

# Importance of advanced simulations of electrical transients in wind turbines

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## 1 Summary

Until recently, electrical dynamics have not always been fully considered during the design of wind turbines. However grid code requirements are becoming increasingly demanding and they have a direct influence on the design process of a wind turbine. Therefore advanced computer models are being developed which are capable of simulating the electrical dynamics in combination with the structural and control dynamics.

The wind turbine generator and converter needs to operate in a wider range around the nominal operating condition. During operation far away from the nominal operating curve, the design limits of the electrical system may be reached. A doubly fed induction generator (DFIG) wind turbine is used to show this effect during turbulent wind conditions. Generator rotor voltage increases with the slip speed and there is a potential possibility that it could reach the rotor converter maximum voltage. At the top of the operating speed range, the converter voltage limit will force the generator to absorb a large amount of reactive power from the grid which would not comply with the grid code requirements. In addition, IGBT converters have current limitations due to thermal stress at low fundamental frequency. As it is shown in this article, this low frequency current limitation may become a design constraint for a DFIG wind turbine.

Electrical faults such as grid faults produce high amplitude, rapid electrical transients and wind turbine designers increasingly need to take them into account. Different options for low voltage ride through (LVRT) are discussed for a wind turbine with a synchronous generator and fully rated converter. Modifications to the wind turbine protection system may be required in order to minimise the possibility of turbine shutdown following a grid fault, as well as to minimise the loading consequences of such events. Two different electrical protection schemes, (i) torque control, and (ii) chopper resistor (braking resistor), are discussed in this article. Even though the torque control scheme alone protects the electrical components, it can excite drive train oscillations resulting in turbine shutdown. As shown in this article, a combination of torque control and braking resistor helps to ride through multiple successive grid faults without shutting down the wind turbine.

## 2 Introduction

Wind turbine dynamics consists of aerodynamics, structural, control and electrical dynamics as illustrated in Figure 1. Air flow through the rotor induces aerodynamic torque and then the torque is transmitted to the generator shaft through a series of structural components, rotor blades, low-speed shaft, gearbox and high-speed shaft. The effect of mechanical dynamics couples to the electrical system via the generator torque and speed. There are interactions between the electrical system and mechanical system of the wind turbine and it is important to consider all four systems together [1].

Wind turbine pitch controllers usually have a low bandwidth in order to reduce the mechanical loading of the turbine. This requires the electrical system to operate in a wider speed range around rated conditions. During operation far away from the nominal operating conditions, the design limits of the electrical system may be reached. The importance of a combined analysis of electrical and mechanical systems is described in section 3 for a DFIG wind turbine.

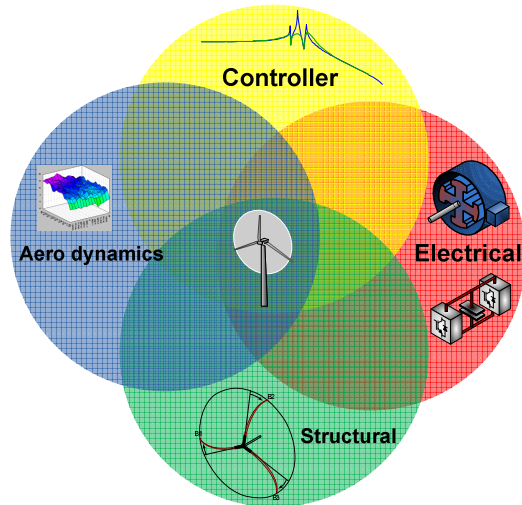


Figure 1: Wind turbine systems

Integration of a large amount of wind generation on power networks imposes requirements that wind farms should be able to contribute to network support and operation. The Grid Codes define these requirements [2][3]. Some of the important requirements defined as in the Grid Codes are LVRT and power factor control. These grid code requirements are becoming increasingly demanding and they impose design constraints.

The response of a wind turbine to a LVRT is of increasing concern for turbine designers. During a LVRT the wind turbine experiences heavy transients and the turbine could reach any of its design limits. In Section 4, different control schemes for LVRT are described for a fully rated converter wind turbine with a synchronous generator.

### 3 Performance of a DFIG

The DFIG is one of the most common variable speed wind turbines [4][5]. Figure 2 shows a schematic diagram of a DFIG with an IGBT converter connected to the rotor windings. There are three control loops in a typical DFIG wind turbine: pitch controller, torque controller and power factor/voltage controller. The pitch controller maintains the rotor speed in high wind speeds [6]. The torque controller moves the wind turbine operating point along the maximum power curve. The power factor/voltage controller maintains the generator power factor at a reference value requested by the system operator.

