be DFIG technology with low voltage ride-through capability and reactive current dispatch. However, all DFIGs are directly connected to the transmission level, so that this case allows analyzing purely the impact of the different generator technology (Aspect 2, see Introduction).

Case 3 - 100% DFIG: As an extreme case, all generation in Area 1 is now substituted by DFIG generation based on the dispatch of Case 1. However, when remaining in power factor control, this case would be voltage-instable. Thus all DFIGs are equipped with voltage control. Of course, it is questionable, if, with regard to other operational aspects, Area 1 could operate with 100% wind generation. But for this transmission system impact exercise, this case shows interesting points.

Case 4 - Infeed at Lower Voltage Level: In contrast to Case 2, all wind generators are now connected to subtransmission levels (Aspect 3, see Introduction). Therefore, the capability of contributing reactive power to the transmission system is lowered because of reactive losses and voltage constraints in the subtransmission systems.

The disturbance investigated is a three-phase short-circuit on on circuit of the tie-line "Line 13" between Area 1 and Area 3 with a subsequent trip of the faulted circuit. The fault location is close to the connection point of the line at Area 1. This three-phase fault represents the most severe disturbance for transient stability problems between Area 1 and Area 3.

For evaluating 'transient stability', the following two indices are used [5], depending on the case:

CCT The critical fault clearing time (CCT) is calculated for all cases. The CCT represents a useful measure for characterizing the transient stability performance of a given dispatch scenario.

Critical Area Exchange This value determines the maximum export of Area 1 to Area 3 at which the system is not becoming instable for three-phase faults with a fault clearing time of 150 ms.

4.1 Base Case

The Base Case represents the normal operation of the system without any wind power connected to the system. Thus the network is characterised by generation, which is located close to the load. The generators are dispatched in a way, that most areas are having a balanced power flow.

In this case Area 1 is importing 550 MW over the interconnection lines. The overall load is 6200 MW, the generation sum up to 5625 MW.

The critical fault clearing time (CCT) can be determined using transient simulations. For this case the result is $t_{CCT} = 282\,\mathrm{ms}$. Fig. 7 shows the speed and the rotor angles of generators in all four areas in comparison for a fault clearing time close to the critical clearing time. The red curve shows the values for a generator in Area 1.

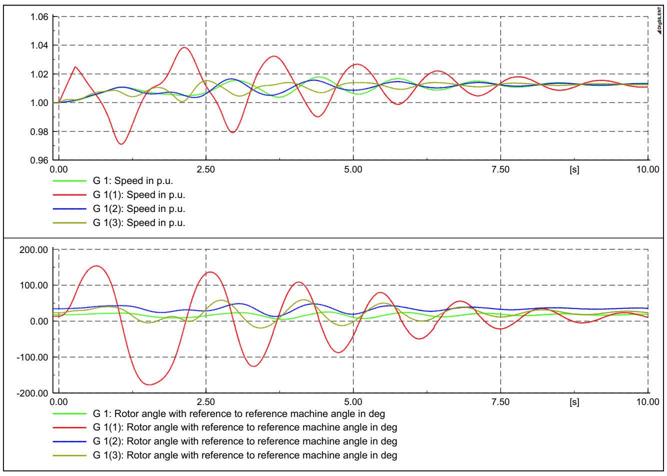

Fig. 7: Stability limit in the base case; Rotor angle and speed of generators in all four areas.

As visible in the figure the generators in Area 1 are highly affected by the fault. The speed and the rotor angle also show the damping of the oscillations after the disturbance.

4.2 Case 1 - Changed Location of Generation

To represent the shift of generation in power systems caused by large wind farms connected to rather weak points in the transmission system, the dispatch is changed and synchronous generators are added to Area 1 and removed in the other areas in in equal measure. Thus the generator dispatch in the other areas is changed in a way that 1600 MW of the conventional generation is disconnected.

Now, the wind farm connecting points are located in the system with low generation and the weakest interconnection to the other areas. The wind farms sum up to 5000 MW in Area 1.

The load demand is the same as in the Base Case. This scenario represents a large change in the load-flow due to displacement of the generation. Area 1 is now exporting power of 4450 MW to Area 3.

The large power transfer increases the rotor angle difference between Area 1 and Area 3 and moves the system closer to the stability limit. Consequently, the critical fault clearing time is reduced to 98 ms for Case 1.

