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Reactive Power Control of Direct Drive Synchronous Generators to Enhance the Low Voltage Ride-Through Capability

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1. Introduction

The development of wind power generation has grown considerably during the last years. The use of wind generators forming groups denominated wind farms, operating together with conventional sources of energy in weak grids has also increased [1]. The increased penetration of wind energy into the power system over the last few years is directly reflected in the requirements for grid connection of wind turbines. These codes are becoming more and more demanding, requiring wind farms to behave more and more as conventional power plants in the power system. Therefore it is essential to analyze the characteristics of wind generators during the network disturbances [2].

Currently, most of the grid requirements address low voltage ride-through (LVRT) and grid support capabilities of the wind generators. The LVRT requirement specifies that wind generators need to remain connected to the grid when an abnormal grid voltage is detected (e.g. during short-circuit faults). The grid support capability specifies wind generators to assist the power system by supplying ancillary services, such as voltage control, to assure a safe and reliable grid operation. Power electronics based solutions for grid interfacing of wind turbines seem to be a very promising technology that can cope with these grid requirements.

The configurations of variable speed wind generation that employ direct drive synchronous generators with permanent magnet and rotor field excitation, present noticeable advantages such as the decoupled control of the generators active and reactive power, the improvement of system efficiency and the fact that the machine stator frequency is decoupled from the grid frequency. The stator converter uses a high frequency switching PWM converter to achieve high control performance with low harmonic distortion, [3].

Due to those aspects in a worldwide basis and specifically in Brazil, there is a trend to install a large amount of wind power based on that technology. The interaction with the grid becomes increasingly important then. This can be understood as follows. When all wind generators would be disconnected in case of a grid failure, these renewable generators will—unlike conventional power plants—not be able to support the voltage and the grid frequency during and immediately following the grid failure. This would cause major problems for the system stability [3].

With the perspective of integration of more wind parks in Brazil the Grid National Operator (ONS) already has set requirements for the behavior of the wind generators protection. Instead of disconnecting them from the grid, the wind generators should be able to follow the characteristic shown in Fig. 1.

Only when the grid voltage goes below the curve (in duration or voltage level), the wind generators is allowed to disconnect. When the voltage is in the gray area, the wind generators should supply reactive power. In this paper a method is proposed that makes it possible for wind generators using direct drive synchronous generators to stay connected to the grid during faults.

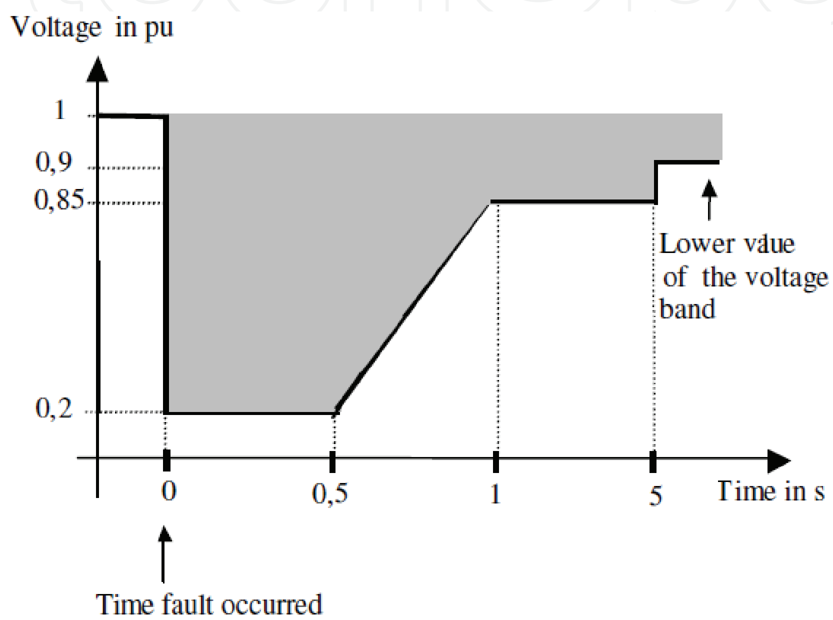

Fig. 1. ONS Requirements for Wind Parks Behaviour during Faults.

The main attention of the chapter is focused on the control strategies of the grid-side converter to provide reactive power support in case of grid disturbances. This control strategy can improve the voltage level during the fault and also contribute to the LVRT requirement.

For strong grids there is a decoupling between the active and reactive powers. Thus the total reactive power injection during a fault is a good solution for this control strategy without to compromissing the power system transient stability. However if the wind farm is connected to a weak electrical grid (i.e. voltage and frequency fluctuations conditions), there may be some power surge problems due to technical constraints related to the weak grid. In this case the proposed control strategy is based in the reactive injection curve defined by the grid code requirement improving the power system transient stability.

In this chapter, a variable speed wind turbine with a power electronic interface (a full power converter system) is considered. It is assumed that the wind turbines are equipped with a voltage dip ride-through facility and have a rapid current controller. Based on these assumptions, the wind park is modeled as a current injection source with current limitation determined by the converter capacity constraint. A similar approach of modeling a wind park was also adopted in [4] and [5]. The reference current is generated in accordance with the E.ON grid code which is then injected into the grid.

