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Regular paper

Direct Drive Permanent Magnet Synchronous Generator Wind Turbine investigation

- *Low Voltage Ride Through capability Dynamic behaviour in presence of grid disturbance*

In this paper, the authors investigated a Direct Drive Permanent Magnet Synchronous Generator Wind Turbine (PMSG-WT). This study deals with control of the PWM back-to-back converter (AC/AC) of the wind turbine, since the average size of WTG installations has increased due to the advent of larger capacity machines, especially variable speed technology, this raise of integration rate of wind energy could lead to propagation of transient stability and could potentially cause local or system wide blackout. This has provoked many utilities to adopt low voltage ride-through capability (LVRT), its analyze is a deferential element for the new Grid Connection Requirement (G.C.R) and the analyze of the dynamic behavior of the PSMG-WT in presence of the grid disturbance, especially the electromechanical stress on the generator and the turbine. Simulations results have been presented under real parameters of 2MW PMSG-WT in case of normal operating conditions and with presence of grid voltage disturbances. Due to the separation of the PMSG to the grid via the back-to-back converter, the influence of the grid disturbance on the generator is reduced compared to the others type of wind turbine such as Double Fed Induction Generator (DFIG) and the Fixed Speed Induction Generator (FSIG).

Keywords: Direct Drive Wind Turbine, PWM back-to-back converter, LVRT capability, voltage dips, electromechanical torque, Generator speed, dynamic behavior**.**

1. INTRODUCTION

The generation of electrical power from wind farms is developing rapidly with the world wide installed capacity. The interaction between the wind farm and the grid will be an important aspect in the planning of wind farm [1]. It is essential to ensure that the grid is capable of staying within the operational limits of frequency and voltage for all foreseen combination of wind power production and consumer load [2, 3] and, to keep, at the same time the grid transient stability [4]. Therefore, a wind turbine is required to be able to 'Ride Through' a severe voltage dip or swell, as well as a frequency disturbance or other occurrences of deteriorated power quality. The turbine should also assist the power system operator to improve the power quality, by supplying 'ancillary services' [2]. For the mechanical design of a wind turbine, this implies that it may have to face heavy torque fluctuations that have their origin at the generator side of the drive train, with the obligation of staying in operation. So far, much research has been done to assess the mechanical loads originating at the turbine side of the drive train, due to wind speed characteristics, turbine aerodynamics and mechanical design.

In this paper we, first developed Permanent Magnet Synchronous Generator (PMSG) associated with back-to-back PWM converter and 2 MW rated power turbine connected to the grid [5].

The control strategy of both rectifier generator side and grid side inverter is developed in the second part of this paper a Voltage Oriented Control **(**FOC) strategy is used to control the converter side the.

A brief grid connection requirements (GCR) rules for connecting wind turbine generators to the grid are investigated as a consequence, the transmission system operators (TSO) considers wind generation system are more and more requested to provide ancillary services in order to behave as a conventional power plants.

A two-mass spring and damper drive train is used in order to contribute to the transient stability of the grid and to reduce power oscillation when the wind turbine is subject of load changes, for example wind gusts

Electrical and electromechanical parameters are simulated and an examples show the impact of a wind gust and a voltage disturbance on the drive train torques.

2. DIRECT DRIVE PMSG WIND TURBINE SYSTEMS

Several techniques are used to convert wind energy. The most popular and largely used is based on the Induction Generator (IG), this system is relatively simple and don't cope with new grid codes, however Double Fed Induction Generator (DFIG) system is more complicated and offers more advantages as for exchange of active and reactive power with the grid and the fulfillment with grid codes. Permanent magnet machines are today manufactured up to a rated power of about 6 MW [5]. They are more efficient than the conventional synchronous machine and simpler because no exciter is needed. In order to convert wind energy to the grid, many technologies of converter are investigated; the simplest is small size permanent magnet generators associated with diode rectifiers.

