Piotr PURA, Grzegorz IWANSKI

Warsaw University of Technology, Institute of Control and Industrial Electronics

Direct Power Control of a Doubly Fed Induction Generator Connected to the Unbalanced Grid with Stator Power and Current Limitations

***Abstract**. The paper describes calculation methods of reference components of instantaneous power for control of DFIG connected to unbalanced power grid. The methods allow to operate with constant electromagnetic torque without exceeding power and current limits of DFIG's stator side. The comparison between different strategies is shown and discussed. Whole control and calculation are performed in αβ reference frame without voltage decomposition into positive and negative sequence. Classic, well-known DPC is used as the main control algorithm..*

***Streszczenie.** W artykule opisany jest algorytm wyznaczania referencyjnej chwilowej wartości mocy użytej w sterowanej zgodnie z algorytmem DPC w maszynie dwustronnie zasilanej współpracującej z siecią asymetryczną. Opisana metoda pozwala na pracę ze stałym momentem elektromagnetycznym bez przekroczenia ograniczeń mocy i prądu stojana MDZ. Artykuł prezentuje porównanie i analizę różnych strategii, w których nie została użyta dekompozycja napięcia na składową zgodną i przeciwną a całe sterowanie zrealizowano we współrzędnych αβ. (**Algorytm bezpośredniej regulacji mocy z ograniczeniami na mocy i prądzie maszyny dwustronnie zasilanej pracującej na sieć asymetryczną**)*

Słowa kluczowe: MDZ, maszyna dwustronnie zasilana, DPC, bezpośrednie sterowanie mocą, sieć asymetryczna.
Keywords: DFIG, doubly-fed induction generator, DPC, direct power control, unbalanced grid.

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Introduction

In recent years, there have been published many papers proposing different control algorithms for doubly fed induction generator (DFIG). Control methods based on nonlinear power flow control, e.g. Direct Power Control (DPC) [1-4], Field Oriented Control (FOC), use variable decomposition into positive and negative sequence components. In these systems Proportional-Integral (PI) controllers are used in synchronous *dq* frame [5,6], and Proportional-Resonant (PR) controllers – in the stationary αβ frame.

Due to DFIG construction and direct connection of its stator to the power grid, DFIG is especially sensitive to grid voltage unbalances, which are common, because of usual location of wind turbines in rural areas. Asymmetrical stator voltage without any countermeasures causes electromagnetic torque ripples in DFIG with the double grid pulsation ($2\omega_g$) and significant amplitude. Therefore, any applied control should consider DFIG unbalanced operation. Recently, many countries are developing Grid Codes [8]. Regarding them, an immediate disconnection of wind turbines at the voltage drop or unbalance is not allowed.

A wind turbine must operate continuously during small unbalances and be able to withstand large ones for time period depending on a type and degree of the asymmetry. Long-lasting voltage drop or deep unbalance may cause a necessity of wind turbine disconnection and a switch to standalone mode operation [9]. Stable DFIG operation with unbalanced grid voltage requires not only compensation of torque ripples, which may cause mechanical stress on gears and bearings, but also control and limitation of the generated phase currents [10]. Depending on a type of asymmetry, the stator currents may exceed the nominal values and may cause overheating of windings, when reference power is too high during grid voltage drop or unbalance, even if referenced power is lower than rated.

Reduction of torque oscillation is presented in the paper, as well as the reference power calculation and their limitation. There is also proposed an algorithm for stator currents limitation calculation. All of the presented concepts do not require signal decomposition and they are performed based on the signals represented in a stationary αβ reference frame. A scheme of the analyzed DFIG set-up is presented in figure 1. The paper is focused on control of the rotor side converter (RSC).

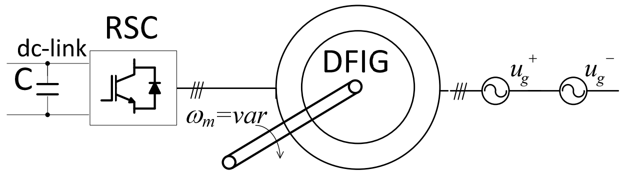

Fig.1. DFIG operation condition. u_g^+ - positive sequence grid voltage, u_g^- - negative sequence grid voltage.

