Influence of Protection System Settings on Wind Farm Dynamic Behaviour during Power System Disturbances

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Summary -- The continuing growth of grid connected wind turbine generation systems worldwide has driven research efforts in understanding their dynamic behaviour and highlighted the importance of grid integration studies. Within this context, this work develops a systematic analysis of the dynamic behaviour of wind turbines during transient disturbances of the power system to which they are connected. As part of a study commissioned by the Brazilian National System Operator (ONS), it aims at characterising the dynamic behaviour of different wind turbine technologies and assessing the effect of the protection system settings on the wind power plant low voltage ride-through capability. Dynamic models were developed in MATLAB/Simulink for variable speed (using doubly fed induction generator – DFIG, and synchronous generator – SG) and fixed speed wind turbines (using induction generator - IG). The results obtained provide a fundamental understanding of the interaction between the system components.

Key Words -- Wind turbines, doubly fed induction generator (DFIG), synchronous generator (SG), induction generator (IG), voltage sag and ride-through.

I. INTRODUCTION

Over recent years the number of wind farms under development worldwide has grown considerably due to the renewable and non-polluting nature of this energy source. As a consequence of the higher contribution of wind energy in power systems, the interaction of wind turbines with the loads and other systems components has increased, influencing the system behaviour as a whole. This has generated great R&D interest into the integration of wind turbines with the power system.

In many countries system operators (SO) have been working on grid codes to address the problems associated with the ongoing growth of wind power. Such grid codes include, amongst other criteria, the “ride-through fault capability” (RTF) of wind turbines or wind farms, i.e. their ability to remain connected to the grid during temporary voltage dips at the point of common coupling (PCC) [1], [2].

Similarly to other countries, the Brazilian National System Operator (ONS) adopted an RTF capability criterion in order to maintain the quality and security of supply [2]. This is illustrated in Figure 1, below.

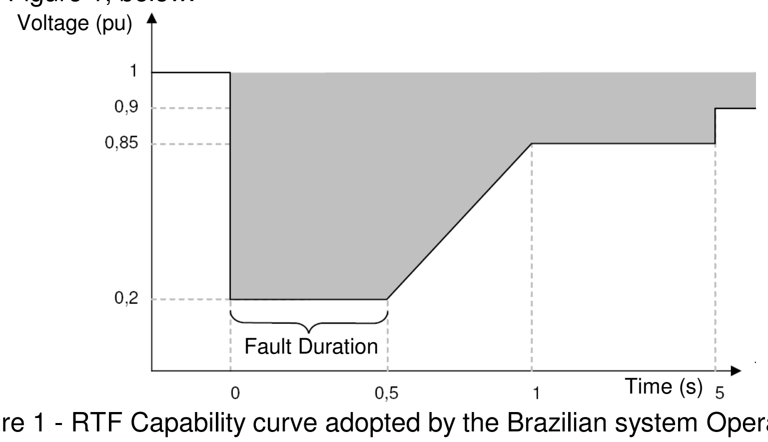

Figure 1 - RTF Capability curve adopted by the Brazilian system Operator (ONS).

The darkened area in that figure represents the requirement for the wind farm to remain connected to the grid during the voltage sag. In contrast, wind turbine requirements found in many modern grid codes are much broader, treating wind power plants as conventional power plants.

An important step towards the verification of the impact of wind turbines on the grid was the standardisation of the tests to be performed proposed in the IEC 61400-21 standard in its latest revision [3]. In this revision, the behaviour of the wind turbines is considered, specifying that tests should be carried out for wind turbines operating at 20% and 100% of rated power under the types of voltage sags prescribed in Table 01. It is worth mentioning here the inclusion of unbalanced fault conditions.