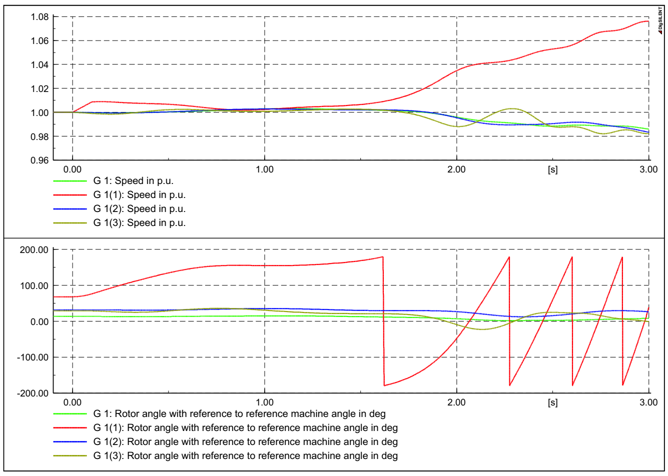

Fig. 8: Case 1 after a fault of $t = 100\,\text{ms} > t_{CCT}$; Rotor angle and speed of generators in all four areas.

In Fig. 8 the rotor angle and the speed of a synchronous generator in each area are recorded. The fault introduced has a duration of $t = 100$ ms, so the time is exceeding the stability limit of t_{CCT}.

In systems with long transmission lines, the critical area exchange is often limited by transient stability constraints. In this case, a fault clearing time of 150 ms was assumed for safely clearing faults with the first protection zone. Thus, the critical area exchange corresponds to the area exchange at which the critical fault clearing time equals 150 ms.

In this paper, load and wind power is assumed to be constant and conventional generation has to be dispatched so that no thermal of stability limits are violated. Thus the conventional generation has to be reduced in Area 1.

If the power transfer is reduced from 4.450 MW to $P_{ex,max} = 3.690$ MW, the CCT stability limit is exactly at 150 ms. This means the export must be reduced by about 750 MW to ensure a stable operation of the network under these circumstances.

4.3 Case 2 - DFIG Technology

In the next scenario the synchronous generators added to Area 1 are now disconnected and substituted by DFIGs consisting of doubly-fed induction generators. The power of the synchronous generators is thus reduced from 10.700 MW to the value in the base case 5.600 MW. So half of the generation is modelled using synchronous generator, the second half is modelled using DFIG wind generators. Thus the change in the technology can be considered and analysed.

Active and reactive power flows are exactly equal to the Case 1 load-flow. Thus this fact is considered during the substitution of generation in the network.

The analysis of the CCT results in a increased stability limit compared to Case 1 with only synchronous generators in service. The time increases to $t_{CCT} = 146$ ms. This means, that the transient network stability is enhanced when DFIG are connected instead of synchronous generators.

Fig. 9 shows the generator values during a short-circuit of 146 ms.

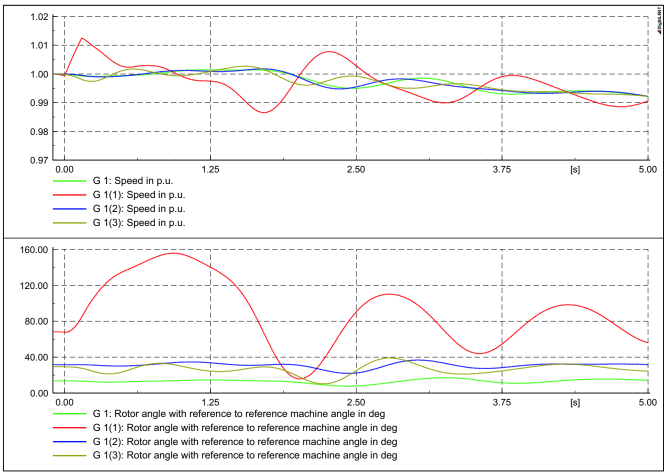

Fig. 9: Stability limit in the Case 2 at $t_{CCT} = 146$ ms; Rotor angle and speed of generators in all four areas.

Accordingly the critical area exchange flow the actual CCT is nearly equal to the minimum fault clearing time of $t_{CCT,min} = 150$ ms. So the power transfer has to reduced only by 50 MW to $P_{ex,max} = 4.400$ MW. This is an increase of about 700 MW with DFIG in service compared to the synchronous generators in service.