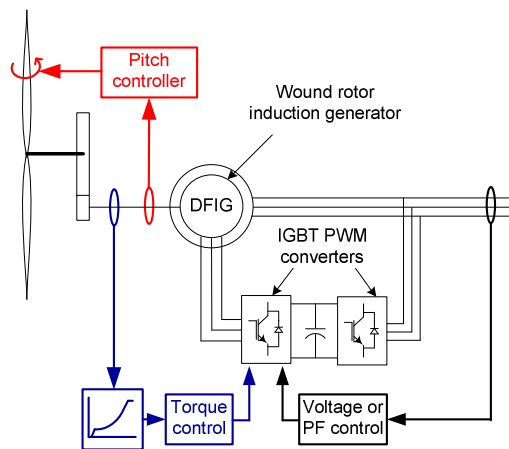


Figure 2: DFIG wind turbine

Figure 3 shows the operating points of a DFIG variable speed wind turbine operating at maximum power during turbulent wind conditions. It can be seen from Figure 3 that the generator needs to operate far away from the nominal operating point. Therefore a torque speed envelope (shown in Figure 4) is defined for the electrical system to operate within.

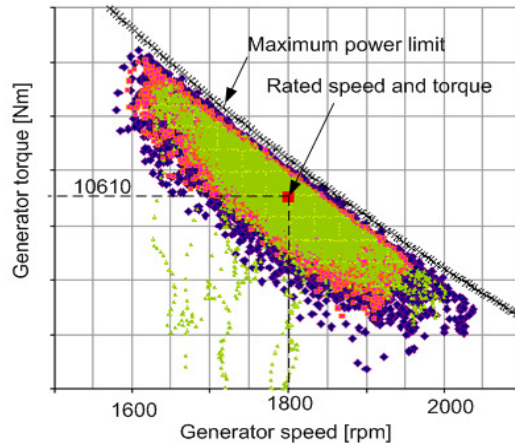


Figure 3: Operating points during turbulent wind conditions

The main power curve shown in Figure 4 ensures that the turbine operates at its maximum aerodynamic efficiency. The operating envelope is defined by generator speed tolerances, maximum generator torque limit and maximum generator power limit. The speed tolerance depends on the turbine pitch control performance.

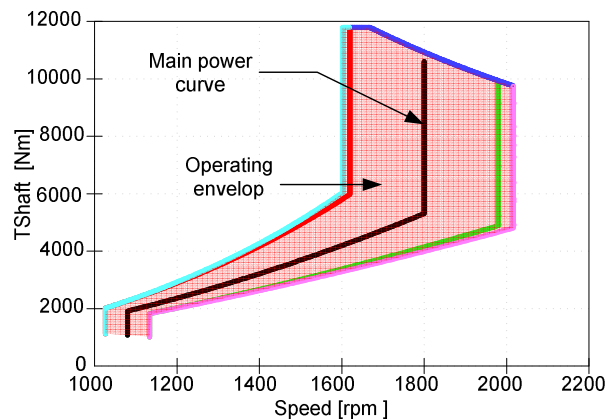


Figure 4: Wind turbine main power curve and operating envelope

### 3.1 Rotor voltage limit and power factor

Rotor voltage variations for the torque speed curves (given in Figure 4) are shown in Figure 5. The rotor voltage increases with the slip speed until it reaches converter maximum voltage of 759 V. The voltage limit on maximum speed occurs at minimum grid frequency and operating with a capacitive power factor. The rotor voltage operating curves shown in Figure 5 are at 47.5Hz grid frequency, 0.95 capacitive power factor and 100% grid voltage.

At the top of the operating speed range, the converter voltage limit will force the generator to absorb a large amount of reactive power from the grid as shown in Figure 6, leading to non-compliance with the grid code requirements for power factor. In order to satisfy the grid code requirements, the turbine should avoid operating above 1800 rpm. This may be achieved by reducing the gearbox ratio.

