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Direct Torque Control of a Doubly-Fed Induction Generator Connected to Unbalanced Grid

Abstract**. The paper presents a direct control of a DFIG electromagnetic torque and proposed scalar variable indirectly responsible for reactive component of instantaneous stator power. The principles of the control are presented and the simulation results of control method performance for balanced and unbalanced grid are given. **(Bezpośrednie kontrola momentu maszyny dwustronnie zasilanej w sieci asymetrycznej)

***Streszczenie.** Artykuł przedstawia algorytm sterowania maszyny dwustronnie zasilanej gdzie bezpośredniej kontroli podlega generowany moment elektromagnetyczny oraz zaproponowana zmienna skalarna, która pozwala na kontrolę chwilowej wartości generowanej mocy biernej. Przedstawiono zasadę działania metody sterowania oraz wyniki symulacyjne przy współpracy maszyny dwustronnie zasilanej z siecią symetryczną i asymetryczną.*

Keywords: doubly-fed induction generator, direct torque control, unbalanced grid operation
Słowa kluczowe: maszyna dwustronnie zasilana, bezpośrednia kontrola momentu, sieć asymetryczna

Introduction

Due to increased amount of renewable energy sources (RES) in total generated national power grids across the Europe, RES reliability and continuous operation is becoming an important issue. Significant generated power share comes from wind energy based plants where one of the commonly used machine type is a doubly-fed induction generator (DFIG). Main features of this type of units include variable speed operation rated from 2/3 up to 4/3 of synchronous one and reduced power three phase back to back voltage converter connected from one side to the grid and from second side to the rotor via slip rings. Converter is usually designed on 1/4 to 1/3 of rated total power.

DFIG based power generation units can operate in stand-alone or grid connected mode. Desired power factor can be easily achieved by rotor side converter (RSC) control and to some extend DFIG set-up has capabilities to reduce unfavourable effects of unbalanced and distorted grid voltage. Analysis and control concept of stand-alone operation with unbalanced and nonlinear load with support of additional energy storage were presented in [1]. Grid operation also has been intensively analysed, some technology disadvantages have been pointed out [2]. Different control strategies have been proposed. Most of them based on linear proportional – integral controllers and pulse width modulation (PI – PWM) control strategies [3][4], the other on nonlinear hysteresis controllers like direct torque control (DTC) [5][6], and direct power control (DPC) [7][8] linear variation of DPC were also developed [9]. Recently some additional functionalities of presented method have been introduced like direct torque and reactive component of instantaneous power control [10]. Even nonlinear models of induction machine and its control have been proposed [11]. Senseless operation of DFIG was also intensively studied [12][13].

Due to imposed on RES operation requirements known as the Grid Codes [14][15] interests of researchers switched to transients especially to low voltage ride through and unbalanced grid operation. Some strategy based on linear proportional integral controller (PI) in synchronous rotating frame with voltage and current signal decomposition into positive and negative sequence have been proposed [16][17], sometimes additional resonant controller (PI+R) is also incorporated to deal with double grid frequency oscillating signal component [18] which represents the negative sequence signal present in frame associated with positive sequence.

This paper presents a novel DFIG direct control method which does not require signal decomposition and allows to operate under unbalanced grid condition with constant torque and generate sinusoidal stator current.

DFIG set-up and mathematical model description

Basic DFIG set-up is depicted in figure 1.

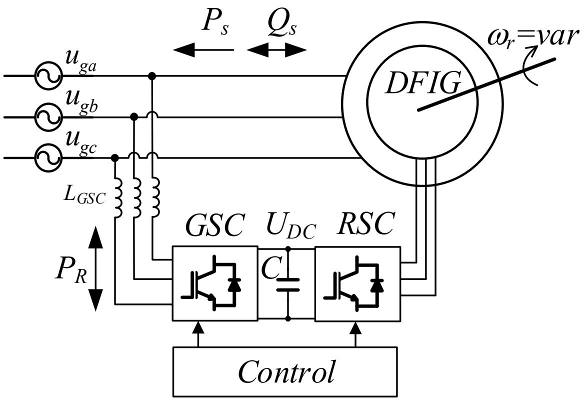

Fig.1. DFIG's connected to grid set-up.

This paper is focused only on control of the rotor side converter (RSC) and the grid side converter (GSC) were treated as independent energy source for DC link charge.

