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LOW VOLTAGE RIDE - THROUGH CAPABILITY OF WIND FARMS

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Abstract: Nowadays wind turbines are generally required to offer ancillary services similar to those provided by conventional generators. One of the most important services wind turbines must offer is to stay connected to the grid in fault situations delivering the reactive current specified in the recent grid codes. In this paper, FACTS solutions for fixed speed wind farms such as DVR (Dynamic Voltage Restorer) are presented as well as classic control and crowbar solutions for variable speed wind turbines.

Keyword: Wind Turbine, Generator, Grid, Facts, DVR, Crowbar.

I. INTRODUCTION

Wind energy is available and clean source of energy that has been used to generate electrical power. The focus on electrical power generated from wind energy has been noticeably increased due to the environmental problems that fossil fuels make. Global warming and greenhouse emissions are the main harmful results of fossil fuel consumption. United States wind power has been quickly spread and wind generation installed capacity for 2014 is increasing. It has reached approximately 50 (GW) of power according to the U.S Department of Energy (DOE) and the American Wind Energy Association (AWEA) and according to the report prepared by the U.S. Department of Energy with contributions from the National Renewable Energy Laboratory (NREL), the wind energy installed capacity by 2030 will be around 20% of the total capacity. Wind power integration to the grid has limitations and standards that have to be followed. Standards for wind integration to the grid are addressed in the Institute of Electrical and Electronics Engineers (IEEE), North American Electric Reliability Corporation (NERC) and by different utility companies.

Wind power integration to the grid has different difficulties and problems due to the variation of the wind speed which results in fluctuation of the wind generated power that leads to fluctuations in voltage and frequency. Grid faults also one of the problems that wind turbine control should take into consideration. Wind turbines should be properly controlled to overcome the grid faults that lead to voltage and frequency drop. It has to have a fault right through capabilities or as it is called voltage ride through to protect the turbine generator form accelerating and damaging mechanical part due to instability that increases vibration and stress on the mechanical parts like the speed conversion system (gear box). Generator acceleration also leads to over current and overvoltage in the DC bus of the electrical conversion system that makes the mechanical system unstable and might damage the electrical converter.

Several countries have achieved relatively high levels of wind power penetration as following in below table (Collection from Wikipedia). Some 80 percent of the global wind power market is now centered in just four countries - which reflect the failure of most other nations to adopt supportive renewable energy policies. Future market growth will depend in large measure on whether additional countries make way for renewable energy sources as they reform their electricity industries.

II. PHASE LOCKED LOOP (PLL)

Low Voltage Ride-Through capability (LVRT) is required by TSO's for connecting wind farms in power systems as it is defined in the main grid codes. Wind farms must remain connected and actively contribute to system stability during a wide range of network fault scenarios.

LVRT requirements differ according to the dynamic characteristics of the power system concerned. Smaller power systems, with little or no interconnection, are prone to frequency instability, and hence, their codes typically emphasize the provision of active power.

1.1 LVRT in fixed speed wind farms:

Fixed speed wind turbines were dominant in the 1990s. Until 1996 they represented 100% of the wind turbines installed in Spain. Today, they represent less than 20%. Fixed speed wind farms are composed of squirrel induction generators coupled directly to the grid. Consequently, the only ways to control them are either to adjust the pitch angle of the turbine blades and thereby their aerodynamic efficiency (C_p) or by varying the voltage applied to the stator.
The mechanical power input stays approximately constant during the voltage dip. However the torque developed by the stator decreases, since it is proportional to the applied voltage squared. As consequence, the energy not absorbed by the grid is accumulated as rotational kinetic energy in the turbine. Pitch control is considered when studying LVRT capability. Blade pitch actuators are powerful to fully pitch the blades within a fraction of a second when necessary. However it has to be taken into account that it is necessary to apply big dynamic forces. Consequently, blade pitch control is not the most convenient way to offer LVRT capabilities. Other alternative to avoid speed instability is to employ an active stall strategy. Once the fault is detected, the pitch is regulated toward a stall position in order to reduce aerodynamic torque.

The most commonly suggested LVRT-strategy for fixed speed wind farms is the application of FACTS devices such as: Static Var Compensators (SVC's), Static Synchronous Compensators (STATCOM's) or Dynamic Voltage Restorers (DVR's).