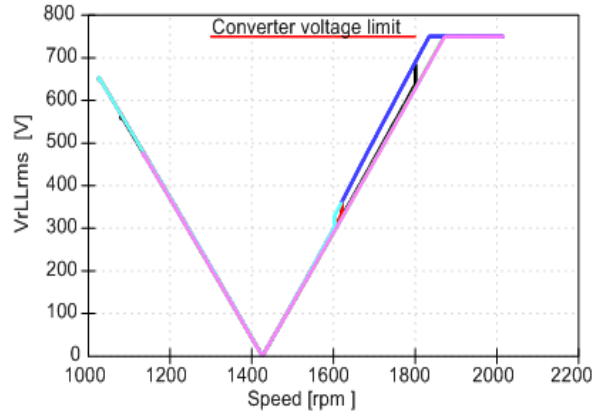


Figure 5: Rotor voltage

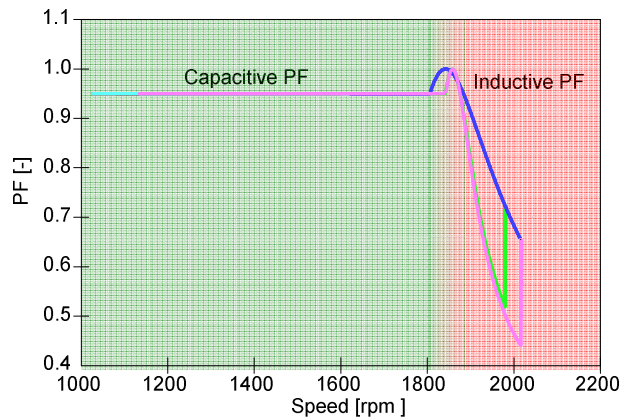


Figure 6: Generator power factor

### 3.2 Rotor current variation

The operating curves for rotor current variations are shown Figure 7 for the same torque speed curves given in Figure 4. Due to high thermal stress IGBT converters have current limitations at low fundamental frequency. This gives rise to an area in Figure 7 marked as a prevented area, and the wind turbine should avoid operating in this region.

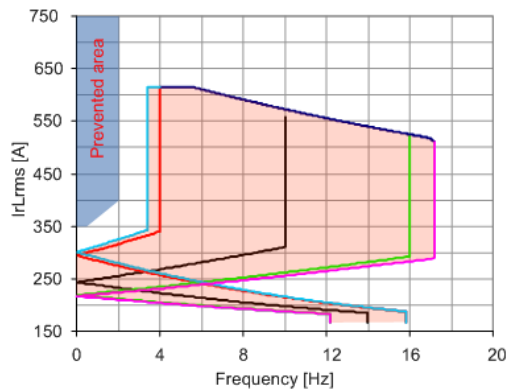


Figure 7: Rotor current for 1800rpm rated speed

In order to avoid absorbing reactive power from grid above 1800 rpm, assume the rated generator speed is reduced to 1600 rpm by changing the gearbox ratio by a factor of 8/9. This change in rated speed gives new operating torque speed curves as shown in Figure 8.

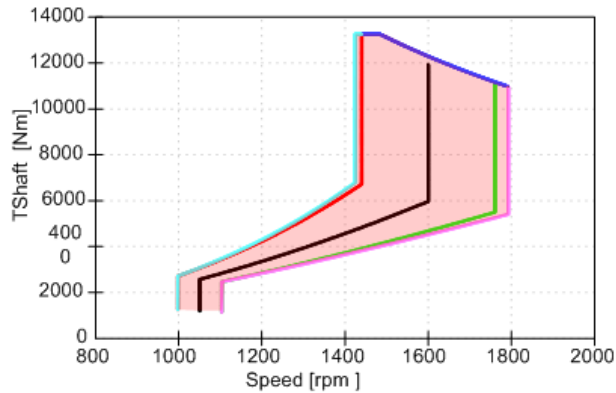


Figure 8: Generator power factor

The rotor current variations for the new torque speed curves are given in Figure 9. It is evident from Figure 9 that selecting a 1600 rpm rated speed is not appropriate due to converter current limitations at low fundamental frequency.

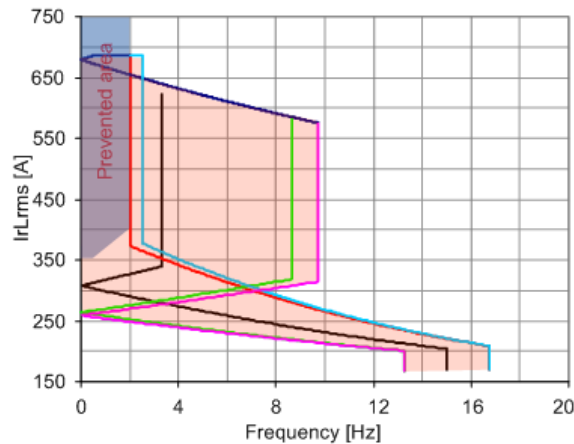


Figure 9: Rotor current variation for 1600rpm rated speed

### 3.3 Mechanical loading

In section 3.1 the generator rated speed was 1800 rpm and it absorbs large amount of reactive power at high speed. On the other hand, in the case of 1600 rpm rated speed (Section 3.2) the converter needs to operate within its high thermal stress region. Both these cases are unacceptable for a wind turbine design; therefore the rotor speed could be set to 1700 rpm and then the pitch controller performance tightened to keep the operating points close to the rated speed.

