Application of Direct Controls to Variable–Speed Wind Generators

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***Abstract*—The well–known principle of the direct torque control applied mainly to squirrel–cage induction motor drives can be generalized and applied to other machines, quantities, converters and systems. These are: other AC machines (double–fed induction and permanent magnet synchronous machine), active and reactive power, direct power control of the line side converter, direct controls of both of the converters in a DC link inverter. These new fields are investigated in this paper generally and their application to the components of a wind generator practically. The limits of the direct torque control in salient–pole permanent magnet synchronous generator are given. A solution is given for the stability problem of the double–fed induction generator. The systems are investigated by simulation, the results show the excellent performance of the proposed controls.**

I. Introduction

THE direct torque control (DTC) thanks to its well–known robustness and simplicity has found wide application to (mainly squirrel–cage) induction motor drives [1]. It implements vector control scheme with closed torque and flux loops without current controllers and PWM modulators to control the two–level voltage source inverter (VSI) supplying the machine. The converter switching states are appropriately selected by a switching table based on the instantaneous errors between the reference and feedback values of the controlled signals. It has become the counterpart of the field oriented control, since the algorithm is much simpler, no current loops, no coordinate transformations, no decoupling, no PWM modulators are required. But the switching frequency is variable and for accurate control the sampling frequency must be higher, requiring larger computing power and faster AD converters [1].

The basic idea can be generalized and applied to other machines, quantities, converter and system.

1) Other Machines: As the development of the torque and the effect of the voltage on the flux are similar in any AC machine, the same principle can be used for all AC machines [4], [6].

2) Other Quantities: Every quantity which has close relation to the torque can be controlled in the same way as the torque. It can be the machine active power. Also, every quantity, which has close relation to the flux can be controlled in the same way as the flux. It can be the reactive power of the machine. This is the direct power control (DPC) [2], [3].

3) Other Converter: The three–phase AC network connected to a line–side converter (LSC) can be modelled by an induced voltage (of the distant generator) and series inductance and resistance, which is the same as an AC machine model in Fig.1. (If it is a machine, the other side, right to $\overline{\psi}^*$ is reduced to eliminate the leakage inductance). Virtual fluxes (of the distant generator) can be introduced. In this way the active and reactive power of the LSC can be controlled similarly to the torque and the flux respectively [2], [3].

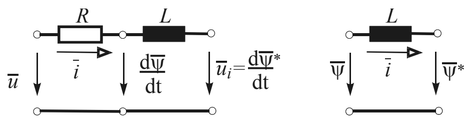

Fig.1. General equivalent circuits of the controlled system.

4) Other System: All converters of a complete system, a variable–speed generator (e.g. in wind power plant) can use direct controls. The machine–side converter (MSC) is controlled with DTC to implement speed control, providing maximum efficiency. The LSC is controlled with DPC, providing high dynamic control of the instantaneous active and reactive power fed to the lines with sinusoidal and symmetrical currents.

In this paper these new fields are investigated, the last one is in the focus, since it can contain all of the others. The "traditional" squirrel–cage induction generator (SCIG) is not discussed. Direct controls are investigated in the following cases: DTC for the MSC of a Permanent Magnet Synchronous Generator (PMSG), DTC for the MSC of a Double–Fed Induction Generator (DFIG) and DPC of a LSC.

Some new aspects, limits and problems of the investigated systems are presented and solutions are given for the determined problems. The proposed methods are validated and investigated by simulation. In the investigations per–unit system is used.

II. Direct Controls Generally

Describing generally, the torque–like quantity is denoted by c_{I} and the flux–like quantity by c_{II}. There are always two fluxes: one of them is controlled by the direct control, it is $\overline{\psi}$. The other is constrained (e.g. by a constrained voltage or by the closed rotor circuit or by the excitation), it is $\overline{\psi}^*$,

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its angular speed is ω^* (in steady state ω^*=const.). c_I can be quickly controlled by the δ angle between the two fluxes. c_{II} can be controlled by the ψ magnitude of the controlled flux. The effect of the control values (δ, ψ) on the controlled values (c_I, c_{II}) must be the same at any operating point.

