Tomasz DRABEK, Tomasz LERCH, Szymon SŁONKA

AGH Akademia Górniczo-Hutnicza, Katedra Energoelektroniki i Automatyki Systemów Przetwarzania Energii

doi:10.15199/48.2016.03.37

Development of vector control system of DFIG using graphically programmed DSP

Abstract. *The vector control of AC electric machines, due to the large number of real-time calculations, is carried out using signal processors. This paper presents the implementation of vector control of doubly fed induction generator using Texas Instruments TMS320F2812 signal processor. The microcontroller has been programmed in a graphic way using MATLAB-Simulink. It performs all the control, including support for the user interface and PWM modulation of inverter output voltages power the DFIG rotor. Implementation was preceded by the appropriate simulations, using the target microcontroller programming blocks. The whole DFIG system has been tested in laboratory conditions using induction machine with a power rating of 10 kW. The tests confirmed the full functionality of the method of programming.*

Streszczenie. *Sterowanie wektorowe maszyn elektrycznych prądu zmiennego, ze względu na dużą liczbę obliczeń koniecznych do wykonania w czasie rzeczywistym realizuje się obecnie na procesorach sygnałowych. W tym artykule przedstawiono implementację wektorowego sterowania mocami generatora MDZ na mikrokontrolerze sygnałowym Texas Instruments TMS320F2812. Mikrokontroler został zaprogramowany w sposób wyłącznie graficzny, z użyciem pakietu MATLAB-Simulink. Realizuje on całość sterowania, łącznie z obsługą interfejsu użytkownika i modulacją PWM napięć wyjściowych falownika zasilającego wirnik MDZ. Implementacja była poprzedzona odpowiednimi symulacjami, z wykorzystaniem docelowych bloków programowych mikrokontrolera. Cały układ MDZ został przetestowany w warunkach laboratoryjnych, z maszyna indukcyjną o mocy znamionowej 10kW. Przeprowadzone testy potwierdziły pełną funkcjonalność zastosowanej metody programowania. (**Opracowanie systemu sterowania wektorowego generatora DFIG z wykorzystaniem graficzne programowego procesora DSP**)*

Keywords: double-fed induction machine, DSP graphical programming.
Słowa kluczowe: maszyna dwustronnie zasilana, programowanie graficzne DSP.

Introduction

One of the main trends in world power engineering development is increase of power production from renewable energy sources, mainly wind power energy [1]. The main aims of this development are increase of energy production effectiveness and costs reduction of wind farms investment and maintenance. Another important purpose of the technical development is obtaining operational properties, enabling stable work of whole electric power system. One of currently used solution, meeting these requirements is doubly fed induction machine (DFIG), working as a generator in wind power station [2 - 4]. Such a solution enables flexible control of active and reactive power with low investment and maintenance costs. The main source of the investment savings is using a machine without permanent magnets. The vector control of the DFIG provide independent active and reactive power control while working with variable speed [5, 6].

The main purpose of the article is to present microprocessor implementation of vector control system of DFIG, working as a generator using graphically programmed DSP (Digital signal processor). To realize the control system, the Texas Instruments *TMS320F2812 DSP* has been used. The graphical programming has been done by using Matlab/Simulink software with Embeded Coder toolbox and Code Composer Studio software by Texas Instruments.

DFIG vector control system synthesis

Implementation of vector control of DFIG power demand stator active and reactive power measurement. Instantaneous power values are calculated from continuous stator currents and voltages measurement. To estimate values of active and reactive power, the instantaneous reactive power theory [7, 8] has been used. According to this theory, in symmetrical three-phase system, active and reactive power could be calculated with following formulas:

$$p_s = u_\alpha i_\alpha + u_\beta i_\beta \tag{1}$$

$$q_s = u_\beta i_\alpha - u_\alpha i_\beta \tag{2}$$

Active and reactive power estimation need values of stator current and voltages in *αβ* coordinates. *αβ* is a non rotating, orthogonal reference frame. Transformation from natural coordinates (*abc*), to *αβ* is realized by Clark transform, which changes three-phase *abc* quantities to two-phase, orthogonal according to relations (for machine with star connected stator winding):

$$u_\alpha = \left(2u_{ab} + u_{bc}\right)\frac{1}{\sqrt{3}} \tag{3}$$

$$u_\beta = u_{bc} \tag{4}$$

Analogical transform is used for phase currents.