Here the application of Dynamic Voltage Restorer (DVR) for restoring the voltage level at the wind farm terminals under fault conditions is studied explaining its structure and control. It is important to notice that in this case DVR is protecting not a critical load but a critical source of power sensitive to voltage dips. Here, power flows in different direction.

1.2 Phase-Locked Loop (PLL)

The mentioned special devices for complying the grid codes such as DVR, STATCOM, DFIG (Doubly Fed Induction Generator) converters and any power electronic converter that manages reactive power actively, need all the information related with the synchronization of the input voltage angle.
In order to mitigate the voltage dip, it is not only needed its precise detection but also to track the phase angle of the fundamental AC voltage. This reference signal can be obtained by the Phase-Locked Loop (PLL). A PLL is a device for tracking periodic signals in order to obtain frequency characteristics. It should provide frequency value and phase of an input voltage.

A PLL is simply a servo system, which controls the phase of its output signal in such a way that the phase error between output phase and reference phase reduces to a minimum.

As it can be seen in Fig.2 that represents the functional block diagram of a PLL and according to, PLL contains three basic components:

- a phase detector (PD)
- a loop filter
- a voltage - controlled oscillator (VCO), whose frequency is controlled by an external voltage

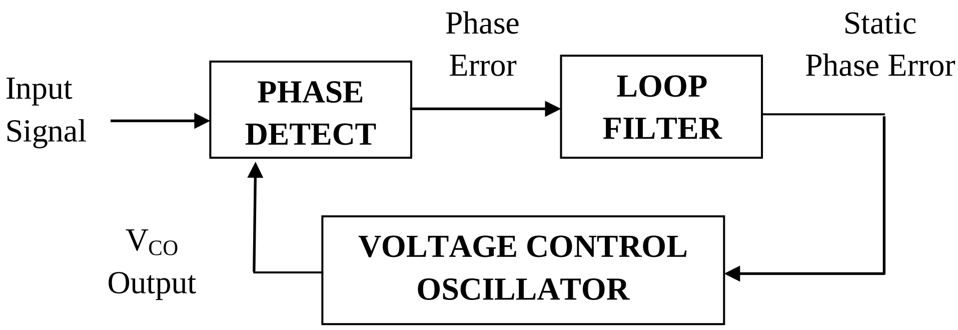

Figure 2: Block diagram of an analog PLL

III. DYNAMIC VOLTAGE RESTORER (DVR)

Dynamic voltage restorer is a Static Var device that has applications in a variety of transmission and distribution systems. It is a series compensation device, which protects sensitive electric load from power quality problems such as voltage sags, swells, unbalance and distortion through power electronic controllers that use voltage source converters (VSC). The first DVR was installed in North America in 1996 - a 12.47 kV system located in Anderson, South Carolina. Since then, DVRs have been applied to protect critical loads in utilities, semiconductor and food processing. Today, the dynamic voltage restorer is one of the most effective PQ devices in solving voltage sag problems.

The basic principle of the dynamic voltage restorer is to inject a voltage of required magnitude and frequency, so that it can restore the load side voltage to the desired amplitude and waveform even when the source voltage is unbalanced or distorted. Generally, it employs a gate turn off thyristor (GTO) solid state power electronic switches in a pulse width modulated (PWM) inverter structure. The DVR can generate or absorb independently controllable real and reactive power at the load side. In other words, the DVR is made of a solid state DC to AC switching power converter that injects a set of three phase AC output voltages in series and synchronism with the distribution line voltages.

Dynamic voltage restorer is a series connected device designed to maintain a constant RMS voltage across a sensitive load. The structure of DVR is shown in Fig.3.

