Mechatronic System “Synchronous Generator-Three-Phase Bridge Rectifier” for Self-Contained Power Facilities

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Abstract—The processes in the system composed of a continuous magnet synchronous generator and a three-phase bridge back emf rectifier are under analysis in this article. Such systems are usable in self-contained facilities to charge accumulation cells in mines and open pits. The authors determine possible regimes of the systems under varying rate speeds of synchronous generator shaft and altered commutation delay angles of the controlled rectifier, derive analytical expressions for determining parameters of the analyzed system, and find generated power limit.

Keywords: synchronous generator, varied rate speed, rectifier, operation regime characteristics

INTRODUCTION
The present day power industry is facing an acute problem of depleting energy feedstock (oil, gas, coal, peat, oil shale, radioactive isotopes). This will largely reduce the wanted heat power and atomic power production. The hydraulic energy production is also restricted by ecological standards. The developed countries plan to increase energy production using renewable energy sources (wind, tidal, solar, geothermal and small hydraulic power stations) to supply autonomous users. Autonomous energy systems are widely used on mobile units (ships, trains, planes) [1]. As for mining industry, the autonomous users may be local chargers for accumulation cells; the chargers are supplied by renewable energy sources, e.g., wind-powered generators, and the accumulation cells are then operated in mines and open pits.

Recently the self-contained electric energy generation facilities widely use synchronous constant magnet dc and ac generators, hereinafter referred to as synchronous magneto generators (SMG).

This article is aimed at analyzing electromagnetic processes in such systems as SMG-rectifier supplying an accumulation cell, i.e. working on back emf under varied shaft rate speed of synchronous generator (SG) in terms of the system with SMG and three-phase bridge rectifier.

The authors, using mathematical model of a synchronous generator and rectifiers, based on common physical notions, determine possible regimes of the system under varied SG shaft rate speed \( n \) and a commutation delay angle \( \alpha \) of the controlled rectifier (CR). Conditions for the regimes are defined mathematically. The involved parameters and \( n \) are calculated depending on rectifying cell conducting state duration \( \lambda \), induced switching angle \( \psi \), currents and flux linkages in SMG and the active power.

1. MATHEMATICAL MODEL OF THE SYSTEM
The mathematical modeling assumes that:
—the generator shaft speed \( n \) is varied), moment of inertia of prime mover is sufficiently high and the speed variation rate is limited and low;
— the SG magnetic system is unsaturated and linear;
— the emf undergoes harmonic variation, with amplitude and frequency in proportion to \( n \);
— the generator is explicit-pole and has damping circuits along the \( X \) and \( Y \) axes;
— the conditions of the theorem on constant flux linkage hold true [2];
— the rectifying cells are ideal.

The used system of relative units includes the following basic values: \( U_b = U_{load} \); \( n_b = n_{min} \)—the minimum rate speed at which the emf amplitude of the SG no-load equals load \( U \);

\[
\omega_b = \omega_{min} = \frac{2\pi p n_{min}}{60}
\]

—the minimal circular SG line frequency; \( X_b = \omega_b [L_f + (L_d'' + L_q'') / 2] \), \( I_b = U_b / X_b \), \( S_b = I_b U_b \)—the basic values of resistances, currents and powers of elements;

\( L_d'', L_q'' \)—the subtransient inductances of the SG starting motor winding along the \( X \) and \( Y \) axes, respectively; \( q = 2L_f / (L_d'' + L_q'') \).

The analyzed system consists of three-phase synchronous magneto generator (SG) and three-phase bridge rectifier semiconductor converter (SC) as shown in Fig. 1. The state of the system is described using the following equations [2, 3]:

\[
\begin{align*}
\begin{bmatrix}
e
\end{bmatrix} - n^* X \begin{bmatrix}
d d
\end{bmatrix} \begin{bmatrix}
i_{SG}^*
\end{bmatrix} = \begin{bmatrix}
u_{SC}^*
\end{bmatrix}, \\
i_{SG}^* + i_{SG}^* + i_{SG}^* = 0, \\
u_{SC1}^* + u_{SC2}^* + u_{SC3}^* = 0, \\
i_{SG}^* = i_{v1}^* - i_{v4}^*, \\
i_{SG}^* = i_{v3}^* - i_{v6}^*, \\
i_{SG}^* = i_{v5}^* - i_{v2}^*
\end{align*}
\]

where \( e = \begin{bmatrix}
e_1^* \\
e_2^* \\
e_3^*
\end{bmatrix}, \begin{bmatrix}
i_{SG}^*
\end{bmatrix} = \begin{bmatrix}
i_{SG}^* \\
i_{SG}^* \\
i_{SG}^*
\end{bmatrix} \)—the vectors of the emf and line currents of SG; \( u_{SC}^* = \begin{bmatrix}
u_{SC1}^* \\
u_{SC2}^* \\
u_{SC3}^*
\end{bmatrix} \)—the vector of input voltage of SC; \( X = \begin{bmatrix}
X_{i1}^* & X_{s}^* & X_{s}^* \\
X_{s}^* & X_{22}^* & X_{s}^* \\
X_{s}^* & X_{s}^* & X_{33}^*
\end{bmatrix} \)—the matrix of inductive resistances of the system;

\[
e_j^* = n^* \sin[\vartheta - \frac{2\pi}{3} (j-1)], \quad j = 1...3; \quad \vartheta = \omega t;
\]

\[
X_{s}^* = -\frac{1}{2(1+q)};
\]

\[
X_{jj}^* = X_j^* + X_f^* = 1; \quad X_j^* = \frac{1}{1+q}; \quad X_f^* = \frac{q}{1+q}.
\]

Here, the voltage in SG and SC is measured relative to zero phases of the generator.