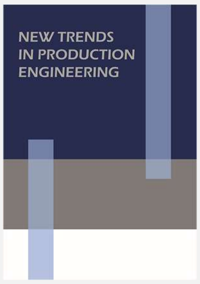
MECHATRONIC SYSTEM WITH THE CONTROL OF VOLTAGE IN PERMANENT MAGNET SYNCHRONOUS GENERATOR



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Abstract. In recent years, the use of Permanent Magnet Synchronous Generator (PMSG) in ship power plant system has increased. PMSGs are characterized by better properties than the classic and commonly used synchronous generators. In comparison with classic synchronous generators, PMSGs do not have a voltage regulator, and hence as the load increases, the voltage at the output of the generator decreases. The article presents the use of an active voltage inverter with the task to maintain a constant voltage on the receiver along with the load's increase. Simulation studies confirming the effectiveness of the proposed method were carried out.

Keywords: PMSG, voltage regulation of PMSG, active inverter

INTRODUCTION

Magnetoelectric generators, in which the rotor is a magnet with rare earth elements (NdFeB, SmCo) (according to terminology – Permanent Magnet Synchronous Generator – PMSG) replace machines with electromagnetic excitation in the power range from a few watts to several dozen megawatts. This is mainly due to the high reliability of these machines, good energy performance, reduced masses and dimensions (Binns and Kurdali, 1979, Chan and Lai, 2007, Chan et all, 2004, Miller, 1989, Gieras and Wing,1997). In recent years, mechatronic systems with PMSG have been widely used in generating sets of autonomous and non-autonomous objects, such as: hybrid vehicles, wind generators, generators airplanes and sea vessels.

The article discusses the mechatronic system of Diesel generator set (D-G), in which the generator is PMSG. In a commonly used generating set with a classic electromagnetic synchronous generator (Matuszak et all, 2015, Nicewicz et all., 2014), the active electrical power at the output is maintained by the diesel speed controller and the reactive power at the output is maintained by the generator's excitation voltage regulator (Smierzchalski, 2004). When using PMSG as an electrical generator, it is not possible to adjust the excitation voltage, which results in a decrease of the output voltage when the load increases (Gawron, 2007). The idea of compensation for voltage reduction at the PMSG output (proposed in the article) is based on the generation of negative (capacitive) reactive power in the generator's rotor. This power is provided by the autonomous inverter that is connected in parallel to the generator and the load.

Block diagram of the mechatronic system with PMSG is presented in Figure 1.

The mechatronic system includes:

- Combustion engine (DE) with speed regulator (SC),
- Synchronous generator (PMSG),
- Autonomous Inverter (AI) with control system,
- Ship's electrical network (220/380 V, 50 Hz),
- Variable load.

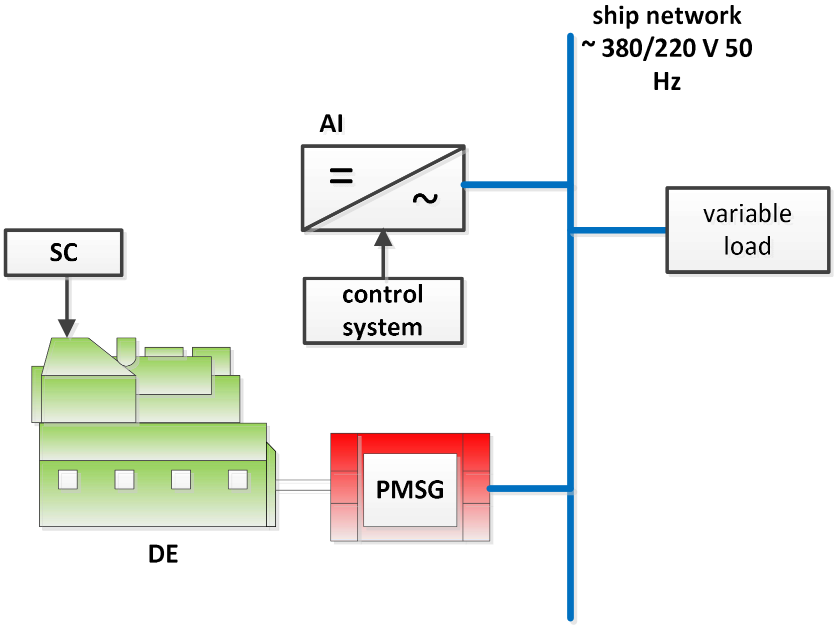

Fig. 1. Mechatronic system with PMSG.

