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Grid Integration of Renewable Energy Systems

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1. Introduction

Integration of renewable energy into the utility grid can be at either the transmission level or the distribution level, depending on the scale of generation. Large renewable energy generation such as wind farms are directly interconnected to the transmission system. Small scale distributed generation is generally interconnected to the medium or low voltage distribution systems. Both types of interconnections present different challenges that must be carefully analysed before systems are designed. This chapter outlines and discusses the most common issues encountered during grid integration of different types of renewable energy systems. The application of detailed simulation methods to identify problems and to find suitable solutions is also highlighted. Few case studies and simulation examples are presented to reinforce the concepts presented in the chapter.

2. Integration of small scale generation into distribution grids

Electricity generation using renewable energy resources is often taking place in small scale due to disperse nature of the resources. Good examples are small hydro, solar photovoltaics, biogas, biomass and small wind turbine based electricity generation systems. The size of these generators typically varies from a few hundreds of kilowatts to several megawatts. These small scale electricity generators are generally connected to the grid at the primary or secondary distribution level and are considered distributed generation (DG) or distributed resources (DR). Distributed resources include both renewable and non-renewable small scale generation as well as energy storage.

2.1 Different types of grid interfaces

Often, the small scale renewable generators are not directly connected to the grid. The generation technology or the operational characteristics requires the use of some interface between the generator and the utility distribution grid. For example, solar photovoltaics (PV) panels generate dc electricity and therefore, a power electronics based dc-to-ac converter is required between the grid and the generator. Some technologies such as induction generator based small hydro or wind can be directly connected to the ac grid. However, concerns such as starting transients, energy conversion efficiency and power

quality issues make connecting them through a power electronics interface a better choice. Table-1 summarizes some of the common types of generation and their preferred interfacing technologies.

Type	Interfacing technology
Fuel cells	Power electronic converter
Wind	Induction generator/power electronic converter
Photovoltaics	Power electronic converter
Small hydro	Synchronous or induction generator, power electronic converter

Table 1. Interfacing technologies

2.2 Issues related to grid integration of small scale generation

Most electric distribution systems are designed, operated and protected on the premise of there being a single voltage source on each distribution feeder. Interconnection of small scale renewable generation to the distribution grid violates this fundamental assumption. Therefore, certain special requirements need to be satisfied when interconnecting distributed generation to the grid in order to ensure safe and reliable operation. Fault clearing, reclosing and inadvertent islanded operation are major protection related concerns [IEEE, 2004]. In many cases, the grid-DG interface is based on power electronics inverters or asynchronous generators. The utilities are concerned about their impact on power quality. The impacts include harmonics, voltage dips, overvoltages, and voltage flicker [IEEE, 2003]. Several studies [Aldferfer et al, 2000; Dugan & McDermott, 2002] have identified that the technical requirements imposed by utilities to address these concerns as a major technical barrier for grid integration of DG. The standards such as IEEE P1547 [IEEE, 2003] provide guidelines for developing the general technical requirements for interconnection of small scale generation.

2.2.1 Protection issues

Protection is one of the most problematic issues related to the interconnection of distributed generation. Radial systems are the most common form of distribution network configuration. They are usually protected using time graded overcurrent protection schemes. Interconnection of DGs may alter the coordination of the existing protection schemes. If not carefully addressed, this can lead to malfunction of protection equipment. The main protection issues related to the interconnection of DG are briefly discussed below.

(a) Change of Short Circuit Levels

Short circuit level is one of the main parameters used in the selection of circuit breakers, reclosers, fuses and current transformers (CTs), and the coordination between overcurrent relays. Short circuit level is characterized by the equivalent system impedance at the fault point and indicates the expected level of the fault current. Time variation of the fault current is influenced by the characteristics of the rotating machinery in the vicinity. Most distribution systems are initially designed as passive networks without DG. However, with the connection of DG, equivalent network impedance can decrease, resulting in an increase in the fault level. Thus, in case of a fault, there can be unexpectedly high fault currents

which may exceed the interrupting capacity of existing circuit breakers. High fault currents can also lead to CT saturation. Also, the changed fault levels can disrupt the coordination between overcurrent relays leading to unsatisfactory operation of protection systems.

