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The controlling of the DFIG Based Wind Energy Conversion System modeling and simulation

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***Abstract*— This paper presents a general modeling and control of the Doubly Fed Induction Generator (DFIG) based Wind Energy Conversion System (WECS). Firstly, We start by modeling the wind turbine. Then, an maximum power point tracking (MPPT) control algorithms is detailed. Thereafter, we given DFIG's mathematic model in the d-q coordinates. Both Grid Side Converter (GSC) and Rotor Side Converter RSC control strategy are presented theoretically based on vector control. Finally, The validity of this control algorithm has been verified by the simulation of the 2-MW DFIG wind turbine system.**

***Keywords*— DFIG, WECS, MPPT, RSC, GSC.**

I. INTRODUCTION

Over the last recent years, Wind Energy Conversion System (WECS) became the center of attention for intensive research, and a number of studies have been done by different groups of researchers. It can be classified into two groups : fixed-speed and variable-speed turbines.

The typical configuration of variable-speed WECS using DFIG considered in this paper is illustrated in figure 1. It can be divided into two principal parts which will be modeled separately: the DFIG whose stator is connected directly to a grid, whereas its rotor is connected to the grid through two static converters bidirectional and a DC-link in a configuration called Back to Back converter (BTB), The back-to-back converter consists of two voltage source converters, one called as the Rotor Side Converter (RSC) and the other called as the Grid Side Converter (GSC) [1,2].

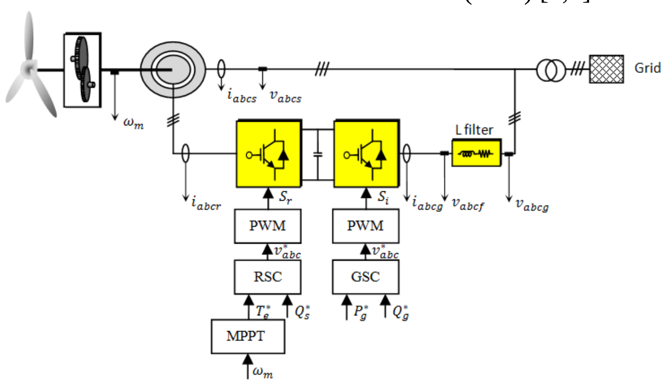

Figure 1. wind energy conversion configuration of DFIG system

II. AERODYNAMIC TURBINE MODEL

A. *Characterizations of wind turbines:*

To classify wind turbines, two terms are commonly used: the tip speed ratio and the power factor [3]:

- The tip speed ratio is given by the following expression

$$\lambda = \frac{\Omega_T R_T}{v_w} \tag{1}$$

where Ω_T is the angular velocity of the wind turbine shaft measured in mechanical radians per second, R_T is the radius of the wind turbine (length of blade) in m, v_w is the wind speed in m/s.

- The power coefficient of the wind turbine is defined by the following relation [2]:

$$\begin{cases} \frac{1}{\lambda_i} = \frac{1}{\lambda + 0.02\beta} - \frac{0.003}{\beta^3 + 1} \\ C_p = C_p(\lambda,\beta) = 0.46\left(\frac{151}{\lambda_i} - 0.58\beta - 0.002\beta^{2.14} - 13.2\right)\left(e^{-18.4/\lambda_i}\right) \end{cases} \tag{2}$$

Figure 2 shows the function in Equation 2 plotted for several values of β.

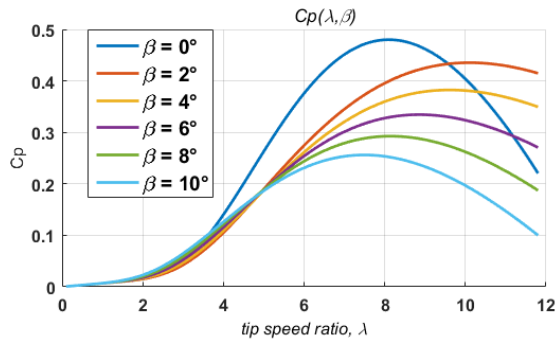

Figure 2. Tip-speed ratio versus power coefficient

B. *Mechanical power of turbine*

The kinetic power of the wind is given by the following relation [3-5]:

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$$P_w = \frac{1}{2}\rho A_T v_W^3 \;, A_T = \pi R_T^2 \qquad (3)$$

