A Novel Rotor Current Controller Scheme for Grid Connected Doubly Fed Induction Generators

Esref Emre Ozsoy[1], Asif Sabanovic[2], Edin Golubovic[3], Metin Gokasan[4], Seta Bogosyan[5]
[1,4,5]Istanbul Technical University, Istanbul, Turkey
[1,4]{eozsoy, gokasan}@itu.edu.tr, [5]sbogosyan@alaska.edu
[2,3]Sabanci University, Istanbul, Turkey
{asif, edin}@sabanciuniv.edu

***Abstract*—This paper presents a novel robust stator voltage oriented rotor current controller structure for grid connected doubly fed induction generators (DFIG). Controller is based on a proportional controller with first order low pass filter disturbance observer which estimates machine parameter dependent nonlinear terms. Therefore, necessity of accurate knowledge of machine parameters is not required. The results are demonstrated in experimental laboratory setup.**

Keywords-component; DFIG, disturbance observer, wind energy)

NOMENCLATURE

i_{sa}, i_{sb}, i_{sc}	Stator a, b and c phase currents
i_{sd}, i_{sq}, i_{rd}, i_{rq}	Stator, rotor d and q axis currents
i_{ra}, i_{rb}, i_{rc}	Rotor a, b and c phase currents
i_{gd}, i_{gq}	Grid d and q axis currents
v_{sa}, v_{sb}, v_{sc}	Stator a, b and c phase voltages
$v_{s\alpha}$, $v_{s\beta}$, $v_{r\alpha}$, $v_{r\beta}$	α and β axis stator voltage
v_{ra}, v_{rb}, v_{rc}	Rotor a, b and c phase voltages
v_{sd}, v_{sq}, v_{rd}, v_{rq}	Stator, rotor d and q axis voltages
R_s, R_r,	Stator, rotor resistances
P_s, Q_s	Stator active and reactive power
P_r, Q_r	Rotor active and reactive power
P_g, Q_g	Grid active and reactive power
L_s, L_r, L_m	Stator, rotor, mutual inductances
L_{rb},	Base value of rotor inductance
ΔL_r	Disturbance of L_r and L_g
p	Number of pole pairs
ω_s	Stator and grid electrical speed
ω_m	Rotor mechanical speed
T_m, T_e	Mechanical and electrical torque
θ_s, θ_r	Stator, rotor electrical angle
T_s	Sample Time
s	Laplace operator
k_p, k_q	Proportional gain of controller
f_d, f_q	Disturbance terms
J	Inertia constant
b	Viscous friction constant

I. INTRODUCTION

Penetration of renewable energy sources, especially wind energy conversion systems has been increasing due to rapid consumption of fuel sources and environmental issues in recent years. Doubly fed induction generator (DFIG) based wind turbines are very advantageous compared to other generator types due to variable speed operation, reduced inverter cost, and four-quadrant active and reactive power flow capability.

There are several studies associated with DFIG control for wind energy conversion systems. Conventional grid connected DFIG controllers usually consist of direct vector control (DVC) strategies which use stator flux [1] or voltage orientation [2] in which the alignment of the d-axis is along with stator flux or voltage in synchronously rotating frame. These DVC schemes control decoupled rotor currents with proportional-integral (PI) controllers.

Grid connected DFIG control strategies may become very fragile against grid voltage problems and parameter variations due to direct grid connection of stator windings [3]. Robustness of the controllers [4] is essential due to increasing power penetration of DFIG based wind turbines in electrical networks. However, conventional DVC techniques are very fragile against parameter and external disturbances.

Direct Power Control (DPC) techniques which control stator active and reactive power without inner current loops are given in [5, 6]. There are also reputable studies using DPC [7, 8, and 9] which are robust against machine parameter variations and grid voltage problems. Several contributions are also encountered which use sliding mode control (SMC). One of the important contributions given in [10] achieves the grid connected DFIG control in harmonically distorted and unbalanced voltages. Robustness against voltage problems is achieved in [11] with second order SMC.

