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Grid Connection Requirements and Solutions for DFIG Wind Turbines

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Abstract – As the number and size of wind farms continue to grow, many countries have established or are developing a set of specific requirements (i.e., grid codes) for operation and grid connection of wind farms. The objective of these grid codes is to ensure that wind farms do not adversely affect the power system operation with respect to security of supply, reliability and power quality. This paper reviews major grid code requirements for wind farms, and investigates various technologies developed by and solutions proposed by researchers and wind turbine manufactures in order to meet these requirements. In addition, some of the authors' work on these issues are discussed and demonstrated by simulation studies.

I. INTRODUCTION

In recent years with growing concerns over carbon emission and uncertainties in fossil fuel supplies, there is an increasing interest in clean and renewable electrical energy generation. Among various renewable energy sources, wind power is currently the fastest growing form of electric generation. Although wind power currently only provides about 3% of European electricity and 2% of the U.S.'s electrical energy demands, it is reasonable to expect a high penetration of wind power into the existing power system in the near future, e.g., by 2030. For instance, the European Wind Energy Association (EWEA) has set a target to satisfy 23% of European electricity needs with wind by 2030 [1]. In the United States, the Department of Energy (DOE) and the American Wind Energy Association (AWEA) examined the feasibility of providing 20% of the nation's electricity from wind by 2030; and the consensus is that this scenario is feasible [2]. In fact, some European countries already achieved high levels of wind power penetration. For instance, according to the data of 2007, wind power accounts for approximately 19% of electricity production in Denmark, 9% in Spain and Portugal, and 6% in Germany and the Republic of Ireland.

With the rapid increase in penetration of wind power in the power system, it becomes necessary to require wind farms to behave as much as possible as conventional power plants to support the network voltage and frequency not only during steady-state conditions but also during grid disturbances. Due to this requirement, the utilities in many countries have recently established or are developing grid codes for operation and grid connection of wind farms. The aim of these grid codes is to ensure that the continued growth of wind generation does not compromise the power quality as well as the security and reliability of the electric power system.

Wind turbine manufactures have to respond to these grid code requirements. Therefore, much research effort has been conducted to develop technologies and solutions in order to meet these requirements.

This paper discusses major grid code requirements for operation and grid connection of wind farms. Also, it investigates various technologies and solutions for wind turbines equipped with doubly fed induction generators (DFIGs) to meet these requirements.

II. GRID CODES

The major requirements of typical grid codes for operation and grid connection of wind turbines are summarized as follows.

1) Voltage operating range: The wind turbines are required to operate within typical grid voltage variations.

2) Frequency operating range: The wind turbines are required to operate within typical grid frequency variations.

3) Active power control: Several grid codes require wind farms to provide active power control in order to ensure a stable frequency in the system and to prevent overloading of lines, etc. Also wind turbines are required to respond with a ramp rate in the desired range.

4) Frequency control: Several grid codes require wind farms to provide frequency regulation capability to help maintain the desired network frequency.

5) Voltage control: Grid codes require that individual wind turbines control their own terminal voltage to a constant value by means of an automatic voltage regulator.

6) Reactive power control: The wind farms are required to provide dynamic reactive power control capability to maintain the reactive power balance and the power factor in the desired range.

7) Low voltage ride through (LVRT): In the event of a voltage sag, the wind turbines are required to remain connected for a specific amount of time before being allowed to disconnect. In addition, some utilities require that the wind turbines help support grid voltage during faults.

8) High voltage ride through (HVRT): In the event the voltage goes above its upper limit value, the wind turbines should be capable to stay on line for a given length of time.

9) Power quality: Wind farms are required to provide the electric power with a desired quality, e.g., maintaining constant voltage or voltage fluctuations in the desired range,

maintaining voltage/current harmonics in the desired range, etc.

10) Wind farm modeling and verification: Some grid codes require wind farm owners/developers to provide models and system data, to enable the system operator to investigate by simulations the interaction between the wind farm and the power system. They also require installation of monitoring equipment to verify the actual behavior of the wind farm during faults, and to check the model.

11) Communications and external control: The wind farm operators are required to provide signals corresponding to a number of parameters important for the system operator to enable proper operation of the power system. Moreover, it must be possible to connect and disconnect the wind turbines remotely.

Grid code requirements and regulations vary considerably from country to country and from system to system. The grid codes in a certain region or country may only cover a part of the above requirements. The differences in requirements, besides local traditional practices, are caused by different wind power penetrations and by different degrees of power network robustness. Because of the relatively high levels of wind power penetration, many European countries currently lead the U.S. in developing grid codes for wind farms.

