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Indirect Torque and Stator Reactive Power Control of Doubly Fed Induction Machine Connected to Unbalanced Power Network

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***Abstract*—The paper deals with methods of either stator current or rotor current vector control of doubly fed induction machine connected to the unbalanced power network. Several alternative control targets, such as fixed electromagnetic torque, symmetrical stator current, or symmetrical rotor current, have been achieved. In spite of the selected target, the stator current is sinusoidal, however in some cases it is unbalanced. The proposed vector control methods do not use separate negative sequence calculation and control. In some targets, filtration of signals is required in order to achieve symmetrical reference variables (positive sequence), which can be either stator or rotor current depending on the assumed target. Laboratory tests results have been presented in the steady state, as well as in transients. Short comparison of stator and rotor current controllers has been made on basis of the laboratory test results.**

***Index Terms*— AC generators, Power generation control, Induction generator**

I. Introduction

THE variable speed doubly fed induction generator DFIG is mainly known for grid connected wind energy conversion systems [1]. It determines, that the main areas of research and development on this technology are related to grid connected operation. Various basic control methods such as Field Oriented Control FOC [2][3], Direct Power Control DPC [4][5], Direct Torque Control DTC [6][7], originally designed for symmetrical grid voltage conditions, have been modified and improved to achieve satisfactory results under mentioned grid unbalanced conditions [8]-[18].

The paper is focused on the inner control of the doubly fed induction machine connected to the unbalanced grid. Outer control like MPPT or reactive power management, providing reference signals are not described. Classic well-known control methods without special modifications cause significant oscillations of the electromagnetic torque and non-sinusoidal stator current. The part of system taken into consideration is marked in Fig. 1.

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Grid side converter control is neglected in this paper due to its lack of influence on the electromagnetic torque pulsations, as well as on rotor and stator current quality. The reference torque can originate from different types of superior control blocks, e.g. MPPT algorithm in the case of wind turbine or total demanded power reference in the case of either internal combustion engine, or pumping storage hydropower plant, or flywheel energy storage.

The paper describes calculation method of reference stator or rotor current (depending on the selected method) for different targets: rejection of electromagnetic torque oscillations with simultaneous sinusoidal (but unbalanced) stator current, balanced sinusoidal stator current, or sinusoidal rotor current. Proposed method is simpler than usually proposed methods, which use a decomposition of measured and/or controlled variables into the positive and negative sequence [8]-[20]. In some papers the decomposition is used for both reference signals calculation and control [8], in some it is used for all reference signals calculation, and in others for calculation of some compensation terms created to reject oscillations of selected variables.

The control method shown in [8] requires many transformations for calculation of compensation terms and four controllers of rotor current symmetrical sequence components. Separate control of positive and negative components creates problems in rotor/stator current limitation. The presented control has been verified under low voltage asymmetry (2%) only in simulation tests.

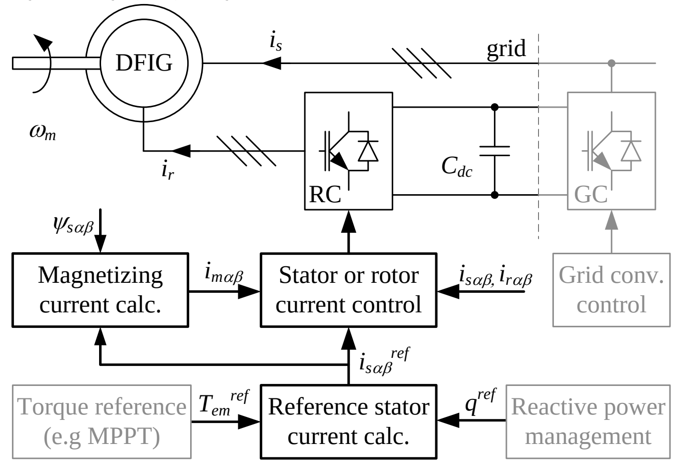

Fig. 1. General scheme of grid connected doubly fed induction machine.

It assumes fixed angular speed of the stator flux and fixed displacement between stator flux and stator voltage, which can be good approximation for low asymmetry, but it may degrade obtained performance for higher asymmetry factors.

One of the fundamental reference papers [9] shows direct power control with hysteresis controllers using symmetrical components decomposition of unbalanced stator voltage. The fixed and oscillatory power components related to positive and negative sequences are determined separately. The control manages the oscillatory power components by introducing a factor k in order to obtain specific targets (constant torque, symmetrical stator current, constant stator power components) and intermediate states (depending on the factor k). Similar concept with compensation of the oscillatory terms of p and q components, has been presented in [10][11]. In all DPC methods, the current limitation requires superior control loop decreasing the value of reference power. Until now the problem has not been discussed not only for DFIG, but for controlled by DPC methods series grid converters too.

In [10] Authors assume fixed angular speed of the stator flux vector, constant phase shift between stator voltage and stator flux. Moreover, equation (24) derived in the paper stays true only for balanced grid. Similar assumption about fixed phase shift between stator flux and stator voltage has been made in [12], in which the basic target (cancellation of electromagnetic torque oscillations) has been achieved. Thus, the reference current does not produce expected stator power. For this target, the structures proposed in this paper are significantly simplified and do not need sequence decomposition of any variables. In [11] Authors assume that derivative of stator voltage α component has the waveform of β component scaled by synchronous speed, and oppositely derivative of β components has the waveform of α component scaled by synchronous speed (eq. 11 in the paper), what is not true for unbalanced voltage, because α and β components may have different amplitudes or phase shift different than 90 degrees as well. Equation (11) is derived based on wrong description of $\alpha\beta$ signals (negative sequence stator voltage $u_{s\beta-}$ and current $i_{s\beta-}$) in equation 9. In [12] Authors again - based on [8] - repeats that the angular speed of stator flux is fixed, what is true only for symmetrical balanced grid. The same assumption has been made for the fixed phase shift between stator voltage and stator flux. However, it has not influenced on the results, because torque oscillations compensation target has not been analyzed in the paper, but balancing of the stator current. For this target the method proposed in this paper is significantly simplified. Both stator voltage/flux angular speed variation and variable angle between stator voltage and stator flux have been discussed in [9].

In [13] Authors properly determine the power equation (numbered 12 in the paper), as a function of stator voltage and stator flux. In the paper there are shown methods of rotor current and rotor voltage limitation. However, the voltage and rotor current limitation is quite complicated and need decomposition of many variables. Moreover, the paper shows the system properties for one target (balanced stator current), for which the method shown in the following paper is much simplified and uses only a single extraction of positive sequence of the reference signal. Moreover, under reduced stator voltage (voltage imbalance is a specific type of voltage dip), rotor current limitation at reference level does not provide limitation of the stator current, because the magnetizing current is lower than rated one. Thus, the stator current is higher than rated one. The paper shows only simulation results.