Where ρ is air density (kg/m^3), A_T is the rotor swept area (m^2),

According to the theory of German scientist *Albert Betz*, the mechanical power extracted from the wind kinetic power is given by:

$$P_T = P_w \times C_P = \frac{1}{2}\rho A_T v_w^3 C_P \qquad (4)$$

C. Torque of the turbine:

the torque of the turbine is expressed according to the angular speed of the rotor and the mechanical power of the turbine by the following relation:

$$T_T = \frac{P_T}{\Omega_T} = \frac{1}{2}\rho A_T v_W^2 C_t \,,\; C_P = C_t \lambda \qquad (5)$$

Where C_t is torque coefficient.

III. Dynamic Turbine Model

A. Turbine Gearbox

The Turbine Gearbox aims at the adaptation between the shaft velocity of the turbine (Low speed shaft) and that of the generator (High speed shaft). In the case of an ideal gearbox, the gear ratio can be modeled mathematically by [3-5]:

$$N = \frac{\Omega_m}{\Omega_T} = \frac{T_T}{T_m} \qquad (6)$$

where N is the gear ratio, T_T and T_m are torque of the turbine on Low and high speed shaft respectively, Ω_T and Ω_m velocity of the turbine on Low and high speed shaft respectively.

B. Equation dynamic of wind Turbine

The fundamental equation of the dynamics which makes it possible to determine the evolution mechanical speed from the torque exerted on the shaft of the rotor of the wind turbine T_T and the electromagnetic torque T_{em} [3-5]:

$$J\frac{d\Omega_m}{dt} = T_m - T_{em} - D\Omega_m \qquad (7)$$

where D is the damping coefficient of turbine.

The diagram of the dynamic model of the wind-based turbine is given in

The diagram of the dynamic model of the wind-based turbine is given in figure 3.

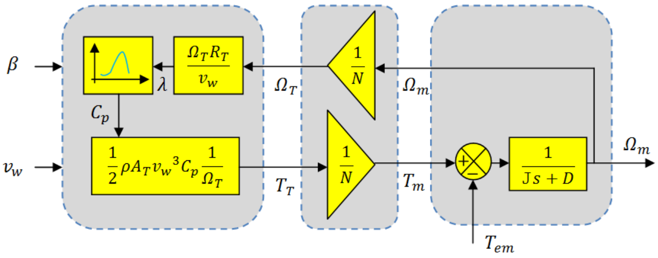

Figure 3. Dynamic model of the wind turbine

IV. Maximum Power Point Tracking (MPPT)

The strategy of this control consists in controlling the electromagnetic couple in order to regulate mechanical speed to maximize the generated electric output [2,4,5].

From the dynamic equation of the turbine, we have:

In permanent mode, one can write (by neglecting the effect of the couple of viscous frictions):

$$T_m = T_{em} \qquad (8)$$

The electromagnetic couple of adjustment is given starting from an estimate of the wind couple:

When the turbine functions with the maximum power point, then: $\lambda = \lambda^{op}$ and $C_P = C_P^{op}$.

The electromagnetic couple of reference must be regulated with the following value:

$$T_{em}^* = \frac{T_T}{N} \qquad (9)$$

Consequently:

$$T_{em}^* = k^{op}\Omega_m^2 \qquad (10)$$

Where

$$k^{op} = \frac{1}{2}\rho A_T R_T^3 \frac{C_P^{op}}{\lambda_P^{op} N^3} \qquad (11)$$

The expression of the couple of reference then becomes proportional to the square of generator speed.

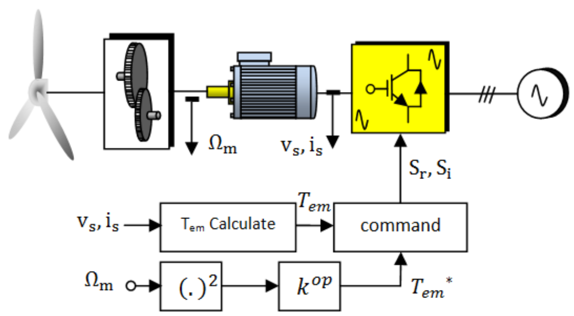

Figure 4. MPPT based on Optimal torque control

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V. MODEL OF DFIG

The mathematical model is expressed, in the reference frame (d-q) turning at the speed of the stator field, by the relations given below[2,5,6]:

A. *The dq voltage equations*

$$\begin{cases} v_{ds} = R_s i_{ds} + \frac{d}{dt}\psi_{ds} - \omega_s \psi_{ds} \\ v_{qs} = R_s i_{qs} + \frac{d}{dt}\psi_{qs} + \omega_s \psi_{qs} \\ v_{dr} = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - \omega_r \psi_{dr} \\ v_{qr} = R_r i_{qr} + \frac{d}{dt}\psi_{qr} + \omega_r \psi_{qr} \end{cases} \quad (12)$$

B. *The dq flux equations*

$$\begin{cases} \psi_{ds} = L_s i_{ds} + L_m i_{dr} \\ \psi_{qs} = L_s i_{qs} + L_m i_{qr} \\ \psi_{dr} = L_m i_{ds} + L_r i_{dr} \\ \psi_{qr} = L_m i_{qs} + L_r i_{qr} \end{cases} \quad (13)$$

Where R_s ,R_r, L_s, L_r are respectively the resistances and inductances of the stator and rotor windings, and L_m is the mutual inductance.

C. *Dynamic Power Expressions*

The active and reactive stator and rotor powers are expressed by:

$$\begin{aligned} P_s &= \frac{3}{2}\mathrm{Re}\{v_s i_s^*\} = \frac{3}{2}(v_{ds}i_{ds} + v_{qs}i_{qs}) \\ P_r &= \frac{3}{2}\mathrm{Re}\{v_r i_r^*\} = \frac{3}{2}(v_{dr}i_{dr} + v_{qr}i_{qr}) \\ Q_s &= \frac{3}{2}\mathrm{Im}\{v_s i_s^*\} = \frac{3}{2}(v_{qs}i_{ds} - v_{ds}i_{qs}) \\ Q_r &= \frac{3}{2}\mathrm{Im}\{v_r i_r^*\} = \frac{3}{2}(v_{qr}i_{dr} - v_{dr}i_{qr}) \end{aligned} \quad (14)$$

D. *Electromagnetic Torque Equation*

$$T_{em} = \frac{3}{2} p \frac{L_m}{L_s}(\psi_{qs} i_{dr} - \psi_{ds} i_{qr}) \quad (15)$$

E. *Mechanical Equation*

$$\begin{aligned} J\frac{d\Omega_m}{dt} &= T_{em} - T_{load} \\ \frac{d\omega_m}{dt} &= \frac{p}{J}.(T_{em} - T_{load}) \end{aligned} \quad (16)$$

Where: J is the inertia on the shaft, ω_m is rotor angular velocity ($\omega_m = p\Omega_m$), T_{load} is the torque on the shaft originating from mechanical means, p is the number of pole pairs.

VI. BACK-TO-BACK CONVERTER MODELLING

The back to back converter can be associates into two[5,6]:
- A first rectifier part.
- An inverter second part.

The storage of the energy on the continuous side is done via a capacitor C of tension V_{dc}

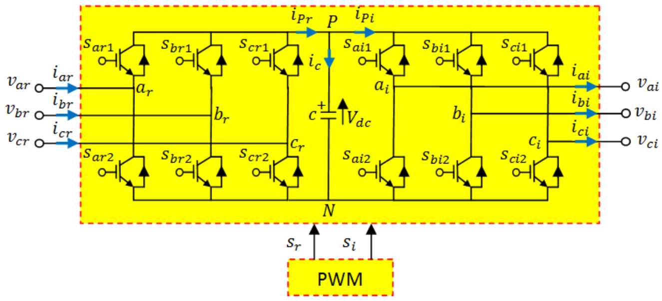

Figure 5. Power circuit of Back-to-back converter

The output voltage of rectifier and inverter of the back to back converter are calculated by using the following relation:

$$\begin{pmatrix} v_{ar} \\ v_{br} \\ v_{cr} \end{pmatrix} = v_{bus}\begin{pmatrix} s_{ar1} \\ s_{br2} \\ s_{cr3} \end{pmatrix}, \begin{pmatrix} v_{ai} \\ v_{bi} \\ v_{ci} \end{pmatrix} = v_{bus}\begin{pmatrix} s_{ai1} \\ s_{bi2} \\ s_{ci3} \end{pmatrix} \quad (17)$$