Many types of inverters can be used in variable-speed wind turbine generator systems. They can be characterized as either network-commutated or self-commutated. Self-commutated inverters are either current source or voltage source inverters. The rated power considered is in the range of 200 kW to 1 MW. Self-commutated inverters*:* These are interesting because their network disturbance can be reduced to low levels. By using high switching frequencies, up to several kHz, the harmonics can be filtered easier than for a network-commutated thyristor inverter. Self-commutated inverters use pulse width modulation technique to reduce the harmonics. To make the harmonics to be low the switching frequency is often 3 kHz or higher. Self commutated inverters are usually made either with Gate Turn Off thyristors, GTOs, or transistors. The GTO inverters are not capable of higher switching frequencies than about 1 kHz. That is not enough for reducing the harmonics substantially below those of a thyristor inverter with filter. Therefore, the GTO inverter is not considered as a choice for the future. It has been made obsolete by the transistor inverters in the range up to 100-200 kW. Today the most common transistor for this type of application is the insulated gate bipolar transistor, IGBT. It is capable of handling large phase current, and it is today used in converters with a rated ac voltage up to 1700 V. A self commutated inverter can be either a voltage source inverter or a current source inverter. Today the voltage source inverter is the most usual type. If it is used to feed power to the network it must have a constant voltage of the dc capacitor that is higher than the peak voltage of the network. The generator is not capable of generating a constant high voltage at low speed and a dc-dc step-up converter must therefore be used to raise the voltage of the diode rectifier.

The wind energy conversion system considered under the study is called “Direct Drive PMSG” is represented on Fig. 1. It is composed of a three-phase P.M.S.G. The generator is connected to a P.W.M rectifier allowing an optimal power extraction by the use of an M.P.P.T algorithm. A P.W.M inverter ensures the injection of the produced power to the AC grid. Between the two converters, a capacitor is used as a voltage DC bus. The system is connected to the grid via a filter to improve the current quality.

The main advantages of this structure are the full decoupling between the two inverters, in fact, in case of grid disturbances, the grid side converter is controlled so it can support the voltage recovery by supplying reactive power and at the same time it secure the transient grid stability [6]. No significant mechanical stress (torque or speed) due to their high dynamic compared to electrical dynamics.

The wind energy conversion system is managed by the transmission system operator (TSO) or the distribution system (DSO) depending on the location of the point common coupling (PCC) of the wind farm. The supervisor receive electrical set-point according to the grid connection requirement (GCR) issued on wind farms grid code and control the two back-to –back converters and the pitch angle β in order to cope with.

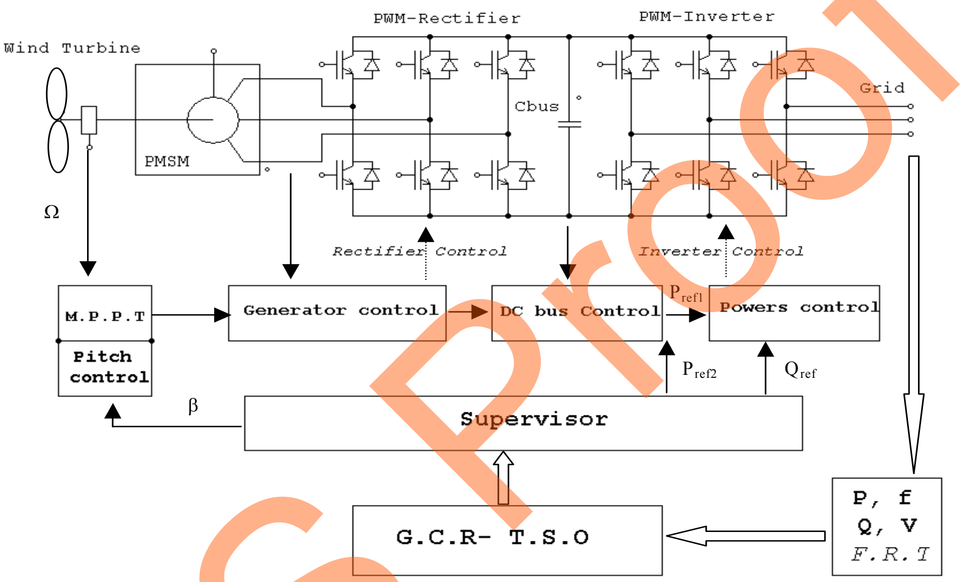

Fig.1: Block diagram of the direct drive wind energy conversion system with G.C.R algorithm control.

3. PWM RECTIFIER SIDE PMSG CONTROL STRATEGY

The control of the PMSG-WT control strategy is composed of three block diagram control related by a supervisor, the generator torque control which can be a Field Oriented Control (FOC) or a Direct Torque Control (DTC) method, the control of the DC bus connecting the two converters and the inverter side grid control which can **be a Voltage Oriented** Control (VOC) or a Direct Power Control (DPC) method using a PLL for synchronizing with the grid.

