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Otakar KURKA[1], Vladimír ŘEŘUCHA[2], Zdeněk KRUPKA[3], Jan LEUCHTER[4]

THE VSCF TECHNOLOGY IN MOBILE ELECTRICAL GENERATING SETS

Summary. New generation of mobile electrical power generating sets (GS) is based on some new technologies. The VSCF (Variable Speed Constant Frequency) approach enables to control the speed in such a way that the optimum speed corresponds to the required power output in order to decrease the fuel consumption and harmful emissions. The variable voltage and frequency of the synchronous generator with permanent magnets is transformed to required constant values by means of power electronic converters. The paper presents to the formulation of the GS mathematical model and gives some results of the system simulations and measurements effected on the GS physical model.

Key words: electrical power generating sets, new generation, VSCF technology, simulations, results.

1. INTRODUCTION

The contemporary electrical power generating sets (gensets GS) operate with constant speed corresponding to the required fixed frequency (50, 60 or 400 Hz). The investigations of GS operation in last years have shown, that the majority of sets operate under low average load that does not exceed 20 % of the rated permanent load. In these conditions both the engine and generator operate with low efficiency, unfavorably affecting the polution and fuel consumption.

New trends of future development in this field show that the next GS generation will be based on some new technologies. Constant speed sets with combustion engines driving brushless field excited synchronous generators of the 2nd generation GS (GS2G) will be soon replaced by 3rd generation GS (GS3G). GS3G consists of an optimally controlled variable speed diesel engine, driving robust synchronous generator with permanent magnets (SGPM) and power electronics constant frequency and voltage control (VSCF technology). For special purposes, as for example airports, aircraft units and air defense systems, high speed gas turbine engines (50 000 RPM and more) with high speed SGPM and corresponding power electronics are under development.

The theoretical solution, research, design and development of GS3G evokes many problems in the field of mechanical and electrical engineering, power electronics, automatic control and mechatronics.

2. GS GENERATIONS

This paper is devoted mainly to some problems of the third GS generation which has been preceded by two generations worth to be briefly mentioned.

The 1st generation (GS1G) was based on the classical constant speed motor-generator electromechanical principle. The field excited synchronous generator driven by combustion engine was controlled by electromechanical, later transductor or tranzistor regulator.

The 2nd generation (GS2G), gradually modernized, is still in use. The Diesel engine, used even for low power outputs, drives usually brushless field excited synchronous generator or asynchronous generator with constant speed corresponding to the required output frequency. The

[1] Prof. Ing. CSc, Military Academy of Brno, Kounicova 65, 612 00 Brno, the Czech Republic, tel. +420-5-41182323, fax. +420-5-4118 2888, e-mail: Otakar.Kurka@vabo.cz.

[2] Prof. Ing. CSc, Military Academy of Brno, Kounicova 65, 612 00 Brno, the Czech Republic, tel. +420-5-41183562, fax. +420-5-4118 2888, e-mail: reruch@cs.vabo.cz

[3] Doc. Ing. CSc, Military Academy of Brno, Kounicova 65, 612 00 Brno, the Czech Republic, tel. +420-5-41182256, fax. +420-5-4118 2888, e-mail: reruch@cs.vabo.cz

[4] Ing., Military Academy of Brno, Kounicova 65, 612 00 Brno, the Czech Republic, tel. +420-5-41183660, fax. +420-5-4118 2888, e-mail: jan.leuchter@vabo.cz

output voltage is controlled by thyristor or by other electronic field current controller. The block diagram of GS1G and GS2G is shown in Fig. 1.