TABLE 01
Specification of voltage sag recommended for immunity analysis of wind turbines

TVD Type	TVD Magnitude	Voltage Magnitude	Fault Duration (s)	TVD Shape
3-phase	90% +/- 5%	90%	0,5 +/- 0.05	Rectangular
3-phase	50% +/- 5%	50%	0,5 +/- 0.05	Rectangular
3-phase	20% +/- 5%	20%	0,2 +/- 0.05	Rectangular
2-phase	90% +/- 5%	95%	0,5 +/- 0.05	Rectangular
2-phase	50% +/- 5%	75%	0,5 +/- 0.05	Rectangular
2-phase	20% +/- 5%	60%	0,2 +/- 0.05	Rectangular

Many dynamic models have been proposed in the literature for the integration studies of grid connected wind turbines. Some of these assess the models, their dynamic behaviour and propose alternatives to improve the RTF capability of the turbines focusing on technological solutions [4]-[6]. Others assess the interactions of the wind power plants with the power system [7], [8]. In [9], a comparison between models is carried out, from the stand point of a power system operator, highlighting their pros and cons, while providing important considerations for the development of computational models.

Within this context, this work uses computational models developed in MATLAB/Simulink to assess the behaviour of grid connected wind turbines during symmetrical and asymmetrical voltage sags. The models include a comprehensive structure of three different wind generation systems: squirrel cage induction generators (IG); synchronous generators (SG); and doubly-fed induction generators (DFIG). From a batch of simulations representing a number of different working conditions, the behaviour of the relevant variables was characterised. Furthermore, a detailed representation of the protection system was also implemented in the models, and given the adjustments and settings made, the RTF capability of each type of technology was obtained.

II. IMPLEMENTED MODELS

The models developed in this work include a representation of the mechanical and electrical dynamics of wind turbines connected to the grid. Specific adjustments to the protection system will determine the grid disconnection point of the wind turbine, thus characterising the performance of a given generator technology. Three generator technologies were implemented, one at fixed speed (IG) and two at variable speed (SG and DFIG). The protection systems implemented in this work were:

- Instantaneous and temporized overcurrent protection: triggered from individual phase current measurement at the wind farm output substation transformer low voltage side (secondary) for the IG and SG configurations. For the DFIG, there is also the need to monitor the rotor and stator variables, thus implementing individual protection of these circuits;
- Instantaneous and temporized undervoltage protection: triggered from individual phase voltage measurement at the wind farm output substation transformer low voltage side (secondary) for the IG and SG configurations. For the DFIG, these are carried out separately for the rotor and stator circuits;
- Instantaneous overspeed protection: triggered from the generator mechanical speed measurement.

The basic model structure developed is shown in Figure 2, and consists of:

- The grid, represented as an ideal voltage source and a series-connected short-circuit impedance;
- The wind power plant substation output transformer (delta-wye connected);
- The power system fault simulator, which consists of switchable impedances connected in parallel to the grid;
- The wind power plant, characterised by the representative models of each generator technology.

A mathematical model simulates the aerodynamic conversion of the turbine rotor, having the rotor torque as the output, which is then use as the input either to the gearbox (IG and DFIG) or the generator (SG). This model is similar to those presented in [7] and [10], and includes the rotor blades pitch control mechanism for power limitation.

The effect of wind speed variations over the generator performance is not relevant in his work [10]. Nonetheless, the pre-fault operating point and the impact of any speed variation over the mechanical torque delivered must be considered.

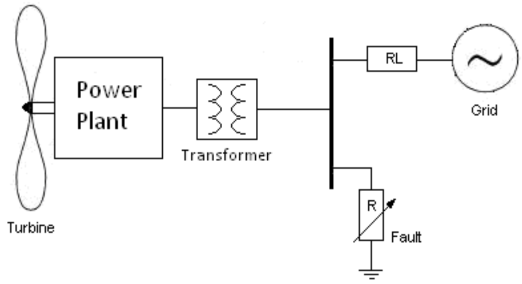

Figure 2 – General model structure implemented.

A. Induction Generator Model (IG)

Figure 3 shows the block diagram of the IG implemented model. It consists of a generator directly connected to the grid, and coupled to the turbine rotor through a gearbox. The gearbox model includes the shaft stiffness using a two-mass representation [9]. A reactive power compensation capacitor bank is also included in the model. For the squirrel cage induction generator, the Simulink library pre-defined full-order model was used.

