Variable Frequency Generation System for Aircraft

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***Abstract*—Today a well-known concept of the use of a synchronous generator with permanent magnet excitation in the power generating system with variable frequency is based on the implementation of voltage control due to the high reactance of the generator. However, this approach eliminates the very important features for generating system, in terms of dynamic performance and methods to selectively load emergency shutdown. For reliable triggering the circuit breakers it is required a sufficiently large value of the current about in 2-3 times greater than the nominal value. This paper describes a method of calculating the parameters of the generator in the power supply system with variable frequency which takes into account real parameters of the system required. The analysis of the energy characteristics of the system in a wide speed range of the generator shaft is presented. Some results of the physical experiments are included to confirm the basic principles of operation of such system.**

I. Introduction

In recent years, the increase of electric power generating sets on the aircraft board was accompanied by a qualitative modification of lowering the requirements for frequency stability of the AC power systems [1]. This fact has contributed to the emergence of new technical solutions in power systems [2] and increased interest in AC power generation systems with variable frequency. Effectiveness of systems with variable speed of the generator shaft is confirmed by many studies [3] and implemented wind farm projects [4]. Exclusion of mechanical stabilizing of the generator shaft speed in general leads to an increase in terms of energy efficiency in common case to 15-20%. For the aircraft, this increase is even more relevant because it provides a significant reduction in the cost of air transportation.

II. Problem Defenition

Synchronous generator (PMSG) with permanent magnet excitation can be considered as an alternative to the widely used three-stage generator for AC power systems with variable frequency. PMSG provides significant advantages in weight, size and reliability, combined with the simplicity of design [5]. Specific gravity of a generator with permanent magnet excitation can reach enormously low values. According to available sources, the specific gravity of the PMSG can be 0.3-0.1 kg/kW [6]. The application of this type generator as a power system with variable frequency at first glance is not advisable, due to the concepts of design are directed to implement tough outer characteristics of the generator with a short-circuit currents in 5-7 times higher than the nominal value. Voltage regulation in this case is only possible due to stabilization of the shaft speed. However, recent developments in the design of the rotor for permanent magnet mounting methods expressed in particular stator circuit parameters, namely increasing its own reactance coil several times with approximately an unchanged leakage inductance. As a result, short-circuit currents decreased to 3-4 times of nominal values, and those values are quite acceptable for aircraft power systems. And from the point of view of building a system of variable frequency power supply, there is the possibility of regulating the output voltage due to armature reaction by injecting reactive power to stator windings.

Before we proceed to a detailed analysis it is necessary to review the current date concept that considers a design PMSG with very high reactance that limit short-circuit currents at the nominal value. This approach generally reduces the level of reactive power used to regulate the voltage at the terminals of the generator [7]. But because of the high reactance it is eliminated important properties of the system, in terms of dynamic performance and most importantly, there aren't the possible mechanisms for the implementation of selective load emergency shutdown in the case of the short-circuit in the load.

III. Structure of The System

The structure of the variable frequency generating system (Fig. 1) consisting of a reactive power regulator circuit in the stator of the synchronous generator activated by semiconductor converter can be presented by various types of converters. Differences in structural variants are based on the choice of the generator parameters providing rated load voltage at a certain shaft speed taken as the nominal value (ω_{nom}) with minimal or no influence of the converter. Deviation of the frequency of the generated voltage assumes

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normal operation of the system, if the deviation is placed in a well-defined range in which it is implemented the corresponding drift compensation by reactive current generated by the converter. So, by the known properties of the synchronous generator at work on various types of load (inductive, capacitive), it is provided the possibility of varying the parameters of the generator and the converter when selecting rated speed permitted range.

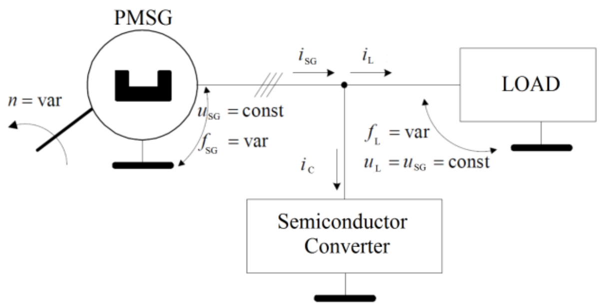


Figure 1. Typical structure of the system.