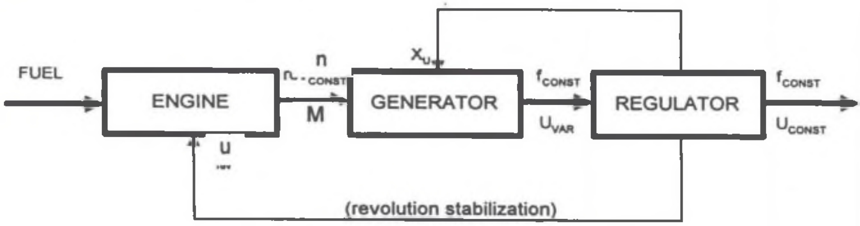

Fig. 1. The block diagram of GS1G and GS2G

The 3rd generation (GS3G) is based on some new technologies. Almost without exception Diesel engines in the whole range of GS and in special cases the high-speed gas turbines are used. The VSCF (Variable Speed Constant Frequency) technology gives the possibility to control the speed in such a way, that the optimum speed corresponds to the required power output in order to decrease the fuel consumption and harmful emissions. The synchronous generator with permanent magnets operates at variable output voltage and frequency. By means of power electronics converters required constant voltage and frequency can be ensured. From this point of view the GS3G differs substantially from GS1G and GS2G. The simplified block diagram of GS3G can be seen in Fig. 2.

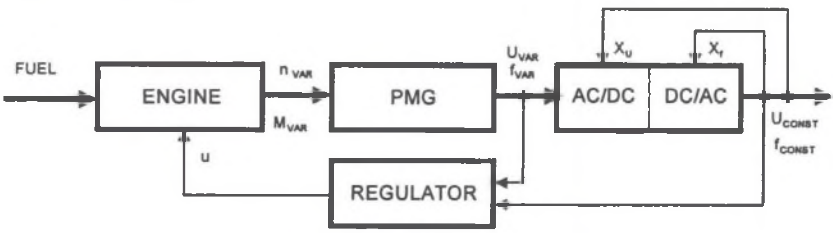

Fig.2. Simplified block diagram of GS3G

The historical change from constant speed to optimally variable speed is based on the analysis of GS loading regimes. Due to the low average load the engine operates at the superfluous high constant speed (usually 3000 or 1500 RPM) in uneconomical and from the point of view of the environment undesirable conditions.

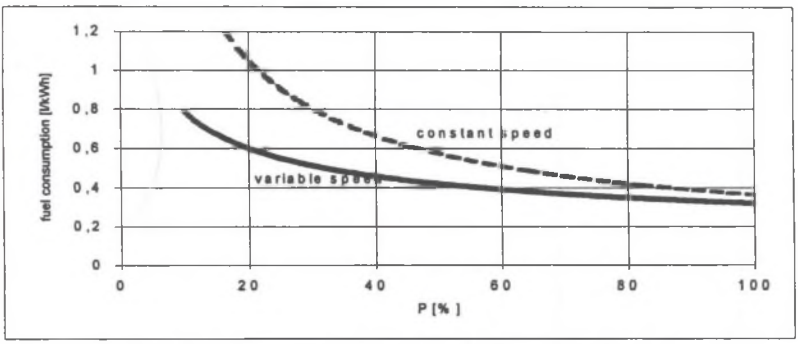

Fig.3. Fuel economy for constant and optimally variable GS speed

Fig.3 shows the expected difference in the fuel economy for constant and optimally variable speed of GS driving engine.

3. THE GS3G MODEL MEASUREMENTS AND SIMULATIONS

In order to solve fundamental theoretical and research problems of GS3G it was decided to build a physical model, consisting of the chosen driving Diesel engine, synchronous generator with permanent magnets, AC/DC, DC/DC and DC/AC converter, output filter and control unit.

Some laboratory measurements were effected to find fundamental parameters and characteristics of appropriate components. On the SGPM no load parameters and characteristics, resistive load characteristics, the shape of output voltage, heating and short circuit parameters were measured. Static and dynamic parameters and I/O characteristics were measured and analyzed to prove the correct function of power electronic converters and the output filter.

To get a general picture of the GS3G components and of the whole system static and dynamic behavior, the measured parameters and characteristics were used in the building up of the mathematical model for simulation of individual components and whole GS3G system. The main objective of this simulation was to discover the most suitable configuration and function of the control unit securing constant frequency, constant voltage and corresponding quality of output electrical energy at the condition of optimal speed, minimum fuel consumption and harmful emissions.