DFIG mathematical description of DFIG in stationary reference frame can be presented as follows in the stationary stator connected reference frame (1)(2)

$$u_s = R_s i_s + \frac{d\psi_s}{dt} \tag{1}$$

$$u_r = R_r i_r + \frac{d\psi_r}{dt} - j\omega_r \psi_s \tag{2}$$

Fluxes can be calculated directly according with equation (3) and (4) because DFIG's rotor phase current can be measured

$$\psi_s = L_s i_s + L_m i_r \tag{3}$$

$$\psi_r = L_r i_r + L_m i_s \tag{4}$$

Other stator flux calculation method usually used for cage motor (5) where there is no direct rotor access

$$\psi_s = \int_o^T (u_s - R_s i_s) dt \tag{5}$$

One of the possibility for electromagnetic torque calculation based on stator flux and current is shown in (6)

$$T_{em} = \frac{3}{2} p_b (\psi_{s\alpha} i_{s\beta} - \psi_{s\beta} i_{s\alpha}) \tag{6}$$

where: u_s, u_r, i_s, i_r, ψ_s, ψ_r - stator and rotor voltage, current and flux vectors respectively, R_s, R_r, - stator and rotor resistance, ω_r - rotor angular slip pulsation, L_s, L_r L_m - stator, rotor and magnetizing inductance, T_{em} - electromagnetic torque, p_b - number of poles pairs.

Stator and rotor inductance consists of magnetizing and leakage component (7).

$$L_s = L_m + L_{s\sigma} \qquad L_r = L_m + L_{r\sigma} \tag{7}$$

where: $L_{s\sigma}$, $L_{r\sigma}$ - stator and rotor leakage inductance.

All used vector variables in stationary αβ frame were obtained accordingly with equation (8) where as the example the stator voltage components are calculated.

$$\begin{bmatrix} u_{s\alpha} \\ u_{s\beta} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} u_{sa} \\ u_{sb} \\ u_{sc} \end{bmatrix} \tag{8}$$

DFIG's set-up analyzed in the paper consist of linear three phase machine and three-wire system without additional fourth wire, which means no zero sequence component on the rotor or stator side.

The slip angular speed is calculated as in (9).

$$\omega_r = \omega_s - p_b \omega_m \tag{9}$$

where ω_s, ω_m - stator and mechanical angular speed.

Proposed control method description

The direct torque control method used for DFIG is based on the principle that in order to control the electromagnetic torque it is necessary to control rotor flux vector magnitude and its angle which is measured in correspondence to stator flux vector in αβ frame (10).

$$T_{em} = \frac{3}{2} p_b \frac{L_m}{\sigma L_r L_s} |\psi_s| |\psi_r| \sin\delta \tag{10}$$

$$\sigma = 1 - \frac{L_m^2}{L_r L_s} \tag{11}$$

where σ - leakage factor, δ - angle between rotor and stator flux vector in αβ frame.

In [4][19] a method for direct torque and reactive power control has been proposed. Its simulated performance for a symmetrical grid is depicted in figure 2. One of controlled variable in the method is rotor flux magnitude the other is electromagnetic torque. For these variables controlled simultaneously it is not possible to maintain constant torque operation and generate sinusoidal stator currents for unbalance grid operation, what is shown in figure 3.

Reference signals value for a specific time period are given in table 1. DFIG is operating with above synchronous speed equal to 2000rpm. DFIG nominal parameters are given in table 3.

Table 1. Reference signal values for simulated model.

t[s]	4.25-4.3	4.3-4.4	4.4-4.5	4.5-4.6	4.6-4.7
Tem[kNm]	0	1.3	0.65	0	0
q[Mvar]	0	0	1	2	0