In general, this type of power system structure, namely in the converter is required to implement a sinusoidal current source [8]. There are many different structural topologies of a static compensator that provide the given current form. One of the most common and at the same time functional solutions may be a voltage source inverter (VSI) operating in active filter mode. Due to the flexible control system of such converter, it is possible to adjust the level of reactive power synchronous generator, and thus the level of the load voltage. Block diagram of such system is shown in (Fig. 2). Analysis of this system is the main goal which the author investigates in this paper.

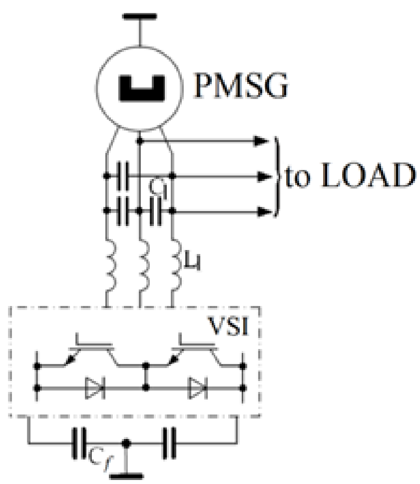


Figure 2. Structure of the variable frequency generation system based on VSI.

IV. THE ANALYSIS OF ELECTROMAGNETIC PROCESSES

To analyze the energy performance and identify modes of PMSG and VSI depending on the generator parameters by the mathematical description in the generation system can be neglected asymmetrical modes and switching processes due to a number of assumptions [9]:

- Switching frequency of the fully controlled semiconductor devices is much more greater than the frequency of the generated voltage;
- Semiconductor components are ideal without the active losses in static and dynamic modes of operation;
- Moment of inertia of the primary motor is large enough and the relative velocity changes its speed is limited and small.

In this case the analysis of modes in the synchronous generators is traditionally carried out in rotated axes oriented to the rotor. The principle of operation generally illustrated by the vector diagram (Fig. 3). This figure describes the operation of the system with a lagging load current angle (φ) between load current (I_L) and load voltage (U_L=U_{SG}). Vector diagram constructed in a rotating coordinate system with frequency ω, under the assumptions of linearity of the magnetic system, the lack of active losses and damping circuits in PMSG. Here Ψ_0, E_0 – permanent magnet flux and EMF; X_d, X_q – inductances of PMSG in the longitudinal and transverse axes, respectively; I_{SG} – stator current consisting of a load current (I_L) and a semiconductor converter current (I_C).

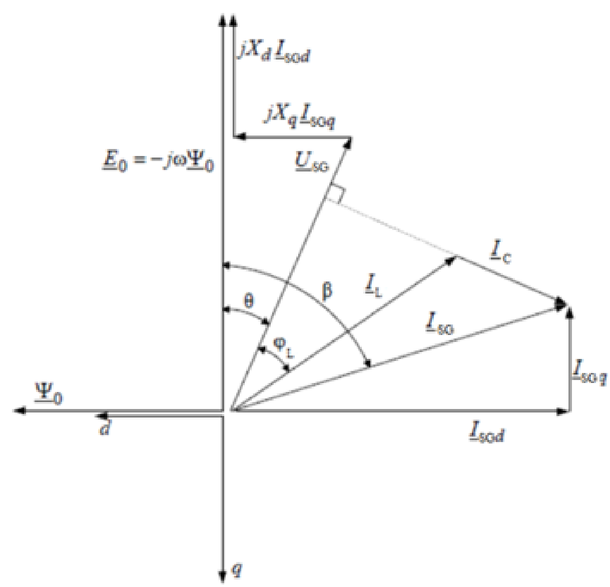


Figure 3. Diagram of electromagnetic processes.

Electromagnetic processes in considered structure of the generation system can be represented by the equivalent circuit (Fig. 4). In this equivalent circuit current sources complexes represent projections of the load current and the converter to the corresponding axis «dq». From the vector diagram is shown above they are follows:

$$\begin{aligned} I_{SGd} &= (I_L \sin(\varphi) \pm I_C)\cos(\theta) + I_L \cos(\varphi)\sin(\theta) \\ I_{SGq} &= -(I_L \sin(\varphi) \pm I_C)\sin(\theta) + I_L \cos(\varphi)\cos(\theta) \end{aligned} \tag{1}$$

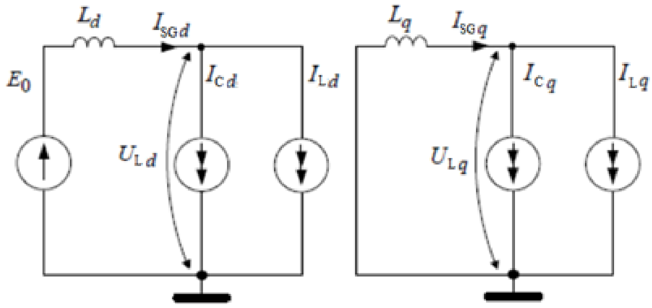


Figure 4. Equivalent scheme.

