ZESZYTY NAUKOWE POLITECHNIKI ŚLĄSKIEJ 2003
Seria: ELEKTRYKA z. 187 Nr kol. 1612

Kazimierz GIERLOTKA, Michał JELEŃ
Institute of Theoretical and Industrial Electrical Engineering

APPLICATION OF DTC METHOD FOR THE CONTROL OF DOUBLE-FED INDUCTION MACHINE

Summary. The application of the slip-ring induction motors working as double-fed machines is recommended when the speed control is confined to a small range around synchronism. They can be applied in drive systems as well as in energy generation systems, for example in wind power plants or in pumped-storage power plants. The paper deals with the possibilities of application of the Direct Torque Control (DTC) method for double-fed machine. By choice of the proper voltage vector of PWM converter this method allows controlling the motor torque and the reactive power in the stator circuit. Principles of direct torque control of double-fed machine and results of the simulation tests of the drive controlled according to presented method are presented in the paper.

ZASTOSOWANIE METODY DTC DO STEROWANIA MASZYNY INDUKCYJNEJ DWUSTRONNIE ZASILANEJ

Streszczenie. Zastosowanie maszyny indukcyjnej pierścieniowej dwustronnie zasilanej jest uzasadnione, gdy regulacja prędkości odbywa się w niewielkim zakresie wokół prędkości synchronicznej. Maszyna ta może pracować zarówno w układach napędowych, jak i generatorowych, np. w elektrowniach wiatrowych [4] lub szczytowo-pompowych [2]. W artykule została przedstawiona możliwość zastosowania metody Bezpośredniego Sterowania Momentem (DTC) do sterowania maszyny dwustronnie zasilanej. Poprzez użycie odpowiedniego wektora napięcia na wyjściu falownika MSI metoda DTC umożliwia niezależne sterowanie momentu maszyny oraz mocy biernej w obwodzie stojana. W artykule przedstawiono zasady sterowania metodą DTC oraz wyniki symulacji układu z maszyną indukcyjną dwustronnie zasilaną.

1. INTRODUCTION

Significant number of variable speed electrical machines is supplied with power electronics converters. Usually they are applied in drive systems but often power electronics converters are used in variable speed generators e.g. in water-power plants, especially in pumped-storage power stations. In this case application of variable speed system with variable value of produced power makes possible operation of water turbine with maximum efficiency for specific load.

In both drive and generator systems the control of the AC machine can be done in two ways:

- machine is supplied with converter on the stator side - the converter has to be able to transmit the whole power of the machine,
- machine is supplied with converter on the rotor side and the stator is connected to the grid - the converter transmits only the slip power.

In the case, when the range of speed control (and the maximum of the slip) is small, application of the second method is justified.

Drive systems with double-fed wound-rotor motor have been known for 100 years. The most frequently used system is constant torque asynchronous cascade. Because of use of diode rectifier in the rotor circuit, this system makes possible only one direction of the power flow from the rotor of the machine to the grid. That‘s why the machine can only work as a motor with subsynchronous speed and as a brake (generator) with supersynchronous speed. Use of PWM voltage inverters instead of rectifiers makes possible bidirectional flow of the power in rotor circuit and four-quadrant operation of the machine in slip-torque co-ordinate system. It is also a possibility to control of reactive power drawn from the grid. In recent years there have been a lot of publications concerning control systems of double-fed induction machine with voltage inverter connected to rotor circuit. Usually in these systems the Field Oriented Control method is used.

Present paper concerns application of Direct Torque Control (DTC) method for the control of double-fed induction machine. This control method for squirrel-cage machine has been known for 20 years and makes possible fast control of torque and flux of asynchronous machine.

2. DIRECT TORQUE AND FLUX CONTROL OF DOUBLE-FED INDUCTION MOTOR

Asynchronous machine equations in the rotor oriented frame of references (in relative quantities):

$$\underline{u}_s = r_s \underline{i}_s + T_N \frac{\mathrm{d}\underline{\psi}_s}{\mathrm{d}t} + j\omega \underline{\psi}_s , \tag{1}$$

$$\underline{u}_r = r_r \underline{i}_r + T_N \frac{\mathrm{d}\underline{\psi}_r}{\mathrm{d}t} , \tag{2}$$

$$\underline{\psi}_s = l_s \underline{i}_s + l_M \underline{i}_r , \tag{3}$$

$$\underline{\psi}_r = l_M \underline{i}_s + l_r \underline{i}_r , \tag{4}$$

$$\tau = \mathrm{Im}\left(\underline{\psi}_s^* \underline{i}_s\right) . \tag{5}$$