The first contribution regarding the usage of disturbance observer [12] in grid connected DFIG structures first appear in [13]. This study presents the simulation results of a direct proportional power controller with a disturbance observer without current control loops.

Despite the robustness of the DPC and SMC techniques summarized above, conventional DVC schemes which use decoupled PI type rotor current controllers as given in [1,2] are very popular due to its simplicity and applicability in real DFIG based wind turbines. Nonlinear cross-coupling terms are fed forward to controller which is dependent on machine parameters. Performance of DVC structure is highly dependent on the accurate knowledge of machine parameters.

This study proposes a stator voltage oriented DVC scheme which is independent on any machine parameter. All the machine parameter dependent terms are estimated via first order low pass filter disturbance observer and fed forward to the current control loop. A proportional controller is sufficient to control decoupled rotor currents. The proposed methodology is validated by using constructed experimental laboratory setup.

This paper is organized as follows; Problem formulation and DFIG dynamics are given in Section 2. Controller design and disturbance observer concept are given in Section 3. Experimental results are demonstrated in Section 4. Section 5 contains the conclusion and future work.

II. Problem Formulation

A. DFIG Operation

Typical DFIG based wind turbines are depicted in Fig.1. The stator is directly connected to the grid, and rotor is directed through a back-to-back converter.

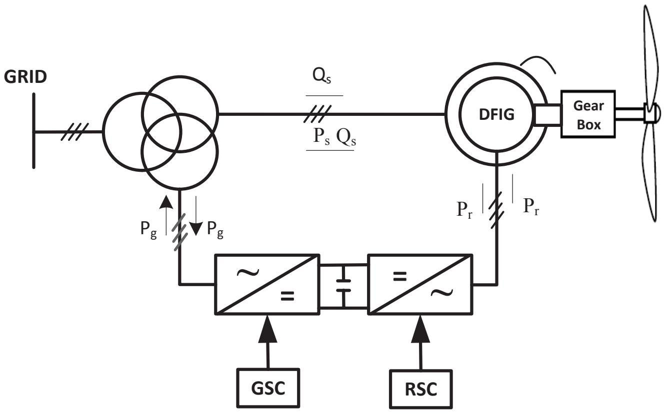

Figure 1. Typical DFIG based wind turbines

Rotor Side Control (RSC) controls the stator power flow via controlling the rotor currents. Grid Side Control (GSC) has a task of maintaining the desired DC bus voltage regardless of the power flow direction. The operation of DFIG could be subdivided into two main operation regions; subsynchronous or supersynchronous speed in which the rotor power flow direction is toward rotor circuit or grid side respectively.

B. Mathematical Model of DFIG

Mathematical model describing the dynamic behavior of DFIG is written considering set of three phase windings both at stator and rotor. DFIG dynamic equations could be written from the equivalent circuit in synchronously rotating dq frame as given in Fig. 2. For more detailed analysis and modeling of DFIG, one can refer several numbers of sources in literature e.g. [14, 15]. DFIG dynamics could simply be defined in the following form.

$$L_{sn}\frac{di_{sd}}{dt} = v_{sd} - \chi_{sd}(i_{sd,q}, i_{rd,q}, \omega_s, L_m, R_s, \Delta L_s, t) \quad (1)$$

$$L_{sn}\frac{di_{sq}}{dt} = v_{sq} - \chi_{sq}(i_{sd,q}, i_{rd,q}, \omega_s, L_m, R_s, \Delta L_s, t) \quad (2)$$

$$L_{rn}\frac{di_{rd}}{dt} = v_{rd} - \chi_{rd}(i_{rd,q}, i_{sd,q}, \omega_s, \omega_m L_m, R_s, \Delta L_s, t) \quad (3)$$

$$L_{rn}\frac{di_{rq}}{dt} = v_{rq} - \chi_{rq}(i_{rd,q}, i_{sd,q}, \omega_s, \omega_m, L_m, R_s, \Delta L_s, t) \quad (4)$$

The terms L_{sn} and L_{rn} are the nominal value of the stator and rotor. Inductances could be expressed as follows;

$$L_{s,r} = L_{s,rn} + \Delta L_{s,r} \quad (5)$$

The function χ represents the nonlinear and parameter dependent equations. All above derivation is realized in stator voltage oriented synchronously rotating frame and the alignment of the stator voltage is considered in d-axis which means that $v_s = v_{sd}$. All the rotor variables are referred to the stator side.

