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Computational Assessment of Control Strategy for PMSG Wind Turbines aiming at Voltage Regulation on Connection Point

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Abstract

The growing deployment of wind energy conversion systems experienced in recent years has been reflected in increasing requirements for connection of such complexes to electric networks. In this way, in a near future, wind farms could be required to behave as conventional power plants, which, besides the characteristics of energy supply, promote support to the electrical system in steady state and transient conditions. In this context, this work is focused in a computational assessment of a control strategy directed to wind energy conversion system with permanent magnet synchronous generator (PMSG) aiming to regulate the voltage at the Point of Common Coupling. Therefore, after the mathematical description of the main physical components of such generating units, it proceeds to the computational implementation and performance evaluation of the control method using the ATP-EMTP simulator.

Key words

Computational Modelling, Reactive Control, Power Quality, Voltage Regulation, Wind Turbine

1. Introduction

Recent data indicate that the interest and growing investments on development and implementation of wind farms have led to, in June 2012, an installed capacity in whole world around 254 GW. It represents an increase of approximately 16% compared to the same period of 2011 [1] and indicates that wind farms effectively play a relevant role in certain areas of the world. Nowadays, the largest markets comprise China, USA, Germany, Spain and India, which concentrate together a total share of 74% of the global wind capacity. Moreover, Denmark, for instance, has a high penetration of wind farms in its energy matrix, with 25% of all electricity consumption covered by wind energy [2].

The use of these complexes is justified by several factors mainly because the energy source is considered clean and with low environmental impact as compared to other electricity generation plants. However, a common characteristic of this type of generation concerns to irregularity of the primary source [3], which usually varies as a function of meteorological conditions. Consequently, this fact implies oscillations of electrical power injected into the grid.

A major point of interest is related to the operation and connection of wind farms. In fact, for many applications, it is recognized that such generation units are connected to grid busses which have low short-circuit levels. Given this condition these interconnections can promote impacts in two senses, which mean that wind farms operation disturbs the system power quality as well as disturbances occurring in electrical grid can affect the wind generators functioning. In this context, it is recognized the existence of several documents and standards such as the IEC 61400-21 [4], IEEE 1457 [5] or national interconnection procedures, which establish operational requirements for these complexes. Among other issues, the guidelines given by these references include requirements related to grid frequency, active power injection, output voltage, voltage fluctuation, harmonic distortion and supportability to faults [6].

In this way, in order to improve the performance of wind farms and allow those generations contribute to the electrical system operation, it is noticed a tendency in the use of such generations for the reactive power compensation and voltage regulation. This methodology directs control strategies to power electronics devices used to connect the wind turbine to the grid, leading these complexes to behave as an active energy source. Generally, the techniques employed to develop the control system are based on vector control theory [7] [8] [9], which ensures that the power extracted from the wind is injected in the grid, simultaneously to the regulation of reactive power flow.

Taking into account that wind farms are energy sources with an exponential growth in the energy matrix of several countries, this brings, consequently, a need to develop methods to improve the operation of such complexes. Considering this scenario, this work is directed to present a control strategy, its computational implementation and performance evaluation using a power system that comprises a wind farm and a typical electrical network. Using this arrangement, it will be evident that, besides the transfer of active power, wind farms can also provide ancillary services to the grid. In particular, the strategy presented in this paper is focused on control the inverter unit, in order to dynamically adjust the reactive power flux and, consequently, behaves with similar characteristics to those found in STATCOM devices. From this perspective, the following points are covered in next sections:

- Summary of requirements related to reactive power control in the operation of wind farms;
- Presentation of equivalent models of wind conversion system with permanent magnet synchronous generators;
- Systematization of a strategy designed to control dynamically the reactive power aiming at voltage regulation at PCC;
- Implementation of the proposed strategy in ATP-EMTP platform and performance evaluation through computational studies;
- Presentation of capabilities/limitations of the proposed strategy.