To illustrate the concerns, consider the distribution system in Figure 1. When the DG is not present, the fault currents seen by the feeder breaker BK and the recloser RC are approximately equal to the fault current I_f ($I_s \approx I_r \approx I_f$). However, when the DG is connected, $I_r = I_s + I_{dg}$, and $I_r > I_s$. This is a condition normally not observed in passive radial networks. This doesn't cause a problem if the recloser interrupting capacity is sufficient to handle the increased fault current. However, it is likely that coordination between the recloser and any downstream fuses (for example between RC and FS₁) is lost. Because both the recloser and fuses operate faster at higher fault currents, the required margins between the recloser fast curve and the fuse minimum melt curve could be reduced to an extent that the coordination is lost.

Fig. 1. Change of fault currents due to DG interconnection

(b) Reverse Power Flow

In radial distribution systems, the power flows are unidirectional. Protection schemes are initially designed based on these power flows. When a DG is connected, the power flows may be reversed [Lopes, 2002]. This could also alter the coordination of protection relays.

(c) Lack of Sustained Fault Current

In order for the protection relays to reliably detect and discriminate fault currents from the normal load currents, the faults must cause a significant and sustained increase in the currents measured by the relays. If the fault current contribution from a DG is limited, it becomes difficult for the overcurrent based protection relays to effectively detect faults. Renewable energy based generation often employs induction generators, small synchronous generators or power electronic converters. Induction generators cannot supply sustained fault currents to three-phase faults and make only a limited fault current contribution to asymmetrical faults. Small synchronous generators are usually not able to supply sustained fault currents that are significantly greater than the rated current. Power semiconductor devices cannot withstand significant overcurrent for sustained periods and therefore power electronic converters are designed to internally limit the output current. The lack of sustained fault current compromises the ability of relays to detect faults. [Barker & de Mello, 2000].

(d) Islanding

Islanding is the situation where a part of the utility network is disconnected from the main grid and operates as an independent system supplied with one or more generators. Islanding results in abnormal variations of frequency and voltage in the 'island'. Opening of an auto recloser during a fault may lead to the formation of two independent systems that

operate at two different frequencies [Jenkins et al, 2000]. Reclosing of the auto recloser while the two systems are out of phase could bring disastrous results. [Borbely & Kreider, 2000]. Further, islanding operation may create an ungrounded system depending on the transformer connection. An unidentified island would be hazardous for the repair crews. Due to the above reasons, islanding is recognized as an unsafe situation and immediate disconnection of the DGs from the grid is recommended upon formation of an island [IEEE, 2003].

2.2.2 Voltage control

Interconnection of DG results in changes in power flows and the voltage profile of the feeder, and generally results in overvoltages under low load or high (DG) production conditions. In weak networks, the DG capacity is generally determined by the voltage limits. Furthermore, the connection status of a DG is not controlled by the utility. Disconnection of a DG during the high load can cause undervoltages, while re-connection of a DG under low load conditions may cause overvoltages. This may lead to poor power quality situation and may result in operation of under/over voltage relays.

Selection of appropriate tap settings for the distribution transformers becomes difficult with the increased penetration of DG. This is specially difficult when the DGs are not equally distributed among the feeders supplied by the same transformer [Uchida et al, 2006]. Such a situation is illustrated in Figure 2 where there are two feeders supplied by the same transformer, but DGs are concentrated on only one of them. Generally, when the DGs are connected, the net current flow through the transformer is reduced because the DGs provide the power to the nearby loads. Consequently, the transformer tap needs to be changed to the light load setting. The resulting decline of the sending voltage can cause a voltage violation at the far end of the feeder without DGs as shown in Figure 2. Leaving the transformer tap at the heavy load setting risks overvoltages on the feeder with DGs. Switched capacitors and static VAR compensators can be used to control the feeder voltages, but these solutions are often too costly.

Fig. 2. Possible DG interconnection configurations

Another issue that affects the operation of DGs at distribution level is the unbalanced voltage profile. As shown in Figure 3, both the loads as well as DGs can be either three-phase or single-phase. Interconnection of single phase sources will increase the system unbalance. On the other hand, inherently unbalanced distribution systems can pose problems for the three-phase DGs connected to it: the resulting unbalance currents in the DG can cause overheating and frequent shutdowns.