In the U.S., the AWEA initiated an activity referred to as the Grid Code to recognize the unique requirements and characteristics of wind farms. This activity resulted in AWEA filing a Petition for Rulemaking at the Federal Energy Regulatory Commission (FERC) in May, 2004 [3]. The FERC issued an order in December 2005 on interconnection requirements for wind energy connected to the transmission networks in the U.S [4]. These requirements are applicable to wind farms larger than 20 MW and mainly cover the following three major technical topics.

1) LVRT capability: The wind farms are required to remain on line during voltage disturbances up to specified time periods and associated voltage levels, as described by Fig. 1. According to this LVRT specification, the wind turbines should remain connected to the grid and supply reactive power when the voltage at the point of connection falls in the gray area. In addition, wind farms must be able to operate continuously at 90% of the rated line voltage, measured at the high voltage side of the wind plant substation transformers.

2) Power factor (reactive power) design criteria: The wind farms are required to maintain a power factor within the range of 0.95 leading to 0.95 lagging, measured at the high voltage side of the substation transformers.

3) Supervisory control and data acquisition (SCADA) capability: The wind farms are required to have SCADA capability to transmit data and receive instructions from the Transmission Provider.

In addition to above three topics, the AWEA recommended to the FERC that transmission providers and wind turbine manufacturers participate in a formal process for developing, updating, and improving engineering models and turbine specifications for modeling the wind farm interconnection.

This paper investigates the technologies and solutions for operation and grid connection of DFIG wind turbines to meet the grid codes related to reactive power and voltage control, active power and frequency control, LVRT, and HVRT requirements.

Fig. 1. Typical low voltage ride through requirement – U.S.

Fig. 2. Configuration of a DFIG wind turbine.

III. CONFIGURATION OF DFIG WIND TURBINE

The basic configuration of a DFIG wind turbine is shown in Fig. 2 [5]. The wind turbine is connected to the DFIG through a mechanical shaft system, which consists of a low-speed turbine shaft and a high-speed generator shaft and a gearbox in between. The generator (i.e., the DFIG) in this configuration is a wound-rotor induction machine. It is connected to the grid at both stator and rotor terminals. The stator is directly connected to the grid while the rotor is fed through a variable frequency dc-link-voltage converter (VFC), which only needs to handle a fraction (25-30%) of the total power to achieve the full control of the generator. The VFC consists of two four-quadrant IGBT PWM converters, namely, a rotor side converter (RSC) and a grid side converter (GSC), connected back-to-back by a dc-link capacitor. The crow-bar circuit is used to short-circuit the RSC to protect it from over-current in the rotor circuit during transient disturbances.

IV. REACTIVE POWER AND VOLTAGE CONTROL

Both the RSC and the GSC can be applied to control the reactive power of the DFIG [5], as shown in Fig. 3. In the d - q synchronous reference frame, the RSC and GSC reactive

power controllers generate the reference signals for the inner-loop current controllers of the RSC and GSC, respectively. The commands of the reactive power controllers can be generated by a supervisory controller of the wind farm, which in turn can be designed to control for example the power factor or the voltage at the grid connection point of the wind farm at a desired value.

Fig. 3. Reactive power control of DFIG wind turbine.

The RSC and the GSC of the DFIG can also be applied to control directly the voltage at the grid connection point of each individual wind turbine [5]. As shown in Fig. 4, if the RSC is arranged to control the terminal voltage of the DFIG, then the GSC can be arranged to be reactive neutral by setting $Q_g^* = 0$. This consideration is reasonable because the VFC rating is only 25-30% of the generator rating and the VFC is primarily used to supply the active power from the rotor to the power grid. Moreover, if the DFIG feeds into a weak power network without any local reactive compensation, both the RSC and the GSC can be applied to control the terminal voltage of the DFIG, as shown in Fig. 5. This control mode however needs control coordination between these two converters. The use of voltage control can mitigate terminal voltage fluctuations of the DFIG caused by the variations of the wind speed, and therefore, improve the power quality when the wind turbine is connected to a weak power network [6]. The voltage control of the GSC is also useful to help reestablish the grid voltage during a grid fault when the RSC has been blocked [7], [8].

Fig. 4. Voltage and reactive power control of DFIG wind turbine.

Fig. 5. Voltage control of DFIG wind turbine.

