MODELLING AND EXPERIMENTAL VERIFICATION OF MOBILE POWER SOURCES WITH VARIABLE SPEED

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This paper brings some practical results of research devoted to the new generation of mobile electrical power sources based on the VSCF technology (Variable Speed — Constant Frequency). In this generation of mobile electrical power sources the driving motor and generator speeds are optimally controlled in accordance with the load power thus decreasing the fuel consumption. The output voltage and frequency are stabilized by means of an electronic power converter.

K e y w o r d s: power generating sets, power converter, optimal control speed of diesel engine

1 INTRODUCTION

Mobile electrical power sources known as Electrical Generator-Sets (EGS) are used for various machines and appliances to increase their mobility. EGS enables independence on the power network. They are used in the army as a power supply of different weapon systems. EGS are quite indispensable in civil defence, crisis management forces and in security forces. They are also used in building industry, agriculture, transport, health service and other branches of industry.

EGS operates very often under a low load, which does not exceed in average more than 20 % of the rated permanent load, as can be seen in Fig. 1. EGS currently in use are based on the classical engine-generator set combination. These EGS are operating with a constant engine speed. Both engine and generator operate often with low efficiency. EGS have adverse impacts on environment, e.g., air pollution, noise pollution and possible fuel and/or lubricant leakage. A higher efficiency and lower operation costs may be achieved by using a new concept of EGS. The new concept is based on the use of diesel engines operating with an optimum variable speed according to the EGS load [1, 3].

2 EGS CLASSIFICATION

The 1st generation of EGS (EGSG1) is based mainly on the classical motor-generator principle with a common electromagnetically excited synchronous generator driven by a petrol or diesel engine at a constant speed corresponding to the required frequency of the output voltage. EGSG1 are very heavy, difficult to handle, noisy and low-efficient.

The 2nd generation of EGS (EGSG2) is characterized by using modern diesel engines, new types of generators (brushless, asynchronous, and synchronous with permanent magnets) and higher efficiency than EGSG1. Nevertheless, these 2nd generation EGS operate still on the classical engine-generator concept with a constant speed engine as EGSG1. The structure of such EGSG2 is described in Fig. 2. The disadvantage of the constant speed system is a high fuel consumption at a low load since the engine still drives with the constant high speed. From the point of view of fuel consumption for each power output, an optimum rpm can be determined. Therefore a variable speed concept brings automatically fuel savings.

The 3rd generation of EGS (EGSG3) is based on the variable speed concept [5, 6]. The diesel engine changes the speed according to the load of the set. The optimum speed is hereby calculated according to the EGS load, the optimality criterion being the minimum fuel consumption. The consequence of the varying engine speed: Both the output voltage and the frequency of the generator are variable and must be converted to the constant value required by the load (usually 3×400 V, 50 Hz). Therefore it is necessary to introduce a power electronic voltage and frequency converter to the new EGS structure. Such a structure is depicted in Fig. 3.

The new generation of EGS brings some primary benefits: fuel consumption savings for low and middle load; decreasing the amount of harmful air and acoustic emissions; longer lifetime and higher reliability of EGS; increasing versatility of output electrical parameters EGS (V and f); increasing of the quality of output energy.

The main disadvantages of the new concept of EGSG3 are higher initial costs than in EGSG2 and EGSG1. These initial costs can be higher by 30 % according to the kind of electronic power converter that stabilizes the output voltage and frequency. The initial costs will be compensated by decreased operating costs.

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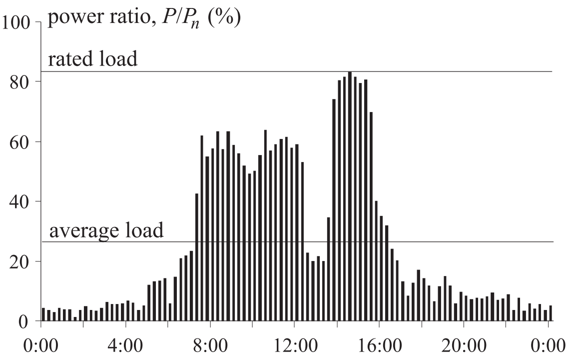

Fig. 1. The average load of EGS.

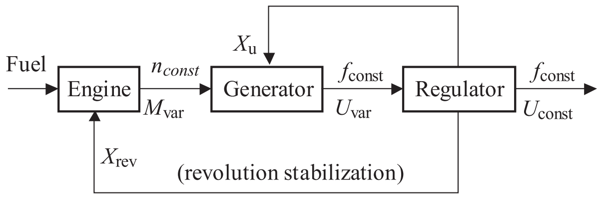

Fig. 2. Flow diagram EGSG2.