3.1 Generator Torque Control

In this work we have used a FOC control strategy for control of the converter side the generator cascaded with an external loop for the setting of the torque reference. This loop is an MPPT (Maximum Power Point Tracking) algorithm used to set the torque reference on the optimal wind torque corresponding to the maxim wind power for each wind speed, Fig4.

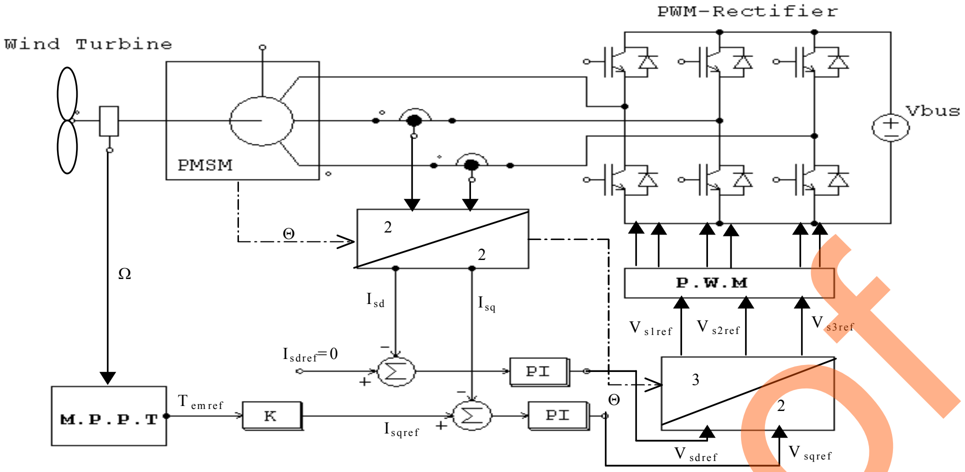

Fig.2: block diagram of Generator Torque Control

The torque control of the synchronous generator is related to the stator (d, q)-direct and quadrature-axis currents (I_{sd}, I_{sq}). The stator (d, q)-voltages references (V_{sdref}, V_{sqref}) are generated by the current controllers. After an inversion of the Park's transformation, we obtain the P.W.M voltage references (V_{s1ref}, Vs2ref, Vs3ref), which generate duty cycles of the generator side converter to obtain the desired DC voltage. The current regulation is carried out by canceling I_{sd}. The reference of the quadrature axis current (I_{sq}) is proportional to the torque reference given by the M.P.P.T algorithm.

3.2 PWM inverter generator side Control strategy

The synchronous generator model is also expressed in the (d, q) synchronous Park's model where the "d'' axis is rotating along the magnetic field direction. If the permanent magnet generator is assumed to be a round-rotor machine, which is a good approximation for surface mounted, in such conditions, the Park equations of the voltage machine are given by Eq. (1).

$$\begin{cases} V_{sd} = R_s.I_{sd} + L_{sd}.\dfrac{dI_{sd}}{dt} - \omega_e.L_{sq}.I_{sq} \\ V_{sq} = R_s.I_{sq} + L_{sq}.\dfrac{dI_{sq}}{dt} + \omega_e.L_{sd}.I_{sd} + \omega_e.\phi_m \end{cases} \tag{1}$$

Where R_s, L_{sd}, L_{sq} are the generator parameters detailed in appendix.
For permanent synchronous machines, the d, q flux components are given by Eq. (2).

$$\begin{cases} \varphi_{sd} = L_s.I_{sd} + \phi_m \\ \varphi_{sq} = L_s.I_{sq} \end{cases} \tag{2}$$

We have adopted the Field Oriented Control (F.O.C) principle for the torque control. By cancelling the direct current I_{sd}, a simple power control can be achieved only by controlling the quadrate current. In this condition the electromagnetic torque is given by Eq. (3).

$$T_{em} = \frac{3}{2}.P.\phi_m.I_{sq} \tag{3}$$

The optimal torque reference is given by the equation below.