The $\overline{\psi}$ flux can be quickly controlled by the two–level inverter, switching proper $\overline{u} = \overline{u}_k$ (k=1..7) voltage vector to the terminals:

$$d\overline{\psi} / dt = \overline{u} - \overline{i} R \approx \overline{u} \; . \tag{1}$$

The voltage vector $\overline{u}_7 = 0$ can be developed in two ways: connecting all machine terminals to the positive bar (7P) or all to the negative bar (7N).

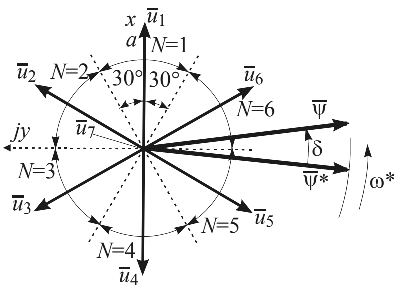

Fig.2. Voltage and flux vectors and the sectors of the controlled flux.

Proper voltage vectors can be selected for the desired flux vector modification (Fig.2.). The quickest ψ or δ modification can be achieved by voltage vectors approximately in phase or perpendicular to the $\overline{\psi}$ flux respectively. Generally, six sectors can be defined for the position of the $\overline{\psi}$ flux (Fig.2., N=1..6). Examining generally the sector $N=i$, the $\overline{u}_k$ voltage vectors are denoted according to Fig.3. (k overflows at 6). Neglecting the resistances, the achievable flux derivatives are equal to the possible voltage vectors (1). It can be proven geometrically, if the $\overline{\psi}$ flux vector is in the ith sector, its magnitude (and c_{II}) can be increased by the $\overline{u}_i$, $\overline{u}_{i+1}$, $\overline{u}_{i+5}$ and can be decreased by the $\overline{u}_{i+3}$, $\overline{u}_{i+2}$, $\overline{u}_{i+4}$ voltage vectors. Whereas the δ angle (and c_I) can be increased by the $\overline{u}_{i+1}$, $\overline{u}_{i+2}$ and can be decreased by the $\overline{u}_{i+4}$, $\overline{u}_{i+5}$ voltage vectors. The $\overline{u}_7 = 0$ voltage does not change the flux magnitude, but by stopping the $\overline{\psi}$ vector δ and c_I are decreased if $\omega^*>0$ and increased if $\omega^*<0$. The positive direction of δ corresponds to positive c_I. The positive direction of c_I corresponds to positive ω^* (convention). Fig.2. is drawn for these conditions for one case. The other case is if the relative position of $\overline{\psi}$ and $\overline{\psi}^*$ is opposite as in Fig.2. to provide positive c_I. In this case δ must be measured from $\overline{\psi}$ and the effect of the voltage vectors to increase or decrease c_I is opposite as described above.

On this basis by hysteresis control c_I and c_{II} can be controlled directly and can be kept in the tolerance band around their reference values. One possible realization of the direct c_I and c_{II} control is presented generally in Fig.4. The

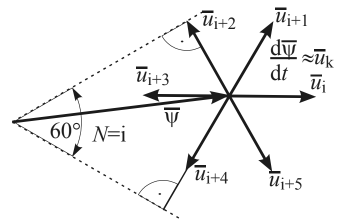

Fig.3. The ith flux sector.

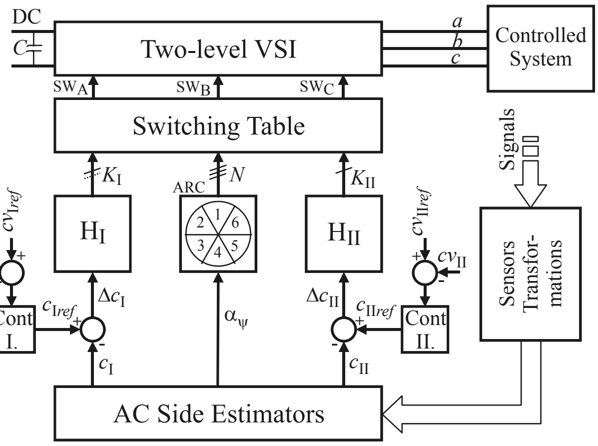

Fig.4. General block diagram of the direct control.

hysteresis controls are H_I and H_{II}. The number of the necessary levels of the hysteresis control depends on the required smoothness of the control and on the controlled quantity. H_{II} is generally a two–level hysteresis control. H_I is not so obvious. Generally, if ω^* is bidirectional H_I is three–level, if unidirectional, under normal condition it can be two–level hysteresis control. If the $\overline{u}_7$ zero vectors are not used, it is always a two–level control. The later is good, if c_I must be changed quickly, but the switching frequency is significantly increased in this case.