3.1. Model of the driving engine

The chosen driving engine is a single cylinder Diesel with the rated power output P_n=7.6 kW at the speed n_n=3000 RPM. Main characteristics of the engine can be seen in Fig. 4. and Fig 5.

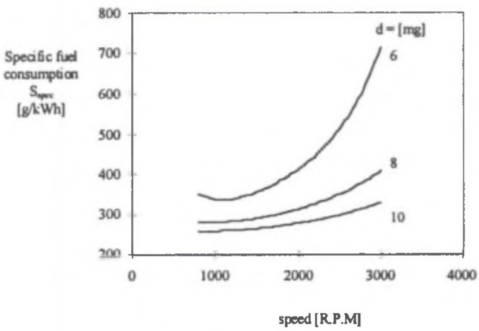

Fig. 4. The engine fuel consumption

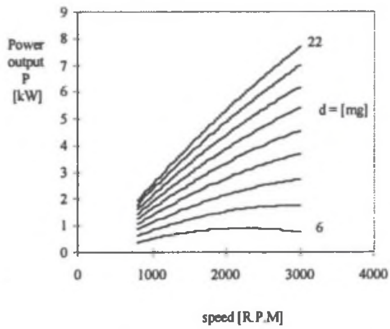

Fig. 5. The engine power output

The engine model includes several partial models: the model of fuel burning and exhaust gas expansion, passive mechanical resistance torque and forces, dynamic torque and model of fuel consumption (fuel injection).

The definition and identification of the mathematical model is based on the physical analysis of the above given phenomena (partial models). The detail analysis of individual partial models is out of the scope of this paper. Fundamental differential equation of the engine behavior is based on the well-known torque equation

$$M_E(d,\omega) = M_D + M_R(\omega) + M_L(P_L)$$

where: M_E is the driving torque of the engine, M_R and M_L is resistant and load torque, respectively. P_L is the load power of GS, ω is the angular velocity and d is a quantum of the fuel injection.

The dynamic torque is

$$M_D = J\frac{d}{dt}\omega = J\dot{\omega},$$

where: J is the moment of inertia. According to this formula, the equation of the engine could be modified to

$$J\dot{\omega} = M_E(d,\omega) - M_R(\omega) - M_L(P_L).$$

Using the approximative expression for M_R and M_E in form of 1-st order polynom, i.e.

$$M_R(\omega) = r_0 + r_1\omega, \qquad M_E(d,\omega) = m_0 + m_1 d,$$

the model of the loaded engine has the form of the 1-st order linear differential equation

$$T\dot{\omega} + \omega = K\cdot d - K_L(M_S + M_L(P_L)),$$

which corresponds to the standard control equation form (see [3]). In the case of GS the engine represents the source of kinematic torque and forces matched together by internal feedbacks.

Here

$$T = \frac{J}{r_1}, \quad [s], \qquad K = \frac{m_1}{r_1}, \quad [mg^{-1}s^{-1}],$$

$$K_L = \frac{1}{r_1}, \quad [N^{-1}m^{-1}s^{-1}], \qquad M_S = (r_0 - m_0), \quad [Nm].$$

Where: T is the time constant, K is the engine gain, K_L is the load gain, M_S is the effective static torque and M_L is the load torque.

When assuming that the engine is controlled in feed-back by proportional controller described by equation

$$d = K_R(\omega_p - \omega) = K_R\cdot e,$$

where: ω_p is the required angular velocity of the engine, ω is the instantaneous velocity and $e = \omega_p - \omega$ is the control error, we can get the differential equation for the feedback system in the form

$$T_C\dot{\omega} + \omega = K_C\cdot\omega_P - K_{LC}(M_S + M_L(P_L)).$$

The important constants of the closed-loop system are

$$T_C = \frac{T}{1+K\cdot K_R}, \quad K_C = \frac{K\cdot K_R}{1+K\cdot K_R}, \quad K_{LC} = \frac{K_L}{1+K\cdot K_R},$$

where: T_C is the time constant, K_C is the engine gain, K_{LC} is the load gain.

