Tomasz LERCH

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

doi:10.15199/48.2016.06.36

Energy- efficient system for induction machine loading on the test bay

Abstract. *This study outlines the conceptual design of an energy-efficient system for applying the load to induction motors in a test bay. The proposed solution uses a doubly fed induction generator (DFIG), resulting in considerable energy savings during the tests of electric machines and in reduction of investment costs, ensuring higher efficiency and allowing the full compensation of reactive power.*

Streszczenie. *W artykule przedstawiono koncepcje energooszczędnego układu obciążenia silników indukcyjnych na stacjach prób wykonujących badania maszyn elektrycznych. W proponowanym układzie zastosowano maszynę dwustronnie zasilaną (MDZ), co jest źródłem istotnych oszczędności energii podczas prób maszyny indukcyjnej a także wiąże się ze znacznie mniejszymi nakładami inwestycyjnymi, osiąga wyższą sprawność oraz pozwala na całkowitą kompensację mocy biernej. (**Energooszczędny układ obciążenia maszyny indukcyjnej na stacji prób**).*

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

Introduction

In accordance with the relevant regulations and guidelines, electrical machines have to be tested in a test bay equipped with a system capable of applying the loads from zero to the breakdown torque range in a controllable manner. Load tests need to be taken for each new type of product being launched. View of induction machine in a test bay is shown in Figure 1. Conventional test bays were typically equipped with the Ward Leonard system wherein the load torque is controlled through regulation of the excitation current. Its main advantage is the simplicity of the power control system and hence, its reliability. However, this setup has certain drawbacks as well, including its actual configuration (a motor –generator set) and hence low efficiency, reactive power import by the machine being tested and by the AC generator and, last but not least, high investment costs. Now, with the advent of power electronic converters, the replacement of the Leonard system became a possibility. The modified solution may use just one induction machine, thus improving the efficiency of the system, enabling the precise control of reactive power and eliminating the problems caused by reactive power import by the loading system. A major drawback of this solution is that the total power exported to the grid via the loading system has to be first converted in an inverter, which considerably increases the investment costs.

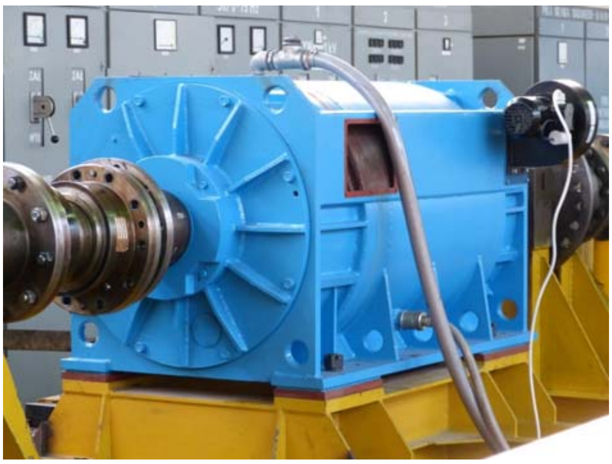


Figure 1. Test bay in the EMAG (Laboratory of Electric Machines) for testing powerful machines – general view

Adapting the solutions well known in wind power engineering, the loading system can now be optimised, taking into account the investment costs and the energy balance.

Application of doubly fed machines in the loading system

The Author developed a design of a modified doubly fed machine system operated as a generator applying the load to the electric machine being tested. The proposed solution uses a wound-rotor induction machine whose rotor is fed via a voltage inverter with a single power flow direction. This system has been widely described in many publications [1,2]. The schematic diagram of the proposed system is shown in Figure 2.

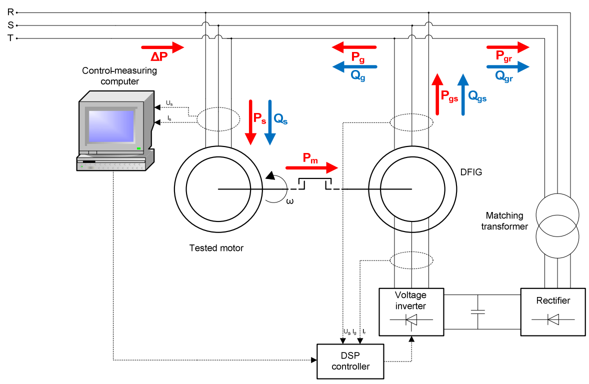
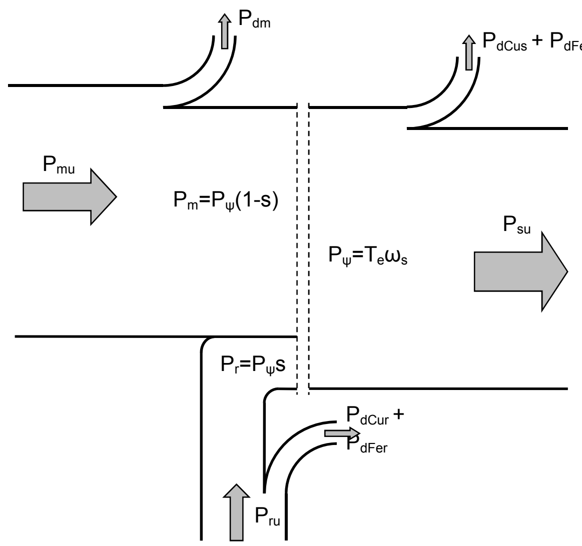