2. Reactive Control Requirements

Modern grid codes stipulate that wind farms must be equipped with mechanisms to control the reactive power flow between the generating units and electrical grid and, in turn, offer additional functions associated to voltage regulation at the point of common coupling (PCC).

Basically, the operation of wind turbines, in which concerns the reactive power regulation, can be classified in three categories:

- Fixed reactive power dispatch: this operational alternative, as illustrated at Fig.1, is based on the control of the reactive power flux independently of the active power produced by the wind turbine. In this case, the reactive power remains constant in a setpoint value which can be, for instance, fixed by the network operator.

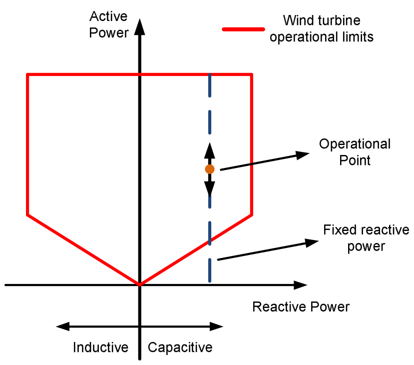

Fig. 1. Fixed reactive power dispatch

- Power factor control: this operational condition consists in adjusting the reactive power flow proportionally to the active power produced by the wind turbine, as shown in Fig. 2.

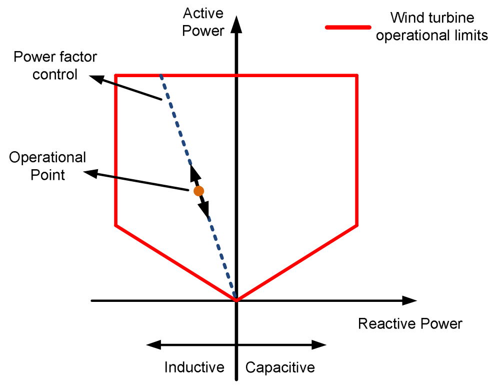

Fig. 2. Power factor control

- Voltage control: this operating mode is characterized by the use of the wind generating units to promote voltage regulation around a reference value. In this way, it can be defined a curve with a specific droop that relates the measured voltage and the reactive power setpoint to the wind turbine, as presented in Fig. 3.

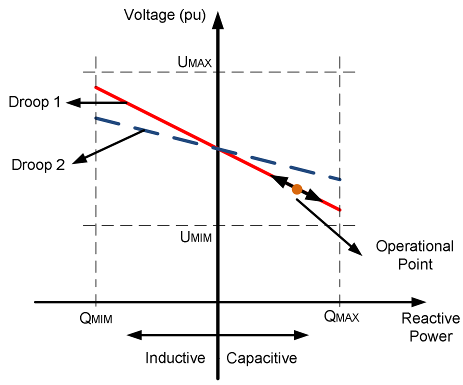

Fig. 3. Voltage control.

Moreover, it is highlighted that some grid codes demands wind turbines to support the system during faults through the reactive power compensation. For instance, Danish grid code [10] requires large wind power plants to provide reactive current in accordance with the profile indicated in Fig. 4. In area B, reactive current injection has a highest priority in relation to active current.

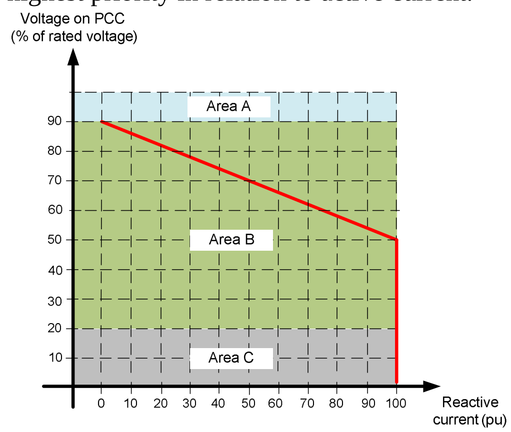

Fig. 4. Reactive current support – Danish Grid Code.