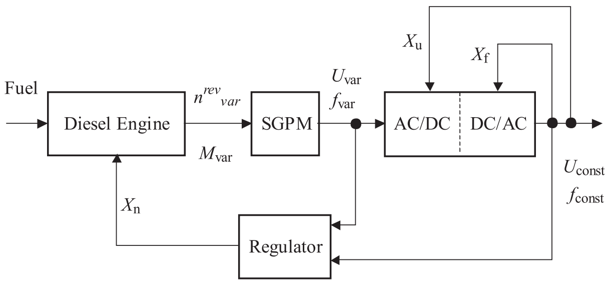

Fig. 3. Flow diagram EGSG3.

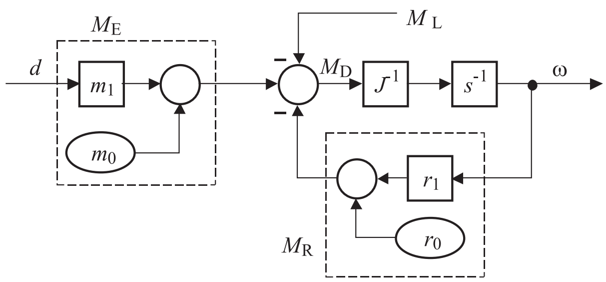

Fig. 4. The structure detail of engine linear model.

3 CONCEPT OF EGSG3

The simplified block diagram of EGSG3 was shown in Fig. 3 with a diesel engine, synchronous generator with permanent magnets, indirect-type converter (AC/DC/AC), output filter and speed control unit. The variable speeds of the diesel engine are optimally controlled in accordance to the load of EGS thus securing the minimum fuel consumption. As a driving engine a modern diesel engine is used. In the military use it means the unification of fuel, which is very important with respect to logistics. Modern diesel engines are compact, fully cased driving units of high efficiency, about 40 %, reliability and low fuel consumption. It is possible to replace the diesel engine by a high-speed gas turbine. The high-speed turbine has the benefit of a considerable size and weight reduction. When compared with a common diesel engine driven EGS, the typical high speed 40 kW EGS driven by a gas turbine has a specific power output about 200 W/kg, while the classical 40 kW one, driven by diesel engine, yields only 20 W/kg.

Synchronous generators with a permanent magnet (SGPM) without an electromagnetic exiting system are used in many modern applications with VSCF technology (Variable Speed — Constant Frequency). SGPM have a maximum efficiency and reliability, and high speeds can be reached. Variable speeds of the diesel engine determine the output voltage and frequency of synchronous generators with permanent magnets. The variable voltage and frequency must be stabilized to a constant voltage and frequency by a power converter [1, 4].

Indirect-type converters (AC/DC/AC) are usually used in all applications of power converters up to a hundred kW of power. The indirect-type converter usually consists of an AC/DC diode rectifier, a DC/DC converter with a transformer and a DC/AC inverter. The function of the DC/DC converter is to stabilize the DC output voltage to the required level $U_{DC} = 570$ V for inverter to have 3×400 V on the output. The main advantage of the diode rectifier is its cost, which is lower than in the following conceptions of control rectifiers.

There several possibilities how to solve the front end of the system. Instead of a diode rectifier as an AC/DC converter, there is a possibility to apply a line controlled thyristor rectifier or PWM transistor based rectifies. The advantage of the PWM modulated converter is a sinusoidal current of the generator. The use of a matrix converter and cycloconverter is not very common for this sort of application.

The EGSG3 can be considered as a comparatively sophisticated mechatronic system consisting of a mechanical part, electromechanical part for mechanical energy conversion, power voltage and frequency transformation and stabilization part including the optimum speed control part based on the microprocessor program.

4 THE THEORETICAL MATHEMATICAL MODEL OF EGSG3

The structure of the new EGS concept with an optimum control system can be seen in the block diagram in Fig. 3. The engine speed is controlled in such a way that the optimum speed corresponds to the required power output in order to decrease the fuel consumption. The kinematical control error e is represented by the difference between the required angular velocity n_p of the engine and the instantaneous velocity n. The nature of the

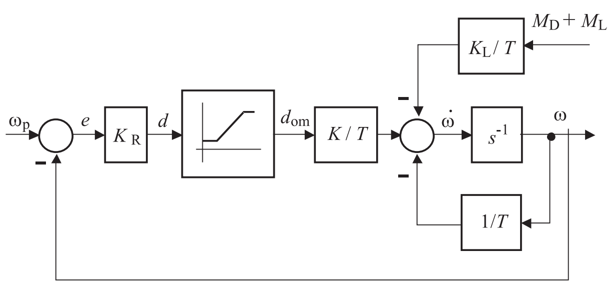

Fig. 5. The feedback system block diagram.

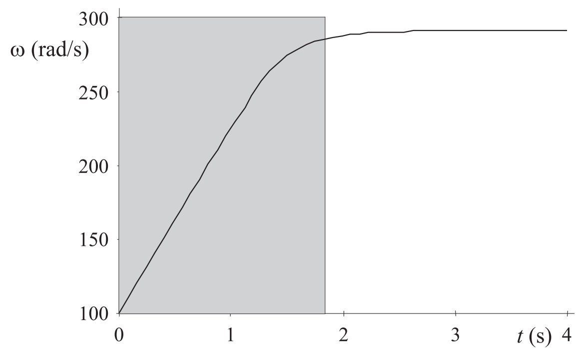

Fig. 6. Transient response.