Fig. 3. Possible DG interconnection configurations

2.2.3 Harmonics and flicker

The quality of power supplied to the customers is one of the major concerns of service providers. The majority of the DGs are interfaced using power electronic converters. Power electronic devices inject harmonics into the system resulting in a poor power quality for the consumers. This can be overcome by using harmonic filters. Harmonic filters may be active, passive or hybrid and must be selected appropriately according to the requirement. In addition the starting of directly connected induction generators may cause voltage flicker. The soft-starting mechanisms are sometimes useful in reducing these voltage fluctuations. Wind generators can also introduce periodic fluctuations in the voltages due to tower shadow effect [Fadaeinedjad et al, 2009].

2.2.4 Interconnection standards and examples of grid codes

In order to address protection and safety issues, DG interconnection standards and guidelines have been introduced. The most widely applied standard is the IEEE Std. 1547-2003, "IEEE Standards for Interconnecting Distributed Resources (DR) with Electric Power Systems 2003" [IEEE, 2003]. Most utilities have adopted the IEEE Std. 1547-2003 in formulating guidelines/ rules for interconnecting DG to their networks. A brief description of the salient features of IEEE Std. 1547-2003 is given below.

IEEE Std. 1547-2003 recommends disconnection of distributed energy resources when the voltage and/or frequency at the point of interconnection deviate from their base values due to faults and other disturbances. The allowable deviations are defined in Tables 2 and 3. Also, for an unintentional island in which the DG energizes a portion of the network, the

DG interconnection system must detect the island and disconnect the DG within two seconds of the formation of an island [IEEE, 2003].

Voltage range (% of base voltage ^a)	Clearing time(s) ^b
$V < 50 \%$	0.16
$50 \% \leq V < 88 \%$	2.00
$110 \% \leq V < 120 \%$	1.00
$V \geq 120 \%$	0.16

^aBase voltages are the nominal system voltages stated in ANSI C84.1-1995.
^bDR ≤ 30 kW, maximum clearing times; DR > 30kW, default clearing times.

Table 2. Interconnection System Response to Abnormal Voltages [IEEE, 2003]

DR size	Frequency range(Hz)	Clearing time(s) ^a
≤ 30kW	> 60.5	0.16
	< 59.3	0.16
> 30kW	> 60.5	0.16
	< {59.8-57.0} (adjustable set point)	0.16 to 300 (adjustable)
	< 57.0	0.16

^aDR ≤ 30 kW, maximum clearing times; DR > 30kW, default clearing times.

Table 3. Interconnection System Response to Abnormal Frequencies [IEEE, 2003]

2.3 Islanding and anti-islanding protection methods

As discussed earlier, formation of unintentional power islands is unsafe an undesirable. Therefore, formation of islands must be swiftly detected and the generators energizing the island must be disconnected. This is commonly known as the anti-islanding protection or the loss-of-main protection. There are several methods that provide anti-islanding protection. They can be broadly categorized into three groups: active methods, passive methods and telecommunication based methods.

2.3.1 Passive methods

The passive islanding detection methods make decisions based on measured electrical quantities such as voltage and frequency. Voltage relay is one of the simplest passive methods used to detect islands. The reactive power imbalance between production and consumption, which occurs after the loss of mains, leads to a change in the voltage level. Thus, the voltage magnitude measured at the DG can be used to detect the island. Trip signals are generated if the measured voltage shows abnormal variation over a predefined period of time. Normally, voltage relays respond to both under-voltage and over-voltage situations. However, voltage collapse is a slow process and detection of islands using voltage relays could be very slow.

Voltage Surge relay (also known as Voltage Vector Shift relay or Voltage Phase Jump relay) is one of the methods used for fast detection of islands. The loss of grid connection results in a sudden change in load and thus, a sudden change in cycle length of the terminal voltage waveform. The cycle duration becomes either shorter or longer, depending on if there is an excess or a deficit of active power in the islanded system. The Vector Shift relay measures

the length of each cycle of the voltage waveform. The cycle duration of the waveform is compared with the duration of the previous cycle. If the difference in the cycle duration exceeds the relay setting, a trip signal is issued. Usually these relays are provided with low voltage blocking facility to block the trip signal if the terminal voltage drops below a threshold level to avoid false operations [Freitas et al, 2005].