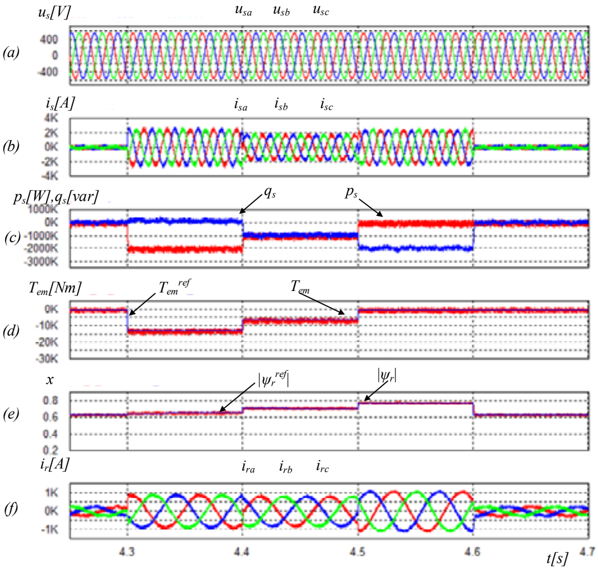

Fig. 2. Balanced grid operation of classic DTC. (a) – stator phase voltages, (b) – stator phase currents, (c) – instantaneous power, (d) – electromagnetic torque and its reference signal, (e) – rotor flux magnitude and its reference , (f) – rotor phase currents.

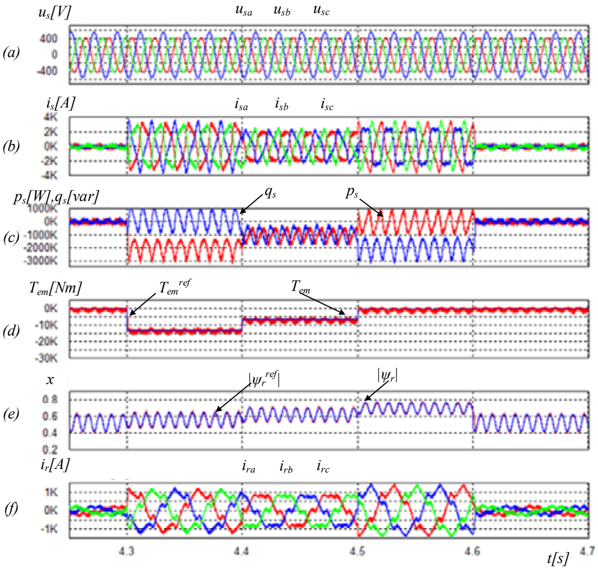

Fig.3. Unbalanced grid operation of classic DTC. (a) – stator phase voltages, (b) – stator phase currents, (c) – instantaneous power, (d) – electromagnetic torque and its reference signal, (e) – rotor flux magnitude and its reference, (f) – rotor phase currents.

Sinusoidal generated currents are desirable. Thus, new control method has been proposed where referenced variables are electromagnetic torque and reactive component of instantaneous power. As the manipulated variables the electromagnetic torque and new scalar value *x* have been proposed. The former is a real (equation (12)) the latter is imaginary product of coupled stator flux vector and stator current vector.

$$x = \frac{3}{2} p_b \operatorname{Re}(\psi_s^* i_s) = \frac{3}{2} p_b (\psi_{s\alpha} i_{s\alpha} + \psi_{s\beta} i_{s\beta}) \tag{12}$$

In order to obtain reference value of *x* the reference stator currents must be calculated. In this paper as control requirements constant torque and sinusoidal stator currents were chosen. Instantaneous power can be calculated using (13) and (14) according to [20].

$$p_s = \frac{3}{2}\left(u_{s\alpha} i_{s\alpha} + u_{s\beta} i_{s\beta}\right) \tag{13}$$

$$q_s = \frac{3}{2}\left(u_{s\beta} i_{s\alpha} - u_{s\alpha} i_{s\beta}\right) \tag{14}$$

Combining (6) and (14) the reference value for stator currents dependency were derived and its form is presented below (15)(16).

$$i_{s\alpha}^{ref} = \frac{2}{3} \frac{q_s^{ref} \psi_{s\alpha} + \dfrac{T^{ref} u_{s\alpha}}{p_b}}{u_{s\beta}\psi_{s\alpha} - u_{s\alpha}\psi_{s\beta}} \tag{15}$$

$$i_{s\beta}^{ref} = \frac{2}{3} \frac{q_s^{ref} \psi_{s\beta} + \dfrac{T^{ref} u_{s\beta}}{p_b}}{u_{s\beta}\psi_{s\alpha} - u_{s\alpha}\psi_{s\beta}} \tag{16}$$

Inserting (15) and (16) into (12) the relation for reference value of new scalar x^{ref} is obtained (17).

$$x^{ref} = \frac{3}{2} p_b (\psi_{s\alpha} i_{s\alpha}^{ref} + \psi_{s\beta} i_{s\beta}^{ref}) \tag{17}$$

Proposed control strategy is analogous to DTC and DPC methods [7, 8]. The αβ plane is divided into 6 sectors as depicted in figure 4. Voltage vectors are constructed for two level three phase voltage converter.