Measured power values, which are inputs of active and reactive power regulators are compared with referenced values given by supervisory power control system. To realize independent active and reactive power control system, it is necessary to transform the measured values to reference frame oriented with stator voltage vector - *xy* frames. Active and reactive power in such oriented *xy* reference frames, in steady state and with assumption $R_s = 0$, could be presented [5, 9] by formulas:

$$p_s = -\frac{L_m}{L_s} u_{sx} i_{rx} \tag{5}$$

$$q_s = -\frac{1}{L_s}\frac{u_{sx}^2}{\omega_k} + \frac{L_m}{L_s} u_{sx} i_{ry} \tag{6}$$

Presented equations prove possibility of independent active and reactive power control and is the basis of control system synthesis. The omission of the stator resistance allows the synthesis of the independent control system of DFIG active and reactive power. However, it should be noted that in the case of low power machines can cause inaccuracy in the control. Value of active power is dependent on *x* component of rotor current and the reactive power value depend on *y* rotor current component. Currents and voltages *xy* components could be obtained by transformation from *αβ* to *xy* defined by relations:

$$u_x = u_\alpha \cos\varphi + u_\beta \sin\varphi\,, \tag{7}$$

$$u_y = -u_\alpha \sin\varphi + u_\beta \cos\varphi\,, \tag{8}$$

where *φ* is the angle between *xy* and *αβ* reference frames.

The control system, apart from stator power measurement, require measurement of *xy* rotor currents components [5, 9, 10]. These values are current regulators inputs. Reference inputs of these regulators are outputs signals of active and reactive power regulators. Outputs of rotor current regulators are reference *xy* rotor voltages, which control the rotor inverter. The control algorithm scheme is presented in Figure 1.

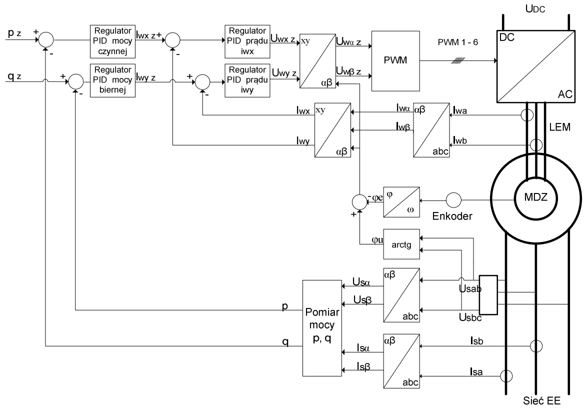

Fig. 1. DFIG power control diagram

Microprocessor based vector control implementation

Vector control systems are built based on signal processors. They are mainly programmed in the C language. The use of DPS and methods of programming have been discussed in [11 - 15]. In our approach the control program has been created using MATLAB/Simulink with Embeded Coder toolbox. The toolbox has been used to convert the control system created in Simulink to program in C language. The program after conversion is compiled and loaded to microcontroller memory by Code Composer Studio software, which is able to communicate with the DSP. These solution enables fast and simple control system prototyping , simulation and testing in the target system. The Embeded Coder toolbox contain function libraries, dedicated to C2000 processors family, produced by Texas Instruments. To realize the control program, the following libraries have been used:

- C281x - library which contain DSP peripherial services functions like PWM generators, analog - digital converters, inputs/outputs, timers and serial communication ports,
- C28x DMC - Digital Motor Control - contain functions used to drives control such as reference frames transforms (Parke, Clarke), space vector generator, speed measurement function, PID regulator,
- C28xIQMath - basic math operations, realized by DSP on fixed - point numbers.
- DSP System Toolbox - library dedicated to DSPs programming. Contains filtering functions, transforms, math and statistical operations.

Graphically created DFIG control program is presented in the Figure 2 (left, green part). The program can be divided functionally to parts which realize functions like: currents, voltages and rotor angle measuring circuits service, transforms of voltages and currents components, active and reactive power calculation, power and current regulation and PWM signals generation. The discretization time of the control system was 200μs.

