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Improved grid integration of wind energy systems

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Abstract. The contribution describes the German situation of grid integration of wind energy. Due to a new edition of the renewable energy law some technical requirements must be fulfilled by the wind turbines. These demands and the possibilities and efforts of the technical realization are described based on the existing technology. Then the necessary steps towards an increased power share of wind energy are introduced. This includes the energy storage in power systems and the retrofit of the existing transmission system.

Key words: wind energy, grid integration, energy storage, transmission system, grid impedance measurement.

1. Introduction

Renewable energy sources contribute with over 15% to the electrical energy consumption in Germany. Among them wind energy has the highest share with over 6%, see Table 1 [1]. This energy share corresponds to 28% of the world-wide wind energy. In 2007 the European governments declared the aim of 20% energy generation from renewable sources in 2020 [2]. At the same time, the national aim of the German government was agreed to a share of 30% of the electrical energy in 2020 [3]. This can be fulfilled only by an extensive increase of the wind energy. Therefore, in addition to the existing onshore wind parks with a total power of 23.9 GW, in 2009 more than 30 offshore wind parks with a total power of 27 GW are in planning. The pre-investigations of the first German offshore wind park "Alpha Ventus" are finished. This year the first 12 wind turbines (WTs) – each with a nominal power of 5 MW – will be installed, 200 devices with 5 MW are foreseen in a second project phase.

Table 1
Share of the renewable sources on the electrical energy consumption in Germany 2008, Source: BEE after Ref. 1

Energy source	Energy share in TWh	Energy share in %
Wind energy	40.3	6.4
Biomass	28.7	4.6
Hydropower	21.8	3.5
Photovoltaic	4.3	0.7
Geothermal	0.04	0.1
Total	**95.1**	**15.3**

This means, in some years the energy contribution from renewable energies will displace a part of the conventional power plants. Generation units will be more distributed. Also big wind park installations work highly distributed, compared to conventional coal or nuclear power plants. Such developments will cause an essential change in the technical structure of the energy supply which has consequences for the power system operation. Firstly, the balance between produced and consumed energy has to be ensured also with distributed and fluctuating energy conversion. Therefore the accuracy of the forecasted amount of energy which influences the generation load profile has to be improved. Secondly, the distributed energy must participate in the grid services, such as voltage and frequency control. This is hindered by the undefined distance between distributed energy supply and consumers which is determined by preferred installation places and weather conditions.

2. German renewable energy law

The renewable energy law (REL) regulates the grid connection rights of renewable sources and the compensation for the generated energy [4]. It is revised every four years to readjust the balance between technical progress and economical conditions. In the 2008 edition technical requirements are added in order to be prepared for the expected high power share of WTs in future. WT deliver their energy discontinuously, depending on weather conditions. To avoid problems with the necessary grid services, the REL describes technical requirements, based on grid connection guidelines [5–7]:

- frequency control (power reduction during over frequency and only low power reduction during under frequency),
- voltage control and reactive power supply,
- behaviour during grid failure events (low voltage fault-ride-through capability),
- power system reconstruction after blackout.

These required properties must be confirmed by a technical certificate from an independent institute. New installed WTs must perform these capabilities to get the prior grid connection. They obtain the additional "grid service bonus" of 0.5 €Cent/kWh if the commissioning is before 2014. Existing WTs which are installed between 2001 and 2009 can refit fault-ride-through and frequency control capabilities to obtain a five-year bonus of additional 0.7 €Cent/kWh. All technical details are mentioned in an edict to the REL, which describes also the organizational rules for the certification [8].

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All requested properties which are required to get the prior grid connection and the grid service bonus have to be offered to the transmission system operator, but will be accepted only depending on the local demands. The requested grid service capabilities will come into operation step by step with the increasing installation numbers of WTs.

3. Demanded grid services

In the guidelines [5–7] the technical details for the required WT grid connection are described. These demands are valid for all grid connected systems, not only for WTs. Figure 1a shows the power curve over frequency, which describes the controlled power reduction during over frequency and the controlled power reduction during under frequency. In case of power unbalances WTs must not disconnect from the grid in the frequency range between 47.5 Hz and 51 Hz in order to assist the grid frequency. The demanded time of supply duration is shown in Fig. 1b. Figure 1c defines the supply of reactive power, which has to be fulfilled by WTs.