In [14] Authors properly determine the power equation which depends not only on the stator current and voltage, but also stator flux. They propose several targets not only for an unbalanced grid, but also for a grid distorted by high harmonics. The issue of voltage high harmonics is out of the scope of this paper and need to be discussed in the future. However, it is difficult to fully assert properties of the proposed control system without dynamic states, such as reference step and voltage dip. Moreover, the stator and rotor current limitation is not discussed in the cited paper.

In [15] the control is based on two equations derived for a balanced grid, which unfortunately are not valid for an unbalanced grid. The equation (15) in [15] is derived under the assumption that stator flux is always delayed by 90 degrees in respect to the stator voltage, what even neglecting stator resistance is true only for a symmetrical grid. For the symmetrical grid there is derived (18) to calculate the reference rotor voltage vector components. In this equation proportional gain is used for power control. Next, it is proposed the rotor voltage equation (20) for an unbalanced grid, but it is not derived separately for unbalanced grid operation, but it is simply replaced the proportional gain in (15) by PIR (proportional-integral-resonant) terms. However, it is not taken into consideration, that previous equations have been derived under the assumption of constant flux and constant stator pulsation ω_s, true only for balanced grid.

Additionally, in order to keep constant electromagnetic torque, there is replaced reference and actual stator power by reference and actual electromagnetic power without adequate justification. The electromagnetic power calculation assumes fixed stator pulsation too, what is not true in unbalanced grid. Authors of [15] present satisfactory results, but it is not clear which equation is responsible for the presented torque. If the torque is kept constant, then controlled electromagnetic power should have ripples due to oscillations of voltage pulsation ω_s. If the presented fixed torque is achieved by scaling the fixed electromagnetic power (calculated by (20)), the recorded signal does not present real torque, but the electromagnetic power scaled by the assumed fixed pulsation ω_s.

This paper presents direct calculation of stator or rotor current references (depending on the control method used). Calculation of the reference signals under unbalanced voltage conditions is made on the basis of constant reference torque T_{em}^{ref} and q_s^{ref} component of instantaneous power. Fixed torque T_{em} and q_s component of stator power assure sinusoidal (nonetheless unbalanced) stator current. This is the most wanted target of the rotor converter control due to elimination of the electromagnetic torque pulsations occurring in other targets. It does not need separate control of negative sequence of measured variables, neither their determination for current reference calculation. Filtration of the oscillatory terms in a rotating dq frame is used for balanced stator or rotor current target and for intermediary targets.

II. Reference Current Calculation

A. Electromagnetic Torque Oscillations Cancellation

Fundamental equations of electric circuits of the doubly fed induction machine are as follows (3)-(6)

$$u_s = R_s i_s + \frac{d\psi_s}{dt} \tag{3}$$

$$u_r = R_r i_r + \frac{d\psi_r}{dt} - j\omega_m \psi_r \tag{4}$$

$$\psi_s = L_s i_s + L_m i_r \tag{5}$$

$$\psi_r = L_r i_r + L_m i_s \tag{6}$$

in which u_s, u_r are the vectors of stator and rotor voltage; ψ_s, ψ_r are the vectors of stator and rotor flux; i_s, i_r, are the vectors of stator and rotor current, respectively, R_s, R_r are stator and rotor resistances, L_s, L_r, L_m are stator, rotor and magnetizing inductance; ω_m – rotor speed.

The stator flux can be calculated according to (7)

$$\psi_s = \int (u_s - R_s i_s) dt \tag{7}$$

but in order to eliminate offsets of the voltage and current sensors and integrator initial state, pre-filters have to be used.

The electromagnetic torque can be found using (8),

$$T_{em} = \frac{3}{2} p_b (\psi_{s\alpha} i_{s\beta} - \psi_{s\beta} i_{s\alpha}) \tag{8}$$

in which $i_{s\alpha}$, $i_{s\beta}$ are stator current vector components in $\alpha\beta$ coordinates, and $\psi_{s\alpha}$, $\psi_{s\beta}$ – stator flux vector components.

According to the instantaneous power theory, the stator power components p_s, q_s can be calculated (9)(10):

$$p_s = \frac{3}{2}\left(u_{s\alpha} i_{s\alpha} + u_{s\beta} i_{s\beta}\right) \tag{9}$$

$$q_s = \frac{3}{2}\left(u_{s\beta} i_{s\alpha} - u_{s\alpha} i_{s\beta}\right) \tag{10}$$

It was deduced in [7]-[16], that fixed both an electromagnetic torque and q component of stator instantaneous power are associated with sinusoidal (nonetheless unbalanced) stator current. Fixed electromagnetic torque is a main control target in many publications related to this topic. Based on (8) and (10), the reference stator current vector in a stationary reference frame can be derived on basis of the reference electromagnetic torque T^{ref} and q^{ref} component of instantaneous power (11)(12).

$$i_{s\alpha}^{ref} = \frac{2}{3} \frac{q_s^{ref} \psi_{s\alpha} + \frac{T_{em}^{ref} u_{s\alpha}}{p_b}}{u_{s\beta}\psi_{s\alpha} - u_{s\alpha}\psi_{s\beta}} \tag{11}$$

$$i_{s\beta}^{ref} = \frac{2}{3} \frac{q_s^{ref} \psi_{s\beta} + \frac{T_{em}^{ref} u_{s\beta}}{p_b}}{u_{s\beta}\psi_{s\alpha} - u_{s\alpha}\psi_{s\beta}} \tag{12}$$

B. Sinusoidal Stator Current

Elimination of electromagnetic torque oscillations of unbalanced grid connected DFIG causes that the generated power is reduced below nominal conditions. The power generation capability in this target is even lower than in the target in which sinusoidal symmetrical stator current is obtained. DFIG may be driven not only by wind turbines, but also by other prime movers, therefore not always a reduction of torque pulsations is necessary.