In some power networks, the controllability of DFIG wind turbines is sufficient to meet grid code requirements on power

factor or voltage (reactive power) regulation. However, many wind turbines are installed in remote, rural areas. These areas usually have electrically weak power grids, characterized by low short circuit ratios and under-voltage conditions. In such grid conditions and during a grid fault, the DFIGs may not be able to provide sufficient reactive power support. Therefore, it would be necessary to use external reactive compensation (e.g., STATCOM) to assist the wind turbines with reactive power and voltage support in order to maintain required power factor and voltage stability [8]. In addition, in order to achieve certain optimal operating performance and economical benefits, it is necessary to coordinate the reactive power or voltage control actions of the wind farm and the external reactive compensator in an intelligent way [9].

V. ACTIVE POWER AND FREQUENCY CONTROL

A. Active Power Control

The RSC usually controls the active power generated by the wind turbine, depending on the available wind energy at a specific moment. At a certain below-rated wind speed, there exists a unique turbine shaft speed where the wind turbine extracts the maximum power from the wind. This optimal operating point (i.e., optimal shaft speed or maximum power point) is usually determined from the wind turbine power characteristics. The RSC control system then regulates the stator active power or shaft speed of the DFIG at this optimal point, as shown in Fig. 6. If the wind speed is above the rated value, the mechanical blade pitch control (Fig. 7) is usually activated to regulate the blade pitch angle to maintain the turbine output power and shaft speed at their rated values. In addition, since the wind direction changes from time to time, a mechanical yaw control can be used to turn the rotor plane of the turbine to face against the wind, in order to extract the maximum wind energy. Such a mechanism is called minimum yaw error tracking.

Fig. 6. Active power/speed control of DFIG wind turbine.

Fig. 7. Blade pitch angle control of DFIG wind turbine.

As discussed in [5], the DFIG wind turbines (especially the large ones) have lightly damped low-frequency torsional oscillation modes due to the existence of the gearbox. Such torsional oscillations can be excited by wind speed variations

or grid disturbances. The insufficiently damped torsional oscillations can lead to large torque oscillations at the gearbox [10] and instability of the wind turbine system [5], [7]. In addition, the torque oscillations at the gearbox significantly increase its mechanical stress, and therefore, increase its failure rate. In order to effectively damp torsional oscillations of DFIG wind turbines, the gain and bandwidth of the DFIG speed controller must be properly designed.

Consider for example a 3.6 MW DFIG wind turbine [5] as shown in Fig. 2. Assuming that the wind speed is step changed from 10 m/s to 13.5 m/s at $t = 10$ s, Fig. 8 shows the responses of the DFIG output active power P_e when using different pairs of PI gains for the speed controller in Fig. 6, where $k_{p1} < k_{p2} < k_{p3} < k_{p4}$, $k_{i1} < k_{i2} < k_{i3} < k_{i4}$ ($k_{p1} = k_{i1} = 0.1$, $k_{p2} = k_{i2} = 0.2$, $k_{p3} = k_{i3} = 1.0$, and $k_{p4} = k_{i4} = 4.0$). Therefore the ratio k_{pn}/k_{in} ($n = 1, 2, 3, 4$) is constant. A larger integral gain yields a higher bandwidth for the closed-loop system. These results indicate that the smallest gain k_{i1} should be used. It provides the closed-loop system with a sufficient low bandwidth so that the low-frequency torsional oscillations are sufficiently damped. In addition, the dynamic performance of the WTG degrades with the increase of the PI gains. The smallest pair of PI gains k_{p1} and k_{i1} provides the best damping performance.

Fig. 8. Effect of the PI gains of the DFIG speed controller.

B. Frequency Control

In a traditional power system, the purpose of active power control of synchronous generators is to maintain the system frequency within a desired range. This is essential for the secure and stable operation of the power system. However, in the most commonly used control and system designs of DFIG wind turbines, the active power and system frequency are decoupled. This prevents the DFIGs from responding to system frequency changes, and therefore, reduces the frequency regulation capability of the power system. With the continuously increasing penetration of wind power, such a problem is becoming severe and may begin to influence the stability of the power system. To maintain the same level of system stability, some grid codes require the wind farms to provide frequency regulation capability.

