A direct torque and reactive power control approach for doubly fed induction generator in wind turbine applications

Qian Liu and Kay Hameyer

Abstract—**This paper focuses on a new direct torque and reactive power control approach for doubly fed induction generators for wind turbines. In order to design the rotor side controller and study the transient behavior, equations which directly describe the dynamics of the torque and reactive power in a doubly fed induction generator are proposed in this paper. Relying on these equations, controllers using internal model control are discussed to guarantee the transient behaviors of the torque and reactive power. These controllers are designed based on stator flux orientation but can also be implemented in a stationary reference frame, where the full order model of the doubly fed induction generator is considered. The stability and robustness of the proposed control approach are demonstrated in the paper. The proposed control approach is implemented and validated in Matlab/Simulink. The simulation results demonstrate different transient dynamics with different transient compensations and the robustness of the proposed direct control approach.**

Index Terms—**doubly fed induction generator, direct torque control, internal mode control, robustness, transient dynamics, voltage dip, wind turbine.**

I. Introduction

Regarding environmental issues, the wind energy technologies are becoming more and more popular and mature. The doubly fed induction generator (DFIG) operated by wind turbines plays a very important role in the wind energy market especially at the MW levels. They have several advantages in comparison to the fixed speed wind turbines with converters of full rated power. In normal operation mode, the rotational speeds of a DFIG wind turbine could be approximately $\pm 25\%$ to $\pm 30\%$ of the synchronous speed so that the wind turbine could extract the maximum power from the wind [1]. On the other hand, the power converter system of the DFIG wind turbine is only rated at 30% of the generator rating, which reduces the requirement of the power electronics and therefore cost.

The behavior of the DFIG, especially the active and reactive power generation, depends on the control strategy of the rotor-side converter (RSC) system. Various control methods have been introduced in the last decade with the objective of tracking the optimal power extracted from the wind. The conventional method of the DFIG control system is the rotor current vector control [2]–[4], which is based on the stator flux or stator voltage fixed reference frame which decouples d and q components of the current. This method is achieved either by algebraic calculations with a PI controller [2] or cascaded PI controllers [3]. These two approaches are easy to implement. However, they are designed based on calculations without considering the stator losses. In addition, the control parameter for the cascaded PI controllers should be chosen carefully to guarantee the stability of the DFIG system.

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Two methods, the direct torque control (DTC) and the direct power control (DPC) are developed as alternatives to the vector control. The conventional DTC approach is based on a switching-table, where neither current controller nor PWM modulator are required [5]. The power quality of this approach are limited by the inverter's switching frequency, which results in undesired torque and speed ripples. In order to overcome these drawbacks, a novel DTC combined with space vector modulation (SVM) for induction machines is introduced in [5]. The controller based on a novel DTC approach shows good performance for the DFIG wind turbine system [1], [6]. The DPC approach is based on the DTC principles and shows high robustness against parameter errors of the DFIG [7]–[9]. However, this DPC approach lacks consideration of the stator transients and the rotor resistance. In addition, the guaranty about the stability of the controllers is not theoretically shown for existing DTC and DPC strategies.

This paper proposes a new direct torque and reactive control approach which combines the ideas of the vector control with those from DTC. The torque and reactive power can be controlled independently and the dynamics of the electrical torque and reactive power can be well expressed without neglecting resistances in stator and rotor. With these expressions, the controllers based on internal mode control (IMC) are designed to guarantee the stability of the torque and reactive power and to improve the transient dynamics. The robustness of the proposed control approach will be discussed. These controllers are validated by simulations in Matlab/Simulink based on data of a Vestas V52 wind turbine. The simulation results demonstrate the performance of the proposed control approach during a torque step response and a voltage dip.

II. Mathematical model of DFIG

The equivalent circuit of a DFIG in Park's reference frame is shown in Fig. 1. Here the generator convention is used, which means that the currents are flowing out of the generator and the power supplying the power grid is defined as positive. Voltage and current are described in d,q reference frame, where q axis leads d axis by $90°$. After the power invariant Park transformation, the dynamic system of the DFIG in synchronous frame can be presented by the

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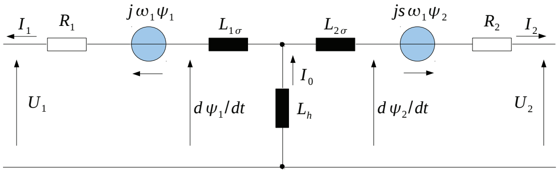

Fig. 1. Equivalent circuit of a DFIG.