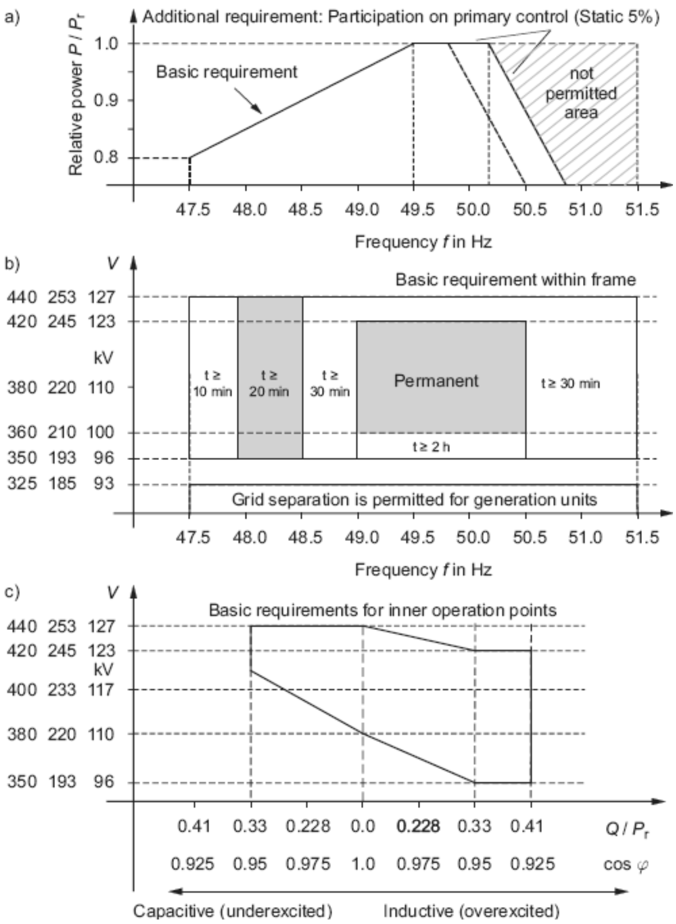

Fig. 1. Grid connection requirements for WTs in Germany after Ref. 5: a) power curve; b) supply duration; c) reactive power supply

In case of a short-time overload, the frequency drops down, see Fig. 2a. Then the power has to be halted above the curve to support the frequency stability. If a grid fault arises, the voltage drops. The height of the voltage drop is determined by the distance to the fault event and the grid structure. To assist the grid voltage in case of such faults, a low voltage fault-ride-trough (LVFRT) capability is necessary. Figure 2b and c show the demanded reaction to grid faults for all kind of power plants. In Fig. 2b boundary 1 describes voltage drops that must not result in instability of the grid connected system; boundary 2 describes voltage drops that must be ridden through.

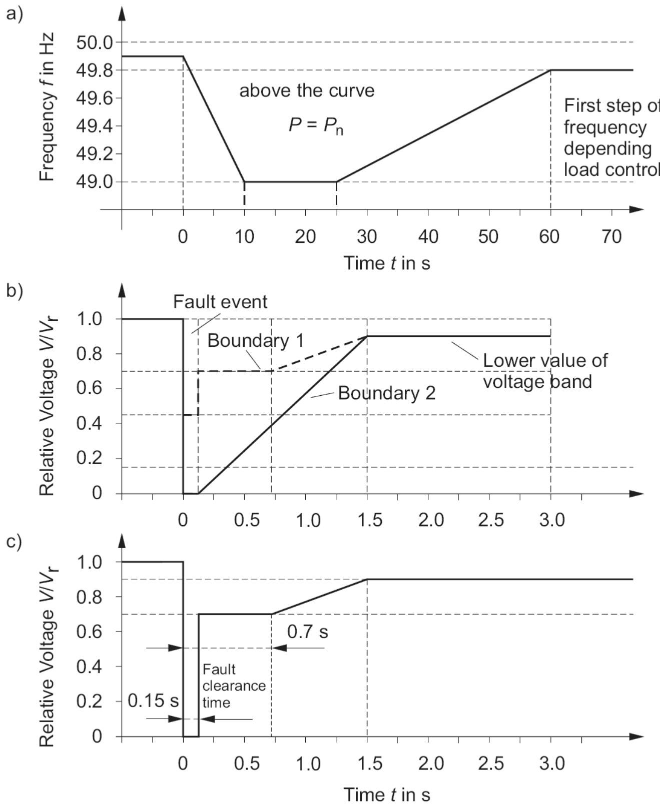

Fig. 2. German low voltage fault-ride-through guidelines for: a) low frequency; b) low-voltage after Ref. 5; c) short-circuit close to generator after Ref. 6

4. Possible grid service capabilities

4.1. Existing wind turbine technology. Depending on their technology, WTs can contribute to the required grid services. Figure 3 shows the generator types as used in WTs. The direct connected induction machine, see Fig. 3a, cannot control active or reactive power and therefore no grid service demands can be fulfilled. It is not possible to realize a low voltage fault-ride-through (LVFRT) with a direct grid connection of the generator. If the induction machine is grid coupled with a full-size voltage-source inverter (VSI), see Fig. 3b, an independent control of active and reactive power as well as LVFRT is possible. These services can also be provided by the double-fed induction machine, see Fig. 3c. Because of its direct stator grid connection some additional effort is necessary, e.g. a crowbar control to avoid over voltage in the rotor circuit during grid voltage drops.

