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Energy characteristics of a DC hybrid generator for a squirrel-cage asynchronous machine

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Abstract

Analytical research methods to determine the power characteristics of generator sets with vector control in an asynchronous squirrel-cage machine were developed and used to calculate the energy characteristics of generator sets with the field-oriented control (FOC) and direct torque control (DTC). The analytical calculations showed that a generator set with direct torque control had slightly better energy characteristics. Confirmation of the analytical calculation results was carried out using simulation models developed in the MATLAB-Simulink package with an environment Simscape Power System.

Introduction

Energy efficiency problems are of paramount importance for the construction of hybrid generator sets for autonomous objects used for land, air, and sea transport. In all the abovementioned units, the rotation speed of the shaft of an electric machine is set by an external source of mechanical energy and can be changed. Many years of practical experience show that asynchronous short-circuited machines can be reliably used in such objects.

A DC generator set with an asynchronous machine contains an active rectifier (AR), which typically uses a battery in its DC link (often in parallel with a supercapacitor). Generating sets, which use more than one electric power source operating at a common load, are called hybrid units. In hybrid generator sets, the voltage at the output of the active rectifier is constant and does not require a stabilization system.

In this article, an asynchronous hybrid DC generator set with a control vector is investigated. Two methods of vector control were investigated, and their energy characteristics were compared.

In recent years, the construction power systems for autonomous objects has primarily used direct current electrical networks (Brodovski & Ivanov, 1974; Takahashi & Noguchi, 1986; Ericsen, Hingorani & Khersonsy, 2006; Mudrik & Nad, 2008; Mudrik, Liptak & Nad, 2008; Oravcova & Mudrik, 2008; German-Galkin, 2013; Kahle, 2014). Without listing all the advantages and disadvantages of AC and DC power networks, we will note only a few features of the latter. In DC networks, it is easier to:

- solve problems with power distribution between generators;
- solve problems due to the use of different sources working on the same network;
- protect people from electric shock and objects from fires and explosions.

The last of the listed features becomes determining in the ship electric networks of an alternating current with the isolated neutral where it is not supposed disconnection of loading from a network in the presence of a current of leakage on the vessel hull (German-Galkin & Hrynkiewicz, 2017).

General questions research energy characteristics of hybrid generator set with vector control

A squirrel-cage asynchronous machine is a nonlinear control object that requires sequential structural and parametric synthesis when constructing a DC generator set. The first step of structural synthesis is the selection of the control method of the asynchronous machine. The methods for controlling an asynchronous machine can be divided into two large classes:

1. Scalar control methods.
2. Vector control methods.

Scalar control methods are implemented using regulators that provide non-linear relationships between the voltage (current) and modulating frequency in AR. Scalar methods of asynchronous machine control are used in the construction of open systems, which do not have high requirements for their dynamics. A generalized study of various methods of scalar control in asynchronous systems was carried out in Ref. (Brodovski & Ivanov, 1974).

Vector control methods are implemented by controlling the phase of the voltage or current in a machine. Generalized investigations of vector control methods in asynchronous systems were carried out in Refs. (Kovacs & Raz, 1963; Slezhanovskij et al., 1983; Kazmierkowski, Blaabjerg & Krishnan, 2002; Orlowska-Kowalska, 2003; Mendes & Cardoso, 2006; Sokolowski, 2006; Sobanski & Orlowska-Kowalska, 2014).

The basis of the analytical methods of research, i.e., the considered class of systems, is the theory developed by A. Bulgakov (Bulgakov, 1970). This consists of the fact that the electromagnetic and energy characteristics of a system are determined by the main (basic) component. Pulses of voltage, current, and power in a system due to the switching of power semiconductor elements cause additional small losses. Based on this position, it is possible to describe and analytically investigate the characteristic modes of system operation on the basic component.

The mathematical description of electromagnetic processes is based on the method of spatial vectors (Slezhanovskij et al., 1983; Depenbrock, 1988; Braslawski, Ishmatov & Barac, 2001; Kajstura & Orlowska-Kowalska, 2004; German-Galkin, 2013; German-Galkin, Sakharov & Tarnapowicz, 2019). When describing electromagnetic processes using spatial vectors, it is possible to compose closed (not recurrent) equations for an asynchronous generator and then use these equations to calculate its energy characteristics.

The block diagram of the generator set is shown in Figure 1, which is marked:

- SCAM – squirrel-cage asynchronous machine,
- AR – an active rectifier,
- CSAR – control system on the active rectifier,
- Bat, H – accumulator and load circuit.