DFIG mathematical description

The control method requires the model of DFIG in αβ frame. The stator and rotor voltage vectors can be represented as follows (1)(2)

$$\bar{u}_s = R_s\bar{i}_s + \frac{d\bar{\psi}_s}{dt} \tag{1}$$

$$\bar{u}_r = R_r\bar{i}_r + \frac{d\bar{\psi}_r}{dt} - j\omega_r\bar{\psi}_s \tag{2}$$

The stator and rotor flux can be presented by equations (3)(4)

$$\bar{\psi}_s = L_s\bar{i}_s + L_m\bar{i}_r \tag{3}$$

$$\bar{\psi}_r = L_r\bar{i}_r + L_m\bar{i}_s \tag{4}$$

The stator flux can be also calculated from (5)

$$\bar{\psi}_s = \int(\bar{u}_s - R_s\bar{i}_s)dt \tag{5}$$

The electromagnetic torque can be calculated from (6)

$$T = \frac{3}{2}p\,\mathrm{Im}(\bar{\psi}_s{}^*\bar{i}_s) = \frac{3}{2}p(\psi_{s\alpha}i_{s\beta} - \psi_{s\beta}i_{s\alpha}) \tag{6}$$

where L_m, L_s and L_r are the magnetizing, stator and rotor inductance respectively, meeting the equations (7)

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

$L_{\sigma s}$, $L_{\sigma r}$ –the stator and rotor leakage inductance, R_s, R_r – the stator and rotor resistance, $\bar{i}_s$ $\bar{i}_r$ $\bar{i}_m$ - the stator, rotor and magnetizing current, $\bar{\psi}_s$ $\bar{\psi}_r$ - the stator and rotor flux.

All vectors are represented by the instantaneous components, what is described by (8) for the stator voltage vector components $u_{s\alpha}$, $u_{s\beta}$

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

where u_{sa}, u_{sb}, u_{sc} – the instantaneous stator phase voltage, $u_{s\alpha}$, $u_{s\beta}$ – the instantaneous stator voltage in stationary $\alpha\beta$ frame.

A relation between stator and rotor side pulsations and the mechanical speed is described by (9)

(9) $$\omega_r = \omega_s - p\omega_m$$

where ω_s, ω_m, ω_r – the stator voltage, rotor mechanical and rotor slip angular speed, p – number of poles pairs.

Principle of constant torque operation

Simplifying (5) by neglecting the stator resistance equation, (5) gets the form (10)

(10) $$\overline{\psi}_s = \int \overline{u}_s dt$$

The stator voltage vector components can be described in $\alpha\beta$ coordinate system as in (11)

(11) $$u_{s\alpha} = u_{s\alpha}^{\max} \cos(\omega t + \alpha)$$
$$u_{s\beta} = u_{s\beta}^{\max} \cos(\omega t + \beta)$$

where $u_{s\alpha}^{\max}$, $u_{s\beta}^{\max}$ - the maximum amplitude of instantaneous stator voltage respectively in α and β axis, α – the initial angle of the stator voltage component in α axis, β – the initial angle of the stator voltage component in β axis.

Substituting (11) into (10), the flux components in $\alpha\beta$ frame take the form presented in equation 12

(12) $$\psi_{s\alpha} = -u_{s\alpha}^{\max} \sin(\omega_s t + \alpha)/\omega_s$$
$$\psi_{s\beta} = -u_{s\beta}^{\max} \sin(\omega_s t + \beta)/\omega_s$$

Assuming sinusoidal shape of the stator current it can be described (13) similarly to voltage

(13) $$i_{s\alpha} = i_{s\alpha}^{\max} \cos(\omega_s t + \gamma)$$
$$i_{s\beta} = i_{s\beta}^{\max} \cos(\omega_s t + \delta)$$

where $i_{s\alpha}^{\max}$, $i_{s\beta}^{\max}$ the maximum amplitudes of the stator current in α and β axis respectively, γ – phase angle of the stator current in α axis, δ – phase angle of the stator current in β axis.

Substituting (12) and (13) into (6) the steady state torque relation takes form (14)

(14) $$T = \frac{3}{2} p \begin{pmatrix} \frac{u_{s\alpha}^{\max}}{\omega_s} \sin(\omega_s t + \alpha) i_{s\beta}^{\max} \cos(\omega_s t + \delta) + \\ \frac{u_{s\beta}^{\max}}{\omega_s} \sin(\omega_s t + \beta) i_{s\alpha}^{\max} \cos(\omega_s t + \gamma) \end{pmatrix} =$$
$$\frac{4p}{3\omega_s} \begin{pmatrix} -u_{s\alpha}^{\max} i_{s\beta}^{\max} \left(\sin(\alpha - \delta)\right) + \sin(2\omega_s t + \alpha + \delta)\right) + \\ u_{s\beta}^{\max} i_{s\alpha}^{\max} \left(\sin(\beta - \gamma)\right) + \sin(2\omega_s t + \beta + \gamma)\right) \end{pmatrix}$$

Fixed torque delivered by doubly fed machine requires that following condition (15) must be kept

(15) $$\frac{i_{s\alpha}^{\max}}{i_{s\beta}^{\max}} \sin(2\omega_s t + \beta + \gamma) = \frac{u_{s\alpha}^{\max}}{u_{s\beta}^{\max}} \sin(2\omega_s t + \alpha + \delta)$$

Relation (15) means that the ratio between voltage amplitudes in α to β axis must be the same as the ratio of stator current amplitudes in α to β axis if constant torque is required. Moreover, the phase shift between the α and the β component of generated current must be the same as the one between the α and β component of stator voltage.