Tightening the pitch controller increases the mechanical loadings of the turbine. Figure 10 compares tower bottom over turning moment for a low- and a high-bandwidth pitch controller.

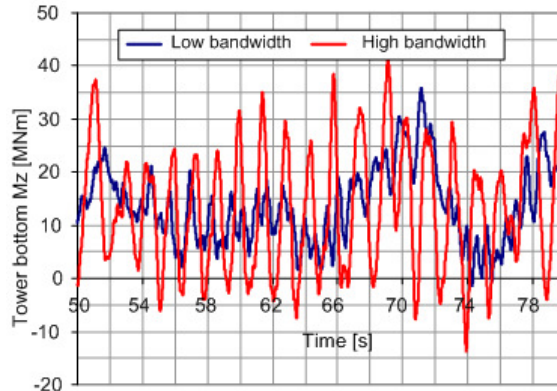


Figure 10: Tower bottom over turning moment

It is shown in this section that the rotor side converter voltage and current limitations have direct influence on the mechanical design of a DFIG wind turbine. Next section describes the effect of electrical transient dynamics during a LVRT on the mechanical system for a fully rated converter wind turbine with a synchronous generator.

#### 4 Performance of a synchronous generator with fully rated converter during LVRT

Wind turbines using four quadrant converters with a synchronous generator are emerging on one of the more popular variable speed wind turbine architectures [7]. A typical configuration is shown in Figure 11, and it has three control loops similar to a DFIG wind turbine. The generator controller moves the wind turbine operating point along the maximum power curve. The grid side controller maintains the DC link voltage at a reference by exporting active power to the grid. Reactive power is supplied to the grid from the grid side converter whenever it is necessary.

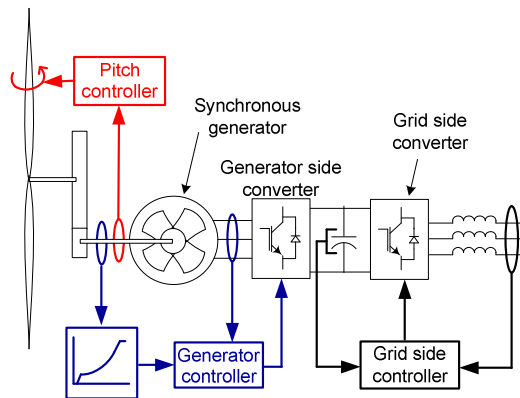


Figure 11: Synchronous generator with fully rated converter wind turbine

##### 4.1 Low voltage ride through

The response of a wind turbine to a grid fault not only has effects on the electrical system but also has a direct influence on the mechanical side of the wind turbine. In order to minimise the possibility of turbine shut-down upon a grid fault, as well as to minimise the loading consequences of such events different protection schemes are discussed in this section.

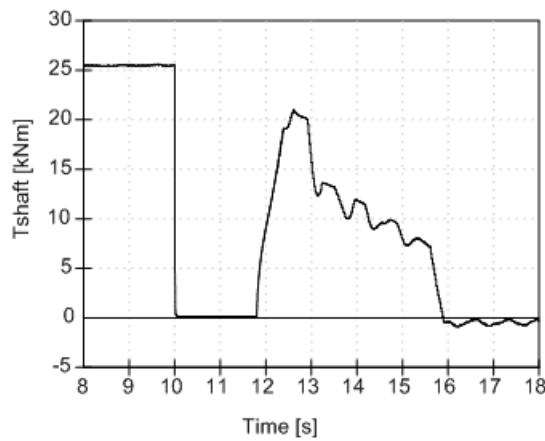
In the event of a grid fault, the DC link voltage will rise rapidly because the grid side converter is prevented from transforming all the active power coming from the generator. Therefore, in order

to maintain the DC link voltage below its upper limit, the excess power has to be dissipated or the generator power has to be reduced.