2.1. Control of the electromagnetic torque

From (3) and (4) we obtain:

$$\underline{i}_s = \frac{\underline{\psi}_s - \frac{l_M}{l_r}\underline{\psi}_r}{l_\sigma}, \tag{6}$$

where:

$$l_\sigma = \frac{l_s l_r - l_M^2}{l_s l_r} l_s = \sigma l_s . \tag{7}$$

From (6) and (5) we obtain motor torque τ:

$$\tau = \frac{1}{l_\sigma}\frac{l_M}{l_r}\psi_s \psi_r \sin\delta_\psi . \tag{8}$$

In double-fed machine the stator flux is mainly dependent on the stator voltage and we may assume that its amplitude and angular speed are constant.

The rotor flux ψ_r of the double-fed machine can be adjusted by rotor voltage. In the rotor oriented frame of references from the rotor voltage equation (2), for r_r=0, we obtain:

$$\underline{\psi}_r = \frac{1}{T_N}\int \underline{u}_r dt . \tag{9}$$

Supplying the rotor of the machine with the voltage inverter, we can apply one of the six active and two zero vectors. Using one of the active voltage vectors affect on the amplitude and position of the rotor flux vector. By changing the angle between fluxes we can control the torque of the machine.

2.2. Control of the reactive power

An advantage of the double-fed machine is opportunity to control of the reactive power in the stator circuit. The reactive power can be expressed as below:

$$q = \mathrm{Im}\left(\underline{u}_s \underline{i}_s^*\right) = u_{sy} i_{sx} - u_{sx} i_{sy}, \tag{10}$$

We can express stator voltage based on (1) and (6):

$$\underline{u}_s = \frac{r_s}{l_\sigma}\underline{\psi}_s - \frac{r_s l_M}{l_\sigma l_r}\underline{\psi}_r + T_N \frac{d\underline{\psi}_s}{dt} + j\omega_s \underline{\psi}_s . \tag{11}$$

From (6), (10) and (11) after transformation we obtain the equation, which determines effect of the rotor flux amplitude ψ_r on the reactive power q of the stator circuit:

$$q = \frac{\omega_s}{l_\sigma}\left(\psi_s^2 - \frac{l_M}{l_r}\psi_{sx}\psi_r\right) + \frac{T_N}{l_\sigma}\left[\left(\psi_{sx} - \frac{l_M}{l_r}\psi_r\right)\frac{d\psi_{sy}}{dt} - \psi_{sy}\frac{d\psi_{sx}}{dt}\right]. \tag{12}$$

So taking into consideration equations 1–12 and applying similar principles as in classical DTC method for the control of the rotor PWM inverter in double-fed machine, we obtain by choose of the proper voltage vector of rotor PWM inverter:

- control of the motor torque by affect on the angle between vectors of stator and rotor fluxes,
- control of the stator reactive power by affect on the rotor flux amplitude.

3. CONTROL STRATEGY

Block diagram of the control system is depicted in fig. 1. Wound-rotor induction machine is connected to the grid on the stator side and supplied with voltage inverter on the rotor side. Motor inverter control system is based on DTC. It consists of the following elements:

- estimation block,
- sector detection block,
- two-level flux comparator,
- three-level torque comparator,
- switching table.

