State-of-the-art Review of Wind Turbine Technologies

This technical report provides detailed information about the steady-state and dynamic behaviour of wind turbine generators.

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Contents

1. **The main types of wind turbine technology**

The assessment of the transient stability of wind turbines plays an integral role in power system security and operation (Salman and Teo 2002). It has been argued that due to the importance and the urgency in generating more electricity from renewable sources such as wind energy and due to the current low levels of such generation then power system stability is not of great concern (Jenkins, Allan et al. 2000). However, the recent increase in wind penetration in Australia, which has resulted in the offset of significant amounts of synchronous generation, has lead to renewed concern about the impacts on power system stability. A study by NEMMCO into the potential security risks due to the predicted high levels of wind generation in South Australia indicates this. The findings were that increased levels of wind generation will have a severe impact on the operation of the power system, particularly in the dispatch of ancillary services (NEMMCO 2004). It is important to understand the impacts of high wind generation in Australia. In Western Denmark the amount of wind generation is so significant that the situation where power generated by wind turbines alone can meet all the demand has been realised. The loss of a large amount of wind generation poses a threat to power system security. Wind turbines that are directly connected at the transmission or the distribution level affect the dynamics of the power system. Clause S5.2.1 in the Rules states that all registered participants are required to assist in preventing transient instability in the power system. With the perspective of greater wind penetration it is important to be able to show that wind generators stay connected during disturbances to the system and can contribute to improve the global system dynamic behaviour (Marcus, Nunes et al. 2004).

The dynamic properties of a wind turbine depends on its construction and on the control system structure and parameters (Lubosny 2003). Mostly it depends on the type of generator employed and how it is connected to the grid; whether directly connected or via power electronics converter. From this perspective there are four (4) main types of wind turbine. The properties of these are listed in Table 12. Their topologies are illustrated in Figure 14.
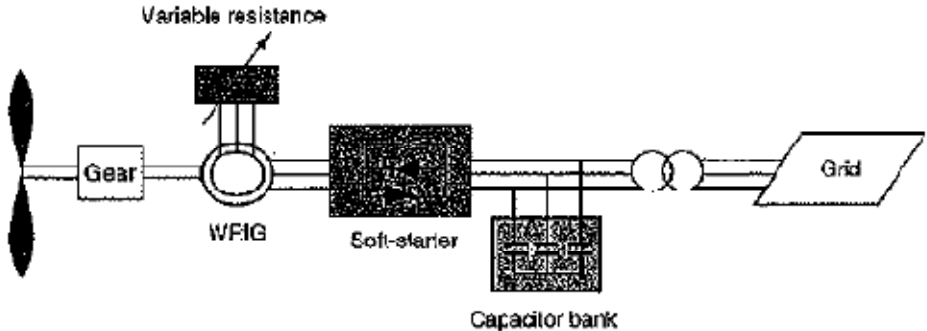
Table 1. The main types of wind turbine

Type	Speed	Generator type	Grid connection
A	Fixed	Squirrel-cage induction	Direct
B	Partly-variable	Wound-rotor induction with dynamic rotor resistance	Direct
C	Variable	Doubly-fed induction	Partial converter
D	Variable	Any (synchronous or induction)	Full converter

The dynamics of the main types of wind turbine varies significantly. The objective of this section of the report is to highlight some of the differences. The different types of wind turbines fit into two main categories; fixed speed or variable speed. There are definite advantages to variable speed wind turbines compared with fixed speed. Variable speed wind turbines are able to extract more energy from the wind and to deliver a better quality of power to the grid. Variable speed wind turbines also tend to be better for system stability than fixed speed ones (Usaola, Ledesma et al. 2003). In order to assess the impacts of wind farms on the transient stability of the power system it is important to understand their dynamics. Useful general concepts include that the dynamic behaviour of wind turbines at full load and partial load are quite different (Lubosny 2003). To competently carry out transient stability studies involving wind turbines it is necessary to understand the structure and behaviour of the basic types.
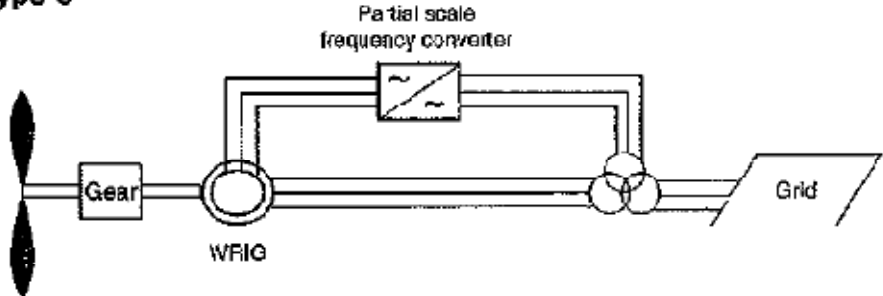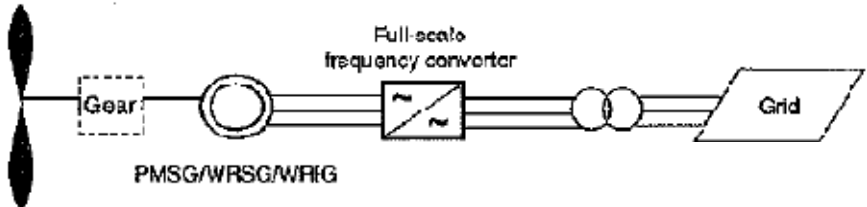
Type A
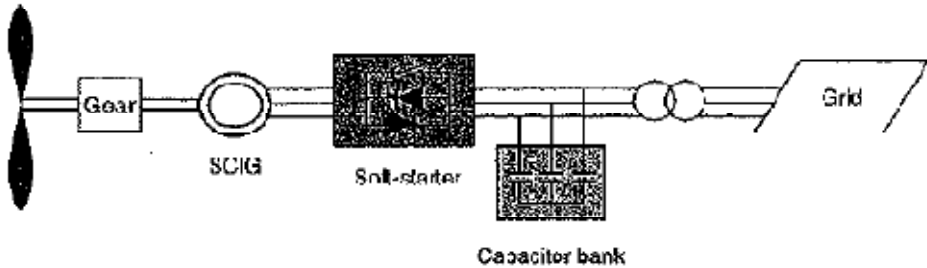
Type B

Type C

Type D

Figure 1. The four main types of wind turbine. Note: SCIG = squirrel cage induction generator, WRIG = wound rotor induction generator, PMSG = permanent magnet synchronous generator, WRSG = wound rotor synchronous generator (source: Ackermann, 2005).