The M.P.P.T algorithm keeps the coefficient Cp at it maximum, Cp=$C_{p\ \max}$, corresponds to $\lambda Cp_{\max} = \lambda_{opt}$

$$\Omega_{opt} = \frac{\lambda_{opt}}{R_v}.V \tag{4}$$

$$P_{vent\_\max} = K_{opt}.\Omega^3 \tag{5}$$

with

$$K_{opt} = \frac{1}{2}.\rho.S_v.\left(\frac{R_v}{\lambda_{opt}}\right)^2.C_{p\ \max} \tag{6}$$

$$T_{emref} = K_{opt}.\Omega^2 \tag{7}$$

For the synthesis of the controllers, chosen as PI controller, we determine the transfer functions between (I_{sd}, V_{sd}) and (I_{sq}, V_{sq}). First, we can write the Park voltages equations as:

$$\begin{cases} V_{sd} = V_{sd1} - emf_d \\ V_{sq} = V_{sq1} - emf_q \end{cases} \tag{8}$$

$$\begin{cases} emf_d = \omega_e.L_{sd}.I_{sq} \\ emf_q = -\omega_e.\phi_m - \omega_e.L_{sd}.I_{sq} \end{cases} \tag{9}$$

Where, the variables emf_d and emf_q are considered as perturbations. The transfer function between the component I_{sq} and the voltage V_{sq1} is given by Eq. (10).

$$\frac{I_{sq}}{V_{sq1}} = \frac{1}{R_s + s.L_s} = \frac{\frac{1}{R_s}}{1+\tau_e.s} \tag{10}$$

3.3 PWM inverter side Grid Control strategy

The control of the grid side inverter is carried out from the DC bus voltage cascaded with the control of currents whose-references are set from desired active and reactive power references. From the closed loop control of the DC bus, an active power reference is generated. A dynamic reactive power reference can be set following the requirements of the grid management service. In particular, it can be cancelled if a unit power factor is required. The grid current references are deduced from the equations between the grid voltages, the active and reactive power in (d, q) reference frame synchronized on the grid network. The reactive and active powers references and the frequency reference are generated from an external loop to satisfy the Grid Connection Requirements [7-8]. From the desired active and reactive powers, the current references are generated. When we impose an active power P_{ref} and a reactive power $Q_{ref,}$ we can determine the current references as:

$$\begin{cases} I_{dref} = \dfrac{P_{ref}.V_d + Q_{ref}.V_q}{V_d^2 + V_q^2} \\ I_{qref} = \dfrac{P_{ref}.V_q - Q_{ref}.V_d}{V_d^2 + V_q^2} \end{cases} \tag{11}$$

The control of the (I_d, I_q) currents (lead to three different actions): the compensation of the grid voltage, the currents decoupling and the closed loop current control. We can demonstrate this by Eq. (12).

$$\begin{cases} V_{dref} = V_d - L_f.\omega_e.I_q + \mathrm{Re}\,g_{Id} \quad (I_{dref} - I_d) \\ \\ V_{qref} = V_q + L_f.\omega_e.I_{fd} + \mathrm{Re}\,g_{Iq} \quad (I_{qref} - I_q) \end{cases} \tag{12}$$

Where Reg_{Id}, Reg_{Iq} are the Id, Iq current Park components P.I controllers. The synthesis of the controller is the same as for the second strategy.

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4. MECHANICAL MODELLING OF THE COUPLING TURBINE-GENERATOR

Some works have used only one mass model for driving the generator this modelling strategy cannot give good results especially in transient stability; in this paper we have taking into count the real mechanical coupling by including the model with two mass.
Compared to conventional synchronous generator, a multi-poles generator has a high number of poles and a large diameter, which causes higher generator inertia. In [9, 10], it is stated that the effective shaft stiffness of a generator is reduced with increasing number of poles. A torsional twist of the shaft connected to a multi-poles generator has thus a stronger impact on the electrical system. It is thus essential to represent the mechanical system by means of a two-mass and damper model in order to get an accurate response from the generator and the power converter. A load changes, for example wind gusts, can excite oscillations, which might be insufficiently damped by the system. A representation by means of a one-mass model would neglect such oscillations. Due to these reasons, the mechanical model is realized by means of a two-mass-model connected via a flexible shaft characterized by a stiffness *k* and a damping *c* (Fig.3). The two masses correspond to the large turbine rotor inertia J_T, representing the blades and hub, and to the generator inertia *J*gen.
The equation of the turbine side is given as:

$$2.J_{rot.}\frac{d\Omega_{rot}}{dt} = T_{rot} - k\theta_{rg} - c(\Omega_{rot} - \tag{13}$$