Conventional synchronous generators provide frequency support in the form of inertia response, primary and secondary response, high-frequency response, etc. Similar to the

conventional synchronous generators, the DFIG wind turbines have a significant amount of kinetic energy stored in the rotating mass of their blades. However, this energy does not contribute to the inertia of the grid as the rotational speed is decoupled from the grid frequency by a power electronic converter. To reintroduce the inertia response, a supplementary controller that responds to the frequency changes of the system is added to the torque control of DFIG wind turbines [11]–[14], as shown in Fig. 9. This supplementary controller adapts the torque set point in response to the rate of change of the system frequency df/dt and the change of the system frequency Δf . If the system frequency drops, the df/dt loop increases the torque set point while the Δf loop cancels out the accelerating torque caused by the difference of the wind turbine mechanical torque and the generator electromagnetic torque. The resulting total set point torque is therefore increased in order to slow down the rotor of the DFIG and thereby release kinetic energy, which in turn contributes to restore the system frequency.

Fig. 9. Supplementary inertia control for DFIG wind turbine.

However, in an inertia control mode the DFIG wind turbine may not be able to effectively participate in the grid primary frequency regulation because it is already controlled to generate the maximum active power, i.e., there is no margin for its output active power to increase during large low-frequency periods. Therefore, in order to provide primary frequency control when system frequency drops, the DFIG wind turbines must operate with a deloaded maximum power curve [14]–[16] during normal frequency conditions, as shown in Fig. 10. Such a deloaded curve can be obtained by shifting the operating point toward the right of the maximum power curve at various wind speeds (v_w). Then a primary frequency controller is integrated into the RSC active power control loop of the DFIG wind turbine. It serves as a supplementary control to respond to system frequency changes. When system frequency drops, e.g., as a result of a sudden load increase or loss of a large generation unit, the output of the primary frequency controller tends to increase the active power set point. Therefore, the wind turbine operating point moves from the deloaded curve toward the maximum power curve. This allows the increase of the active power generated by the wind turbine, and therefore, contributes to frequency control of the system. In Fig. 10, an additional control signal ΔP_2 can be added to the active power set point. This controllability enables the DFIG wind turbines to respond to a request from the system operator to achieve desired power flow control,

automatic generation control (AGC), and other system control objectives. Moreover, the primary frequency control of the RSC must be coordinated with the pitch control of the wind turbine, in order to prevent overloading or over-speeding of the wind turbine generator during frequency regulation.

Fig. 10. Control of DFIG wind turbine with primary frequency regulation.

VI. LOW VOLTAGE RIDE THROUGH

This contrasts with the utility requirements, just a few years back, when all wind turbines were required to disconnect during grid faults. The major technologies and solutions to achieve LVRT of DFIG wind turbines include: 1) using an active crow-bar circuit (Fig. 2) [7], [8], [17]-[19], 2) using an energy management system connected to the intermediate dc bus (energy storage or dump load) [20], [21], 3) using an improved rotor current control for stator flux regulation [22], 4) using external reactive compensation [7], [8], and 5) using an additional series grid-side converter (SGSC) [24]-[26].

A. Active Crow-Bar Circuit

Grid faults, even far away from the location of the wind turbine, can cause voltage sags at the connection point of the wind turbine. Such a voltage sag results in an imbalance between the turbine input power and the generator output power, which initiates the machine stator and rotor current transients, the converter current transient, the dc-link voltage fluctuations and a change in speed. One of the major problems of the DFIG wind turbines operating during grid faults is that the voltage sags may cause over voltage in the dc-link and over currents in the DFIG rotor circuits and the RSC, which in turn may destroy the RSC.

To protect the RSC from over-voltage or over-current during grid faults, an active crow-bar circuit is usually used to short-circuit the rotor windings of the DFIG and the RSC is blocked from switching [7], [8], [17]-[19]. During this time, the wind turbine generator (WTG) does not trip and continues its operation. However, since the controllability of the RSC is naturally lost, there is no longer the independent control of active and reactive power in the DFIG. The DFIG becomes a conventional squirrel-cage induction generator (SCIG). It produces an amount of active power and starts to absorb an amount of reactive power. The GSC can be arranged to control the DFIG stator voltage. It operates like a STATCOM to regulate the reactive power exchanged with the grid.

However, this controllability of the GSC is limited because of the small capacity of the converter. To prevent the WTG from over-speeding, the pitch angle controller can be activated to keep the speed at the predefined value. During the RSC blocking, its control system continues monitoring the rotor current, terminal voltage, dc-link voltage active and reactive powers and rotor speed of the DFIG. When the grid fault has been cleared and when the voltage and the frequency in the utility grid have been reestablished, the RSC restarts switching and the crow-bar circuit is disconnected. The voltage control of the GSC is deactivated and its reactive power command is reset to zero. When the RSC has restarted, the DFIG again has independent active and reactive power control and the WTG returns to normal operation. References [7] and [8] investigated in detail such an uninterrupted operation feature of DFIG wind turbines during grid faults. Some typical results are shown in Figs. 11-13 for a 3.6 MW DFIG wind turbine.