Sinusoidal symmetrical reference stator current may be obtained by elimination of the negative sequence from the reference signal. One of the possible ways to obtain this target is shown in Fig. 2. Current components in $\alpha\beta$ frame are transformed into some arbitrarily oriented frame dq, then 100Hz oscillations representing negative sequence are filtered, and finally they are transformed back to $\alpha\beta$ frame. Reference angular speed should be set close to the nominal grid frequency, but it is not required to precisely synchronize coordinate system with the positive sequence of grid voltage. Transformation to arbitrarily oriented dq frame is used only to eliminate negative sequence of reference current, and not for control of these variables. When grid frequency is not exactly 50Hz, positive sequence component will be represented by low frequency signal (e.g. 0.2Hz), whereas frequency of the negative sequence component will be (100Hz +/-0.2Hz). Provided that parameters of band stop filter (frequency band 20Hz, central frequency 100Hz) are set properly, oscillations of dq components will be eliminated and low-frequency signal will pass unchanged for damping factor equal one.

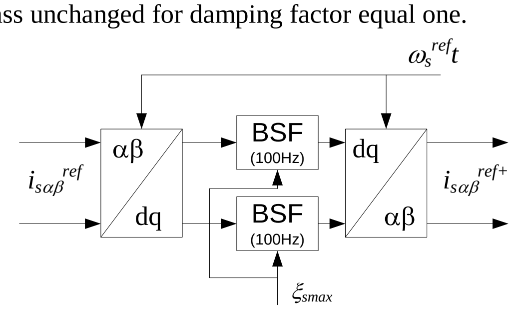

Fig. 2. Method of reference stator current positive component calculation.

In this target, the reference torque T_{em}^{ref} and q_s^{ref} component of power are treated as signals close to the average values, because some oscillations occur. However, this oscillations are not determined separately in any way to obtain sinusoidal stator current, like it is in other control methods.

C. Sinusoidal Rotor Current

Reference rotor current calculation requires determination of magnetizing current under unbalanced grid voltage conditions. Magnetizing current vector components in the stationary frame is calculated by (13) and (14)

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$$i_{m\alpha} = \frac{\psi_{s\alpha} - L_{\sigma s} i_{s\alpha}^{ref}}{L_m} \tag{13}$$

$$i_{m\beta} = \frac{\psi_{s\beta} - L_{\sigma s} i_{s\beta}^{ref}}{L_m} \tag{14}$$

in which $L_{\sigma s}$ is the stator leakage inductance and L_m is the magnetizing inductance. According to the standard equations of DFIG, magnetizing current i_m is a sum of stator i_s and rotor i_r current, so the reference rotor current can be calculated by (15).

$$i_r^{ref} = i_m - i_s^{ref} \tag{15}$$

Finally, the reference rotor current vector components are described by (16)(17).

$$i_{r\alpha}^{ref} = \frac{\psi_{s\alpha} - L_{\sigma s} i_{s\alpha}^{ref}}{L_m} - i_{s\alpha}^{ref} \tag{16}$$

$$i_{r\beta}^{ref} = \frac{\psi_{s\beta} - L_{\sigma s} i_{s\beta}^{ref}}{L_m} - i_{s\beta}^{ref} \tag{17}$$

Similarly to the calculation method of positive sequence of reference stator current (Fig. 2), the reference positive sequence of rotor current can be obtained (Fig. 3).

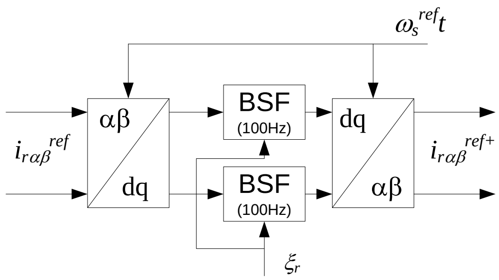

Fig. 3. Calculation method of reference rotor current positive components.

In this target (symmetrical, sinusoidal rotor current), the oscillations of electromagnetic torque are comparable to the case of symmetrical stator current target, especially in the high power machines in which power factor is relatively high and magnetizing current is relatively low. However in this case, both stator and rotor current are sinusoidal (stator current is unbalanced). Symmetry of the rotor current in the case of stator current control requires, according to (15), additional calculation of a new reference stator current $i_{s\alpha\beta}^{refnew}$ (Fig. 4).

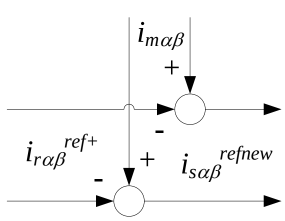

Fig. 4. Method of reference stator current calculation for symmetrical sinusoidal rotor currents target.

D. Progressive Targets Change due to the Current Limitation

Using the proposed control structures it is possible to apply progressive current balancing to increase available stator power without exceeding of either stator current or rotor current limits. Progressive balancing of respective currents is possible by progressive change of the band pass filters damping factors in the schemes from Fig. 2 and Fig. 3 respectively. In the case of progressive balancing of stator current, one of possible criteria is limitation of the stator phase current on the rated value.

The structure which can be used for detection of stator overcurrent in any phase is presented in Fig. 5. Reference stator phase current i_{sa}^{ref+}, i_{sb}^{ref+}, i_{sc}^{ref+} are obtained from $\alpha\beta$ components after transformation $\alpha\beta$ to abc. The abc reference stator phase currents are calculated from $i_{s\alpha\beta}^{ref+}$, which is the output signal from balancing structure from Fig. 2.

Absolute values of reference phase current signals are filtered to obtain their average values. They are compared with their maximum values scaled by adequate factors between amplitude, rms (1.41) and average (1.11) of absolute value of sine wave. The difference between average value of stator reference phase current and assumed limit is integrated to provide indicators of stator phase overcurrent. Maximum value ξ_{smax} among obtained indicators ξ_{sa}, ξ_{sb}, ξ_{sc} is used as a damping factor for band-pass filters from Fig. 2.

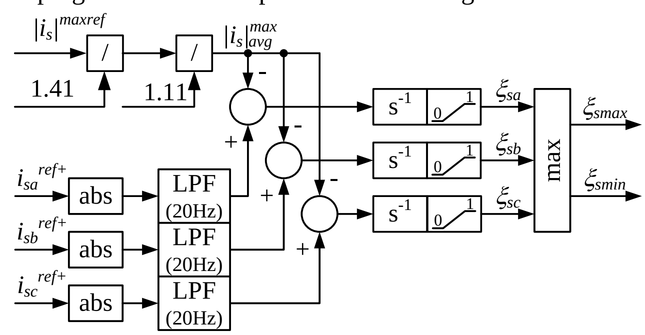

Fig. 5. Method of stator over-current detection in all phases.

The progressive balancing using the structure from Fig. 5 allows to obtain symmetrical current when all reference phase current reaches their limits, but it does not allow to avoid further increase of all phase currents, when reference torque or reactive power increases. To limit all phase currents at maximum assumed level, additional structure should be applied. The example of structure used for all currents limitation is shown in Fig. 6. This structure limits the stator current vector length, but the limitation is fully activated, when all phase currents reaches the limit. The minimum ξ_{smin} from among phase over-current indicators ξ_{sa}, ξ_{sb}, ξ_{sc} is selected as the indicator activating symmetrical current limitation. When all phase currents obtain the referenced limit, the minimum over-current indicator reaches 1.