3. PMSG Modelling and Control

The configuration of the wind energy conversion system is shown Fig. 5. Each generating unit comprises a wind-turbine representation, a permanent magnet synchronous generator, a back-to-back converter and a step-up transformer. The mathematical models of these elements are presented in next sections. It should be highlighted that the overall system was implemented in ATP-EMTP platform.

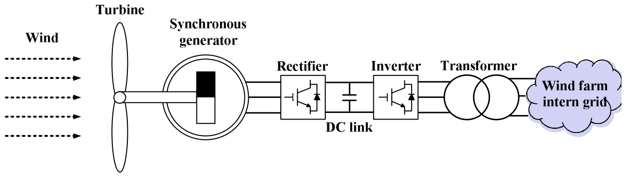

Fig. 5. Wind energy conversion system.

A. Wind-turbine model

The mechanical power (P_{mec}) produced by the wind turbine is given by (1).

$$P_{mec} = \frac{1}{2} C_p(\lambda, \beta)\, \rho\, A\, {v_{wind}}^3 \quad (1)$$

where: ρ – the air density; C_p – power coefficient; A – area swept by turbine blades; v_{wind} – wind speed.

As the power available on the turbine shaft is proportional to the cube of wind speed, its characteristics are fundamental in the modelling process. According to reference [11], the wind signal is composed, classically, by the sum of four components, as expressed in (2):

$$v_{wind} = v_{base} + v_{gust} + v_{ramp} + v_{noise} \quad (2)$$

where: v_{base} – base wind speed; v_{gust} – gust component; v_{ramp} – ramp wind component; v_{noise} – wind signal noise.

B. Permanent Magnet Synchronous Generator Model

The PMSG model used in this work is based on traditional time domain synchronous machine equations, which include the magnetic flux produced by the permanent magnet as a constant value on leakage machine fluxes. In this context, the relationship between the voltages, leakage fluxes and currents are shown in (3) and (4).

$$[V_g] = -[R_e] * [I_g] - \frac{d[\lambda_e]}{d_t} \quad (3)$$

$$[\lambda_e] = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} & k_{aF} \\ L_{ba} & L_{bb} & L_{bc} & k_{bF} \\ L_{ca} & L_{cb} & L_{cc} & k_{cF} \end{bmatrix} \cdot \begin{bmatrix} i_{ga} \\ i_{gb} \\ i_{gc} \\ F_{IP} \end{bmatrix} \quad (4)$$

where: $[V_g]$, $[I_g]$, $[\lambda_e]$ – voltage, current and leakage flux vector, respectively; $[R_e]$ – stator resistance matrix; L_{ii} – stator self-inductance (i = a, b or c); L_{ij} – mutual inductance between two phases of the stator (i or j = a, b or c and $i \neq j$); k_{iF} – magnetic coupling factor between stator and rotor (i = a, b or c); i_{ga}, i_{gb} and i_{gc} – stator currents; F_{IP} – magnetic flux of the permanent magnet.

In other hand, the electromagnetic torque (T_{el}) can be calculated by (5).

$$T_{el} = \frac{n_p}{2} F_{IP} \sum_i i_{gi} \frac{dL_{iF}}{d\theta_e} \quad (5)$$

where: n_p – number of poles of the generator; ${dL_{iF}}/{d\theta_e}$– derivatives of the magnetic coupling coefficient, where i assumes: a, b, c.

Additionally, equation (6) relates the mechanical torque from wind turbine (T_{mec}), the electromagnetic torque (T_{el}), the turbine angular speed (ω_{mec}) and the inertia (J) of the turbine-generator assembly.

$$T_{mec} - T_{el} = J \frac{d\omega_{mec}}{dt} \quad (6)$$

C. Back to back model and control

Among the several converter topologies used in wind energy conversion systems, the structure employed in this work is shown in Fig. 6. It consists in a two-level voltage source converter (VSC) configured as a back to back structure [12], which is the most adopted solution for wind turbines in the range of 1.5-3 MW rated power [2]. The switching signals for the VSC semiconductors were generated by a space-vector pulse width modulation (SVPWM).