following [2]:

$$U_{d1} = -R_1 I_{d1} - \omega_1 \psi_{q1} + \frac{d\psi_{d1}}{dt} \quad (1)$$

$$U_{q1} = -R_1 I_{q1} + \omega_1 \psi_{d1} + \frac{d\psi_{q1}}{dt} \quad (2)$$

$$U_{d2} = -R_2 I_{d2} - s\omega_1 \psi_{q2} + \frac{d\psi_{d2}}{dt} \quad (3)$$

$$U_{q2} = -R_2 I_{q2} + s\omega_1 \psi_{d2} + \frac{d\psi_{q2}}{dt} \quad (4)$$

where the subscripts 1 and 2 denote stator and rotor quantities. ω_1 is the stator angular speed in electrical radian. The quantity s is the slip of the stator and rotor speeds in electrical radian which is defined by $s = 1 - \frac{p}{2}\frac{\omega_2}{\omega_1}$, where p is the pole number of the DFIG, ω_2 is the rotor speed in mechanical radian. The flux linkage ψ is estimated by:

$$\psi_{d1} = -L_1 I_{d1} - L_h I_{d2} \quad (5)$$

$$\psi_{q1} = -L_1 I_{q1} - L_h I_{q2} \quad (6)$$

$$\psi_{d2} = -L_2 I_{d2} - L_h I_{d1} \quad (7)$$

$$\psi_{q2} = -L_2 I_{q2} - L_h I_{q1} \quad (8)$$

where $L_1 = L_{1\sigma} + L_h$ and $L_2 = L_{2\sigma} + L_h$. Here $L_{1\sigma}$ and $L_{2\sigma}$ are the stator and rotor leakage inductances respectively. L_h is the mutual inductance. The electromagnetic torque of the DFIG is calculated by:

$$T_e = \frac{p}{2}(\psi_{q2} I_{d2} - \psi_{d2} I_{q2}) \quad (9)$$

Since the reactive power of the DFIG rotor can be controlled by the grid-side converter (GSC), here only the reactive power of the DFIG stator is considered:

$$Q_1 = \omega_1(\psi_{d1} I_{d1} + \psi_{q1} I_{q1}) \quad (10)$$

III. Control approach in stator flux oriented frame

The revised direct torque and reactive power controllers combine the ideas of the vector control and those of DTC. The controllers are derived based on decoupled currents in the stator flux oriented (SFO) reference frame. Afterwards, these controllers which directly control the torque and reactive power are transformed back and implemented in the stationary reference frame.

A. Dynamics in stator flux oriented frame

Referring the DFIG model to SFO reference frame, where the d-axis is along the direction of the stator flux and using superscript s to denote the quantities in SFO reference frame, we have $\psi^s_{d1} = |\psi_{d1}|$ and $\psi^s_{q1} = 0$. Substituting (5)-(8) into (9) and (10), the expression of the electromagnetic torque and reactive power can be rewritten into the following equations in the SFO reference frame:

$$T_e = -\frac{p}{2}\frac{\psi^s_{d1} L_h I^s_{q2}}{L_1} \quad (11)$$

$$Q_1 = -\frac{\omega_1(\psi^s_{d1})^2}{L_1} - \frac{\omega_1 L_h \psi^s_{d1} I^s_{d2}}{L_1} \quad (12)$$

To find the description of the dynamics for electromagnetic torque T_e and reactive power Q_1, the rotor dynamics $d\psi_{d2}/dt$ and $d\psi_{q2}/dt$ in (7) and (8) are revised in the SFO reference frame:

$$\frac{d\psi^s_{d2}}{dt} = -(L_2 - \frac{L_h^2}{L_1})\frac{dI^s_{d2}}{dt} + \frac{L_h}{L_1}\frac{d\psi^s_{d1}}{dt} \quad (13)$$

$$\frac{d\psi^s_{q2}}{dt} = -(L_2 - \frac{L_h^2}{L_1})\frac{dI^s_{q2}}{dt} \quad (14)$$

Inserting (13) (14) into (3) and (4), the The dynamic rotor equations can be rewritten in form of the dynamic current equations in the SFO reference frame:

$$U^s_{d2} = -R_2 I^s_{d2} - s\omega_1 \psi^s_{q2} - \sigma L_2 \frac{dI^s_{d2}}{dt} + \frac{L_h}{L_1}\frac{d\psi^s_{d1}}{dt} \quad (15)$$

$$U^s_{q2} = -R_2 I^s_{q2} + s\omega_1 \psi^s_{d2} - \sigma L_2 \frac{dI^s_{q2}}{dt} \quad (16)$$

where $\sigma = 1 - \frac{L_h^2}{L_1 L_2}$ is defined as the total leakage coefficient of the DFIG.