This equivalent circuit corresponds to a system of equations in rotating axes with the assumptions and takes into account the effect of the asymmetry in the magnetic circuit of the generator`s rotor, i.e. saliency. In this paper the saliency we will intend as ratio of the main generator`s inductances (including leakage inductance) in the longitudinal and transverse axes $k=L_q/L_d$. The system of equations taking into account the expressions (1) describing the stationary processes in system, excluding the active losses in the windings of the generator and the VSI in this case would be as follows:

$$\begin{aligned} U_{\mathrm{L}d} &= -k\cdot X_d(I_{\mathrm{L}}\sin(\varphi)\pm I_{\mathrm{C}})\sin(\theta)+k\cdot X_d\cdot I_{\mathrm{L}}\cos(\varphi)\cos(\theta) \\ U_{\mathrm{L}q} &= E_0 - X_d(I_{\mathrm{L}}\sin(\varphi)\pm I_{\mathrm{C}})\cos(\theta)-X_d\cdot I_{\mathrm{L}}\cos(\varphi)\sin(\theta) \end{aligned} \quad (2)$$

where:

$$\tan(\theta)=\frac{I_{\mathrm{L}}\cos(\varphi)}{\dfrac{U_{\mathrm{L}}}{k\cdot X_d}+I_{\mathrm{L}}\sin(\varphi)\pm I_{\mathrm{C}}}$$

In general, the solution of this system under different criteria, which are a kind of defining constraints on the load side at the appropriate operation of the system, namely, the rotational speed of the generator shaft, allows us to find the optimal requirements for the design parameters of the generator and to identify the main qualitative and quantitative indicators of the energy in the system. The limiting criteria the most part are the power distribution curve of the load in frequency range and the requirements for a value of the short circuit current. For reasons to generalize the results, we introduce the relative units as base units are the rated voltage and nominal value of the load current:

$$U^*_{\mathrm{SG}}=U^*_{\mathrm{L}}=U_{\mathrm{nom}};\quad I^*_{\mathrm{L}}=I_{\mathrm{nom}};\quad I^*_{\mathrm{C}}=\frac{I_{\mathrm{C}}}{I_{\mathrm{nom}}};$$

$$I^*_{\mathrm{Lmax}}=\frac{I_{\mathrm{Lmax}}}{I_{\mathrm{nom}}};\quad S^*_{\mathrm{SG}}=U^*_{\mathrm{SG}}\cdot I^*_{\mathrm{SG}};$$

$$I^*_{\mathrm{SG}}=\sqrt{\left(I^*_{\mathrm{L}}\sin(\varphi)\pm I^*_{\mathrm{C}}\right)^2+\left(I^*_{\mathrm{L}}\cos(\varphi)\right)^2}$$

Based on the fact that the symmetrical short-circuit in the stator windings currents flow only by the longitudinal component ($\underline{I}_{\mathrm{SG}}\approx \underline{I}_d\approx \dfrac{\underline{E}_0}{jX_d}$) we can introduce into the equations system the parameter determining the dependence of the output voltage from the desired coefficient of short-circuit current with respect to the nominal value $I^*_{\mathrm{SC}}=\dfrac{I_{\mathrm{SC}}}{I_{\mathrm{nom}}}$.