2. Grid requirements and fault ride-through capability

For this study, a set of minimum technical requirements concerning the installation of new wind farm was defined. The interconnection requirements, active and reactive power control and fault ride-through capability are based on the E.ON grid codes and ONS requirements.

The Wind Farm covered by the ONS requirements should present Fault Ride Through Capability in order to stay connected to the grid if during and in the moments subsequent to a fault or system disturbance the wind farm terminal voltage is above the value defined in the Time-Voltage characteristic curve presented in Fig. 1. Below the line, the wind park is allowed to trip.

For OEN grid code, it is required that during voltage dips a demand of reactive power injection must follow a specified curve. This requirement, besides improving the voltage levels in the electric grid in a defect condition, allows the wind park not to be removed of the system by the trip of the under voltage relay, increasing the ride-through capacity.

The generating plants must support the grid voltage with additional reactive current during a voltage dip. To do this, the voltage control must be activated as shown in Fig. 2 in the event of a voltage dip of more than 10% of the rms generator voltage. The voltage control must take place within 20 ms after fault recognition by providing a reactive current on the voltage side of the generator transformer amounting to at least 2% of the rated current for each percent of the voltage dip. A reactive power output of at least 100% of the rated current must be possible if necessary [EON]. The reactive injection curve is generated in accordance with the E.ON grid code as shown in Fig 2.

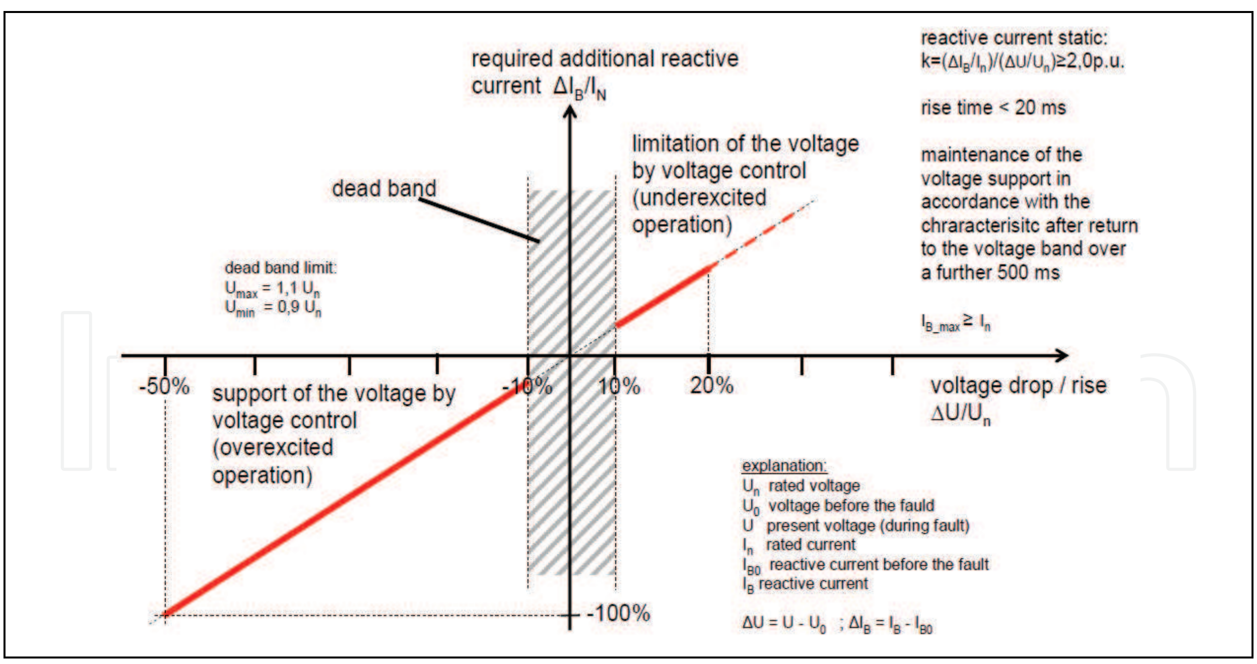

Fig. 2. The Principle of Voltage Support in Event of Grid Faults

When the voltage dip goes larger than 10% of the rated generator voltage the control action should act 20 ms after the identification of the fault, supplying reactive current on the low voltage side of the generator transformer at least 2% of the nominal current for each 1% of voltage dip.

3. Direct drive PMSG wind generators and controls

3.1 Modeling assumptions

The first stage in the simulation process is to model individual system components with an appropriate degree of complexity. The structure of the direct drive PMSG wind power system is shown in Fig. 3, in which the generator-side converter is a diode rectifier, the grid-side converter is a Pulse Width Modulation (PWM) inverter used to sustain the dc-bus voltage and regulate the grid-side power factor controlled independently through the decoupled d-q vector control approach for modern PMSG wind generators designs. The DC-link created by the capacitor in the middle decouples the operation of the two converters, as shown in Fig. 3.