The programming scheme of the corresponding feed-back control model is given in Fig. 6.

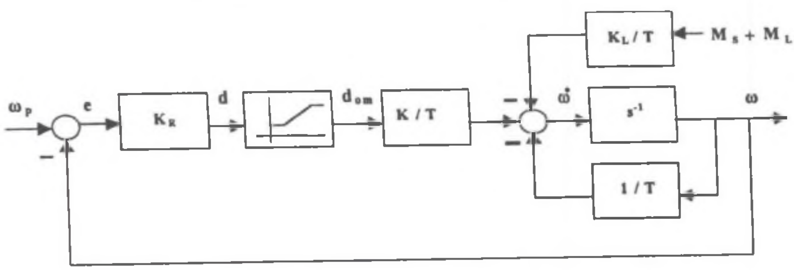

Fig.6. The feed-back system block diagram

The resultant feed-back model has was and the system behavior was simulated in MATLAB – SIMULINK environment (see [3]).

3.2. Model of the synchronous generator

The designed synchronous generator with permanent magnets (SGPM) has the following parameters: 2p = 12, P_n = 4 kW, cos fi = 0.8, n_n = 3000 RPM, U_n = 400/230 V, f = 300 Hz. The variable output no load voltage changes within the range from 210 V to 420 V at a speed varying from 1500 RPM to 3000 RPM (frequency 150 Hz to 300 Hz). The generator can be integrated to the engine and arranged with an inner stator and outer rotor replacing at once the engine flywheel as shown in Fig.7.

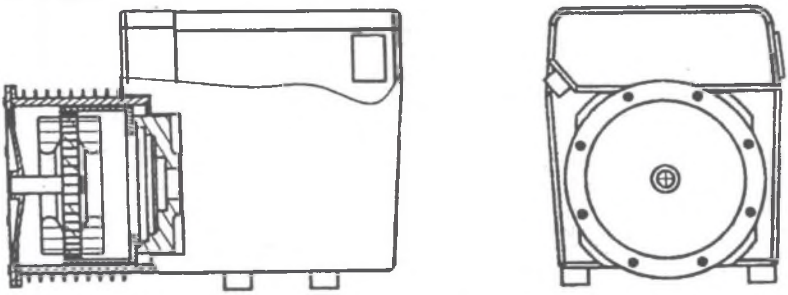

Fig.7. The GS3G engine and SGPM arrangement

On the base of theoretical analysis and fundamental parameters measurements the simplified mathematical model has been derived.

The loading current is expressed by the equation

$$I_L = \frac{P_L}{U_L} = \frac{P_L}{k_e\omega} \quad ,$$

where P_L is the generator output power U_L is the output voltage k_e is the voltage coefficient.

When taking into account the losses (efficiency) as a function of loading current

$$\eta = \eta(I_L)$$

the load model can be expressed as

$$M_L(P_L) = \frac{P_L}{k_e\omega^2}(k_e\omega + p_1P_L)\text{, or}\quad M_L(P_L) = \frac{k_eP_L}{k_e\omega - q_1P_L}$$

where p_1 and q_1 are the identified coefficients of approximation polynomia, $q_0 = p_0 = 1$.

$$\eta = \eta(I_L) = (p_0 + p_1I_L)^{-1}\text{, or}\quad \eta = \eta(I_L) = (q_0 - q_1I_L)$$

The resultant equation for the model of the generator expressed in the term of the load torque M_L as a function of power output P_L and instantaneous angular velocity ω is

$$M_L(P_L) = \frac{P_i}{\omega} = \frac{P_L}{\eta\cdot\omega} = \frac{P_L}{\omega}\frac{U_0^2 - R_{ef}P_L + p_1U_0P_L}{U_0^2 - R_{ef}P_L} = [\frac{P_L}{\omega}(1 + P_L\frac{R_{ef} + p_1k_e\omega}{k_e^2\omega^2 - R_{ef}P_L})],$$

where R_{ef} is the effective armature winding resistance, P_i is the generator input power, P_L is the generator output power and U_0 is the generator no load voltage.