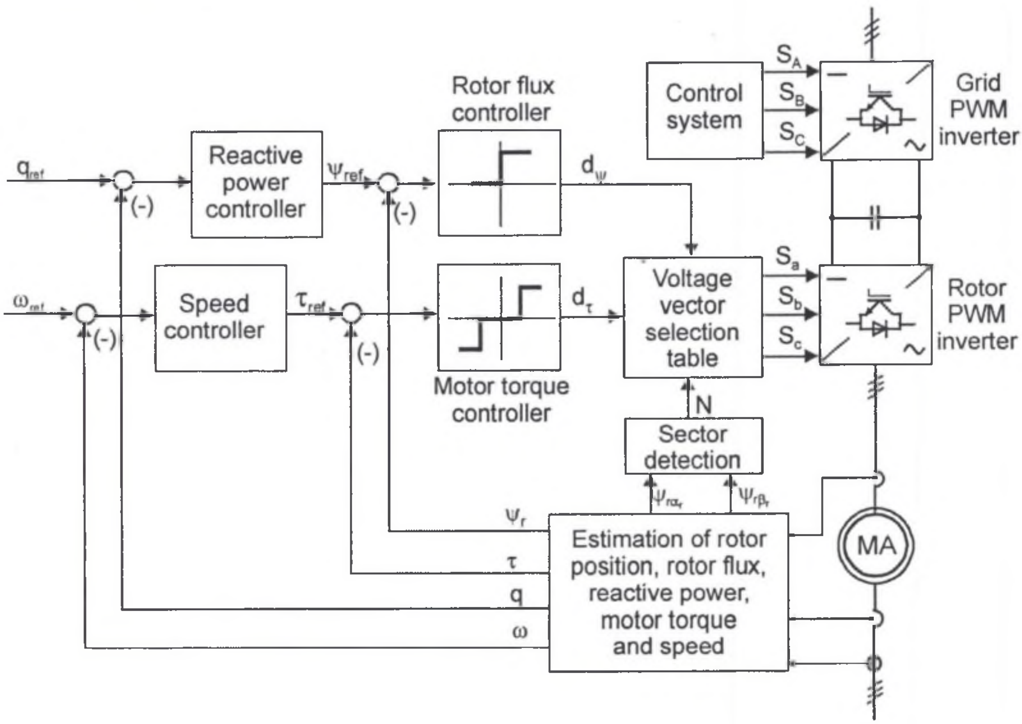

Fig. 1. DTC-based control system of double-fed induction machine

Rys. 1. Układ sterowania maszyny dwustronnie zasilanej oparty na metodzie DTC

In DTC method it is necessary to estimate the rotor flux and the torque of the machine. The control of the motor PWM inverter is carried on in the frames of references tied to the rotor, so the rotor flux should be estimated in this frame of references. It can be realized applying the method presented in [8]. Estimated values of the rotor flux and motor torque are compared with reference ones ψ_{ref} and τ_{ref} using hysteresis comparators. Based on output signals of comparators $d\tau$, $d\psi$ and number of sector, which the rotor flux vector is situated in, the appropriate voltage vector is chosen from switching table 1 in order to keep the flux and torque within the limits of two hysteresis bands.

Reference values of torque and rotor flux are output signals of speed and reactive power PI controllers, respectively. In the case of generator systems the controller of active power is applied instead of speed controller.

Table 1

Switching table

d_τ	d_ψ	Voltage vector
-1	0	$\underline{U}_{N+2}$
	1	$\underline{U}_{N+1}$
0	0	**Zero vector**
	1	
1	0	$\underline{U}_{N-2}$
	1	$\underline{U}_{N-1}$

4. SIMULATION TESTS

Simulations were carried out in MATLAB-SIMULINK. The whole control system of double-fed induction motor was prepared as digital system with discretization time of 10 μs.

4.1. Step change of load torque

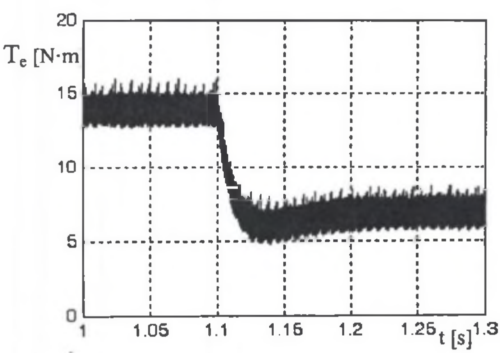

Fig. 2. Electromagnetic torque for step change of load torque

Rys.2. Moment elektromagnetyczny dla skokowej zmiany momentu obciążenia

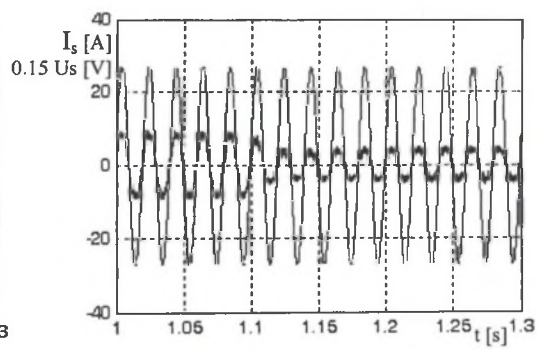

Fig. 3. Stator voltage and current for step change of load torque

Rys.3. Napięcie i prąd stojana dla skokowej zmiany momentu obciążenia

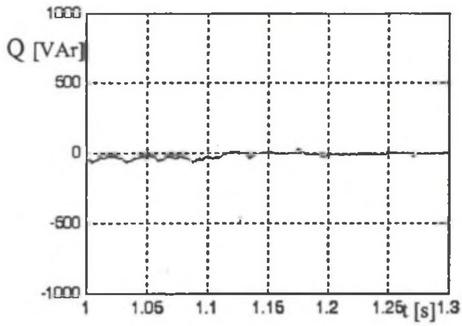

Fig. 4. Reactive power for step change of load torque
Rys.4. Moc bierna dla skokowej zmiany momentu obciążenia