The equation of generator side is given as:

$$2J_{gen}\frac{d\Omega_{gen}}{dt} = T_{gen} + k\theta_{rg} + c(\Omega_{rot} - \tag{14}$$

Where J is the inertia constant, T is the torque, is the angular speed. Subscripts $_{rot}$ and $_{gen}$ indicate the turbine and generator quantities, respectively. The shaft stiffness and damping constant values are represented in k and c. all the quantities are in pu values. Variable ,
in the electrical radian, is the electrical twist angle of the shaft which is given by

$$\frac{d\theta_{rg}}{dt} = \Omega_{base} \tag{15}$$

where Ω_{base} is the base value of angular speed.

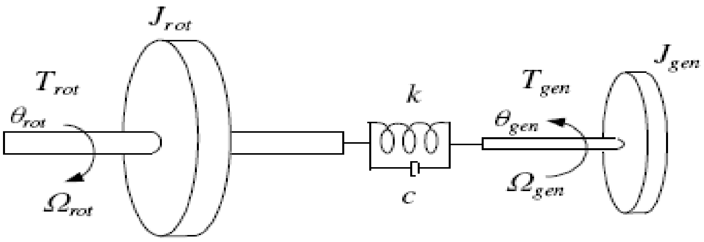
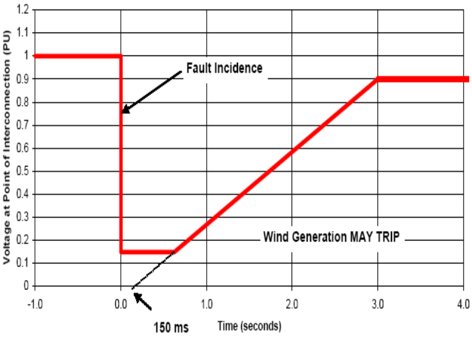


Fig.3: 2-mass-spring and damper model of the drive train [9].

5. ANCILLARY SERVICES FOR CONNECTING WIND FARM TO THE GRID: GRID CONNECTION REQUIREMENT (G.C.R)

The wind electrical energy's production has known a very significant evolution; we quote, as an example, a rate of penetration into the total power production of more than 20% in Denmark, 5% in Spain and in Germany [11, 12]. Compared to conventional power production stations, wind farms are not subjected to the same laws for the control system and for the grid connection. This is due primarily to the stochastic characters of the primary energy and the quality of the produced energy, which differs according to the country. After the experience feedbacks of first wind farms operating at fixed speed and in addition with the little experience feedback from farms operating at variable speed, the TSO met many problems of energy management from these wind farms. One of their objectives is the improvement of this energy management by new control procedures for advanced wind farm systems. To achieve this goal, an analysis of the regulations and behaviours of wind parks are necessary and constitute a stage, which appears as impossible to circumvent for the design and the ordering of future Wind Energy Conversion Systems (WECS).

Recently, in several countries, disconnection orders can be given to wind farms at once a fault, even transitory, occurs into the voltage value or frequency. This situation is penalizing and can compromise the balance between production consumption, which can lead to the network instability. Basing itself on the principle that these new sources gradually replace conventional sources, their integration into the public electrical network must respect strict requirements, which lead to a system of stable and reliable production. Among these requirements let us note the practical example of a short circuit of well defined duration, which is not detected by the protections (integrated into the wind farm) and cannot lead to the disconnection [13, 14]. In other words, the production must be maintained as much as the sizes of the fault did not reach limits specified by the ancillary services. In this paper we focus on the most concerned countries in Europe's experiments for instance Denmark, Germany, Scotland, France in addition to the United States of America, as well as the tendencies in this field.



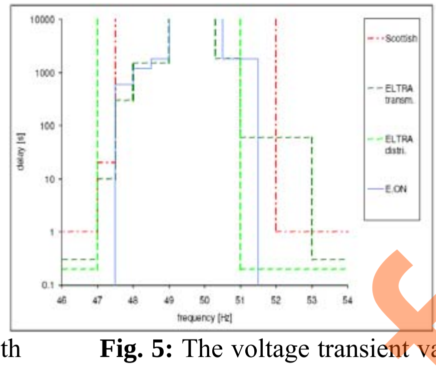


Fig. 4: Frequency variation domain with with an accepted re-establishment profile [15].