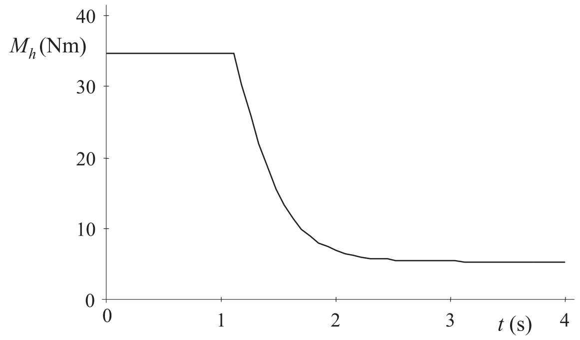

Fig. 7. Driving torque M_E.

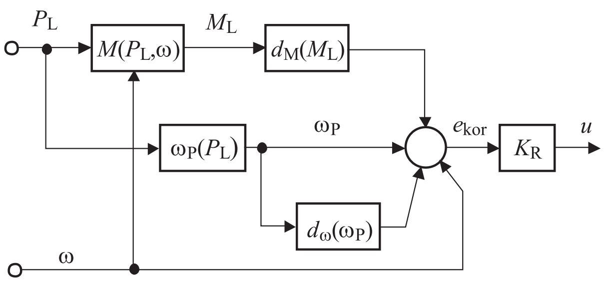

Fig. 8. The EGSG3 control system structure.

transient phenomenon must be non-periodic, the control must be short and accuracy must be guaranteed.

The design of the feedback regulator of EGS driving engine requires appropriate engine identification with mathematical description. The fundamental differential equation of engine behaviour is based on the well-know torque equation

$$M_E = M_D + M_r + M_L \,, \tag{1}$$

where M_E is the driving torque of the engine, M_D is the dynamic torque, M_r and M_L are resistant and load torques. The dynamic torque M_D is expressed by equation (2). J is the framework moment of inertia.

$$M_D = J\frac{\mathrm{d}\omega}{\mathrm{d}t} = J\dot{\omega}\,. \tag{2}$$

Simplified expressions M_E for and M_r in the form of 1st order polynomials are used

$$\begin{aligned} M_E &= f(d,\omega) \doteq f(d) = m_0 + m_1 d\,, \\ M_r &= f(d,\omega) \doteq f(\omega) = r_0 + r_1\omega\,, \end{aligned} \tag{3}$$

where the driving torque M_E is increasing by d and slightly changed by angular velocity ω and M_r. Parameter d is a quantum of fuel injection. The resistant torque M_r is a function of angular velocity ω and the effect of d can be neglected.

Load torque M_L can be expressed as a function of load power P_L or load current I_L for output voltage.

$$M_L = f(P_L) = f(I_L) = a_0 + a_1 I_L\,. \tag{4}$$

Equation (1) of the engine could be modified to (5). Using the approximate expression for M_r, M_E and M_L we can get the differential equation for the feedback system in the form (6) and (7). Hence, the model of the loaded engine has the form of the 1st order linear differential equation (8). In the case of EGS the engine represents the source of kinematic torque and forces matched together by internal feedbacks. The structure detail of the linear model of the engine is shown in Fig. 3.

$$J\dot{\omega} = M_E(d,\omega) - M_r(\omega) - M_L(I_L)\,, \tag{5}$$

$$J\dot{\omega} = (m_1 d + m_0) - r_1\omega + r_0) - M_L\,, \tag{6}$$

$$J\dot{\omega} + r_1\omega = m_1 d - (r_0 - m_0) - M_L\,, \tag{7}$$

$$T\dot{\omega} + \omega = Kd - K_L(M_S + M_L)\,, \tag{8}$$

where T is a 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.

$$\begin{aligned} T &= \frac{J}{r_1}\,(\mathrm{s})\,, \quad K = \frac{m_1}{r_1} \\ K_L &= \frac{1}{r_1}, \quad M_S = (r_0 - m_0). \end{aligned} \tag{9}$$

It is possible to say: the engine is a very hard source of torque and relatively soft source of speed. When assuming that the engine is controlled in feed-back by a proportional controller with amplification K_R described by equation

$$d = K_R(\omega_P - \omega) = K_R e\,, \tag{10}$$

where ω_P is the required angular velocity of the engine, ω is the instantaneous velocity and e is the control error.

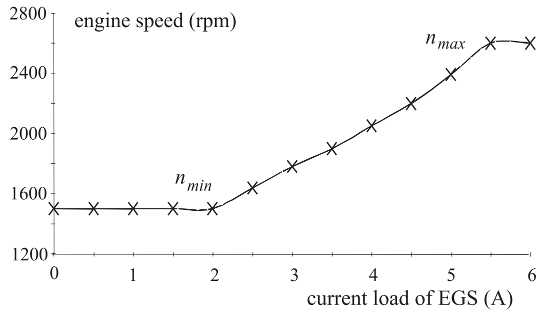

Fig. 9. Characteristics of optimum speeds with respect to the minimum fuel consumption.