Frequency relay is another example of passive detection methods. Under-frequency can occur if the grid connection is lost at a situation where the local load exceeds the production of the generator, whereas over-frequency situations can arise if there is a surplus production at the time of grid disconnection. Thus, the frequency relays can take decisions based on the frequency of the voltage at the DG. The over-frequency or under-frequency elements are used to trip the generator from the system. If the real power in the island is almost balanced, the change of frequency of the islanded section will be low, making the relay ineffective. Rate of change of frequency (ROCOF), which is the time derivative of the frequency, is also frequently used to detect power islands. ROCOF relays are popular as they response much faster than the frequency relays.

2.3.2 Active methods

In the active detection methods, disturbances are injected into the network and islands are detected based on system responses to the injected disturbance [Freitas et al, 2005]. Reactive error export, fault level monitoring, system impedance monitoring and frequency-drift are some of the active island detection methods.

The reactive error export method controls the DG excitation current to generate a known value of reactive current. This cannot be supported when the DG is not connected to the grid. The change in the reactive power measured during the formation of power island is used to detect the situation [Redfern et al, 1993; Kane & Fox, 1997]. The fault level monitoring method uses a point-on-wave switched thyristor in series with a shunt inductor. The thyristor is triggered at a point close to the voltage zero crossing and the current through the shunt inductor is measured. It is possible to estimate the system impedance and the fault level using the measured current pulse. The fact that the fault level drops when the grid connection is lost, is used to detect the islanding. Usually the estimation of fault level is repeated at every half cycle [Redfern et al, 1993; Kane & Fox, 1997]. System impedance monitoring as its name implies, is a method that detects loss of mains (LOM) by actively monitoring the system impedance. A high frequency (HF) source is connected via a coupling capacitor at the point of interconnection (PCC). The capacitor is in series with the equivalent network impedance. With the presence of connection to the utility grid, the equivalent impedance at the PCC is low; therefore the HF-ripple at coupling point is negligible. However, after islanding, the equivalent impedance at the PCC increases dramatically and the divided HF-signal is clearly detectable [Redfern et al, 1993; Kane & Fox, 1997].

The frequency drift LOM detection method is specifically used in inverter interfaced DGs. The output current of the converter is controlled to a frequency which is slightly different to the nominal frequency of the system. Under normal conditions, the terminal frequency is dictated by the powerful bulk supply. If the mains supply is lost, frequency will drift until a certain shutdown level is exceeded [Ropp et al, 1999; Hung et al, 2003].

2.3.3 Telecommunication-based Methods

The telecommunication-based methods use communicated circuit breaker status signals to alert and trip DGs when islands are formed. Their performance is independent of the type of distributed energy resources involved. Telecommunication based systems can be implemented in conjunction with SCADA systems. In this approach, the states of the circuit breakers in the grid are continuously tracked. The circuit breaker state information can be used to determine whether a part of the system has become an island, using predetermined logic. Transfer tripping schemes can be considered as a decentralized version of the SCADA based system described above. In transfer trip schemes, a logic circuit uses information of circuit breaker states to determine if a part of the grid has been islanded.

Comparison of rate of change of frequency (COROCOF) at the substation and the DG location is another telecommunication-based method. The rate of change of frequency is measured at the substation and if it exceeds a certain limit, a block signal is sent to the DG end. If the rate of change of frequency at DG is greater than a set point, and if there is no block signal received from the substation end, the DG will be tripped.

Out of the above described methods under/over voltage, under/over frequency, rate of change of frequency (ROCOF) and voltage vector surge (VVS) relays are the most widely used methods for anti-islanding protection. One of the main disadvantages of these methods is the possibility of nuisance tripping of DGs during other system disturbances such as load switching, faults, etc.