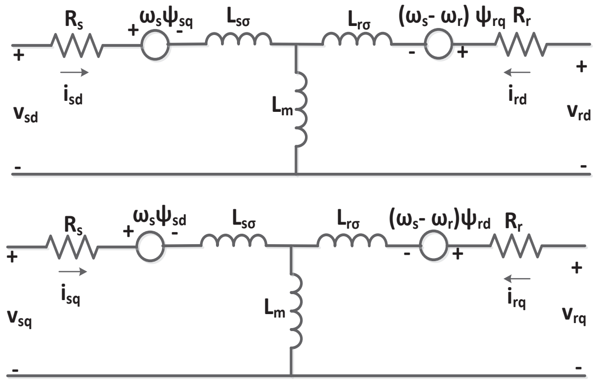

Figure 2. DFIG Equivalent Circuit

Equation of motion could be simply defined by the following relation:

$$\frac{d\omega_m}{dt} = \frac{1}{J}(T_m - T_e + b\omega_m) \quad (6)$$

Finally, Stator active and reactive power could be described by the equations below.

$$P_s = \frac{3}{2}(v_{sd}i_{sd} + v_{sq}i_{sq}) \quad (7)$$

$$Q_s = \frac{3}{2}(v_{sq}i_{sd} - v_{sd}i_{sq}) \quad (8)$$

Dynamic behavior of DFIG is fully described, and rotor current controller is discussed in the following section.

III. Rotor Side Current Controller Design

Rotor current dynamics are given in Eq. (3) and Eq. (4). It is obvious from definition that dynamic equation is separated into nonlinear parameter dependent function χ and measurable rotor currents and voltages. Current errors could be given as following equation.

$$\varepsilon_{id} = i_{rd}^{ref} - i_{rd} \quad (9)$$

$$\varepsilon_{iq} = i_{rq}^{ref} - i_{rq} \tag{10}$$

The derivative of the errors is defined as follows.

$$\frac{d\varepsilon_{id}}{dt} = \frac{di_{rd}^{ref}}{dt} - \frac{di_{rd}}{dt} \tag{11}$$

$$\frac{d\varepsilon_{iq}}{dt} = \frac{di_{rq}^{ref}}{dt} - \frac{di_{rq}}{dt} \tag{12}$$

If Eq. 3 and 4 are substituted into Eq. 11 and 12 respectively, the following equations could be obtained.

$$\frac{d\varepsilon_{rd}}{dt} = -\frac{V_{rd}}{L_{rn}} + \underbrace{\left(\frac{di_{rd}^{ref}}{dt} + \frac{\chi_{rd}}{L_{rn}}\right)}_{f_d} \tag{13}$$

$$\frac{d\varepsilon_{rq}}{dt} = -\frac{v_{rq}}{L_{rn}} + \underbrace{\left(\frac{di_{rq}^{ref}}{dt} + \frac{\chi_{rq}}{L_{rn}}\right)}_{f_q} \tag{14}$$

The terms f_d and f_q are highly nonlinear and exact calculation of those terms are almost impossible. Therefore these terms will be considered as disturbance.