The task of the autonomous inverter (AI) is to maintain a constant voltage in the electrical network when the load changes.

METHODOLOGY OF RESEARCH

When creating the AI control algorithm, enabling the operation of PMSG with changing load, the inverter is controlled in a system with negative feedback (Bulgakov, 1970, Kovacs and Rac, 1959).

Electromagnetic processes in the system can be examined on the basis of the equivalent scheme presented in Figure 2.

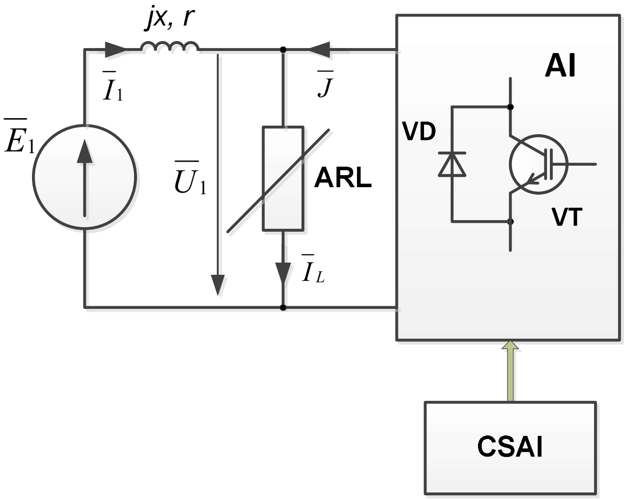

Fig. 2. Equivalent scheme of the mechatronic system with PMSG.

The equivalent scheme (Fig. 2) includes an autonomous inverter (AI), which is a controlled current source, connected in parallel to variable load ARL and winding of the synchronous generator’s armature, the equivalent scheme of which is a serial connection of electromotive force (*E1*) and impedance (*x, r*).

The mathematical description in the coordinate system rotating synchronously with the PMSG shaft can be presented in the following form:

$$\begin{aligned} &\overline{E}_1(t) = \overline{U}_1(t) + L\frac{d\overline{I}_1(t)}{dt} + r\overline{I}_1(t) + jx\overline{I}_1(t), \\ &\overline{I}_L(t) = \overline{I}_1(t) + \overline{J}(t) \end{aligned} \tag{1}$$

where:

$\overline{E}_1(t)$ - spatial vector of electromotive force for the PMSG stator

$\overline{U}_1(t)$ - spatial vector of voltage on the ARL load

$\overline{I}_1(t)$ - spatial vector of the stator current

$\overline{J}(t)$ - spatial vector of the first harmonic of the generated current

$\overline{I}_L(t)$ - spatial vector of the ARL load current

$x = \omega \cdot L,$ - reactance of the stator of PMSG generator

Changes in the values of currents, voltages and EFM may be observed during transitional process.

In the steady state, when (Wierzejski, 1972) $r << x$ the system of equations (1) transforms into the form:

$$\begin{aligned} &\overline{E}_1 = \overline{U}_1 + jx \cdot \overline{I}_1, \\ &\overline{I}_L = \overline{I}_1 + \overline{J} \end{aligned} \tag{2}$$

The use of a controlled source of current (regulation of amplitude and current phase) enables to maintain unchanging voltage in the electrical network when changing the load through the use of the reactive capacitive current generated by AI.

Figure 3 presents a vector analysis based on equations (2).