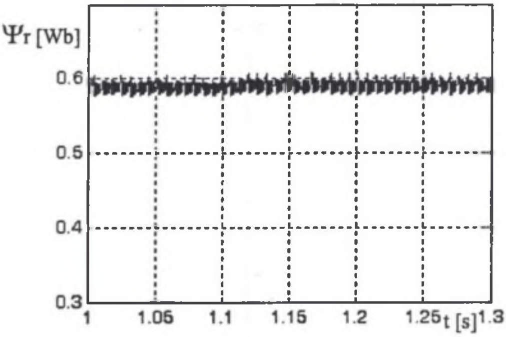

Fig. 5. Rotor flux amplitude for step change of load torque
Rys.5. Amplituda strumienia wirnika dla skokowej zmiany momentu obciążenia

The transient responses due to a step change of load from τ_N to $0{,}5\tau_N$ are depicted in fig. 2-5. Speed of the machine is kept to $0{,}5\omega_N$. The reference value of τ_{ref} is an output signal of speed controller (fig. 2). The reference value of reactive power q_{ref} is set at 0 (fig. 4) so motor works with unity power factor (fig. 3). The amplitude of the rotor flux is changed by control system to maintain zero value of reactive power (fig. 5).

4.2. Step change of the reference value of reactive power

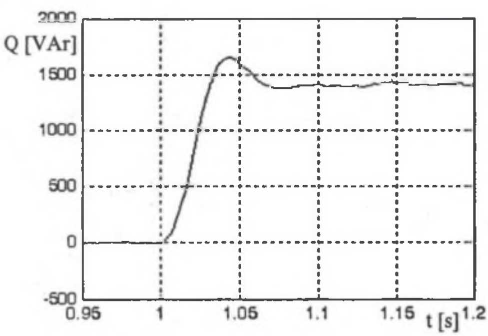

Fig. 6. Reactive power for step change of the reference value of reactive power
Rys.6. Moc bierna dla skokowej zmiany mocy biernej zadanej

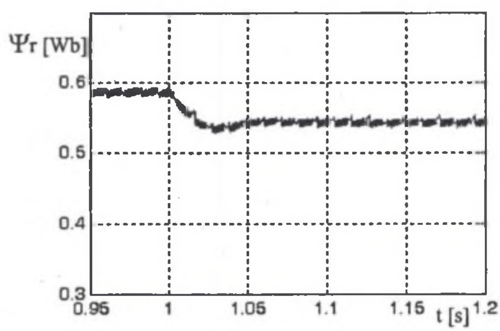

Fig. 7. Rotor flux amplitude for step change of the reference value of reactive power
Rys.7. Amplituda strumienia wirnika dla skokowej zmiany mocy biernej zadanej

The transient responses due to a step change of reference value of reactive power from 0 to $0{,}5q_N$ and constant value of load ($\tau = \tau_N$) are depicted in fig. 6-9. Speed of the machine is kept to $0{,}5\omega_N$. The reference value of rotor flux amplitude ψ_{ref} is an output signal of reactive power controller (fig. 7) and it changes due to change of reactive power. Before step change of reactive power motor works with unity power factor (fig. 9) and after that the power factor changes. There is no affect of these quantities on electromagnetic torque (fig. 8).

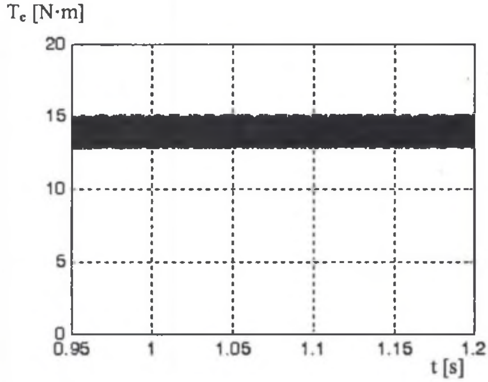

Fig. 8. Electromagnetic torque for step change of the reference value of reactive power
Rys.8. Moment elektromagnetyczny dla skokowej zmiany mocy biernej zadanej

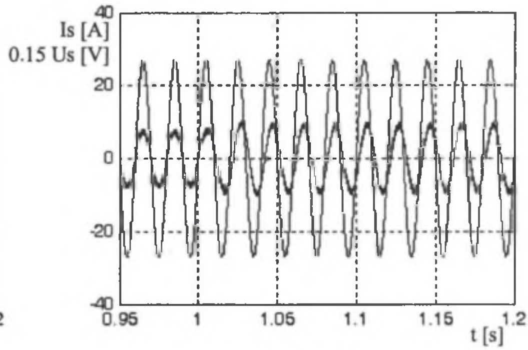

Fig. 9. Stator voltage and current for step change
Rys.9. Napięcie i prąd stojana dla skokowej zmiany mocy biernej zadanej