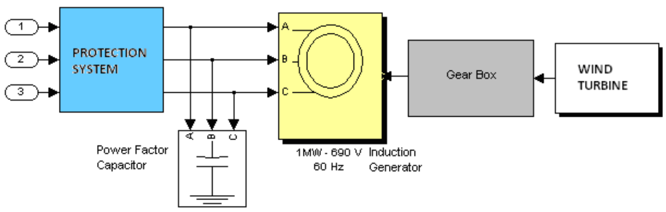

Figure 3 – Block diagram of the induction generator model.

B. Synchronous Generator Model (SG)

The model implemented consists of a direct-driven synchronous generator, represented by a full order model, with independent field excitation connected to the grid through frequency converters. The converters are modelled using IGBT pre-built blocks, defined as ideal switches.

The grid side converter controls the DC bus voltage by injecting current into the grid, thus working as an inverter, whereas the generator side converter controls the turbine output power, thus working as a controlled rectifier. The control pulses applied to the converters are independent PWM signals.

A breaking *chopper* is used in the DC bus to dissipate the excess energy in the bus capacitor. It is used when the capacitor voltage surpasses a pre-determined value (a reference value of 110% was used in this work), thus avoiding overvoltages and increasing the RTF capability of the turbine [4]. Also included in the model is an output LC filter to reduce the harmonic content produced by the converters. The model structure is shown in Figure 4.

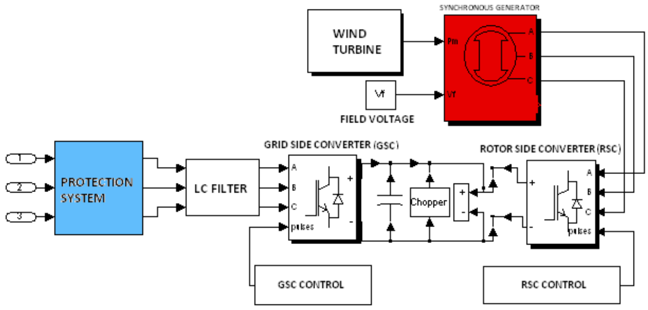

Figure 4 – Block diagram of the synchronous generator model.

C. *Doubly-fed Induction Generator Model (DFIG)*

The DFIG model used is also pre-defined in Simulink's library, and represents a full-order wound-rotor induction machine. The stator windings are directly connected to the grid which the rotor circuit is fed through a AC/DC/AC converter composed of two 3-phase IGBT converters interconnected by a DC link. This configuration allows for bidirectional power flow into the machine rotor, so that it can operate both at sub- and super-synchronous speeds.

A vector control strategy is implemented to control the power injected/consumed by the rotor, generating the independent PWM pulses to the converters IGBT switches. The grid side converter controls the DC bus voltage. The rotor side converter controls the rotor active power and the stator reactive power using a stator flux-oriented control strategy, which ensures an almost ideal decoupling between active and reactive power control.

Similarly to the IG model, the gearbox model include the shaft stiffness. And like the SG model, an LC filter is implemented at the grid side converter output and a breaking chopper is used to limit the DC bus voltage at 1.1 pu. The model structure for the DFIG is shown in Figure 5.

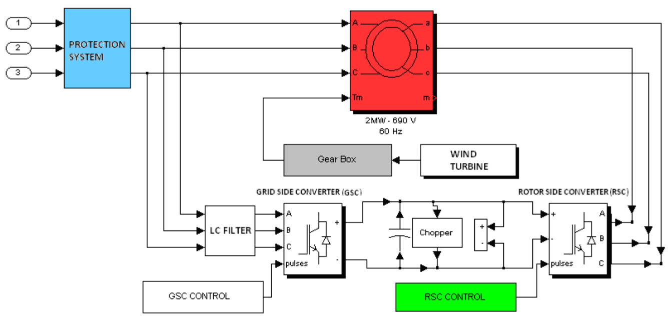

Figure 5 – Block diagram of the doubly-fed induction generator model.