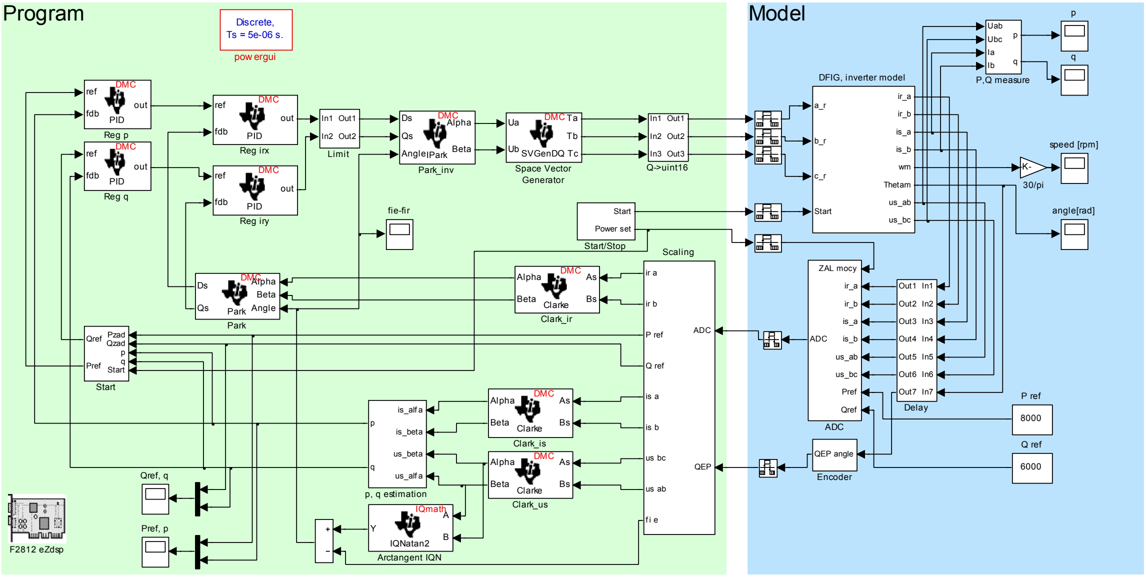

Fig. 2. Control program and electromechnical system model

Simulation

The simulation study of DFIG have been carried using different computational techniques which have been shown in many articles [16 - 20]. In our case, it was most convenient to carry simulations of control system operation with the DFIG in Simulink environment. In one model, both control program (dedicated to DSP), and the model of electromechanical system have been tested. Parameters of the electromechanical part have been set to approximate conditions of the laboratory system. The main element is the model of wound rotor induction machine from SimPowerSystems library.

Similarly as at laboratory system, it is a machine with P_N = 10 kW, U_N = 380 V, f_N = 50 Hz and n_N = 1445 rpm. The machine is propelled by the second identical machine, working as a motor, modeled in similar way. In case of variable speed simulation, the speed is given by Ramp function. The DFIG, at the stator side, is connected to grid, modeled as a three - phase voltage source with rated voltage 380 V. At the rotor side, the machine is powered by three - phase inverter, controlled by reference rotor voltages, generated by control program. The others elements of the model are circuit breakers and voltages and currents measurement blocks. Important part of the model are also blocks which simulate analog digital converters and incremental encoder used to speed measurement and rotor angle. The model is presented in Figure 2. Exemplary simulation results are presented in Figure 3. It shows waveforms of stator active and reactive power, generated by DFIG during step changes of referenced power values and continuous, linear speed variation from 1650 rpm at t = 0, to 1175 rpm at t = 5 s. These waveforms prove ability to independent active and reactive power control. Step change of active power do not influence on value of generated reactive power in steady state operation. Similarly change of referenced reactive power do not influence active power value. In the moment of one referenced value change, in the second a small fluctuations are visible, but it do not disturb in correct system operation. Both active and reactive power reach referenced values in short time without overshoot. It proves correct operation of regulators.