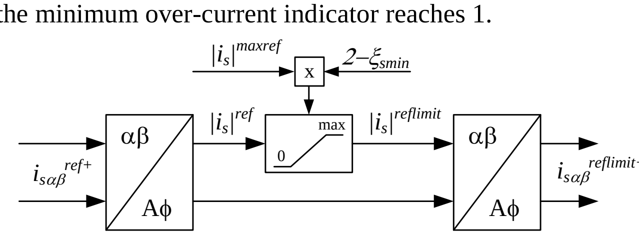

Fig. 6. Method of stator symmetrical current limitation.

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In the case of rotor current limitation, all rotor phase currents are symmetrical, but they have negative sequence oscillations of frequency equal to double grid frequency minus slip frequency. Hence, although in $\alpha\beta$ frame it is rotor current balancing process, and the structure from Fig. 3 can be used, from the point of view of rotor phase currents it is a process of harmonics progressive elimination. Thus, we shouldn't analyze the rotor phase overcurrent separately, because all currents have the same character. Instead, the maximum current vector length is taken into consideration. The maximum rotor current vector length $|i_r^{ref}|^{max}$ can be calculated using the structure from Fig. 7. This structure calculates separately average value of vector length $|i_r^{ref}|^{avg}$ and magnitude of the vector length oscillations $|i_r^{ref}|_{osc}^{max}$. Sum of both signals is the maximum rotor current vector length.

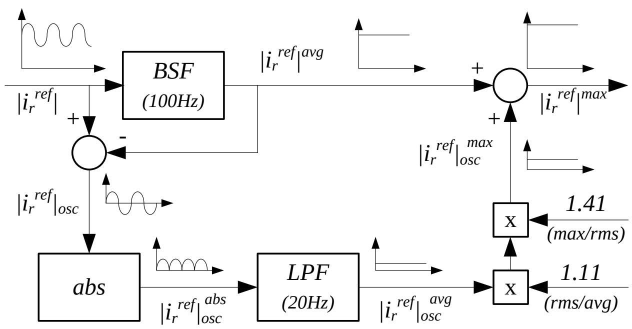

Fig. 7. Method of rotor current vector maximum length calculation.

As a result of comparison of reference vector length with assumed limit, a single indicator of rotor overcurrent is obtained (Fig. 8).

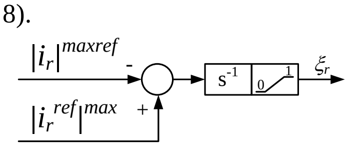
Fig. 8. Method of rotor over-current detection.

This single indicator is used simultaneously for both – progressive balancing (in the mean of progressive elimination of rotor current harmonic related to negative sequence) – Fig. 4, and for the rotor current vector length limitation shown in Fig. 9.

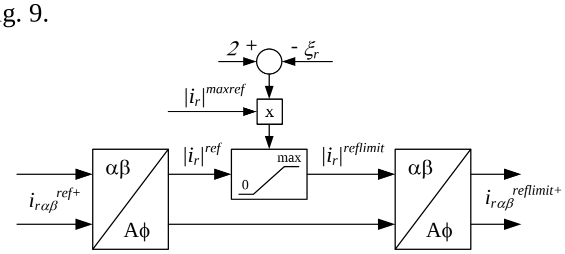

Fig. 9. Method of rotor sinusoidal current limitation.

All structures from Fig. 5 to 9, can be mixed. Progressive balancing of stator current can be made by limitation of rotor current, and progressive reduction of rotor current harmonics by stator current limitation. Moreover, proposed criteria for stator and rotor current balancing are not the only ones. Others can be e.g. extraction of maximum possible stator power, limitation of machine losses. However, they do not require to modify a main part of the proposed control.

III. Vector Control with PR Controllers

A. Rotor Current Vector Control

Scheme of the proposed vector control of DFIG with rotor current proportional-resonant PR controllers with the main target (electromagnetic torque oscillations cancellation) and optional targets (balanced stator or rotor current) is presented in Fig. 10.

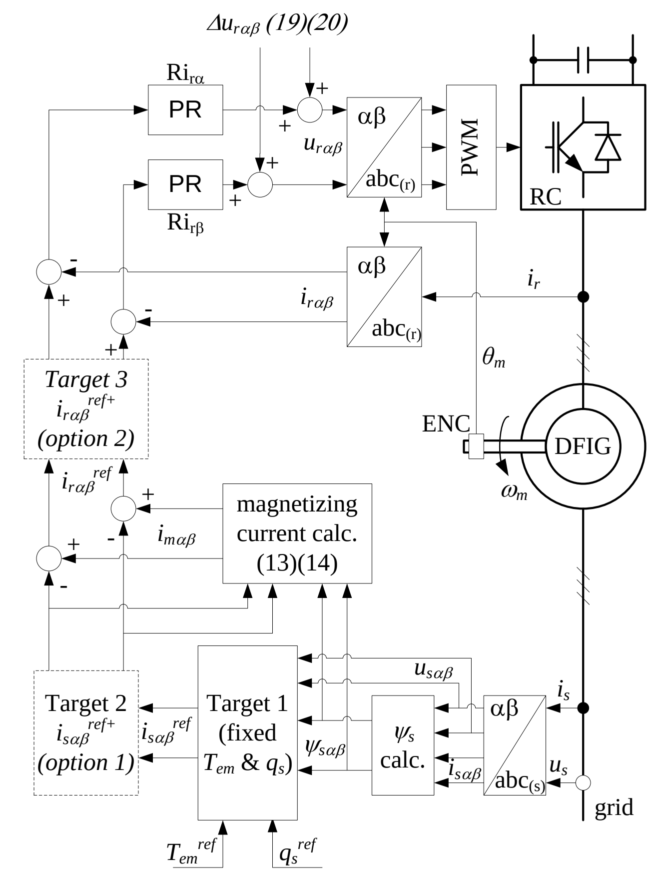

Fig. 10. Scheme of the proposed rotor current vector control of rotor converter with proportional resonant PR controllers.