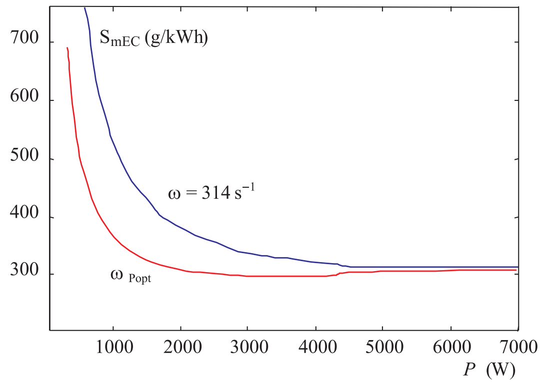

Fig. 10. The fuel economy of EGS new generation.

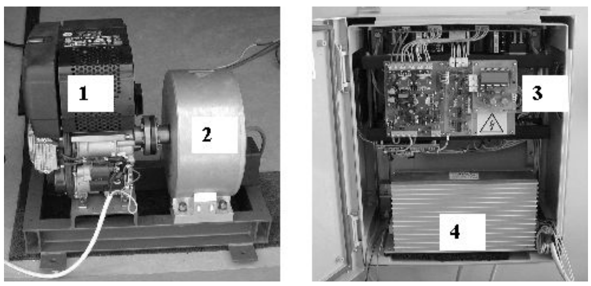

Fig. 11. Experimental model (1-diesel engine, 2-SGPM, 3-AC/DC/AC converter, 4-filter).

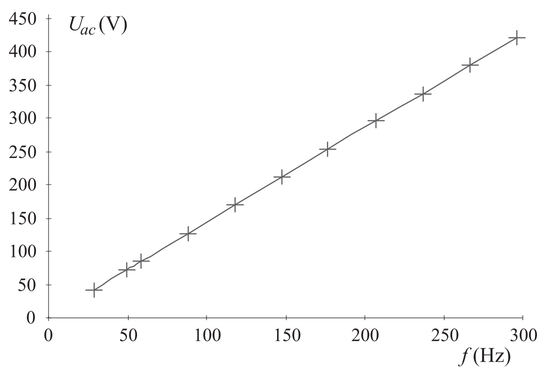

Fig. 12. I/O characteristic of synchronous generator with permanent magnet.

We can obtain the differential equation for the feedback system in the form

$$\frac{T}{1+KK_R}\dot{\omega}+\omega=\frac{KK_R}{1+KK_R}\omega_P-\frac{K_L}{1+KK_R}(M_S+M_L) \tag{11}$$

$$T_C\dot{\omega}+\omega=K_C\omega_P-K_{LC}(M_S+M_L)\,. \tag{12}$$

Here T_C is the time constant, K_C is the engine gain, K_{LC} is the load gain. The resultant output differential equation for the feedback system in the concrete form is as follows

$$17.9\dot{\omega}+\omega=100.7\,d-74.6(0.5+M_L)\,, \tag{13}$$

for $T_C = 17.9$ s; $K_C = 100.7\,\mathrm{mg}^{-1}\mathrm{s}^{-1}$; $K_{LC} = 74.6$ $\mathrm{N}^{-1}\mathrm{m}^{-1}\mathrm{s}^{-1}$; $M_S = 0.5$ Nm.

The output characteristic of the engine is given by equation

$$P(d,\omega)=M(d,\omega)\omega=1.35d\omega-0.0134\omega^2-0.5\omega\,. \tag{14}$$

The programming scheme of the corresponding feedback control model is given in Fig. 5. The input of the feedback control model is ω_P (required velocity) and the output is ω (instantaneous velocity). Fuel injection d is limited $(d_{\min}, d_{\max})$ by using a limiter. The resultant feedback model has been defined and the system behaviour has been simulated in MATLAB – SIMULINK [8]. Transient actions are caused by changes of the engine angular velocity ω_P or load torque M_L and we are especially interested in the time of regulation (T_{reg}). The regulation time is given by equation (15) for the value of proportional regulator $K_R = 1$. The solution results confirm stability and aperiodicity. Time T_{reg} is 3× longer than the time constant T_C. The results of control errors $e_{\omega\omega p}(t)$ and $e_{\omega M}(t)$ are shown in Fig. 6. The control error $e_{\omega\omega p}(t)$ depends on the change of the engine speed and $e_{\omega M}(t)$ depends on the engine load torque M_L. Then time T_C is equal to 0.53 s and the regulation time is 1.59 s [8].

$$T_{\mathrm{reg}} \doteq 3T_C=\frac{3T}{1+K_R K}\,. \tag{15}$$

Figure 6 gives the transient response of the system from 100 to 300 rad/s for $M_L = 0$ Nm and $K_R = 0.5$. The evolution of the driving torque is shown in Fig. 7. The driving torque is constant at the start and is limited by $d_{\max}$.