Figure 2. Conceptual design of the loading system incorporating a doubly fed induction generator

The converter power fed to the rotor is dependent on the maximal slip experienced by the doubly fed machine. Breakdown torque of induction machine occurs at a few percent of slip rate, so when a DFIG is used as the loading system, the power rating of power electronic converter will account for less than 10% of the total loading system. Moreover, operation under positive slip only indicates the uni-directional power flow via the converter to the rotor [3]. That is illustrated by the power balance of the system, shown in Figure 3. It appears that embracing this concept will lead to a significant reduction of investment costs through the use of a uni-directional converter and the converter power will equal a percent fraction of the entire generator power.



P_{su} – stator power; P_Ψ – rotating field power; T_e – electromagnetic torque; ω_s – rotating field pulsation; P_m – mechanical power; P_{mu} – mechanical usable power; s – slip ratio; P_r – rotor power (slip power); P_{dCus} – stator winding losses; P_{dCur} – rotor winding losses; P_{dFes} – stator core losses; P_{dFer} – rotor core losses; P_{dm} – mechanical losses

Figure 3. Active power flow in a proposed system incorporating a doubly fed machine

Active and reactive power control in a doubly fed machine is effected through feeding the current components supplying the rotor [4 – 6], which requires a vector control system. A schematic diagram of the vector control system used in the system being developed is shown in Figure 4. Implementation of such control system involves extensive real-time calculations, hence the controllers are typically based on signal processors.

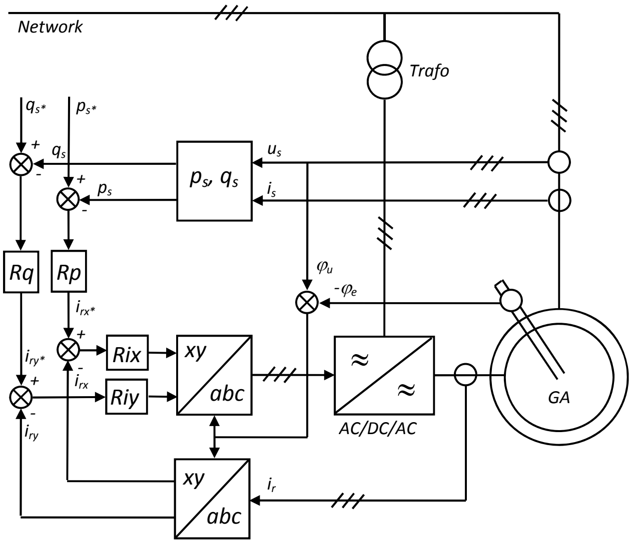


Figure 4. Schematic diagram of a vector control system for the doubly-fed machine

The main objective underpinning the loading system being developed was minimisation of energy consumption, which is an important problem during lengthy testing of high power machines. Mechanical power delivered by the machine being tested is converted into electric energy in a DFIG.

A fraction of power, dependent on the slip rate, will “circulate” in a closed stator-rotor circuit, whilst its major part is consumed by the tested machine. Directions of active power flow within this system are indicated by red arrows in Figure 2. Power is fed from an external source only to cover the losses in the tested machine and in the DFIG system. As the active power flow path is closed-looped and short, the calculated efficiency of the loading system is expected to increase to 84%. Hence, in the proposed solution the power station supplying the test bay during the tests of high power machines should have the power ratings equal to 20% of that of the largest tested machines.

As active power in doubly fed machines is converted in the stator and rotor line, the total converted power becomes [7]:

$$p = p_s - s \cdot p_s \tag{1}$$

where: s - slip rate, p_s - power converted in the stator line.