Rotor circuit model (17) can be derived from (3)-(6), and σ is the leakage factor represented by (18).

$$u_r = R_r i_r + \sigma L_r \frac{di_r}{dt} + \frac{L_m}{L_s}(u_s - R_s i_s) + j\omega_m (L_r i_r + L_m i_s) \quad (17)$$

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \quad (18)$$

The terms (19)(20) are the decoupling and feedforward for the control paths of rotor current components. Application of PR terms for current control are widely described in literature.

$$\Delta u_{r\alpha} = \frac{L_m}{L_s}(u_{s\alpha} - R_s i_{s\alpha}) + \omega_m (L_r i_{r\beta} + L_m i_{s\beta}) \quad (19)$$

$$\Delta u_{r\beta} = \frac{L_m}{L_s}(u_{s\beta} - R_s i_{s\beta}) - \omega_m (L_r i_{r\alpha} + L_m i_{s\alpha}) \quad (20)$$

B. Stator Current Vector Control

Doubly fed induction machine state depends on the rotor converter control. There is a relation between stator and rotor current and it is possible to control the stator current directly by the rotor side converter. The relation between stator current and required rotor voltage is described by (21). It is obtained similarly to (17) by its derivation from (3)-(6).

$$u_r = -\frac{L_r}{L_m}\left(R_s i_s + \sigma L_s \frac{di_s}{dt}\right) + R_r i_r + \frac{L_r}{L_m} u_s + \\ + j\omega_m (L_r i_r + L_m i_s) \quad (21)$$

The decoupling terms (22)(23) are used to obtain linear model of stator current control plant.

$$\Delta u_{r\alpha} = R_r i_{r\alpha} + \frac{L_r}{L_m} u_{s\alpha} + \omega_m (L_r i_{r\beta} + L_m i_{s\beta}) \quad (22)$$

$$\Delta u_{r\beta} = R_r i_{r\beta} + \frac{L_r}{L_m} u_{s\beta} - \omega_m (L_r i_{r\alpha} + L_m i_{s\alpha}) \quad (23)$$

The complete structure of direct stator current control by the rotor side converter with the main and two optional targets is presented in Fig. 11.

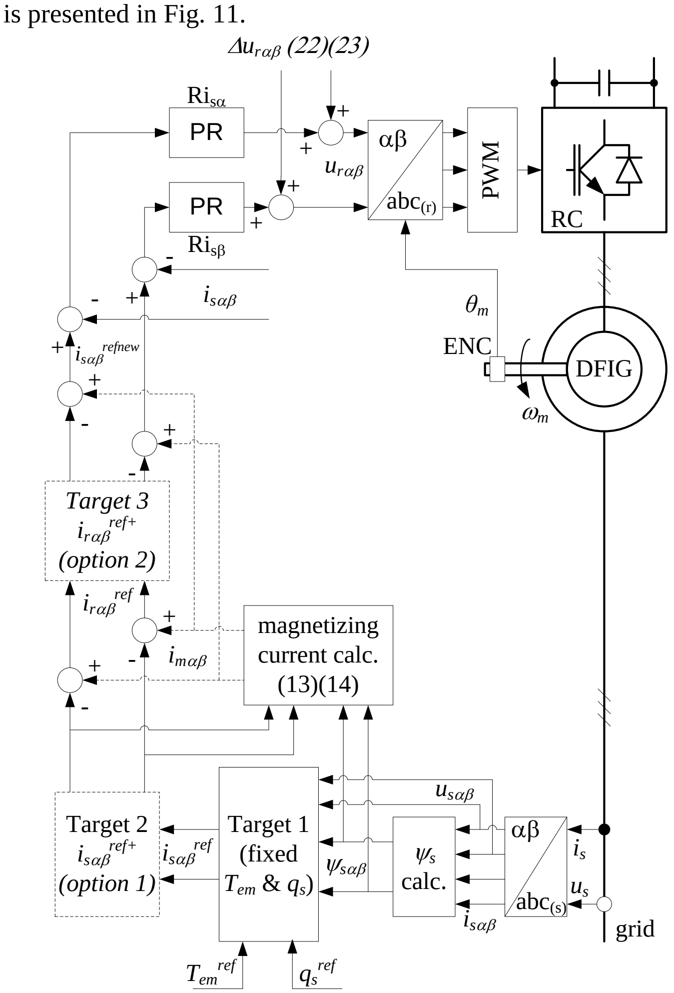

Fig. 11. Scheme of the proposed stator current vector control of rotor side converter with proportional resonant PR controllers.

IV. Experimental Results of Proposed Vector Control Methods Under Unbalanced Grid

A. Experimental Test Rig

Experimental tests for RC and GC vector control have been obtained in a laboratory rig with low-power (7.5kW) DFIM. Scheme of the laboratory unit is shown in Fig. 12. Typical voltage oriented control for grid side converter GC has been applied to control the DC link voltage. Applied control of GC is well-known from the literature. Its operation does not influence the machine torque, rotor current and stator current, so it will not be discussed here. Grid converter is supplied from the matching transformer MT mounted in order not to increase the DC-link voltage above the value required by RC converter.

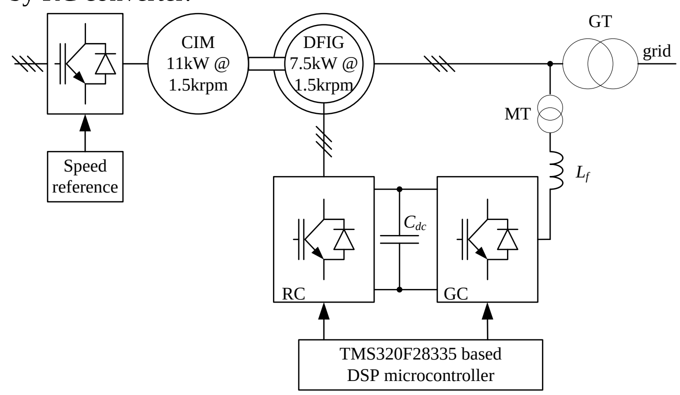

Fig. 12. Scheme of the laboratory test unit with 7.5kW DFIM.

Parameters of the doubly fed induction machine used in laboratory tests are shown in the Table I. Experimental tests have been done with 20% asymmetry factor of the grid voltage. Asymmetry has been obtained with multi-tap grid transformer GT connected between the grid and DFIG power generation unit. The phase voltage of transformer between DFIG generation unit and laboratory grid are following: 220/120/120V shifted by 2π/3 respectively, what gives 186/140/140V of stator phase voltage related to the virtual neutral point (eliminated zero sequence).