$$M_E=f(d)\doteq 1.35d_{\max}+0.9=36\,\mathrm{Nm}, \tag{16}$$

$$e_s=\frac{\omega_p+K_L(M_S-M_L)}{1+K_R K}\doteq 6.6\,\mathrm{rad/s}. \tag{17}$$

The static error of the system is calculated by means of formula (17). This equation expresses also the control tolerance (e). The steady-state value of instantaneous velocity (ω) is

$$\omega=\frac{K_R K\omega_P-K_L(M_S+M_L)}{1+K_R K}\doteq 293.4\,\mathrm{rad/s}. \tag{18}$$

A further control requirement is to keep the minimum fuel consumption for a given EGS load. The minimum of

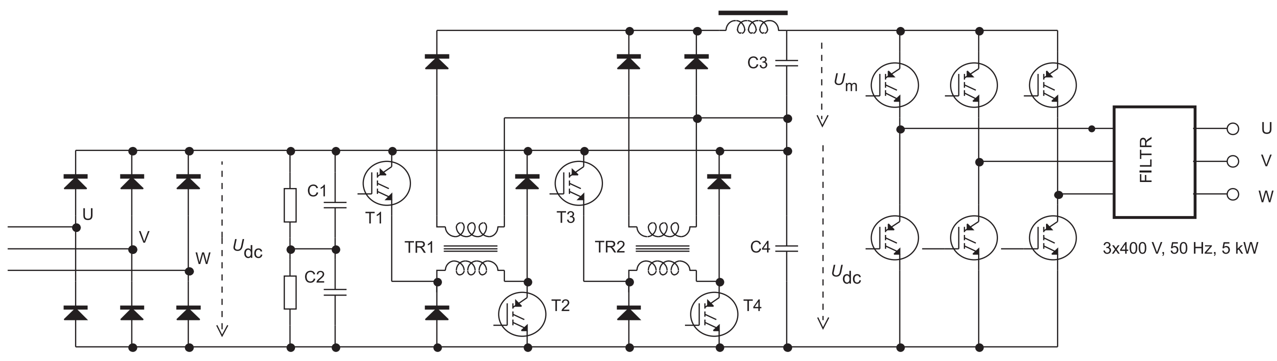

Fig. 13. The schematic diagram of our experimental AC/DC/AC converter model.

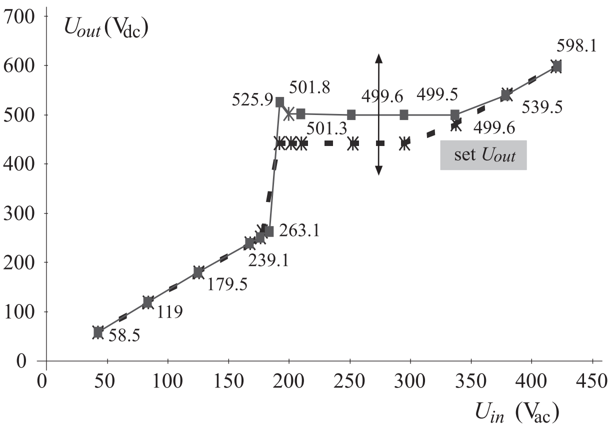

Fig. 14. I/O characteristic of DC/DC converter.

fuel consumption will be ensured by the controller of the required speed of the diesel engine, which generates the optimum angular velocity of the engine under instantaneous load with respect to chosen optimisation criteria. One of the variants of EGSG3 control system structures including three of the above mentioned control components is given in Fig. 8. This structure corresponds to the chosen control law, given by the relation

$$u = \{\omega_p(P_L) + d_\omega(\omega_p(P_L)) + d_\omega(M_L(P_L, \omega)) - \omega\}, \quad (19)$$

where d_ω, d_M are correction values of steady-state errors of the angular velocity ω and of the load torque M_L.

The optimum control of the diesel engine speed according to the EGS load is shown in Fig. 9. For load currents I_L smaller than 2 A the driving engine operates at a low speed (1500 rpm for standard diesel engine). This speed is characterized by lower fuel consumption and quiet run. For load currents higher than 2 A the speed is adjusted according to the determined speed/load characteristics in the region of about 5 A, corresponding to the speed 2600 rpm.

The simulated relation between the specific EGSG3 fuel consumption and power output for constant angular velocity $\omega = 314\,\mathrm{s}^{-1}$ and for optimally controlled velocity ω_{opt} is in Fig. 10. The results of simulations correspond to the expectation and values obtained by measurements and experiments performed on a series of the 2nd generation of generating sets with a constant speed of the engine and on a model of EGS with an optimally controlled speed.

The results of efficiency analyses shows the following:

- The efficiency of EGS with a constant speed of the engine for 20 % nominal load is 11 % and the efficiency of EGS with optimum speed control is 32 %.
- The efficiency of both EGS with constant speed and variable speed for 100 % nominal load is 32 %.

