DEVELOPMENT OF A WIND TURBINE SIMULATOR FOR WIND ENERGY CONVERSION SYSTEMS – EXPERIMENTAL RESULTS

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***Abstract* – The wind turbine simulator consists of a 5HP induction motor, which drives a doubly fed induction generator and is driven by a 19kVA inverter and real-time control software. A control program based on C language is developed that obtains wind profiles and, by using turbine characteristics and rotation speed of induction machine, calculates the theoretical shaft torque of a real wind turbine. The shaft torque of the induction machine is regulated according by controlling stator current demand of the inverter. In this way, the inverter has driven induction motor acts like a real wind turbine to the energy conversion system. The simulation and experimental results of the proposed wind turbine simulator show that scheme is viable.**

***Keywords* – renewable energy, wind energy, wind turbine simulator.**

I. INTRODUCTION

With exhausting of traditional energy sources (fossil fuels) and the creation of the restricted international environment regulations after the adoption of The Kyoto Protocol to the Convention on Climate Change, renewable and clean energy is receiving much attention all over the world [1]. As a result of increasing environmental concern, the impact of conventional electricity generation on the environment is begin minimized and efforts are made to generate electricity from renewable sources [2].

The main advantages of electricity generation from renewable sources are the absence of harmful emissions to the environment [3]. One way of generating electricity from renewable sources is to use wind turbines that convert the wind energy into electricity [4]. As a consequence many researchers are fixing their interest in this field, and wind power generation technique is beginning development rapidly. A typical wind energy conversion system consists of a wind turbine, a gearbox and a doubly-fed induction generator (DFIG). This typical system is shown in Fig. 1.

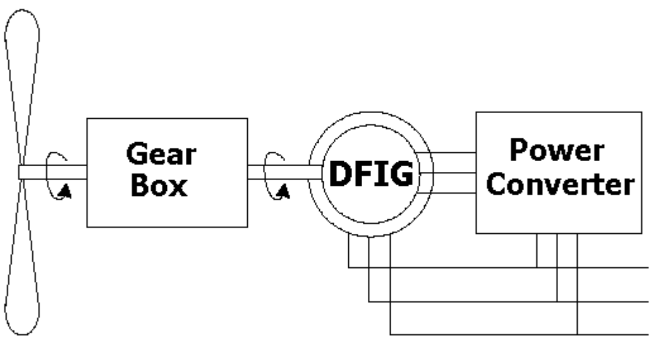

Fig. 1. Wind energy conversion system.

The wind turbine simulator presented in this paper is to simulate the external characteristics of a real wind turbine shown in Fig. 1, by an electrically controlled induction motor (IM) drive system. At a given wind speed, the operating point of the wind turbine is determined by the intersection between the turbine characteristic and the load characteristic. Usually, the load is an electrical generator, such as a doubly-fed induction generator or synchronous generator. The structure of the wind turbine simulator is presented in Fig. 2.

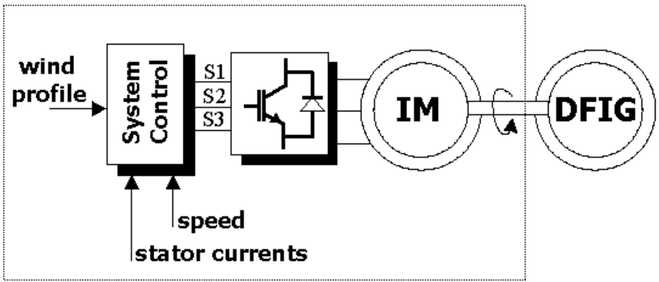

Fig. 2. Wind turbine simulator.

In this way, the paper presents a laboratory set-up to be used as wind turbine simulator. The simulator can be used for research applications to drive an electrical generator in a similar way as a wind turbine, by reproducing the torque developed by a wind turbine for a given wind speed. The power characteristic of a wind turbine is physically implemented by an induction motor drive. The shaft power and speed of the induction motor represent the power and speed of the wind turbine.