Next, the desired closed loop dynamics can be written as;

$$\frac{d\varepsilon_{rd}}{dt} + k_p \varepsilon_{rd} = 0 \tag{15}$$

$$\frac{d\varepsilon_{rq}}{dt} + k_q \varepsilon_{rq} = 0 \tag{16}$$

If the errors are written into the desired closed loop dynamics, the following equations could be written.

$$-\frac{v_{rd}}{L_{rn}} + f_d + k_p \varepsilon_{rd} = 0 \tag{17}$$

$$-\frac{v_{rq}}{L_{rn}} + f_q + k_q \varepsilon_{rq} = 0 \tag{18}$$

Finally, desired voltage references are obtained as follows.

$$v_{rd}^{ref} = L_{rn} k_p \varepsilon_{rd} + \hat{f}_d \tag{19}$$

$$v_{rq}^{ref} = L_{rn} k_q \varepsilon_{rq} + \hat{f}_q \tag{20}$$

Where $\hat{f}_d$ and $\hat{f}_q$ are estimated disturbances. These terms could be estimated by using first order low pass filter disturbance observer [12]. The rotor dynamics in Eq. 3 and 4 could be rewritten as follows.

$$f_d = v_{rd} + L_{rn} \frac{di_{rd}}{dt} \tag{21}$$

$$f_q = v_{rq} + L_{rn} \frac{di_{rq}}{dt} \tag{22}$$

If Eq. 21 and 22 is written in s domain and implementing first order low pass filter disturbance observer concept [12];

$$\hat{f}_d = (v_{rd} + sL_{rn} i_{rd}) \frac{g_d}{s + g_d} \tag{23}$$

$$\hat{f}_q = (v_{rq} + sL_{rn} i_{rq}) \frac{g_q}{s + g_q} \tag{24}$$

The terms g_d and g_q are the low pass filter cutoff gains. More details on the disturbance observer design procedure can be found in [12].

As a result of the dynamic equations and estimated disturbances, DVC based controller structure could be given in Fig. 3.

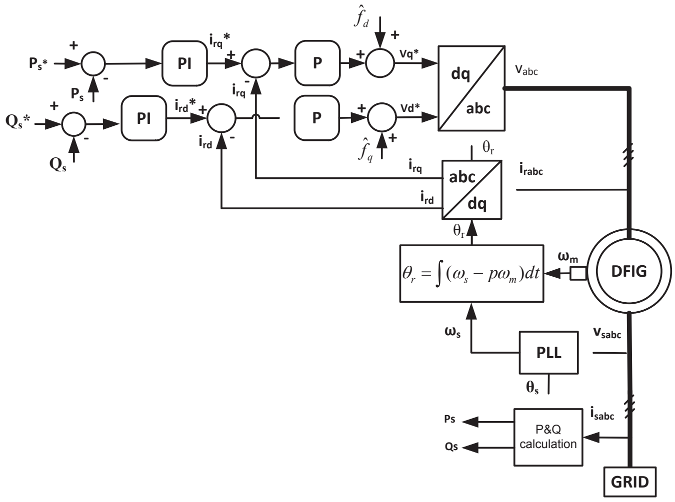

Figure 3. Proposed Control Structure

Decoupled rotor currents are controlled via proportional controller with first order low pass filter disturbance observer. Space vector pulse width modulation (SVPWM) is used to generate voltage references in the experiments. PI controllers in the outer loops realize the desired power references. Voltage angle detection is realized by conventional three-phase synchronous reference frame phase-locked loop (3Φ- SRF-PLL) [16].

IV. Experimental Results

Experimental setup in Fig. 4 is used in the experiments. Squirrel cage induction machine (SCIM) is driven by a commercial inverter representing the wind. Commercial drive adjusts the speed of DFIG. DFIG plate data is given in table 1; gain and cut off frequency of the controllers are given in Table 3. dSPACE ds1103 controller board is used. Algorithms are generated in Controldesk by using C programming language. Sample time of the controller is 100µs. Semikron Semistack (21f_b6u_e1cif_b6ci_12_v12) inverter is used in the experiments. Stator and rotor three phase currents are measured and sent to ds1103 controller board. Stator and grid voltages simultaneously measured for synchronization purposes. DFIG will only be operated in subsynchronous speed. Hence, DC link voltage is kept constant at 120V with a power supply. Stator active and reactive power step response tests are applied and the performance of the controllers is demonstrated.