III. DYNAMIC BEHAVIOUR ASSESSMENT

Having defined the dynamic model representation for the three technologies under study, a batch of simulations were carried out using a 1MW IG, a 2MW SG and a 2MW DFIG wind turbines, so as to characterise the dynamic behaviour of each one under voltage dips. The simulations considered a range of operating conditions, under different wind speeds and types of voltage dips, with varying amplitude and duration.

These simulation tests were carried out so as to understand the behaviour of each technology under the voltage sags. As a result, this section presents a summary of the time domain behaviour of the relevant system variables, which were then used to guide the adjustments made to the protection system settings. The simulation results shown here were obtained for the wind turbines operating at rated wind speed, under a 3-phase voltage dip with amplitude of 80% (grid voltage at 20%) and 200ms duration for the IG and SG, and 500ms duration for the DFIG.

1) *Induction Generator*

Under a voltage dip, the induction generator supplies, to fault point, high currents during a short period of time, in demagnetization process. After that, the current drops, depending of the level of voltage and power delivered. This behaviour can be seen in Figure 6, where, after the initial peak, the currents drop gradually to a steady value.

Similarly, the power (Figure 6) and the torque, undergo an oscillatory peak, resultant of the DC current component supplied by the machine to the fault point. As expected, the generator speed increases, also in a slightly oscillatory mode, as a result of the reduced electrical energy conversion capability by the generator. Therefore the input wind energy is stored as kinetic energy on the rotor blades (Figure 7). This excess energy is dumped when the fault ends, causing a peak in the output power and hence the generator output current. If during this process the generator speeds up too much (past the breakdown torque speed curve point), the generator loses its electromechanical stability, and cannot recover after the voltage dip has finished.

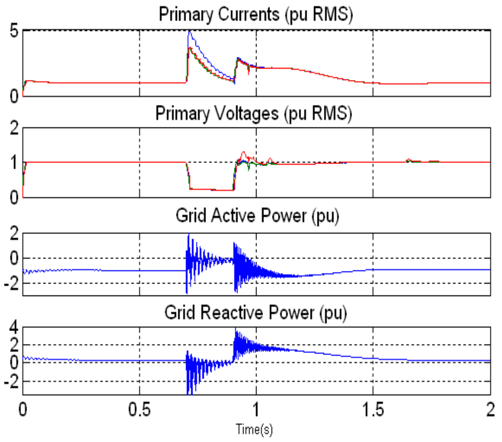

Figure 6 – Currents and voltages (pu-rms) on the grid, active and reactive power for the induction generator

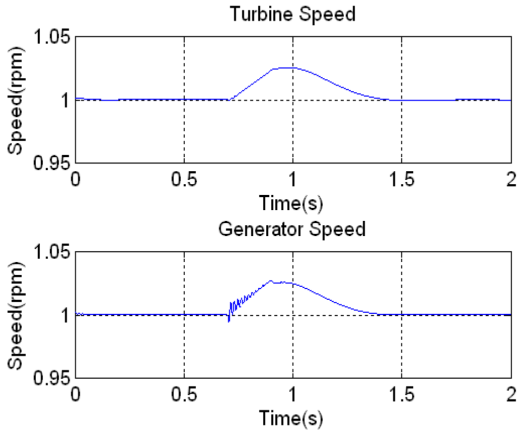

Figure 7 – Wind turbine and generator speed (rpm) for the induction generator

2) *Synchronous Generator*

Under a voltage dip, the synchronous generator currents have a natural tendency to increase (Figure 8), however, due to the fast action of the controllers they do not peak, presenting a very short transient behaviour. Furthermore, the control system help keep their value within the limit established in the controller, preventing undesired currents values (the limit used in the study was 1.5 pu). A slight difference between the phase currents profile can be observed in Figure 9, which is due to the voltage dip not being perfectly balanced.

When a severe fault happens, there is a considerable reduction in the active power delivered to the grid (Figure 8), due to the current limit imposed by the converter. However, the generator keeps operating through the fault. The excess energy is, in this case, is also stored in the DC bus capacitor, rising its voltage (Figure 9).