TABLE I
Parameters of 7.5 kW DFIG from Laboratory Unit

Symbol	Parameter	Value
P_n	Rated power	7.5kW
U_{sn}	Stator rated voltage (Δ/Y)	220/380V
I_{sn}	Rated stator current (Δ/Y)	27.4/15.7A
U_{rn}	Rated rotor voltage (0 rpm)	182V
I_{rn}	Rotor rated current	15A
R_s	Stator resistance	0.43Ω
L_s	Stator inductance	130mH
R_r	Rotor resistance	0.71Ω
L_r	Rotor inductance	130mH
L_m	Magnetizing inductance	120mH
n_{mn}	Rated speed	1445rpm
p_p	Number of poles	4

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B. Rotor Current Control Experimental Results

In the experimental tests there are presented waveforms of unbalanced stator voltage, stator current, rotor current, *q* and *p* components of stator power, and electromagnetic torque T_{em}, respectively. Oscillograms have been obtained in the transient caused by step change of the torque from zero to 50% (25Nm) of nominal value (50Nm). Larger torque is impossible due to two reasons. The first one is significant asymmetry of the stator voltage, which produces lower stator flux. The other is that, the induction machine is designed to take the reactive power from the grid, so the rotor current is relatively low in relation to apparent power of the machine. In the case of magnetization from the rotor side, as it is made in high power DFIG generation units, the rated value of active component of current cannot be achieved without rotor overcurrent.

In Fig. 13 the main target, which is cancellation of electromagnetic torque oscillations, has been shown. A 100Hz oscillations of the controlled variables (T_{em}, q_s) are eliminated and stator current is sinusoidal. Naturally in this target the *p* component of stator power has significant oscillations. Small oscillations of stator power q component is visible due to limitation of the machine parameters identification accuracy, and - what is more important - nonlinearity of the magnetic circuit. To achieve precise compensation of *q* component oscillations, these nonlinearities have to be taken into account for the magnetizing current calculation. However, we cannot expect that considering nonlinearities, stator current will be sinusoidal when constant T_{em} and q_s will referenced.

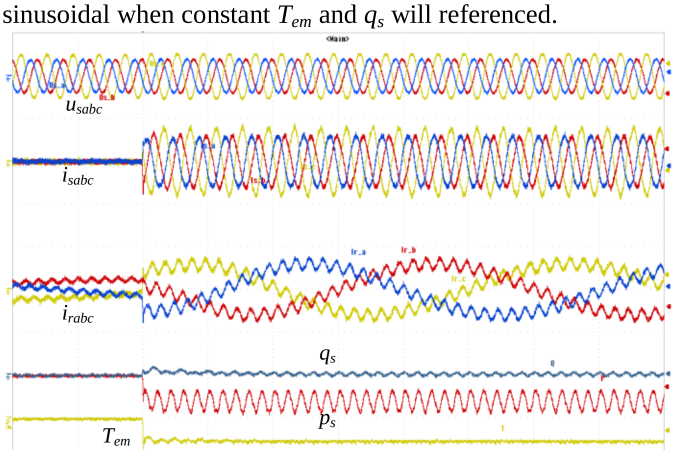

Fig. 13. Three phase stator voltage, stator current, rotor current, p and q stator power components, and electromagnetic torque obtained in laboratory tests for the electromagnetic torque oscillation cancellation target at rotor current control.

Fig. 14 presents the case of step change of reference q component of instantaneous stator power from zero to 3kvar at 50% of the rated torque for the torque oscillations cancellation target. Fig. 15 presents the case of dynamic changes of control targets (from the left side: sinusoidal rotor current, symmetrical stator current, torque oscillations cancellation) for rotor current control. The conditions are -25 Nm (half of the rated torque), and 3kvar of reactive power.

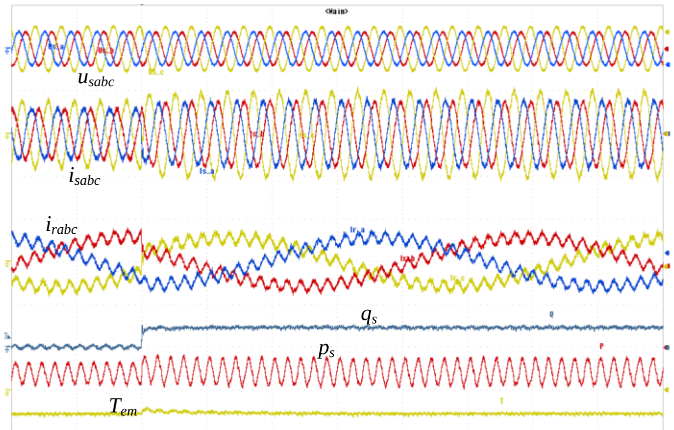

Fig. 14. Three phase stator voltage, stator current, rotor current, p and q stator power components, and electromagnetic torque obtained in laboratory tests for the symmetrical stator current target during step change of reference q power component at rotor current control.

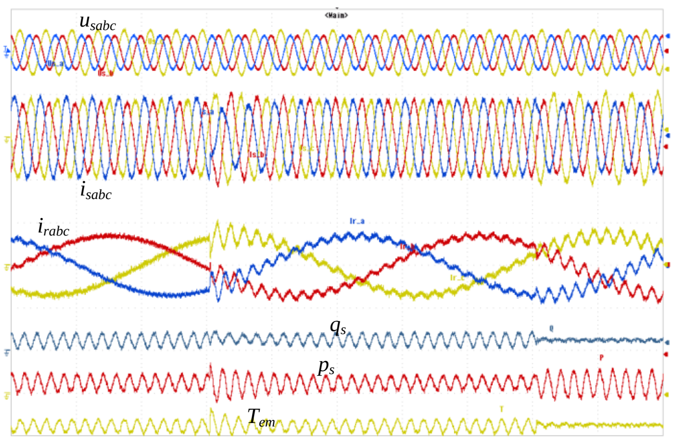

Fig. 15. Three phase stator voltage, stator current, rotor current, p and q stator power components, and electromagnetic torque obtained in laboratory tests during changes of required targets (from the left side: sinusoidal rotor current, symmetrical stator current, torque oscillations cancellation) at rotor current control.

C. Stator Current Control Experimental Results

Direct stator current control by rotor side converter does not require determination of magnetizing current for cancellation of electromagnetic torque oscillations and for the symmetrical stator current target. From this point of view, stator current control is the most convenient in these two targets and provides similar performance to rotor current control. More precise control of stator current provides smaller pulsations of stator power q component during torque oscillations cancellation target (Fig. 16).

Fig. 16 presents the case of fundamental target which is electromagnetic torque oscillations cancellation at stator current control. It is visible that the stator current control allows more precise stabilization of q power component than in case of rotor current control (comp. Fig. 13). This is because it does not need calculation of magnetizing current, which bases on machine parameters, which are imperfectly identified.

