Direct torque control of a doubly-fed induction generator of a variable speed wind turbine power regulation

Z. Mahi, C. Serban and H. Siguerdidjane

***Abstract*—A Direct Torque Control method (DTC) is presented, for a doubly-fed induction generator (DFIG) of a variable speed wind turbine, operating above the rated power. Nonlinear state-feedback control law has been used to provide the torque reference so as to reduce the produced electrical power tracking error. Direct torque control principles have been introduced, in this paper, to control the induction generator by means of a rotor connected voltage source inverter as an alternative to the classical field-oriented control methods widely used in drive control.**

I. INTRODUCTION

THE increasing interaction between the wind farms and the electrical network made necessary to design an optimal and a more adapted control law. Compared to the conventional constant speed wind turbine, the variable speed systems have the advantage to improve the dynamic behaviour, reduce the mechanical stress and the electrical fluctuations as well.

A multivariable control law has been designed in [1] and turns out to be a better alternative to the classical control strategies based on classical linear regulators (PI [3],[4], LQ [5],[6] and LQG [7]). This control law has been validated with an aero-elastic wind turbine simulator FAST developed by the National Renewable Energy Laboratory (NREL), Colorado and has shown significant improvements of the produced electrical power quality. However, it was not possible to study the integration of the wind turbine in the electrical network due to the fact that the electrical quantities outputs were not accessible.

So then, in order to perform the connection of the wind turbine into the grid, then it is necessary to conceive a generator control strategy. The electrical generator chosen is the doubly fed induction generation (DFIG) (Fig. 1). It consists of an induction machine with a stator directly connected to the grid and a rotor connected to the grid via two reversible AC/DC converters. The main advantages of this system are the structural robustness and the reduced converter needed for the same classical squirrel induction generator.

One of the interesting control strategies is the direct torque control strategy (DTC) as an alternative to the classical field oriented control method (FOC). The advantages of this technique are the lower parameter dependency and the simple structure. Moreover, there is no need of estimators for the torque and flux and release from additional lowest dynamics which will be eventually generated by a state observer.

As matter of fact, the DTC strategy has been used with success in [2] for a variable speed wind turbine. However, the power tracking regulation is limited due to the fact that it consists of a simple approximation only and therefore ignores the wind-up effects soliciting the mechanical structure of the aeroturbine.

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So, our idea is to combine both powerful multivariable control law mentioned above and the DTC strategy in order to more improve the produced electrical power quality and increase the robustness against the different perturbations causing a structural stress.

The paper is organized as follows: the fist part is devoted to the description of the aeroturbine model and to explicit the non-linear torque control law designed in [1]. In the second part, an induction generator model is detailed and allowed us to explain the DTC strategy control. Finally, the third part presents the simulation results of the control system, which show quite satisfactory performance.

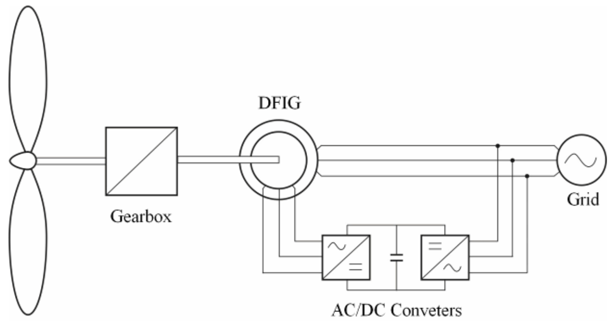

Fig. 1 Variable speed wind turbine with a doubly-fed induction generator

II. WIND TURBINE MODELING

A. Wind turbine aerodynamics

A wind turbine is generally represented as an electromechanical system composed of an aeroturbine, a gearbox, and a generator as shown in Fig 2.