A. Stator Active Power (P_s) Step Response Test

P_s step response test is applied at subsynchronous speed (143 rad/s). P_s reference is increased to 180W (Fig. 5) at arbitrary instant of experiment. Q_s is kept constant at zero (Fig. 6). It is obviously shown from the results that P_s and Q_s successfully follow the references.

The resultant i_{rd}&i_{rq} and i_{sd}&i_{sq} change according to applied steps are shown in Fig. 7 and Fig.8, respectively. The plots of Q_s and P_s (Fig. 5 and 6) and the resultant rotor and stator currents (Fig. 7 and Fig. 8) obviously show that decoupled stator active (P_s) and reactive power (Q_s) control is achieved.

Rotor phase currents at arbitrary instant are in Fig. 9. Stator voltage vs. stator current is shown in Fig. 10 which definitely shows that power flow is toward the grid.

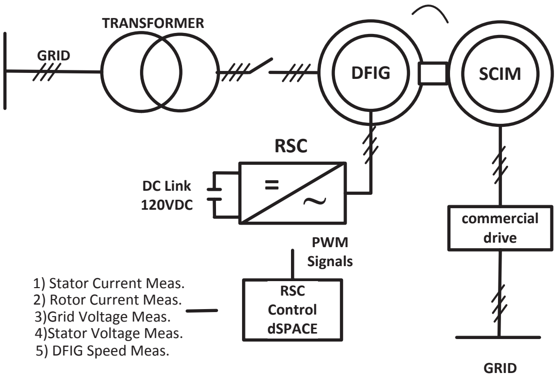

Figure 4. Experimental Setup

TABLE I. DFIG PLATE DATA IN EXPERIMENTS

Symbol	Quantity	Unit
Power	1.1	KW
Stator Voltage	220/380	Volt(D/Y)
Stator Current	6.4/3.7	Amper
Power Factor	0.67	-
Speed	1360	rpm
Rotor Voltage	70	Volt
Rotor Current	12	Amper

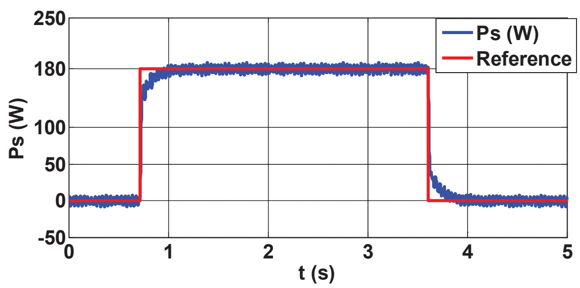

Figure 5. Active Power (P_s) at P_s step response test

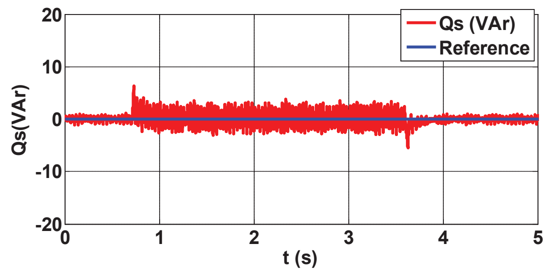

Figure 6. Reactive Power (Q_s) at P_s step response test

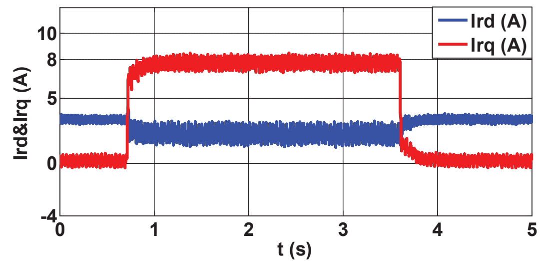

Figure 7. The resultant rotor currents to achieve power control

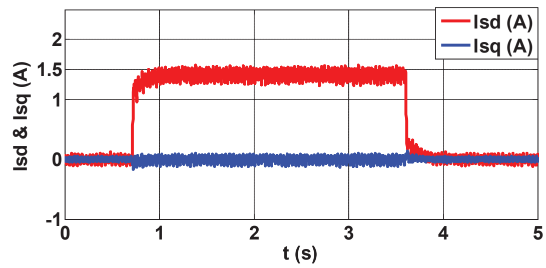

Figure 8. Stator a phase voltage(v_s) vs. current (i_s)