Standard DPC will be used as the main control algorithm, which in details was presented in [1]-[4]. Instantaneous power components are calculated according to (16) and (17).

(16) $$p_s = 1.5\left(u_{s\alpha} i_{s\alpha} + u_{s\beta} i_{s\beta}\right)$$

(17) $$q_s = 1.5\left(u_{s\beta} i_{s\alpha} - u_{s\alpha} i_{s\beta}\right)$$

where p_s – active component of instantaneous power, q_s – reactive component of instantaneous power.

Based on the placement of instantaneous stator flux in the rotor coordinated frame and the signals from hysteresis active and reactive power controllers, the optimal voltage vector is chosen from a switching table and applied to RSC. Further figures present the cases with symmetrical (Fig.8) and unbalanced grid voltage (Fig.9) operation of DFIG with fixed reference power components values, i.e. without elimination of the electromagnetic torque pulsations. It is necessary to modify the reference p component of the instantaneous stator power to obtain sinusoidal stator current and constant torque.

Calculation of reference power for DPC

If value of applied instantaneous stator current represented in $\alpha\beta$ is based on the condition (15), the stator current maximum amplitudes could be described as (18)

(18) $$i_{s\alpha}^{\max} = i_{s\alpha\beta}^{\max} \frac{u_{s\alpha}^{\max}}{u_{s\alpha\beta}^{\max}} \qquad i_{s\beta}^{\max} = i_{s\alpha\beta}^{\max} \frac{u_{s\beta}^{\max}}{u_{s\alpha\beta}^{\max}}$$

where $u_{s\alpha\beta}^{\max}$, $i_{s\alpha\beta}^{\max}$ – respectively the bigger amplitude of α or β stator voltage and stator current vector component.

The definitional value of active power, which take into consideration (11), (13) and (18) take the form (19).

(19) $$P_s = \frac{3}{2} \int_0^T \left(u_{s\alpha} i_{s\alpha} + u_{s\beta} i_{s\beta}\right) dt =$$
$$\frac{3}{2} u_{s\alpha}^{\max} i_{s\alpha}^{\max} \int_0^T \left(\cos(\omega_s t + \alpha)\cos(\omega_s t + \gamma)\right) dt +$$
$$\frac{3}{2} u_{s\beta}^{\max} i_{s\beta}^{\max} \int_0^T \left(\cos(\omega_s t + \beta)\cos(\omega_s t + \beta + \gamma)\right) dt =$$
$$\frac{3}{2} \frac{\left(u_{s\alpha}^{\max 2} + u_{s\beta}^{\max 2}\right)}{u_{s\alpha\beta}^{\max}} i_{s\alpha\beta}^{\max} \cos(\gamma)$$

Reactive component of instantaneous power can be calculated similarly, what is presented in (20).

(20) $$Q_s = \frac{3}{2} \int_0^T \left(u_{s\beta} i_{s\alpha} - u_{s\alpha} i_{s\beta}\right) dt =$$
$$\frac{3}{2} u_{s\beta}^{\max} i_{s\alpha}^{\max} \int_0^T \left(\cos(\omega_s t + \beta)\cos(\omega_s t + \gamma)\right) dt -$$
$$\frac{3}{2} u_{s\alpha}^{\max} i_{s\beta}^{\max} \int_0^T \left(\cos(\omega_s t + \alpha)\cos(\omega_s t + \beta + \gamma)\right) dt =$$
$$\frac{3}{2} \sin\beta \frac{\left(u_{s\alpha}^{\max} u_{s\beta}^{\max}\right)}{u_{s\alpha\beta}^{\max}} i_{s\alpha\beta}^{\max} \sin(\gamma)$$

In steady state average value of active and reactive power depends on the maximum current $i_{s\alpha\beta}^{\max}$ (the highest of $\alpha\beta$ components amplitude) and the phase angle between corresponding voltage and current components. Moreover, the reactive power depends on the angle between α and β component of voltage, which must be kept equal to the one for current components in order to meet the relation described by (15). The reference angle φ and reference maximal current can be calculated using reference active P_s and reactive Q_s power (obtained from the superior controllers) by equations (21), (22).