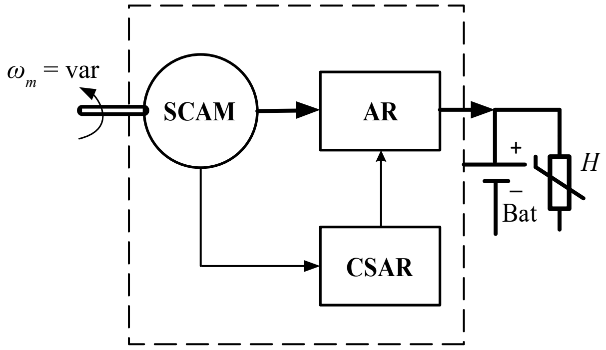


Figure 1. Block diagram of a hybrid asynchronous generator set

The main feature of this system is that power on the load is the power of the asynchronous machine and the battery. If the machine generates more power than the required load, the battery is charged and stores energy; otherwise, the battery is discharged and provides additional power to the load. This property of a hybrid generating set eliminates oscillating processes in the system.

The basis for the construction of vector control methods in asynchronous systems is the structural synthesis method described in Ref. (Boychuk, 1971). Further development of this method was carried out in O.S. Popov's work when used to solve inverse dynamic problems (Popow, 2005).

The main condition for the structural synthesis of asynchronous systems is the choice of the reference (basic) vector (Slezhanovskij et al., 1983). Setting the reference vector determines the relationship between the variables of the asynchronous machine state and the angular frequency (coordinate velocity). In Ref. (Slezhanovskij et al., 1983) six basic structures of asynchronous systems were presented, which were designated according to the selected reference vector as: $\overline{U}_S, \overline{U}_R, \overline{I}_S, \overline{I}_R, \overline{\Psi}_S, \overline{\Psi}_R$.

A moment in asynchronous systems is defined as the product of a pair of resulting spatial vectors. The equations of moment for all combinations of vectors are given in (Slezhanovskij et al., 1983; Sokolowski, 2006). The equations of moment for two combinations of the resulting vectors with the greatest distribution in asynchronous systems are chosen below.

$$
\begin{aligned}
M &= \frac{3}{2} p k_r \left[\bar{\Psi}_R \times \bar{I}_S\right] \\
M &= \frac{3}{2} \frac{p}{L'_S} \left[\bar{\Psi}_R \times \bar{\Psi}_S\right]
\end{aligned}
\tag{1}
$$

The first of these equations corresponds to a system with a field oriented control (FOC) (Kovacs, & Raz, 1963; Blaschke, 1971; German-Galkin, Sakharov & Tarnapowicz, 2019), and the second to a system with direct torque control (DTC) (Depenbrock, 1988; Titinen, Pohjalainen & Lalu, 1995; Nash, 1997; Kajstura & Orlowska-Kowalska, 2004; Ericsen, Hingorani & Khersonsy, 2006; Sokolowski, 2006; Wang, Lu & Prokhorov, 2015; Wolkiewicz, Tarchała & Kowalski, 2015).

Compared with scalar control methods, vector control methods have much better dynamics, which causes a wide spread not only in fast precision systems, but also in powerful power systems of various autonomous objects. For such systems, both dynamic properties and energy properties are essential.

The energy performance of asynchronous systems is evaluated in the steady-state operating modes when setting the torque and speed on the shaft of the asynchronous machine in a closed system.

In this article, a study on the energy characteristics of asynchronous generation systems was implemented for an asynchronous machine power of 15 kW with the following passport data and parameters: $U_{AB} = 400$ V, ($U_{1m} = 310$ V), $f_1 = 50$ Hz, ($\omega_1 = 3141/\mathrm{s}$), $R_S = 0.2147$ Ω, $R_R = 0.2205$ Ω, $L_S = L_R = 0.06518$ H, $L_m = 0.06419$ H, $J = 0.102$ kgm^2, $p = 2$.

Mathematical description and investigation of generator set with field-oriented control (FOC)

The mathematical description of a system in the steady-state operating mode with the basic flux vector of the rotor must meet several conditions:

- The rotor flux $\bar{\Psi}_R$ is set and maintained at a constant value.
- The shaft speed of the squirrel-cage asynchronous machine is set.
- The orientation of the rotating coordinate system ensures that the projections of the flux vector of the rotor are equal: $\Psi_{Ry} = 0$, $\bar{\Psi}_R = \Psi_{Rx} = \mathrm{const}$.