Moreover, the influence of magnetic circuit nonlinearity (treated as a kind of disturbance) on the stator current waveform is significantly compensated by current controllers. However, compensation of influence of magnetic circuit nonlinearity on the stator current waveform introduces small oscillations of electromagnetic torque which for this tests has been calculated based on the current model of DFIG instead of the equation (8). Current model is intentionally used for torque calculation in the waveforms registration to have additional prove, that the proposed structure is correct. The use of the same equation for control and observation does not fully prevent against the errors in presented theory. The response on reference *q* power step at stator current control is similar to the same case at rotor current control analogously to the similarity between Fig. 16 and Fig. 13, so it will not be separately shown.

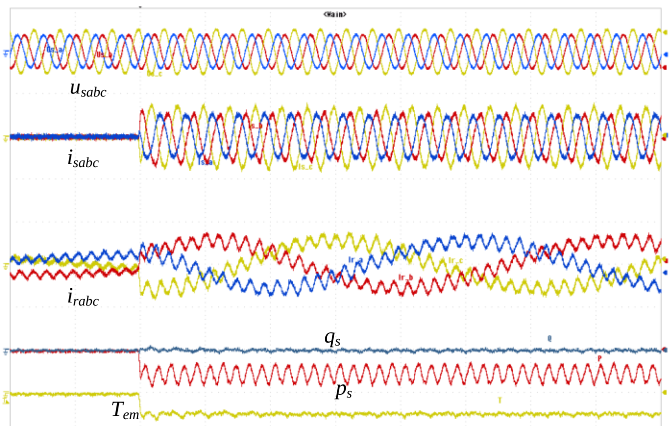

Fig. 16. Three phase stator voltage, stator current, rotor current, p and q stator power components, and electromagnetic torque obtained in laboratory tests for the electromagnetic torque oscillation cancellation target at stator current control.

Fig. 17 presents the case of dynamic changes of required targets (from the left side: sinusoidal rotor current, symmetrical stator current, torque oscillations cancellation) for stator current control. The conditions are -25 Nm (half of the rated torque), and 3kvar of q component of instantaneous power, that means they are similar to the case presented in Fig. 15. It can be seen that response on the targets change at stator current control (Fig. 17) is similar to the same case at rotor current control from Fig. 15. It can also be seen in both figures, that power and torque oscillations have almost the same level under the same conditions for both targets – symmetrical sinusoidal stator current and sinusoidal rotor current. This is because the magnetizing current is relatively low in relation to the stator or rotor current.

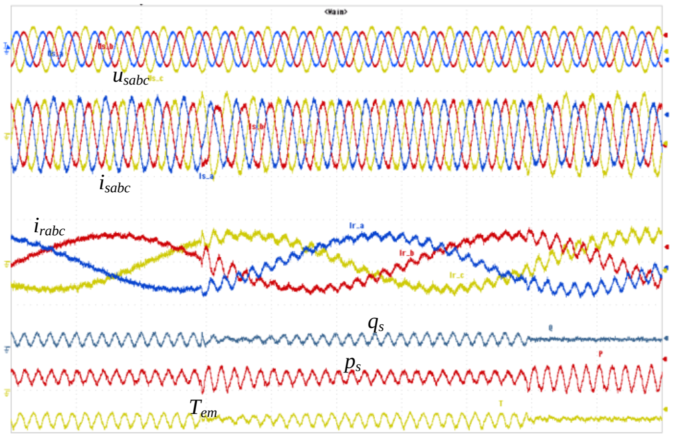

Fig. 17. Three phase stator voltage, stator current, rotor current, p and q stator power components, and electromagnetic torque obtained in laboratory tests during changes of required targets (from the left side: sinusoidal rotor current, symmetrical stator current, torque oscillations cancellation) at stator current control.

Fig. 18 presents the transient caused by stator (grid) voltage single phase dip (20% voltage sag in one phase) at stator current control for fundamental target, which is electromagnetic torque oscillations cancellation. For symmetrical grid voltage the system operates like typical FOC or VOC controlled DFIG, and during the voltage dip it tries to keep the electromagnetic torque and q component of power at reference level.

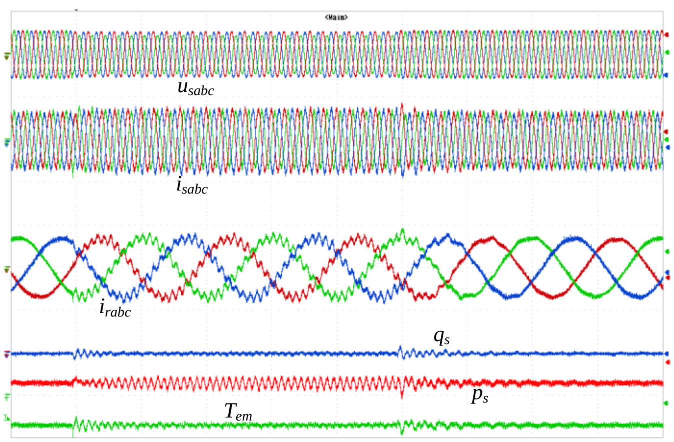

Fig. 18. Three phase stator voltage, stator current, rotor current, instantaneous stator power components, and electromagnetic torque obtained in laboratory tests during 20% single phase voltage dip the electromagnetic torque oscillation cancellation target at stator current control

D. Progressive Targets Change due to the Current Limitation

The proposed methods of progressive stator or rotor current balancing and limitation has been verified in the laboratory unit. Fig. 19 presents the case in which the progressive balancing of stator current and its limitation has been implemented. The ramp of reference torque has been started at -25Nm and stopped at -30Nm, but at around -27Nm, the stator current is fully balanced and reaches its assumed limit.

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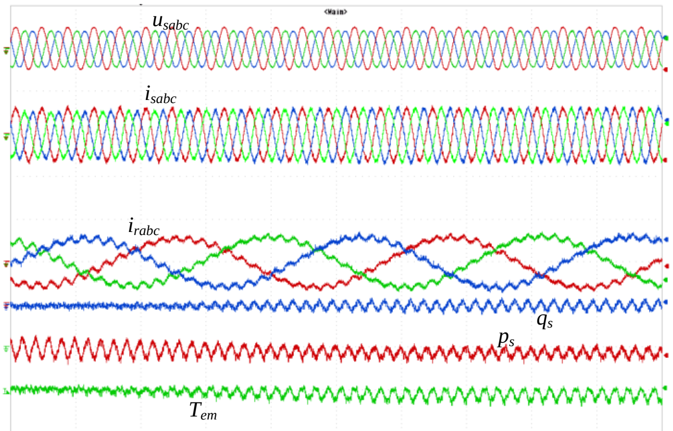

Fig. 19. Three phase stator voltage, stator current, rotor current, instantaneous stator power components, and electromagnetic torque obtained in laboratory tests during slow change of reference torque causing progressive balancing an limitation of stator current at stator current control.