$$\varphi = tg^{-1}\left(\frac{u_{s\alpha}^{\max 2} + u_{s\beta}^{\max 2}}{2u_{s\alpha}^{\max}u_{s\beta}^{\max}\sin(\beta-\alpha)}\frac{Q_s}{P_s}\right) \quad (21)$$

$$i_{s\alpha\beta}^{\max ref} = \frac{4P_s u_{s\alpha\beta}^{\max}}{3(u_{s\alpha}^{2} + u_{s\beta}^{2})\cos(\varphi)} \quad (22)$$

For the assumed voltage conditions and constant torque requirements expressed by (15), the q component is independent of voltage asymmetry, it is fixed and equal to reference Q_s. The p component depends on the grid voltage asymmetry and consists of an average value equals to the reference P_s and a oscillatory component of the double grid frequency. Magnitude of these oscillations have to consider the grid voltage conditions, the reference maximal current $i_{s\alpha\beta}^{\max ref}$ and the angle φ.

Substituting equation (11) and (13) into (16) and taking into consideration equation (18), (21) and (22) the relation for instantaneous active power component can be described by equation (23).

$$p_{ins} = \frac{3}{2}\frac{i_{s\alpha\beta}^{\max}}{u_{s\alpha\beta}^{\max}}\begin{pmatrix}\left(u_{s\alpha}^{2} + u_{s\beta}^{2}\right)\cos\varphi + \\ -\left(u_{s\alpha}u_{s\alpha}^{d} + u_{s\beta}u_{s\beta}^{d}\right)\sin\varphi\end{pmatrix} \quad (23)$$

where φ – the reference angle between respective components of the stator voltage and the stator current, $u_{s\alpha}^{d}$, $u_{s\beta}^{d}$ – the α and the β component of the stator voltage delayed by $\pi/4$ respectively.

Calculating average value of p_{ins} (23), the classical definition of active power is received (24).

$$P_{avg} = \frac{1}{T}\int_{t}^{t+T} p_{inst}\,dt \quad (24)$$

Division of the equation (23) by (24) gives the relation for normalized reference active component of instantaneous power.

$$p^{norm} = \frac{p_{inst}}{P_{avg}} \quad (25)$$

The reference value of active and reactive component of instantaneous power used in control algorithm.

$$p^{ref} = P_s^{ref}\, p^{norm} \quad (26)$$

$$q^{ref} = Q_s^{ref} \quad (27)$$

where p_{inst} – the active component of instantaneous power, P_{avg} – the average value of p_{inst}, p^{norm} – the normalized active component of instantaneous power, p^{ref} – the reference value of active component of instantaneous power used directly in control, P_s^{ref} – the reference of stator active power received from a superior control algorithm, e.g. MPPT (Maximum Power Point Tracking), Q_s^{ref} – stator reactive power reference, from the superior control.

The principle of reference power calculation algorithm based on average value is presented in figure 4.

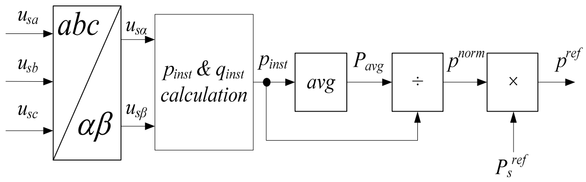

Fig.4. Calculation of normalized average active component of instantaneous power principle.

Results of DPC control with applied calculated reference power are presented in figure 10. The only limit is average value of the reference power, therefore, there is no direct control of amplitude of the stator phase currents, which may be increased due to the grid voltage unbalance. For low asymmetry factor (<10%) the stator phase currents do not significantly exceed its nominal values.

Limitation on reference maximal active power value

In order to limit value of the phase currents a new algorithm is proposed. It limits the value of active component of instantaneous power. Figure 5 and 6 present its principle.

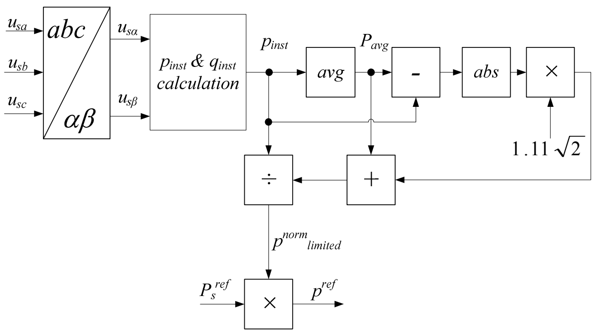

Fig.5. Calculation principles of normalized limited active component of instantaneous power.