The aerodynamic power extracted from the wind has the following expression:

$$P_a = \frac{1}{2}\rho\pi R^2 C_p(\lambda,\beta)v^3 \tag{1}$$

where $\lambda = \frac{\omega_r R}{v}$ is the tip speed ratio, β is the pitch blade inclination, and $C_p(\lambda,\beta)$ is the power coefficient determined with a curve specific to each aeroturbine.

We have:

$$P_a = T_a\omega_r \tag{2}$$

where T_a, the aerodynamic torque, is given by:

$$T_a = \frac{1}{2}\rho\pi R^3 C_q(\lambda,\beta)v^2 \tag{3}$$

and where $C_q(\lambda,\beta)$ is the torque coefficient determined with a curve specific to each aeroturbine too.

B. Modeling

The scheme of the aeroturbine using two-mass model is as showed in Fig. 2. The mechanical equations are:

$$J_r\dot{\omega}_r = T_a - B_r\omega_r - T_{ls}$$
$$J_g\dot{\omega}_g = T_{hs} - B_g\omega_g - T_{em} \qquad (4)$$
$$T_{ls} = K_{ls}(\omega_r - \omega_{ls}) - B_{ls}(\theta_r - \theta_{ls})$$

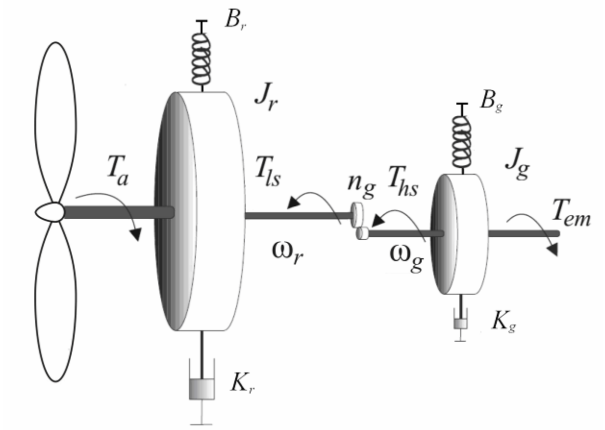

Fig. 2 Two-mass model of the variable speed wind turbine

By assuming that, the shaft may be considered as rigid. It is possible to simplify equations (4) into a single one-mass model scheme (Fig.3):

$$J_t\dot{\omega}_r = T_a - K_t\omega_r - T_g \qquad (5)$$

with

$$J_t = J_r + n_g^2 J_g$$
$$K_t = K_r + n_g^2 K_g$$
$$T_g = n_g T_{em}$$

and $n_g = \dfrac{\omega_g}{\omega_{ls}} = \dfrac{T_{ls}}{T_{hs}}$

where n_g is the gearbox ratio.

For the reader convenience, all the symbols and notations are given at the end of this paper.

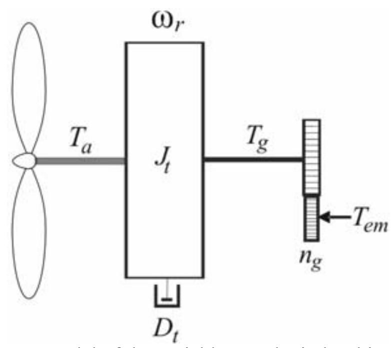

Fig. 3 One-mass model of the variable speed wind turbine

C. Control strategy

The main control objective is to obtain the optimal power tracking with a minimal solicitation of the wind turbine components.

A novel non-linear control strategy has been developed in [1] so as to reduce the power tracking error combined with a linear-based law pitch control. The non-linear control contributes to really improve the produced electrical power compared to the classical control described in the literature (PI, LQ and LQG.)

The principle of the multivariable control strategy is to impose the desired dynamics to the power tracking error. It is expressed by a state feedback torque control law combined with a PI pitch regulation in order to keep the rotor angular speed near to the nominal value.