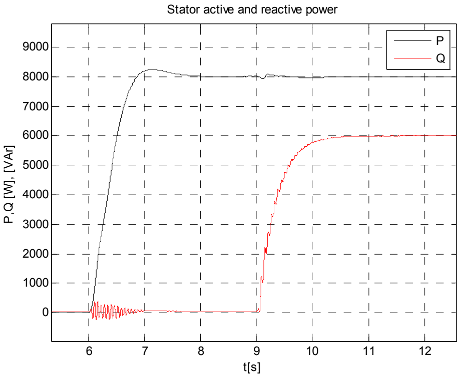

Fig. 3. Active and reactive power waveforms (simulation)

Laboratory research

The schematic diagram of the laboratory system is presented in Figure 4. The wound rotor induction machine is propelled by separately excited DC machine. For rotor currents and stator currents and voltages measurement, the LEM transducers have been used. Signals measured by the transducers have been adjusted to voltage ranges acceptable by DSPs analog - digital converter. Rotor speed and angle measurement has been realized by using incremental encoder with resolution 1000 pulses per rotation. The inverter in rotor circuit is a voltage source inverter, built for laboratory purposes, based on intelligent power module IPM 75 A / 1200 V. The module contain 6 IGBT transistors with drivers and protections. Maximum frequency of the transistors switching is 20 kHz. Important part of the inverter is galvanic separation of the control signals, realized by using optical fiber. This solution guarantees galvanic separation between power circuits and control system.

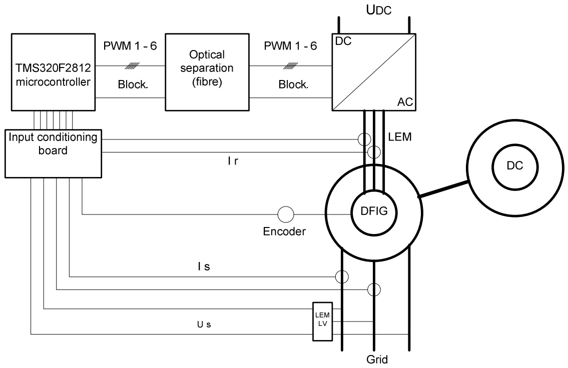

Fig. 4. Schematic diagram of laboratory stand

Results of the laboratory system operation are presented in following figures. Figure 5 presents active and reactive power waveforms of DFIG in case of step change in referenced active power during constant value of reactive power (positive values means produced power, negative - consumed). Rotor currents waveforms corresponding to this case are presented in Figure 6.

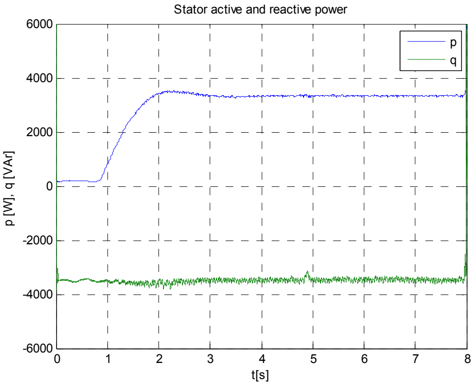

Fig. 5. Active and reactive power waveforms during step change in referenced value of active power

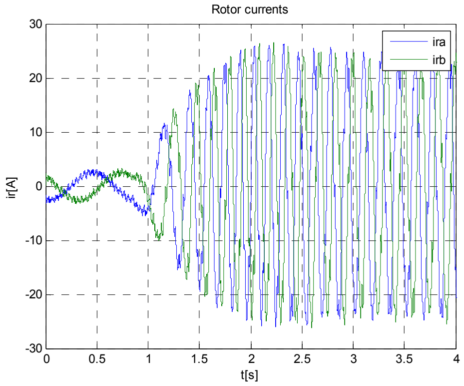

Fig. 6. Measured rotor currents waveforms during step change in active power referenced value