Fig. 5: The voltage transient variation Required by different operators [16].

6. SIMULATIONS RESULTS AND PERFORMANCES

The studied system is considered as complex system, it presents several non-linearity, and with different strong coupling, it is multi-scale time, multi-domains and presents high order model. These specifications complicate the design, the study and the global system analysis. In this context, the design of this class of system with an «Approach system" is very interesting using a global systemic modelling available for the design by the analysis and simulation. The studied system presents different energizing domain couplings, so it is interesting to use a formalism representation for modelling. Bond Graph technique is one of the powerful tool used for the systemic modelling, it is an energetic representation based on the flux and effort elements, multi-domains and offer a compartmental analysis and syntheses using the causality propriety [17, 18]. The simulation of bond Graph models is possible using 20-sim Software, [www.20sim.com].

6.1 Grid normal operation performances

In figure 6 we represent the current and the voltage across the generator, the machine operates at a very low speed and with neutral power factor which imposed by the control strategy of the rectifier.

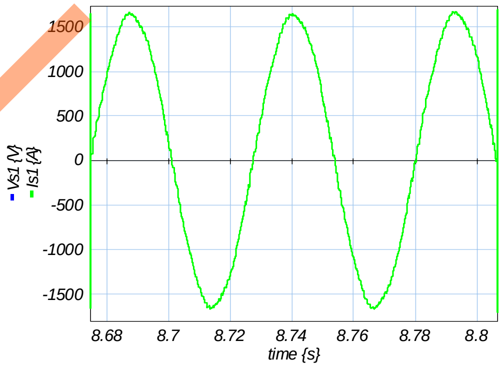


Fig. 6: Voltage and the current generator associated to the PWM rectifier

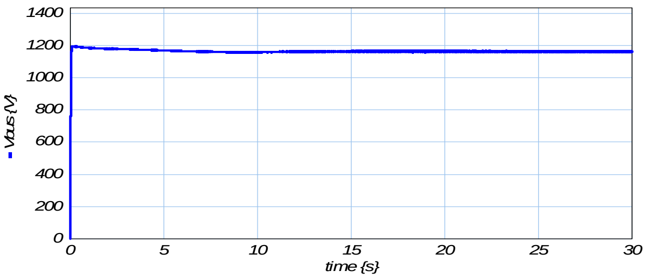


Fig.7: Performance DC bus regulation.

In figure7, the voltage DC bus is represented; we notice the performance of this regulation which set to 1200 V. this voltage is chosen in order to feed the grid side inverter to transfer active/ reactive power to the grid.

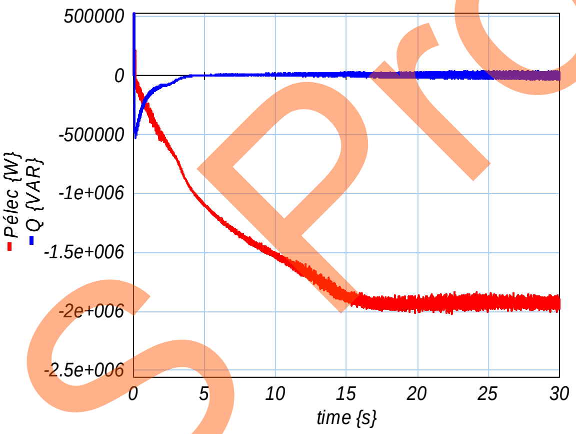


Fig.8: Powers control performances when a zero reactive power is imposed.

Figure 8 depicts the behaviour of active and reactive power in normal operation; the reactive power is set to zero by the grid side inverter control. The active power reference is given from the DC bus regulation, which means the MPPT- PWM Rectifier control, or from the pitch regulation when it is necessary to reduce the active power with an aerodynamic dynamic.

6.2 LVRT performances of the direct drive of the PMSG-WT.

To reproduce the same conditions fixed by the G.C.R on the voltage grid, we have simulated the scenario represented on figure8.