II. WIND TURBINE MODEL

The wind turbine consists of a rotor that extracts energy from the wind and converts it into mechanical power. In practice, the characteristics of a wind turbine can be represented in a simplified form of power performance coefficient (C_p) and tip speed ratio (λ). The $C_p - \lambda$ curve is usually used in industry to describe the characteristics of a wind turbine. The tip speed ratio of a wind turbine is given by:

$$\lambda = \frac{\omega_r R}{V} \tag{1}$$

Where:

R - the turbine rotor radius in meters (m);

ω_r - turbine rotor speed in radians per second (rad/s);

V - the wind speed in meters per second (m/s).

The performance coefficient that is a function of the tip speed ratio and the pitch angle (β) can be calculated by:

$$C_p = 0.22\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\frac{12.5}{\lambda_i}} \tag{2}$$

With:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{3}$$

The wind turbine characteristic calculated from performance coefficient and tip speed ratio, for various values of pitch angle is shown in Fig. 3, where the best efficiency is obtained when $\beta = 0^\circ$.

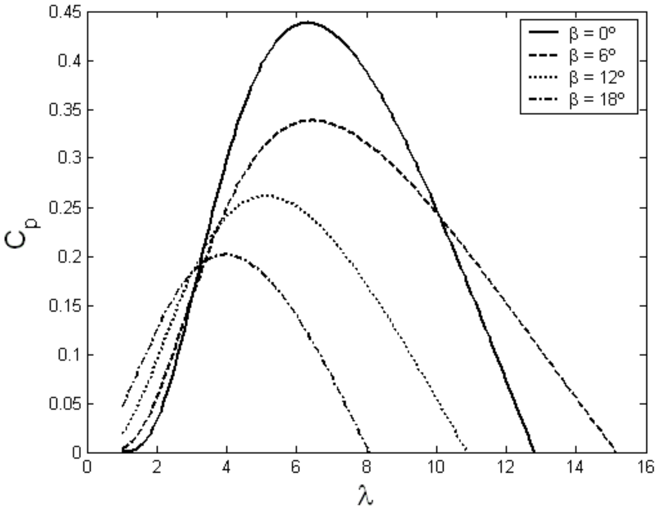

Fig. 3. $C_p - \lambda$ characteristics of a real wind turbine.

The following well know equation between wind speed and power extracted from the wind is:

$$P_{WT} = \frac{1}{2}\rho A V^3 C_p \tag{4}$$

Where:

P_{WT} - power extracted from the airflow (W);

ρ - air density (kg/m^3);

A - area covered by the rotor (m^2).

The mechanical power extracted from the wind can be calculated from (1) to (3), as shown in Fig. 4 for various values of wind speed. The curves represent the characteristics of a 2.2kW, three blades horizontal axis wind turbine with a rotor diameter of 1.65 meters. The initial operation wind speed (V_{cut-in}) is 5 m/s and the rated wind speed is 12m/s. In the high wind speed region the pitch angle is increased to shed some of the aerodynamic power. Ideally, the wind turbine should be operated at maximum performance coefficient $(C_{p_{MAX}})$ most of the time.

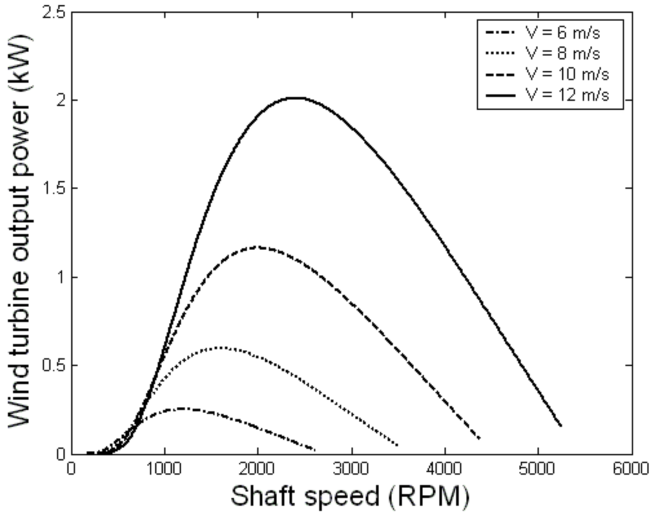

Fig. 4. Power-speed characteristics of a wind turbine.