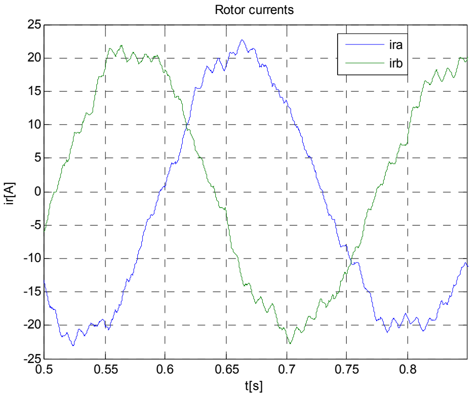

Fig. 7. Rotor current waveforms in steady state

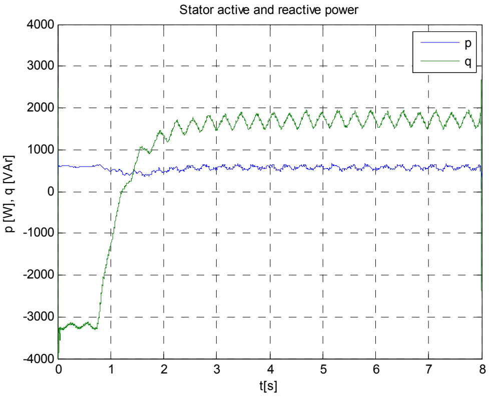

Fig. 8. Active and reactive power waveforms during step change in reactive power referenced value

One period of the current waveform is shown in Figure 7. Figure 8 presents step change in reactive power with constant set value of the active. The active power step response could be approved. The control system in sufficiently short time enables to achieve the referenced value of generated active power, without significant overshoot. Important is also fact, that active power regulation do not influence on reactive power. During generated active power increase, rotor currents increase and speed decrease, what is visible in rotor currents frequency raise. In case of motor operation, the system with DFIG operates similarly.

The instantaneous power estimation algorithm (according to 1), has been tested for generator and motor machine operation. Calculated power values have been compared with the measured values. Important disadvantage of the used algorithm is its sensitivity even for small disturbances in measured signals and presence of DC component in the signals. The disturbances caused oscillations in measured instantaneous power. Necessary was lowpass filtration of the calculated power.

The current waveform is not an ideal sinusoid and include some deformations, but it does not influence correct machine operation. The deformation could be caused by regulators operation, which inputs are measured currents and voltages with disturbances. The overall correctness of inverter operation is confirmed by lack of DC component in rotor current.

According to observations of performed tests, it can be stated, that the control system in case of reactive power regulation operates also properly. The referenced value is reached both for positive and negative values, and there is no significant influence on active power level. In recorded waveforms, the 3.3 Hz oscillations of reactive power are visible. It is result of the reactive power estimation algorithm (2) sensitivity for disturbances and DC component in measured currents and voltages. The oscillations are not visible in reactive power measured by different methods and do not influence correctness and quality of DFIG operation.

Summary

The evaluatin board with DSP, used for DFIG vector control system prove to be sufficient and fully functional solution. Various peripherials of the microcontroller enables all controlled system signals handling. Significant advantage of used microcontroller is a real possibility of graphical programming. Using the Matlab/Simulink software with additional libraries, gives possibility to fast programming and using of ready to use Simulink functions. It also enables to test the program operation in simulation way. Performing the simulation makes possible to test whole system operation in different conditions, which enables to find the errors in the program before using it in real target system. This feature reduces the time of real system start-up. There is also possibility to control simulated system by real microcontroller (hardware in the loop).

Finally it could be stated the used programming manner is fully effective, convenient for programmer and has many useful features, which are not offered by classic way of microcontrollers programming.

Niniejszy artykuł powstał w wyniku prac prowadzonych w projekcie realizowanym w ramach Programu Badań Stosowanych w ścieżce B pt.: „Dedykowana metodyka zarządzania projektami inwestycyjnymi w obszarze dystrybucji energii elektrycznej.” Umowa nr PBS3/B9/42/2015 o wykonanie i finansowanie.

***Authors**: dr inż. Tomasz Lerch, Akademia Górniczo-Hutnicza, Katedra Energoelektroniki i Automatyki Systemów Przetwarzania Energii, al. A. Mickiewicza 30, 30-059 Kraków, E-mail: lerch@agh.edu.pl; dr inż. Tomasz Drabek, Akademia Górniczo-Hutnicza, Katedra Energoelektroniki i Automatyki Systemów Przetwarzania Energii, al. A. Mickiewicza 30, 30-059 Kraków, E-mail: drabek@agh.edu.pl; mgr inż. Szymon Słonka, Akademia Górniczo-Hutnicza, Katedra Energoelektroniki i Automatyki Systemów Przetwarzania Energii, al. A. Mickiewicza 30, 30-059 Kraków, E-mail: slonka.szymon@gmail.com*