2. Type A: Fixed-speed wind turbine equipped with SCIG

The squirrel-cage induction generator (SCIG) is the most common type used in fixed-speed wind turbines. Induction generators are employed because they are cheap and due to their superior characteristics. This type of wind turbine is not equipped with wind wheel and generator control systems, and therefore is more reliable than other types (Lubosny 2003). The problems which can occur with SCIG equipped wind turbines are (1) during a fault the rotor speed increases and can become excessive, and (2) after a fault is cleared the terminal volts may not recover, both of which can cause it to be disconnected from the grid. Furthermore, since the excitation for a SCIG is sourced directly from the grid it continually absorbs reactive power (increasingly with speed) and is incapable of controlling its terminal voltage. These issues pose significant challenges in terms of controlling the voltage and balancing the reactive power demands in the power system, which impacts on system stability. In terms of the stability, fixed-speed wind turbines are a robust concept and may ride-through most unbalanced and balanced faults in the power system (Akhmatov 2005). However, compared with other types the stability performance of wind turbines which use the SCIG (directly coupled to the grid) is relatively poor (Marcus, Nunes et al. 2004).

The first-order swing equation that describes the motion of the generator shaft is

$$2H\frac{ds}{dt} = T_e - T_m \ \ (4)$$

Where H is the sum of constant inertia of the rotating mass in per unit, s is the slip, T_e is the electrical torque and T_m is the mechanical torque from the turbine hub.

During a fault there is an imbalance between the electrical torque and the mechanical torque that leads to an acceleration of the generator, which can result in loss of stability. Similar to the equal-area criterion for synchronous generators, for an induction generator to remain connected to the power system, a fault must be cleared by the critical clearing slip and the corresponding speed. This conclusion is completely dependent on the steady-state torque-slip curve of the induction generator (Chen, Li et al. 2006). Salman and Teo have developed a novel method for determining the critical clearing slip of a wind turbine with SCIG based on the torque-slip curve (Salman and Teo 2002).

The dynamic response of an induction generator to a fault will be examined using the torque-slip curve shown in Figure 15. Note that since transient stability studies are concerned with what happens following a disturbance, the torque-slip curve is derived based on post-fault conditions. The stability limit of an induction generator changes for different post-fault operating conditions (i.e. different terminal voltages). It is the post-fault torque-slip curve that determines the ability of an induction generator to recover to its steady-state operation (Jenkins, Allan et al. 2000).
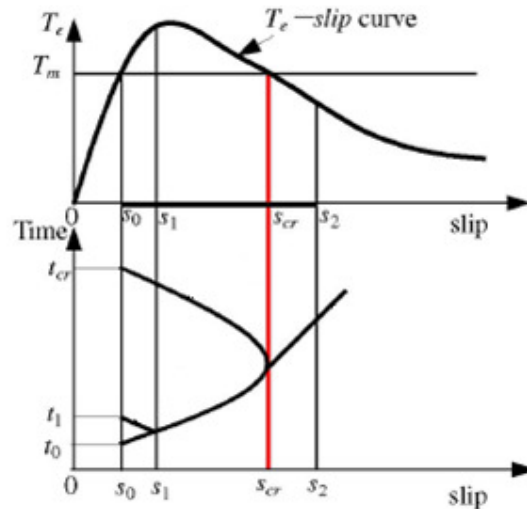

Figure 2. Configuration of torque-slip and time-slip curves for three-phase short-circuit fault (Chen, Li et al. 2006)

In steady-state operation the electrical torque T_e is equal to the mechanical torque T_m and the generator operates at constant slip s_0. When a fault occurs at t_0, T_e collapses to zero (ignoring the electrical transients), while the slip at that instant remains the same. The collapse of T_e results in a net increase in the accelerating torque on the rotor (since T_e <T_m in Equation 4) and a continuous increase in slip. If the fault is cleared at time t_1, when slip has increased to s_1, then T_e will recover from zero to a point on the torque-slip curve that is greater than T_m. This will cause a net decrease in acceleration torque (due now to T_e >T_m in Equation 4) and the rotor will return to its original slip s_0 (assuming that the voltage is the same as what it was prior to the fault). For an induction generator the electrical torque T_e of the generator is proportional to the square of the generator terminal voltage. On the other hand, if the fault is cleared at slip s_2 then when T_e recovers from zero it will always be less than T_m and the generator will continue to accelerate, causing it to trip due to over speed. Therefore, the slip s_{cr} is the critical clearing slip for this operating condition at which the SCIG is capable of recovery from a fault (Chen, Li et al. 2006).

Assuming that the mechanical torque T_m remains the same during a fault, the acceleration of the generator is determined by the moment of inertia of the rotor and the shaft stiffness. Unlike an equivalent steam or hydro unit a wind turbine has high inertia and low stiffness of the shaft between the turbine and generator (Akhmatov 2005). The low stiffness means that during steady-state operation the shaft stores a substantial amount of potential energy, which is due to the rotational displacement caused by the two opposing torques T_e and T_m (Jenkins, Allan et al. 2000). When T_e collapses during a fault, the stored potential energy in the shaft is transferred as kinetic energy to the rotor, which contributes significantly to its acceleration. Under these conditions Equation 4 is strictly not correct in describing the motion of the wind turbine drive system. The contribution of the shaft stiffness of the wind mill drive train to the acceleration of the generator cannot be ignored (Jenkins, Allan et al. 2000). Muyeen *et al.* state that at least a two-mass shaft model is necessary for accurate transient stability analysis of wind turbines as (Muyeen, Hasan Ali et al. 2007), for example, that suggested in (Akhmatov 2005).

There are three main stability issues for standard induction generators to be considered:

(1)   Trip due to overspeed

By using the law of conservation of energy of mechanical energy, the maximum speed change of an induction generator immediately after a fault is calculated by (Salman and Teo 2002)

$$\Delta \omega_G = \frac{T_m - T_e}{\sqrt{K_s J_G}} \quad (5)$$

Where $\Delta \omega_G$ is the speed change of the generator at the faults inception, K_s is the shaft stiffness and J_G is the moment of inertia of the generator rotor.

The maximum post-fault speed ω_f of an induction generator is determined by adding the steady-state speed ω_o with the maximum speed change (i.e. $\omega_f = \omega_o + \Delta \omega_G$) (Salman and Teo 2002). If ω_f exceeds the critical clearing speed ω_{cr} then the generator could become unstable and should trip due to overspeed. It is imperative that unstable or even potentially unstable generators are tripped as fast as possible. A case study has shown that when left untripped many induction generators would oscillate and produce a disturbance that could last up to 4 seconds before overspeed protection trips them (Usaola, Ledesma et al. 2003). The problem is that such a prolonged

disturbance could invoke the tripping of other wind generators which would not have otherwise been tripped (Usaola, Ledesma et al. 2003).

(2)   Excessive reactive power demand

During a fault an SCIG can decrease the transient stability margin of the power system due to an increase in reactive power demand. The reactive power absorption Q_E and the terminal voltage U_S of an induction generator are speed dependent according to the relation (Akhmatov 2005)

$$Q_E = U_S^2 \frac{X_T(\omega_G)}{R_T^2(\omega_G) + X_T^2(\omega_G)} \qquad (6)$$

Therefore, when the generators speed increases during a fault, the reactive power absorption of the induction generator also increases. The additional reactive power demand from the generator has to be met somehow by the system. This can lead to unacceptably low voltages and to potential voltage collapse due to inadequate reserves of reactive power. The situation becomes worse for wind turbines equipped with induction generators which are installed in locations remote from synchronous generators.