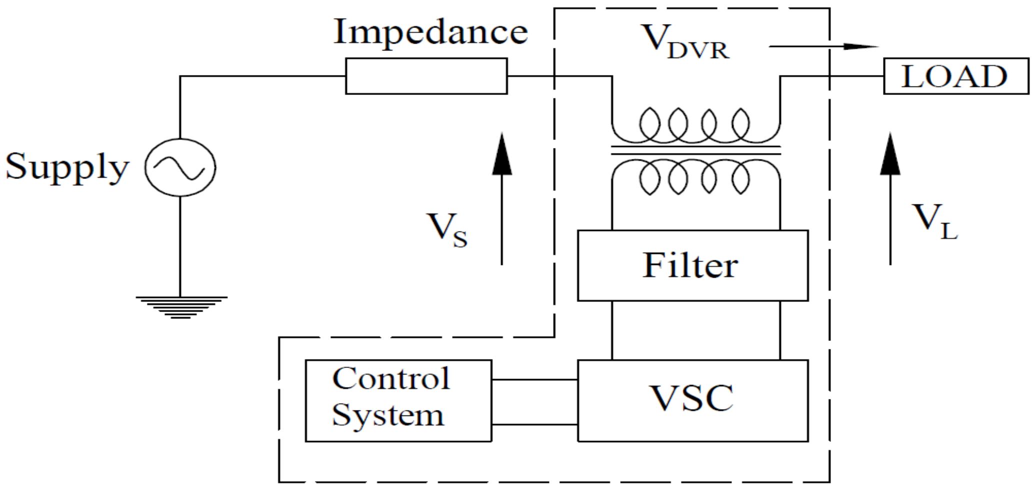

Figure 3: Schematic diagram of DVR

The DVR consists of:

a. ***Voltage Source Converter (VSC):*** Voltage Source Converter converts the dc voltage from the energy storage unit to a controllable three phase ac voltage. The inverter switches are normally fired using a sinusoidal Pulse Width Modulation scheme.

b. ***Injection Transformer:*** Injection transformers used in the DVR plays a crucial role in ensuring the maximum reliability and effectiveness of the restoration scheme. It is connected in series with the distribution feeder.

c. ***Passive Filters:*** Passive Filters are placed at the high voltage side of the DVR to filter the harmonics. These filters are placed at the high voltage side as placing the filters at the inverter side introduces phase angle shift which can disrupt the control algorithm.

d. ***Control system / Energy storage device:*** Examples of energy storage devices are dc capacitors, batteries, super-capacitors, superconducting magnetic energy Storage and flywheels. The capacity of energy storage device has a big impact on the compensation capability of the system. Compensation of real power is essential when large voltage sag occurs.

IV. BASIC OPERATION OF DFIG

The DFIG wind turbines use wound rotor induction generators, where the rotor winding is fed through a back-to-back variable frequency and amplitude PWM converter. The variable frequency rotor voltage permits the adjustment of the rotor speed to match the optimum operating point at any practical wind speed. The variable frequency converter consists of a rotor side converter (RSC) and a grid side converter (GSC) and only handles rotor power. Consequently the control of the machine can be carried out with a converter that is sized for a power around 25%-30% of the rated power of the turbine. As compared to variable speed turbines that use full power converter connected to the stator, the converter of the DFIG is lower cost and lower sized. The main objective of the RSC is to control the DFIG stator active power, speed and reactive power. While the GSC keeps the voltage of DC link constant.