In order to avoid overvoltages in the capacitor, the breaking chopper starts to operate, dumping the excess energy on the breaking resistor. After the fault, the excess energy in the capacitor is injected into the grid through the action of the grid side converter, incurring in a power peak on the grid. Therefore, the presence of the chopper increases the turbine RTF capability.

Due to the independently controlled double converter configuration, grid side disturbances do not produce severe electromechanical transients on the generator side (Figure 9), showing the existing decoupling between the grid and the generator.

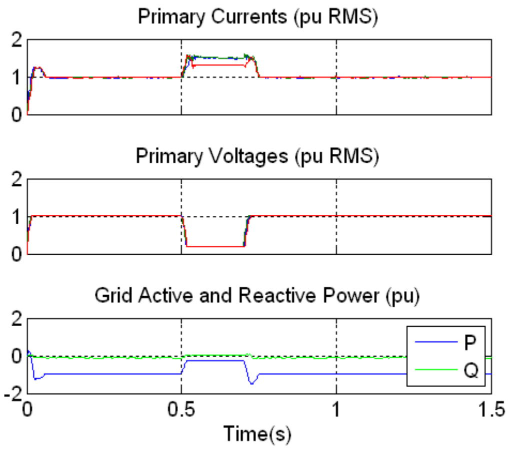

Figure 8 – Grid currents and voltages and active power (pu-rms) for the synchronous generator

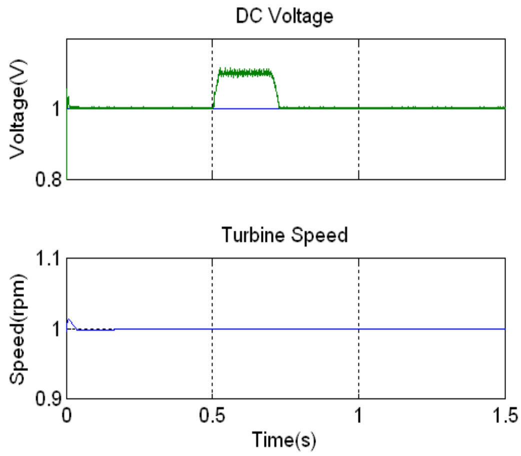

Figure 9 - DC capacitor voltage and wind turbine speed (rpm) for the synchronous generator

3) Doubly-fed Induction Generator

The DFIG is more affected than the SG, however, it presents better results than the IG during temporary voltage dips. Due to the sudden voltage drop, the stator currents develop DC components, which are seen on the rotor side as AC and are superimposed to the currents injected by the converter, which in turn have slower dynamics. Furthermore, the demagnetization on the stator circuit tends to be compensated through the rotor circuit, incurring on an increase of the currents until these are limited by the converter control system. The sum of both these current components will be perceived on the grid. The voltages and currents can be seen in Figure 10.

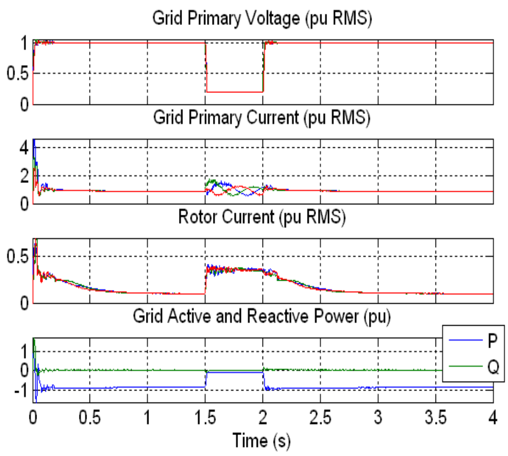

Figure 10 - Currents and voltages (pu-rms) on the grid, rotor currents (pu-rms) and active and reactive power for the DFIG