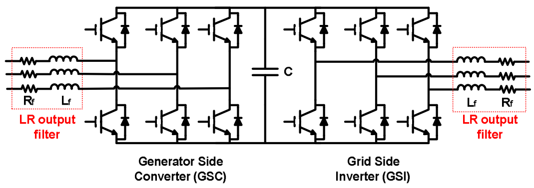

Fig. 6. Power converter.

Additionally, in order to attenuate the switching harmonics, it is adopted a LR (inductive-resistive) output filter in both sides of the power converter. The design of the inductor is based on the adoption of the current ripple attenuation as described in [13] and defined in (7).

$$L_f = \frac{V_f}{2\sqrt{6} f_{sw} i_{ripple}} \quad (7)$$

where: V_f – phase-neutral voltage applied to the filter; f_{sw} – switching frequency; i_{ripple} – current ripple;

In this context, the GSI mathematical representation can be obtained through the relationship between the converter output voltages and grid voltages, as expressed by (8).

$$\begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} = R_f \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L_f \cdot \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (8)$$

where: V_a, V_b and V_c – phase grid voltages at transformer low voltage side; E_a, E_b and E_c – GSI output voltage; i_a, i_b and i_c – GSI output current; R_f and L_f – equivalent resistance and inductance of GSI output filter.

Based on vector control theory, a synchronous reference frame is adopted to model the control system. Classically, this theory allows the representation of three-phase variables in a dq system, through the transformation defined in (9).

$$\begin{bmatrix} V_d' \\ V_q' \\ V_0' \end{bmatrix} = \frac{2}{3} \begin{bmatrix} cos(\theta) & cos(\theta - {}^{2\pi}/_{3}) & cos(\theta + {}^{2\pi}/_{3}) \\ -sen(\theta) & -sen(\theta - {}^{2\pi}/_{3}) & -sen(\theta + {}^{2\pi}/_{3}) \\ {}^{1}/_{\sqrt{2}} & {}^{1}/_{\sqrt{2}} & {}^{1}/_{\sqrt{2}} \end{bmatrix} \cdot \begin{bmatrix} V_a' \\ V_b' \\ V_c' \end{bmatrix} \quad (9)$$

where: V_a', V_b' and V_c' – three-phase instantaneous voltage; V_d', V_q' and V_0' – direct, quadrature and zero components, respectively; θ– reference angle.

Consequently, in *dq* reference frame, the GSI output voltages are expressed by (10) and (11).

$$V_d = E_d - R_f I_d - L_f \frac{dI_d}{dt} + \omega_{el} L_f I_q \quad (10)$$

$$V_q = E_q - R_f I_q - L_f \frac{dI_q}{dt} - \omega_{el} L_f I_d \quad (11)$$

where: V_d and V_q – direct and quadrature grid voltage, respectively; E_d and E_q – direct and quadrature GSI output voltages, respectively; I_d and I_q – direct and quadrature output current; ω_{el} – angular frequency of grid voltages.

On the other hand, the instantaneous active (p) and reactive (q) power in *dq* reference frame is defined by (12) and (13).

$$p = \frac{3}{2}(V_d I_d + V_q I_q) \quad (12)$$

$$q = \frac{3}{2}(V_d I_q - V_q I_d) \quad (13)$$

Considering the grid voltages as the reference for the *dq* transformation, it implies that $V_d = |V|$ and $V_q = 0$. Consequently, the instantaneous active and reactive powers will be expressed by (14) and (15).

$$p = \frac{3}{2}|V| I_d \quad (14)$$

$$q = \frac{3}{2}|V| I_q \quad (15)$$

where $|V|$ assumes the grid voltages module.