Next, we define the notion of changing the frequency range of the generated voltage $D=\omega_{\max}/\omega_{\min}$ and short circuit current $I_{\mathrm{SC}}=\dfrac{D\cdot E_{0\min}}{D\cdot\omega_{\min}\cdot L_d}$ (including the fact that short-circuit current does not depend on the rotational speed of the generator shaft). Translating the system of equations (2) to a p.u. values, we obtain the following system of equations (3), which allows us to identify the main energy indicators of the system at maximum load currents:

$$\begin{aligned} U^*_{\mathrm{L}d} &= k\frac{D\cdot E^*_{0\min}}{I^*_{\mathrm{SC}}}\left(I^*_{\mathrm{Lmax}}\cos(\varphi)\cos(\theta)-(I^*_{\mathrm{Lmax}}\sin(\varphi)\pm I_{\mathrm{C}})\sin(\theta)\right) \\ U^*_{\mathrm{L}q} &= \frac{D\cdot E^*_{0\min}}{I^*_{\mathrm{SC}}}\left(I^*_{\mathrm{SC}}-(I^*_{\mathrm{Lmax}}\sin(\varphi)\pm I_{\mathrm{C}})\cos(\theta)-I^*_{\mathrm{Lmax}}\cos(\varphi)\sin(\theta)\right) \end{aligned} \quad (3)$$

On the basis of previous calculations and vector diagrams, the maximum current of the inverter depends on the choice of EMF E^*_0. Since we are not given a clear choice over the entire range of values E^*_0 lets the basis for calculating be the criteria of equality for maximum values of the current at the edges of the frequency range. Moreover, we assume that at minimum speed there is the maximum load current, and at the maximum frequency there is idle load. To find $E^*_{0\min}$ a system of equations must be solved for the maximum VSI current ($I_{\max}$) with varies values of $E^*_{0\min}$ and the corresponding parameters of the system characterizing modes with maximum currents of VSI, and then introducing the condition of equality of the maximum values of VSI to solve the system with respect to the minimum value of the generator`s EMF. Next, value $E^*_{0\min}$ can be used to find interested energy indicators. Fig. 5 shows the dependence of the minimum value of the generator`s EMF from maximum current load under the minimum speed of the generator at different values of the saliency.

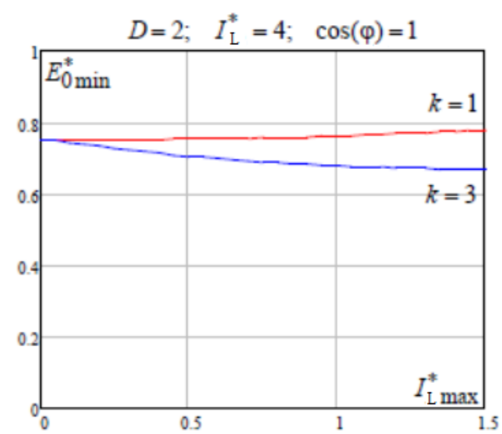
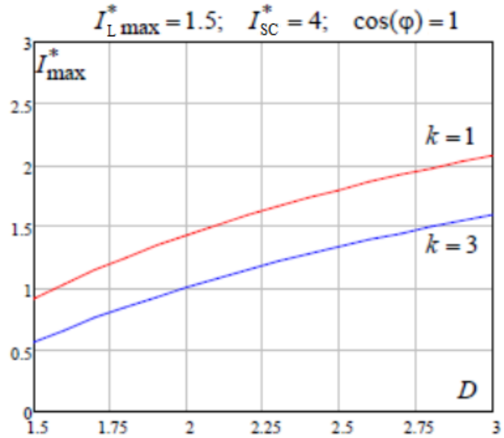
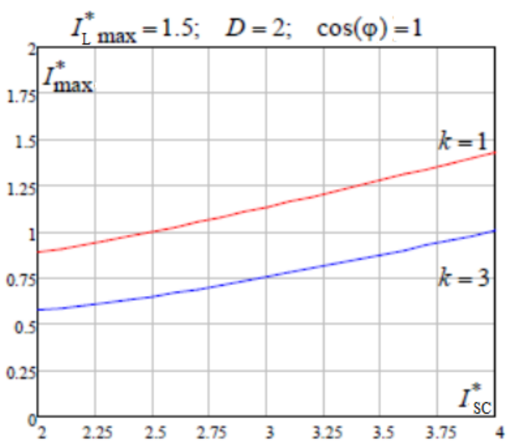


Figure 5. EMF dependence on maximum value of load current

We should also consider the dependence the maximum VSI current value of the maximum load current in the minimum speed mode. Fig. 6 shows characteristics for maximum VSI current of the load current in the minimum speed mode for different values of the power factor and the saliency.



a)