2.3.4 Intentional islanding and Microgrids

Although islanded operation of DG has recognized as hazardous situation, a generator or cluster of generators operating as an island (microgrid) may be able to supply a part of the local load when grid supply is not available. This type of operation is commonly known as intentional islanding. Numerous technical issues have to be addressed to make intentional islanded operation a reality [Freitas et al, 2005]. The Power balance needs to be maintained between production and consumption. An effective protection coordination must be maintained under both grid connected and islanded modes. In order to reach such a high level of local autonomy, it requires solving advanced control and protection functions.

3. Interconnection studies

When interconnecting a renewable energy based generator, the grid interface needs to be designed to meet applicable regulatory requirements set by the local utility. In order to verify the requirements pertaining to protection, control and power quality, detailed simulation studies need to be performed. Time domain simulation using Electromagnetic Transient (EMT) programs is a powerful method that can be used for studies involving controller tuning, protection setting, power quality investigations and system validations. EMT programs typically come with a built-in library that include detailed rotating machine models (synchronous, induction, permanent magnet, etc.), transformers models (including iron core saturation), frequency dependent transmission line and cable models, measurement transformer (CT, VT and CCVT) models from which realistic secondary waveforms can be derived for protection system validation. In addition to electrical components, facilities exist for simulating complex control systems. These computer

programs also offer the ability of modeling of power electronic systems in detail. Thus, they can be used for studying all type of DG interfaces:

- directly connected synchronous/induction generators,
- converter connected DC sources (fuel cell, PV),
- doubly fed induction generators (DFIG), and
- converter connected variable frequency synchronous generators.

Few simulation studies that demonstrate different interconnections interfaces and issues are discussed in the following sections. The simulations were carried out using the industry standard PSCAD/EMTDC software program.

3.1 Soft-starting of fixed speed induction generator wind turbines

The first example is a fixed speed wind generator interconnected to a medium voltage (MV) distribution system. The distribution system shown in Figure 4 is adopted from a benchmark MV distribution system proposed by CIGRE for DG integration studies [Rudion, 2005]. The network is normally operated as a radial system, although two disconnect switches (S2 and S3) are available for network reconfiguration.

Fig. 4. Medium voltage distribution system

In detailed simulation studies, it is customary to use a reduced model of the network. In the simplified distribution network shown in Figure 5, a section of the network (upstream of bus 8) is replaced by its Thevenin's equivalent circuit. Parts of the network that are of interest for the study are represented in detail. In this example, it is assumed that bus 11 is supplying a critical load sensitive to power quality problems. Therefore, the feeder section from bus 8 to bus 11 is represented in detail. The direct coupled wind generator is represented using a detailed induction machine model. Although it is not critical for this study, a detailed wind turbine model with pitch control is also used.

Fig. 5. Simplified distribution system

Fig. 6. Voltage at bus 11 during the wind generator start-up.

Fig. 7. Wind generator real and reactive power output during the start-up.

The usual starting procedure is to let the wind turbine accelerate the generator to a specific predetermined speed (close to the synchronous speed) and then connect the generator terminal to the grid supply. The machined speeds up, (in motoring mode), drawing both real and reactive power from the grid. This starting procedure has caused a large voltage dip at bus 11 as can be seen in Figure 6. This is a result of the machine initially darwing a significat amount of starting current from the system. The real and reactive power exchange between the induction generator and the grid during this period is shown in Figure 7. One low cost solution to this problem is the use of a thyrister based soft starter [Peters et al, 2006]. The variation of bus 11 voltage with the soft starter is shown in Figure 8. As evident from the simulaion results, the soft starter can significantly reduce the voltage dip. The real and reactive power exchanges with the soft starter is shown in Figure 9.

Fig. 8. Voltage at bus 11 during soft starting of the wind generator.

Fig. 9. Wind generator real and reactive power output with soft starting

3.2 Fault current contribution of different generators

The nature of fault current contribution of different DG interface technology can be accurately analysed through detailed electromagnetic transient simulations. The output current produced by a synchronous generator connected to bus 7, during a three-phase short circuit at bus 8 is shown in Figure 10. The output currents of (i) a direct coupled induction generator, (ii) a direct coupled induction generator with external rotor resistance, and (iii) a doubly fed induction generator (DFIG) for the same fault are shown in Figs. 11, 12, and 13 respectively. The lack of sustained fault current in the latter three cases is clearly visible. It should be noted that with power electronic interfacing (e.g. DFIG, PV), the shape of the fault current is influenced by the converter protection and control strategy.