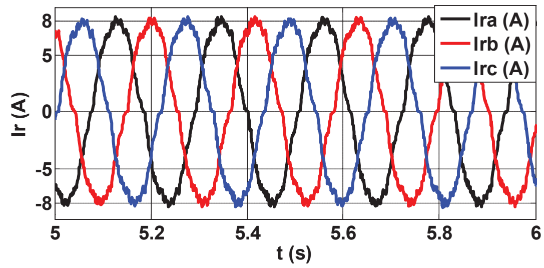

Figure 9. Rotor phase currents at arbitrary instant

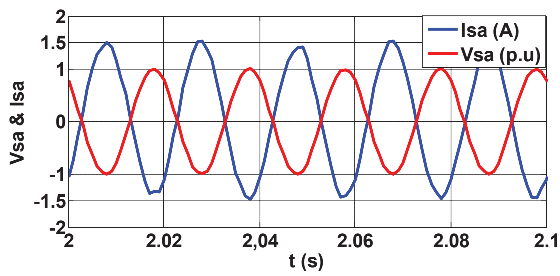

Figure 10. Stator a phase voltage (v_{sa}) vs. current (i_{sa}) at arbitary instant

B. *Stator Reactive Power(Q_s) Step Response Test*

Q_s step response test is applied at subsynchronous speed (143 rad/s). Q_s reference is increased to 160W (Fig. 11) at arbitrary instant of experiment. P_s is kept at constant at zero (Fig. 12).

The resultant i_{rd}&i_{rq} and i_{sd}&i_{sq} change according to applied Q_s are shown in Fig. 13 and Fig.14, respectively. The plots of Q_s and P_s (Fig. 11 and 12) obviously show that decoupled stator active and reactive power control is achieved. Rotor and stator currents reasonably change according to decoupling (Fig. 13 and Fig. 14).

Rotor and stator phase currents at arbitrary instant are shown in Fig. 15 and Fig. 16, respectively. Stator phase a current (i_{sa}) vs. stator phase a voltage (v_{sa}) obviously show that power factor is leading (Fig. 17).

Grid voltage and calculated voltage angle by applied PLL algorithm in [16] is shown in Fig. 18 which definitely shows the accurate calculation of PLL voltage angle.