From Fig. 4, it is noted the output power of the wind turbine is related to its shaft speed and wind speed. In order to reproduce the turbine characteristics of Fig. 3 and Fig. 4 in a laboratory, a micro-controller and PC based control system is development. The wind speed signal needed for the simulation can be obtained form measured wind data or can be set in artificial form by users.

III. EXPERIMENTAL SYSTEM DESCRIPTION

The three-phase IGBT inverter converts the fixed DC link voltage obtained from a three-phase bridge rectifier into a three-phase variable frequency variable voltage source, feeding to the induction machine prime mover of a doubly-fed induction generator, which acts as the load of the wind turbine simulator.

A Texas TMS320F2812 DSP controls the three-phase inverter. The DSP calculates the values of the stator voltage and sends out the appropriate pulses to the IGBT driver circuits, based on the errors between the demand current and actual current using current control strategy.

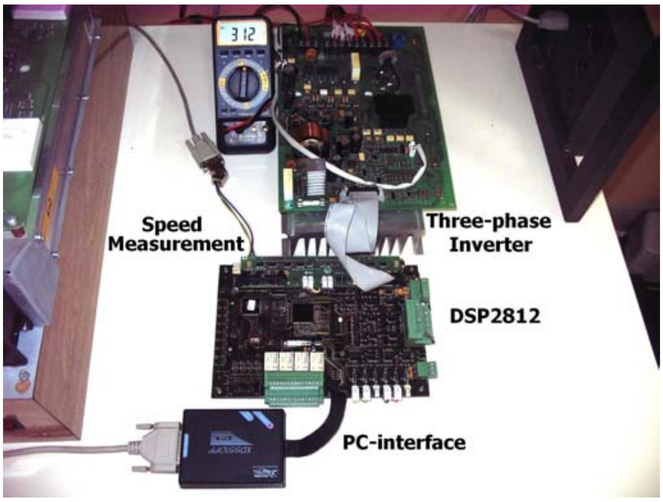

Fig. 5. Hardware to control wind turbine simulator.

IV. INVERTER CONTROL

The control strategy used to regulate the torque of the induction machine was a vector control with indirect field orientation. Indirect field orientation is based on the slip relation between stator currents and rotor flux of the machine in dq-axis for convenience. This method makes use of the fact that satisfying the slip relation is a necessary and sufficient condition to produce field orientation [5].

The rotor position (θ_m) information is obtained directly from a shaft encoder and the slip position (θ_{slip}) is derived from a slip calculator implementing by:

$$\omega_{slip} = \frac{\frac{1}{\tau_r} i_{sq}}{\frac{1}{\tau_r s + 1} i_{sd}} \tag{5}$$

Where:

ω_{slip} - slip frequency (rad/sec);

i_{sq} - quadrature component of the stator current (A);

i_{sd} - direct component of the stator current (A);

τ_r - time constant of the rotor flux (sec).

The rotor flux angle (θ_r) is obtained by summing a rotor position signal and slip position signal. A blocks diagram of the slip calculation is shown in Fig. 5.

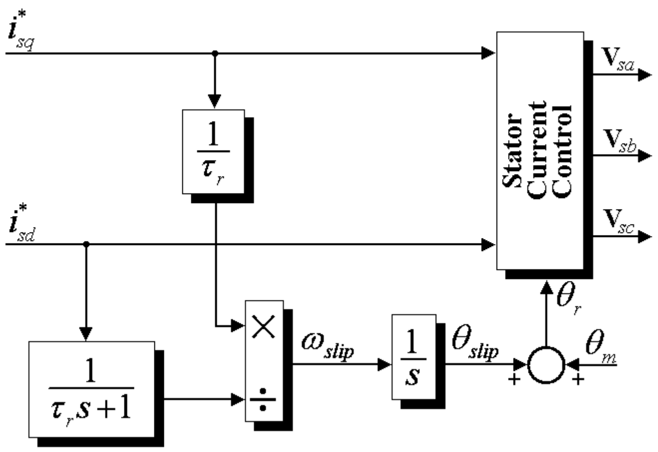

Fig. 5. Blocks diagram for the calculator of the rotor flux angle used to the field orientation.