1) Torque control

The electromagnetic torque is calculated via a non-linear controller with the purpose of imposing first order dynamics to the power tracking error which is defined as follows:

$$\varepsilon_p = P_{nom} - P \qquad (5)$$

The first order imposed dynamics are:

$$\dot{\varepsilon}_p + a_0\varepsilon_p = 0 \quad a_0 > 0 \qquad (6)$$

Also, if we consider the power expression $P_e = T_g\omega_r$ and using (5) and (6) then it comes out:

$$-\dot{\omega}_r T_g - \omega_r\dot{T}_g + a_0\varepsilon_p = 0 \qquad (7)$$

and yields:

$$T_g = \int \frac{1}{\omega_r}\left(-\dot{\omega}_r T_g + a_0\varepsilon_p\right)dt \qquad (8)$$

2) Pitch control

Besides, a pitch regulation is needed in order to reduce the torque fluctuations and to limit the rotor and generator speed.

It consists of a classical PI controller obtained from the local linearization of the non-linear model of the aeroturbine about the nominal operating point,

$$\Delta\beta = K_P(\omega_{nom} - \omega_r) + K_I\int(\omega_{nom} - \omega_r)dt \qquad (9)$$

The parameters K_P and K_I are shown to be:

$$K_p = 10\ ,\ K_I = \frac{10}{T_s} \qquad (10)$$

to meet the requirements. Where, T_s is a constant time depending on the chosen operating point of the aeroturbine.

III. DFIG Control law

A. DFIG modeling

The model is obtained with a d-q frame based on the Park transformation which allows us to convert the rotating stator and rotor quantities into fixed quantities in the corresponding rotating reference frame. The dq quantities are obtained from the 3-phases abc reference frame as follows:

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = P(\theta)\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \qquad (11)$$

where θ is the electrical angle and $P(\theta)$ the Park transformation matrix with

$$P(\theta) = \sqrt{\frac{2}{3}}\begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin(\theta) & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix}$$

which can be illustrated in Fig. 4:

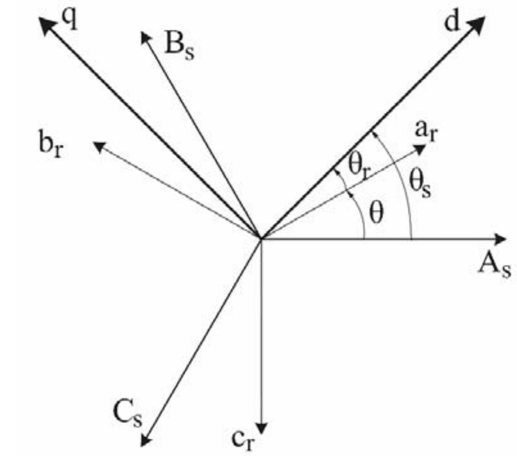

Fig. 4 Park transformation

The obtained mathematical model is well-known in the literature [8]. The generator convention is used and means that the active and reactive powers are positive when they fed into the grid. The equations are then:

$$
\begin{aligned}
v_{ds} &= -R_s i_{ds} - \omega_S \psi_{qs} + \frac{d\psi_{ds}}{dt} \\
v_{qs} &= -R_s i_{qs} + \omega_S \psi_{ds} + \frac{d\psi_{qs}}{dt} \\
v_{dr} &= -R_r i_{dr} - \omega_R \psi_{qr} + \frac{d\psi_{dr}}{dt} \\
v_{qr} &= -R_r i_{qr} + \omega_R \psi_{dr} + \frac{d\psi_{qr}}{dt}
\end{aligned}
\tag{12}
$$

$$
\begin{aligned}
\psi_{ds} &= -(L_s + L_m) i_{ds} - L_m i_{dr} \\
\psi_{qs} &= -(L_s + L_m) i_{qs} - L_m i_{qr} \\
\psi_{dr} &= -(L_r + L_m) i_{dr} - L_m i_{ds} \\
\psi_{qr} &= -(L_r + L_m) i_{qr} - L_m i_{qs}
\end{aligned}
\tag{13}
$$