In consideration of this relationship, the control system in the proposed solution was modified to enable the feeding of mechanical power as the power load applied by the DFIG. Mechanical power is expressed as the product of electromagnetic moment and angular velocity of the rotor:

$$p_m = T_e \cdot \omega_r \tag{2}$$

Implementation of thus modified control system requires an electromagnetic torque observer. In the case of a slip-ring machine both the rotor and stator currents are directly measurable. The recommended solution, therefore, is a torque observer [8], to determine its value basing on the rectangular components of the machine’s current.

$$T_e = pb \cdot Lm \cdot (i^s_{r\alpha}{}' \cdot i_{s\beta} - i^s_{r\beta}{}' \cdot i_{s\alpha}) \tag{3}$$

Rotor current components have to be recalculated in terms of the stator line and transformed to a rectangular reference system *αβ* associated with the stator, which is handled by the signal processor in the control system.

Very significant advantage of a doubly fed induction generator is that reactive power imported or exported to the grid by the system can be effectively controlled, and thus it may compensate for the reactive power consumption by the machine being tested. This aspect is of primary importance because induction machines have a relatively high reactive power demand, leading to current consumption of the order of 30% of the nominal ratings. When high power machines are being tested, this current adds an extra load upon the supply station, bringing about further active power losses. In the proposed solution reactive power need not be fed to system at all. Flow of reactive power is illustrated by blue arrows in Figure 2.

Simulation tests of a loading system incorporating a DFIG

The adequacy of the proposed system performance was verified through simulation tests performed in the Matlab Simulink environment. A dynamic model was developed comprising a machine being tested and the loading system incorporating a DFIG. All key components of the double fed induction generator were taken into consideration: a slip ring machine, a matching transformer and an power electronic converter. The simulation model is shown in Figure 5.

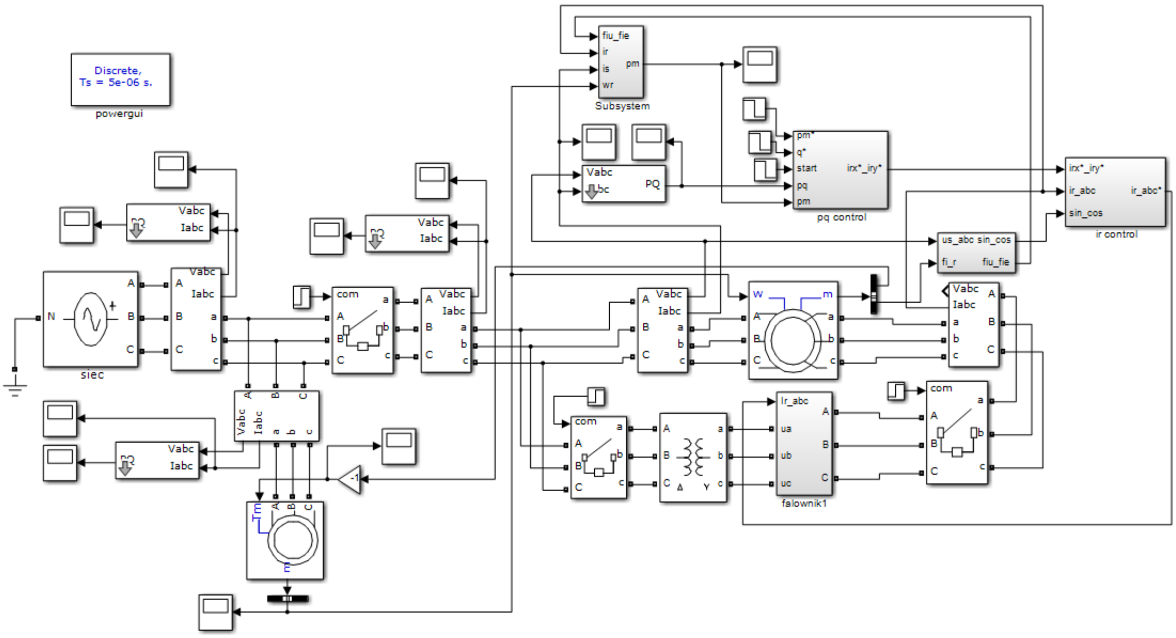


Figure 5. Simulation model of a loading system incorporating a DFIG

Loading system performance.

Simulation results are given as time series plots of power (output) at selected points of the loading system registered when the system is switched on and controlled. Figure 6 plots the active and reactive power absorbed by the tested machine under the idle run and after the loading system is switched on. Active power taken by the machine under the idle run is related to the machine losses considered in the model.