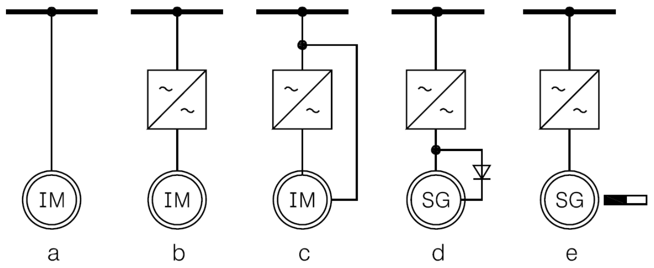

Fig. 3. Generator types: a) direct coupled induction machine; b) induction machine with full-size VSI; c) double-fed induction machine; d) electrical excited synchronous generator with VSI; e) Synchronous Generator (SG) with permanent magnet excitation

Electrical or permanent excited synchronous generators with full-size VSI, see Fig. 3d, and Fig. 3e, can fulfill all demanded grid services because of their sophisticated power control properties.

4.2. Realization of the grid services. Grid services are additional tasks for WTs, which were originally designed to deliver active power in the rated operation range. Therefore their realization is a different item for new and existing devices. We can consider the demanded grid service properties step by step.

Frequency control. A frequency control includes power reduction during over frequency and only low power reduction during under frequency, see Fig. 1a and Fig. 2a. Participation on the frequency control hinders frequency instability due to unbalance between generated and consumed power. In the UCTE grid a static of $\Delta P/\Delta f = 18000$ MW/Hz is defined. If for example a power plant with a power P_{PP} of 2000 MW drops out, the frequency decreases:

$$\Delta f = \frac{P_{PP}}{\Delta P/\Delta f} = \frac{2000 \text{ MW}}{18000 \text{ MW/Hz}} = 0.11 \text{ Hz} \qquad (1)$$

In the literature the complete realization of such control circuits is described in detail [9]. The frequency control capability of WTs requires:

- adapted frequency protection relays,
- adapted grid side inverter control,
- adapted generator control,
- modified pitch-control for power reduction,
- a chopper unit is necessary in the dc link.

The control of WTs is detailed explained in the literature [10–13], the sophisticated power control of power electronic converters was investigated earlier [14–17].

Voltage control. An increase of the reactive power will increase the grid voltage. If the reactive current i_r is defined to

$$i_r = -I_r \cdot \cos(\omega \cdot t + \varphi_{V,G})$$

an additional voltage difference is generated over the grid inductance L_G:

$$\begin{aligned} \Delta u_r = L_G \frac{di_r}{dt} &= I_r \cdot \omega \cdot \sin(\omega \cdot t + \varphi_{V,G}) \\ &= u_r \cdot \sin(\omega \cdot t + \varphi_{V,G}). \end{aligned} \qquad (2)$$

A voltage control and reactive power supply, as depicted in Fig. 1c, requires:

- adapted voltage protection relays,
- adapted grid side inverter control,
- independent control of active and reactive power of the grid side inverter.

This results in additional current load. Therefore the grid inverter must be rated for the nominal active current plus the necessary reactive current for the control of the grid voltage. A main problem is that the wind park devices must compensate also the reactive power of the transformers and cables to the PCC. If the PCC is on higher voltage levels, this means a compensation of some transformers, see Fig. 4. Formerly installed WTs will have such inverter rating reserve only accidentally. Generally it is possible to generate the reactive power with additional equipment such as central compensation units. The reactive power management of wind parks was described earlier [18].

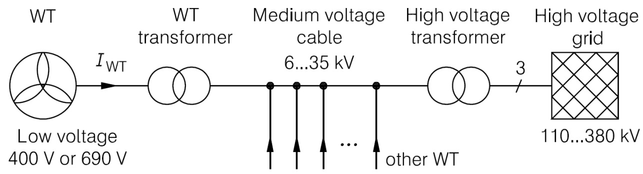

Fig. 4. Grid connection of WTs in a wind park

Behaviour during failure events. The behaviour during grid failure events (low voltage fault-ride-trough capability), see Fig. 2b and 2c, is applicable for all WTs with inverter grid connection. This property is important to avoid the switch-off of WTs within big areas after short voltage drops. A realization means in detail:

- adapted voltage protection relays,
- new control circuits on the grid side inverter,
- modified control of the generator inverter,
- a chopper unit is necessary in the dc link,
- double-fed induction generators need a crowbar.