The electrical angular velocity of the rotor is:

$$\omega_R = \omega_S - p\omega_r \tag{14}$$

The electric torque may be expressed with the stator and the rotor fluxes and/or currents for example:

$$T_e = pL_m (i_{qs} i_{dr} - i_{ds} i_{qr}) \tag{15}$$

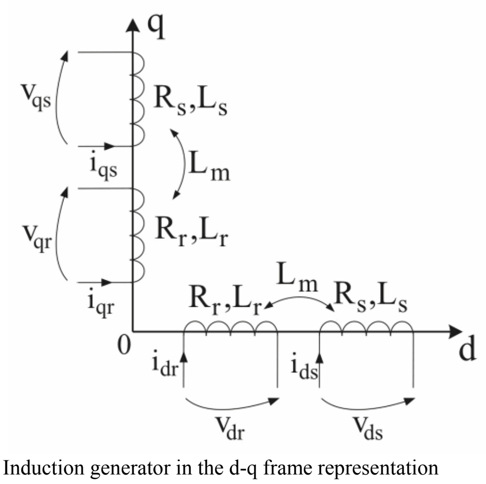

Fig. 5 Induction generator in the d-q frame representation

B. DFIG control law

1) DTC Principle

The suggested control strategy is the Direct Torque Control (DTC) chosen for having a simplest structure and the lower parameter dependency compared to the classical solution of the Field Oriented Control method.

This technique is based on the "direct" determination of the firing angle sequence imposed to the 'back-to-back' converter. This method has been developed for the direct regulation of the torque and the flux. The electromagnetic torque of the machine is a function of the stator and the rotor fluxes and the angle in between:

$$T_e = \frac{3}{2} p \frac{L_m}{\rho L_s L_r} \psi_s \psi_r \sin(\gamma) \tag{16}$$

The stator flux is established according to the network frequency. Then, it is possible to manipulate both torque and rotor flux by imposing the right voltage phasor as illustrated in Fig. 6. The torque is regulated by manipulating the angle γ between the rotor and the stator fluxes. One may notice that the rotor flux is established faster then the stator one.

We can finally consider that the radial and the tangential part of the voltage phasor manipulate the rotor flux and the torque respectively.

The voltage phasor is defined via an optimal switching table by using the logical output of the torque and flux hysteresis comparators and the location of the flux.

TABLE I
COMMUTATION RULES

		Sector i(θ)
Δ Ψr=1	*Δ T=1*	u_{Ri+1}
	Δ T=0	u_{Ri-1}
Δ Ψr=0	*Δ T=1*	u_{Ri+2}
	Δ T=0	u_{Ri-2}

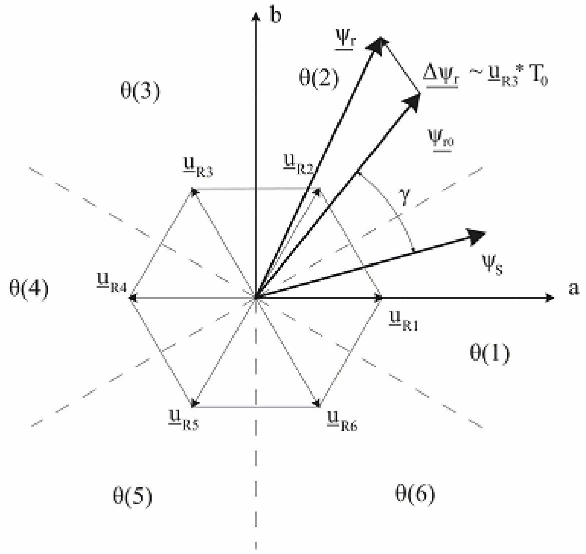

Fig. 6 DTC principle

2) Flux and torque estimation

The flux and torque are directly calculated from the measured currents and the machine parameters.