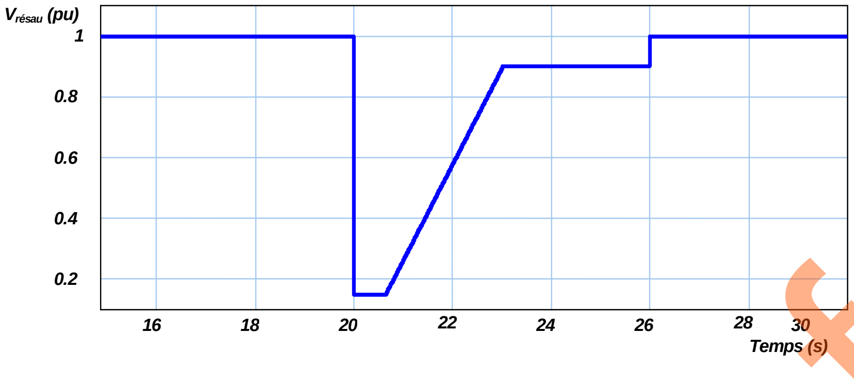


Fig. 9: Studied voltage dip on Medium voltage grid (deep h=85% for time=0.650s, h=10% for time=3s: G.C.R grid code E.O.N Netz Germany)

With this voltage dip profile, in order to maintain the wind farm connected to the grid and to save the grid transient stability we must control the wind power turbines by providing the active and reactive power at the same time.

In figure 10 we show a scenario where the reactive power is provided for about 150 ms when the voltage at the common point coupling (PCC) is at the minimum, this is to assist the grid, then, the active power increase with a pre-determined ramp rate (20%) to ensure the transient grid stability.

In figure 11 we represent another scenario where only reactive power is supplied to the grid with a pre-determined control strategy; the reactive power reference (Qref) is related to the voltage dip (0.1 pu). The active power is generated when 1 the fault clearance occurs [9-10].

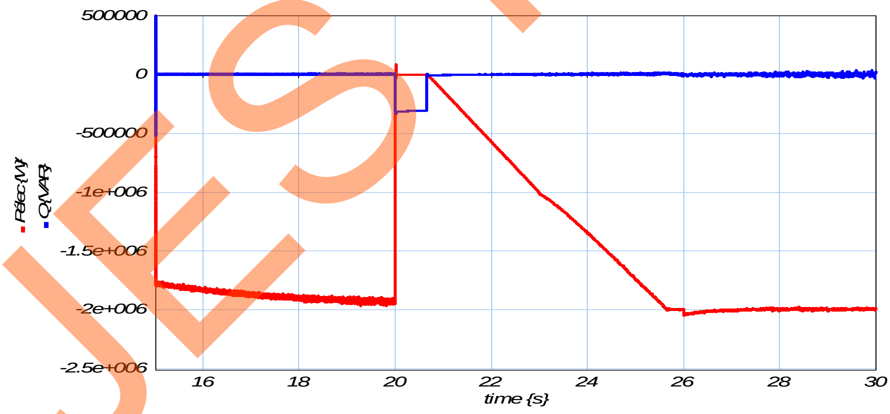


Fig. 10: Active and reactive power injection in case of balanced grid short circuit

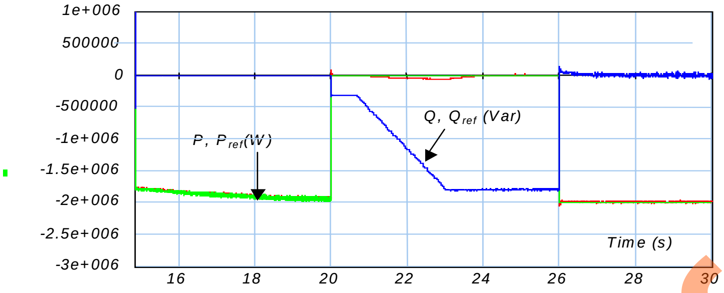


Fig.10: Injection reactive power (h=85% Q_{max}=30KVAR, h=10% Qmax=1, 8 MVAR).

In figure 11 we represent the current flow to the grid generated by the inverter grid side, the shape is not affected by the grid fault.