Fig. 11 shows the voltage profiles at the grid connection point (PCC) of the WTG. Before $t = t_1$, the power system is at normal operation. 30 ms after applying the short circuit (at $t_2 = 2.03$ s), the RSC is blocked to protect it from over-current. 200 ms after applying the short circuit (at $t_3 = 2.2$ s), the fault is cleared. With the GSC and some external reactive compensation for transient voltage support, the PCC voltage is quickly reestablished shortly after the fault has cleared. When the PCC voltage returns to a predefined value, the RSC starts switching. Finally, 500 ms after blocking the RSC (at $t_4 = 2.53$ s), the RSC restarts successfully and the WTG returns to normal operation.

Fig. 12 shows the magnitude of the rotor current I_r . During the RSC blocking, the rotor current magnitude is within its limit value (1.0 kA) by connecting a suitably designed resistive crow-bar circuit to the DFIG rotor windings. In addition, with a proper restarting procedure and a suitably designed control system, the RSC successfully restarts with only a small transient in the rotor current.

Fig. 13 shows the total active power generated by the induction generator, P_e , and rotor active power, P_r . During the RSC blocking from t_2 to t_4 , the DFIG still generates an amount of active power but there is no active power flowing through the rotor circuit ($P_r \approx 0$) since the RSC is short circuited.

In addition, it has been shown in [23] that with a suitably designed LVRT scheme, the DFIG wind turbines can even bring some operation and control benefits to bear on power system transient performance and stability. Consider for example the modified IEEE 10-machine 39-bus New England system [23] as shown in Fig. 14, in which the synchronous generator G6 is equipped with a power system stabilizer (PSS) and the synchronous generator G7 is replaced by a large wind farm. This wind farm consists of over one hundred individual WTGs. Each individual wind turbine is equipped with a DFIG that represents a 3.6 MW WTG system. To reduce the reactive power demand from the DFIGs, the wind farm is equipped with static reactive compensation in the form of switched shunt capacitors. They are placed at bus 36 where the wind farm is connected to the power network.

Fig. 11. Grid fault ride through of DFIG wind turbine: V_t .

Fig. 12. Grid fault ride through of DFIG wind turbine: I_r .

Fig. 13. Grid fault ride through of DFIG wind turbine: P_e and P_r .

Fig. 14. Single-line diagram of the IEEE 10-machine 39-bus New England system with a large wind farm.

A 150 ms three-phase short circuit is applied at the bus 22 end of the transmission line 21-22; the fault is cleared by

tripping line 21-22 from the system. Therefore after the fault, the system changes to a new operating condition. With a suitably designed control system and uninterrupted operation scheme using an active crow-bar circuit, the WTGs in the wind farm G7 successfully ride through this grid fault.

Figs. 15 and 16 compare the transient responses of the magnitude of bus 36 voltage (V_{36}) and the angular speed of G6 (ω_6), respectively, for two cases: the 39-bus system with (i.e., G7: wind farm) and without the wind farm (i.e., G7: SG where G7 is a conventional synchronous generator). In the case of G7: SG, the short circuit results in significant transient low-frequency oscillations in V_{36} and ω_6 . After the fault is cleared, the control system drives the SGs and the power system slowly back to a new steady-state operating point. The grid voltage slowly recovers and the low-frequency power oscillations can not be effectively damped even using the power system stabilizer (PSS). Another test is performed for the same grid fault, but the PSS of G6 is deactivated. Under such a condition, the angular stability of the SGs is lost. Without further actions, the entire power system may lose stability. Compared to the results without the wind farm (G7: SG), the low-frequency oscillations of V_{36} and ω_6 with the wind farm (G7: wind farm) are significantly reduced in magnitude and quickly damped. This result is important because it indicates that the wind farm also has a significant contribution in improving the transient performance and stability of the associated power system.

Fig. 15. Transient response of the 39-bus system: V_{36} .

Fig. 16. Transient response of the 39-bus system: ω_6 .