To analyse this effect more in detail, Fig. 10 shows the rotor angle and the speed of the generator in Area 1 for Case 1 (red curve) and 2 (blue curve) for a similar fault clearing time of 80 ms. As it can be seen in the first plot, the speed during the fault is nearly identical of both cases. The acceleration of the synchronous generators is mainly influenced by their inertia and by the active power output of the generators.

Here the DFIG are reducing their output during the fault, thus they are not contributing to the acceleration of the inertia in Area 1. The acceleration of the rotors is similar because the inertia and the active power is reduced by 50%.

After the fault is cleared the active power control of the DFIG is acting very fast helping the system to recover quickly. Due to the reduced inertia compared to Case 1, the rotor angle is reaching a lower maximum, increasing the transient stability of the system considerably.

In Fig. 11 the voltages are shown for both cases. It can be shown that the voltage drop during the fault is deeper

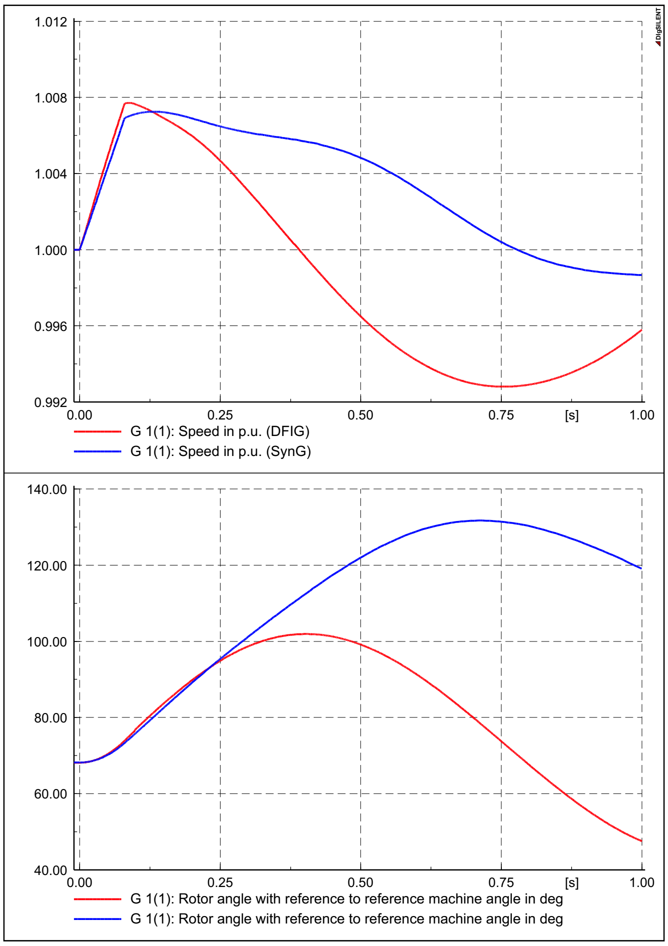

Fig. 10: Speed Response of the system to a fault of 80 ms for Case 1 and Case 2 by comparison.

with doubly-fed induction generators (red curve) than with synchronous generators (blue curve). This is due to the reactive current support during a fault being limited to around rated current in case of DFIGs. Conventional synchronous generators have a considerable thermal overloading capability and can supply reactive current up to three or four times rated current to the system.

With regard to voltage recovery after the fault has been cleared, the results of Fig. 11 show that DFIGs have a negative impact on voltage recovery. Slower voltage recovery increases the risk of other units to disconnect on undervoltage, especially the own supply of conventional power plants could trip. However, the slower voltage recovery is mainly due to the fact that the DFIGs of this example are all in power factor control mode and none of them in voltage control. Fast voltage control of DFIGs, similar to AVRs of conventional generators could improve voltage recovery substantially.

4.4 Case 3 - 100% DFIG in Area 1

In Case 3, the entire generation of Area 1 is based on DFIG technology. Consequently, there are no synchronous generators left in Area 1 that could possibly go instable. The load-flow is equal to Cases 1 and 2.