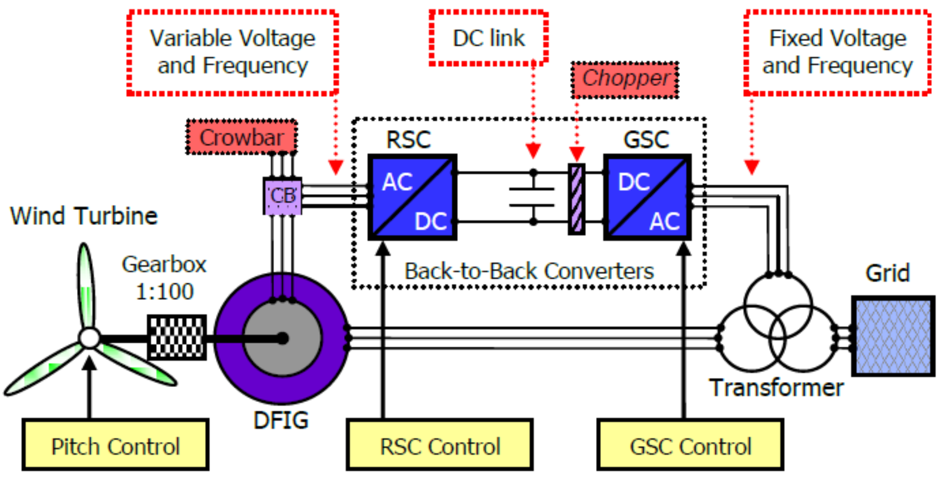

Figure 5: Basic operation of DFIG

A DFIG system is essentially a wound rotor induction generator with slip rings, the stator directly connected to the grid and the rotor interfaced through a back-to-back partial scale power converter. The DFIG is doubly fed by means that the voltage on the stator is applied from the grid and the voltage on the rotor is induced by the power converter. The converter consists of two conventional voltage source converters (rotor-side converter RSC and grid-side converter GSC) and a common link DC-bus, as illustrated in Fig. 5.

It contains two protection circuits, a DC-chopper and an AC-crowbar to avoid DC-link over-voltages during grid faults. The chopper module is not essential for fault ride-through operation but it increases the normal range of DFIG operation by smoothing the DC-link voltage during heavy imbalances of active power on rotor- and line-side converter. Theoretically converters and choppers could be designed to withstand even terminal short-circuits but economic considerations normally limit to a lower rating.

Following deep voltage sags caused by grid short circuits the rotor currents and thus the RSC currents rise rapidly. The DC short circuit component on the stator side appears on the rotor side as an alternating current with high initial peak. When the current exceeds a certain limit the IGBTs will be stopped to protect the converter but the current and thus the energy continues to flow into the DC-link through the freewheeling diodes leading to fast voltage increase. To keep the DC voltage below the upper threshold first the chopper is switched on by IGBT switches. Depending on the level of energy flow into the DC link and the chopper design this measure may be successful in most cases. When the DC voltage is maintained by the chopper the RSC goes back into operation following a few milliseconds and the DFIG can be controlled again even if it is operating on a low voltage level. However, in extreme situations the DC voltage may increase further. As the next line of protection the crowbar is fired and the rotor is short-circuited. The crowbar firing is triggered by the DC-voltage. The characteristic operating modes of the RSC and the crowbar during FRT are shown in Fig. 6. When the crowbar is switched on the wind turbine operates as a slip-ring asynchronous machine. After a short transient period the machine becomes a reactive power consumer which is counterproductive in respect of the grid voltage support as required by the grid codes. However, the crowbar is switched on only for a time period of 60-120 ms, because the crowbar thyristor switches used in many applications will not interrupt the currents before their zero-crossing, the exact interruption time is not predictable. Therefore, between crowbar interruption and RSC resynchronization a possible time slot with open rotor circuits characterized as mode 3 in Fig.6 can exist.

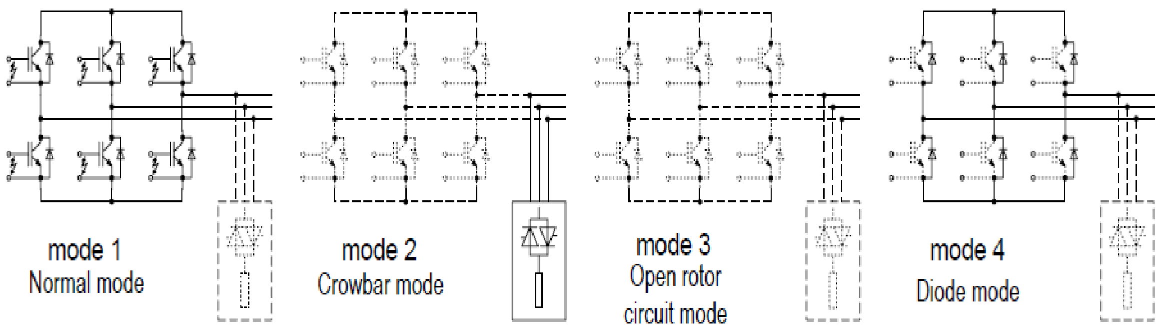

Figure 6: Operation modes of DFIG Converter during FRT

V. DFIG CROWBAR SCHEME

The function of the conventional crowbar protection system when a short circuit occurred the RSC is disabled and bypassed , at the same time external resistors is coupled via the slip rings to the rotor winding instead of the converter as shown in Fig. 7, so the controllability of active and reactive power gets unfortunately lost.