So, the maximum efficiency of the EGS is about 32 %, if the power output on the load is the same like the power generated by the diesel engine.

The computer simulation of EGS system with variable speed shows that the major drawback of this new generation of EGS is the engine-generator dynamics at a sudden transient from low load to high load in a very short time. The electronic converter can improve the dynamic behaviour of the whole EGS system.

5 EXPERIMENTAL VERIFICATION OF EGSG3

In order to solve fundamental theoretical and research problems of EGSG3 it was decided to build an experimental model consisting of a chosen driving diesel engine, synchronous generator with permanents magnet SGPM, indirect AC/DC/AC converter, output filter and speed control unit. The photograph of our experimental model of EGS with optimum speed according the load is in Fig. 11.

Preliminary calculations and simulations of the 6 kW EGSG3 driving part resulted in the choice of a diesel engine with power output 7 kW at 3000 rpm and 3 kW at 1500 rpm. The output characteristic of our 12 pole SGPM connected to the diesel engine by means of a mechanical clutch is shown in Fig. 12.

The SGPM output voltage, varying in the range from 200 to 400 V at frequency 100 to 300 Hz is to be converted to stabilized 570 V_{DC} by AC/DC and DC/DC converters. As shows in Fig. 13, a three-phase diode rectifier is used as an AC/DC converter and a DC/DC converter is designed as a STEP-UP converter (FORWARD). If the output voltage of the rectifier is less than 570 V, then the

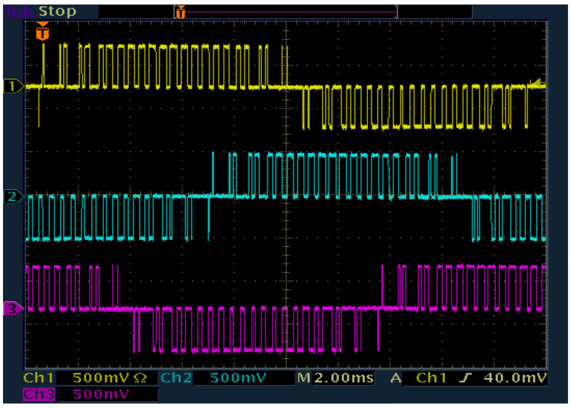

Fig. 15. Output voltages (line-line) of DC/AC converter.

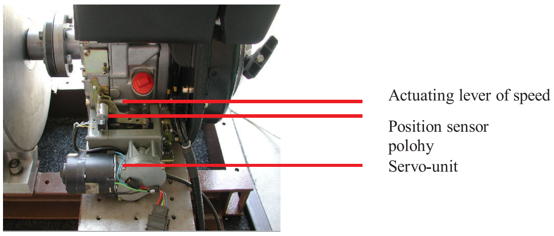

Fig. 16. The detail photo of speed control system of EGS.

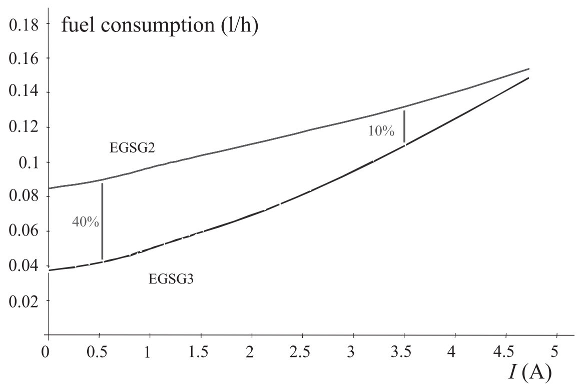

Fig. 17. The experimental results of fuel economy for EGSG2 and EGSG3.

DC/DC converter increases the voltage. The output characteristic of the DC/DC FORWARD converter is shown in Fig. 14. The U_{DC} level can be adjusted according to the generator operating conditions in the control region from U_{Acmin} to U_{Acmax}.

The frequency converter can be adjusted to the required constant output frequencies (50, 60, 400 Hz) at the corresponding output voltage. The output voltage amplitude and shape will be controlled by means of the output voltage evaluation unit. The unit will evaluate the three-phase information as to transform the amplitude of the rotating vector of the output voltage. The general scheme of our experimental model of AC/DC/AC converter is given in Fig. 13. Figure 15 shows the output voltage (line-line) of our experimental three phase inverter without filter and with RL load.

The photo detail of the control speed unit is shown in Fig. 16. The required speed ω_p of the engine is adjusted by an actuating lever and the instantaneous speed is calculated from a position sensor which measures the instantaneous position of actuating lever. The servo unit is controlled by a microprocessor and adjusts the required speed by means of the actuating lever.

The values obtained by measurements and experiments on the experiment model of EGSG3 and on the series of the 2$^{\mathrm{nd}}$ generation of generating sets correspond to the expectation and simulation (see Figs. 10 and 17). The maximum fuel economy is for low-load about 40 %.