B. Energy Storage

The second solution for LVRT enhancement of DFIG wind turbines is to use an energy storage system (ESS) connected to the dc-link [20], [21], as shown in Fig. 17. The ESS will serve

as either a source (if the DFIG rotates at subsynchronous speed) or a sink (if the DFIG rotates at supersynchronous speed) of active power, and therefore, contributes to control power imbalance of the system and maintain the dc-link voltage constant during grid faults. Such a solution avoids the problems of transfer between different operating modes when using a crow-bar circuit. However, the cost is that the RSC must be sized accordingly in order to allow fault currents to flow through the DFIG rotor circuit. Moreover, additional energy storage devices are required, which also increases the cost and complexity of the system.

Fig. 17. DFIG wind turbine with an energy storage system connected to the dc-link of the converters.

C. Improved Rotor Current Control

It has been shown in [22] that during a grid fault, dc as well as negative-sequence components may be induced in the stator flux linkage of the DFIG, resulting in a large EMF induced in the rotor circuit. The RSC control algorithm is therefore modified such that the rotor current is controlled to cancel both the dc and the negative-sequence components in the stator flux linkage during grid faults. In addition, in order to successfully ride through grid faults, the two aspects of the current control objective must be coordinated so that the rotor current and voltage are always kept within the safe operating area (SOA) of the switching device (e.g., IGBT) in the RSC. This method does not need any additional hardware, e.g., crow-bar circuits or energy storage devices. However, whether the control objective is achievable depends on the severity of the fault and the prefault condition of the DFIG wind turbine. Therefore, this method may not be applicable to all the grid fault and system operating conditions.

D. Dynamic Reactive Compensation

It has been shown in [7] and [8] that in the case of a weak power network and during a grid fault, the GSC may not be able to provide sufficient reactive power and voltage support due to its small power capacity. As a result, there can be a risk of voltage instability and the subsequent tripping of the WTGs. To prevent such a contingency, external dynamic reactive compensation, e.g., a STATCOM, is required to provide transient voltage support to help the DFIG wind turbines ride through grid faults. The STATCOM can also be used for steady-state voltage and power factor regulation of the DFIG.

E. Additional Series Grid-Side Converter (SGSC)

References [24] and [25] propose to use an additional SGSC to enhance LVRT performance of DFIGs. The SGSC is connected to the open terminals of the DFIG's stator windings which normally form the Y point as shown in Fig. 18. The GSC as in the conventional DFIG system (Fig. 2) is called a parallel GSC (PGSC). This configuration allows the SGSC to directly control the net voltage applied to the stator windings, and therefore, the stator flux of the DFIG. The SGSC control system is designed such that the undesirable oscillatory synchronous frame stator flux response is transformed into a bounded exponential response. Therefore, during voltage sags the SGSC regulates the stator flux quickly to a new level compatible with the voltage at the grid connection point of the DFIG. This contributes to LVRT of the DFIG. However, this LVRT method needs additional hardware, and therefore, increases the cost and complexity of the system. In addition, the stator flux control of the SGSC is based on an assumption that the system parameters, e.g., stator resistance, inductance, frequency, etc., can be estimated perfectly accurately. This however may not be achievable in the real system applications.

In another configuration which is topologically similar to that in Fig. 18, the SGSC is connected to the main terminals of the stator windings via a series injection transformer, as shown in Fig. 19. This configuration has been shown to have improved LVRT capability during unbalanced grid faults with deep voltage sags [26].

Fig. 18. DFIG wind turbine with a Y point connected SGSC.

Fig. 19. DFIG wind turbine with a transformer interfaced SGSC.

VII. HIGH VOLTAGE RIDE THROUGH

With the rapid increase of large offshore wind farms, a new problem associated with the response of wind turbines to temporary over-voltages has arisen due to load shedding or unbalanced faults [27]. Over-voltages may lead to the reversal of the power flow in the GSC. Under such a condition, current

may flow from the grid into the dc-link. As a result, the dc voltage will rise. To protect the converters, the dc voltage has to be reduced to its rated value. A simple solution to resolve this problem is to use a DC chopper to connect to the dc-link of the converters, as shown in Fig. 20. This DC chopper limits the dc voltage by short-circuiting the dc-link through the chopper resistors.

Fig. 20. DFIG wind turbine with a DC chopper.

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IX. CONCLUSIONS

This paper has reviewed major grid code requirements for operation and grid connection of wind farms, and has investigated some technologies and solutions for the wind farms equipped with DFIG wind turbines to meet these requirements. The major features, benefits, and shortcomings of these technologies and solutions have been discussed. The authors's work on some of these issues, including reactive power and voltage control, active power and speed control, and LVRT of DFIG wind turbines has also been discussed and demonstrated by simulation results.

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