If these conditions are met, the mathematical description of electromagnetic and electromechanical processes in the system in the steady-state operating can be represented by the following equations (Slezhanovskij et al., 1983):

$$
\begin{aligned}
U_{Sx} &= R_S I_{Sx} - \omega_k L'_S I_{Sy} \\
U_{Sy} &= R_S I_{Sy} + \omega_k L'_S I_{Sx} + k_R p \omega_m \Psi_{Rx} \\
I_{Sx} &= \frac{1}{L_R k_R} \Psi_{Rx} \\
\omega_k &= \frac{k_R R_R I_{Sy}}{\Psi_{Rx}} + p\omega_m \\
T_e &= 1.5 p k_R \Psi_{Rx} I_{Sy}
\end{aligned}
\tag{2}
$$

In the system of equations (2),

$$
r = \left(R_S + k_R^2 R_R\right),\ L'_S = \left(L_S - \frac{L_m^2}{L_R}\right),\ k_R = \frac{L_m}{L_R},
$$

are SCAM parameters; U_{Sx}, U_{Sy}, I_{Sx}, I_{Sy}, Ψ_{Rx}, ω_m are the SCAM voltage, current, rotor flux, and rotor angular speed, respectively; T_e is the electromagnetic moment; J is the total moment of inertia of the motor and the reduced working mechanism; p is the number of motor pole pairs. The implementation of the selected control law requires compliance with the condition that the angular velocity of the coordinate system is determined from the fourth equation of system (2) as a function of machine state variables.

The algorithm for calculating the energy characteristics of a generating set with FOC contains the following sequence:

1. Set the rotor flux corresponding to the nominal voltage and frequency.
2. Set the range of change in torque and speed of the machine, and from the equations in system (2), find I_{Sy} and ω_k.
3. After determining the voltages from the first and second equations of system (2), the active (P_S) and reactive (Q_S) power of the generator is calculated:

$$
\begin{aligned}
P_S &= 1.5\left(U_{Sx} I_{Sx} + U_{Sy} I_{Sy}\right) \\
Q_S &= -1.5\left(U_{Sx} I_{Sy} - U_{Sy} I_{Sx}\right)
\end{aligned}
\tag{3}
$$

The energy characteristics of an asynchronous generator set with FOC, calculated by equations (2), (3) are presented in Figure 2.

The projections of the surface on the basic plane represent the dependency between speed and torque on the output of the generator set at constant power. These projections can be used to determine restrictions on the variation ranges of speed and torque on the output of the generator set.