The magnitude and the angle of the rotor flux are determined using (α, β) reference frame as follows:

$$\psi_r = \sqrt{\psi_{\alpha r}^2 + \psi_{\beta r}^2}$$
$$\angle \psi_r = atg\left(\psi_{\alpha r} \Big/ \psi_{\beta r} \right) \tag{17}$$
$$T_e = pL_m\left(i_{qs}i_{dr} - i_{ds}i_{qr}\right)$$

IV. Simulation results

The simulation results have been performed to verify the efficiency of the proposed controller which combines a non-linear controller and a DTC one. The aeroturbine and the induction generator parameters used are showed in Table II.

TABLE II
WIND TURBINE PARAMETERS

Rotor diameter	43.3 m
Gearbox ratio	*43.165*
Hub height	*36.6 m*
Generator system electrical power	*600 kW*
Maximum rotor torque	*162 kN.m*

The first performed simulation consists of the angular speed tracking using a PI regulator as illustrated in Fig. 7.

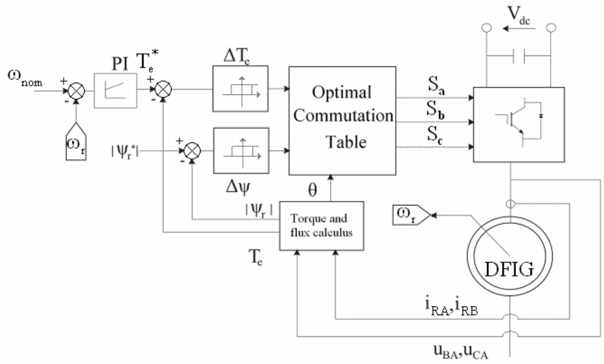

Fig. 7 Speed regulation using DTC strategy

One may observe that (Fig. 8), the DTC achieves a good rotor speed regulation for +/- 3 rad/s steady state error.

Figures 11 and 13 shows the electrical torque and the rotor flux responses which confirm the efficiency of the DTC strategy by the relatively small steady state error (Fig.12, Fig. 14)

The second performed simulation, both multivariable control and the DTC strategies are used according to the scheme of Fig. 8. The electrical power produced exhibits good performance with a relatively small steady state error depending on the torque one (Fig. 19.)

Figures 15 and 17 shows the electrical torque and the rotor flux responses which confirm too, as in the previous simulation, the efficiency of the DTC strategy by the relatively small steady state error (Fig.16, Fig. 18)

The torque and flux display some fluctuations. Nevertheless, the performance are not deteriorated, in comparison with the results given in [8].

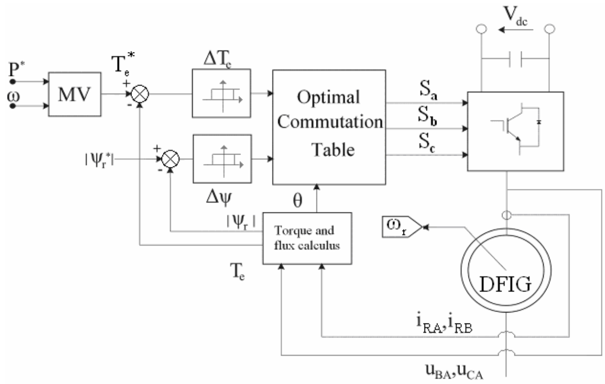

Fig. 8 Multivariable control and DTC strategies schemes

V. Conclusion

In this work, it has been proposed a controller which combines a DTC strategy with a multivariable strategy developed in [1] in order to guarantee good performance as confirmed by the resulting simulations. The control objectives have been met. The extension to the wind farm behavior using a similar procedure is being planned to be studied in a near future.