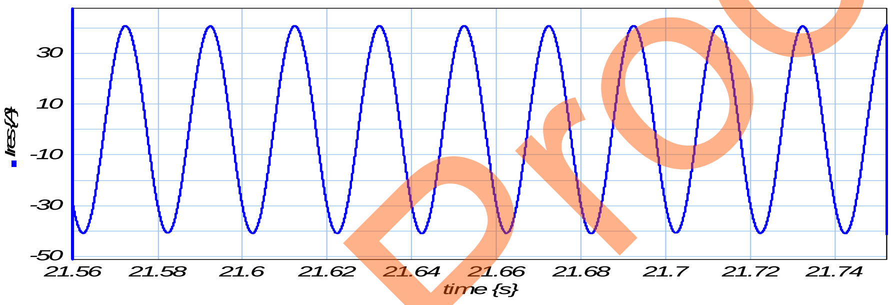


Fig.11: Current flow during the grid fault

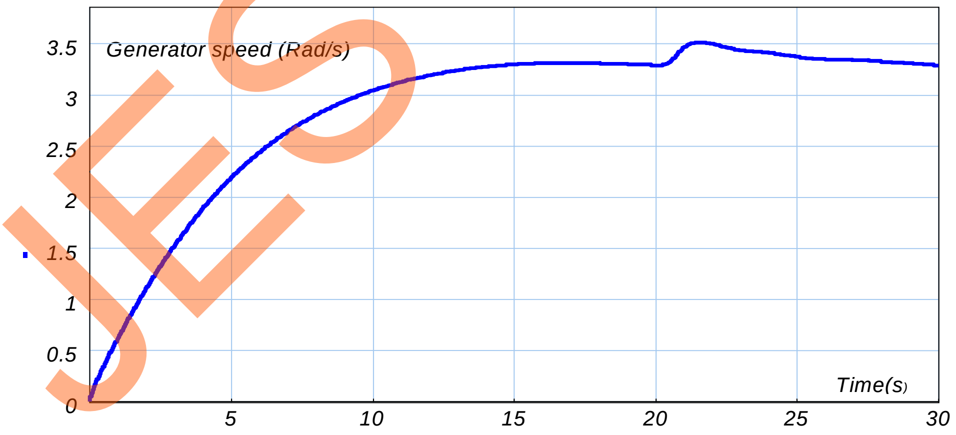


Fig.12: Grid voltage fault effect on the generator speed.

Figure 12 shows the weak effect of the voltage dip on the generator speed, this is due to the full decoupling between the generator and the grid via the converters. This is one of the advantages of the direct drive technology allowing a continuous electricity production even with very large grid disturbance or during the off-peak hours load diagram. The produced electricity is converted to an others energy consumption (water pumping, water desalination...).

7. CONCLUSION

In this paper, a model for a variable speed wind turbine with multi-pole permanent magnet synchronous generator has been developed, the model contains representations of a permanent magnet generator, a back-to-back voltage source converter and its control, the aerodynamic rotor, a two mass model representation of the shaft system A control method has been designed for normal operation conditions in order to satisfy grid connection requirements; we showed the performance of this control .. For the inverter side the grid, the control method is based on based on active and reactive power control associated to external loop including pitch control and low voltage ride through compensation by injecting reactive power. This study shows that the direct drive system is able to ride through the balanced voltage grid fault by reducing active power and supplying the maximum possible reactive power to maintain the current constant until clearance of the voltage fault. Also, this control strategy contributes to the transient stability of the grid by controlling the ramps rate of active power. Due to the decoupling between the generator and the grid by the back-to-back inverter the dynamic behaviour of the generator is slightly affected in presence of grid fault, this disturbance appeared by a light increase the speed of the generator.

Appendix

ϕ_m : Permanent magnet flux (Wb)
L_{sd}, L_{sq} : Direct and quadrature-axis cyclic inductances, respectively ($L_{sd} = L_{sq} = L_s$)
$X_{sd,q}$: Direct and quadrature-axis X value (current or voltage) of the generator
R_s : Stator resistance of the generator phase
P : Number of pole pairs
$\frac{L_s}{R_s} = \tau_e$: Electrical time constant of the generator
s : Laplace operator
ω_e : Electrical pulsation (rad/s)
Reg_{Id}, Reg_{Iq} : The d, q current regulators, respectively
$X_{d,q}$: Direct or quadrature-axis value of the X (current or voltage) of the grid
P_{ref}, Q_{ref} : Active and reactive reference values of the grid power.
Ørestad-DTU, Denmark, 2003.
$X_{d,q\ ref}$: Reference of the direct or quadrature-axis value of the X (current or voltage) of the grid

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