Taking the time derivative in both sides of equation (11) and inserting (16), an equation which describes the dynamic electromagnetic torque T_e is obtained:

$$\frac{dT_e}{dt} = -\frac{R_2}{\sigma L_2} T_e + \frac{p\psi^s_{d1} L_h}{2\sigma L_1 L_2}(U^s_{q2} - s\omega_1 \psi^s_{d2}) - \frac{p L_h I^s_{q2}}{2L_1}\frac{d\psi^s_{d1}}{dt} \quad (17)$$

The situation of the reactive power Q_1 is slightly different. To simplify the expression of the reactive power dynamics, we define a revised reactive power:

$$Q_{rev} = Q_1 + \frac{\omega_1(\psi^s_{d1})^2}{L_1} = -\frac{\omega_1 L_h \psi^s_{d1} I_{d2}}{L_1} \quad (18)$$

Similar to the electromagnetic torque T_e, the dynamic equation of the reactive power Q_{rev} can also be deduced by taking the time derivatives in both sides of equation (12) and inserting equation (15).

$$\frac{dQ_{rev}}{dt} = -\frac{R_2}{\sigma L_2} Q_{rev} + \frac{\omega_1 \psi^s_{d1} L_h}{\sigma L_1 L_2}(U^s_{d2} + s\omega_1 \psi^s_{q2}) - (\frac{L_h}{\sigma L_1 L_2}\psi^s_{d1} + I^s_{d2})\frac{L_h \omega_1}{L_1}\frac{d\psi^s_{d1}}{dt} \quad (19)$$

where the derivative of the stator flux $d\psi^s_{d1}/dt$ in (17) and (19) is determined by:

$$\frac{\psi^s_{d1}}{dt} = U^s_{d1} + R_1 I^s_{d1} \quad (20)$$

Combining equations (17) and (19), the transient electromagnetic torque and reactive power can be directly obtained. Within the equations, the stator transients and resistance are not neglected. With this, the transient torque and reactive power can be directly studied. Notice, although the expression is relatively complex, the state space described by (17) and (19) is linear when ignoring the complex compensation terms. This is helpful for the controller design and stability investigations, which will be discussed in the following section. A simplification could also be made by neglecting the stator transient dynamics due to the fact that the terminal voltage of a DFIG is almost constant, that is $d\psi_{d1}^s/dt = 0$. However, in order to show its influence during a voltage dip, the stator transients are considered and will be discussed in this paper.

B. Direct torque and reactive power control

The direct control of the torque and reactive power is based on equations (17) and (19). To simplify the expressions and compensating the coupling quantities during the controller design, denote

$$U_{q2}^{'s} = \frac{p\psi_{d1}^s L_h}{2\sigma L_1 L_2}(U_{q2}^s - s\omega_1\psi_{d2}^s) - \frac{pL_h I_{q2}^s}{2L_1}\frac{d\psi_{d1}^s}{dt} \quad (21)$$

$$U_{d2}^{'s} = \frac{\omega_1\psi_{d1}^s L_h}{\sigma L_1 L_2}(U_{d2}^s + s\omega_1\psi_{q2}^s) - \left(\frac{L_h}{\sigma L_2 L_1}\psi_{d1}^s + I_{d2}^s\right)\frac{L_h\omega_1}{L_1}\frac{d\psi_{d1}^s}{dt} \quad (22)$$

Rewriting equations (17) and (19) yields the following form:

$$\frac{dT_e}{dt} = -\frac{R_2}{\sigma L_2}T_e + U_{q2}^{'s} \quad (23)$$

$$\frac{dQ_{rev}}{dt} = -\frac{R_2}{\sigma L_2}Q_{rev} + U_{d2}^{'s} \quad (24)$$

Based on (23) and (24), the electromagnetic torque and the reactive power are controlled by $U_{q2}^{'s}$ and $U_{d2}^{'s}$ respectively. To guarantee the stability and robustness of the torque and reactive power, controllers based on IMC are introduced to estimate the rotor voltage [10], [11].

The IMC approach can be used as controller design procedure for the drive train of an AC machine if the model of the machine is already known. This IMC approach is well known for the decoupled current control and it behaves robust against the model mismatch [10], [11]. Similar to (17) and (19), the system for torque and reactive power is a decoupled linear system of first order. Since

$$Q_{rev}^{ref} = Q_1^{ref} + \omega_1(\psi_{d1}^s)^2/L_1$$
$$Q_{rev}^{ref} - Q_{rev} = Q_1^{ref} - Q_1$$

always holds, Fig. 2 shows the general principle for the IMC of torque and reactive power, where the transfer function $G(\lambda)$ for the torque and reactive power is:

$$G(\lambda) = \frac{1}{\lambda + \frac{R_2}{\sigma L_2}} \quad (25)$$

where λ is the Laplacian operator. According to IMC, the controller $C(\lambda)$ is chosen to be

$$C(\lambda) = \frac{k}{\lambda + k}\tilde{G}^{-1}(\lambda) \quad (26)$$

where the $\tilde{G}(\lambda)$ is the estimated model of the torque and reactive power. k is a positive constant. By assuming the estimated model $\tilde{G} = G$, the controller $F(\lambda)$ with respect to the torque error (or reactive power error) can be determined:

$$F(\lambda) = (1 - C(\lambda)\tilde{G}(\lambda))^{-1}C(\lambda) = k + k\frac{R_2}{\sigma L_2}\lambda \quad (27)$$