(3)   Post-fault terminal voltage does not recover

Even if an induction generator remains stable and does not trip following a disturbance, the post-fault terminal voltage may never recover to its pre-fault condition. In a relatively weak system there is the possibility of de-excitation of the machine if there are insufficient reactive power reserves to re-excite the machine following the loss of the rotor magnetic field during a disturbance.

3. Type B: Partly-variable-speed equipped with dynamic rotor resistance

The type of wind turbine being discussed here employs a wound-rotor induction generator (WRIG) which is equipped (singly-fed) with a converter to control the resistance of the rotor. The ability to vary the rotor resistance allows for the control of generator slip and rotational speed and a blade pitching system is used to maintain optimal rotational speed of the wind wheel. This type of wind turbine is referred to as partly-variable-speed (Akhmatov 2005). The ability to operate over a wide speed (slip) range means that the wind turbine rotates at an optimal speed which extracts more energy from the wind (at partial load). Wind turbine input power is highly variable and unsteady, resulting in large and rapid variations in power transfer (Causebrook, Atkinson et al. 2007). The limited slip range (only around 2%) of a standard induction generator results in the mechanical power variations caused by the wind to pass almost directly (with little smoothing) to the stator (Lubosny 2003). The ability to control the rotor resistance leads to an increase in the dynamic slip range making it possible to smooth the power transferred to the grid – which is the main goal of this system (Akhmatov 2005). This control [the control of rotor resistance] is mostly applied to reduce flicker emission from the wind turbines to the grid as the mechanical power variations are converted to the kinetic energy of the rotor and absorbed by the external rotor resistance of the converter (Akhmatov 2005). The same sorts of stability issues for standard induction generators occur for those with dynamic rotor resistance (DRR). For example, the induction generator with DRR still continuously absorbs reactive power from the grid. However, with DDR it is possible to expand the critical clearing slip, and combined with blade pitch control, to increase the dynamic stability limit for an induction generator. Thus, compared with a standard type (fixed-speed Type A wind turbine) the stability performance of an induction generator with DRR is better.

Equation 4 shows that the electrical torque T_e developed by an induction machine is a function of rotor resistance R_r such that (Kundur 1994)

$$T_e = 3\frac{P_f}{2}\left(\frac{R_r}{s\omega_s}\right)\frac{V_e^2}{(R_e + R_r/s)^2 + (X_e + X_r)^2} \qquad (7)$$

Where P_f is the number of poles of the induction machine, X_r is the rotor reactance, ω_s is the synchronous speed, V_e is the Thevenin's voltage at the terminals and R_e and X_e are the Thevenin's resistance and reactance of the stator, respectively. These are taken from the machine data and per-phase equivalent circuit, where all quantities are referred to the stator side.

The torque-slip curves in Figure 16 are for an actual wind turbine generator with DRR. There are three torque-slip curves plotted for different (increasing) values of the external rotor resistance; where R_{r_rated} is the rated short-circuit resistance of the rotor, R_{r_crow} is the equivalent rotor resistance with 'crowbar' connection and R_{r_max} is the equivalent rotor resistance with maximum external resistance applied. The significance of these quantities will become apparent later. Between standstill and synchronous speed (slip equal to 1 and 0, respectively) the machine acts as a motor. Beyond synchronous speed, when slip is negative, it acts as a generator. For generator operation the torque-slip curve has a single well-defined peak. Importantly, Figure 16 shows that (1) the slip at maximum torque is directly proportional to the rotor resistance R_r, and (2) the value of maximum torque (peak of the torque-slip curve) is independent of R_r (Kundur 1994).
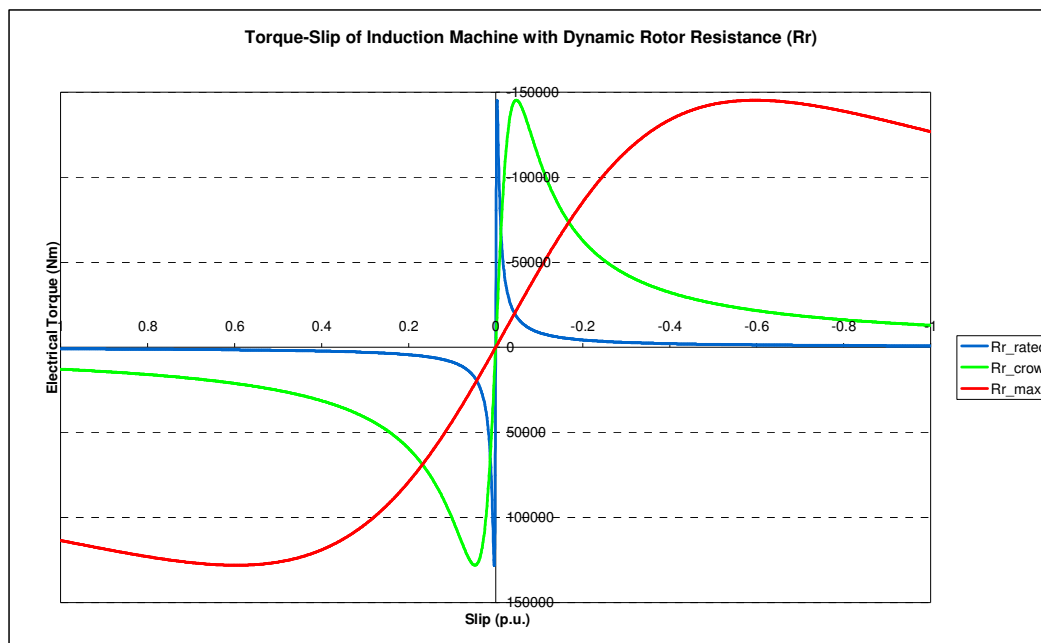

Figure 16. Torque-slip curve for a wind turbine equipped with an induction generator with DRR

There are different prerogatives and hence control strategies for the DRR depending on the operating state of the wind turbine. During start-up a large amount of torque is required to take the speed of rotation of the induction generator from stand-still to above synchronous. At start-up the blade pitching system is used and the generator is effectively 'soft-started' by increasing rotor resistance to a maximum (i.e. R_{r_max}). Notice the high level of torque at $s = 1$ (stand-still) for R_{r_max} compared with that for R_{r_rated} in Figure 3. A large rotor resistance at start-up achieves a high

starting torque and keeps the magnitude of the in-rush current low and the power factor high (Akhmatov 2005).