Therefore, the control of the active power supplied to the grid can be achieved by adjusting the GSI direct current component as well as the reactive power flow is managed by controlling the quadrature current.

A similar mathematical model can be developed to the GSC in such a way that the direct and quadrature current control determines the active and reactive power produced by the synchronous generator.

D. *Grid Side Inverter Control Strategy*

The strategy applied to GSI is based on cascade control and it is shown in Fig. 7. In order to allow the GSI behaves with similar characteristics to those found in STATCOM devices, even in low wind conditions, the control objectives are:

- keep DC link voltage constant, ensuring that the active power fed by the GSC is directly injected into the grid;
- adjust, dynamically, the reactive power flow in order to regulate the fundamental voltage around a reference value. In this way, an additional control loop is included which is represented by a droop curve. This one relates the measured voltage and the reactive current, allowing a decentralized voltage regulation.

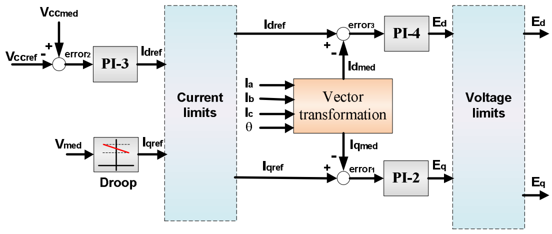

Fig. 7. GSI control strategy

It should be noted that the converter operational limits are included in control loops. In this way, I_{dref} and I_{qref} are compared to GSI current limits so that the avoid operation under overcurrent conditions. Similarly, to guarantee a linear operation, E_d and E_q are examined in relation to the maximum output voltage.

Considering that the control loops provide E_d and E_q voltages, it is performed the inverse vector transformation. This operation results in three-phase voltage used in SVPWM, as presented in Fig. 8.

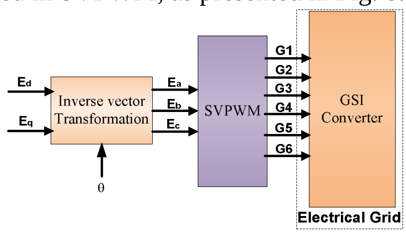

Fig. 8. GSI pulses generation

To ensure the synchronisation of the grid connected inverter, a PLL (Phase Locked Loop) is required to estimate the grid voltage angle used in *dq* transformation. In the present work, it is used a DSRF-PLL (Double Synchronous Reference Frame PLL) presented at Fig. 9 [14-15].

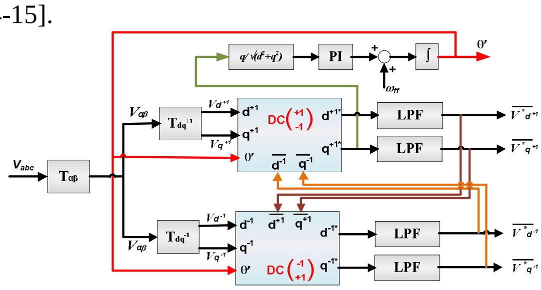

Fig. 9. DSFR-PLL structure.

4. Computational Assessment

In order to evaluate the performance of the control strategy directed to PMSG units, it was chosen a wind condition characterized by a base component of 10 m/s with a random noise and a gust leading to a peak value of 13 m/s. In this way, Fig. 10 shows the wind profile used as primary energy source. The ramp component is not considered in this study.

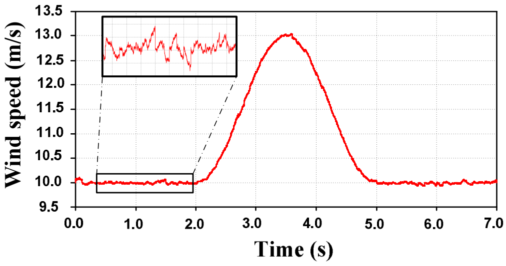

Fig. 10. Wind profile.