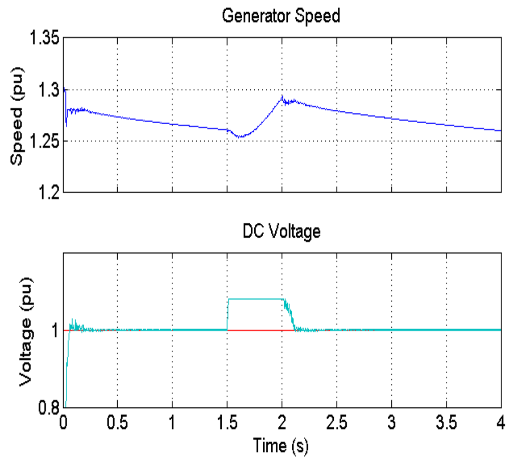

Figure 11 – Generator speed and DC bus voltage for the DFIG

Similarly to the SG, the DC bus voltage increases (Figure 11), causing the chopper to act. When the fault is finished, the excess energy in the capacitor is injected on to the grid (Figure 10), which explains the high rotor current values for some time after the fault is cleared. Due to the drop in the electromagnetic torque during the sag, the turbine speed increases (Figure 11), and then decreases slowly after the fault, due to the high rotor inertia.

The behaviour will be quite different if the disturbance happens in low wind speed, because the converter will operate with reverse active power flow. In this case, the chopper will not act, because the DC voltage will decrease during the voltage sag.

IV. LVRT CAPABILITY RESULTS

Given the effects caused by the voltage dips on the different generator technologies, a study was carried out on the impact of the protection system settings on the RTF capability of the system. In order to do that, simulations were run for different operating conditions as well as fault characteristics, so that capability curve profiles could be obtained and adjusted.

1) Induction Generator

As previously shown, the induction generator presents critical overcurrent and overspeed characteristics. The current peak at fault time is usually very high with a small decay time constant. Therefore, the generator thermal limits are not reached and the instantaneous overcurrent protection should be adjusted not to actuate during this short transient. The most critical aspect is during the fault recovery transient, which present smaller currents with higher time constants. Therefore, both instantaneous and temporized overcurrent protection settings should considered for this longer transient. Since the undervoltage profile is dictated by the voltage dip, the protection system should be adjusted to follow the grid code under study, represented by Figure 1.

Another limitation with this type of technology is the generator stability. If the fault is too drastic or takes too long, the generator speed could increase beyond its stable operating region (breakdown torque), thus resulting in disconnection of the wind power plant from the grid, either due to the overspeed or overcurrent protection actuation. Therefore, if the unstable region is reached (broken red line in Figure 15) the power plant will be disconnected, independently of the protection system settings.

Considering the limits adopted by the Brazilian SO, the instantaneous and temporized undervoltage settings were set to 0.2 pu and 0.8 pu, respectively, with timings equal to 60ms and 1s. Overspeed protection was set to act in 500ms for an amplitude greater than 1.2 pu.

The overcurrent settings adjustment procedure is not a simple task for the squirrel cage induction generator wind turbine. First, because the current dynamics varies considerably with the fault amplitude and duration, especially considering the phase angle of the remaining grid voltage. Second, because this technology is greatly affected during the voltage dip, therefore, adjustments that may improve the RTF capability of the machine may be damaging to a real operating system. Therefore, in this work a conservative approach was adopted for the instantaneous and temporized overcurrent settings, which were adjusted to 3 pu (100ms) and 1.5 pu (1s), respectively. Figure 12 shows the resulting profile of the adjustments, indicating separately the actuating region of each protection device, for a grid with a short-circuit ratio, R_{SC} = 20, at the point of common coupling.

Nonetheless, it should be noticed that the limits adopted by the Brazilian SO are not yet fully met because they overlap the generator unstable operating region, at the bottom of the curve. The overcurrent protection settings should either have their limit values or their actuation times increased, so that a more adequate curve be obtained. However, such adjustments must, at most, lead the system to the reach the border of the dotted line region, since the generator loses its stability inside this region.