The dynamics of the Type B wind turbine are different during partial and full loading. At partial load the objective of the controllers is to extract the maximum amount of power from the wind, whereas at full load it is to keep the electrical power output constant. During partial loading (between cut-in and rated speed) the rotor resistance varies between R_{r_rated} and R_{r_max} (Figure 3) and the blade pitch angle is controlled to achieve an optimal rotation speed of the turbine which extracts maximum power from the wind. To understand this concept consider that the mechanical power P_M extracted from the wind is a fraction of the total power P_V determined by the power coefficient $C_P(\lambda,\beta)$ of the wind turbine such that

$$P_M = P_V.C_P(\lambda,\beta) \qquad (8)$$

The power coefficient is a complicated function of tip-speed-ratio λ and blade pitch angle β. It is a number between 0 and 1 which according to Betz's theorem cannot exceed its theoretical limit of 0.59 in three-blade wind turbines. There is a maximum power coefficient for a given wind speed and corresponding optimal tip-speed-ratio. The optimal tip-speed-ratio is defined as

$$\lambda^{OPT} = \frac{\omega_M^{OPT}.R}{V} \qquad (9)$$

Equation 9 shows that for a given wind speed and a corresponding optimal tip-speed-ratio there is an optimal rotational speed of the turbine which is ω_M^{OPT}. At partial load the rotational speed of the wind wheel of a variable speed wind turbine is controlled around at ω_M^{OPT} to maximise the power coefficient $C_P(\lambda,\beta)$ and hence maximise the power extracted from the wind. During partial loading the ability for power variation damping is not great but does exist (Lubosny 2003).

The dynamic response of an actual Type B wind turbine rated at 2.1 MW at partial load is shown in Figure 17. At partial load an increase in wind speed causes a significant change in the operating point for this type of wind turbine (Lubosny 2003). At an initial wind speed of 9.57 m/s the wind turbine is generating 1.5 MW and consuming 0.61 MVAr of power. A ramp increase of 4 m/s in wind speed occurs at t = 5 seconds and takes the effective wind speed up to 13.57 m/s by t = 10 seconds. The increase in real power due to the increase in wind speed is 0.6 MW. The wind speed and the rotor speed of a wind turbine are directly proportional (Akhmatov 2005). Therefore the ramp increase in wind speed causes the generator rotor to accelerate by a maximum of around 12.8 rad/s, during which time the external resistance (DRR) is increased by the converter, increasing generator slip. The control of generator slip is achieved by continuous monitoring of the input torque to the generator. If the change in mechanical torque from the wind wheel with respect to speed is positive (i.e. $\delta T_m/\delta s > 0$) then to maintain an optimal tip-speed-ratio the generator slip is increased by increasing the rotor resistance. If $\delta T_m/\delta s < 0$ then the generator speed is reduced by decreasing the effective rotor resistance. If $\delta T_m/\delta s \approx 0$ the rotor resistance is held constant. The addition of a pitch controller is used to optimise the rotational speed of the wind turbine at partial load. During partial loading the blade pitch angle is fixed at a negative angle to maximise the power extracted from the wind. At around t = 7.73 s the blade pitch angle controller increases the angle to reduce the rotational speed and limits the power extracted from the wind. This occurs at a time when the wind turbine reaches its rated maximum output power of 2.1 MW.

The objective of control at full load is to keep the electrical power output constant. At full load when the power extracted from the wind by the wind wheel changes the rotor converter alters the generator slip to compensate. In effect the surplus of energy is transformed into the potential energy in the rotating shaft, causing the rotor speed to increase. The external rotor resistance is increased by the converter (increasing slip) to keep the output power of the generator constant, hence dampening power variations caused by the wind. The external rotor resistance and the slip are eventually returned to what they were prior to the increase in wind speed. The generator slip must be kept as low as possible to maximise efficiency. During disturbances oscillations may appear in the output power due to the dynamic mechanical forces which act on the wind wheel, that are determined by its mechanical characteristics. These mechanical oscillations manifest themselves in the rotor as torsional oscillations (called mechanical eigenswings) and some travel through the shaft and the generator and appear as harmonics on the grid (Lubosny 2003). A study by Lubosny has shown that for this reason the Type A and the Type B wind turbines do not satisfy the IEEE standards or the IEC standards for quality of supply (Lubosny 2003).
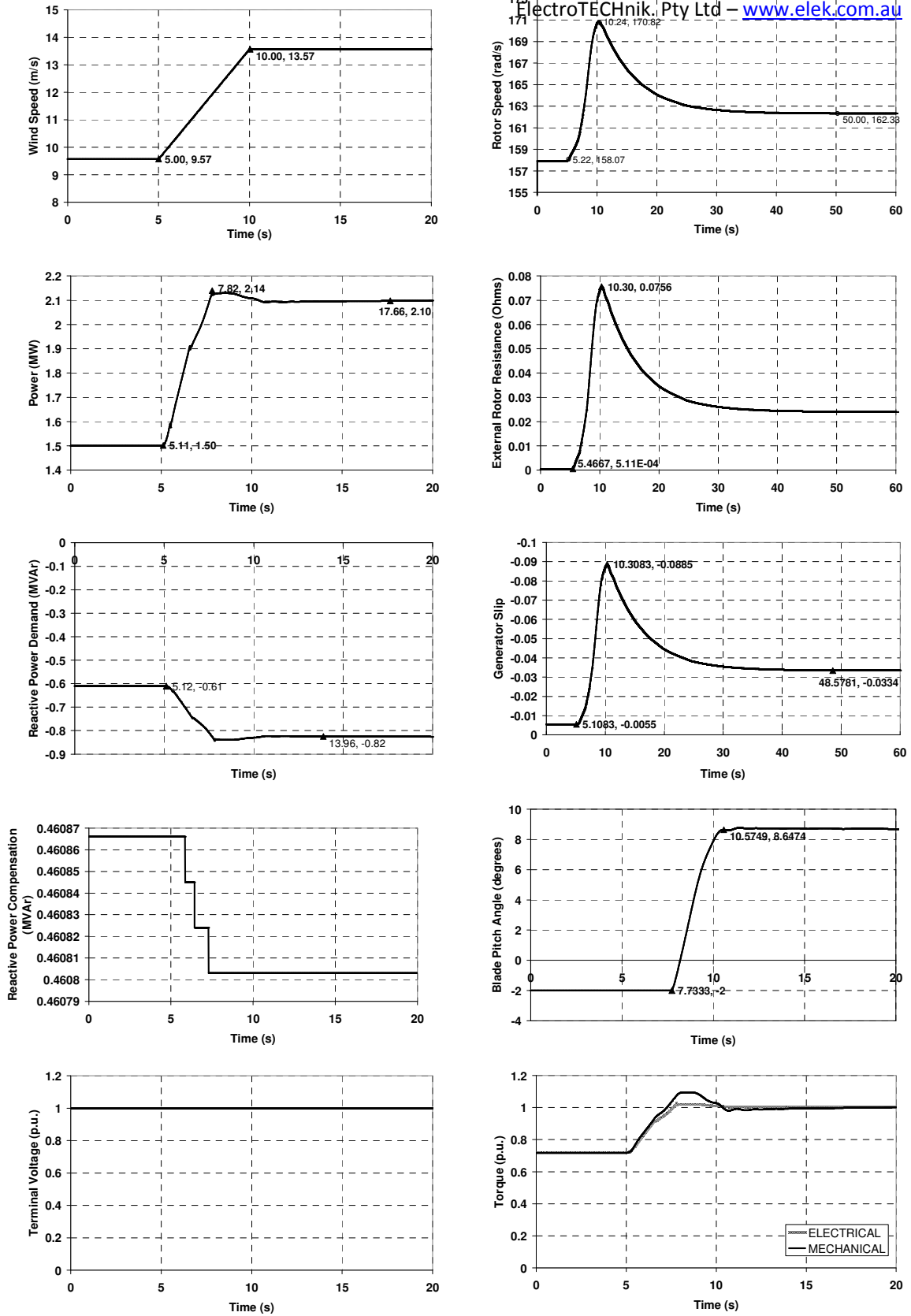
Figure 17. Dynamic responses of wind turbine with SCIG and DRR to ramp increase in wind speed at partial load