Denoting the torque error and reactive power error as

$$e_t = T_e^{ref} - T_e, \quad e_Q = Q_1^{ref} - Q_1$$

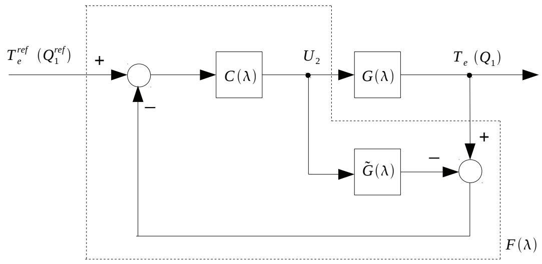

Fig. 2. Principle of internal model for torque and reactive power control.

the voltage reference $U_{d2}^{'s}$ and $U_{q2}^{'s}$ are calculated by

$$U_{d2}^{'s} = ke_Q + k\frac{R_2}{\sigma L_2}\int e_Q dt \quad (28)$$

$$U_{q2}^{'s} = ke_t + k\frac{R_2}{\sigma L_2}\int e_t dt \quad (29)$$

Transforming $U_{d2}^{'s}$ and $U_{q2}^{'s}$ back to actual rotor voltages U_{d2}^s,U_{q2}^s by (21), (22), we have

$$U_{d2}^s = \frac{\sigma L_1 L_2}{\omega_1\psi_{d1}^s L_h}U_{d2}^{'s} + \frac{\sigma L_2 I_{d2}^s}{\psi_{d1}^s}\frac{d\psi_{d1}^s}{dt} + \frac{L_h}{L_1}\frac{\psi_{d1}^s}{dt} - s\omega_1\psi_{q2}^s \quad (30)$$

$$U_{q2}^s = \frac{2}{p}\frac{\sigma L_1 L_2}{\psi_{d1}^s L_h}U_{q2}^{'s} + \frac{\sigma L_2 I_{q2}^s}{\psi_{d1}^s}\frac{d\psi_{d1}^s}{dt} + s\omega_1\psi_{d2}^s \quad (31)$$

The closed-loop transfer function of the toque and reactive power is

$$T(\lambda) = G(\lambda)[1 + C(\lambda)(G(\lambda) - \tilde{G}(\lambda))]^{-1}C(\lambda) = \frac{k}{k + \lambda}$$

It can be noticed, that the steady state errors of the torque and reactive power are equal to 0. The positive constant k is designed for desired closed-loop bandwidth. For a first order system, the 10% up to 90% rising time is related to k as $t_r = ln(9)/k$ [10]. When comparing (30) and (31), there is an additional $\frac{L_h}{L_1}\frac{\psi_{d1}^s}{dt}$ for the d-axis rotor voltage, which indicates that the stator transient dynamic has asymmetric effects on electromagnetic torque and reactive power.

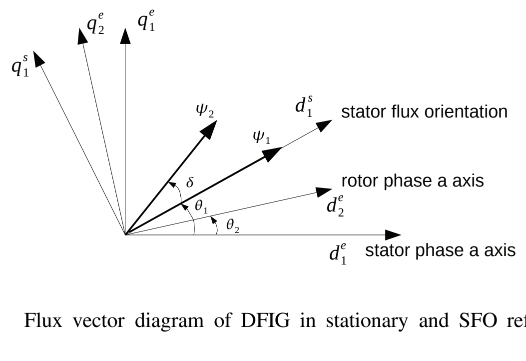

Fig. 3. Flux vector diagram of DFIG in stationary and SFO reference frame.