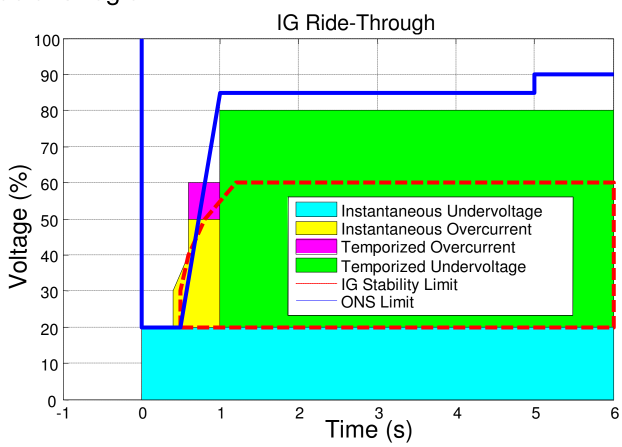

Figure 12 – Induction generator RTF capability curve (R_{SC}=20).

2) Synchronous Generator

Since the converters are independently controlled in the synchronous generator configuration, this technology offers better support under TVDs than induction generators. However, because of the converters current limitation, it cannot tolerate as high a current loading. Therefore, the protection settings must be more conservative than those for the induction generator.

In this case, the only protection settings that should be considered are the overcurrent and undervoltage ones. The undervoltage settings are again adjusted against the system operator guidelines and present the same values as the previous case.

As shown in the previous section, the current profile does not show peaks; therefore the instantaneous overcurrent setting is not too relevant, having been adjusted to 2 pu (100ms). The focus then turns to the temporized overcurrent protection settings.

During the more drastic voltage dips, the currents are kept at the limit imposed by the controller, which is 1.5 pu. Therefore, it is reasonable to set the temporized overcurrent setting to this limit. Given that the ONS curve shows a dip duration of 1 second, this value should suffice to meet the required profile while keeping the converter operating under acceptable conditions. Figure 13 shows the three areas which correspond to the set protection actuation regions.

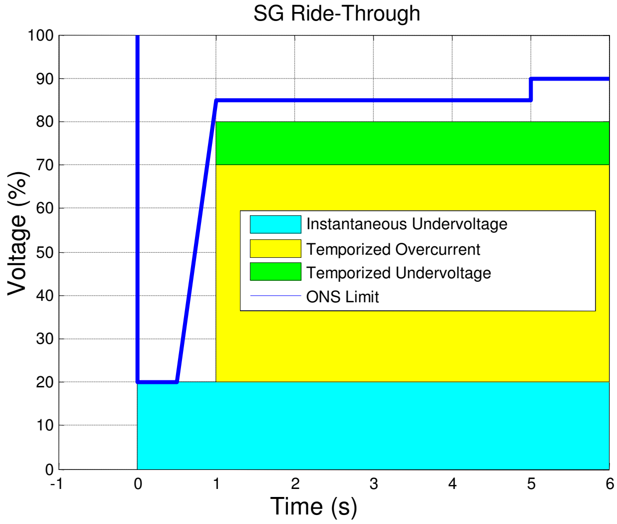

Figure 13 – Synchronous generator RTF capability curve (R_{SC}=20).

It is emphasised that the RTF capability of the system is highly dependent on the quality of the converters control loop. In the simulations it was noticed that, even with the controller imposed limits, the overcurrent protection would actuate at times, since the controller could not clamp the current at a specific limit value, due to the oscillations that would happen around this point.

It can be seen from Figure 13 that this is a more robust technology than the induction generator one, and that the limit profile is perfectly met. It is also possible, through slight changes in the amplitude and duration settings that the capability curve be modified as needed, since the security of the system is still maintained.

3) Doubly-fed Induction Generator

This turbine technology showed to be greatly affected during the TVD simulations. It could be noticed from the results that both stator and rotor overcurrent protection as well as the overspeed one are critical to its adequate performance. The instantaneous and temporised undervoltage protection system settings were adjusted in the same way as the previous cases.

In this configuration, the induction generator is allowed to vary its rotational speed within ±30% of the synchronous speed. Therefore, the overspeed protection was adjusted allowing a 20% excess on top of the generator normal operating speed, i.e. 1.56 pu.