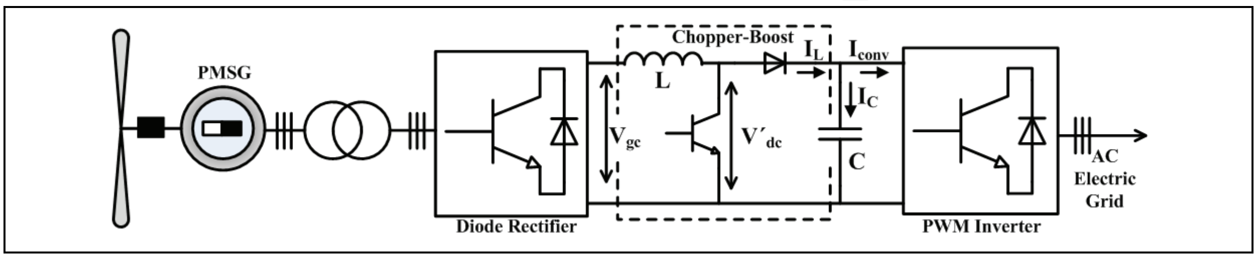

Fig. 3. Configuration of a PMSG Wind Generators

It has been demonstrated that the PMSG speed changes during voltage dips are negligible [6]. This is because the power supply to the DC circuit from the machine-side converter is approximately constant. So in terms of the grid connecting point (PCC) results, the PMSG mechanical behavior is not particularly relevant. So the model of the PMSG and the machine-side converter, can be omitted. A constant DC power current source can be used to represent these instead (thus neglecting the machine side power fluctuations), and the simulation results at the PCC will not be greatly compromised [6].

3.2 Simplified model

The model introduced in this section is a simplification of the model used in the previous section. In this model, the DC link voltage is controlled with a boost-chopper. The grid-side inverter is controlling the reactive power as usual. Fig. 4 shows the structure of this simplified model with the modified grid-side inverter controller.

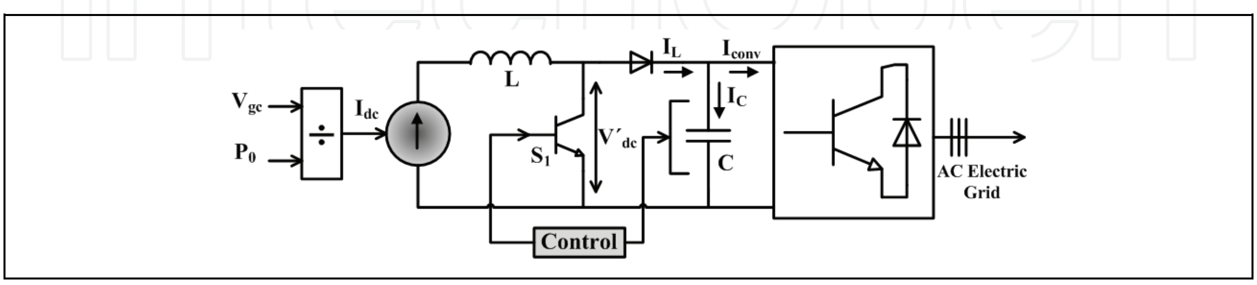

Fig. 4. Structure of the Simplified Model

In Fig. 4, P_0 represents the initial active power at the beginning of the simulation, based on the assumption of constant wind speed (wind power) in the wind farm during the short simulation time frame.

4. Models of the converters

Wind generators based on synchronous machines are connected to the electrical grid through static converters as illustrated previously in Fig. 3. In these cases it is required to model both converters, that is, the converter connected to the electrical grid and the one connected to the generator stator, which are both self-commutated PWM converters.

4.1 The grid-side converters models

The grid side converter as showed in Fig. 5 is controlled using a synchronous reference frame. The active part of the complex current becomes Iq and the reactive part is Id. The ouput power of the converter may be written as:

$$S = P_s + jQ_s = V_q\left(I_q - jI_d\right) \tag{1}$$

The converter terminal voltage, V´, is defined as:

$$V' = \frac{\sqrt{3}}{2\sqrt{2}} m V_{DC} \tag{2}$$

The pulse-width modulation index m is the control variable of the PWM converter. Equation (2) is valid for $0 \leq m < 1$.

Reactive power is controlled directly by the reactive current Iq. If the converter is to operate with unity power factor, the reference for the reactive current must be set equal to zero. The output signals in the converter model are the pulse modulation.