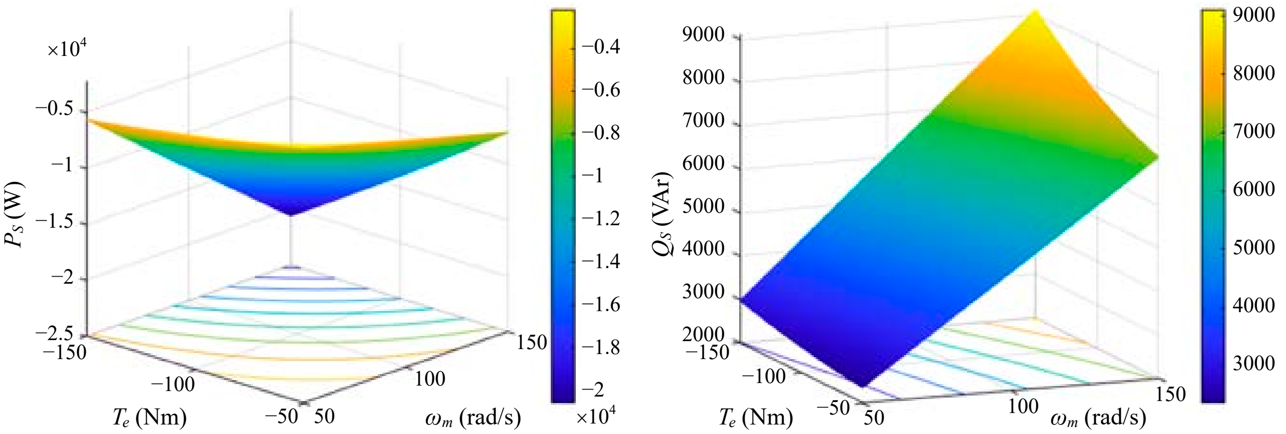


Figure 2. Active and reactive power of a generator set with FOC

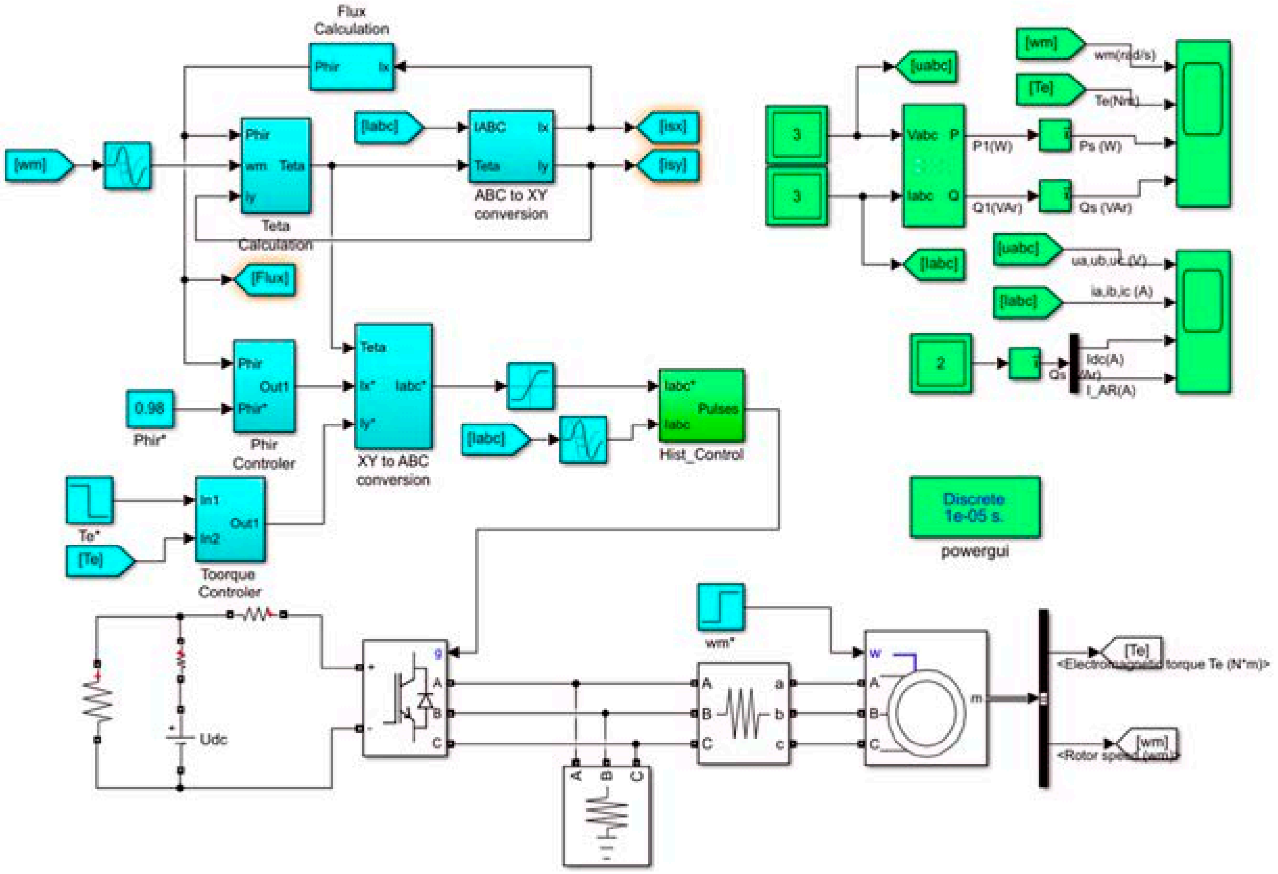


Figure 3. Model of a generator set with FOC

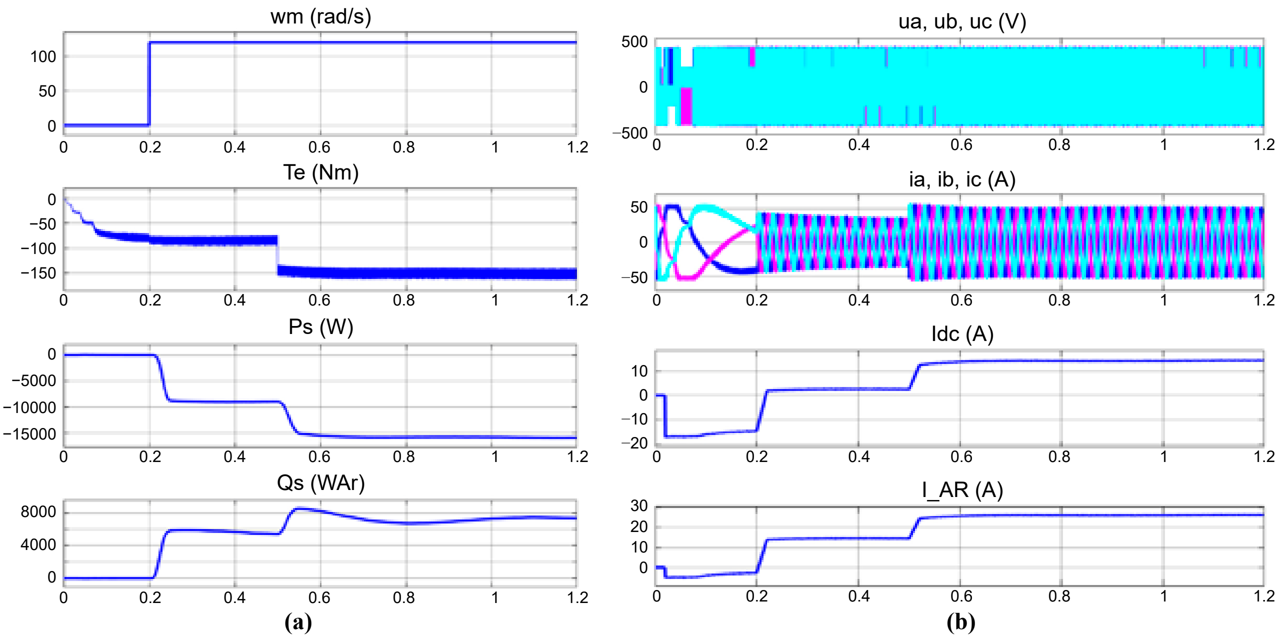
The active and reactive electric power have a non-linear dependency on the speed and torque output.

The energy characteristics of a system with FOC show that the range of permissible speeds and moments of the generator decrease with increasing power output from the generator.