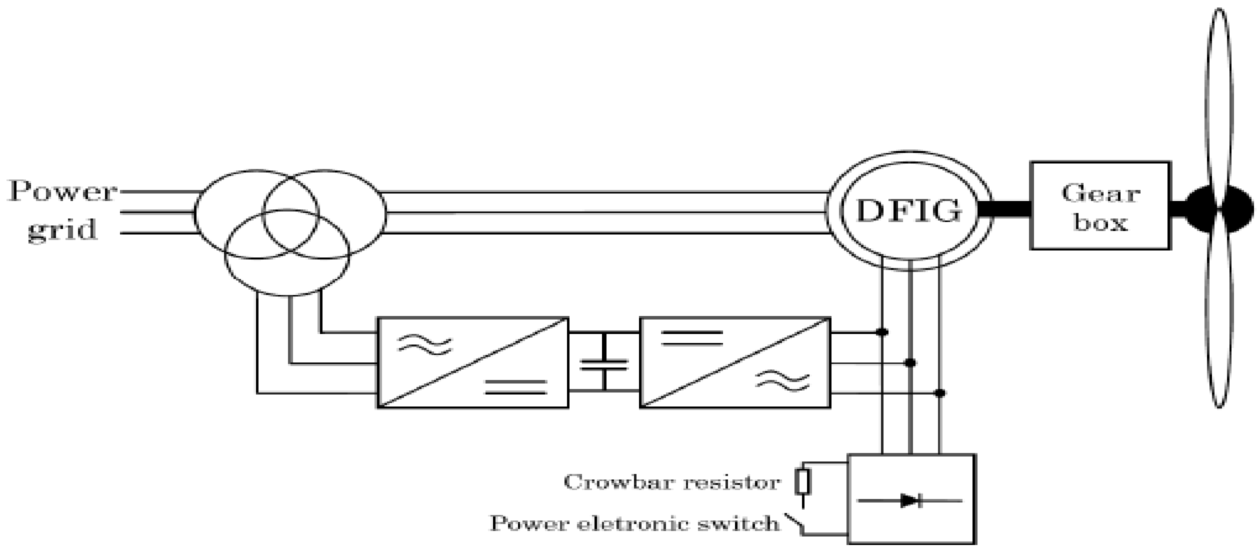

Figure 7: DFIG crowbar scheme

The crowbar implemented in the DFIG model has been presented in figure 6. It consists of a diode bridge and a controlled crowbar resistor, able to be connected with a power electronic switch. During the voltage dip situation, the high rotor currents will be diverted through the crowbar protecting the rotor side converter. While crowbar is working, DFIG is acting as a squirrel cage induction generator. In this section the effect of the crowbar resistance on rotor currents is analyzed, see Fig. 8. It is proven how high values of crowbar resistance damp rotor currents more than low values. On the other hand, electromagnetic torque will fluctuate more as long as the crowbar resistance decreases.

The crowbar system used in modern wind turbines is based on a three-phase series resistance controlled by power electronics. The crowbar system is activated during over-current on the rotor windings or/and over-voltage on the DC link. Most of the time, these atypical values appear after a short circuit close to the wind farm. The steps involved during the activation and the deactivation of the crowbar system by the circuit breakers (CB) are summarized:

- Disconnection of the rotor windings from the RSC.
- Insertion of the three-phase resistance in series to the rotor windings.
- Disconnection of the crowbar system from the rotor windings.
- Reconnection of the RSC to the rotor windings.

If the voltage at the DC link or/and the current at the rotor windings are at a normal levels, the operation returns to its normal, however, if not, the activation of the crowbar system can be restarted (the second activation is undesirable). Considering more restrictive grid codes, the use of DC-Chopper system in the DC-link is also recommended to avoid the reinsertion of the crowbar system to enable the reestablishment of the terminal voltage control by the RSC. The DC-Chopper is a thyristor controlled resistance, in which the unbalance of electrical power injection into the power system by the GSC and the electrical power injected into the DC-link by the RSC is dissipated.