IV. CONTROL APPROACH IN STATIONARY FRAME

The electromagnetic torque and reactive power control in the stationary reference frame is based on the control approach in SFO reference frame. In this section, the superscript e is used for the quantities in the stationary reference frame. Fig. 3 shows the flux vector diagram in the stationary and SFO reference frame. The rotor voltage of DFIG in the stationary reference frame can be obtained by shifting the quantities in the SFO reference frame:

$$U_2^e = U_2^s e^{j\theta_1} = (U_{d2}^s + jU_{q2}^s)e^{j\theta_1} \tag{32}$$

Combining (30) and (31), we have the following expression:

$$\begin{aligned} U_2^s =& (\frac{\sigma L_1 L_2}{\omega_1 L_h \psi_{d1}^s} U_{d2}^{'s} + \frac{L_h}{L_1}\frac{d\psi_{d1}^s}{dt} + j\frac{2\sigma L_1 L_2}{pL_h\psi_{d1}^s}U_{q2}^{'s}) \\ &+ \frac{\sigma L_2}{\psi_{d1}^s}\frac{d\psi_{d1}^s}{dt} I_2^s + js\omega_1\psi_2^s \end{aligned} \tag{33}$$

where $U_{d2}^{'s}$ and $U_{q2}^{'s}$ are obtained by IMC as discussed in the previous section, which are PI controlled quantities over torque and reactive power tracking errors. The quantities enclosed by the brackets on the right side of equation (33) are independent from the reference frame since ψ_{d1}^s is the amplitude of stator flux and $U_{d2}^{'s}$ and $U_{q2}^{'s}$ only depend on torque and reactive power.

To estimate the stator flux in the stator flux and angle referring to the stationary reference frame, the equation for the DFIG stator can be rearranged into the following equation under the generator convention:

$$U_1^e = -R_1 I_1^e + \frac{d\psi_1^e}{dt} \tag{34}$$

Derived from (34), the stator flux in stationary reference frame is:

$$\psi_1^e = \int (U_1^e + R_1 I_1^e) dt \tag{35}$$

where U_1^e and I_1^e can be measured with high accuracy [8]. The relation $\psi_{d1}^s = |\psi_1^e|$ always holds with high accuracy. The stator flux angle θ_1 is calculated by

$$\theta_1 = tan^{-1}(\frac{\psi_{q1}^e}{\psi_{d1}^e}) \tag{36}$$

The dynamic stator flux $d\psi_{d1}^s/dt = d|\psi_1^e|/dt$ is sensitive to the measurement noise. A filtered derivative can be utilized to overcome this shortage.

Eventually, substituting (33) into (32) and expressing the equation with all the quantities estimated in the stationary reference frame, the rotor voltage of DFIG U_2^e is calculated:

$$U_2^e = U_2^{'e} e^{j\theta_1} + \frac{\sigma L_2}{|\psi_1^e|}\frac{d|\psi_1^e|}{dt} I_2^e + js\omega_1\psi_2^e \tag{37}$$

$$U_2^{'e} = \frac{\sigma L_1 L_2}{\omega_1 L_h |\psi_1^e|} U_{d2}^{'s} + \frac{L_h}{L_1}\frac{d|\psi_1^e|}{dt} + j\frac{2\sigma L_1 L_2}{pL_h|\psi_1^e|}U_{q2}^{'s} \tag{38}$$

The rotor flux ψ_2^e in stationary reference frame can be estimated by $\psi_2^e = -L_2 I_2^e - L_h I_1^e$ due to equations (7) and (8). However, this estimation is sensitive to the parameter error of L_h. To reduce the estimation error of the rotor flux ψ_2^e which caused by parameter error of L_h according to (40) and (41), ψ_2^e can be estimated by:

$$\psi_2^e = \frac{L_h}{L_1}\psi_1^e - \sigma L_2 I_2^e \tag{39}$$

The block diagram of the direct torque and reactive power control is shown in Fig. 4. The torque and reactive power are controlled independently by IMC. This control approach is implemented in the stationary reference frame by directly calculating the torque and reactive power errors. In another aspect, the transient power is based on equations (17) and (19), where the corresponding IMC controllers guarantee the stability of the DFIG system. In order to show the influence of the compensation terms in (37) and (38), denote:

- Full transient compensation (FTC): all compensation terms in (37) and (38) are considered.
- Partial transient compensation (PTC): the compensation term $\frac{L_h}{L_1}\frac{d|\psi_1^e|}{dt}$ is neglected.
- No transient compensation (NTC): neglect all stator transients in (37) and (38).
- No compensation (NC): neglect both the stator transients and $js\omega_1\psi_2^e$.

During a voltage dip, stator transients (FTC,PTC) have critical influences to damp the torque and reactive power oscillations. Under regular operating condition, the transients of the generator stator are negligible so that the controller with NTC is sufficient to guarantee the torque and reactive power transients. The compensation $js\omega_1\psi_2^e$ is important for this direct control approach. The torque and reactive power are controlled decoupled after compensating $js\omega_1\psi_2^e$. Controllers with NC would degrade the transient dynamics of the torque and reactive power. The detailed influences of the different compensations are shown in the simulation results.