The reactive power pulsating in this system is approximately half the active power.

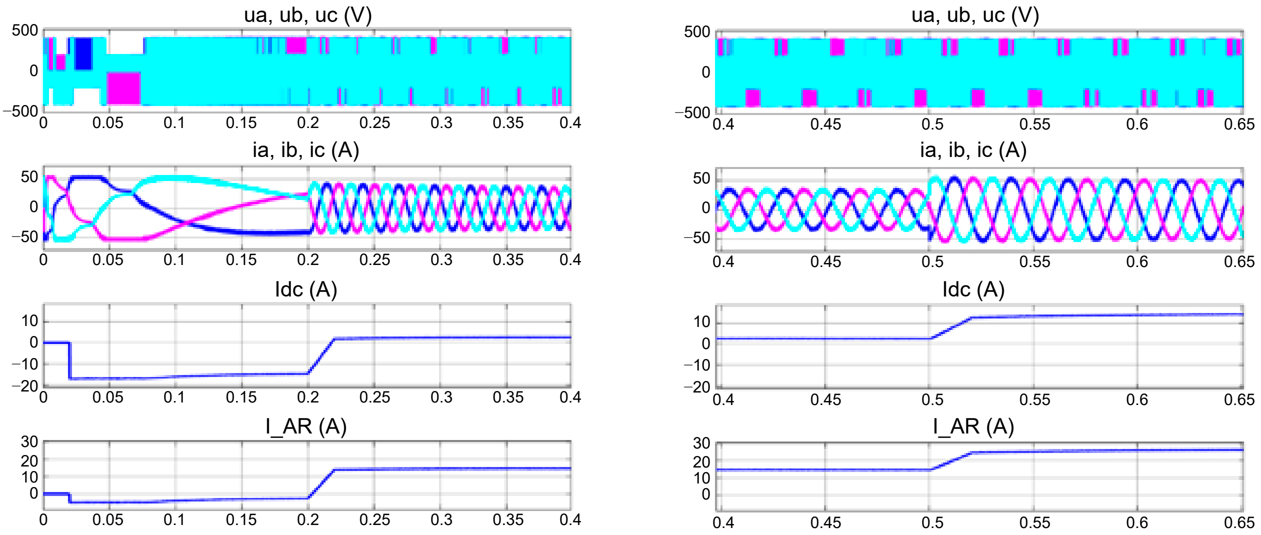
The results of the theoretical calculations were tested on a simulation model that was developed in the MATLAB-Simulink package with environment Simscape Power System. This model is shown in Figure 3.

Figure 4 shows the energy (Figure 4a) and electromagnetic (Figure 4b) processes in the steady-state and transient modes of the system obtained for the model. Figure 5 shows the electromagnetic processes when the speed (t = 0.2 s) and the moment (t = 0.5 s) are changed.