The voltage vector to be switched is determined by three quantities: Δc_I error of c_I, Δc_{II} error of c_{II} and the α_ψ angle of $\overline{\psi}$. The feedback signals for the final controls are calculated by the AC Side Estimators, using the necessary sensed and transformed (to the used coordinate system) signals. This is always a proper model of the controlled system. If the terminal voltages of the PWM inverter are to be sensed their sensing can be saved, if the U_{dc} DC link voltage and the switching states (SW_A, SW_B, SW_C) of the inverter are known.

The reference values of the finally controlled quantities (c_{Iref}, c_{IIref}) can be set by outer closed–loop controllers (Cont.I, Cont.II). or can be set to constant or to a calculated value. The H_I and H_{II} hysteresis controllers determine K_I and K_{II}, forming one part of the address of the Switching Table. Generally, switching between two states, the larger value of K (e.g. 1) corresponds to increasing, the smaller (e.g. 0) to decreasing c. The tolerances of H_I and H_{II} are $\pm\Delta C_I$ and $\pm\Delta C_{II}$ respectively. The other part of the address is determined by the output of the sector selection (ARC). The content of the Switching Table depends on the application.

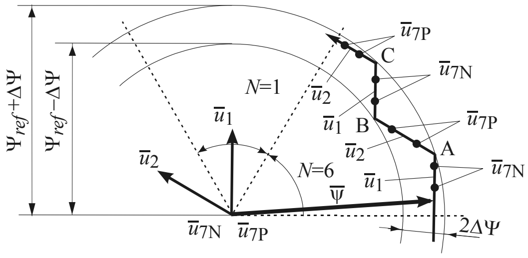

Fig.5. Locus of the controlled flux vector.

The qualitative locus of flux $\overline{\psi}$ with the control in Fig.4. is given in Fig.5. (N=6). If $c_{\mathrm{II}}=\psi$ (direct flux control) $\rightarrow$ $\Delta C_{\mathrm{II}}=\Delta\Psi$ and $c_{\mathrm{II}ref}=\psi_{ref}$, else they can be calculated (see later). The switching states at points A, B and C are changed by $\mathrm{H_{II}}$, whereas the • points are caused by $\mathrm{H_I}$. At points A and C K_{II} is changed from 1 to 0, whereas at point B from 0 to 1. At • points K_{I}=0 else $K_{\mathrm{I}}=\pm1$. Crossing a sector border alone does not cause a switching.

III. DTC FOR MSC OF PMSG

This is very similar to SCIG, but the quantities are different. In the case of salient–pole rotor (this is the examined case) there is a condition for proper operation of torque control [6].

A. Direct Control

The corresponding quantities to the general ones are presented in Table I:

TABLE I.
THE CORRESPONDING QUANTITIES IN DTC–MSC–PMSG.

General	PMSG	Meaning
a, b, c, x, y	*sa, sb, sc, sx, sy*	stator phases and coordinate system connected to stator phase *a*
$\overline{u}$, $\overline{\psi}$	$\overline{u}_s$, $\overline{\psi}_s$	stator voltage and flux
α_ψ	α_{ψ_s}	angle of $\overline{\psi}_s$ in *sx–sy*
$\overline{\psi}^*$, ω^*	$\overline{\psi}_p$, ω	pole–flux, constrained by the permanent magnet excitation and its angular speed
$\bar{i}$	$\bar{i}_s$	stator current
c_{I}, c_{II}	m, ψ_s	torque and the magnitude of the stator flux
cv_{I} Cont.I	w PI	angular speed of the machine closed–loop speed control
cv_{II} Cont.II	ψ_s open–loop	magnitude of the stator flux speed dependant ψ_s flux reference
K_{I}, K_{II}	KM, KΨ	

Here Fig.1. is not correct. There are different inductances in the d (fixed to $\overline{\psi}_p$) and q directions (L_d and L_q).