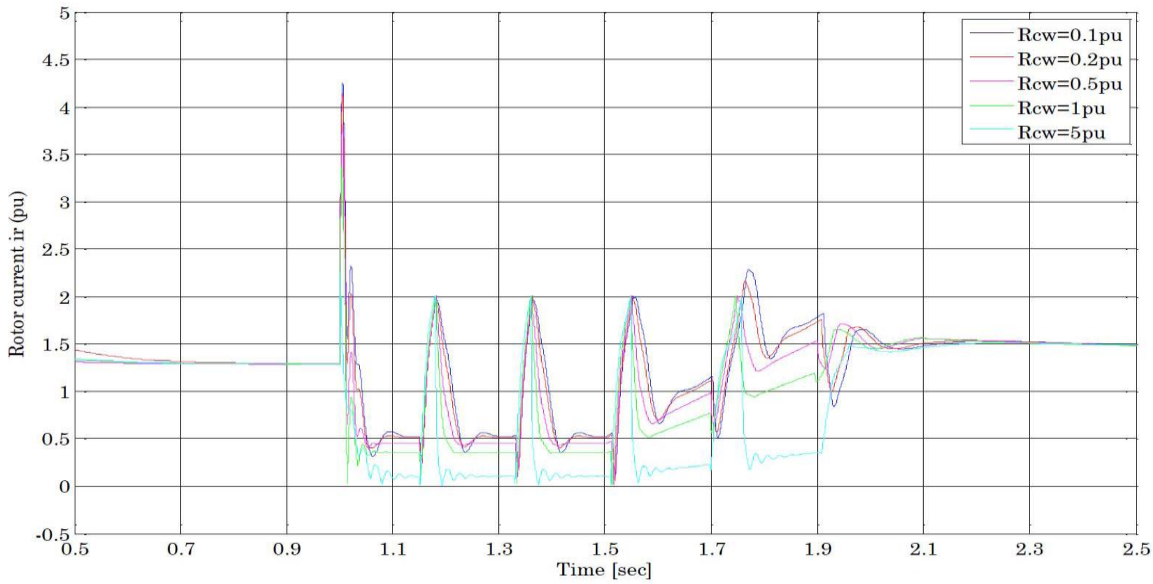

Figure 8: Rotor currents with different crowbars applied

The crowbar resistance values are referred to the rotor resistance of the laboratory machine. Hence, 1 p.u. equals 1.8 Ω. During the recovery of the voltage, it can be seen that the higher value of the crowbar resistance, the bigger variation of the rotor current. The reason is simple: when high value of the crowbar resistance is used, rotor currents are small in comparison when lower crowbar resistances are used. Once the crowbar is disconnected, the machine control has to re-assume DFIG control. In this situation, if rotor currents are very low due to high crowbar resistances, the machine control will try to recover the set point by increasing rotor currents. In any case, it can be seen how currents rise in the moment of the crowbar activation. This increasing on the current value is lower than without crowbar, and the rotor can withstand currents slightly higher than the nominal for a short time due to its relatively large thermal constant.

The effect of the crowbar resistance on the electromagnetic torque must be analyzed as well. Fig. 9 shows how the fluctuation of the electromagnetic torque depends also on the crowbar resistance.