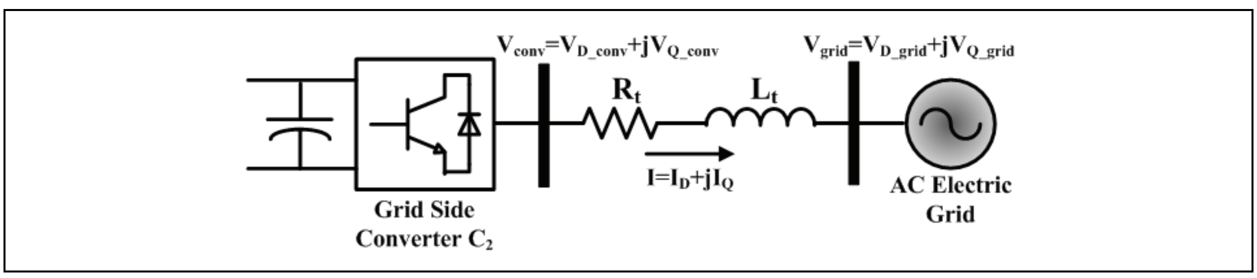

Fig. 5. Grid-Side Converter Schematic

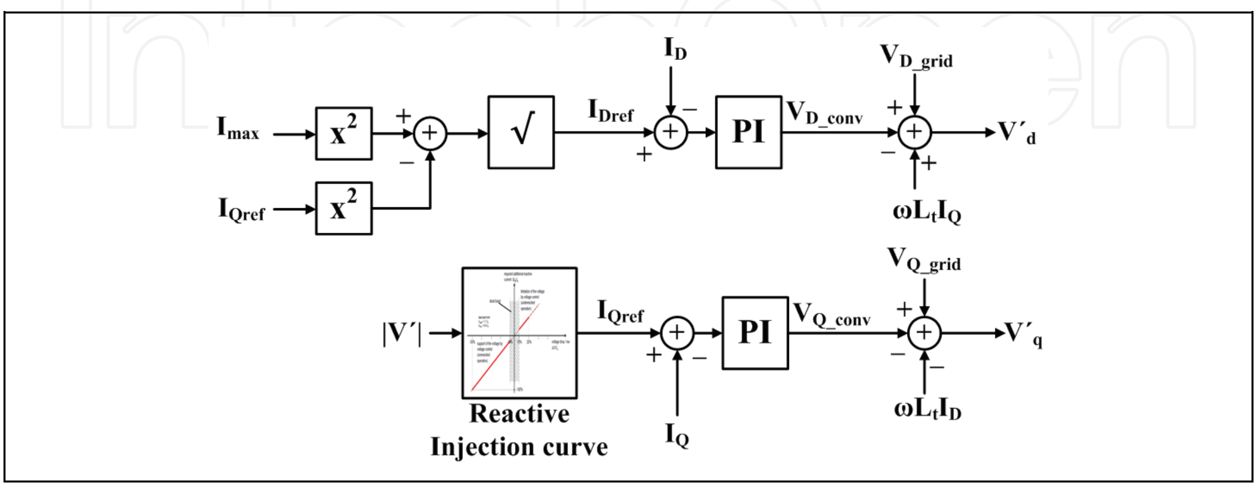

Fig. 6. Control Loop for the Grid-Side Converter

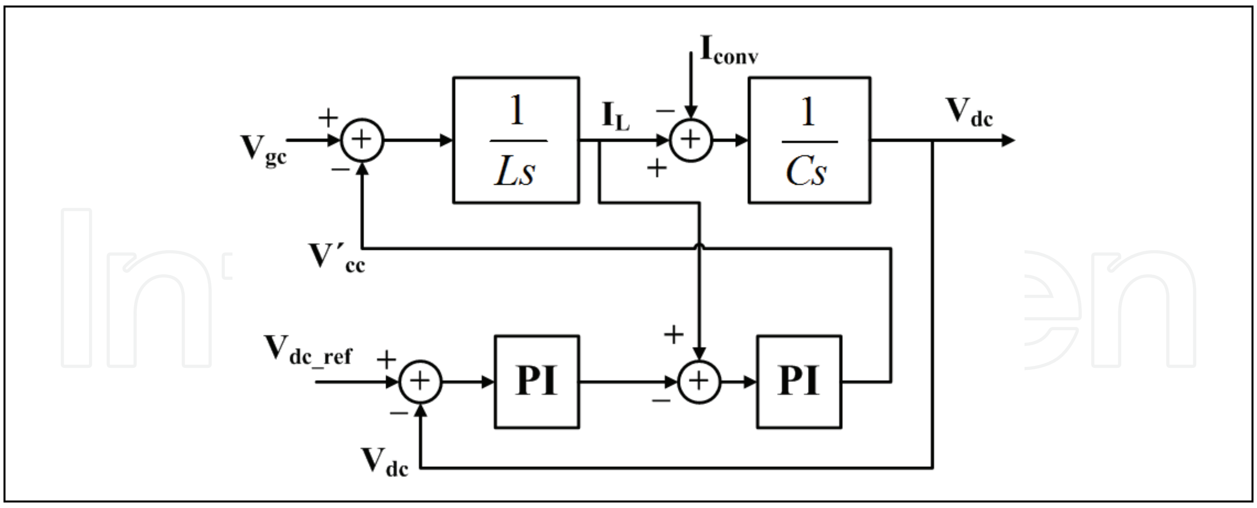

Fig. 7. Control Loop for the DC-Link Voltage

5. The sample power system

The electrical network used as a basis for this investigation is similar to that in [7]. For this system, a wind park is planned to be installed at bus 2 as illustrated in Fig. 8. The wind park to be connected is considered in this study as a dynamic equivalent, this way, an equivalent wind generator of 16MW and 400 V is considered. Each machine has a rated capacity of 2 MW and is designed to operate with rated terminal voltage of 400 V. The wind park is to be connected to the distribution electrical grid by 0.4/13.8 kV transformers. Besides the wind farm generation, two conventional diesel electric plants of 75 MVA and 36 MVA respectively connected to buses 1 and 3 are rated to supply the electric load of this system.

The model parameters of the speed and voltage regulators and synchronous generators of the diesel units were obtained from [9] and [10]. The equivalent automatic voltage regulator used is an IEEE Type 1 model. The equivalent primary machine of the synchronous generator and its speed governor are first-order models with proportional/integral frequency control [11], [12].