The torque of the salient–pole synchronous machine can be expressed by the fluxes and the small angle δ between them (δ is measured from $\overline{\psi}_p$):

$$m=\psi_{sd}i_{sq}-\psi_{sq}i_{sd}=\frac{\Psi_p\psi_s}{L_d}\sin\delta+\frac{\psi_s^2}{2}\left(\frac{1}{L_q}-\frac{1}{L_d}\right)\sin 2\delta \quad (2)$$
$$=M_{cm}\sin\delta+M_{rm}\sin 2\delta.$$

The first part of the final equation is the cylindrical torque, the second is the reluctance torque. If the rotor is cylindrical, only the first exists, but it is the dominant part at the nominal operating point in the case of the salient–pole machine also.

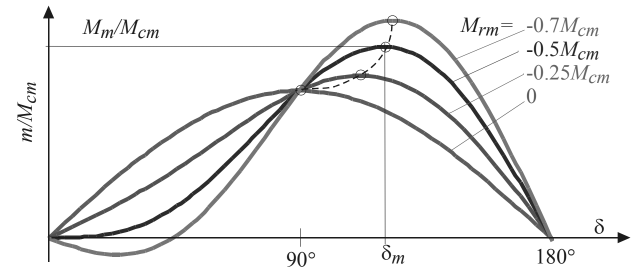

Fig.6. The $m(\delta)$ curves of the salient–pole synchronous machine if $L_q \geq L_d$.

Fig.6. shows the characteristic $m(\delta)$ curves of the salient–pole synchronous machine if $L_q \geq L_d$ (only for $\delta\geq0$). For a cylindrical–rotor machine M_{rm}=0 and the torque maximum $M_m=M_{cm}$ is at $\delta_m=90°$. If $L_q>L_d$ then $M_{rm}<0$ and the $M_m>M_{cm}$ torque maximum is at $\delta_m>90°$:

$$\delta_m=\arccos\left(\frac{\Psi_m/\psi_s-\sqrt{(\Psi_m/\psi_s)^2+8}}{4}\right), \quad (3)$$

$$\Psi_m=\Psi_p/(1-L_d/L_q). \quad (4)$$

B. Limit of the DTC

As described generally, the direct control can work only if the effect of the control value (δ) on the controlled value (m) is always the same. Mathematically this condition can be expressed as $\mathrm{d}m/\mathrm{d}\delta\geq0$. Considering (4) it can be true in the $-\delta_m\leq\delta\leq\delta_m$ range if $M_{rm}\geq-M_{cm}/2$. Expressing it in another way using (2) and (4):

$$\psi_s\leq\Psi_m. \quad (5)$$

As can be seen in Fig.6. at the $M_{rm}=-M_{cm}/2$ border case at δ=0° $\mathrm{d}m/\mathrm{d}\delta=0$. For machine with a given $L_d/L_q<1$ ratio, (4) limits the ψ_s flux magnitude (or the ψ_s/Ψ_m ratio). E.g. if $L_d/L_q=0.5$ the limit is $\psi_s\leq\Psi_m=2\Psi_p$. Equation (5) means, that for direct torque control, in the $\psi_s>\Psi_p$ field–strengthening range the ψ_s flux magnitude is limited to Ψ_m by control aspect. For cylindrical rotor machine and for salient–pole machine with $L_d/L_q>1$ this limit does not exist. Of course, flux magnitude is limited by the saturation also.

Hereafter it is assumed, that (5) is satisfied.

C. Implementation

The torque and the stator flux of the machine are controlled by a two–level inverter connected to the stator of the machine. $\mathrm{H_I}$ is generally a three–level hysteresis control of the torque. $\mathrm{H_{II}}$ is a two–level hysteresis control of the stator flux.

Signals to be sensed: Stator phase currents and voltages. For the coordinate transformation the position of the pole–flux (rotor) must be known by measurement or by estimation. The Switching Table is given in Table II. (k indices of $\overline{u}_k$ are given).

The wind generator operates in two–quadrant mode, its speed can be only positive ($w>0$). It can be proven that in this case the KM=–1 lines in the Switching Table in normal conditions are never used. So H_I can be a two–level hysteresis controller.

TABLE II.
THE SWITCHING TABLE FOR DTC–MSC–PMSG.