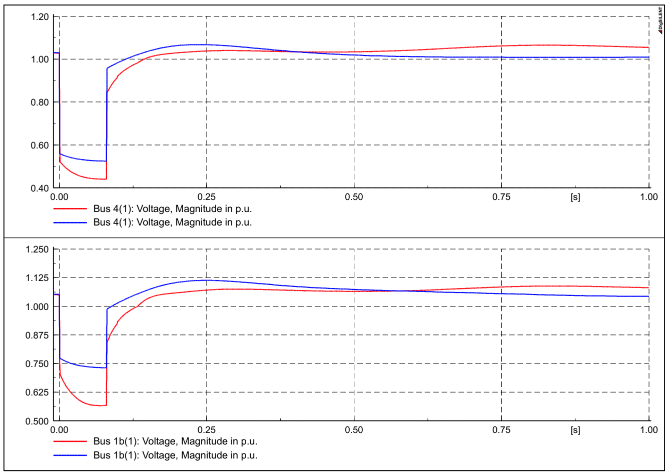

Fig. 11: Voltage Recovery of the system to a fault of 80 ms for Case 1 and Case 2 by comparison.

To ensure voltage stability in Area 1, all DFIGs have to be equipped with voltage control. Otherwise the voltage in the area would collapse and no stable operation can be maintained.

Fig. 12 shows the response of generators in the areas 0, 2 and 3 for a three-phase short-circuit for 250 ms. Compared to the previous cases, the generators show no operation point, which is near instability.

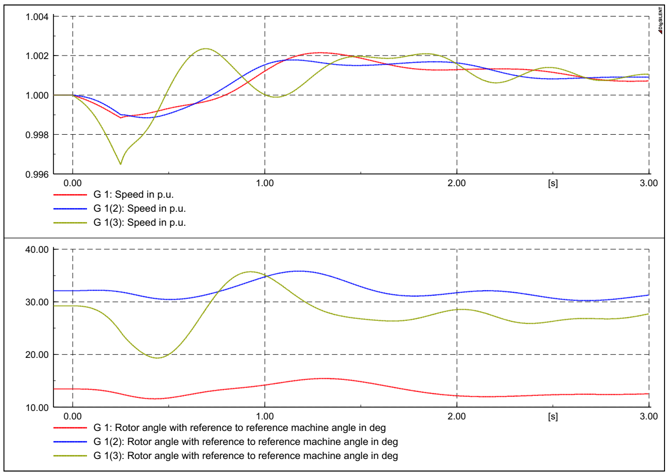

Fig. 12: Speed Response of the system to a fault of 250 ms for Case 3.

To see the behaviour of Area 1, where all generation is modelled with DFIG, Fig. 13 shows the active power of one wind farm. Additionally the voltage in Area 1 and the power transfer between Area 1 and 3 is shown.

The results indicate, that the system does not encounter a transient stability limit when operated with DFIG only. Depending of the control range of the wind generators, the voltage in the system can be held constant very well by the fast voltage control, the DFIG combined with the PWM converter is capable of.

In the case that no conventional synchronous generators

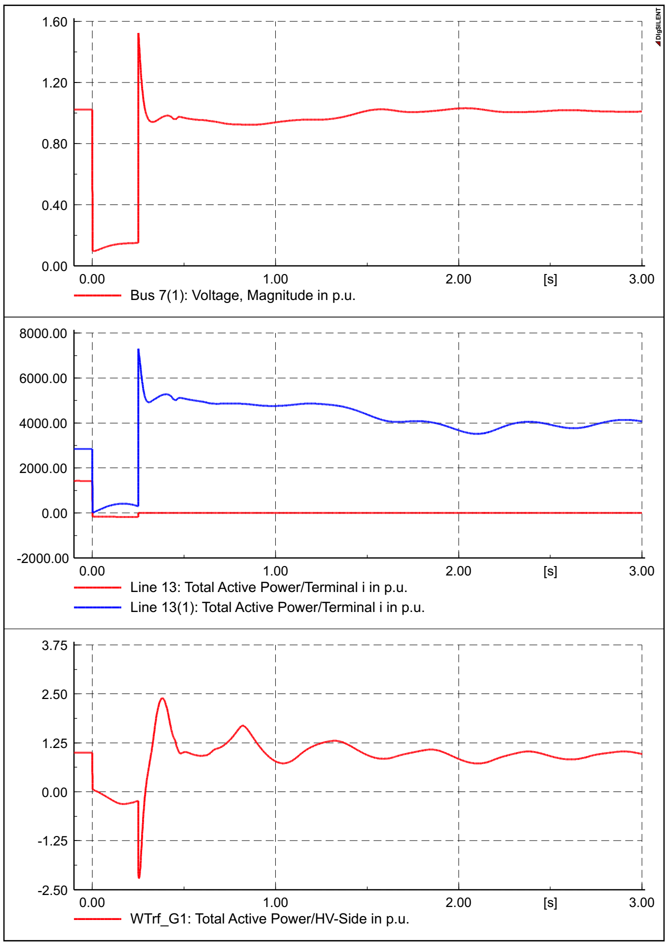

Fig. 13: DFIG Response to a fault of 250 ms with active voltage control.