Firstly, the active component of instantaneous power p_{inst} is calculated according to (23), then average value of p_{inst} - P_{avg}. Next, p_{inst} is divided by the sum of P_{avg} and previously calculated amplitude of the oscillatory component of p_{inst}. Obtained in this manner signal has maximal value equal to 1.0 and in this paper it is called $p^{norm}{}_{limited}$. Signals used in calculation of limited active power component are shown in figure 6.

$$p^{ref} = P_s^{ref}\, p^{norm}{}_{limited} \quad (28)$$

$$q^{ref} = Q_s^{ref} \quad (29)$$

where $p^{norm}{}_{limited}$ – limited normalized reference value of active component of instantaneous power.

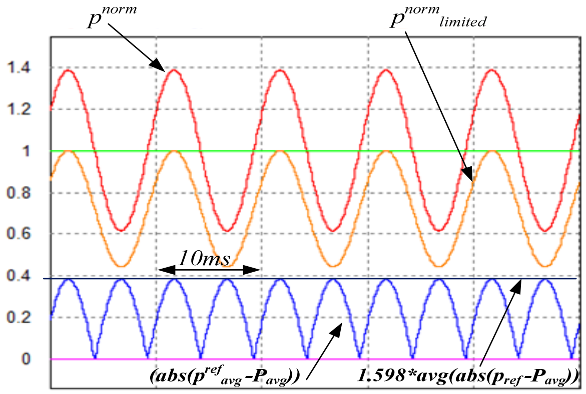

Fig.6. Reference active component of instantaneous power calculation principle.

Results of the proposed method for reference signal calculation are presented in figure 11. The phase currents do not exceed the nominal values of 2MW DFIG (Table 1 and Table 2), they are below them. The presented method is adequate for the case when the reference reactive power equals zero. For nonzero required reactive power, the algorithm must be modified to limit the stator current , but not the power.

Limitation on stator current

In order to fully exploit the generating abilities of DFIG, an algorithm limiting the maximum value of the stator current was developed. Its diagram is shown in figure 7.

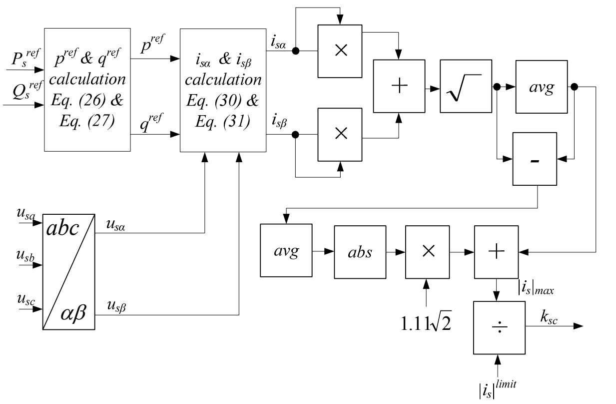

Fig.7. Calculation principle of the maximal stator current amplitude.

The algorithm depicted in figure 7 is based on a calculation of the maximum magnitude of the stator current vector. Firstly, the amplitudes of required stator current based on measured stator voltage in $\alpha\beta$ frame and reference powers signals (generated by a superior control algorithm) are determined (30, 31). Then, the square root of the received value is calculated, in this way the magnitude of instantaneous current vector is calculated. Next, the average value of vector magnitude is determined, as well as the amplitude of its oscillatory component in the stator current amplitude. Next, the average value of the stator current amplitude is added to the amplitude of its oscillatory component. As a result, the maximum value of the stator current vector

magnitude is calculated. The signals have the same character as those depicted in figure 6, but instead of the instantaneous power, the stator current vector is taken into consideration.

If the value of calculated current exceeds the previously defined limit, the signal of instantaneous reference power is multiplied by factor k_{sc} (33) and the value of generated power decreases (34) and (35).

$$i_{s\alpha} = \frac{2}{3}\frac{p^{ref}u_{s\alpha} + q^{ref}u_{s\beta}}{u_{s\alpha}^2 + u_{s\beta}^2} \tag{30}$$

$$i_{s\beta} = \frac{2}{3}\frac{p^{ref}u_{s\beta} - q^{ref}u_{s\alpha}}{u_{s\alpha}^2 + u_{s\beta}^2} \tag{31}$$

$$|i_s| = \sqrt{i_{s\alpha}^2 + i_{s\beta}^2} \tag{32}$$

$$k_{sc} = \frac{|i_s|^{limit}}{|i_s|_{\max}} \tag{33}$$

$$p^{ref}{}_{limited} = k_{sc}P_s^{ref}p^{norm} \tag{34}$$

$$q^{ref}{}_{limited} = k_{sc}Q_s^{ref} \tag{35}$$

where k_{sc} – the scaling factor depending on amplitude of generated current and its limit, $p^{ref}{}_{limited}$ – limited reference value of active component of instantaneous power, $q^{ref}{}_{limited}$ – the limited reference value of reactive component of instantaneous power .