Fig. 10. Fault current contribution from a synchronous generator

Fig. 11. Fault current contribution from an induction generator

Fig. 12. Fault current contribution from an induction generator with external rotor resistance. Note the faster decay than in the normal induction generator case in Figure 11.

Fig. 13. Fault current contribution from a doubly fed induction generator (crow bar operation is not simulated).

3.3 PV grid integration

Interconnection of a 250 kW photovoltaic (PV) power system in place of the wind turbine is considered in this example. Detailed models of the PV array, power converter and its controller with maximum power point tracking (MPPT) are used in the simulation. The system behaviour under rapidly changing solar radiation intensity is examined. The schematic of the PV system in PSCAD/EMTDC is shown in Figure 14. Figure 15 shows the variation of the solar radiation intensity. The voltage at bus 14 under the simulated solar radiation variation is shown in Figure 16. The real and reactive power output of the PV inverter is shown in Figure 17. The inverter output current shown in Figure 18 is highly distorted, and its harmonic spectrum is shown in Figure 19. This distorted current causes voltage distortion. The harmonics spectrum of the voltage at bus 14 is shown in Figure 20. If the harmonic distortion is unacceptable, it is necessary to install a filter at the PCC of the PV power system.

Fig. 14. Schematic of the grid connected PV system simulation (for the simplicity, the ac system is shown as an equivalent source).

Fig. 15. Variation of the solar radiatin intensity

Fig. 16. Variation of the voltage at bus 7

Fig. 17. Real and reactive power output of the inverter

Fig. 18. Inverter output current

Fig. 19. Harmonic spectrum of the inverter current (Fundamental 0.28 kA)

Fig. 20. Harmonic spectrum of the voltage at bus 7 (Fundamental 7.43kV)

4. Integration of large scale renewable energy generation

Large scale renewable energy based generation such as conventional hydro, steam turbines operated with biomass or geothermal energy use conventional technology based on synchronous generators. Utilities are well experienced with this established technology. However, interconnection of large scale wind farms poses entirely different set of challenges, mainly due to the intermittent nature of the wind and the desirability for variable speed operation of the generators.

4.1 Issues related to grid integration of large wind farms

Recent rapid growth of wind energy generation has resulted in the development of large wind farms with capacities in excess of 100 MW. Such large scale wind farms are generally interconnected to the transmission grid. In some countries like Germany and Spain, the installed wind generation capacity has reached several thousand megawatts and the installed wind capacity is continuously increasing. However, power output of the wind generators cannot be dispatched. Despite the advances in short-term (and long-term) wind forecasting technology, accurate forecasting of wind speed is difficult. Therefore, a significant spinning reserve and stand by capacity is required to cover the fluctuations in wind farm production. Although the distribution of wind farms over a wide geographic area provides some cushioning effect, the possibility of simultaneous low production from all wind farms cannot be entirely ruled out.

During a disturbance such as a short duration voltage dip caused by a short circuit in the high voltage transmission network, several thousand megawatts of wind generation can get disconnected depriving real power to the grid. Such a condition can result in serious stability problems within the power system. Thus, new connection requirements for large wind farms have been introduced by many system operators. These new connection regulations such as fault ride through capabilities compel wind turbines to have a supporting effect on grid operation.

A typical fault ride through capability requirement, expected from large, modern wind farms is shown in Figure 21. It specifies the time duration that the wind farm is required to stay connected, for different levels of voltage depressions. This is an attempt to ensure that the wind farm is capable and ready to supply power to the system immediately after clearing the fault to maintain system stability.

Fig. 21. Typical fault ride through requirements. The actual fault ride through curve can vary depending on the transmission operator.

The 'strict' fault ride through standards presents serious challenges to the wind turbine system designer.