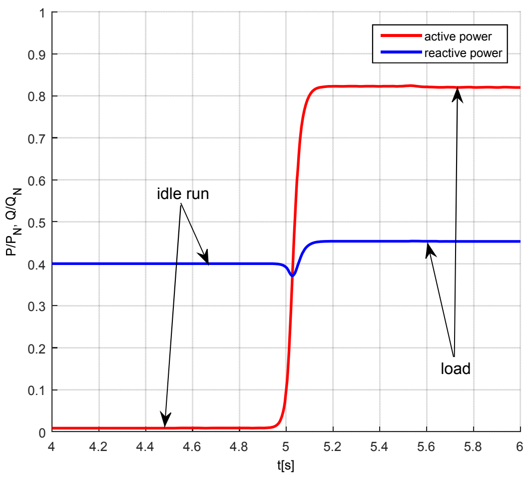


Figure 6. Tested machine power under loading

The use of an power electronic converter does not affect the actual current waveform fed to the machine being tested, which is well illustrated by plots in Figure 7.

Testing of the system performance involves also the analysis of power registered on clamps in the double fed induction generator. Plots of active and reactive power at this point are shown in Figure 8. The first step change is registered at the moment the stator circuit is switched on, when the machine will consume the full reactive power as well as active power to make up for the windings losses. The next step change is associated with switching on of the matching transformer supplying the rotor circuit. When the control system is on, the applied mechanical power and reactive power become zero.

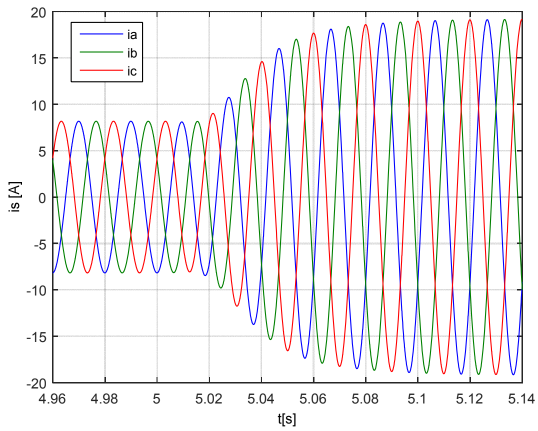


Figure 7. Tested machine current under loading

As the system controls the reactive power in the stator circuit of the doubly fed machine, reactive power shown in the plot is absorbed by the matching transformer. Similarly, the zero mechanical power registered on the shaft is indicative of further active power consumption to make up for the loss in the doubly fed machine. The final step change revealed in Figure 8 is associated with the control system operation at specified parameter settings. Active power equals power exported by the DFIG to the grid whilst mechanical power on the shaft is being controlled. The reactive power fed equals the sum of reactive power absorbed by the matching transformer and by the machine being tested. The expended inductive reactive power measured on DFIG clamps equals the power imported by the machine being tested, which can be seen by comparing Figure 6 and Figure 8. It is worthwhile to mention that an increase of reactive power exported by the DFIG to the grid is accompanied by a slight decrease of the expended active power, which is attributable to an increased current demand required to fully magnetise the machine from the rotor end, leading to an increase of active power losses in this line.

Power plots at the point where the modelled test bay is connected to the supply grid are shown in Figure 9. Step power changes revealed in the plot are associated with the switching in the DFIG system and correspond to those registered on DFIG clamps. Of primary importance is the final plot section obtained under the conditions when the machine being tested operates under load and reactive power at the connection point is fully compensated.