Figure 18 shows the response of a Type B wind turbine at full load for to a three-phase fault that occurs at t = 5 s and lasts for 120 ms. During the disturbance the control of the DRR and blade pitching is used to increase the dynamic stability limit. This leads to improvements of voltage stability and reduction of capacity demands for dynamic reactive compensation (Akhmatov 2005). Equation 4 shows that the rotor resistance R_r of an induction machine influences the shape of the torque-slip curve. In the previous section describing the Type A wind turbine it was explained that the stability limit is dependent on the torque-slip curve and the corresponding critical clearing slip s_{cr}. Figure 4 shows that the critical clearing slip is expanded and hence the dynamic stability limit is increased if the rotor resistance is increased. Thus when the three-phase fault occurs the rotor resistance is increased. This results in the critical speed being expanded. During a fault excessive currents may be induced into the rotor circuit. The power electronics on the rotor (consisting of insulated-gate bipolar transistors (IGBTs)) must be protected against thermal overload and against electrical transients (Lubosny 2003). Once certain limits are exceeded then the converter is blocked and the rotor circuit is shorted with a 'crow-bar' resistance. In this case, the converter is blocked during the fault (indicated by the Crowbar Status flag). Once the fault is cleared and electrical transients on the rotor circuit reduce to within tolerable limits then the converter is restarted again. After the fault is cleared the fluctuations of the electrical and mechanical torques that are present can lead to excessive over-speeding due to an imbalance caused by a lack of decelerating (electrical) torque. The temporary reduction in the mechanical torque by the blade pitching improves voltage stability and ride-through capability (Lubosny 2003). The rotational speed of the shaft is reduced following the fault and the mechanical fluctuations are effectively damped thereafter by the blade pitching system.
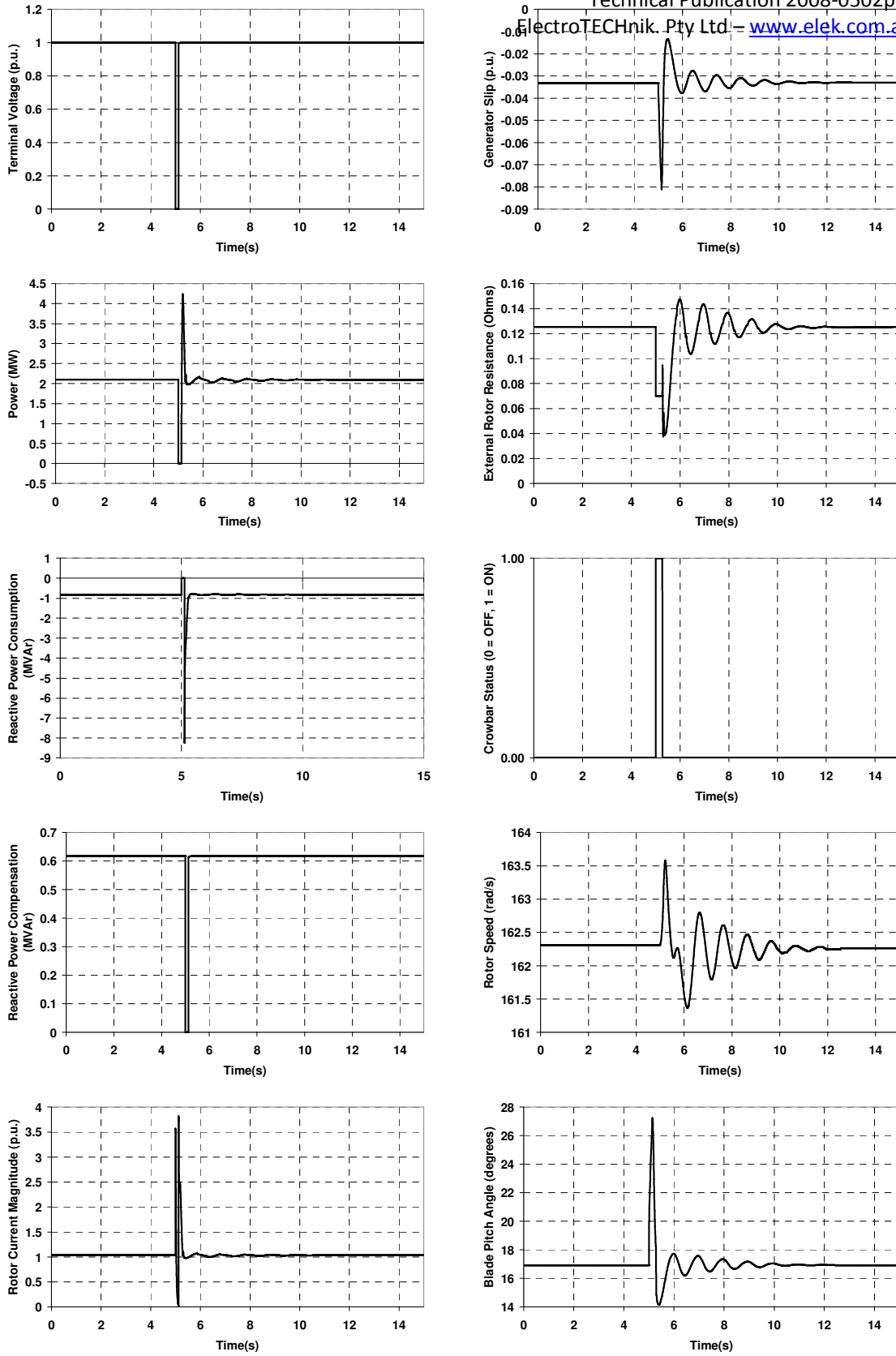
Figure 18. Dynamic responses of wind turbine with SCIG and DRR to three-phase fault at terminals