- During the fault, the power transfer capability of the wind turbine generator (WTG) is diminished. This will result in mechanical over speeding of the machine and the turbine blades. This will place mechanical stress on blades and the other rotating parts.
- During the fault recovery period, depending on the generator technology employed, the WTG may draw increased amounts of reactive power from the system. This will result in a poor fault recovery response.
- The nature and the magnitude of the fault current contribution from the wind farm depend on the WTG technology. A good understanding of this is necessary to design equipment ratings and for protection and control settings.
- Turbine blade pitch control must be capable of regulating the input mechanical power. During faults, fast pitch control of blades will limit the mechanical over speeding of rotating elements.
- Application of appropriate FACTS based reactive power compensation devices can help improve the overall performance of the wind farm.

The requirement of reactive power for voltage support is one of the key issues related to wind power generation. Most wind generation systems use induction generators. Unlike synchronous machines, induction machines do not have reactive power control capability. Interconnection regulations require the wind farms to maintain the power factor within a narrow range, usually within ± 0.95 . If the wind generators are not capable of meeting this requirement, dynamic reactive support must be provided. Usually the reactive power support is provided using a combination of a capacitor bank and static var compensators (SVCs)/STATCOM. The sudden disconnection of the wind turbine generators while the capacitor bank is still connected can result in overvoltage at the generator terminals. This is a major protection problem related to the large wind farms.

The type of reactive power compensation method and devices used at a wind farm also plays an important role in the performance of the wind farm during the period immediately following the clearance of a system fault. Reactive power capability of a capacitor bank (and

SVC's) is directly related to the 'available' terminal voltage. Due to this reason, capacitor banks have a degraded reactive power capability during fault recovery when in fact, their reactive power capability is most needed. FACTS based voltage source converters (e.g STATCOM) does not have this inherent drawback and is generally the superior option, purely from a reactive power capability point of view. The selection of the reactive power compensation scheme and its control strategy must be carefully evaluated.

Synchronous condensers are another reactive power compensation option for large wind farms. They have a slower response compared to a STATCOM, but do provide inertia to the system. This may have advantages, especially when interconnecting to weak ac systems with dynamic stability concerns.

Other possible challenges that require detailed investigation may include:

- Turbine power electronic design and controller optimization
- The design of filters and protection systems
- Interactions between numerous turbines
- Problems of wind farms connected into series compensated systems
- Power quality issues including voltage flicker
- Starting and synchronizing of wind farms to the grid.
- Sub synchronous resonance issues due to interaction of the electric network and the complex shaft/gear system of the wind turbine.

Detailed studies, based on electromagnetic transient programs is essential to identify possible interconnection issues and to find optimum solutions.

4.2 Modeling and simulation requirements

4.2.1 Turbine characteristics

The power transferred by the turbine blades is given by (1)

$$P_{mech} = \frac{1}{2} \rho \cdot A_r \cdot C_p(\lambda, \beta) \cdot V_w^3 \quad (1)$$

$$\lambda = \frac{\Omega_r r_r}{V_w} \quad (2)$$

where C_p is the power coefficient, β is the pitch angle, λ is the tip speed ratio, V_w is the wind speed, Ω_r is the rotor speed (on the low-speed side of the gearbox), r_r is the rotor-plane radius, ρ is the air density and A_r is the area swept by the rotor. The power coefficient, C_p , represents the aerodynamic characteristics of the blade. Note that in Figure 22, C_p is plotted as a function of the 'tip speed ratio'. Tip speed ratio is a measure of the relative speed of wind compared to the rotational speed of the blades. The C_p characteristics can be altered through blade pitch angle (β) control, thereby controlling the amount of mechanical power available to the generator for power conversion. The exact characteristic of C_p depends on the particular design of the blade. The function $C_p(\lambda, \beta)$ can be approximated using analytical equations or determined by tests.

Fig. 22. Typical variation of C_p with wind speed

4.2.2 Turbine pitch control

The control system that orders the pitch angle (β) and the response of the actuators and other mechanical parts may need to be adequately represented in the simulation study. It should be noted that due to the large inertias involved (turbine blades), the overall response of pitch control is 'slow' and is in the order of a few seconds.

4.2.3 Wind generator technology

Most wind turbine generators at present are based on asynchronous generators. It is advantageous to operate these machines at variable speeds during low wind speed conditions. To produce constant voltage and frequency from these asynchronous generators operating at variable speed, they are often interfaced with the grid using various setups of power electronics and controls. The power electronic interface also allows for other desirable features. The controls are sophisticated and complex.