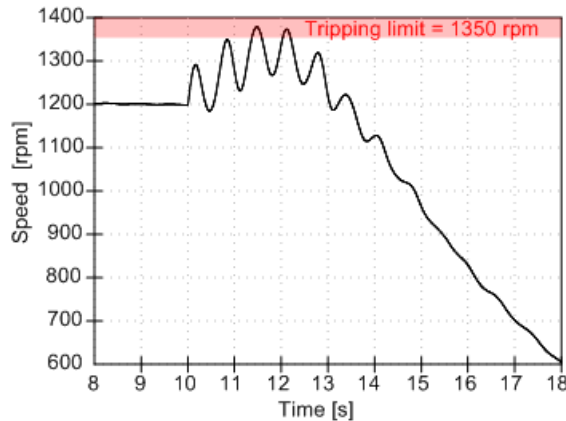
#### 4.1.1 Torque control

One way of maintaining the DC link voltage below the upper limit during a fault is to reduce the generator power. The generator power can be rapidly reduced by reducing the generator torque.

A grid fault was applied at 10s (at the wind turbine terminal) for 625ms and then the voltage is increased to rated voltage at 13s. Figure 12 shows the response of the turbine when using the torque control as the protection method. Because of the grid fault, the wind turbine grid side converter power drops to zero and the DC link voltage increases. This triggers the protection system to drop the torque from its rated value to zero immediately after the fault (see Figure 12 (a)).



(a) Generator torque variation



(b) Generator speed

Figure 12: LVRT response when using torque control only

Dropping the torque from rated to zero has two effects on drive train dynamics; it increases the rotor speed and it excites drive train oscillation as shown in Figure 12 (b). The rotor accelerates because the generator provides zero reaction torque while the turbine rotor generates full aerodynamic torque. Wind turbine rotor is made up of flexible blades and flexible shafts and it is subjected to structural oscillation. Therefore the step change in the generator torque induces generator shaft oscillation. The rotor speed given in Figure 12 (b) reaches the over speed

tripping value of 1350 rpm. This triggers the turbine safety system which forces the turbine to shutdown.

#### 4.1.2 Braking resistor

An alternative approach to maintaining the DC link voltage below the upper limit during a grid fault is to use a braking resistor in the DC link. The braking resistor dissipates excess power as heat.

According to IEC 61400 edition 3, wind turbines effectively need to ride through three successive faults within 90 s as might be generated by auto-reclose of network circuit breakers. Figure 13 shows the response of the wind turbine for three successive faults at 10s, 20s and 30s. As soon as the DC link voltage reaches its maximum limit, the braking resistor is switched on.

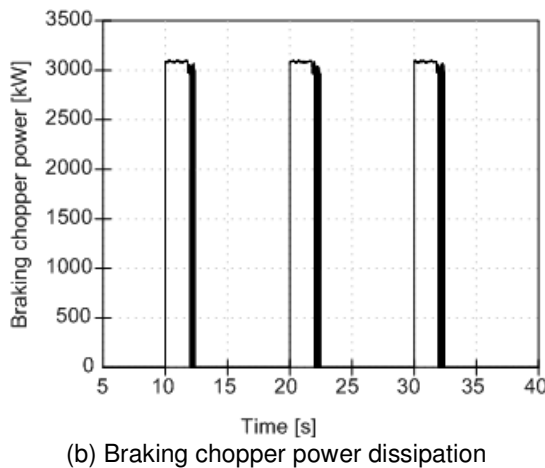
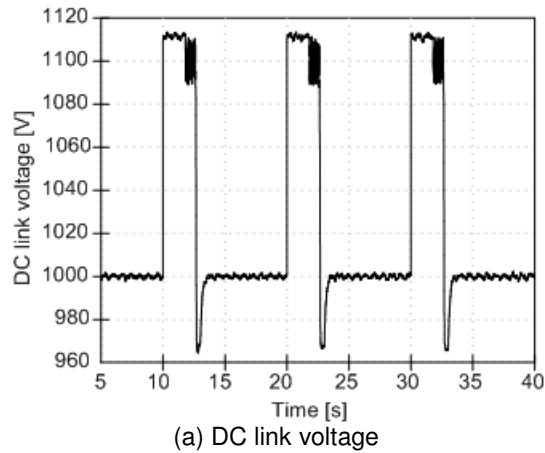