4. Type C: Variable-speed wind turbine equipped with DFIG

The Type C wind turbine is the most widely used concept today (Blaabjerg 2006). In contrast to the Type A and Type B wind turbines discussed previously, the wind turbine equipped with doubly-fed induction generator (DFIG) is variable speed and a fully controlled system with enhanced dynamic performance. Variable speed operation has two main advantages: (1) more energy is able to be extracted from the wind; and (2) power fluctuations are smoothed and mechanical stresses on the shaft and gearbox are reduced. The doubly-fed generator concept utilises a wound rotor induction machine with an AC current applied to the rotor windings, thus it can be regarded as a traditional induction generator with a nonzero rotor voltage (Lei, Mullane et al. 2006). Variable speed operation is enabled by controlling the frequency of the current applied to the rotor with respect to that of the stator. The stator of the generator is directly coupled to the grid at a fixed frequency whereas the rotor is supplied via a converter at a different frequency. As such the generator is said to be "doubly-fed". The converter, which is connected between the rotor circuit and the grid, effectively decouples the grid frequency from the rotor mechanical frequency. An advantage of the Type C wind turbine is that since the frequency converter only has to deal with the rotor power then it needs only to be partially rated. This makes it more economical than the Type D wind turbine, where a fully rated converter connected between the stator and the grid is required. A speed variation of ±30% around synchronous speed can be achieved with a power converter rated at 30% of nominal power (Werner 2001; Blaabjerg 2006).

For the Type C wind turbine system both active and reactive power can be controlled independently. Reactive power can be supplied by the generator to support grid voltages. The controllability of reactive power help the DFIG equipped wind turbine play a similar role to synchronous generators (Lei, Mullane et al. 2006). Unlike the induction generators of the Type A and Type B wind turbines the DFIG is not directly excited from the grid, so does not consume reactive power from the grid. The Type C wind turbine does not need either a soft starter or reactive power compensation (Blaabjerg 2006). A problem is that during severe disturbances to protect the sensitive power electronics the frequency converter is blocked and the rotor circuit is shorted with a crowbar resistance to damp current transients. The result is that at controllability is lost and the machine becomes a standard induction generator.

The doubly-fed machine has significant advantages over the standard induction machine. To understand how speed is controlled consider Equation 10 which states that the resultant magnetic field produced by the phase windings in a three-phase machine supplied by a balanced source rotate at a speed in revolutions per minute (N_s) determined by the frequency (f) of the source in hertz (Hz) and the number of poles (P) in the machine such that

$$N_s = \frac{120f}{P} \quad (10)$$

The stator and the rotor circuits of a doubly-fed machine are supplied from separate sources and thus develop two magnetic fields which rotate at different speeds. It is the relative speed of the stator and the rotor fields which determines the speed of the machine. To understand this consider an example similar to that given by (Wildi 2006). Suppose that the stator windings of 3-phase, 4-pole wound rotor induction machine are connected to a 50 Hz source and that a second source of 15 Hz is applied to the rotor windings. According to Equation 9 the resultant flux created by the field of the stator will rotate with respect to a stationary point in a clockwise direction at a speed $N_s = 120f / p = 1500rpm$. The resultant flux created by the field of the rotor will rotate in the same direction but more slowly at $N_s = 450rpm$. However, for the stator field to *lock* with the rotor field they must rotate at the same speed with respect to the stationary point (Wildi 2006). To achieve this the rotor must turn clockwise at a sub-synchronous speed equal to $1500 - 450 = 1150rpm$. It is important to understand that: "If the rotor were to run at any other speed, the rotor poles would slip past the stator poles and the average torque would be zero. The machine would come to a stop." (Wildi 2006). This behaviour is synonymous with that of a synchronous generator. In fact, the doubly-fed machine is a special case of a synchronous machine which runs at a slip determined by the frequency applied to the rotor f_R and that applied to the stator f_S (both in Hz) such that

$$s = \frac{f_R}{f_S} \quad (11)$$

Another situation presents itself. If the phase sequence of the source on the rotor circuit is reversed then the resultant flux created by the field of the rotor windings will rotate in the counter-clockwise direction at $N_s = 450rpm$. Under these conditions the rotor must rotate again in the clockwise direction but at a super-synchronous speed $1500 + 450 = 1950rpm$.

It can be generalised that depending on the frequency and the phase sequence of the source applied to the rotor circuit the DFIG can either run at super- or sub-synchronous speed determined by Equation 12 and Equation 13, respectively (Wildi 2006). This is different from a SCIG which can only operate at super-synchronous speeds within a very limited range (slip).

$$n_{\mathrm{sup}} = \frac{120}{P}(f_S + f_R) \quad (12)$$

$$n_{sub} = \frac{120}{P}(f_S - f_R) \quad (13)$$

Depending on whether the wind speed is high or low the rotor frequency and phase with respect to the stator frequency the DFIG will rotate either above or below synchronous speed. As a result the wind turbine can be controlled to rotate at an optimal speed which extracts the maximum power from the wind. The power transfer between the DFIG and the grid is determined by its speed (Akhmatov 2005). When the generator runs at super-synchronous speed real power is transferred from both the rotor and stator to the grid. When the generator runs at sub-synchronous speed real power is transferred to the grid from the stator while the rotor circuit absorbs real power from the grid. But this is not the end of the story. As already pointed out, if the DFIG were operated in such a manner (i.e. with constant rotor frequency) then it would behave like a synchronous machine and be prone to the same sorts of problems, such as difficulties with starting and synchronisation with the grid and oscillatory transients and pull-out torque (Werner 2001). The situation is different, however, when the AC excitation of the rotor is made dependant on the line voltage vector and the angular position of the rotor (Werner 2001). The machine then loses its synchronous characteristics entirely and can operate at variable speed (Werner 2001). This leads to the consideration of the frequency converter.

The frequency converter of the Type C wind turbine serves a most important purpose; it facilitates variable speed operation by decoupling the power system frequency from the rotor frequency. Its operation has two main functions, these are (1) to convert (rectify) the current drawn from the grid into DC; and (2) to convert (invert) the DC current into an AC current at the desired frequency and phase. However, as mentioned previously, depending on the speed of rotation of the generator the rotor circuit may either be delivering or absorbing power. Therefore, it must be possible for power to flow through the frequency converter in both directions. The typical configuration for a Type C wind turbine power converter consists of two back-to-back pulse-width-modulated (PWM) voltage source inverters connected via a DC link. Power is able to flow from the grid to the rotor and vice versa because an inverter can be controlled to act as rectifier simply by changing its commutation (firing) angle by 180 degrees (Hart 1997).