For example they possess the capability of controlling the voltage, real and reactive power output of the machine within some design range, while meeting other constraints such as limiting the positive power ramp rate of the machine. Controller design and settings must ensure low-voltage ride-through compliance. In the future, it is expected that wind turbines would be able to provide more functionalities such as advanced governor functions and controlled ramp down during high wind speed events.

There are several wind generator technologies with the more common WTG schemes being,

- Induction machines directly connected to the grid with external reactive power compensation
- Wound rotor induction machines with an external variable resistor in the rotor circuit to control slip (speed)
- Doubly-fed induction machines, which employ an ac-dc-ac converter between the stator and rotor circuits
- Conventional or permanent magnet synchronous machines connected to the grid through a fully-rated ac-dc-ac converter.

Detailed, high band width models of machines that does not neglect the stator flux transients are required for detailed analysis of such events as

- starting and synchronization wind generators,

- accurate fault ride through analysis
- DFIG control and protection (crow bar etc.)
- VSC based back to back ac-dc-ac converter design including dc line/cable resonance issues.

4.2.4 Power system model

Electromagnetic transient simulations allow for accurate representation of power system equipment. This may include nonlinear core models of transformers and reactors, induction motor and other dynamic loads, overhead lines and cables considering inter-conductor mutual effects, accurate representation of power electronic switching devices, FACTS devices and also control systems.

In general, grid integration requires understanding the needs of the power system, knowledge of machine capabilities, and application knowledge of the power converter and control capability to put the entire picture together. Thus a typical study needs modelling of the grid, wind resource, wind turbine, generator, power electronics, controllers and protection.

4.3 Simulation example

In this example, the application of an SVC to enhance voltage control and system stability is demonstrated. The single line diagram of the high voltage transmission system used for the study is shown in Figure 23 [Jiang et al, 2005].

Fig. 23. High voltage transmission system model.

A wind farm is connected to Bus 12. For this study, all generators in the wind farm are represented by a single equivalent generator. In order to provide voltage support, an SVC is connected at bus 6. A fault is applied on the 230 kV transmission line connecting Bus 1 and

Bus 6. The fault is cleared by opening the line breakers after 9 cycles. The response of the wind generators with and without the SVC in operation is shown in Figs. 24 and 25. It is clear that the wind farm is unstable for this fault if not for the voltage support from the SVC.

Fig. 24. With the SVC in operation, the generator speed reaches a stable steady state upon the removal of the fault

Fig. 25. Without the SVC in operation, the wind generator is unstable.

5. Conclusion

Various issues and challenges that need to be addressed in grid integration of renewable energy systems are discussed. The major concerns in interconnection of the small scale renewable energy generation at the distribution level are related to protection, voltage control and power quality. The reserve requirements, reactive power requirements and the grid support during the disturbances are among the major issues to be considered in grid interconnection of the large wind farms. The importance of the simulation tools in grid integration studies is demonstrated through several case studies.

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Renewable Energy is energy generated from natural resources-such as sunlight, wind, rain, tides and geothermal heat-which are naturally replenished. In 2008, about 18% of global final energy consumption came from renewables, with 13% coming from traditional biomass, such as wood burning. Hydroelectricity was the next largest renewable source, providing 3% (15% of global electricity generation), followed by solar hot water/heating, which contributed with 1.3%. Modern technologies, such as geothermal energy, wind power, solar power, and ocean energy together provided some 0.8% of final energy consumption. The book provides a forum for dissemination and exchange of up-to-date scientific information on theoretical, generic and applied areas of knowledge. The topics deal with new devices and circuits for energy systems, photovoltaic and solar thermal, wind energy systems, tidal and wave energy, fuel cell systems, bio energy and geo-energy, sustainable energy resources and systems, energy storage systems, energy market management and economics, off-grid isolated energy systems, energy in transportation systems, energy resources for portable electronics, intelligent energy power transmission, distribution and inter-connectors, energy efficient utilization, environmental issues, energy harvesting, nanotechnology in energy, policy issues on renewable energy, building design, power electronics in energy conversion, new materials for energy resources, and RF and magnetic field energy devices.

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