Sector borders values are given in table 2. In figure 5 the whole proposed control method is depicted with torque and q component of instantaneous power set as the reference, and with torque and new scalar variable used in the direct control algorithm.

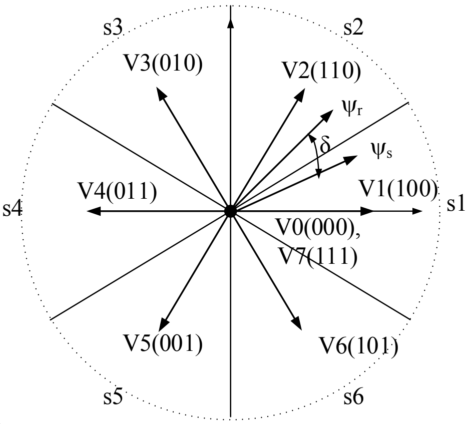

Fig.4. Sector and vector plane placement.

Table 2. Sectors placement

sector	Range in radians
s1	$\frac{11}{6}\pi - \frac{1}{6}\pi$
s2	$\frac{1}{6}\pi - \frac{3}{3}\pi$
s3	$\frac{3}{6}\pi - \frac{5}{6}\pi$
s4	$\frac{5}{6}\pi - \frac{7}{6}\pi$
s5	$\frac{7}{6}\pi - \frac{9}{6}\pi$
s6	$\frac{9}{6}\pi - \frac{11}{6}\pi$

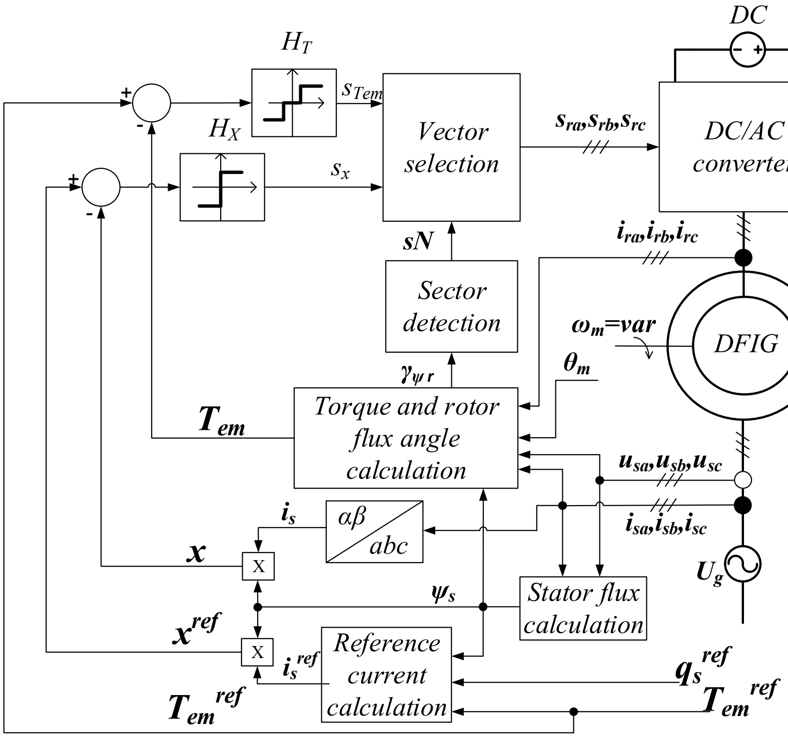

Fig.5. Proposed control algorithm.

Firstly, the stator and rotor currents are measured and both fluxes are being calculated (3), (4). Then the electromagnetic torque (6) and auxiliary scalar *x* (12) is calculated. Values of the reference signals is determined on the basis of arbitral given electromagnetic torque and reactive component of instantaneous power (12) and (15), (16). Obtained manipulated variable and their references are compared and their differences are given as inputs of three-level torque and two-level variable *x* hysteresis controllers respectively.

Based on the s_x and s_{Tem} outputs of the hysteresis controllers and location of the rotor flux vector in rotor coordinates plane a specific RSC voltage vector is applied. The optimal switching table constructed according with the proposed algorithm is presented in table 3.