REFERENCES

[1]. Chen Z, Blaabjerb F. Wind energy – the worlds fastest growing energy source. IEEE Power Electron. Soc. Newslett. 2006; 3: 15–19.
[2]. [2] Muller S, Deicke M, De Doncker RW. Doubly fed induction generator systems for wind turbines. IEEE Ind. Appl. Mag. 2002; 3: 26–33.
[3]. Datta R, Ranganathan VT. Variable-speed wind power generation using doubly fed wound rotor induction machine – a comparison with alternative schemes. IEEE Trans. Energy Convers. 2002; 3: 414–421.
[4]. Tazil M, Kumar V, Bansal RC. Three-phase doubly fed induction generators: an overview. IET Electric Power Applications 2010; 4: 75–89.
[5]. Bogalecka E, Krzeminski Z. Control systems of doubly-fed induction machine supplied by current controlled voltage source inverter. Int. Conf. Electrical Machines and Drives; 08-10 Sep 1993; Oxford, GB: IET. pp. 168-172.
[6]. Girlotka K, Jeleń M, Jarek G. Sterowanie polowo zorientowane z wymuszeniem dynamiki maszyny dwustronnie zasilanej. Przegląd Elektrotechniczny 2010; 02: 164.
[7]. Akagi H, Kanazawa Y, Nabae A. Generalized theory of the instantaneous reactive power in the three-phase circuits. IEEJ International Power Electronics Conference; 1983; (IPEC-Tokyo). pp. 1375–1386
[8] Czarnecki LS. Moce w obwodach elektrycznych z niesinusoidalnymi przebiegami prądów i napięć. Warszawa, Polska: Oficyna Wydawnicza Politechniki Warszawskiej, 2005.
[9] Lerch T. Transient states of wind power plant with doubly fed induction generator. Przegląd Elektrotechniczny 2011; 118–124.
[10] Yamamoto M, Motoyoshi O. Active and reactive power control for doubly-fed wound rotor induction generator. IEEE Trans. Power Electron. 1991; 4: 624–629
[11] Gallardo S, Carrasco JM, Galvan E, Franquelo LG. DSP-based doubly fed induction generator test bench using a back-to-back PWM converter. 30th Annual Conference of IEEE Industrial Electronics Society; 2–6 Nov. 2004 IEEE. pp. 1411–1416
[12] Babu BC, Mohanty KB. DSP based stator flux oriented control of doubly-fed induction generator for wind power generation system. Electrical, Electronics and Computer Science (SCEECS), 2012 IEEE Students' Conference on; 1–2 March 2012; Bhopal, India: IEEE. pp. 1–6
[13] Mesbah M, Islam S. Real time digital controller of grid connected Doubly-Fed Induction wind turbine generator. Developments in Renewable Energy Technology (ICDRET), 2012 2nd International Conference; 5–7 Jan. 2012; Dhaka, Bangladesh: IEEE. pp. 1–6
[14] Che Y, Ren J, Chen J, Chen X. Research on grid-side PWM converter based on DSP for double fed wind power generation system. International Conference on Power Electronics Systems and Applications (PESA); 08-10 Jun 2011; Hong Kong, China: IEEE. pp. 1–6
[15] Wojnicki I, Rad M. Rapid design and development of control applications for electrical engineering. Automatics 2013; 17: 263–270
[16] Dufour C, Belanger J. Real-time simulation of doubly fed induction generator for wind turbine applications. Power Electronics Specialists Conference, PESC; 20-25 June 2004; IEEE. pp. 3597–3603
[17] Tapia A, Tapia G, Ostolaza JX, Saenz JR. Modeling and control of a wind turbine driven doubly fed induction generator. IEEE Trans. Energy Convers 2003; 2: 194–204
[18] Ekanayake JB, Holdsworth L, Wu X, Jenkins N. Dynamic modeling of doubly fed induction generator wind turbines. IEEE Trans. Power Syst. 2003; 2: 803–809
[19] Seung-Ho S, Ji-Hoon I, Hyeong-Jin C, Seung-Gi J. Simulation Modeling and Experimental Validation of Generator Control Strategy in DFIG System. Applied Power Electronics Conference, APEC March 2007 Anaheim, CA, USA: IEEE. pp. 1329–1333
[20] Ting L, Mike B, Meliksah O. Doubly-fed induction generator wind turbine modelling for detailed electromagnetic system studies. IET Renewable Power Generation 2013; 7: 180–189