Figure 11 shows the network simulated. The hypothetical wind farm, which has the configuration shown in Fig. 12, is composed by 10 generating units and is connected to the bus 2. Additionally, Table I presents the main parameter of the electrical system here considered.

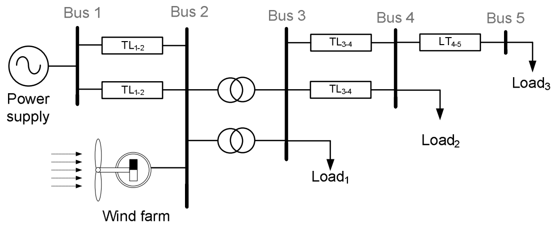

Fig. 11. Electrical network.

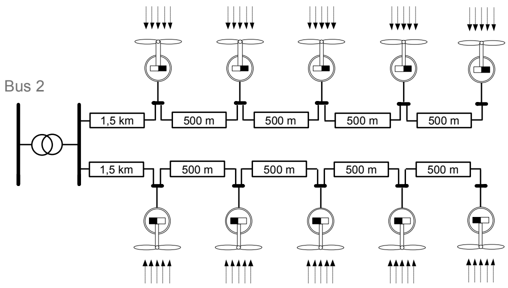

Fig. 12. Wind farm configuration.

Table I. Main parameters of the electrical system

Wind Turbine	Radius (m)	21.0
	Rated speed (m/s)	12.0
Synchronous generator	Rated voltage (V)	600.0
	Rated Power (MVA)	2.0
	Number of poles	60.0
GSC parameters	Filter (mH)	1.5
	Switching frequency (kHz)	2.0
DC Capacitor	Capacitance (μF)	4000.0
GSI parameters	Filter (mH)	1.5
	Switching frequency (kHz)	2.0
Step up Transformer	Primary/Secondary Voltage (kV)	0.69/ 34.5
	Rated power (MVA)	2.0
	Percentual resistance (%)	1.0
	Percentual impedance (%)	8.0
Power supply	Voltage (kV)	138.0
	Short circuit (MVA)	670.0
Wind farm cables parameters	Resistance (Ω/km)	0.2
	Inductance (mH/km)	0.4
	Capacitance (μF/km)	0.2

The performance analysis comprises the following situations:

- Case 1: Wind farm operation with a fixed reactive power dispatch. In this case, the generating units will not supply reactive power, implying that the setpoint is $q = 0$;
- Case 2: Wind farm operation controlling the power factor at PCC around 0,97 inductive;
- Case 3: Wind farm with voltage regulation capabilities, considering the control strategy directed to GSI described in the present work.

As a direct consequence of the wind conditions imposed on the complex and in accordance with the equations that describe the relationship between the turbine shaft speed and the mechanical power at the generator input, Fig. 13 highlights the active power injected into the network along the studied period of time. In this context, before the imposition of the gust, it is noticed that the wind farm injects about 6 MW on the grid. However, this variable reaches levels close to 11 MW at the moment of wind maximum value. Additionally, it is emphasized that the pitch control does not act in the chosen wind conditions. Complementarily, Fig. 14 shows the direct current produced by a single wind generator.

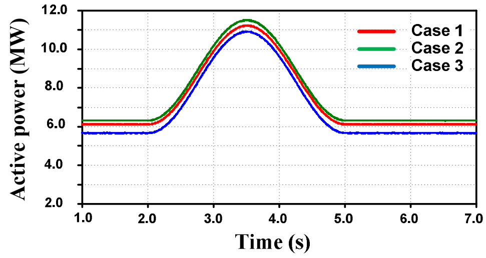

Fig. 13. Active power injected into the grid.