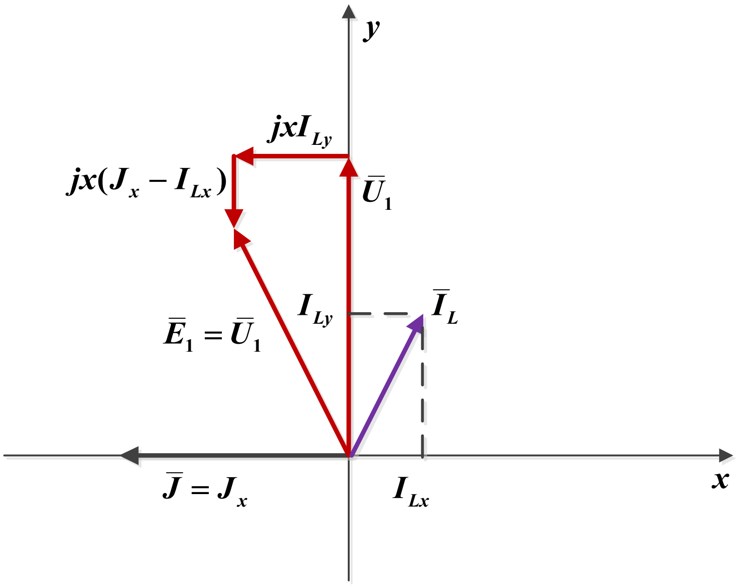

Fig. 3. Vector graph of currents and voltages of the mechatronic system with PMSG.

When constructing a vector chart, the fact that the vector $\overline{E}_1$ remains constant and even $\overline{E}_1 = \overline{U}_1$ after the load change is taken into account.

CALCULATION AND MODELING

Further analysis of the mechatronic system with PMSG is carried out with the use of the vector diagram of currents and voltages (Figure 3) on the basis of equations (2). Relations of the geometric vectors are show that:

$$\begin{aligned} E_{1x} &= x \cdot I_{Ly}, \\ E_{1y} &= U_1 - x \cdot (J_x - I_{Lx}), \\ U_1 &= \sqrt{(xI_{Ly})^2 + \left[U_1 - x\left(J_x - I_{Lx}\right)\right]^2} \end{aligned} \tag{3}$$

On the basis of equations (3), it is possible to determine the inverter's current, which ensures voltage stability when the load changes:

$$J_x = I_{Lx} + \frac{U_1}{x} - \sqrt{\left(\frac{U_1}{x}\right)^2 - I_{Ly}^2} \tag{4}$$

Load currents in relation to active and reactive power can be presented by equations (5):

$$I_{Lx} = \frac{Q_L}{1.5U_1}, \quad I_{Ly} = \frac{P_L}{1.5U_1} \tag{5}$$

Equations (4) and (5) enable to determine the inverter current depending on the active and reactive power of the load. These calculation results in three-dimensional space are shown in Figure 4.

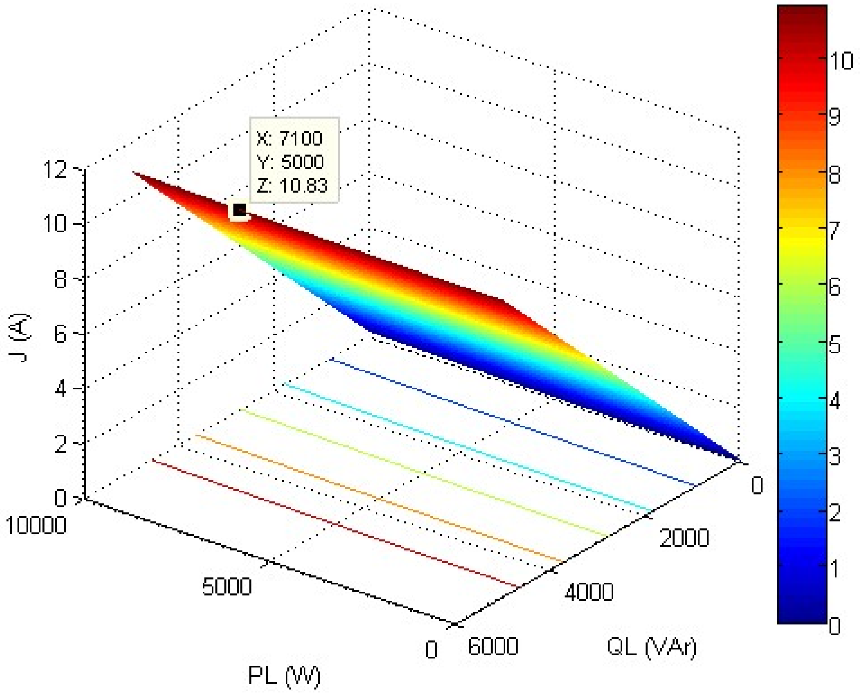

Fig. 4. The relations of the inverter current *J* on the active (*PL*) and reactive (*QL*) power of the load.