(a) (b)

Figure 4. Energy (a) and electromagnetic (b) processes in a FOC system



(a) (b)

Figure 5. Electromagnetic processes in the FOC system when the speed (a) and torque (b) are changed

Mathematical description and investigation of asynchronous generator set with direct torque control (DTC)

The first samples of asynchronous systems with DTC were tested in the late 1980's in Germany on diesel-electric locomotives as traction devices. In 1995 in Finland, ABB developed the first direct-controlled ACS600 series electric drive (Depenbrock, 1988; Titinen, Pohjalainen & Lalu, 1995; Nash, 1997; Kajstura & Orlowska-Kowalska, 2004; Ericsen, Hingorani & Khersonsy, 2006; Sokolowski, 2006; Wang, Lu & Prokhorov, 2015; Wolkiewicz, Tarchała & Kowalski, 2015).

Torque in a DTC system is defined as the vector product of the rotor and stator fluxes.

$$T_e = \frac{3}{2} p \frac{1}{L'_S} \overline{\Psi}_R \times \overline{\Psi}_S = \frac{3}{2} p \frac{1}{L'_S} \Psi_R \Psi_S \sin\theta = \\ = \frac{3}{2} p \frac{1}{L'_S} \Psi_R \Psi_{Sy} \qquad (4)$$

This means that the increment sign of the moment can be positive or negative depending on the sign of the increment Ψ_{Sy}.

The control system in the rotating coordinate system was dual-channel.

Channel "x" is supported by a permanent module of the stator flux $\left|\overline{\Psi}_1\right| = \text{const}$.

Torque control is carried out in channel "y".

Inverter control is carried out in accordance with the table of optimum switching (Sokolowski, 2006).This table is recorded in microprocessor which is controlled by depending on the sign $\Delta\overline{\Psi}_S$ and ΔT_e.

All the above enables to begin to develop the mathematical description direct torque control system.

1. Direct torque control should be carried out with vector modulation in the inverter. This allows the output voltage of the inverter to be replaced by the first harmonic.
2. The electromagnetic processes are described by state variables $\overline{\Psi}_S$ and $\overline{\Psi}_R$.
3. The base vector in DTC is set of rotor magnetic vectors $\overline{\Psi}_R = \Psi_{Rx} = \Psi_R$.
4. The electric control system has a dual-channel structure in the rotating coordinate system. Channel "x" is supported by a permanent module of stator magnetic flux. Channel "y" is used to control the torque.
5. The conversion of control signals into inverter switching signals is performed using a table of optimum switching.

Then, the mathematical description of the system becomes:

$$\begin{aligned} U_{Sx} &= \frac{1}{T_S'}\Psi_{Sx} - \frac{k_R}{T_S'}\Psi_R - \omega_k \Psi_{Sy} \\ U_{Sy} &= \frac{1}{T_S'}\Psi_{Sy} + \omega_k \Psi_{Sx} \\ \Psi_{Sx} &= \frac{1}{k_S}\Psi_R \end{aligned} \tag{5}$$

$$\begin{aligned} \omega_k &= p\omega_m + \frac{k_S}{T_R'}\frac{\Psi_{Sy}}{\Psi_R} \\ I_{Sx} &= \frac{\Psi_{Sx} - \Psi_R}{L_S'} \\ I_{Sy} &= \frac{\Psi_{Sy}}{L_S'} \\ T_e &= \frac{3}{2}p\frac{k_R}{L_S'}\Psi_R \Psi_{Sy} \end{aligned} \tag{5}$$

In the system of equations (5):

$$T_S' = \frac{L_S'}{R_S},\ k_S = \frac{L_m}{L_S},\ L_R' = L_R - \frac{L_m^2}{L_R},\ T_R' = \frac{L_R'}{R_R}$$

are the SCAM parameters.

The energy characteristics of the system calculated by the equation system (5) are presented in Figure 6.

A comparison of the obtained characteristics with similar systems with FOC (Figure 2) shows that the DTC system consumed slightly less reactive power, which decreased the total current and losses due to active resistance in the machine and the semiconductor converter.

The results of the theoretical calculations were tested using the simulation model shown in Figure 7.

Figure 8 shows the energy (Figure 8a) and electromagnetic (Figure 8b) processes in the steady-state and transient modes of the system, obtained by simulations in the Sim Power System package.

Figure 9 demonstrates the electromagnetic processes when the speed (t = 0.2 s) and the moment (t = 0.5 s) were changed.