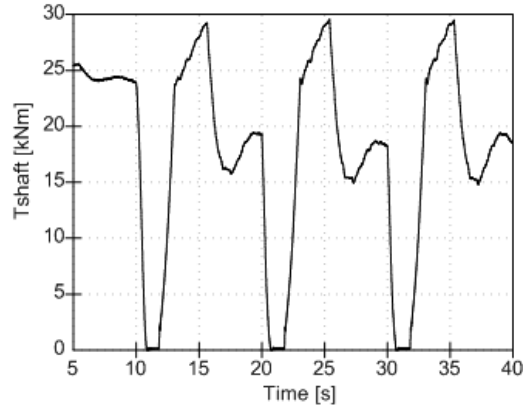
Figure 13: LVRT response when using braking resistor only

The braking resistor in Figure 13 (b) operates at the turbine rated power; therefore the generator can maintain its full torque. From a mechanical system point of view, maintaining full reaction torque is desirable as it avoids any drive train oscillations during the faults. However it should be noticed that the braking chopper is used for 7.5s in total within 40s, and the total heat dissipation may cause overheating.

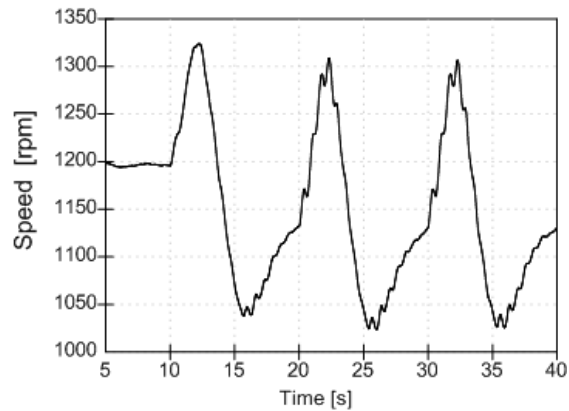
### 4.1.3 Combination of torque control and braking resistor

Instead of using the braking chopper continuously during a grid fault, the generator torque can be changed in a controlled manner so that the use of the braking chopper is reduced.

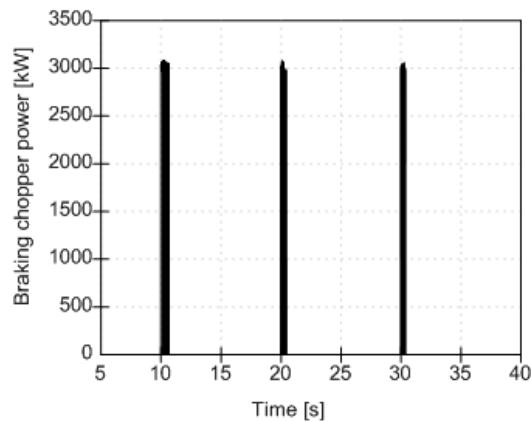
The generator torque is gradually decreased in Figure 14 (a) to avoid any drive train oscillation (see Figure 14 (b)). Finally, the braking resistor power dissipation shown in Figure 14 (c) is only used for about 2.5s in total for the three successive grid faults.



(a) Generator torque ramp



(b) Generator speed



(c) Braking chopper power

Figure 14: LVRT response with the combination of torque control and braking resistor

## 5 Conclusion

The wind turbine generator and converter needs to operate in a wider range around the nominal operating condition. During operation far away from the nominal operating curve, the design limits of the electrical system may be reached. A DFIG wind turbine requires higher rotor voltage when operating at capacitive power factor. The rotor side converter has voltage limits and therefore the grid code requirement for power factor could determine the maximum generator speed. Due to high thermal stress, IGBT converters have current limitations at low rotor frequency. This may limit the operation of the turbine when operating between the synchronous and rated speed. Therefore the converter voltage and current limitations may require the turbine pitch controller to be tightened so that the turbine operates close to rated speed. However, tightening the pitch controller increases the mechanical loading of the turbine. Therefore there is a compromise between the electrical and mechanical systems. This example shows the importance of a combined analysis of electrical, mechanical and control systems.

In an event of a grid fault, the DC link voltage of a fully rated converter wind turbine will rise rapidly. In order to maintain the DC link voltage below its upper limit, different protection schemes were investigated using torque control and a braking chopper. Dropping the generator torque suddenly results in drive train oscillation and could lead to turbine shutdown. Using a braking resistor maintains the generator reaction torque and is therefore desirable from mechanical system point of view, but the heat dissipation could result in an unacceptable temperature rise. However, it is shown in this paper that a combination of torque control and braking chopper can be an effective solution for successive grid faults.

## 6 Reference

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