4.3. Step change of the reference value of the speed

The transient responses due to a step change of reference value of speed (fig. 10) from $0{,}7\omega_N$ to $1{,}3\omega_N$ and constant value of load ($\tau = \tau_N$) are depicted in fig. 10-11. The reference value of reactive power q_{ref} is set at 0. There is no affect of change of speed on reactive power in stator circuit (fig. 11).

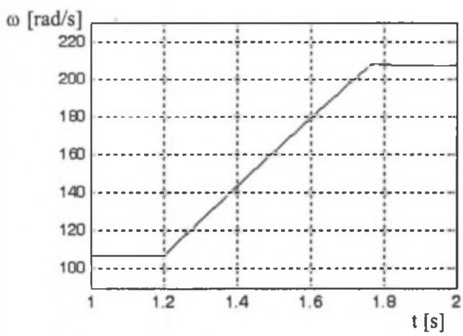

Fig. 10. Speed of the machine for step change of the reference value of speed
Rys.10. Prędkość maszyny dla skokowej zmiany prędkości zadanej

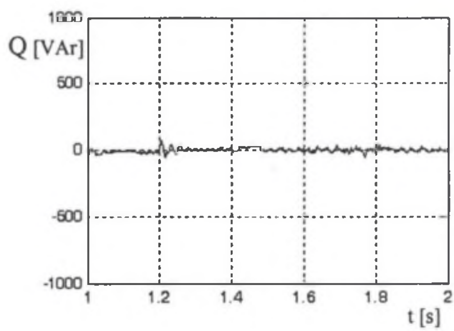

Fig. 11. Reactive power for step change of the reference value of speed
Rys.11. Moc bierna dla skokowej zmiany prędkości zadanej

5. CONCLUSIONS

In DTC-based system with double-fed induction machine it is possible to independently control of torque of the machine and reactive power drawn from the grid. The motor can work with zero reactive power in stator circuit (the reactive power is delivered to the rotor circuit).

DTC method offers excellent dynamic properties, which is limited by the PI controller's characteristics. Another advantage of DTC is its simplicity and easy microprocessor realization because of low computation time. In the system with double-fed induction machine this time increases a little because the co-ordinate transformation to rotor reference frame is needed.

Presented simulation tests are the first step to realization of the laboratory system with double fed induction machine controlled according to DTC method.

REFERENCES

1. Depenbrock M.: *Direkte Selbstregelung (DSR) für hochdynamische Drehfeldantriebe mit Stromrichterspeisung*, EtzArchiv, no 7, 1985, pp.211-218.
2. Kelber Ch. R., Schumacher W.: *Control of double-fed induction machines as an adjustable speed motor/generator*, European Conference "Variable Speed in Small Hydro", Grenoble, 2001.
3. Morel L., Godfroid H., Mirzaian A., Kauffmann J. M.: *Double-fed induction machine: converter optimization and field oriented control without position sensor*, IEEE Proc. Electr. Power Appl. Vol. 145, No 4 July 1998, pp. 360-368.
4. Radel U., Navarro D., Berger G., Berg S.: *Sensorless field oriented control of a slipring induction generator for 2.5 MW wind power plant from Nordex Energy Gmbh*, 9th Europ. Conf. on Power Electronics and Applic. EPE'2001, Graz, 2001.
5. Takahashi I., Noguchi T.: *A new Quick-response and high efficiency strategy of an induction motor*, IEEE Trans. Ind. Appl. IA-22, 1986, pp.820-827.
6. Datta R., Ranganathan V.T.: *Direct Power Control of Grid-Connected Wound Rotor Induction Machine Without Rotor Position Sensors*, IEEE Transactions on Power Electronics, Vol. 16, No. 3, May 2001.
7. Arnalte S., Burgos J. C., Rodriguez-Amendo J. L.: *Direct Torque Control of a Doubly-Fed Induction Generator for Variable Speed Wind Turbines*, Electric Power Components and Systems, 30: 199-216, 2002.
8. Krzeminski Z.: *Sensorless Multiscalar Control of Double Fed Machine for Wind Power Generators*, PCC Osaka 2002. pp. 334-339.

Recenzent: Prof. dr hab. inż. Zbigniew Krzemiński

Wpłynęło do Redakcji dnia 15.10.2003 r.