Over voltage generation in double-fed induction generators due to supply voltage sags was described earlier [19]. The LVFRT retrofit is feasible only for new WTs and maybe for some existing systems with inverters, if the equipment cost are below the additional compensation by the grid service bonus.

Power system reconstruction after blackout. The requested power system reconstruction after blackout can be realised with a synchronisation to the grid voltage after blackout. Further requests like black start capability can be realised only with additional energy storage. Energy storage is a main problem in the power system, which is discussed in more detail in the next section.

5. Needs for further grid integration

5.1. Storage needs. In 2005 a German study was published, which investigated the need for energy storage as well as enhancement of the transmission system and the grid capacity for penetration with renewable energies [20]. Two main results of this study were:

- An increase of renewable energies in Germany up to 20% until 2015 works without additional energy storage in the grid.
- Wind power can be integrated in the grid up to a power of 48 GW.

The last result of the study was concluded without considering the new technical capabilities of WTs as described in Sec. 3 and the technical potential of new power control techniques such as smart grids and grid control with WTs [21–24]. To consider the newest technical developments, a second study for grid integration of distributed systems was started, that is not finished yet. Storage technologies are well-known and were analysed in detail in the literature [25]. In a VDE-study the storage capability of different technologies for the power system was investigated with the result that only pumped hydropower, compressed air storage and sophisticated hydrogen storage are feasible solutions [26].

For energy storage in the power system some demands are important:

- Sufficient storage capacity,
- Economical acceptable installation costs,
- Acceptable efficiencies.

Pumped hydropower costs ca 1000 €/kW and has generally no high potential for an extended capacity. Compressed air storage cost ca 700 €/kW and needs natural cavities. From technical and economical point of view it is a long way to a feasible hydrogen storage management.

In Germany some problems arise due to a high local penetration of the grid with wind energy. Some federal states have very high per capita percentages of wind power, such as Saxony-Anhalt (39%), Mecklenburg-Western Pomerania (36.5%), Schleswig-Holstein (35.98%) and Brandenburg (30%). For some of these power hot spots local solutions for energy storage are required. One proposal is the use of future mining lakes in open cast mining as new pumped hydropower plants. This solution is currently under study, technical possibilities are in development [27].

An alternative to the conventional used storage concept is the demand response, which means the use of controllable consumers. In this control non-critical processes are switched off and on. This works for electrical storage heating, electrical water heating, cooling and heating devices, air conditioning devices, circular pumps, exhausters, air compressing pumps and power plants with combined power and heating. The potential of this customer control is 46,000 GWh/a only for big cooling units in Germany [28]. This is half of the expected energy feed-in of all renewable sources in Germany for the year 2012.

5.2. Grid retrofitting and construction. Even if storage devices may be developed, the transmission capacity for the transport of the energy to the consumers is furthermore important. With increasing cost and time effort, the following retrofit measures can be applied to increase the transmission capacity:

- use of temperature monitoring systems to take advantage of external wind cooling during time intervals of increasing feed-in from wind parks; the transmission capacity increases up to 50%,
- installation of high-temperature compound conductors with a composite core; the transmission capacity increases up to 100%,
- increasing of transmission voltage, a raise from 220 kV to 400 kV increases the power per system from 400 MVA to 1600 MVA.

In the first two cases the transmission losses increase, too. Due to the n-1-reliability at least two parallel systems must be retrofitted. The new building of transmission lines is a long-term procedure because of the necessary permissions. Also the grid connection points (points of common coupling – PCC) must be utilized fully according to the existing grid capacity. This is possible with the exact determination of the grid impedance. Equipment for the measurement of the frequency depending grid impedance exist only for the low voltage level. In our institute a device for measurements on the medium voltage level is in development.

6. Conclusions

Increasing unit powers up to 6 MW and increasing installation numbers of WTs require a systematic methodology for the grid integration of onshore and offshore wind parks. The main tasks are the system stability and reliability of the power supply. This requires the participation on grid services of WTs and other distributed resources. In the new German Renewable Energy Law technical properties for grid services are demanded. Depending on the wind turbine technology different expenses are necessary for their implementation.

In addition to the technical adaptation of the WTs to the grid demands with further increasing wind energy share also new energy storage devices are requested. The possibilities for a technical realisation of units with high storage capacity are limited to pumped hydropower, compressed air storage and maybe later hydrogen storage. Therefore the use of mining lakes of open cast mining might be a solution in future. As a temporary solution the customer control should be applied. But also the transmission system must be retrofitted. This can happen with temperature monitoring, use of high-temperature conductors and the increase of the transmission voltage.

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