The two back-to-back inverters have different purposes and hence control strategies. The objective of the grid side inverter is to keep the DC link voltage constant, providing a path for rotor power to and from the grid at unity power factor. This way the exchange of reactive power with the grid is made completely through the stator of the generator (Pena 1996). The rotor-side inverter maintains the stator voltage and the generated electrical power of the machine. Both inverters (the grid-side and the rotor-side) are voltage source inverters. It is preferable to operate the rotor-side inverter as a variable frequency voltage source (i.e. without current control) in order not to impede transient currents in the rotor windings which are caused by disturbances on the rotor side (Pena 1996). The voltage source of the rotor-side inverter is supplied from the DC-link is composed of a capacitor C and possibly an inductor L. The DC-link capacitor serves several purposes. Since the instantaneous input current may assume negative values then this must be absorbed by the DC-link capacitor (Trzynadlowski 2001). The DC-link capacitor also serves as a source of high frequency components of the input current to the rotor-side inverter so that it is not drawn from the power system via the grid-side inverter. In addition, the DC-link capacitor smooths and stabilises the DC voltage. The optional DC-link inductor serves a less important function which is to provide an extra screen against high-frequency current drawn by the rotor-side inverter.

The rotor- and grid-side inverters are so-called 'vector controlled'. The vector control method is based on the *d-q* transformation of the machine and system quantities. For the DFIG the interest is in the control of rotor currents. Equation 14 states the three-phase sequence of currents i_a, i_b and i_c are converted into a two-dimensional space vector which rotates in the complex plane such that

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (14)$$

Under balanced conditions the zero-sequence component current i_0 is equal to 0. The two current components i_d and i_q are completely equivalent to the three-phase currents i_a, i_b and i_c. Note that the d-q transformation can be applied to any three phase machine or system quantities.
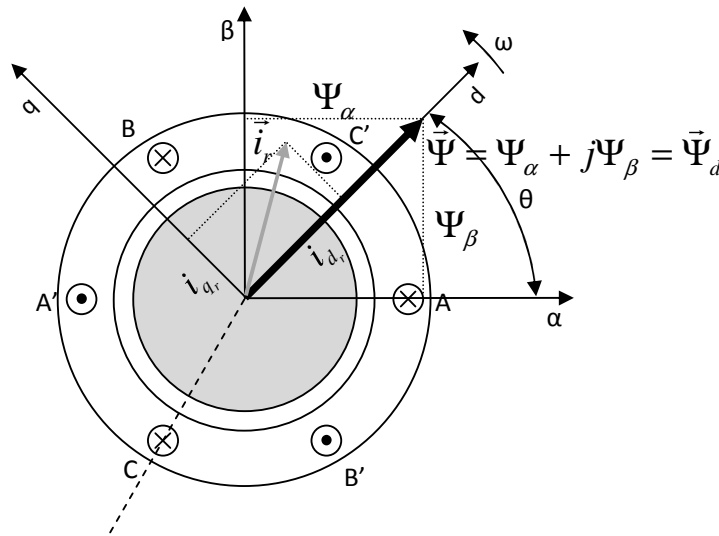

Figure 19. Cross-section of induction machine showing resultant magnetic field (having α and β components) produced by the windings. Control of the rotor-side inverter in the d-q reference frame is aligned with the peak of this field.

The resultant magnetic field produced by the windings in a three-phase machine is a sinusoid which rotates around the periphery of the machine. This can be represented as a space vector with expression in a fixed reference frame (α, β) with origin at the centre of the machine given as $\vec{B} = B_\alpha + jB_\beta$ and with position (maximum value) $\phi = \arctan B_\beta / B_\alpha$. The control of the rotor-side inverter works by aligning the d-axis of the rotating d-q reference frame for current control with the peak of the stator flux vector. This concept is shown in Figure 19.

By aligning the d-q reference frame with the stator flux vector they rotate at the same speed ω. Therefore in the steady-state the flux expression in this reference frame is a constant value in the d-axis $\vec{\Psi} = \vec{\Psi}_d$ and the sinusoidal variable becomes a constant (DC) value. However, to fix the position of the rotating reference frame it is necessary to know the position of the stator flux. In order to align the d-q reference frame for control of the rotor-side inverter it is necessary to know the position (the angle) of the resultant magnetic field for use in Equation 14. This can be estimated from the voltages and currents of the stator, which are known. As mentioned, the d-axis (direct) of the rotating reference frame is aligned with the stator flux vector while the q-axis is placed 90° leading. Now all the magnitudes can be expressed and controlled with respect to this reference frame. The goal of vector control is to make the space vector, in this case the stator flux vector, rotate at a desired speed and to adjust the magnitude to a desired value.

Once the d-q reference frame is appropriately fixed then the d- and the q-axis components of the current can be independently controlled to achieve different regulations of the machine. As i_{dr} is aligned with the stator flux vector, more current implies more flux. Thus the d-axis current of the rotor-side inverter is responsible for the exciting the machine and if the rotor is fed with enough of this current then no excitation current is required from the stator (i.e. no reactive power is drawn from the grid). As the q-axis component i_{qr} is perpendicular to the stator flux it is directly related with the torque in the rotor. The turning torque in the rotor is proportional to the product of the magnetic field by the current perpendicular to it. Therefore, torque regulation can be achieved by varying either the magnitude of the magnetic field (i.e. with i_{dr}) or the current perpendicular to it (i.e. with i_{qr}). The magnetic field (i_{dr}) is usually kept constant as the magnetic time constant is slower than the electrical. Accordingly, only i_{qr} is modified to achieve the desired electrical torque of the machine. This behaviour is analogous to the DC motor where the magnetic field (excitation current) is kept constant and only the armature current modified to achieve torque regulation. The two current magnitudes i_{dr} and i_{qr} can be controlled independently. The d-axis current is used to control reactive power and electrical torque is controlled by means of the q-axis current. As the current components are constant in the steady-state then simple proportional-integral (PI) controllers can be employed.

The control of the grid-side inverter is principally the same as for the rotor-side; only the reference frame is different. The control reference for the grid-side inverter control is the three-phase grid voltage which can be resolved into a stationary vector using the following transformations:

$$v_\alpha = \sqrt{3}v_{ab} + \frac{\sqrt{3}}{2}v_{bc}, \quad v_\beta = \frac{3}{2}v_{bc} \qquad (15)$$

The three-phase grid voltages (v_a, v_b, v_c) are converted into the two-dimensional stationary αβ reference frame using Equation 15 and then into a rotating space vector $\vec{v}$ in the d-q reference frame, obtaining two voltage components v_d and v_q. Note that this transformation has no physical meaning as the magnitudes are not referred to any geometrical position of the machine. Control of the grid side inverter is then aligned with the grid side voltage vector in the d-q axis and is concerned with keeping the DC link voltage constant. This is done by charging and discharging the DC link capacitor. If the DC link voltage goes down the capacitor must be recharged and real power must be absorbed from the grid. If the DC link voltage goes up the capacitor must be discharged and real power is supplied to the grid. The goal of the grid-side inverter is to feed the rotor-side inverter with constant voltage to enable its proper operation.