The vector control strategy forces the inverter output currents to track demand current. The output currents are detected by current sensors and compared with the demand current waveforms. The q-axis component of the stator current is used to control the torque and the rotor flux magnitude can be controlled through the d-axis component. The dq-axis stator current control is shown in Fig. 6, in a simplified form using blocks diagram.

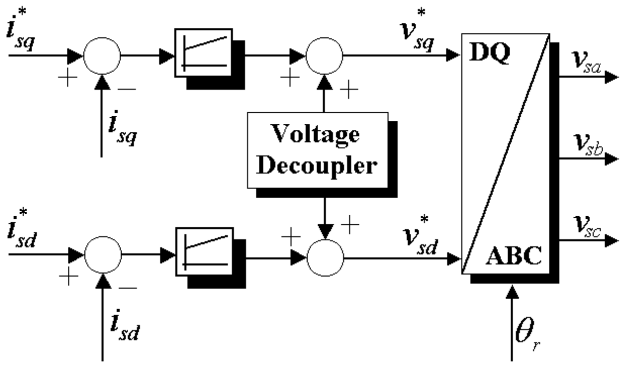

Fig. 6. Blocks diagram of the stator current control.

V. SIMULATION RESULTS

The wind speed profile used to obtain the simulation results is presented in Fig. 7. A variation in ramp, during a period from 0.5sec to 2.5sec, increases the initial wind speed (4m/s) until the rated wind speed (12m/s) to verify the all range operation of the wind turbine simulator.

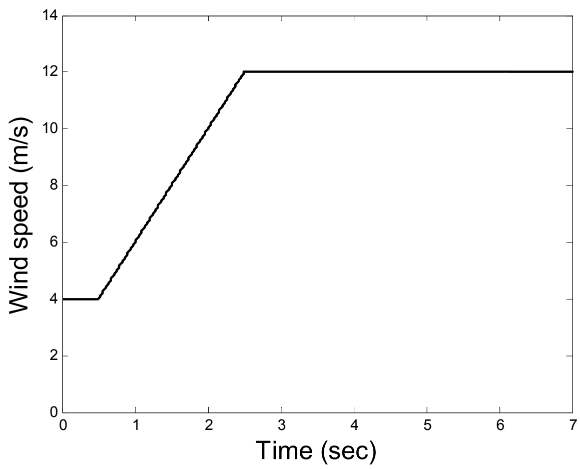

Fig. 7. Wind speed profile.

The response of the electromagnetic torque and the torque reference under a wind speed variation are shown in Fig. 8. It can be observed that the system tracks the maximum power point until rated electromagnetic torque is achieved.

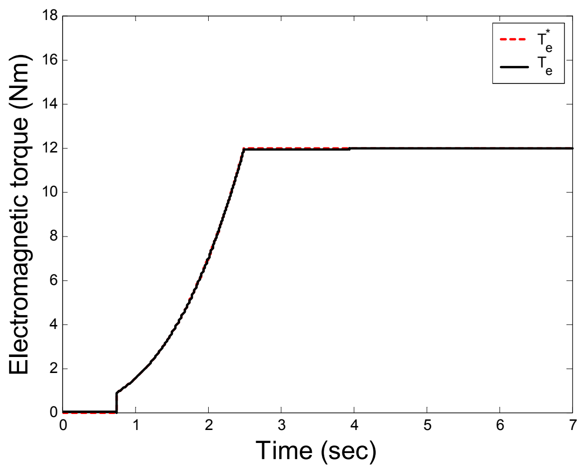

Fig. 8. Electromagnetic torque of the induction machine.

In the similar form, Fig. 9 shows the reference and the actual values of quadrature axis stator current, which is proportional to induction machine torque.