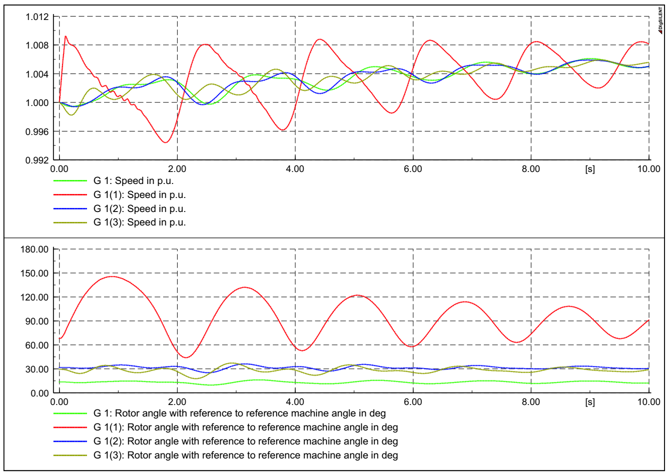

Fig. 14: Stability limit in the Case 4 at $t_{CCT} = 101\,\text{ms}$; Rotor angle and speed of generators in all four areas.

are left in the area, the area exchange flow is just limited by the steady state stability limit.

4.5 Case 4 - Infeed at Lower Voltage Level

Case 4 investigates the influence of the fact, that wind generation is most often not directly connected to transmission levels but to subtransmission or even distribution levels. To represent a realistic case of wind farm connections and to show the impact of this characteristic of wind generation, the complete amount of wind power of 5000 MW is now connected to Area 1 via 30 km cables.

Because of reactive power losses in subtransmission systems, the reactive power contribution of wind farms is lowered, in this case and conventional synchronous generators operate at lower power factors. This effect is usually partly compensated by additional reactive power compensation, such as shunt capacitors or SVCs but usually, synchronous generators tend to operate at lower power factors in the presence of a high amount of wind power.

Now the critical fault clearing time has reduced considerably due to the different reactive power conditions in Area 1. The CCT is calculated to $t_{CCT} = 101\,\text{ms}$ (Fig. 14). This time is similar to Case 1 with a relocation of the synchronous generators without DFIG connected.

5 Conclusion

This paper investigates the impact of wind generation on transient stability. For this purpose, the model of a transmission system with a typical topology was set up and the impact of a large amount of wind power on this system was studied.

Three main aspects, in which wind generation differs from conventional generation was in the center of interest of this study. These aspects are:

- Location of Wind Generation
- Generator Technology
- Connection of Large Wind Farms to Lower Voltage Levels

Different scenarios have been set-up analyzing the impact of each of the above mentioned aspects on transient stability individually leading to the following conclusions:

The location of wind generators can have a very large impact on transient stability. Especially when high wind resources are located in one particular area leading to highly modified power flows including increased tie-line flows, critical fault clearing times can be considerably reduced and additional lines might be required.

The actual generator technology has a considerable impact on transient stability. In this paper, just variable speed wind generators have been analysed (DFIGs) and it has been shown that this technology is able to improve transient stability margins, when being equipped with low voltage ride-through capability, reactive current boosting and ideally with fast voltage control. This also applies to wind generators based on converter-driven synchronous generators. Wind generators based on fixed-speed induction machines however, have not been analyzed but their negative impact on dynamic voltage stability issues is well known.

The integration of wind generation into subtransmission and distribution systems has a negative impact on transient stability, because the reactive contribution is highly limited due to reactive losses in subtransmission and distribution systems.

Generally, it could be shown that different aspects of wind generation lead to a different type of transient stability impact. In actual cases, there will always be a superposition of the above mentioned aspects, including a variety of generator types and voltage levels to which wind generators are connected. So there is no general statement possible, if wind generation improves transient stability margins or if the impact is rather negative. The answer depends on system properties, location of wind resources and generator technologies and the problem has to be analyzed individually for each case.

Other stability effects, such as voltage stability, oscillatory stability or frequency stability, which are as important as transient stability, have not been subject to this paper.

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