Notation and symbols

v	wind speed (m.s^{-1})
ρ	air density (kg.m^{-3})
R	rotor radius (m)
P_a	aerodynamic power (W)
T_a	aerodynamic torque (N.m)
λ	tip speed ratio
$C_p(\lambda,\beta)$	power coefficient
$C_q(\lambda,\beta)$	torque coefficient
ω_r	rotor speed (rad.s^{-1})
ω_g	generator speed (rad.s^{-1})
T_{em}	electromagnetic torque (N.m)
T_g	generator torque in the rotor side (N.m)
T_{ls}	low speed shaft (N.m)
T_{hs}	high speed shaft (N.m)
J_r	rotor inertia (kg.m^{é})
J_g	generator inertia (kg.m^{é})
J_t	turbine total inertia (kg.m^{é})
K_r	rotor external damping (N.m.rad^{-1})
K_g	generator external damping (N.m.rad^{-1})
B_r	rotor external stiffness (N.m.rad^{-1})
B_g	tenerator external stiffness (N.m.rad^{-1})
B_t	turbine total external stiffness (N.m.rad^{-1})
v_s, v_r	stator and rotor voltages (V)
i_s, i_r	stator and rotor currents (A)

ψ_s , ψ_r	stator and rotor fluxes (V.s)
R_s , R_r	stator and rotor resistances (Ω)
X_{abc}	variables in the abc reference frame
X_{dq}	variables in the dq reference frame
X_s	stator variable
X_r	rotor variable
ω_S	stator angular speed (rad.s^{-1})
ω_R	rotor angular speed (rad.s^{-1})
L_s	stator leakage inductance (H)
L_r	rotor leakage inductance (H)
L_m	mutual inductance(H)

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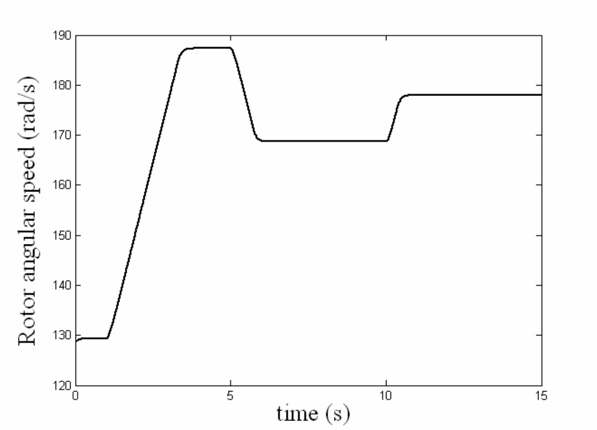