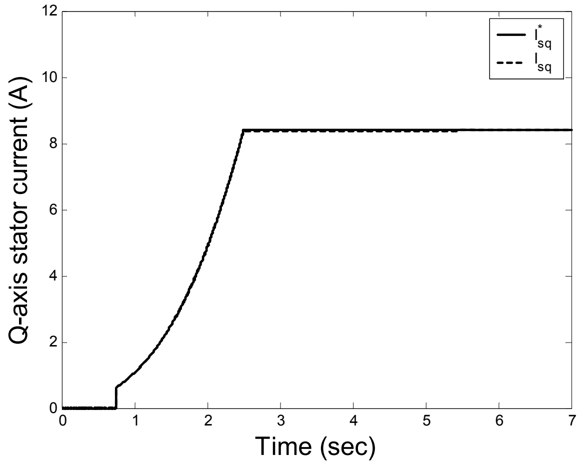

Fig. 9. Reference and actual q-axis stator current.

The d-axis stator current used to control the rotor flux magnitude is maintained constant. The d-axis current reference and actual values are shown in Fig. 10.

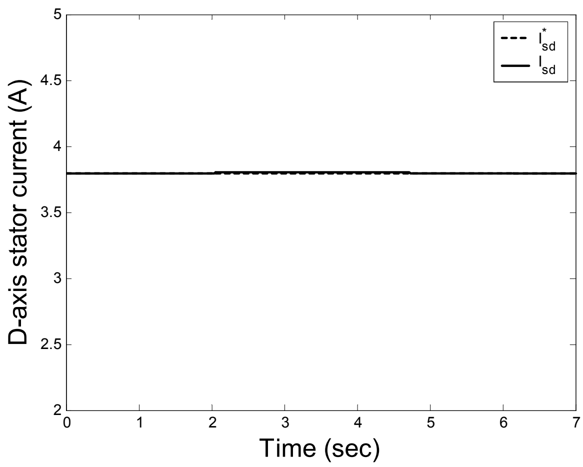

Fig. 10. Reference and actual d-axis stator current.

The active output power of the wind turbine simulator is presented in Fig. 11. When the torque was increased, the output power was increased too, until the rated value.

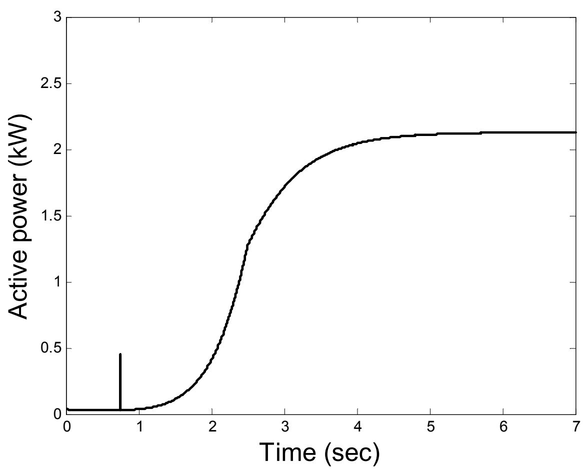

Fig. 12. Active power of the wind turbine simulator.

Fig 13 shows shaft speed of the wind turbine simulator. As the wind speed changes, the shaft speed should be adjusted to optimize the power produced.

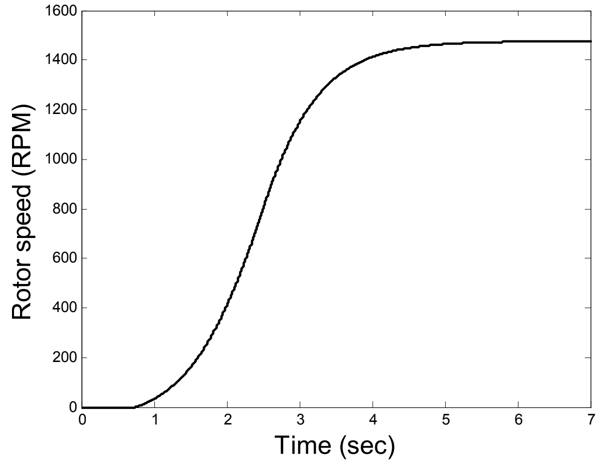

Fig. 13. Wind turbine simulator speed.