The stator and rotor overcurrent settings had to be jointly adjusted, since stator currents are reflected on the rotor. The energy split between the stator and rotor circuits at rated power should also be considered, which in this case is 80% and 20%, respectively. Therefore, for safe operation of the converters, an instantaneous current limit of 50% of the rated value was adopted for the rotor, while the temporised protection was set to the converter defined limit, i.e. 35% of the rated current, for 1 second. The admissible stator overcurrent should not be too high so as to affect the rotor circuit, therefore the instantaneous and temporized stator current settings were respectively adjusted to 1.5 pu and 1 pu, with temporization set to 1 second. Figure 14 shows the different protection systems actuation regions.

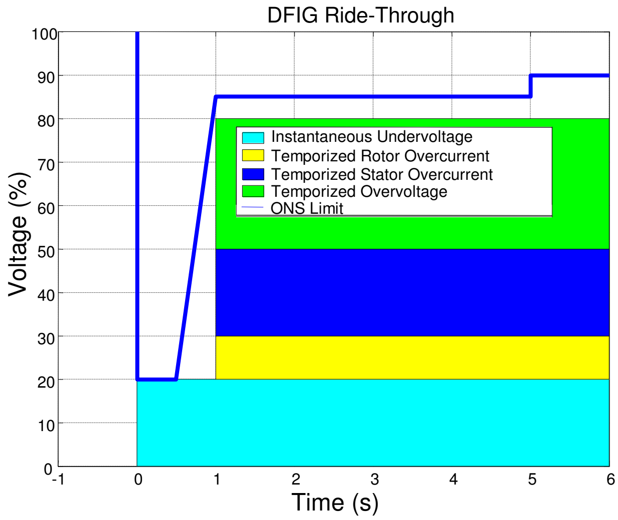

Figure 14 – Doubly-fed induction generator RTF capability curve (R_{SC}=20).

The DFIG showed to be as robust a technology as the SG, showing strong dependence on the control loop characteristics as well, since the rotor overcurrent protection would occasionally actuate during the more drastic dips due to the oscillations around the established limit value.

It was verified that the required ONS capability curve was met, and that by varying the timing and amplitudes of the settings, the curve profile could be changed as long as safe system operation was maintained. Despite the good LVRT performance, this technology is more affected than the SG, showing worse power quality indices during the voltage dips. Furthermore, the considerable increase in the generator speed and its slow recovery is prejudicial for the system operation. It is noted that the overspeed protection actuation region did not appear in Figure 14 because, for the settings used, the other protection systems actuated before considerable speeds were reached.

V. CONCLUSIONS

As part of a study sponsored by the Brazilian National System Operator (ONS), this work aimed at characterising the dynamic behaviour of three different wind turbine technologies and, from the results obtained, assessing the effect of the protection system settings on the wind power plants low voltage ride-through capability.

As expected, the excursion of the electromagnetic and mechanical variables is more severe for the fixed speed technology (induction generator). However, the system as whole is more robust and more tolerant to such variations. Due to the generator loss of stability issue, the protection system settings alone may not be able to ensure compliance to the LRVT capability profile proposed by the ONS under specific fault conditions. Furthermore, the requirement of an overspeed limitation mechanism during the fault, such as blade pitch control strategy is highlighted [10].

The variable speed technology using the synchronous generator tolerates smaller excursions of the electromagnetic variables, while showing little to no effect on the system mechanical dynamics. However, the system as a whole is more sensitive to overcurrents, being highly dependent on the control system characteristics. The adjustment of the protection system settings for compliance with the ONS grid code can be easily achieved, provided that the grid side converter presents a high enough current limit.

Finally, the DFIG system showed good LVRT capability characteristics, despite being severely affected during faults, during which the generation presents very low power quality indices. Furthermore, in order to operate adequately during faults, it is necessary to use additional protection devices, such as the chopper-crowbar combination [11].

The simulation results obtained provided fundamental understanding of the transient behaviour of three different wind turbine technologies in respect to their grid integration and LVRT capability characteristics. The importance of such results for the power system operator lies on the fact that they can help in the system operation and design as well as in the assessment and definition of grid code requirements, as in this case for the Brazilian National System Operator.

VI. ACKNOWLEDGEMENTS

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