The details of the generator model analysis are given in [3].

3.3. Model of voltage and frequency converter

To simplify the solution of the optimum control problem let us suppose, that the power losses in the converter are negligible, then

$$P_{GS} = P_L \quad\text{and}\qquad I_{GS} = \frac{P_{GS}}{U_{GS}}$$

where P_{GS} is the GS (converter) power output, I_{GS} is the GS load current and U_{GS} is the GS output voltage.

The time constants of electrical and electromagnetic transients are negligible in comparison with the mechanical and electromechanical time constants of both the driving engine and generator. The moment of inertia of the generator is integrated in the dynamical behavior of the engine. The simplified wiring diagram of the converter can be seen in Fig. 8 illustrating the whole schematics of GS3G structure.

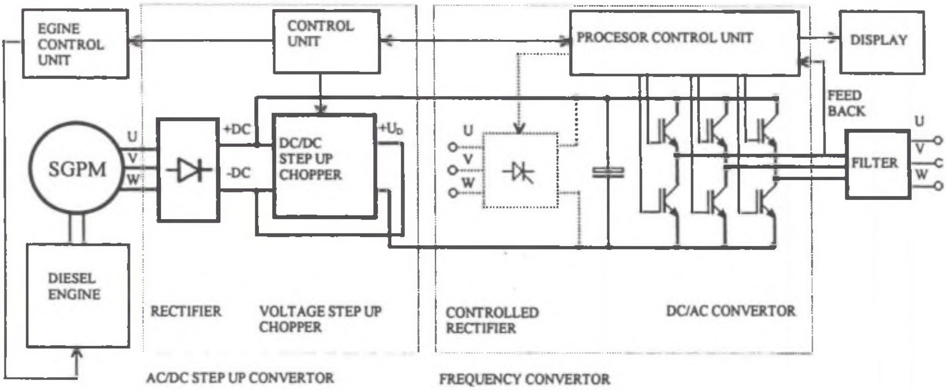

Fig. 8. The GS3G structure block diagram with power electronics part

4. THE GS3G OPTIMAL CONTROL

The objective of the GS3G optimum control is to adjust such a speed (angular velocity) of the engine and generator which corresponds to the required power output at optimum speed and at the same time it ensures the minimum fuel consumption.

From the GS3G system analysis it follows that the appropriate individual requirements to the control can be solved independently. The control law can be fulfilled by three separated subsystems creating fundamental components of the designed control structure:

- the required course of transient process will be ensured by the feed-back controller;
- steady-state errors (deviations) will be eliminated by the integral part of the controller or by means of compensating couplings (feed-backs) from error sources to the control error
- the minimum fuel consumption will be ensured by the module of required angular velocity, which generates optimum angular velocity of the engine depending on the instantaneous load with respect to the chosen optimum criteria.

One of the variants of GS3G control system structures including three above mentioned control components is given in Fig. 9.

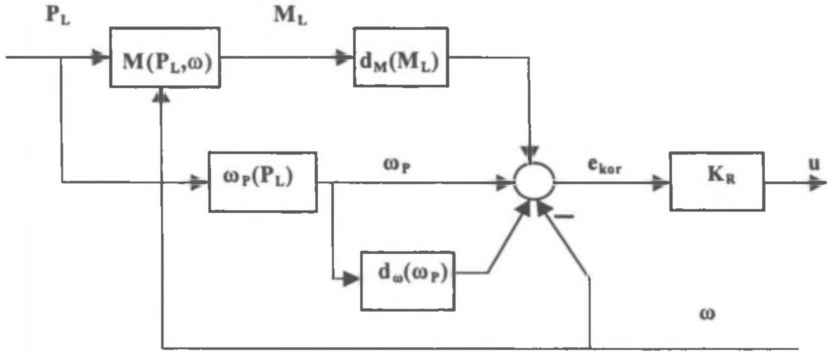

Fig.9. The GS3G control system structure

This structure corresponds to the chosen control law, given by the relation

$$u = R(\omega, P_L) = K_R\{\omega_P(P_L) + d_\omega[\omega_P(P_L)] + d_M[M_L(P_L, \omega)] - \omega\}.$$