Table 3. Optimal switching table

		SECTOR					
Δx	ΔT	s1	s2	s3	s4	s5	s6
1	1	V5(001)	V6(101)	V1(100)	V2(110)	V3(010)	V4(011)
	0	V0(000)	V7(111)	V0(000)	V7(111)	V0(000)	V7(111)
	-1	V3(010)	V4(011)	V5(001)	V6(101)	V1(100)	V2(110)
-1	1	V6(101)	V1(100)	V2(110)	V3(010)	V4(011)	V5(001)
	0	V0(000)	V7(111)	V0(000)	V7(111)	V0(000)	V7(111)
	-1	V2(110)	V3(010)	V4(011)	V5(001)	V6(101)	V1(100)

Simulation results

Simulation were performed in PSIM software. As the control plant, the model of 2MW DFIG has been used. Its parameters are given in table 3. Sampling frequency of the implemented algorithm has been set to 10kHz.

Table 3. DFIG nominal parameters

Rated power P_n	2MW
Stator voltage U_{Sn}	690V
Stator rated current I_s	1760A
Rated U_{rRMS}	2600V
Stator/rotor turns ratio	0.34
R_s	2.6mΩ
R_r	2.6mΩ
$L_{\sigma s}$	0.087mH
$L_{\sigma r}$	0.087mH
L_m	2.5mH
n_s	1500rpm
Number of poles pairs p	2

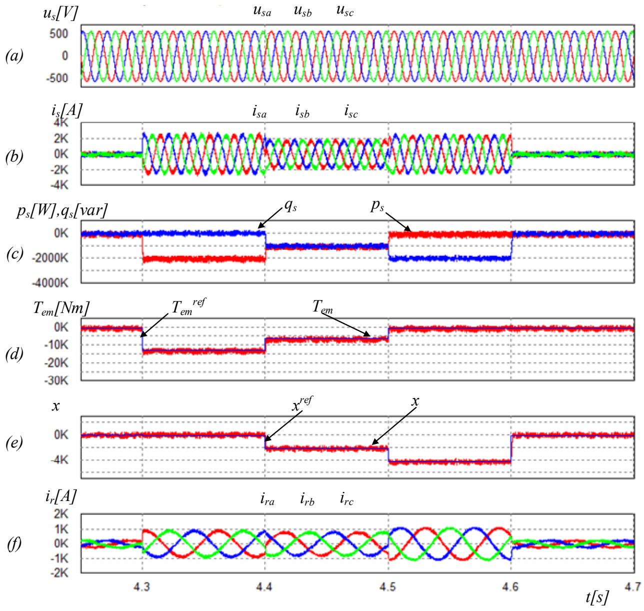

Fig.6. Constant speed and symmetrical grid operation. (a) – stator phase voltages, (b) – stator phase currents, (c) – instantaneous power, (d) – electromagnetic torque and its reference signal, (e) – controlled scalar *x* and its reference x^{ref} , (f) – rotor phase currents.

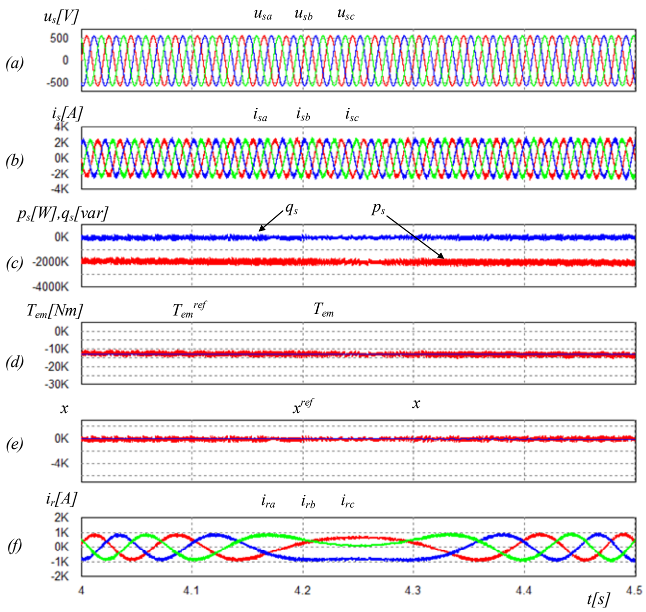

Fig.7. Variable speed and symmetrical grid operation. (a) – stator phase voltages, (b) – stator phase currents, (c) – instantaneous power, (d) – electromagnetic torque and its reference signal, (e) – controlled scalar *x* and its reference x^{ref} , (f) – rotor phase currents.