Results of the proposed method are shown in figure 12.

Simulation results

Simulation of the proposed strategies for a 2MW DFIG was conducted using PSIM software. The nominal DFIG's parameters are given in the Table 1. Figure 8 shows operation with balanced grid. Figure 9 – 12 shows simulation results with 20% voltage unbalance. Comparing figure 9 (d) with figure 10 – 12 (d) it can be observed that the electromagnetic torque has a significant drop in pulsation amplitude. The reference signals and generated instantaneous power are shown in part (c) of the figures. Table 2 presents RMS values of the stator phase currents after a step change of reference power, what occurs in t=5s.

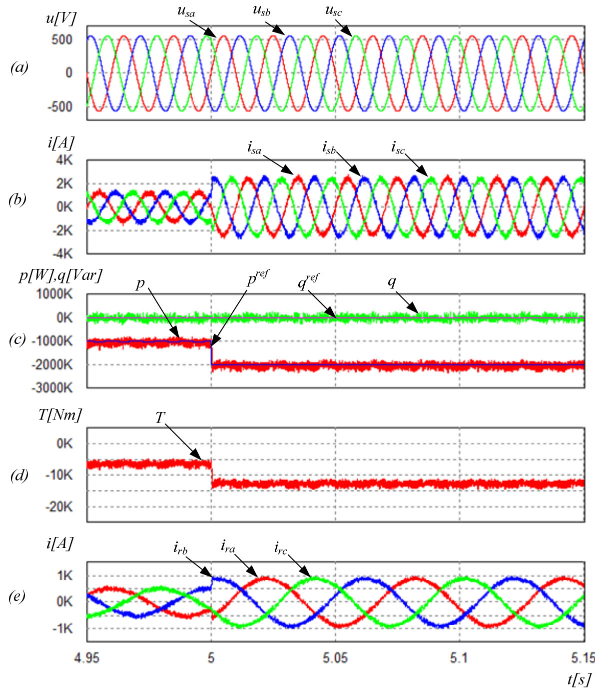

Fig.8. Simulation results of 2MW DFIG connected to symmetrical grid. (a) – stator phase voltages u_{sa}, u_{sb}, u_{sc}, (b) – stator phase currents i_{sa}, i_{sb}, i_{sc}, (c) – active and reactive instantaneous power components p, q along with their references p^{ref}, q^{ref}, (d) – electromagnetic torque T, (e) – rotor phase currents i_{ra}, i_{rb}, i_{rc}.

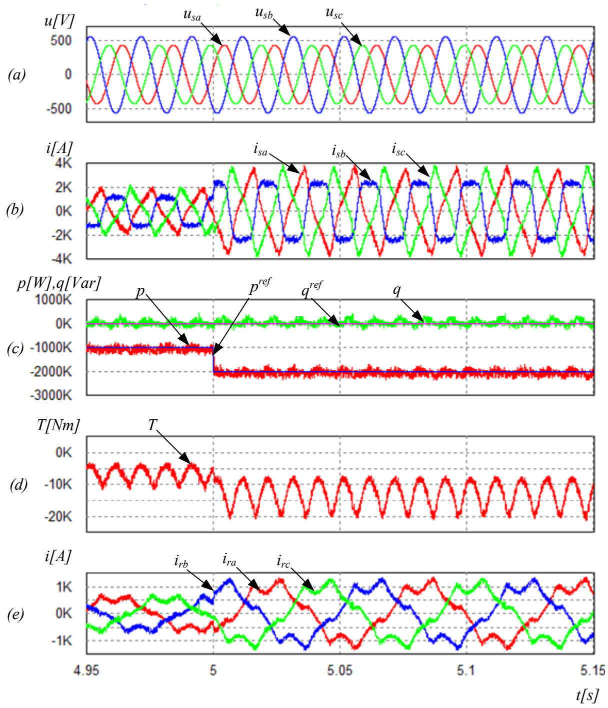

Fig.9. Simulation results of 2MW DFIG connected to asymmetrical grid with 20% negative voltage sequence. No electromagnetic torque pulsation compensation, power limit – average values. (a) – stator phase voltages u_{sa}, u_{sb}, u_{sc}, (b) – stator phase currents i_{sa}, i_{sb}, i_{sc}, (c) – active and reactive instantaneous power components p, q along with their references p^{ref}, q^{ref}, (d) – electromagnetic torque T, (e) – rotor phase currents i_{ra}, i_{rb}, i_{rc}.