KΨ	KM	*N* 1	2	3	4	5	6
1	1	**2**	**3**	**4**	**5**	**6**	**1**
	0	**7P**	**7N**	**7P**	**7N**	**7P**	**7N**
	–1	**6**	**1**	**2**	**3**	**4**	**5**
0	1	**3**	**4**	**5**	**6**	**1**	**2**
	0	**7N**	**7P**	**7N**	**7P**	**7N**	**7P**
	–1	**5**	**6**	**1**	**2**	**3**	**4**

IV. DTC FOR MSC OF DFIG

DFIG is a slip–ring wound–rotor induction generator. Its stator is connected directly to the three–phase AC network. Its rotor is supplied by a two–level voltage source inverter (MSC). It well suits to wind generator application, where it operates in a small speed range around synchronism.

A. Direct Control

The corresponding quantities to the general ones are presented in Table III:

TABLE III.
THE CORRESPONDING QUANTITIES IN DTC–MSC–DFIG.

General	DFIG	Meaning
a, b, c, x, y	*ra, rb, rc, rx, ry*	rotor phases and coordinate system connected to rotor phase *a*
$\bar{u}$, $\overline{\psi}$	$\bar{u}_r$, $\overline{\psi}_r$	rotor voltage and flux
α_ψ	α_{ψ_r}	angle of $\overline{\psi}_r$ in *rx–ry*
$\overline{\psi}^*$, ω^*	$\overline{\psi}_s$, ω_{ψ_s}	stator flux, constrained by the constant stator voltage and its angular speed in *rx–ry*
R, L	R_r, L'_r	rotor resistance and transient inductance
$\bar{i}$	$\bar{i}_r$	rotor current
c_I, c_{II}	*m*, ψ_r	torque and the magnitude of the rotor flux
cv_I Cont.I	*w* PI	angular speed of the machine closed–loop speed control
cv_{II}	*a)* ψ_r	magnitude of the rotor flux
	b) Q	reactive power
Cont.II	*a)* open–loop	ψ_{rref} is calculated from the desired reactive power operation
	b) PI	reactive power controller
K_I, K_{II}	KM, KΨ	

The torque of the induction machine can be expressed by the fluxes and the small angle δ between them (δ is measured from $\overline{\psi}_r$, × means vector product):

$$m = -\overline{\psi}_r \times \bar{i}_r = -\overline{\psi}_r \times \left(\frac{\overline{\psi}_r - \overline{\psi}_s}{L'_r} \right) = \frac{\psi_r \psi_s}{L'_r} \sin\delta \approx \frac{\psi_r \psi_s}{L'_r} \delta \quad (6)$$

B. Implementation

The torque and the rotor flux of the machine are controlled by a two–level inverter connected to the rotor of the machine. H_I is a three–level hysteresis control of the torque. H_{II} is a two–level hysteresis control of the rotor flux.

Signals to be sensed: Stator phase currents and voltages. To get α_{ψ_r} in *rx–ry*, the position of the rotor must be sensed or estimated.

This is the case, where δ is measured from the controlled flux (opposite to the general figure). As described generally, in this case the effect of the voltage vectors is reversed. The Switching Table must be modified compared to the SCIG or PMSG: the KM=±1 lines must be exchanged (Table IV.).

TABLE IV.
THE SWITCHING TABLE FOR DTC–MSC–DFIG.

KΨ	KM	*N* 1	2	3	4	5	6
1	1	**6**	**1**	**2**	**3**	**4**	**5**
	0	**7P**	**7N**	**7P**	**7N**	**7P**	**7N**
	–1	**2**	**3**	**4**	**5**	**6**	**1**
0	1	**5**	**6**	**1**	**2**	**3**	**4**
	0	**7N**	**7P**	**7N**	**7P**	**7N**	**7P**
	–1	**3**	**4**	**5**	**6**	**1**	**2**

Since this machine works above and under the synchronous speed, ω_{ψ_s} can be positive and negative also. That is why it uses the KM=–1 lines, H_I is always a three–level hysteresis controller, if $\bar{u}_7$ is used.