Fig. 9 Rotor angular speed with PI and DTC

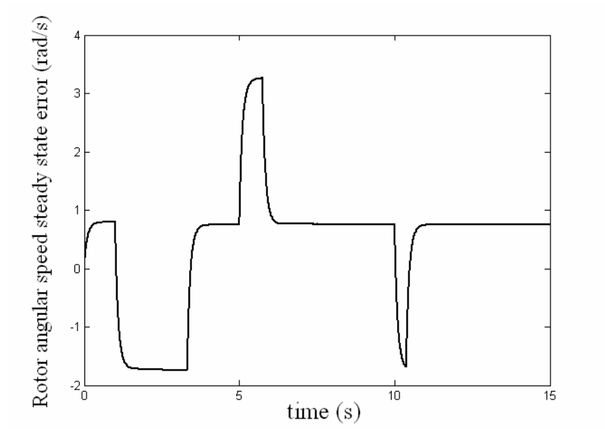

Fig. 10 Rotor angular speed steady state erroe with PI and DTC

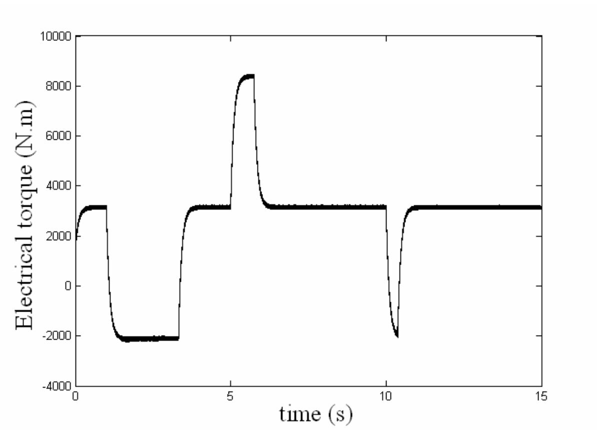

Fig. 11 Electrical torque with PI regulation and DTC

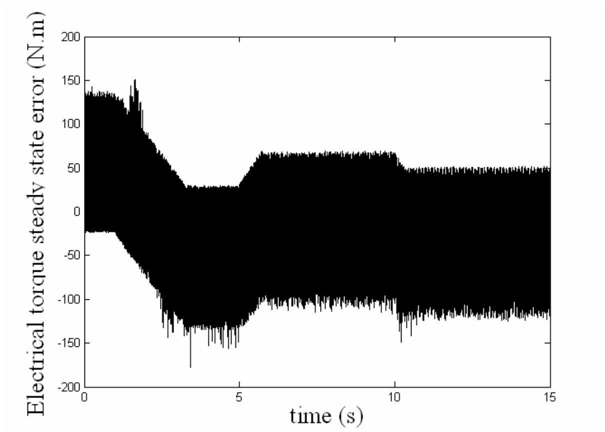

Fig. 12 Electrical torque steady state error with PI regulation and DTC

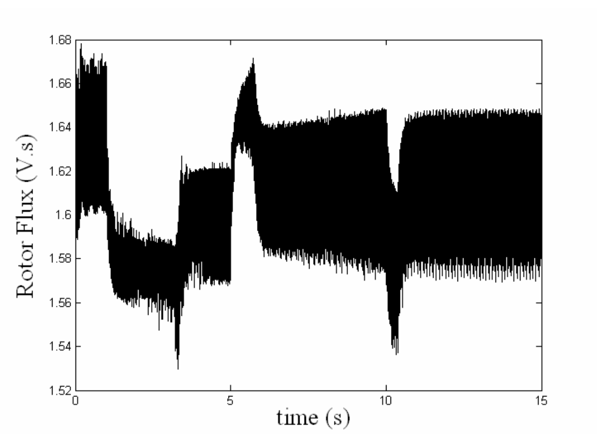

Fig. 13 Rotor flux with PI regulation and DTC

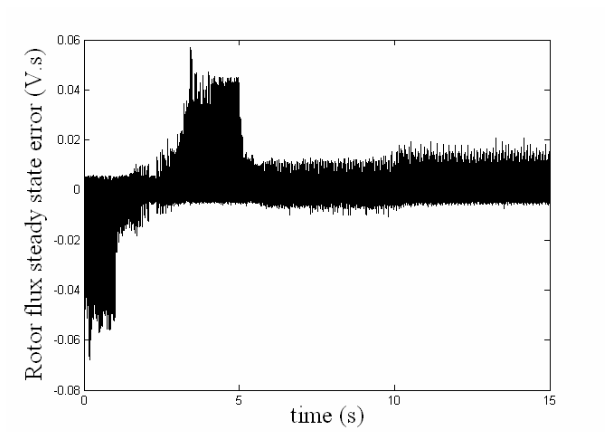

Fig. 14 Rotor flux steady state error with PI regulation and DTC

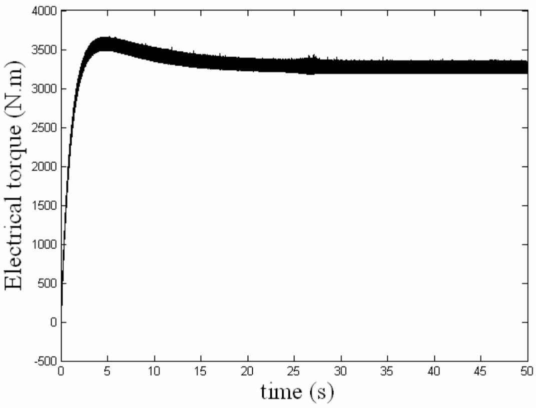