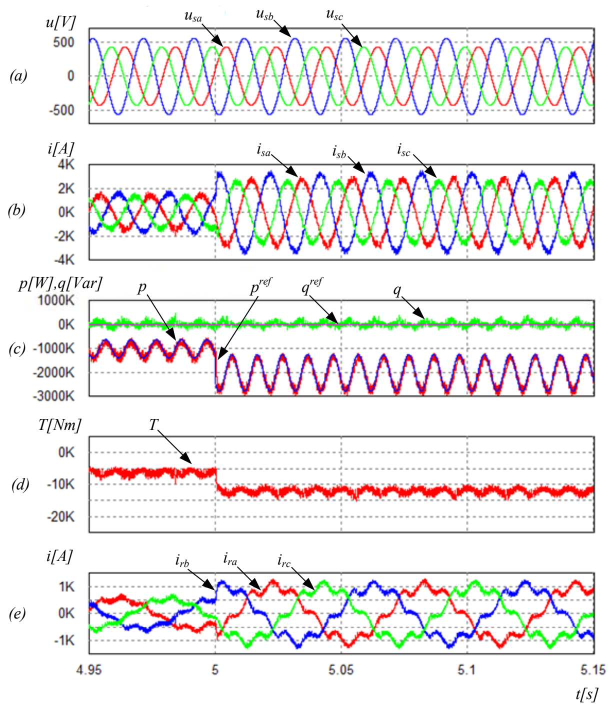

Fig.10. Simulation results of 2MW DFIG connected to asymmetrical grid with 20% negative voltage sequence. Electromagnetic torque pulsation compensation, power limit – average values (a) – stator phase voltages u_{sa}, u_{sb}, u_{sc}, (b) – stator phase currents i_{sa}, i_{sb}, i_{sc}, (c) – active and reactive instantaneous power components p, q along with their references p^{ref}, q^{ref}, (d) – electromagnetic torque T, (e) – rotor phase currents i_{ra}, i_{rb}, i_{rc}.

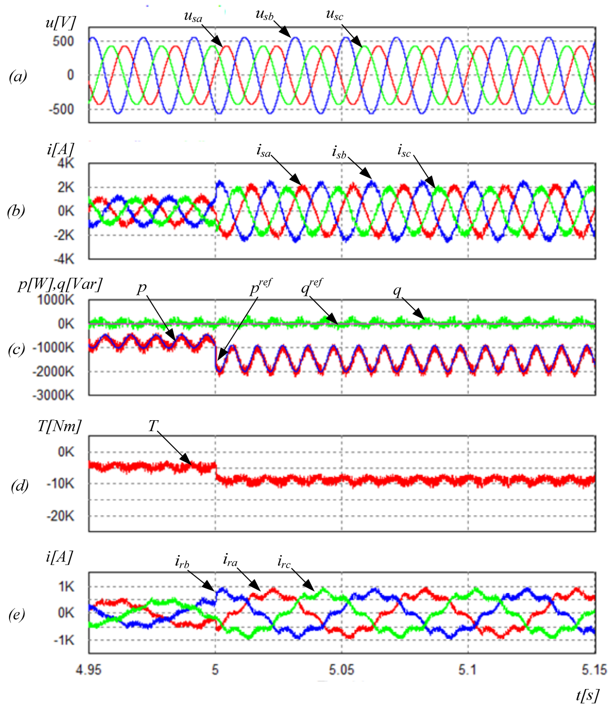

Fig.11. Simulation results of 2MW DFIG connected to asymmetrical grid with 20% negative voltage sequence. Electromagnetic torque pulsation compensation, power limit – maximal values (a) – stator phase voltages u_{sa}, u_{sb}, u_{sc}, (b) – stator phase currents i_{sa}, i_{sb}, i_{sc}, (c) – active and reactive instantaneous power components p, q along with their references p^{ref}, q^{ref}, (d) – electromagnetic torque T, (e) – rotor phase currents i_{ra}, i_{rb}, i_{rc}.