Fig. 20 presents the same function of control system (balancing and limitation of stator current) in the case in which the reference q power component has been increased to the level for which the stator current exceeds the assumed maximum level. Thus, after full balancing, the stator current is limited on the assumed maximum value. The basic control method applied in this test is stator current control.

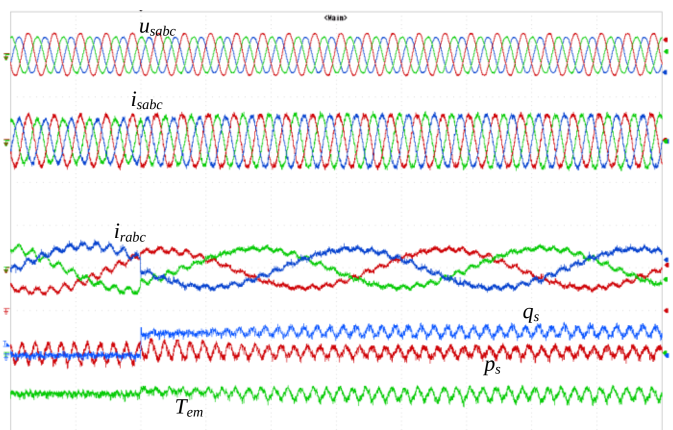

Fig. 20. Three phase stator voltage, stator current, rotor current, instantaneous stator power components, and electromagnetic torque obtained in laboratory tests during step change of reference q power component causing progressive balancing and limitation of stator current at stator current control.

Fig. 21 presents the case of progressive elimination of rotor current harmonics after detection of rotor current maximum values reaching the maximum assumed level. This function has been achieved during the ramp change of reference electromagnetic torque from -25Nm to 35Nm, whereas at around -30Nm the rotor current harmonics has been fully eliminated. Then, the rotor current vector length reaches maximum assumed value. The basic control method applied in this test is rotor current control.

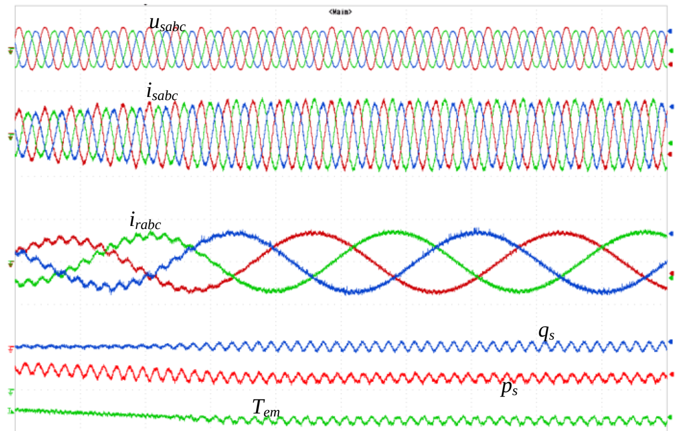

Fig. 21. Three phase stator voltage, stator current, rotor current, instantaneous stator power components, and electromagnetic torque obtained in laboratory tests during slow change of reference torque causing progressive reduction of harmonics and limitation of rotor current at rotor current control.

Fig. 22 presents the case, in which the initial process is full elimination of rotor current harmonics due to high reference electromagnetic torque (higher than -30Nm). When the reference torque is changed by step to -15Nm, the rotor current leaves the limitation region and the control method reaches its basic target which is electromagnetic torque oscillations cancellation. The basic control method applied in this test is the rotor current control.

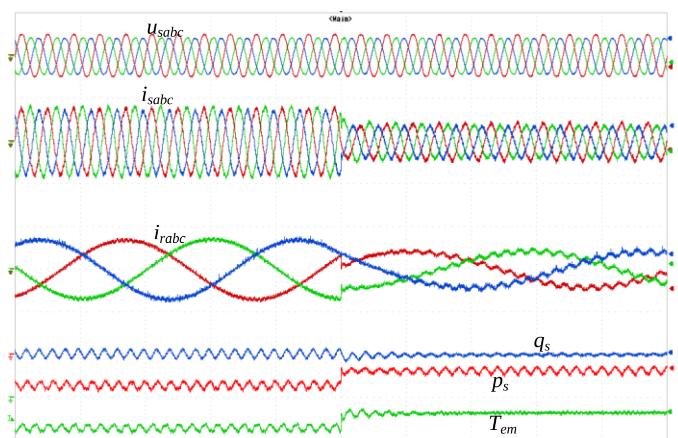

Fig. 22. Three phase stator voltage, stator current, rotor current, instantaneous stator power components, and electromagnetic torque obtained in laboratory tests during step change of reference electromagnetic torque presenting outgoing from the rotor current limitation region to electromagnetic torque oscillation cancellation target at rotor current control.

V. Conclusion

The paper shows a simple and effective method of calculation of the reference rotor current based on reference electromagnetic torque and q_s component of stator instantaneous power. It allows to keep fixed torque and sinusoidal stator current during unbalanced grid voltage operation without sequence decomposition of any measured or controlled variables for the main target, which is electromagnetic torque oscillations cancellation. Other targets such as sinusoidal rotor current or symmetrical stator current can be easily obtained by filtration of the reference stator or rotor current signals in the dq rotating frame. The synchronization of rotating frame with stator voltage or flux is not necessary, as the control method is made in the stationary αβ frame. Applied band pass filters with adaptive damping factor in the method of stator currents balancing or rotor current harmonics elimination allows to obtain intermediary states between targets and currents limitation.

The rotor current control and stator current control methods with proposed ways of reference signals calculation provides similar properties in both, steady and dynamic states. Laboratory results show that magnetic circuit nonlinearity has insignificant influence on the reference signals calculation. It causes that some small oscillations on indirectly controlled variables, which are the electromagnetic torque T_{em} and q component of stator instantaneous power, still occur especially in the rotor current control method. However, it is not visible for linear model of the DFIG. It can be easily checked by the readers using simulations.

Research on the proposed structures can be focused on taking the magnetic circuit nonlinearities into consideration in magnetizing current calculation and also on elaboration of other criteria for progressive current balancing and limitation, which however do not influence the main structure of the proposed methods.

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