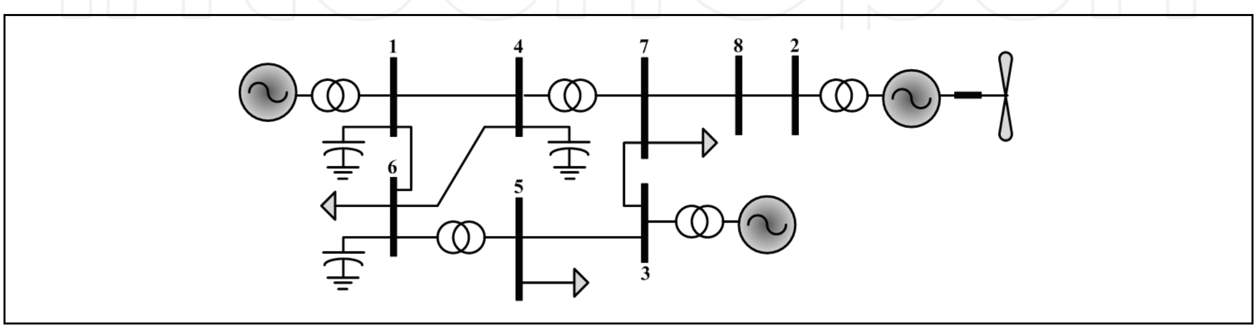

Fig. 8. Electrical Grid with Wind and Diesel Generation

6. Results

The simulation studies were performed considering a new operational practice that recommends to keep the wind generators in operation even during the fault period. The evaluation of reactive power injection during the fault will be performed on two conditions: the first is the adopted by Brazilian grid code which does not require the reactive power injection. The second injects reactive power following the EON curve.

6.1 Case I

The wind park generation at bus 2 was simulated using the full capacity of the park at 2 MW rated power on each synchronous generator. The short circuit was located near bus 1, starting at t = 1s, and lasting for 500 ms.

Fig. 9 shows the voltage profile on PCC during the fault period. It is observed that voltage dip is below the minimum of the ONS curve adopted in Brazil, consequently in this case the wind park is disconnect of the grid due the under voltage relay trip. For this case the voltage at the PCC does not return to nominal value due to instability problem on the system. The system transient stability was also affected due to wind park to be disconnected as shown in Fig. 10.

With the adoption of the reactive injection criteria it is observed that the voltage profile is over the limit of the ONS curve. Thus the wind park is maintained connected to the grid increasing the ride-through capacity.

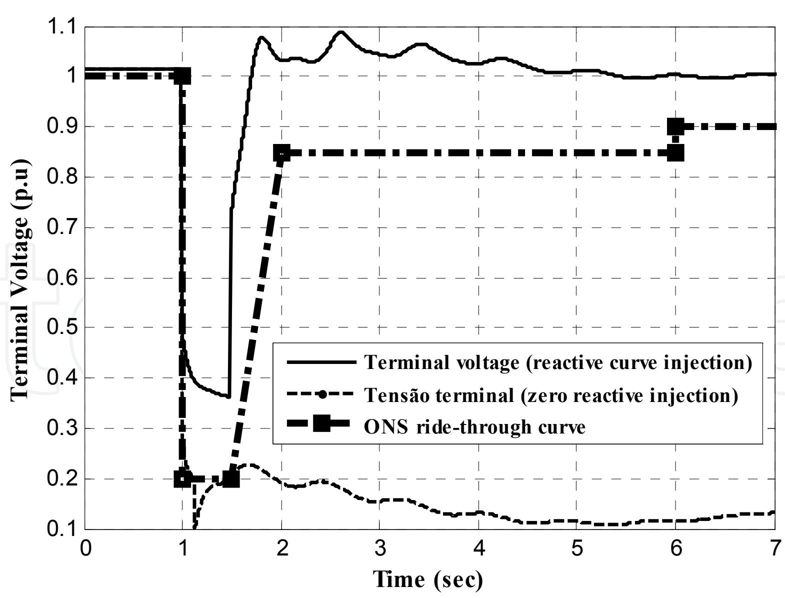

Fig. 9. Voltage Behaviour at PCC

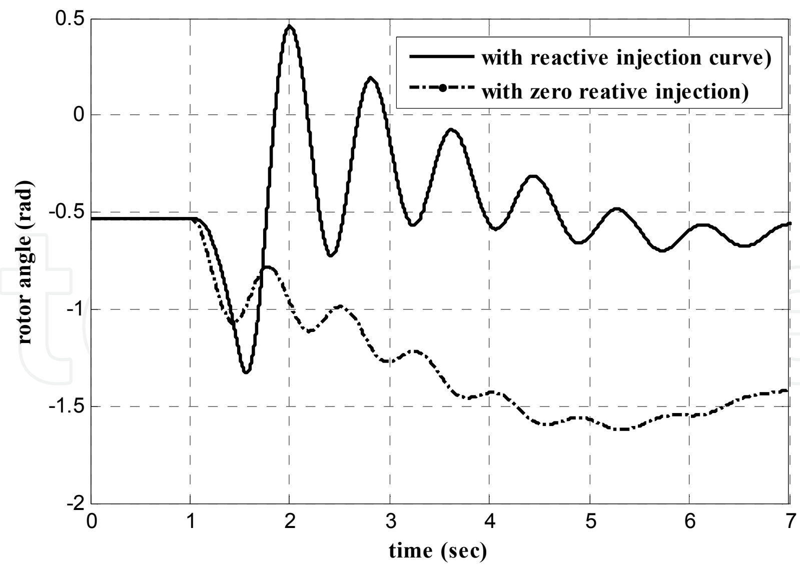

Fig. 10. Rotor Angle of the Synchronous Generator at bus 1.