C. Calculation of the Flux Magnitude Reference

In the investigations the version *a)* is used for cv_{II}. The reference value of the rotor flux ψ_{rref} is calculated according to the well–known fundamental harmonic vector diagram assuming $\cos\varphi_{s1}$=–1 and $R\approx 0$. In this case the stator current has only active (torque developing *q*) component:

$$\psi_{rref} = \psi_s \sqrt{(1 + L'_r / L_m)^2 + (L'_r m_{ref} / \psi_s^2)^2} \approx \psi_s \left(1 + L'_r / L_m\right)$$

where L_m is the magnetizing inductance. (7)

If the approximate value of (7) is used, the $\cos\varphi_{s1}$=–1 condition is not satisfied, the stator current has a small inductive component at $m_{ref}\neq 0$. It can be established that the necessary rotor flux reference is approximately proportional to ψ_s, i.e. to U_ℓ line voltage.

D. Stator Flux Pulsation

In the case of double supply of an induction machine, problem can arise with the stator flux magnitude ψ_s: a not or slightly damped pulsation (approximately with the line frequency) appear [5]. It is detected in our investigations also.

The physical reason is the following: If the rotor current is controlled with fast controllers (directly or indirectly as in the case of the DTC), it means a current constrain in the rotor. It corresponds to approximately an open rotor circuit. In this way the induction machine looses the inherent damping effect of the short–circuited rotor. This lack of damping causes the pulsation of the stator flux, which is also constrained by the supply line voltage (unusual two–side constraints).

One way to compensate the pulsation is to implement slower current controller in the *q* (torque developing) channel. It is not good in dynamic aspect. Anyhow, it is not feasible for DTC, since there are no current controllers, the currents are controlled indirectly.

The other way is a modification of the flux reference (7) by the derivative of the ψ_s through a first order lag component. In Laplace form the modification is:

$$\Delta\psi_{rref} = -s\psi_s \frac{K}{1+Ts} . \quad (8)$$

Proper selection of the parameters (K, T) can compensate the pulsation without significant modification of the reactive current. The results will be given among the tests.

V. DPC for LSC

Here the principle is applied to new quantities: the active and reactive power.

A. Direct Control

As described generally, the three–phase network connected to the AC side of a PWM rectifier can be modelled similarly to AC machines (Fig.1.). The corresponding quantities are presented in Table V. Virtual fluxes $\overline{\psi}_\ell$ and $\overline{\psi}_L$ can be introduced as the integral of the corresponding voltages (R_ℓ is neglected).

TABLE V.
THE CORRESPONDING QUANTITIES IN DPC–LSC.

General	DPC–LSC	Meaning
a, b, c, x, y	*La, Lb, Lc, Lx, Ly*	line phases and coordinate system connected to line phase *a*
$\overline{u}$, $\overline{\psi}$	$\overline{u}_L$, $\overline{\psi}_L$	line voltage at the converter terminals and virtual flux from $\overline{u}_L$
$\overline{u}_i$	$\overline{u}_\ell$	the induced voltage of the distant generator
α_ψ	α_{ψ_L}	angle of $\overline{\psi}_L$ in *Lx–Ly*
$\overline{\psi}^*$, ω^*	$\overline{\psi}_\ell$, $\omega_{\psi_\ell} = \omega_\ell$	virtual flux from $\overline{u}_\ell$ constrained by the network and its angular speed
R, L	R_ℓ , L_ℓ	line resistance and inductance
$\overline{i}$	$-\overline{i}_\ell$	line current
c_{I}, c_{II}	p_ℓ , q_ℓ	active and reactive power to the network
cv_{I} Cont.I	u_{dc} PI	DC link voltage closed–loop u_{dc} control
cv_{II} Cont.II	q_ℓ open–loop	reactive power to the network constant reactive power reference
K_{I}, K_{II}	KP, KQ	

Defining an α–β coordinate system with real α axis fixed to $\overline{\psi}_\ell$, the active and the reactive power can be expressed by α–β quantities (by active and reactive current components) and considering $\psi_\ell = L_\ell i_\ell + \psi_L$ by the magnitudes of the fluxes and the small angle δ between them:

$$p_\ell = -U_\ell i_{\ell\beta} = U_\ell \frac{\psi_L \sin\delta}{L_\ell} \approx \frac{U_\ell \psi_L \delta}{L_\ell} , \quad (9)$$

$$q_\ell = -U_\ell i_{\ell\alpha} = -U_\ell \frac{\Psi_\ell - \psi_L \cos\delta}{L_\ell} \approx \frac{U_\ell}{L_\ell}\left(\psi_L - \Psi_\ell\right). \quad (10)$$