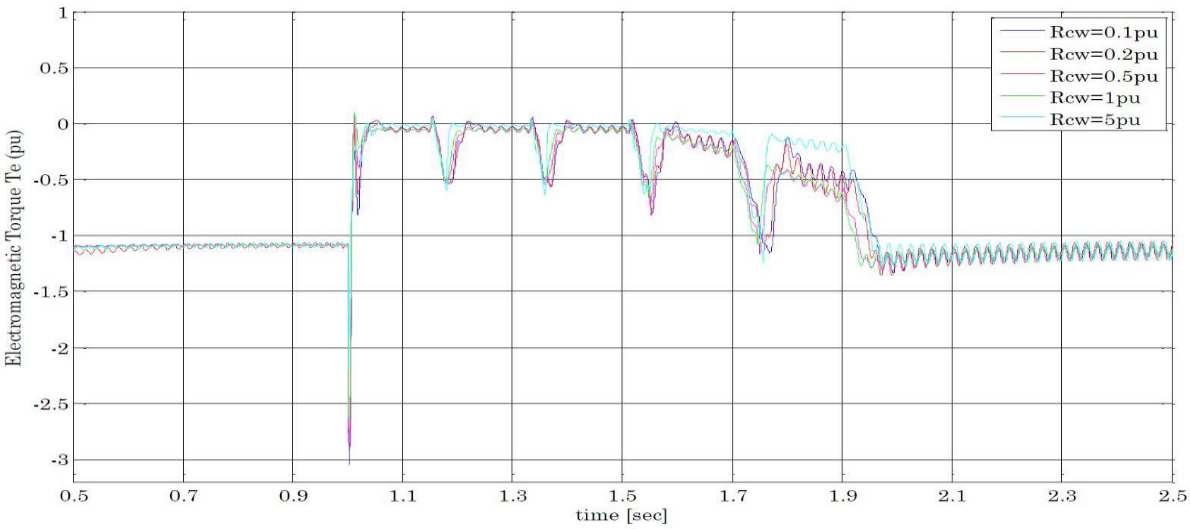

Figure 9: Electromagnetic torque with different crowbars applied

Torque fluctuations are more noticeable for low crowbar resistances but the difference is not significant. Thus, the main design factor will be the current waveform. Considering the previously exposed facts and the obtained results, the crowbar resistor is set to a value of 1 p.u. By setting the crowbar resistor to 1 p.u, the comparison between different locking times is presented. The chosen values have been 150 ms in one case.

Note that, as it was introduced above, some control actions must be taken for the reconnection of the RSC. In this case, the reference signals for the active and reactive power during the voltage dip are set to the instantaneous actual value. When the crowbar is released, the reference signals are slowly directed to the original set point. In figures 10, 11 and 12 the results are shown.