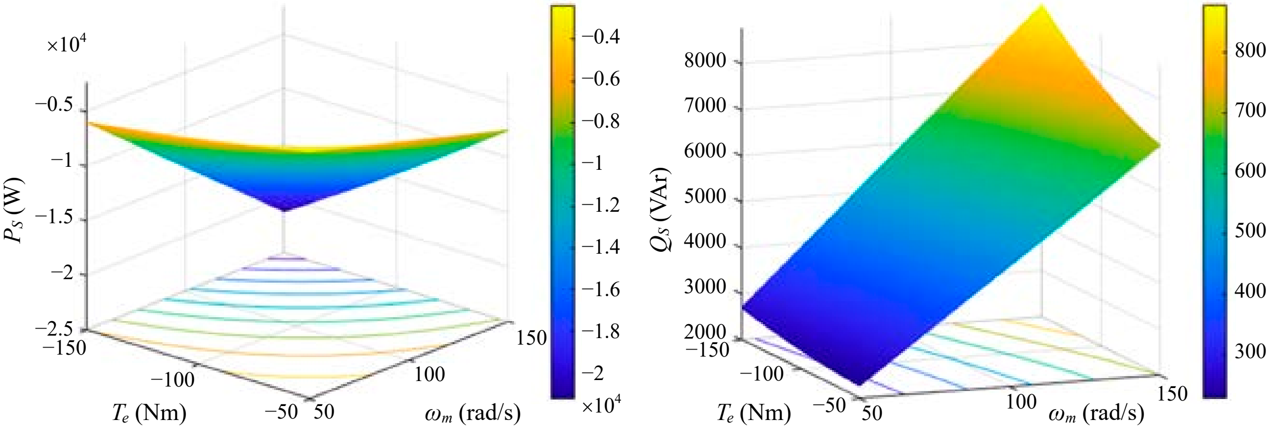


Figure 6. Active and reactive power of a generator set with DTC

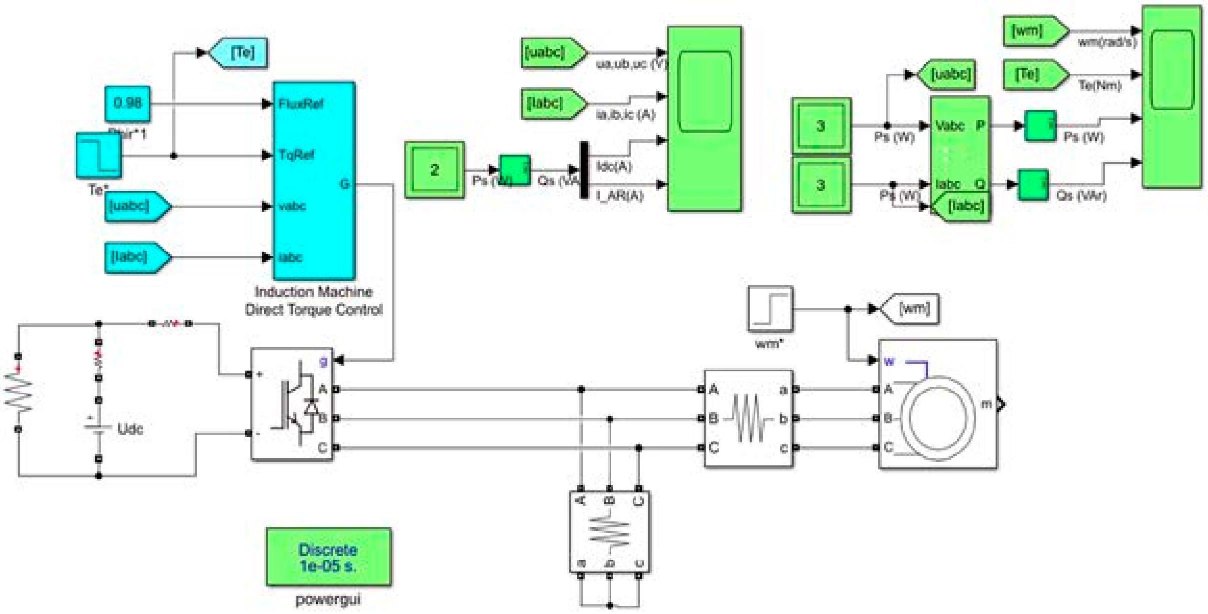


Figure 7. Model of a generator set with DTC

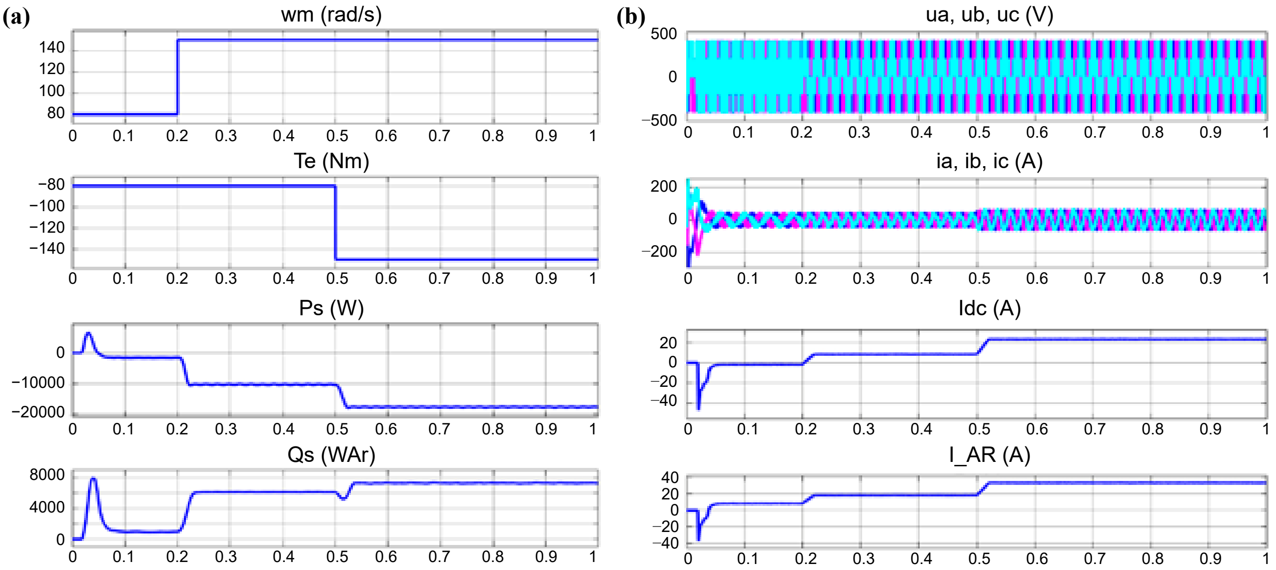


Figure 8. Energy processes (a) and electromagnetic processes (b) in a DTC system

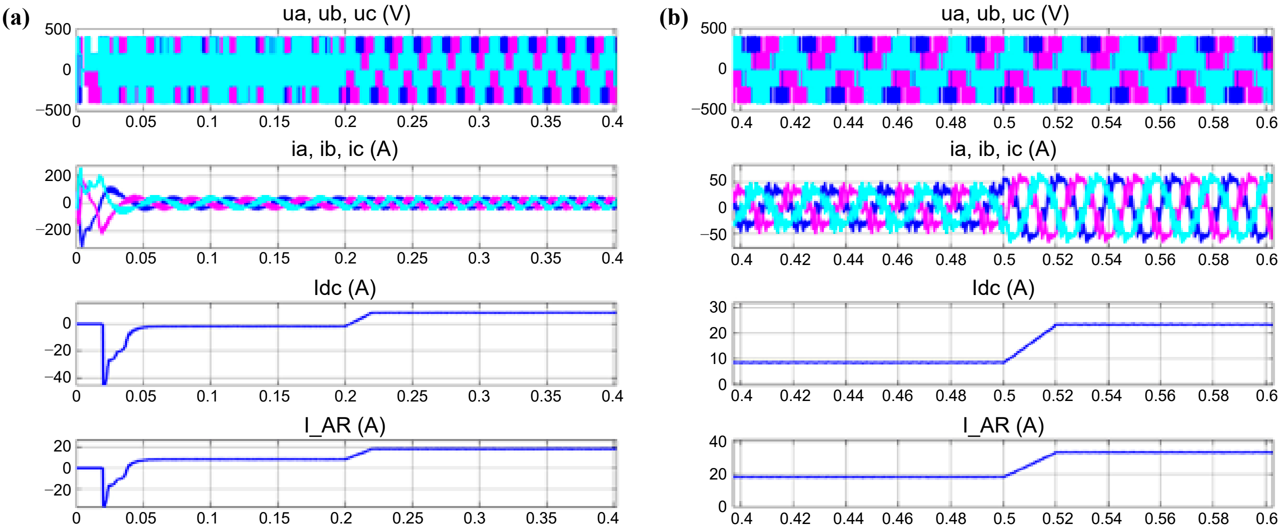


Figure 9. Electromagnetic processes in a DTC system when the speed (a) and torque (b) are changed

Conclusions

The results of analysis, calculation, and modeling of generator sets with an asynchronous squirrel-cage machine was used to determine the range of speed and torque changes on the machine shaft to obtain the required electrical power. These results were obtained for two vector control laws of a machine:

1. With field oriented control (FOC).
2. With direct torque control (DTC).

A comparison of the energy characteristics of the systems showed that in the system with DTC, the reactive power was less than in the system with FOC. Less consumed reactive power reduced the total current and losses due to active resistance of the machine and the semiconductor converter.

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