Here K_R is the controller gain and d_ω, d_M are correction values of steady-state errors of angular velocity ω and of load torque M_L. As the most important part of the control law is the model of the required angular velocity, i.e.

$$\omega_P = \omega_P(P_L).$$

This equation is found as a result of the minimizing procedure, where the quality criterion is the model of the GS fuel consumption per hour S_h or the GS specific consumption S_m having form

$$S_h = \frac{0,9}{\pi} \cdot d \cdot \omega \quad \text{or} \quad S_m = \frac{S_h}{P_L} = \frac{0,9\ d \cdot \omega}{\pi P_L} = \frac{0,9\ d}{\pi M_L}.$$

Taking into account identified models of the engine and of the generator we can derive the consumption model S_h in form

$$S_h(P_L, \omega) = \frac{0,9}{\pi}[P_L(1 + P_L \frac{R_{ef} + p_1 K_e \omega}{k_e^2 \omega^2 - 2 R_{ef} P_L}) + r_1 \omega^2 + (r_0 - m_0)\omega].$$

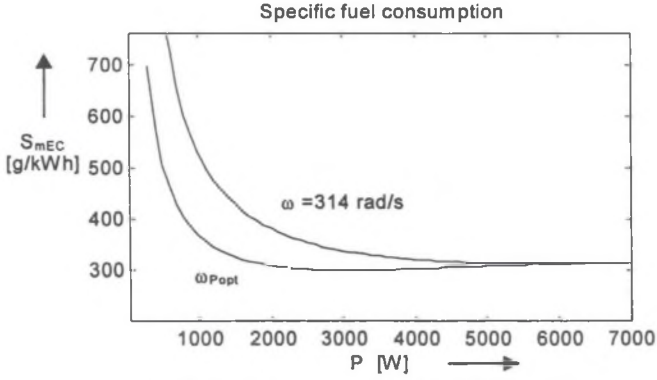

Fig. 10. The fuel economy of simulated GS3G model

The optimal angular velocity model has been derived as a solution of the equation

$$\frac{\partial}{\partial \omega} S_h(P_L, \omega) = 0 \qquad \text{or} \qquad \frac{\partial}{\partial \omega} S_m(P_L, \omega) = 0$$

This model is applied in the region of angular velocity according to the activity of the frequency converter.

The resultant simulated relation between specific GS3G fuel consumption and power output for constant angular velocity ω = 314 s^{-1} and for optimum controlled ω_{Popt} is given in Fig.10.

The results of simulations correspond to the expectations (see Fig. 3) and values obtained by measurements and experiments performed on series of the2nd generation of generating sets in use [1], [4] and on the model of the 3rd generation VSCF generating set.

5. CONCLUSIONS

The mathematical analysis and simulation of static and dynamic behavior of the GS3G VSCF structure proved that the dynamical properties of the system enable to formulate of control laws and thus to solve successfully the control requirements by the use of the minimum fuel consumption optimizing criterion.

The results of simulation were partially proved by measurements on the realized physical GS3G model, consisting of diesel engine, synchronous generator with permanent magnets, voltage and frequency power electronic converter at different operating regimes.

One of serious problems not satisfactorily solved yet is the system behavior at high sudden increase of loads from low loads at low speed close to the idle run to high loads demanding maximum speeds.

The physical and mathematical GS3G model will be further improved and precised to acquire more parameters, characteristics and to get more experience for the practical development of new VSCF generation of mobile electrical generating sets.

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Recenzent: Dr hab. inż. Aleksander Żywiec
Profesor Politechniki Śląskiej

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