The signs are determined to be positive at powers flowing to the network. Interpreting (9) and (10) the active power can be controlled by δ whereas the reactive power by the ψ_L flux magnitude using hysteresis controls keeping them in the ranges ±Δ*P* and ±Δ*Q*. Explicitly these result in hysteresis control of the α–β line current components with ranges $\pm\Delta I_{\ell\alpha} = \mp\Delta Q / U_\ell$ and $\pm\Delta I_{\ell\beta} = \mp\Delta P / U_\ell$. As the reactive power is controlled by the ψ_L flux magnitude, it results in a hysteresis control of the ψ_L flux magnitude with $\psi_{ref} = \Psi_\ell + (L_\ell / U_\ell) q_{\ell ref}$ reference value and $\Delta\Psi = (L_\ell / U_\ell)\Delta Q$ tolerance (Fig.5.).

B. Implementation

The reference value of the active power control is set by a closed–loop control of the U_{dc} DC link voltage. The basic aim of the control is to keep the U_{dc}=const. value and providing sinusoidal and symmetrical line currents. The DC voltage controller sets such an active power reference value, which provides power balance, keeping constant energy in the DC link capacitance. Basically the output of the controller can be interpreted as the reference value of the charging current of the capacitance. To get power, it should be multiplied by U_{dc} [2], [3]. Since it is quite constant, this step can be saved. With the selected positive direction of the active power, a sign–negation of the controller output is necessary to get correct $p_{\ell ref}$.

The reference value of the reactive power can be set to constant (e.g. $q_{\ell ref} = 0$ for $\cos\varphi_\ell = -1$).

Both hysteresis controllers are two–level. Also the torque–like quantity is controlled by a two–level controller, since the ω_ℓ is unidirectional.

Signals to be sensed: Line phase currents and voltages at the converter terminals. The Switching Table is given in Table VI.

TABLE VI.
THE SWITCHING TABLE FOR DPC–LSC.

KQ	KP	N 1	2	3	4	5	6
1	1	**2**	**3**	**4**	**5**	**6**	**1**
	0	**7P**	**7N**	**7P**	**7N**	**7P**	**7N**
0	1	**3**	**4**	**5**	**6**	**1**	**2**
	0	**7N**	**7P**	**7N**	**7P**	**7N**	**7P**

VI. Simulation Results

To investigate the proposed systems and algorithms a simulation system is developed in Simulink. The machines are modelled by their state equations in the appropriate reference frame. The converters and the network are considered to be ideal. The simulations are performed with variable–step.

A. The Investigated System

From the theoretically described systems only the most characteristic one is selected to be presented because of the limited place. It is a DFIG with DTC–MSC and DPC–LSC. The main parameters of the system are: Δ*m*=5%; $\Delta\psi_r = 1\%$; $\Delta p_\ell = \Delta q_\ell = 10\%$; $L_\ell = 0.1$; $L_m = 2$; $L'_r = 0.2$; *C*=10; $T_{sn} = 157$ (nominal starting time);

The wind turbine is modelled with its nominal wind–speed curve. The synchronous speed of DFIG is set to the middle of the wind generator usual operating range, bellow the W_N nominal speed of the turbine (W_N/W_1=10/9=1.1111).

B. The Investigated Process

The initial conditions: w=0.7; Ψ_s=1; $i_{sd} = \Psi_s / L_m = 0.5$; $i_{sq} = 0$; $i_{rd} = i_{rq} = 0$; The DC link capacitance C is charged (U_{dc}=3). The speed reference jumps to w_{ref}= W_N (above synchronism). First the machine accelerates in motor mode with torque limit 1.4, then after a small overshoot the nominal speed is reached as the new steady–state generator mode operating point M=–1 (Fig.8.). ψ_{rref} is set to the approximating value in (7). $q_{\ell ref}$ is set to zero and the overall reactive power of the three–phase network is controlled.

C. The Results

Using the proposed method to compensate the stator flux magnitude pulsation (8) with properly selected parameters, the pulsation can be kept at an acceptable level (Fig.7b). Higher compensation would more deviate the flux developing d current component from the ideal value (Fig.11b,c).