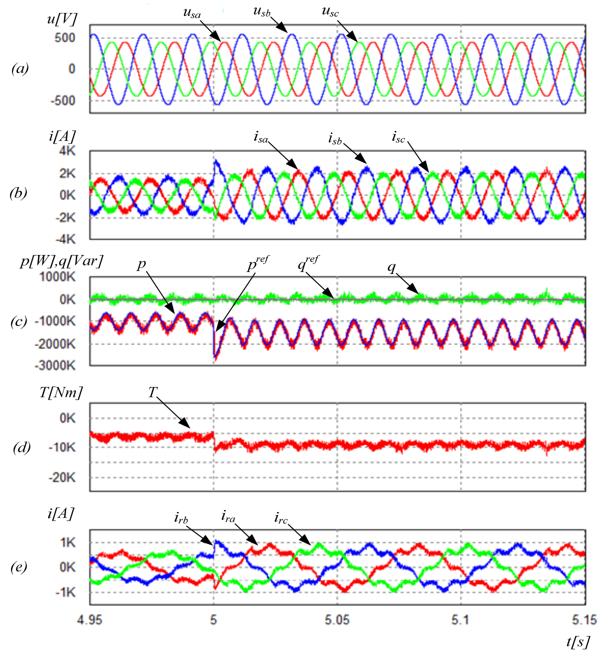

Fig.12. Simulation results of 2MW DFIG connected to asymmetrical grid with 20% negative sequence voltage component. Electromagnetic torque pulsation compensation, current limit – the maximal value of stator current magnitude. (a) – the stator phase voltages u_{sa}, u_{sb}, u_{sc}, (b) – the stator phase currents i_{sa}, i_{sb}, i_{sc}, (c) – active and reactive instantaneous power components p, q along with their references p^{ref}, q^{ref}, (d) – electromagnetic torque T, (e) – rotor phase currents i_{ra}, i_{rb}, i_{rc}.

Table 1. Simulated DFIG parameters

Rated power P_n	*2MW*
Stator voltage U_{Sn}	*690V*
Stator rated current I_s	*1760A*
Rated U_{rRMS}	*2070V*
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 pole pairs p	*2*

Balanced voltage operation with a nominal load presented in the figure 8 gives a reference of maximal phase current, which must be applied in every possible case (table 2 – record 1 – 1.72kA) in order to not overload the DFIG. In all simulation, there is a step change of load at t=5s, from 50% to 100% nominal power is applied. In the figure 9 not only the maximal value of the phase current (9b, table 2 record 2) exceeds the nominal value over 450A but also the torque (9c) has significant ripples. Applied torque oscillation limitation algorithm, which simulation results are presented in figure 10, allows to reduce the magnitude of torque ripples (10c), but the stator current in phase *b* still exceeds its nominal value nearly 600A (table 2 record 3). Proposed power limitation shown in figure 5 reduces the torque oscillation and limits currents amplitude (figure 11 and table 2 record 4). The reduction is significant, up to 1.67kA. The last proposed limitation method shown in figure 6 and its operation results in figure 12 (also table 2 record 5) allow to keep the constant torque operation and approach the phase current limit without exceeding it (up to 1.71kA).

Table 2. Stator current RMS values after a step load change at 5s

Limit and method	Stator RMS currents		
	I_{sa}[kA]	*I_{sb}[kA]*	*I_{sc}[kA]*
Fig. 8. Reference - average power, symmetrical grid	*1.72*	*1.73*	*1.72*
Fig. 9. Reference - average power, asymmetrical grid, no torque pulsation compensation	*2.16*	*2.05*	*2.16*
Fig. 10. Reference - average power, asymmetrical grid, torque pulsation compensation	*1.93*	*2.33*	*1.83*
Fig. 11. Reference – limited maximum reference power, asymmetrical grid, torque pulsation compensation	*1.41*	*1.67*	*1.35*
Fig. 12. Reference – limited maximal length of stator current vector, torque pulsation compensation	*1.45*	*1.71*	*1.37*

Summary

This paper presents the control strategy, which allows to minimize an electromagnetic torque oscillation of a DFIG connected to unbalanced power grid. There are also proposed methods of calculation of the reference power signals and their setup limits which are derived in αβ stationary frame without grid voltage decomposition. Furthermore, the algorithm, which limits instantaneous maximum stator current amplitude, is proposed. The algorithm with limited maximum magnitude of the stator current vector allows to better utilize the DFIG than the algorithm with limited maximum p component of instantaneous power, but still the stator current limit may not be reached in some cases of grid unbalance.

A full exploitation of the DFIG during grid connection operation with unbalanced power network requires determination of the position of the long axis of the stator current vector hodograph. This matter is a topic for thenext stage of research.

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***Authors**: M.Sc. Piotr Pura, Institute of Control and Industrial Electronics, Koszykowa 75, 00-662 Warsaw, Poland, E-mail: piotr.pura@ee.pw.edu.pl;*

Ph.D. Grzegorz Iwanski, Institute of Control and Industrial Electronics, Koszykowa 75, 00-662 Warsaw, Poland, E-mail: iwanskig@isep.pw.edu.pl