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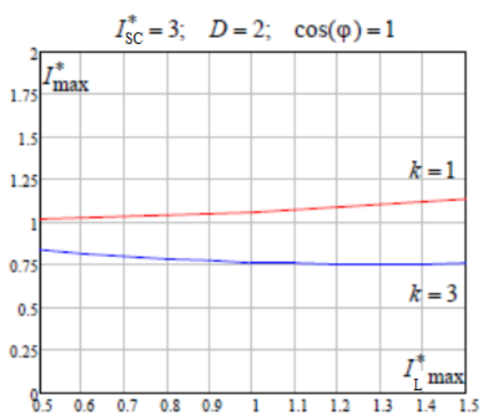
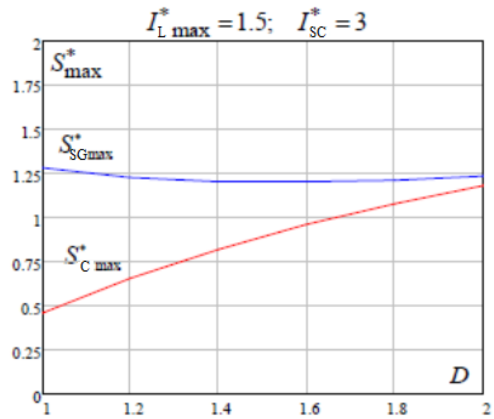


c)



d)

Figure 6. System`s energy characteristics: a – The maximum value of converter current in frequencies range; b - The maximum value of converter current in range of different values of required short-circuit currents; c - The maximum value of converter current in range of different values of load currents; d – apparent power of PMSG and converter in frequencies range.

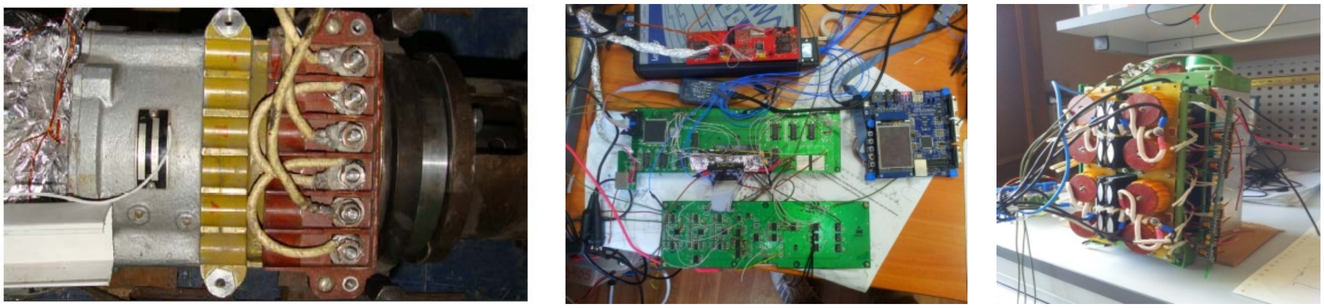
The presented results of calculations show the required levels of PMSG and converter powers which can be assumed for the selected of appropriate parameters of the generating system with variable frequency.

V. Experiment Results

Presented in this paper the mathematical model for the analysis of electromagnetic processes in the generation system based on variable frequency synchronous generator with permanent magnets and semiconductor converter generally gives common results about the energy performance of the system. Correctness of the identified characteristics should be established by physical experiment. Implemented physical layout for this study consists of a synchronous generator with electromagnetic excitation and voltage source inverter. Due to difficulties with the acquisition of expensive synchronous generator with permanent magnet excitation, we have decided to use the generator with electromagnetic excitation. In general, such an approach would only proof the basic principles of the implementation of such a generating system. Fig. 7 shows photographs of the test layout. Four experiments were carried out. Two experiments at 800 Hz and two at 1600 Hz. Excitation current was varied for each frequency to realize deviation in output voltage. The voltage source inverter injected reactive current into the stator circuit of the generator, in such way regulating the load voltage. The results of the experiments are shown in Fig. 8 and in Table I.