3D graphics presented in Figure 4, showing the dependence of inverter current *J* on active (*PL*) and reactive (*QL*) power, indicates that the required current of the inverter *J* does not depend on active power (*PL*) in the load, but is determined only by reactive power (*QL*).

On the basis of the performer analysis, was design the simulation model of the system shown in Figure 5, in which the inverter control signal is calculated according to formula (5), was constructed.

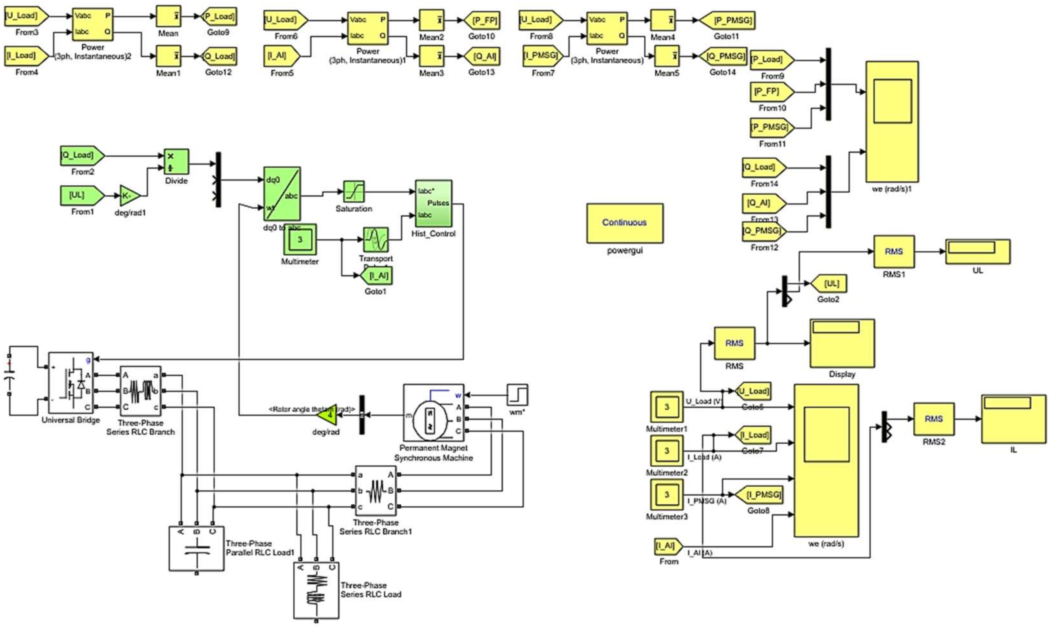

Fig. 5. Model of the mechatronic system with PMSM.

RESULTS

Figure 6 shows the current and voltage waveforms obtained in simulation studies of the system with PMSG (Figure 5) during the stabilization of the U_L receiver's voltage.