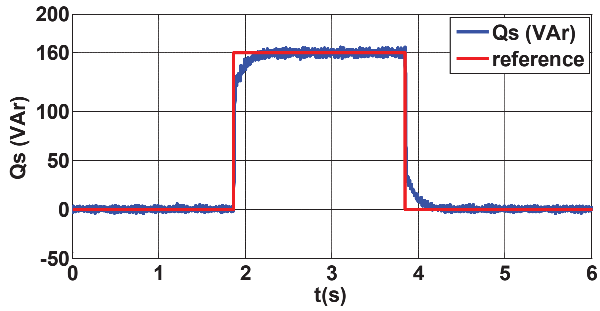

Figure 11. Reactive Power at Q_s step response test

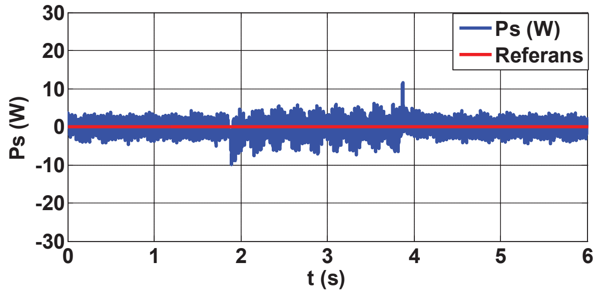

Figure 12. Active Power at Q_s step response test

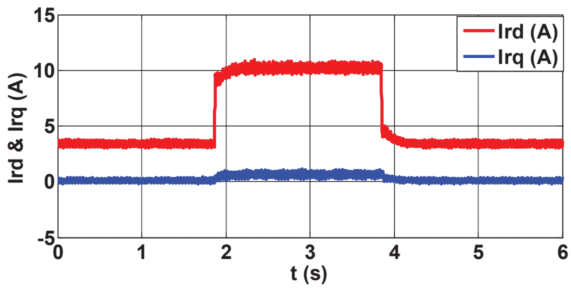

Figure 13. The resultant rotor currents

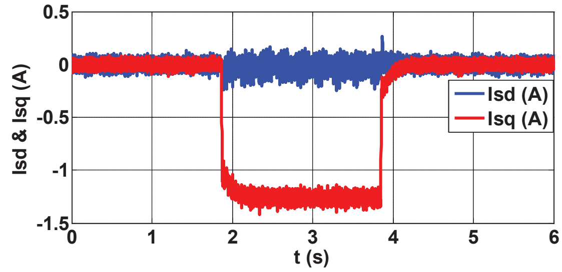

Figure 14. The resultant stator currents

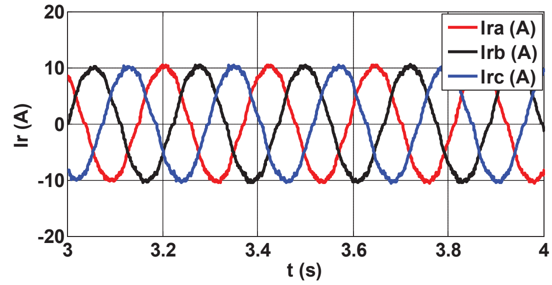

Figure 15. The resultant rotor line currents

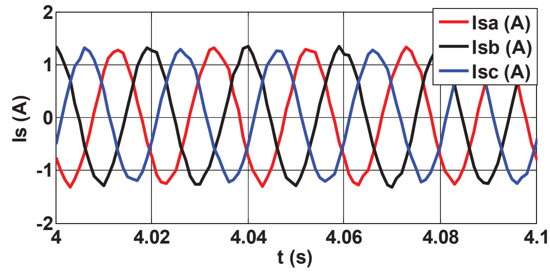

Figure 16. Stator line currents at arbitrary instant

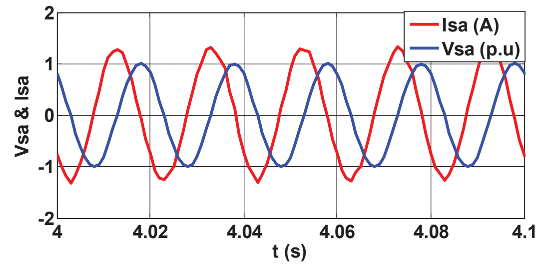

Figure 17. Stator a phase voltage (v_{sa}) vs. current (i_{sa}) at arbitary instant

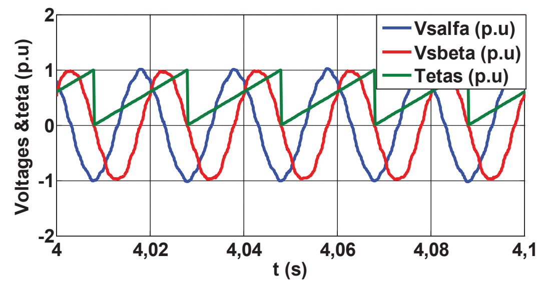

Figure 18. Stator voltages and voltage angle at arbitrary instant

CONCLUSION

DFIG is the most popular generator type in wind turbines because of several advantages summarized in introduction. Robustness of the system is essential due to direct connection of stator windings to the grid. This study demonstrated a novel current controller which is robust against machine parameter variations. Experimental results obviously show decoupled active and reactive power is achieved with proposed controller. The proposed methodology could simply be applied to real wind turbine structures due to its simplicity and applicability. Future work will mainly consist of developing the same control structure to GSC.

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