The real and reactive power exchanged between the grid and the rotor can be defined as

$$\begin{aligned} P &= 3(v_d i_d + v_q i_q) \\ Q &= 3(v_d i_q + v_q i_d) \end{aligned} \qquad (16)$$

By aligning the d-axis of the grid-side inverter control reference frame along the position of the grid voltage vector $\vec{v}$ then the q-component of the voltage v_q is zero and since the amplitude of the supply voltage is constant then the d-component v_d is also constant. Therefore, the active and reactive power is proportional to the control of i_d and i_q, respectively. The real and reactive power can be controlled independently. This means that the grid-side converter control is similar to the control of Statcoms. Since the grid-side inverter is concerned only with the flow of real power to keep the DC-link capacitor voltage constant then it is only necessary to regulate i_d and the other current component i_q is free. This flexibility permits the grid-side inverter to supply reactive power to support grid voltages during steady-state operation and during transients with the limitation being its rating (around 30% of the generator rating).

It is important to understand the behaviour of DFIG equipped wind turbines during disturbances such as grid faults. Due to an imbalance between mechanical input and electrical output power a fault leads to acceleration of the rotor. The voltage dip caused by the fault and transfer of power to the grid at a reduced voltage then leads to an increase in stator currents. The magnetic coupling between the stator and the rotor produces high induced currents in the rotor. The machine and converters are protected by a voltage limiter and an over-current crowbar circuit. Typically the power electronics of the frequency converters are rated to around 30% of the rated power of the generator. The reduced size of the converter is the main advantage of the Type C over the Type D wind turbine concept. However, the relatively small size of the converter introduces restrictions to the current transients which may be present in the rotor circuit during disturbances and makes these converters amongst the most sensitive parts of the wind turbine (Akhmatov). Therefore the advantage of a smaller converter is lost during system faults.

During faults the frequency converter must be controlled in collaboration with the wind turbine pitch controller (Lei, Mullane et al. 2006). To avoid excessive over-speeding of the generator the blade pitching system is used to reduce the power drawn from the wind of the wind wheel. In order to avoid damage to the power electronics the rotor-side converter is blocked and short-circuit placed across the rotor windings with a fixed crow-bar resistance. When the crowbar is triggered the DFIG effectively becomes a SCIG directly coupled to the grid with increased rotor resistance (Aparicio, Chen et al. 2007). With the rotor-side converter blocked and bypassed via a resistance the controllability of real and reactive power is lost and the magnetisation of the machine is carried out via the stator which leads to reactive power being drawn from the grid. The value of the crowbar resistance is chosen to damp the rotor current transients before the rotor-side converter reconnects, its value influences the reactive power absorbed by the generator. With the rotor-side converter blocked it is still possible to continue to operate the grid-side inverter as a Statcom to provide voltage support (Hansen, Michalke et al. 2008). This is possible since the grid-side converter is not directly connected to the rotor which means that it is not necessary to disconnect it.

A study by Marcus *et al*. has shown that an increase in the global transient stability margin of a network is possible where wind turbines equipped with DFIG's are employed. In the studies a simple system consisting of a single conventional synchronous generator, a wind farm of 38 turbines, a load and an infinite busbar representing the rest of a large network was modelled. A three-phase fault was applied near the synchronous generator bus. The determination of the transient stability margin was the point at which the synchronous generator became unstable. The critical clearing time (CCT) of the synchronous generator, which is defined as the maximum duration of a fault which will not lead to loss of synchronisation, was improved from 445 ms for a wind farm consisting of squirrel cage induction generators to 500 ms for DFIGs. The simulations performed show that half and one third of wind generation tripped in the case of SCIGs would be tripped with DFIGs.

During a fault the rotor speed control causes an increase in DFIG power output, which improves the balance between powers in the system and contributes to a reduction of synchronous generator acceleration during the fault. Following clearance of the fault the controllers work to counteract the real power deviation, the rotor current varies and then returns to the previous value before the fault. During a fault the rotor-side inverter controls the q-axis rotor currents in order to temporarily produce the specified electrical power to the system. By generating compensated rotor currents, energy is extracted from the rotor and forced into the network, contributing to the balance between mechanical and electrical power and therefore contributing to the maintenance of system stability.

5. **Type D: Variable-speed wind turbine equipped with Full Converter**

References:

Akhmatov, V. (2005). Induction generators for Wind Power, Multi-Science Publishing.

Aparicio, N., Z. Chen, et al. (2007). "Performance of Doubly-Fed Wind Power Generators During Voltage Dips."

Blaabjerg, F. (2006). Power electronics for modern wind turbines, Morgan & Claypool Publishers.

Causebrook, A., D. J. Atkinson, et al. (2007). "Fault Ride-Through of Large Wind Farms Using Series Dynamic Graking Resistors." IEEE Transactions on Power Systems **22**(3).

Chen, Z., H. Li, et al. (2006). "Comparison and Evaluation of Induction Generator Models in Wind Turbine Systems for Transient Stability of Power System." 2006 International Conference on Power System Technology.

Hansen, A. D., G. Michalke, et al. (2008). "Co-Ordinated Voltage Control of DFIG Wind Turbines in Uninterrupted Operation during Grid Faults." Wind Energy.

Hart, D. W. (1997). Introduction to Power Electronics. United States, Prentice Hall.

Jenkins, N., R. Allan, et al. (2000). Embedded Generation. London, The Institute of Electrical Engineers.

Kundur, P. (1994). Power System Stability and Control, McGraw-Hill Professional Publishing.

Lei, Y., A. Mullane, et al. (2006). "Modeling of the Wind Turbine With a Doubly Fed Induction Generator for Grid Integration Studies." IEEE Transactions on Energy Conversion **21**(1).

Lubosny, Z. (2003). Wind Turbine Operation in Electric Power Systems. Germany, Springer.

Marcus, V. A., J. A. Nunes, et al. (2004). "Influence of the Variable-Speed Wind Generators in Transient Stability Margin of the Conventional Generators Integrated in Electrical Grids." IEEE Transactions on Energy Conversion **19**(4).

Muyeen, S. M., M. Hasan Ali, et al. (2007). "Comparative study on transient stability analysis of wind turbine generator system using different drive train models." IET Renewable Power Generation **1**(2): 131-141.

NEMMCO (2004). Assessment of Potential Security Risks due to High Levels of Wind Generation in South Australia - Summary of DIgSILENT Studies (Stage1). P. S. P. a. Development.

NEMMCO (2008). Geberator System Data and Model Guidelines: Determination and Report.

Pena, R. (1996). "Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation." IEEE Transactions on Energy Conversion **143**(3).

Salman, S. K. and L. J. Teo (2002). "Investigation into the Estimation of the Critical Clearing Time of a Grid Connected Wind Power Based Embedded Generator." 2002 IEEE/PES Transmission and Distribution Conference and Exhibition.

Trzynadlowski, A. (2001). Control of Induction Motors. San Diego, Academic Press.

Usaola, J., P. Ledesma, et al. (2003). "Transient stability studies in grids with great wind power penetration. Modelling issues and operation requirements." Proceedings of IEEE.

Werner, L. (2001). Control of electrical drives, Springer.

Wildi, T. o. (2006). Electrical machines, drives, and power systems, Pearson Prentice Hall.