The regulation time from the low speed of the engine (low load) to the high speed (high load) takes about 2 to 5 s (see Fig. 18) that is in accordance with the previous computer analysis in MATLAB. It seems that the solution of our power converter with an electrolyte capacitor in the inter-circuit does not help with dynamic behaviors of EGS with VSCF technology. Hence, the power converter must operate with energy storage like UPC sources.

6. THE EFFECT OF POWER ELECTRONICS CONVERTER ON THE EFFICIENCY OF EGSG3

One of the major results of the experimental on physical model with an indirect-type converter (AC/DC/AC) and synchronous generator with permanent magnets is the decrease of the total EGS efficiency by means of power electronics. The power converter causes a decrease in the efficiency by losses of the converter and by the effect of power converters on the permanent magnet synchronous generator [1, 2].

The energetic efficiency of the converter is closely associated with losses of the switch elements and control circuits. The losses of the converter by the control circuit are small and so the total losses of the converter are usually calculated only for losses in the switch elements. The total losses of the switch $\Delta P_{\mathrm{Total}}$ consist of on-state losses ΔP_{on}, off-state losses ΔP_{off} and transient losses ΔP_T.

$$\Delta P_{\mathrm{total}} = \Delta P_{on} + \Delta P_{off} + \Delta P_T\,, \tag{20}$$

$$\Delta P_{on} = I_C\, V_{CE(sat)} = I_C (V_{CE} + R_C\, I_C)\,, \tag{21}$$

$$\Delta P_T = f_s\Big(\int_0^{t_{t-on}} v_{ce}(t)\, i_c(t)\mathrm{d}t + \int_0^{t_{t-off}} v_{ce}(t) i_c(t)\mathrm{d}t\Big) \tag{22}$$

where losses ΔP_{on} for transistor are given by Eqs. 21 and transient losses ΔP_T are given by Eqs. 22. Voltage $V_{CE(sat)}$ is the saturation voltage of the collector-emitter and I_C is the collector current. Voltage $V_{CE(sat)}$ presents the voltage drop for switch ON. The collector current is a function of the collector-emitter voltage U_{CE} and gate-emitter voltage U_{GE}.

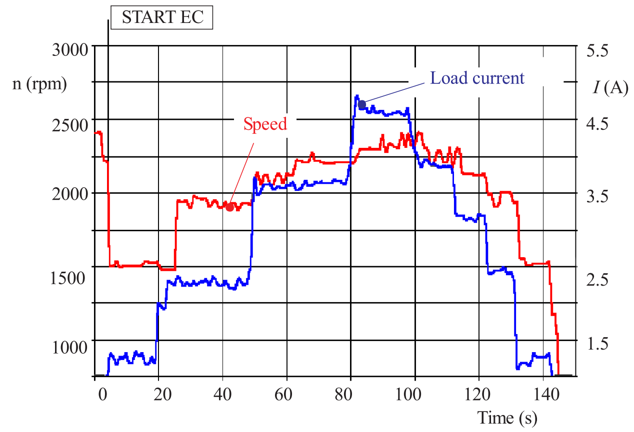

Fig. 18. Result of speed control system on the experimental model of EGS with variable speed.

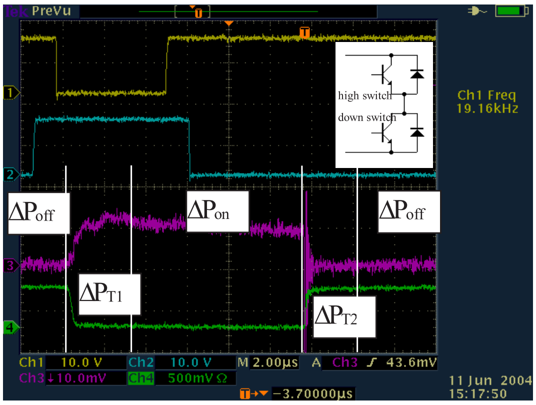

Fig. 19. Switching detail of experimental inverter model with switch frequency 19 kHz.

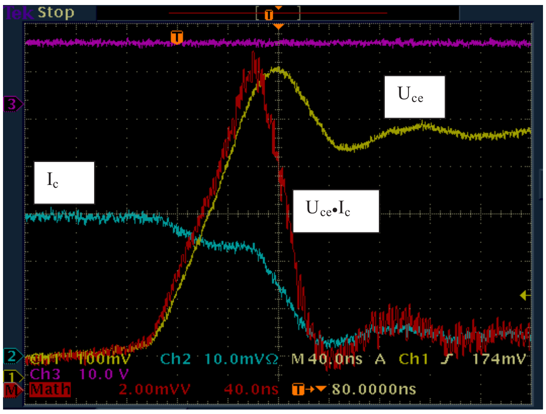

Fig. 20. Switching detail of transient (off-on).

The losses ΔP_{off} are usually 10 % of ΔP_{on}. The transient losses ΔP_T are expressed by Eqs. 22. The transient losses ΔP_T are a function of the switch frequency f_s. This sort of losses is load-dependent too.