The current i_c that flows DC-link is given by the following relation:

$$i_c = i_{pr} - i_{pi} = (s_{ar1}i_{ar} - s_{br1}i_{br} - s_{cr1}i_{cr}) - (s_{ai1}i_{ai} - s_{bi1}i_{bi} - s_{ci1}i_{ci}) \quad (18)$$

VII. VECTOR CONTROL OF THE DFIG

A. *Rotor-side Converter (RSC) control*

Vector control is one of the most widely used control schemes for the DFIG based Wind Turbine Systems. Alignment to the stator flux simply means that the d-axis of the reference frame is chosen to coincide with the stator flux vector. This causes the q-axis component to be zero in the equations [6-10]. We can write:

$$\begin{cases} \psi_{ds} = \psi_s \\ \psi_{qs} = 0 \end{cases} \quad (19)$$

The rotor voltage dynamics are derived by aligning the rotor voltage equation to the stator flux. we have:

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$$\begin{cases} v_{dr} = R_r i_{dr} + \sigma L_r \dfrac{d}{dt} i_{dr} - \omega_r \sigma L_r i_{qr} + \dfrac{L_m}{L_s}\dfrac{d}{dt}\psi_s \\ v_{qr} = R_r i_{qr} + \sigma L_r \dfrac{d}{dt} i_{qr} + \omega_r \sigma L_r i_{dr} + \omega_r \dfrac{L_m}{L_s}\psi_s \end{cases} \quad (20)$$

where $\sigma = 1 - \dfrac{L_m^2}{L_s L_r}$ is the total leakage factor.

Consequently, the torque and reactive power are controlled independently from each other. The torque expression in the dq frame can be simplified as follows:

$$T_{em} = \frac{3}{2} p \frac{L_m}{L_s} \psi_s i_{qr} \Rightarrow T_{em} = K_T i_{qr} \quad (21)$$

And the stator reactive power expression in the dq frame:

$$Q_s = -\frac{3}{2}\omega_s \frac{L_m}{L_s}\psi_s \left(i_{dr} - \frac{\psi_s}{L_m} \right) \Rightarrow Q_s = K_Q \left(i_{dr} - \frac{\psi_s}{L_m} \right) \quad (22)$$

A general RSC control structure is shown in Figure 6.

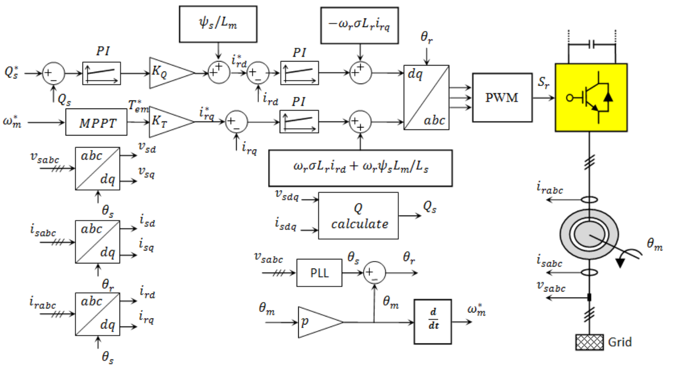

Figure 6. Bloc diagram of the RSC control [2,9]

B. Grid-side Converter (GSC) control

The objective of the grid-side converter is : (1) to keep the DC link voltage V_{dc} constant, and (2) to set a unit power factor [10]. In order to achieve these goals, many studies use the concept of vector control in the synchronous dq reference frame with voltage-oriented [6-10].

According to Kirchhoff voltage law, the voltage balance across the filter (R_f ,L_f) connected to the grid are given bellow:

$$\begin{cases} v_{af} = R_f i_{ag} + L_f \dfrac{d}{dt} i_{dg} + v_{ag} \\ v_{bf} = R_f i_{bg} + L_f \dfrac{d}{dt} i_{bg} + v_{bg} \\ v_{cf} = R_f i_{cg} + L_f \dfrac{d}{dt} i_{cg} + v_{cg} \end{cases} \quad (23)$$

Through a $(abc \to \alpha\beta)$ transformation, then $(\alpha\beta \to dq)$ transformation, we can get the voltage equation in the dq synchronously rotating frame:

$$\begin{cases} v_{df} = R_r i_{dg} + L_f \dfrac{d}{dt} i_{dg} + v_{dg} - \omega_s L_f i_{qg} \\ v_{qf} = R_r i_{qg} + L_f \dfrac{d}{dt} i_{qg} + v_{qg} + \omega_s L_f i_{dg} \end{cases} \quad (24)$$

Where ω_s the supply angular frequency.