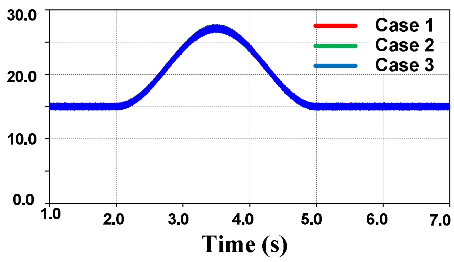

Fig. 14. Direct current of a single wind generator.

On the other hand, Fig. 15 presents the reactive power flow between the wind farm and the electrical network. As expected in case 1, the generating units operate around the setpoint established. Concerning case 2, one can note a dynamical change in the reactive power flow, once this variable is calculated as a function of the active power produced. In regards to case 3, the reactive power flow is defined according to the droop used in the control system, which was adopted as 2%. Additionally, Fig. 16 presents de quadrature current produced by an individual generating unit. A negative value indicates a capacitive current.

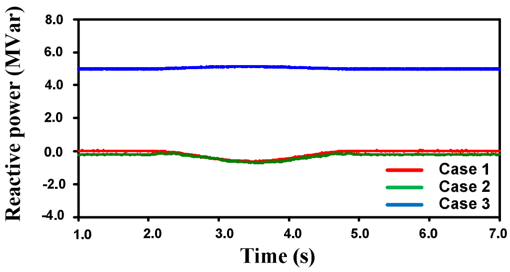

Fig. 15. Reactive power injected into the grid.

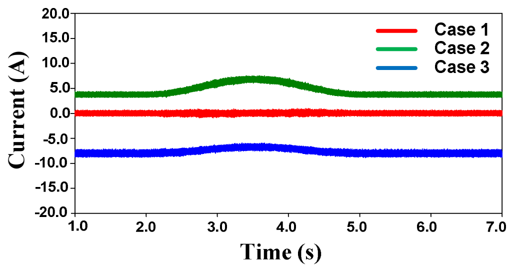

Fig. 16. Quadrature current of a single wind generator.

Finally, Fig. 17 shows the RMS voltage at bus 2. It can be noticed that the injection of active power on the electrical system, without reactive power flow adjustment, causes voltage variations at the connection point. The voltage regulation by a droop control, as presented in case 3, shows the better response. In fact, considering that the terminal voltage is used to feedback the control system, the reactive power flow, consequently, is optimized to regulate the voltage around the reference value. In operation by controlling power factor, the reactive power is determined by the active power produced, and such value may not meet the operational needs of the electric grid. Moreover, increasing the number of generating units, the capacity of the wind farm to regulate the voltage is improved.

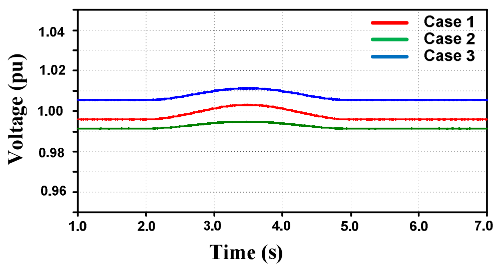

Fig. 17. RMS Voltage profile at Bus 2

5. Conclusions

This paper described the physical structure of a wind energy conversion system with permanent magnet synchronous generator, with emphasis in a control strategy directed to the grid side inverter unit aiming at voltage regulation on connection point. The overall system was implemented on ATP-EMTP platform, enabling the assessment of connection impacts arising from the integration of such power plants in electrical network.

The voltage regulation mechanism is based on vector control theory, which simplifies the mathematical modelling of power flow between the generating units and the electrical grid. In this context, it can be noted that direct current adjustment allows the management of the active power injected into the grid and, consequently, enables the DC voltage regulation. On the other hand, the reactive power flow can be controlled by the quadrature current, enabling the inverter unit behaves with similar characteristics to those found in STATCOM devices.

With respect to computational results, these show real situations occurring on power system and, from a qualitative point of view, present an acceptable standard of physical performance. Even though the voltage regulation by a droop control presents an improvement on stead state voltage, the authors recognize that further investigations are still necessary

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