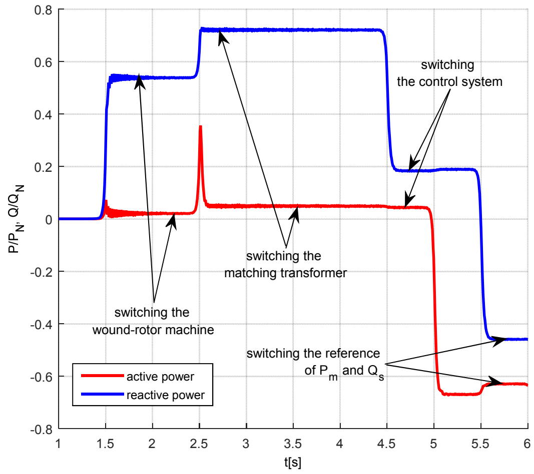


Figure 9. DFIG power during the switching on and regulation

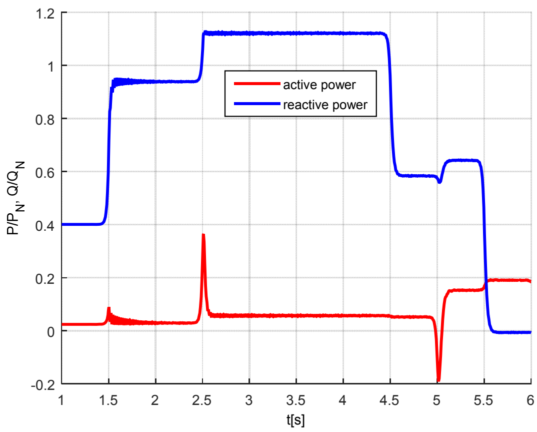


Figure 9. Power registered at the point the test bay is connected to the grid

To better illustrate the power flow in the modelled system, Figure 10 and Figure 11 separately plot the active and reactive power at three investigated measurement points. Active power imported by the tested machine is converted into mechanical power on the shaft, and then the doubly fed machine re-converts the mechanical into electrical power. The energy conversion processes in both machines feature a certain efficiency and hence the difference between power imported by the machine being tested and that exported by the DFIG has to be supplied from the grid.

Reactive power is absorbed by all induction-type receivers, in the system being modelled these include the two machines and the matching transformer. A specific feature of a doubly fed machine used in the proposed system is its ability to expend reactive inductive power because rotor windings are fed from an electronic power converter. Reactive power expended by the stator circuit compensates for the reactive power demand of the remaining system components. If the reactive power fed by the DFIG equals the total demand of the tested machine and of the transformer in the rotor line, the overall reactive power fed to the system from the grid will become zero.

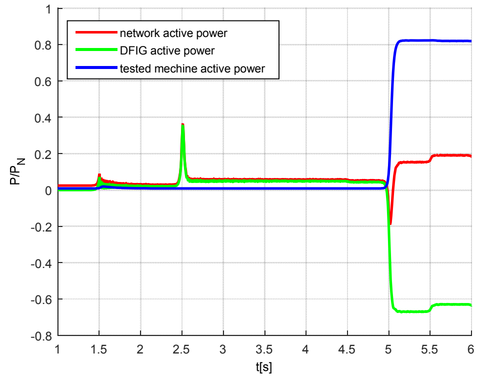


Figure 10. Active power at specified points of the system

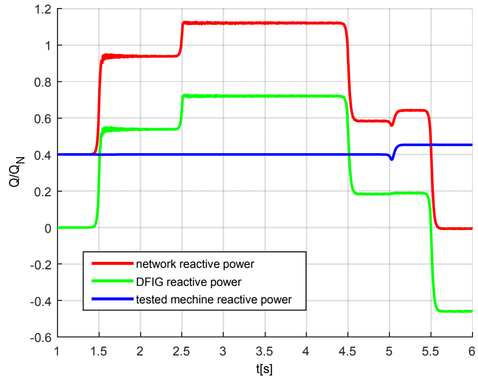


Figure 11. Reactive power at specified points of the system

Conclusions

Simulation tests have shown that the use of a doubly fed induction generator in the loading system allows the costs of test bay to be optimised or the range of machines for testing to be increased. Besides, the active power consumption by the test bay can be significantly reduced whilst reactive power is fully compensated.

Tomasz Lerch, Katedra Maszyn Elektrycznych, Akademia Górniczo-Hutnicza w Krakowie, lerch@agh.edu.pl

REFERENCES

[1] Tazil M, Kumar V, Bansal RC. Three-phase doubly fed induction generators: an overview. IET Electric Power Applications 2010; 4: 75–89.
[2] 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.
[3] Lerch T. Transient states of wind power plant with doubly fed induction generator. Przegląd Elektrotechniczny 2011; 6: 118–124.
[4] 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.
[5] Yamamoto M, Motoyoshi O. Active and reactive power control for doubly-fed wound rotor induction generator. IEEE Trans. Power Electron. 1991; 4: 624–629
[6] Xu L, Cartwright P. Direct active and reactive power control of DFIG for wind energy generation. IEEE Trans. Energy Convers 2006; 3: 750–758
[7] Muller S, Deicke M, De Doncker RW. Doubly fed induction generator systems for wind turbines. IEEE Ind. Appl. Mag. 2002; 3: 26–33.
[8] Lin C, Zheng H, Zhi L, Yan H. The Vector Analysis of Doubly Fed Wind Generator's Power-angle Characteristic. 2011 Third International Conference on Measuring Technology and Mechatronics Automation (ICMTMA); 6-7 Jan. 2011; Shangshai, China: IEEE. pp. 991 – 994