Switching details of our experimental model of the inverter with a switch frequency 19 kHz are shown in Fig. 19. There were analysed losses of every switch separately by Eqs. 20. The first curve of Fig. 19 shows switching of the high switch and the second curve shows switching down the switch of the 3 phase IGBT bridge. The third curve is the voltage on the down switch and the fourth curve is the current through the down switch. Oscilloscopic record of the transient (off-on) is shown in Fig. 20 and losses ΔP_T are the top curve ($U \bullet I$).

The summary of the results of losses measured on the experimental model of AC/DC/AC converter are about 20 % and the efficiency of our converter is ±80 %. The losses increase according to the frequency of the generator. A high frequency is characterized by bigger losses than a low frequency. The losses in the converter are distributed as follows: – AC/DC — 5 %; – DC/DC — 7 %; – DC/AC — 5 %; – control components and others — about 3 %.

The converter also adds extra losses in the synchronous generator of the EGS system. Non-harmonic currents of the electronic converter create these extra losses injected into the generator. The effect and results of very detailed analyses are in [1]. The losses in the speed generator and converter depend on the selected type of rectifier of AC/DC/AC converter. Our above-mentioned solution of AC/DC/AC converter with an uncontrolled diode rectifier with a large capacitor filter at the output brings a non-sinusoidal current from the generator with large current peaks. Current harmonics of the converter create extra losses injected into the generator. The amplitude of h-harmonics of the generator current can be expressed by equation (23). According to this equation h-harmonics of the current is a function of the first harmonics [7].

$$i_s(t) = \frac{2\sqrt{3}}{\pi} I_{dc}\Big(\sin\omega_1 t - \frac{1}{5}\sin 5\omega_1 t - \frac{1}{7}\sin\omega_1 t + \frac{1}{11}\sin\omega_1 t + \dots\Big)\,. \tag{23}$$

In this case the produced harmonics are of order (24)

$$(6k \pm 1)\,, \tag{24}$$

where $k = 1, 2, 3 \dots$.

The natural question arises: should a fully controlled PWM IGBT rectifier be employed or is the version with a diode rectifier satisfactory? The results of our efficiency analyses of the synchronous generator with permanent magnets as a function electronic converter configuration can be found in [1] and in [4]. The summary can be drawn as follows:

- the total efficiency of EGS is decreasing from 32 % to 28 % in the power AC/DC/AC electronic converter and the total losses of EGS in our converter with an uncontrolled rectifier are 7 %;
- the solution of AC/DC/AC converter with PWM controlled rectifier can decrease the total losses of EGS from 7 % to 4 % by electronic converter (Fig. 21), and so the efficiency of the system with a controlled PWM rectifier is better than in the solution with an uncontrolled diode rectifier;
- PWM rectifier is more expensive than the diode rectifier and so the solution with PWM rectifier can bring higher initial costs;

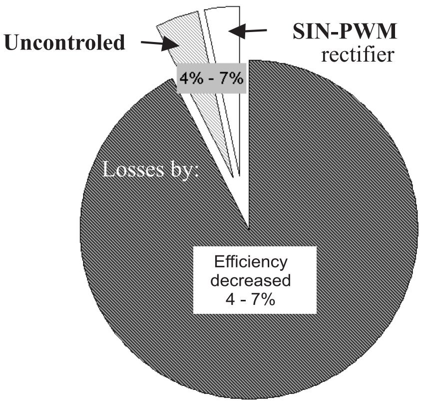

Fig. 21. Total efficiency of EGS is decreasing according converter configuration.

7 CONCLUSIONS

The 1st and 2nd generation of EGS operate with a constant engine speed corresponding to the required output voltage frequency. Both the engine and the generator operate often with a low efficiency at a low and medium load. A higher efficiency and lower operation costs may be achieved by using a new concept of EGSG3 with an optimum variable speed according to the EGS load. The diesel engine adjusts its speed according to the EGS load. The optimum speed is hereby determined according to the EGS load with a minimum fuel consumption optimality criterion. Both the generator output voltage and the frequency are variable and are to be converted to constant values by power converter.

It is necessary to say that the efficiency of EGS with a variable speed at the rated load is lower than the efficiency of ECS with a constant speed without power converters. The decrease of efficiency is caused by the power electronics itself and by the effect of power electronics on the permanent magnet synchronous generator. This efficiency decrease is not negligible and it is important to design a suitable converter structure with its own high efficiency and with a low effect on the generator efficiency.

The main handicap of the new concept EGS are higher initial costs EGS than in EGS with a constant speed. These initial costs can be higher by 30 % according to the kind of voltage and frequency converters and so it is important to look for a new system topology of the electronic converter with a high efficiency to take into account the results of the analysis of efficiency and decreasing price.

The authors of the paper are members of a research team prepared to solve the main problems of new technologies in EGS, to build models of respective variants and to introduce positive results in practice.

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