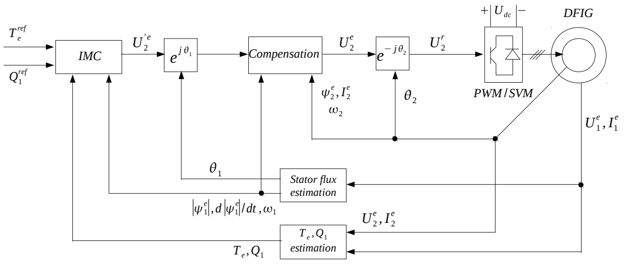

Fig. 4. Direct torque and reactive power control of a DFIG.

A. Robustness analysis

Referring to equations (28), (29), and (37) to (39), the parameters which could influence the control behavior are R_2, σL_2 and $\frac{L_1}{L_h}$. Since the leakage inductances $L_{1\sigma}$ and $L_{2\sigma}$ are relatively small when compared to the mutual inductance L_h and the leakage flux magnetic path is air, the variation of the leakage inductances during operation is insignificant [8]. The parameters which effect the control behavior are the rotor resistance R_2 and mutual inductance L_h. The parameter R_2 only contributes to the PI controllers described by (28) and (29). The error of R_2 can be tolerated by the robustness of the designed IMC controller [11] so that the stability of the controllers can still be guaranteed. The influence of the parameter error of L_h can be analyzed by the following calculations:

$$\begin{aligned} \sigma L_2 &= \frac{L_1 L_2 - L_h^2}{L1} = \frac{(L_{1\sigma} + L_h)(L_{2\sigma} + L_h) - L_h^2}{L_{1\sigma} + L_h} \\ &= \frac{(L_{1\sigma} + L_{2\sigma})L_h + L_{1\sigma}L_{2\sigma}}{L_{1\sigma} + L_h} \approx L_{1\sigma} + L_{2\sigma} \end{aligned} \tag{40}$$

$$\frac{L_1}{L_h} = \frac{L_{1\sigma} + L_h}{L_h} \approx 1 \tag{41}$$

Equations (40) and (41) show that the parameters σL_2 and $\frac{L_1}{L_h}$ are insensitive to the parameter error of the mutual inductance L_h. Theoretically we can conclude that the given control approach is robust.

B. Comparison of other control approaches

The proposed control strategy shows an explicit design procedure and methodology, in which the control parameter ensures the stability of the DFIG system. The proposed control approach in this paper can be directly applied to the torque and reactive power control in such a way that the transformation of the quantities to the SFO reference frame is not necessary. Comparing to the existing DTC and DPC control approaches, the proposed control approach provides explicit equations (17) and (19), which can directly describe the transient behavior of the torque and reactive power with rotor resistance considered. Based on these equations, the stability and robustness of the IMC controllers can be guaranteed. In addition, the proposed control approach considers the transients of the stator flux, which play an important role during a voltage dip. However, one drawback of the proposed control approach is that the transients of the stator flux must be calculated online if FTC or PTC is utilized, which will increase the calculation cost.

V. Simulation Results

Simulations of the proposed direct torque and reactive power control approach are carried out using Matlab/Simulink. The simulated DFIG is based on the parameters available from Vestas V52 Leroy Somer DFIG, with a rated power of $850\,\mathrm{kW}$, rated speed $1620\,\mathrm{rpm}$ and rated voltage $690\,\mathrm{V}$. Fig. 5 shows the transients of the torque and reactive power during a voltage dip. Initially the DFIG is operating at half of its rated torque and zero reactive power. At $3\,\mathrm{s}$, a voltage dip about 75% rated voltage occurs. The controller with NTC can stablize the the torque and reactive power within $1\,\mathrm{s}$. However, a large oscillation reveals due to the stator transients. The controller with PTC has an excellent damping effect on the torque, where the oscillation is only about 4%. The controller with FTC has excellent damping effects on both torque and reacitive power. However, it causes an extremely slow system convergence, which is not acceptable.

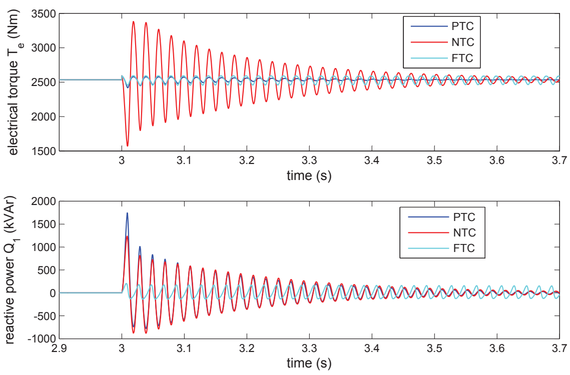

Fig. 5. Transients of electromagnetic torque and reactive power by the proposed control strategy with various compensation approaches during a voltage dip.