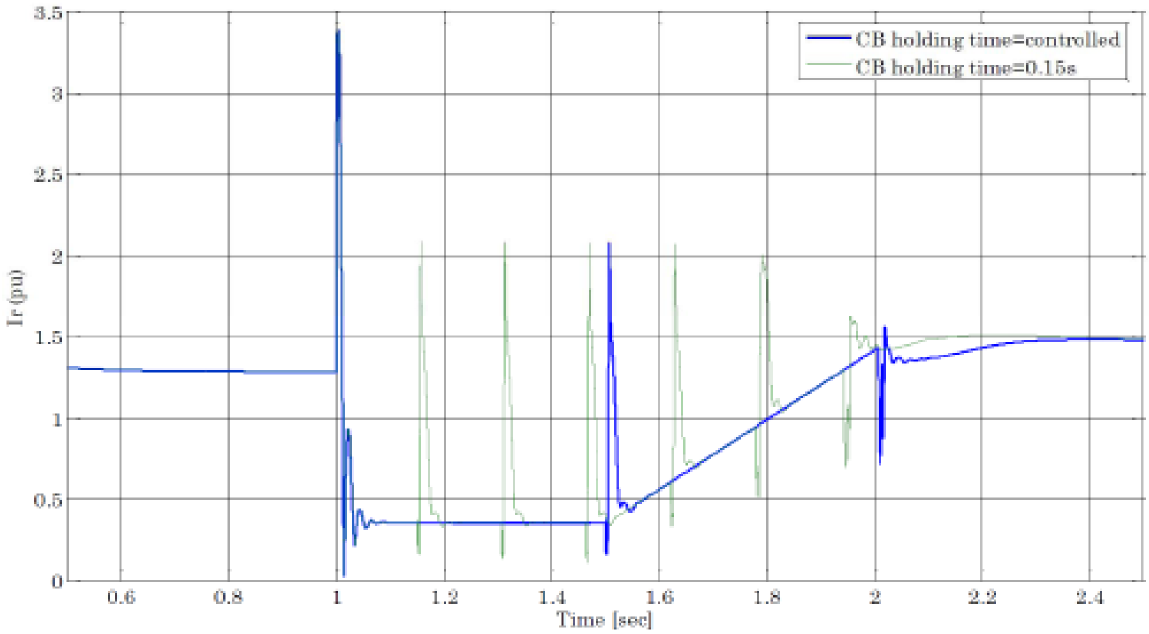

Figure 10: Rotor current with different crowbar locking-times

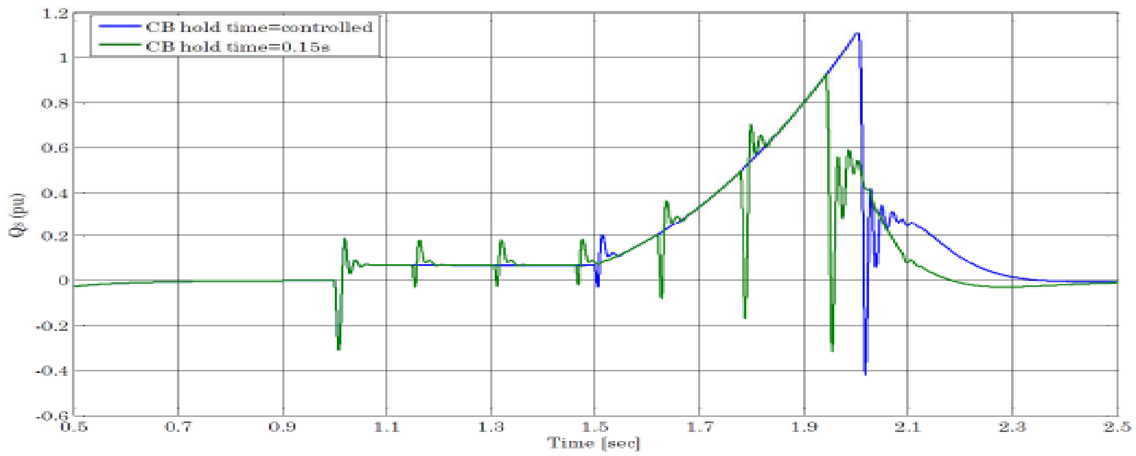

Figure 11: Reactive power with different crowbar locking-times

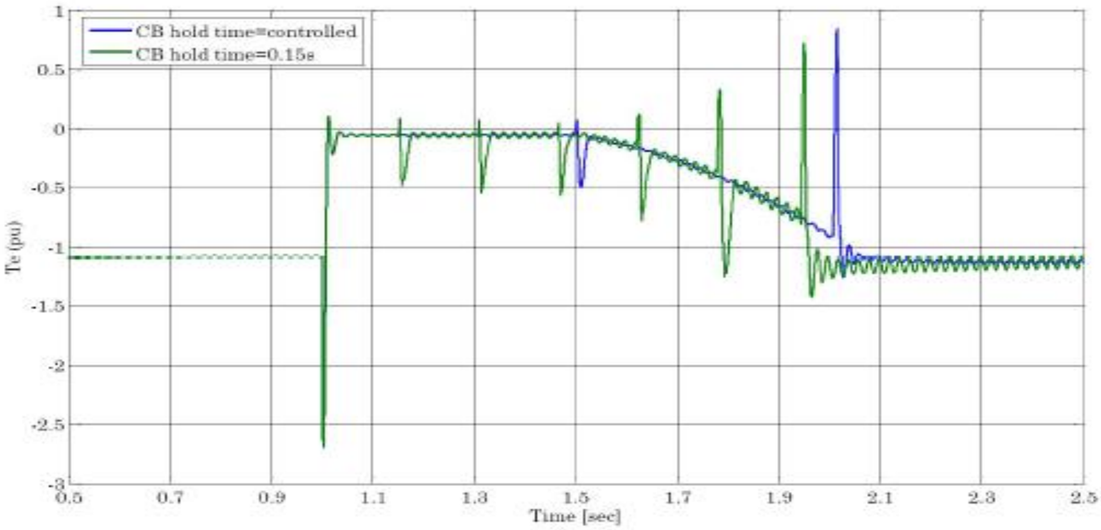

Figure 12: Electromagnetic torque with different crowbar locking-times

VI. CONCLUSION

Wind turbines must participate in the increase of power system stability. One of the most important facts is their ability to withstand voltage dips. Fixed Speed wind turbines do not fulfill the grid codes by themselves. FACTS devices such as DVR are needed in this task. Variable Speed Wind Turbines are more flexible offer in reactive power control. In this seminar, it has been shown how crowbar devices act when facing voltage dips.

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