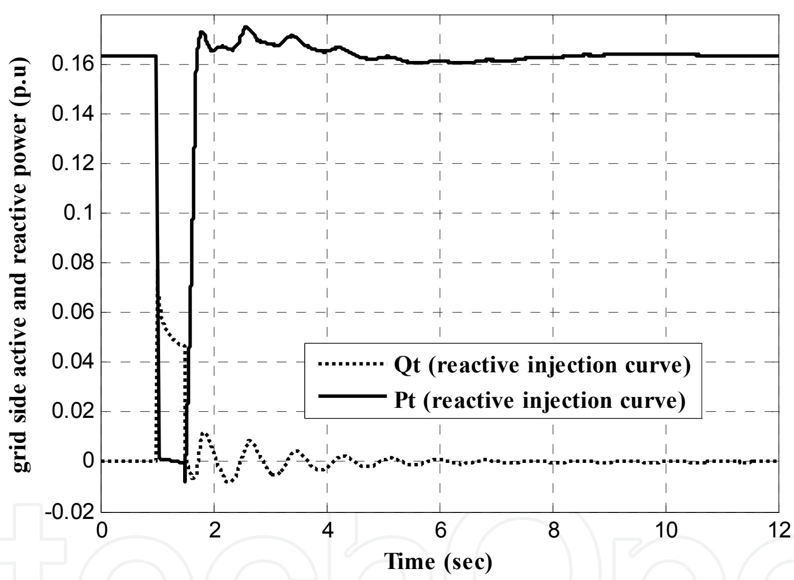

Fig. 11. Reactive and Active Power at PCC

6.2 Case II

The wind park generation at bus 6 was simulated using the full capacity of the wind park at 2 MW rated power on each synchronous generator. The short circuit was located near bus 6, starting at t = 1s, and lasting for 200 ms. Fig. 12 shows the voltage profile on PCC during the fault period. It is observed that the voltage dip is 0.65 p.u for the case of zero reactive injection, whereas for the case of following the reactive power injection curve the voltage dip is 0.8 p.u. and the reactive current support is provided within 20 ms after the fault detection in accordance with the E.ON regulation requirement. Thus the reactive power injection curve improves voltage profile and the ride-through capability.

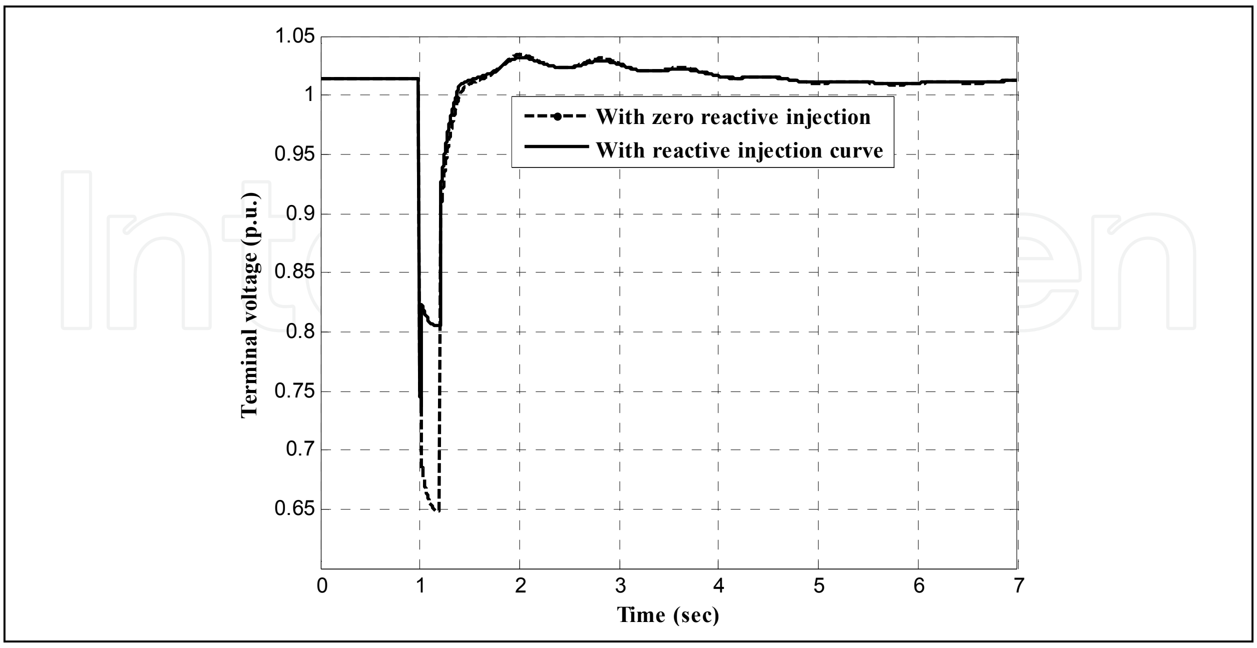

Fig. 12. Voltage Behaviour at PCC

Fig. 13 shows the converter reactive power which follows the reactive injection curve during the fault, improving the voltage profile as shown in Fig. 12.
The E.ON grid code requirements allow the active power injection by the converter when the voltage dip is above 0.5 p.u. as shown in Fig. 14. It is also observed after fault cleaning time a power injection ramp until the reference power. This method increases the transient stability margin as shown in Fig. 15, in which it is observed a small rotor angle oscillation with the reactive power injection curve.