To investigate the transients of the torque and reactive power under regular operating conditions, simulations are performed in such a way that the DFIG is operating at its rated angular speed and voltage. The torque steps from 0 to the rated torque at $5\,\mathrm{s}$ and to half of rated torque at $5.3\,\mathrm{s}$. The reactive power steps from 0 up to $600\,\mathrm{kVAr}$ at $5.6\,\mathrm{s}$. Fig. 6

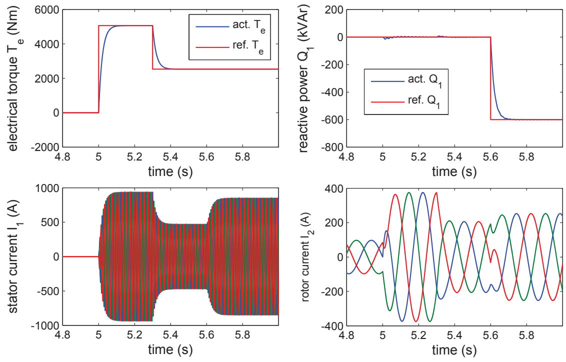

Fig. 6. Torque and reactive power step response for PTC and NTC at constant angular speed.

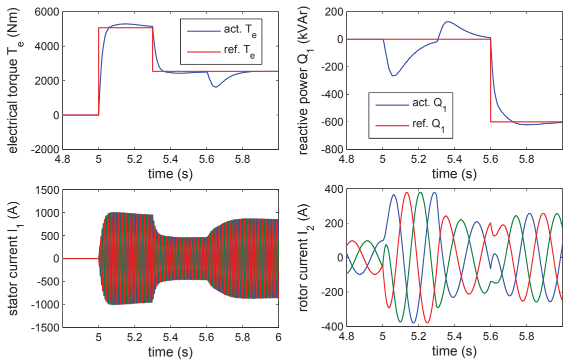

Fig. 7. Torque and reactive power step response for NC at constant angular speed.

shows the simulation results for controllers with PTC and NTC (the results for PTC and NTC are identical, which are shown by the same figure). For PTC and NTC, good dynamic performance is achieved as the torque and reactive power converge within $0.1\,\mathrm{s}$ and no overshot occurs. The same behaviors are also shown by both stator and rotor currents. Fig. 7 shows the simulation results for the controller without compensation. Although the torque and reactive power can converge to their reference values, the variation in the torque and causes large oscillations for the reactive power (vice versa) since the torque and reactive power can no longer be controlled independently. Combining the situation in voltage dip and regular operation, the controllers with PTC and NTC are recommended for the proposed control approach.

Fig. 8 shows the transients for controllers with PTC and NTC (transients of PTC and NTC are identical) at varying angular speed, where the angular speed varies from sub-synchronous speed to super-synchronous speed. The torque and reactive power still show good dynamics without overshots for the step response. It indicates that the varying angular speed has no influence on the proposed direct torque and reactive power control approach, which guarantees the transient dynamics of the proposed control strategy for the DFIG of the wind turbine during wind speed variation.

Fig. 9 and Fig. 10 show the robustness of PTC and NTC at 100% R_2 and $100\% L_h$ errors respectively (transients of PTC and NTC are identical). It can be noticed even at 100% R_2 error, the torque and reactive power can still converge fast with small overshots. At $100\% L_h$ error, the behaviors of the torque and reactive power almost remain the same with

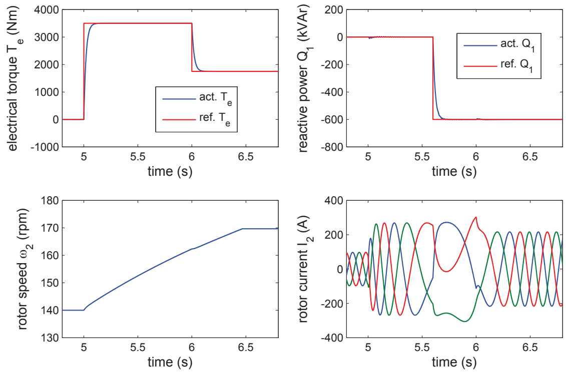

Fig. 8. Torque and reactive power step response for PTC and NTC at varying angular speed.

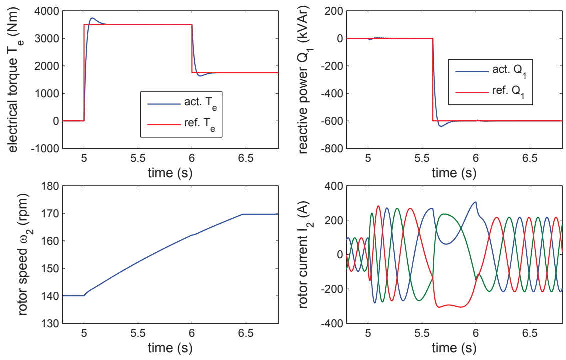

Fig. 9. Torque and reactive power step response for PTC and NTC at varying angular speed with 100% R_2 error.