The d-axis of the dq reference frame will be aligned with the grid voltage angular position. So,

$$\begin{cases} \sqrt{{v_{dg}}^2 + {v_{dg}}^2} = v_{dg} = v_g \\ v_{qg} = 0 \end{cases} \quad (25)$$

we get

$$\begin{cases} v_{df} = R_r i_{dg} + L_f \dfrac{d}{dt} i_{dg} + v_{dg} - \omega_s L_f i_{qg} \\ v_{qf} = R_r i_{qg} + L_f \dfrac{d}{dt} i_{qg} + \omega_s L_f i_{dg} \end{cases} \quad (26)$$

The active power is proportional to i_{dg} as:

$$P_g = \frac{3}{2}\left(v_{dg} i_{dg} + v_{qg} i_{qg} \right) = \frac{3}{2} v_{dg} i_{dg} \Rightarrow i_{dg}^* = K_{Pg} P_g^* \quad (27)$$

The reactive power is proportional to i_{qg} as:

$$Q_g = \frac{3}{2}\left(v_{qg} i_{dg} - v_{dg} i_{qg} \right) = -\frac{3}{2} v_{dg} i_{qg} \Rightarrow i_{qg}^* = K_{Qg} Q_g^* \quad (28)$$

A general GSC control structure is shown in Figure 7.

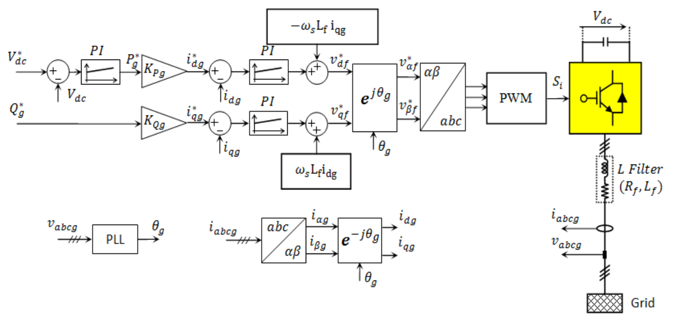

Figure 7. Bloc diagram of the GSC control [2,9]

VIII. SIMULATION RESULTS

In this section, we present the simulation results of the proposed control strategies for a DFIG based wind generation are conducted by using the Matlab/Simulink package. The

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DFIG is rated at 2 MW, and the main system parameters used in the simulation are listed in Table 1.

TABLE I THE MAIN SYSTEM PARAMETERS

System	Parameter
DFIG	Rated power : 2 MW, Rated stator voltage : 690 V_{rms} Rated stator current : 1760 A_{rms} Rated torque : 12.7 k.Nm, Pair of poles : 2, Rated rotor voltage :2070 V_{rms} R_s = 2.6 mΩ, $L_{\sigma s}$ = 87 mH, L_m = 2.5 mH, $L_{\sigma r}$ = 783 mH, R_r = 2.9 mΩ, $L_{\sigma r}$ = 87 µH, $L_s = L_m + L_{\sigma s}$ = 2.587 mH, $L_r = L_m + L_{\sigma r}$ =2.587 mH
Multiplier	N = 100
DC BUS	C_{bus} = 80 mF, V_{dc}= 1150 V
L Filter	R_f = 20 µΩ, L_f = 40 mH
Turbine	J = 127 kg.m^2, R = 42 m
GRID	V_s = 690 V, f = 50 Hz

The switching frequency of the power switches of the GSC and RSC is set to 4 kHz, and the frequency of the AC grid was 50 Hz.

To maximum value of the power coefficient corresponding, we choose a null pitch angle ($\beta = 0$ rad).

The grid-side converter controller is examined under the following condition; The reference of the DC bus voltage V_{dc}^* is set at 1150 V, and the reactive power reference value Q_g^* is set to zero for unity power factor operation of the converter.

The rotor-side converter controller is examined under the following condition; The reference torque T_{em}^* is calculated according to OT MPPT strategy, and The reference stator reactive power value Q_s^* is set to zero for unity power factor.