The three-phase stator currents are shown in Fig. 14. It can be seen, when the torque reference is zero and only DC current is applied to maintain the IM magnetized.

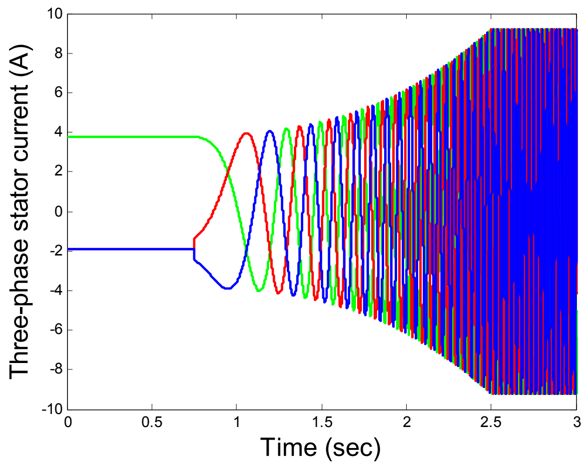

Fig. 14. Three-phase stator current of the IM.

The rotor flux angle used in the indirect field orientation obtained from the slip calculator is shown in Fig. 15. The correct estimation is very important to the system control.

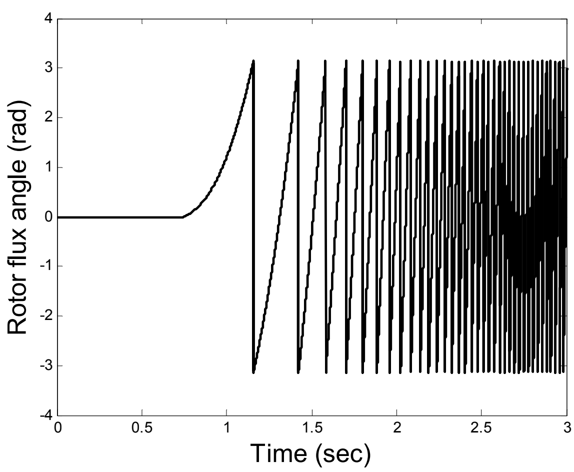

Fig. 15. Rotor flux angle to the indirect field orientation.

VI. EXPERIMENTAL RESULTS

In the practical implementation, the wind profile used to test the wind turbine simulator is presented in Fig. 16 and Fig. 17. Wind speed variation (4m/s until 12m/s) was used to calculate the torque reference for the system control. The torque reference is shown in Fig. 16 and Fig. 17 for an up and down wind speed variation, respectively.

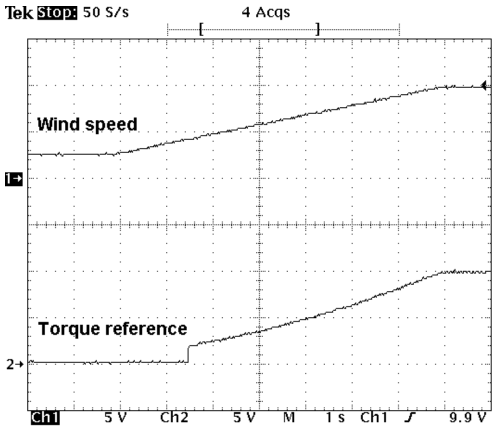

Fig. 16. Wind speed variation (up).
Vertical scales – Ch1: (6m/s)/div. Ch2: (6Nm)/div.

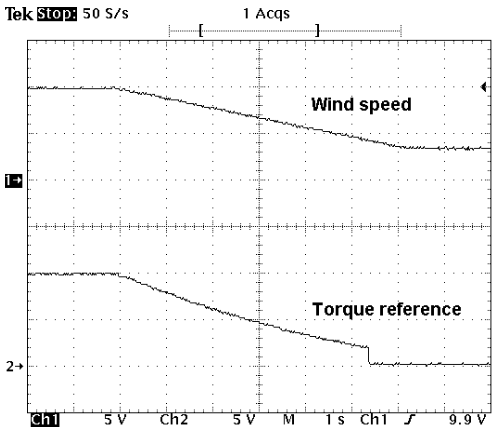

Fig. 17. Wind speed variation (down).
Vertical scales – Ch1: (6m/s)/div. Ch2: (6Nm)/div.