The motor→generator transition at t≈30 can be identified in most of the figures. The mechanical power (p_m) and the line power with negative sign ($-p_\ell$) are almost identical apart from the losses (Fig.9.). The p_{LSC} power of the LSC is small, since it is the rotor circuit power $m(w_1–w)$.

The desired $\cos\varphi_\ell \approx \pm 1$ power factor of the line current is achieved since $q_{\ell ref} = 0$ (Fig.10. and Fig.11c,d). Controlling ψ_r to the given reference result in i_{sd}≈0 and i_{rd}≈ψ_s/L_m≈0.5 in steady–state since in this way the reactive (magnetizing) current component of the generator is provided by the rotor–side, so the stator current power factor is $\cos\varphi_s \approx \pm 1$.

VII. CONCLUSION

The generalized and formalized description of the direct controls is presented. The possible fields of application are discussed. Two of them are combined to form the control method of a complete system: a wind generator. This application is investigated by simulation. The results show the excellent performance of the proposed controls.

Easy feasible solution is found for the flux pulsation problem of DFIG. The limit of the DTC application is given for PMSG.

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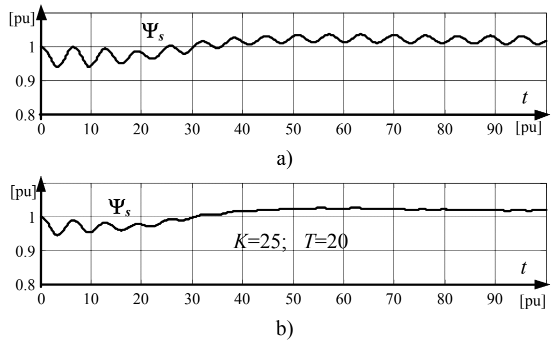


Fig.7. Stator flux magnitude: a) Unstable. b) Stabilized.

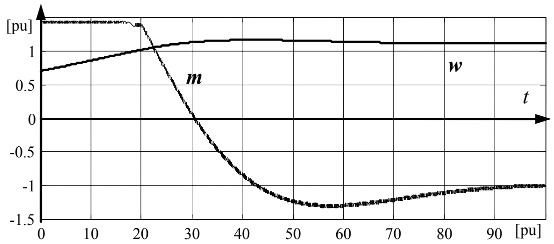


Fig.8. The torque and the speed of the machine.

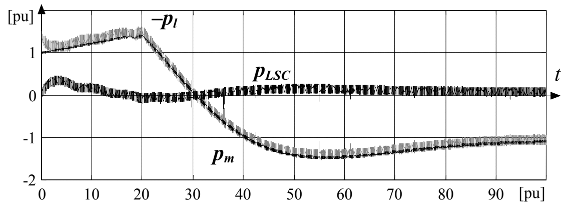


Fig.9. Active powers: line, mechanical and LSC.

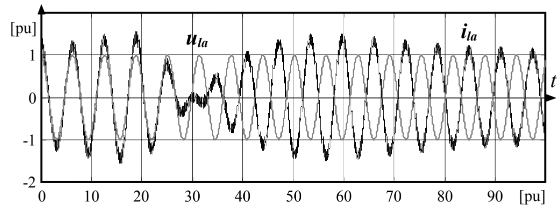
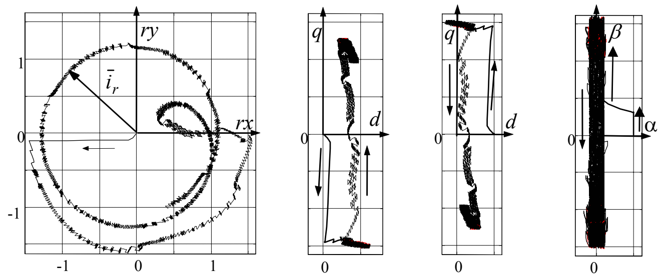


Fig.10. Line phase voltage and current.



a) $\bar{i}_r$, rotor reference frame. b) $\bar{i}_r$, d–q c) $\bar{i}_s$, d–q d) $\bar{i}_\ell$, α–β

Fig.11. Loci of the current vectors.