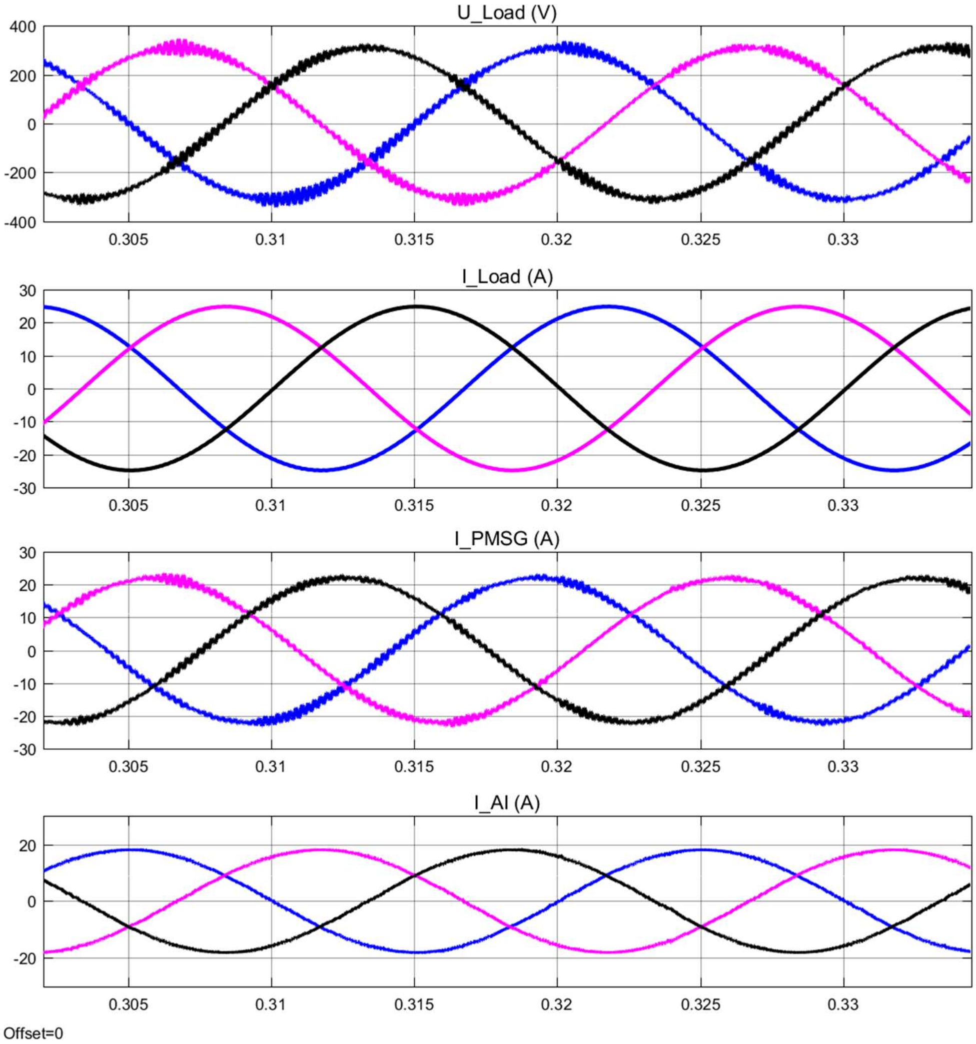

Fig. 6. Electromagnetic processes in a PMSG mechatronic system with U_L regulation.

The inverter current is ahead of the voltage on the load by 90° – it means that the inverter does not need an energy source in the power supply circuit. In the simulation model, the capacitor is switched on in the supply circuit (Figure 5).

Figure 7 presents dependences of active and reactive power in steady state in the mechatronic system with PMSG at drop compensation of the UL receiver's voltage. Curves (Figure 7) show that reactive power of the inverter must exceed the reactive power of the load for the stabilization of the receiver's voltage. This is also visible in the vector graph (Figure 3).