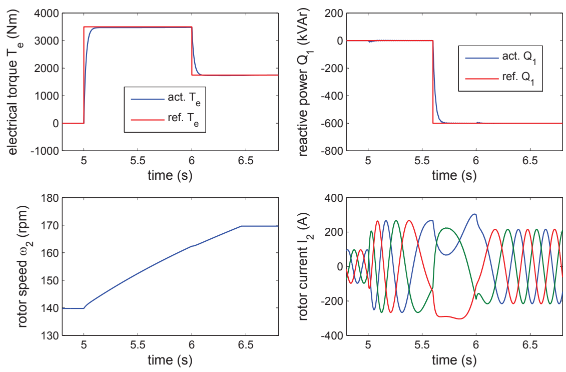

Fig. 10. Torque and reactive power step response for PTC and NTC at varying angular speed with 100% L_h error.

the no-error case, which proves the theoretical conclusions on robustness in the previous section.

VI. Conclusion

In this paper, a novel direct torque and reactive power control approach for DFIG applied to wind turbines is introduced. The proposed control approach is based on equations which describe the dynamics of the torque and reactive power. The rotor voltage is directly calculated by the errors of the torque and reactive power based on IMC with compensations, where the stability and robustness of the controllers are guaranteed. The influences of the compensations are investigated by simulation results. The PTC and NTC both ensure good torque and reactive power dynamics for regular operation. In addition, the PTC shows good damping effects against torque oscillations during a voltage dip, so that the inrush current during the voltage dip can be greatly reduced to protect the wind turbine system and improve the fault ride through capability. In the end of this year, the proposed control strategy will also be tested on a Vestas V52 wind turbine and a 10 kW test bench.

References

[1] B. B. Pimple, V. Y. Vekhande, and B. G. Fernandes, "New direct torque control of dfig under balanced and unbalanced grid voltage," in *Proc. TENCON 2010 - 2010 IEEE Region 10 Conf*, 2010, pp. 2154–2158.

[2] J. G. Slootweg, H. Polinder, and W. L. Kling, "Dynamic modelling of a wind turbine with doubly fed induction generator," in *Proc. Power Engineering Society Summer Meeting*, vol. 1, 2001, pp. 644–649.

[3] S. Li, R. Challoo, and M. J. Nemmers, "Comparative study of dfig power control using stator-voltage and stator-flux oriented frames," in *Proc. IEEE Power & Energy Society General Meeting PES '09*, 2009, pp. 1–8.

[4] A. PERDANA, "Dynamic models of wind turbines: Contribution towards the establishment of standardized models of wind turbines for power system stability studies," Ph.D. dissertation, CHALMERS UNIVERSITY OF TECHNOLOGY, 2008.

[5] Y.-S. Lai and J.-H. Chen, "A new approach to direct torque control of induction motor drives for constant inverter switching frequency and torque ripple reduction," vol. 16, no. 3, pp. 220–227, 2001.

[6] B. B. Pimple, V. Y. Vekhande, and B. G. Fernandes, "New direct torque control of dfig under balanced and unbalanced grid voltage," in *Proc. TENCON 2010 - 2010 IEEE Region 10 Conf*, 2010, pp. 2154–2158.

[7] L. Xu and P. Cartwright, "Direct active and reactive power control of dfig for wind energy generation," vol. 21, no. 3, pp. 750–758, 2006.

[8] D. Zhi and L. Xu, "Direct power control of dfig with constant switching frequency and improved transient performance," vol. 22, no. 1, pp. 110–118, 2007.

[9] P. Zhou, Y. He, and D. Sun, "Improved direct power control of a dfig-based wind turbine during network unbalance," vol. 24, no. 11, pp. 2465–2474, 2009.

[10] L. Harnefors and H.-P. Nee, "Model-based current control of ac machines using the internal model control method," vol. 34, no. 1, pp. 133–141, 1998.

[11] H. Jia-bing, H. Yi-kang, and Z. J. Guo, "The internal model current control for wind turbine driven doubly-fed induction generator," in *Proc. 41st IAS Annual Meeting Industry Applications Conf. Conf. Record of the 2006 IEEE*, vol. 1, 2006, pp. 209–215.

VII. Biographies

Qian Liu finished his B.sc in Electrical Engineering at Shanghai Jiao Tong University, China. He received his Master degree in Control Engineering from Technical University of Kaiserslautern, Germany. Currently he is a research associate in the Institute of Electrical Machines at RWTH Aachen University, Germany. His current research focuses on wind turbines, energy storage systems, analysis and control of electrical machines and electromotive applications.

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