Fig. 15 Electrical torque with the multivariable control and DTC strategies

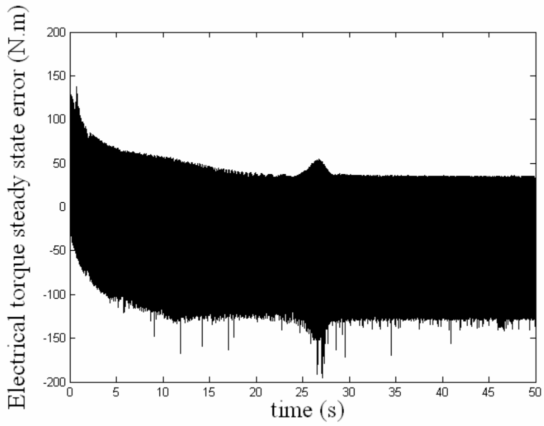

Fig. 16 Electrical torque steady state error with the multivariable control and DTC strategies

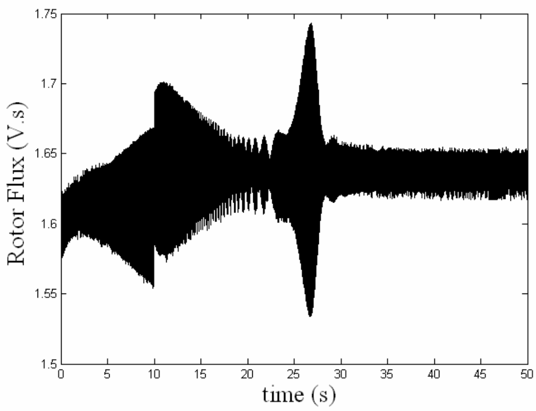

Fig. 17 Rotor flux with the multivariable control and DTC strategies

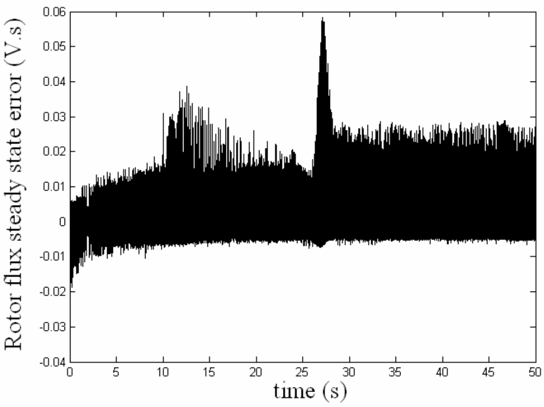

Fig. 18 Rotor flux steady state error regulation with the multivariable control and DTC strategies

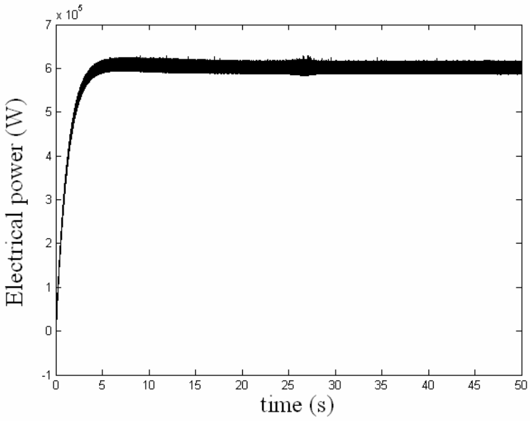

Fig. 19 Active power regulation with the multivariable control and DTC strategies