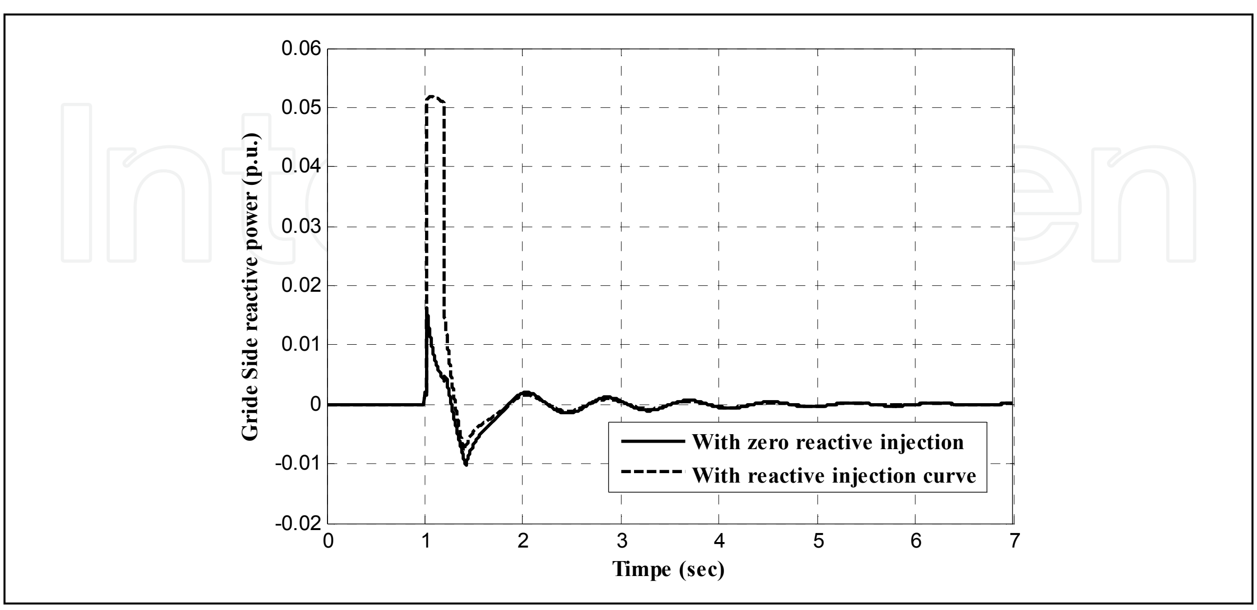

Fig. 13. Reactive Power at PCC

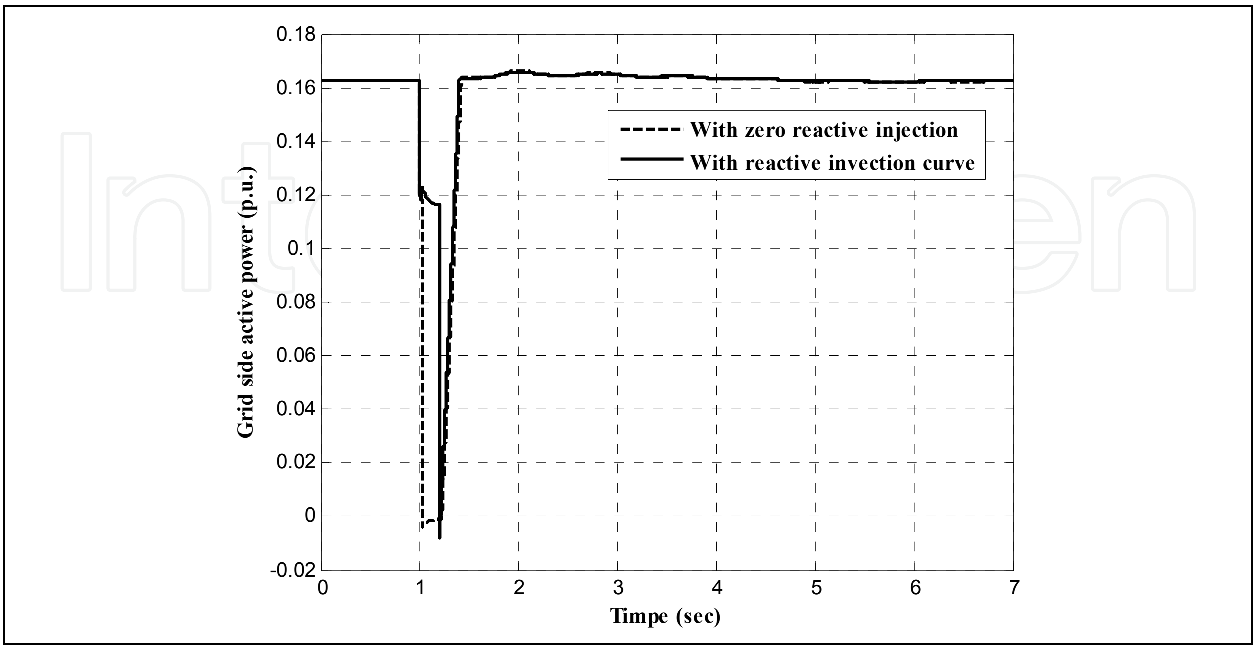

Fig. 14. Active Power at PCC

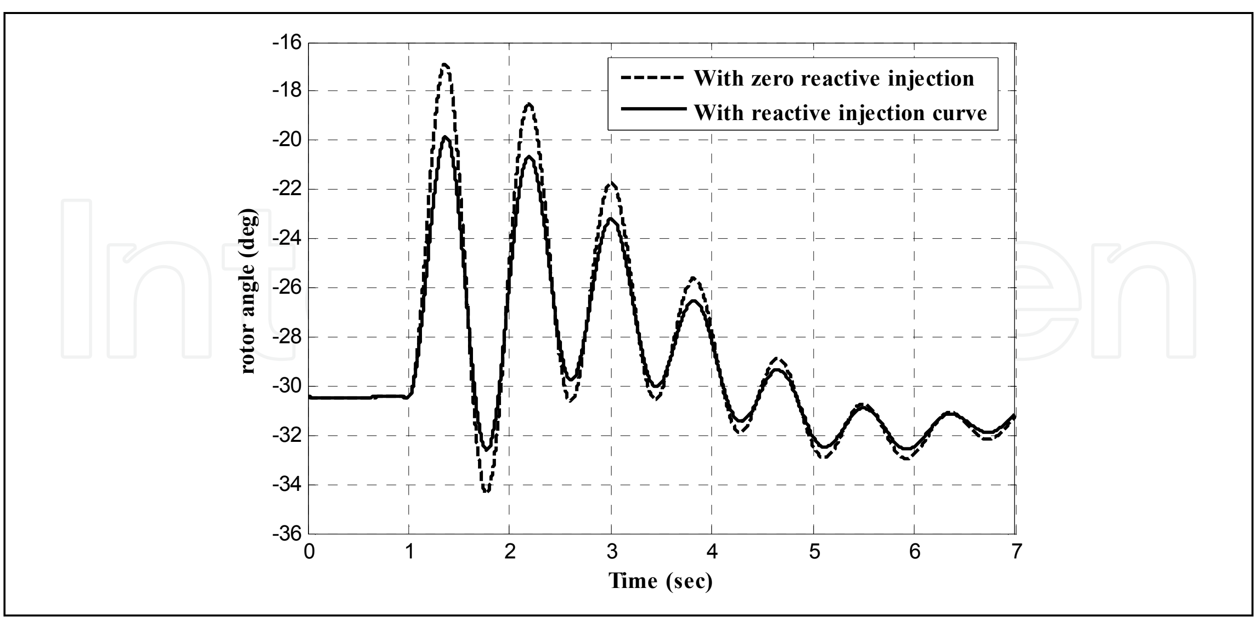

Fig. 15. Rotor Angle of the Synchronous Generator at Bus 1

7. Conclusion

In this chapter, it was explored the performance of alternative voltage control strategies applied to direct drive synchronous wind generators, more specifically with permanent magnetic (PMSG). The reactive power control of the grid-side converter is investigated for voltages purposes. The E.ON fault response code for wind farms is taken as the base case for the study. The simulated results presented in this chapter have considered that the proposed operational procedure has kept running during the fault period (ride-through capability) the wind generators, and also offers the possibility to supply reactive power during the voltage dip in order to facilitate voltage restoration. This is possible with the control of the grid side converter. The results have demonstrated that the consequence of this new approach is positive in the sense of maintaining transient voltage and rotor angle stability, once a variable speed wind generator technology, as direct drive synchronous generator is used.

8. References

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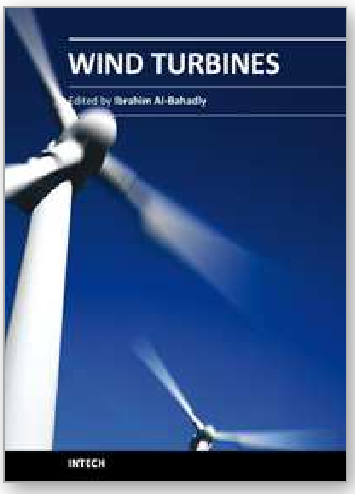

Wind Turbines

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The area of wind energy is a rapidly evolving field and an intensive research and development has taken place in the last few years. Therefore, this book aims to provide an up-to-date comprehensive overview of the current status in the field to the research community. The research works presented in this book are divided into three main groups. The first group deals with the different types and design of the wind mills aiming for efficient, reliable and cost effective solutions. The second group deals with works tackling the use of different types of generators for wind energy. The third group is focusing on improvement in the area of control. Each chapter of the book offers detailed information on the related area of its research with the main objectives of the works carried out as well as providing a comprehensive list of references which should provide a rich platform of research to the field.