The q-axis stator current reference can be calculated from the desired torque of the induction machine. The reference torque and q-axis current reference are shown in Fig. 18.

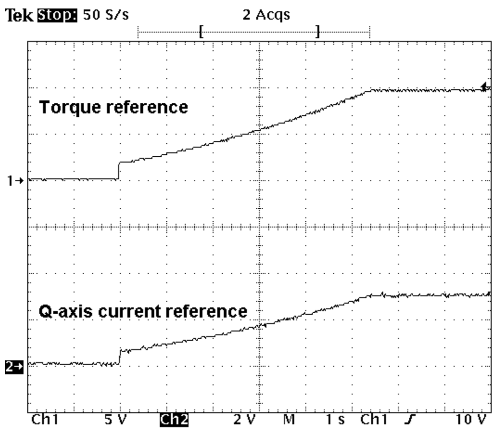

Fig. 18. Q-axis current reference obtained form torque.
Vertical scales – Ch1: (6Nm)/div. Ch2: (5A)/div.

Fig. 19 shows experimental results for the wind speed shown in Fig. 17. It can be observed that real stator current tracks the current reference to produce the desired torque.

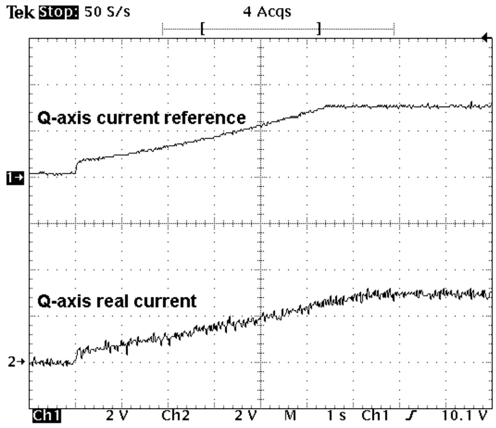

Fig. 19. Reference e real q-axis stator current.
Vertical scales – Ch1: (5A)/div. Ch2: (5A)/div.

The rotor flux of the induction machine should be maintained constant for a correct system control. The d-axis stator current used to control the rotor flux and your constant reference are shown in Fig. 20.

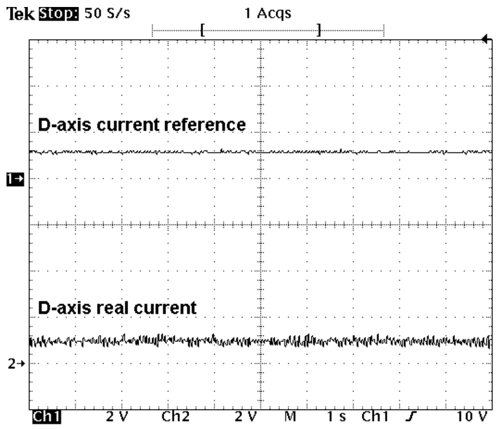

Fig. 20. Reference and real d-axis stator current.
Vertical scales – Ch1: (5A)/div. Ch2: (5A)/div.

Fig. 21 shows the q-axis and d-axis stator current to verify the influence between the dq-axis. It can be observed that there is no influence in order to obtain an efficient control.

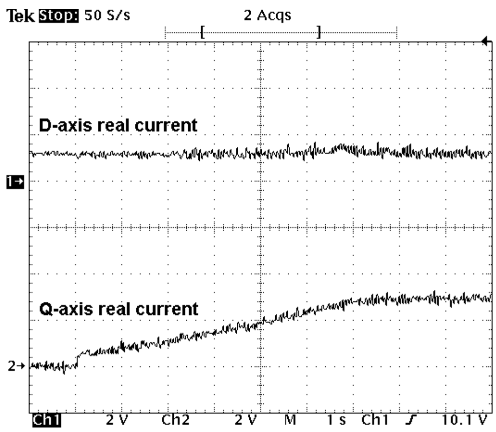

Fig. 21. Q-axis and d-axis stator current.
Vertical scales – Ch1: (5A)/div. Ch2: (5A)/div.