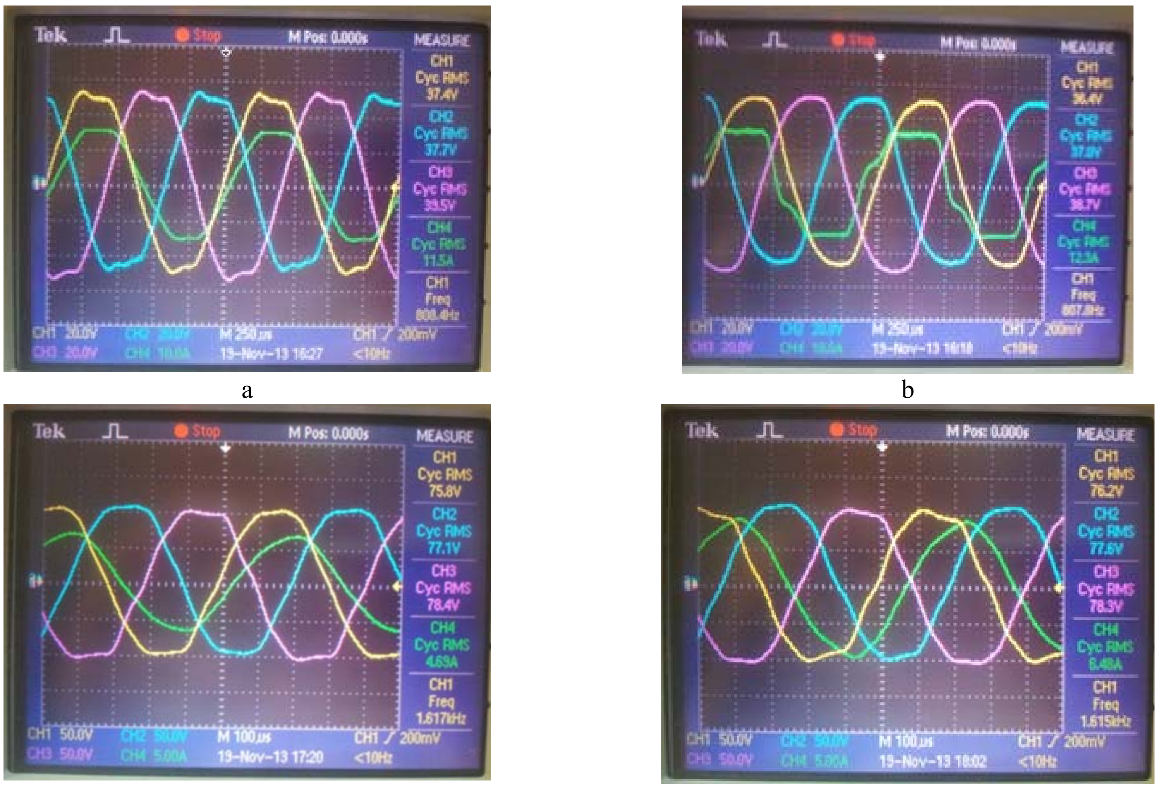
TABLE I. EXPERIMTNE RESULT

	Fig. 8a	*Fig. 8b*	*Fig. 8c*	*Fig. 8d*
Frequency, f (Hz)	800	800	1600	1600
VSI current, I_C (A)	0	5.9	0	5.17
Excitation current of SG (%)	70%	50%	30%	50%
Load voltage, U_L (V)	37.5	37	77	77



a b c

Figure 7. Experimental stand: a – Synchronous generator; b – digital control system; c – voltage source inverter



a b c d

Figure 8. Synchronous generator`s voltage and current diagrams (see table I).

CONCLUSION

In this paper the brief analysis of variable frequency AC power system for aircraft based on permanent magnet synchronous generator and voltage source inverter were presented. The main advantage of such system is that the short circuit current bypass the converter. So, the performance of the converter is increased due to the VSI will conduct low level of the rated currents. In this paper was showed that the saliency of the generator provides lower values of current to be generated by the VSI. The calculation of dependencies shows that low level of short-circuit current as higher level of generator inductances favorably influence on the performance and weight of the system. The results of physical experiments proved some principal ideas.

The main advantage of considered power supply system that it is implemented with application of synchronous generator with permanent magnet excitation with a high energy performance and reliability. In this paper, general approach for calculating the electrical parameters of the generator is presented. Such a method of determining the parameters allows calculating the main inductance and EMF of the PMSG considering the various system requirements. The presented analysis has a synergistic effect. While developing of such systems it is often difficult to find the optimal parameters of the generator and inverter due to the designing of the whole system is made at different stages. The approach allows an objective way to the implementation of a generating system with variable frequency. By the way, the results achieved should be treated as data obtained in the analysis of common case. They do not show outstanding characteristics of the system performance, but do not reduce its merits. In subsequent studies, the authors assume to publish the results of calculation of dynamic characteristics.

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