Figure 8 shows the wind speed profile varies as a step function with wind speed of 8, 10, and 12 m/sec

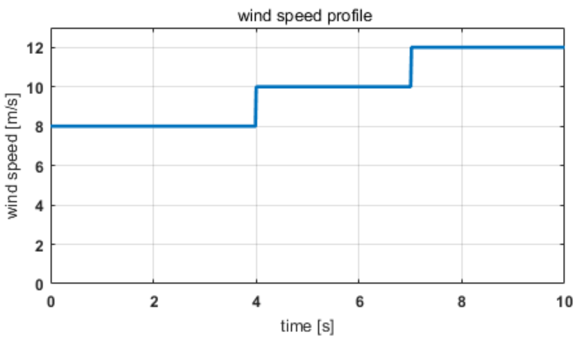

Figure 8. wind speed profile

Figure 9 shows the electromagnetic torque corresponds to a MPPT strategy and the generator electromagnetic torque.

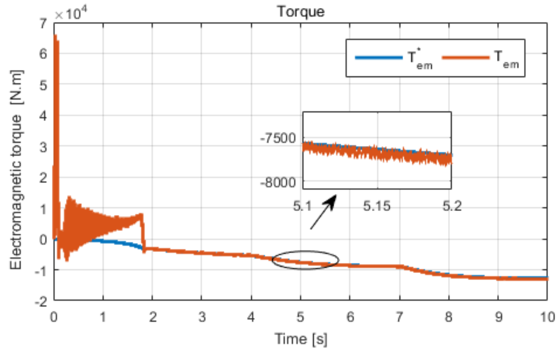

Figure 9. Electromagnetic torque

Figure 10 shows the stator reactive power.

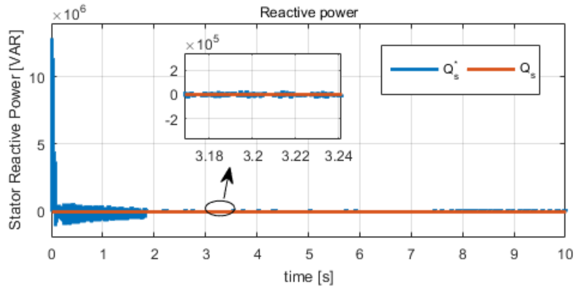

Figure 10. Stator reactive power

The evolution of the DC bus voltage can be seen in Figure 11

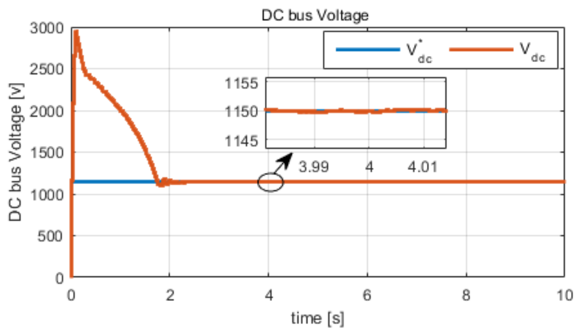

Figure 11. DC bus voltage

Figure 12 shows the phase shift between the stator current and the stator voltage is 180°. This means that the stator active power is deliver to the grid.

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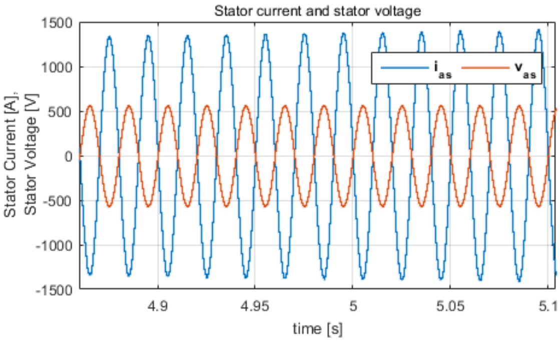

Figure 12. the stator current and the stator voltage

IX. Conclusions

In this paper, the modeling of the DFIG based on Wind Energy Conversion System (WECS) have been considered and clearly explained. Control strategies and fundamental mathematical equations of the RSC, GSC and MPPT have been presented in detail. The simulation results of DFIG controlled by RSC control and GSC control showed when the wind speed changed for given profile.

The obtained result using MATLAB®/Simulink® allows verify confidently working principle of the DFIG based on WECS.

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