The torque and speed of wind turbine simulator developed, for the wind speed shown in Fig. 17, are presented in Fig. 22. The torque is proportional to the q-axis stator current.

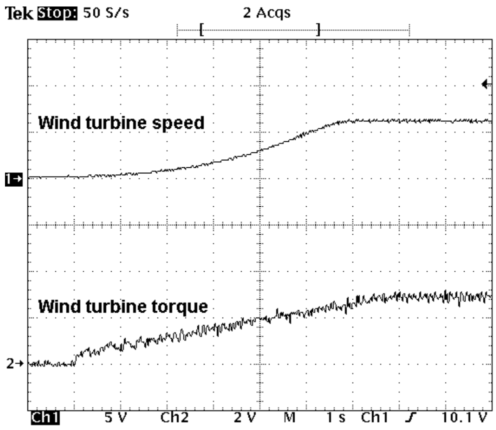

Fig. 22. Torque and speed of the induction machine.
Vertical scales – Ch1: (1000rpm)/div. Ch2: (6Nm)/div.

When the torque reference is set to zero, only DC current is used to maintain the induction motor magnetized. The phase-A stator current and torque of the wind turbine simulator is shown in Fig. 23. Fig. 24 shows in the similar form, the rotor flux angle used in the field orientation when the torque was increased.

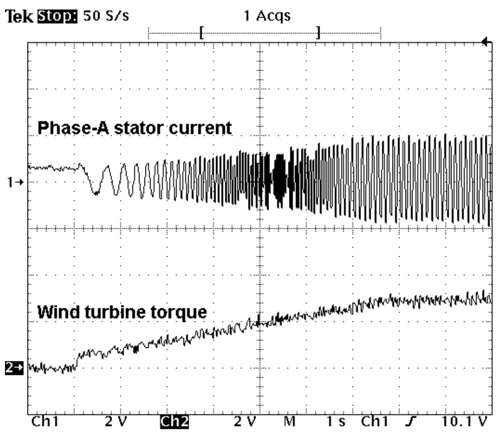

Fig. 23. Phase-A stator current of the induction machine.
Vertical scales – Ch1: (5A)/div. Ch2: (6Nm)/div.

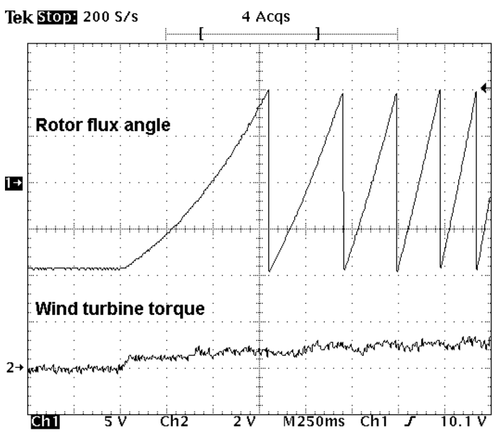

Fig. 24. Rotor flux angle used in field orientation.
Vertical scales – Ch1: (π/2)/div. Ch2: (6Nm)/div.

VII. CONCLUSION

This paper presented the wind turbine simulator implemented in laboratory by an AC motor drive with torque control strategy. A wind profile created on computer program was used to calculate the wind turbine torque and, consequently, the q-axis stator current (proportional to motor torque) necessary to system control strategy.

The control algorithms for wind turbine simulator are implemented in a DSP from Texas Instruments. This DSP is a commercial board designed for motor control systems. It is based on TMS320F2812 fix-point DSP.

The simulation results presented show that the steady-state characteristics of wind turbine simulator are similar to those of the given wind turbine. The experimental results show the appropriate behavior of the system and that scheme is viable.

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