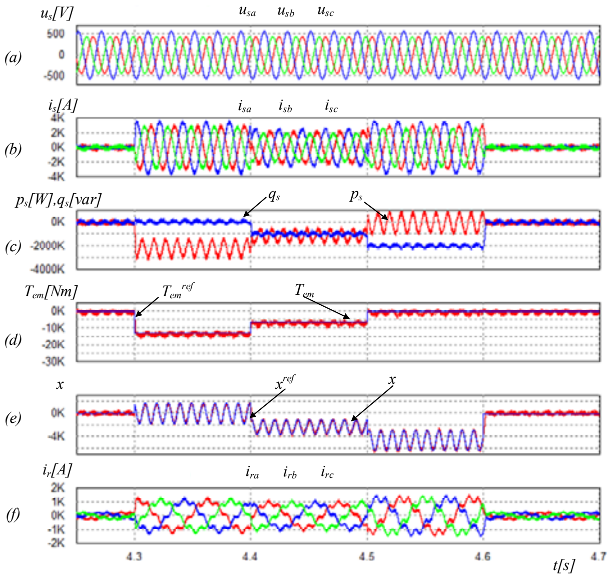

Fig.8. Constant speed and asymmetrical grid operation (20% of negative sequence voltage). (a) – stator phase voltages, (b) – stator phase currents, (c) – instantaneous power, (d) – electromagnetic torque and its reference signal, (e) – controlled scalar *x* and its reference x^{ref} , (f) – rotor phase currents.

Simulation results of proposed control algorithm for symmetrical (figure 4 and 5) and asymmetrical (figure 6 and 7) power grid with 20% of negative sequence grid voltage component, is presented. DFIG in figure 4 and 6 is operating with constant speed equal 2000rpm, figure 5 and 7 deals with variable speed operation. Reference signals values are identical to those in table 1.

For symmetrical grid, described control algorithm performance is comparable with the DTC and DPC algorithms. Stator and rotor currents are sinusoidal. Electromagnetic torque and instantaneous power have fixed values and proposed algorithm allows to decupled control of this variables with simultaneous sinusoidal stator current.

In the case of unbalanced grid operation, proposed algorithm and its reference signals calculation method allows to maintain constant torque operation (figure 8(d) and figure 9(d)) and sinusoidal stator current generation (figure 8(b) and figure 9(b)).

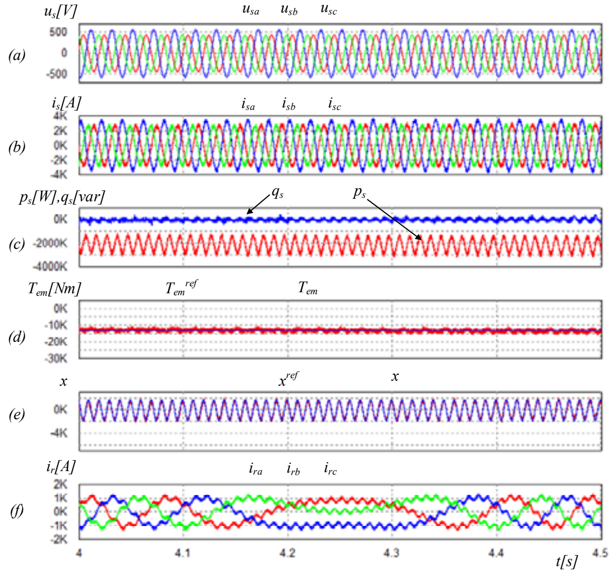

Fig.9. Variable speed and asymmetrical grid operation (20% of negative sequence voltage). (a) – stator phase voltages, (b) – stator phase currents, (c) – instantaneous power, (d) – electromagnetic torque and its reference signal, (e) – controlled scalar *x* and its reference x^{ref}, (f) – rotor phase currents.

Conclusions

The paper presented a direct control method for a DFIG with the electromagnetic torque and a new scalar variable defined as dot product of stator flux and stator current vectors used as an inner control variables for direct control algorithm. Proposed algorithm allows for indirect control of electromagnetic torque and reactive component of stator instantaneous power. Simulation results with symmetrical and unbalanced grid were presented. The method allows to generate sinusoidal stator current at constant torque and does not require any signal decomposition. The next stage of research will be a laboratory set-up verification.

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