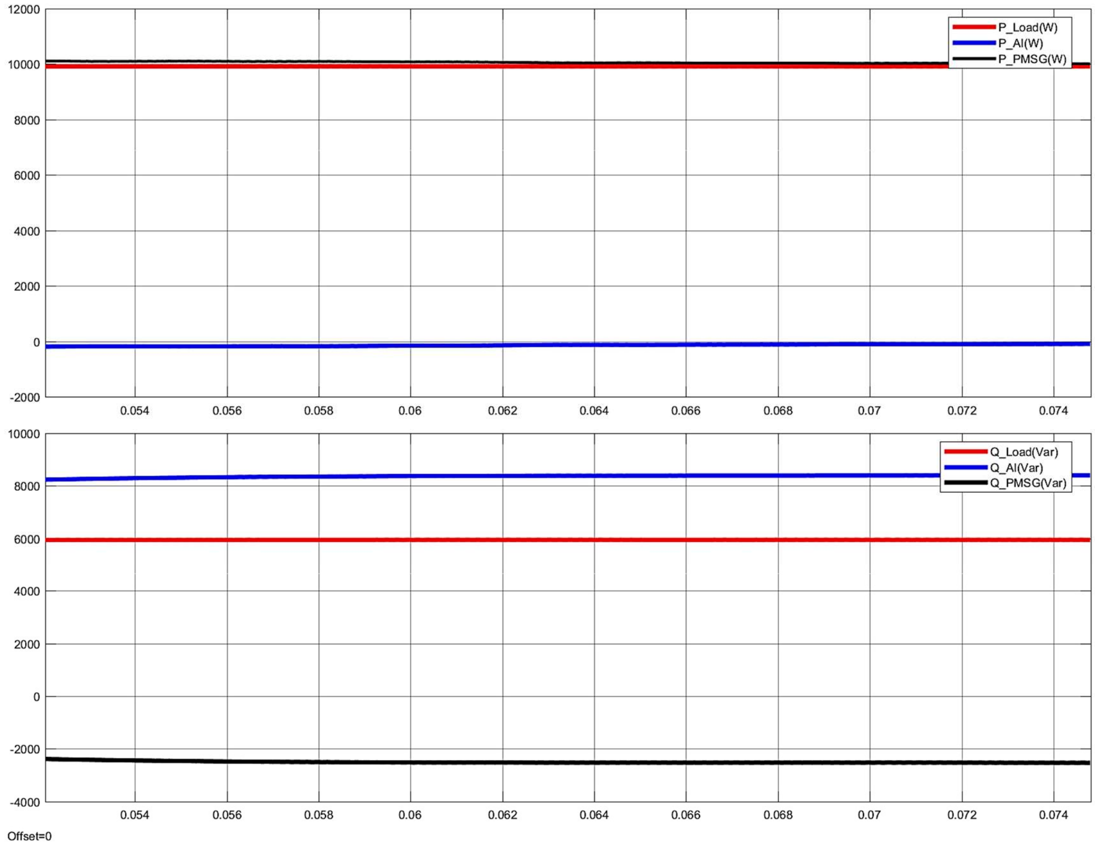

Fig. 7. Energy processes in a PMSG system with U_L regulation.

Figure 8 shows a comparison of voltage changes at the UL receiver depending on the load current with the control system – with AI and without AI.

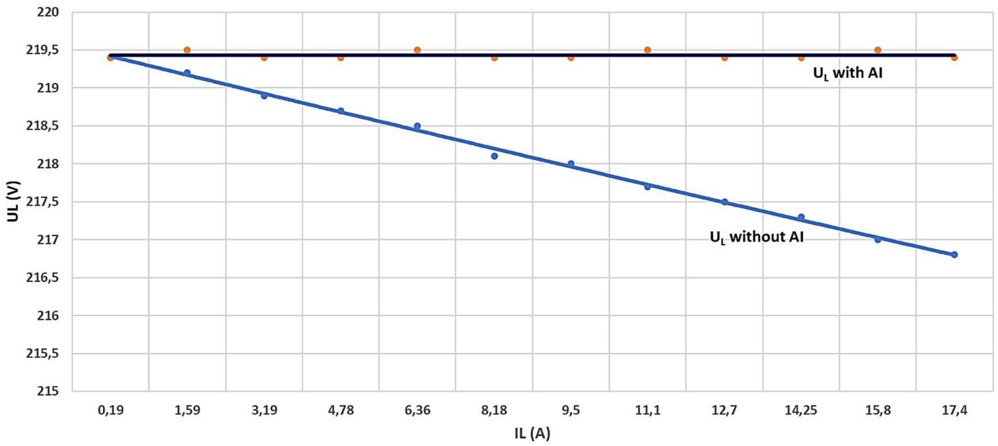

Fig. 8. Comparison of voltage changes on the U_L receiver in the function of I_L load current – with and without an active AI inverter.

DISCUSSION

The results of examination presented in Figures 6 and 7 confirmed the theoretical assumptions. The AL active inverter is a source generating only negative reactive power (this is synonymous with the active capacitive filter). The results of the simulation test of the system presented in Figure 8 show that the connection of the active inverter in parallel load maintains a constant U_L voltage with the increase of load on the receiver.

CONCLUSION

The idea of maintaining a constant voltage PMSG proposed by the authors in the article is based on the properties of a synchronous electrical machine. In this machine, the armature's impact at a resistive-inductive load causes the decrease of voltage along with the increase of current in the load. At capacitive load, the impact of the armature causes the increase of voltage along with the increase of current in the load. During the occurrence of both discussed phenomena, the summarization of streams in field magnet and armature takes place and the voltage drop compensation is observed. The idea was implemented with the use of an active inverter ("active capacity filter").

ACKNOWLEDGEMENTS

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