Configuration for Mobile Power Source

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***Abstract*- This paper brings some practical results of research devoted to the optimum configuration for mobile power source, based on the VSCF (Variable Speed – Constant Frequency) technology. In this Electrical Generator - Sets (EGS) the driving motor and generator speed is optimally controlled in accordance with the load power thus decreasing the fuel consumption. The output voltage and frequency are stabilized by means of power electronics converter. The paper gives short outline of some problems in research and development of the new generation of EGS.**

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 army as the power supply of different weapon systems. EGS are quite indispensable in civil defence, crisis management forces and naturally in security forces. They are also used in building industry, agriculture, transport, health service and other branches of industry.

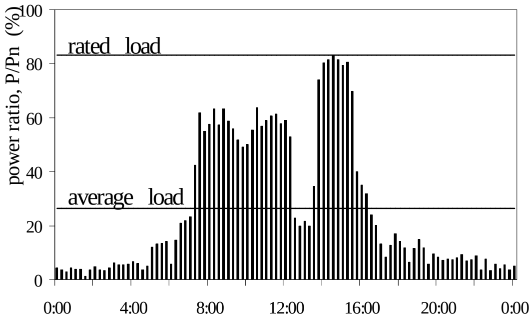


Fig.1. The average load of EGS

EGS operates very often under 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 classical engine – generator set combination. These EGS are operating with 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. Higher efficiency and lower operation costs may be achieved by using new concept of EGS. The new concept is based on the use of diesel engines operating with optimum variable speed according to the EGS load.

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 petrol or diesel engine at a constant speed corresponding to the required frequency of output voltage. EGSG1 are very heavy, difficult to handle, noisy and low-efficient.

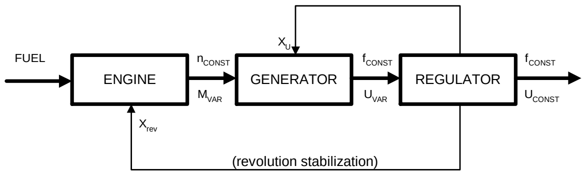


Fig.2. Flow diagram EGSG2

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 constant speed engine as EGSG1. The structure of such EGSG2 is described in Fig. 2. The disadvantage of the constant speed system is high fuel consumption by 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 generation brings automatically fuel savings.

The 3rd generation of EGS (EGSG3) is based on the variable speed generation concept. The diesel engine changes the speed according the load of the set. The optimum speed is hereby calculated according to the EGS load with the optimality criterion the minimum fuel consumption. The consequence of 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 x 400V, 50Hz). 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.

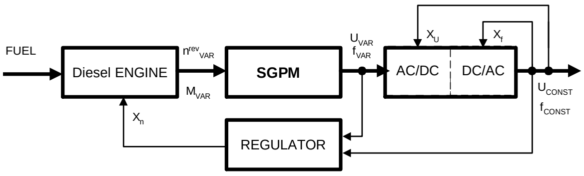


Fig. 3. Flow diagram EGSG3

New generation of EGS brings some primary benefits:

- the 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 (voltage and frequency);
- increasing of the quality of output energy.

The main handicap of new concept EGSG3 create higher initial costs EGS then EGSG2 and EGSG1. These initial costs can be higher by 30 % according to kind of power electronic converter that stabilize output voltage and frequency. The initial costs will be compensated by decreased operating costs.

3. Concept of EGSG3

The simplified block diagram of EGSG3 was shown in Fig. 3 with diesel engine, synchronous generator with permanent magnets, indirect-type converter (AC/DC/AC), output filter and speed control unit. Optimally variable speeds of diesel engine are optimally controlled in accordance by the load of EGS thus secures the minimum fuel consumption. As a driving engine 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 engine is compact, fully capsuled driving units of high efficiency about 40 % and reliability, low fuel consumption. It is possible to change diesel engine high-speed gas turbine. High-speed turbine has the benefit of a considerable size and weight reduction. When compared with common diesel engine driven EGS, the typical high speed 40 kW EGS driven by gas turbine has the 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 permanent magnet without electromagnetic exiting system are used in many modern applications with VSCF technology (Variable Speed – Constant Frequency). There have maximum efficiency, reliability and high speeds can be reached. Variable speeds of diesel engine correspondent with output voltage and frequency of synchronous generator with permanent magnets (SGPM). The variable voltage and frequency must be stabilized in the constant voltage and frequency by power electronics converter.

Indirect-type converters (AC/DC/AC) are usually used on the whole applications of power converters up to a hundred kW of power. Indirect-type converter is usually set up diode rectifier AC/DC, DC/DC converter and DC/AC converter (inverter). The function of DC/DC converter is stabilized output DC voltage to the required level U_{DC}=570V for inverter to do 3x400 V on the output. The main advantage of diode rectifier is cost, which is few then following conceptions of rectifiers.

There several possibilities how to solve the front end of the system. Instead of diode rectifier as an AC/DC converter, there is a possibility to apply line controlled thyristor rectifier or PWM transistor based rectifies. The advantage of the PWM modulated converter is a sinusoidal current of generator.

The use of matrix converter and cycloconverter is not very common for this sort of application.

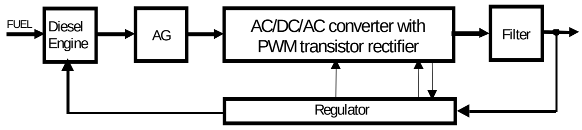


Fig. 4. Concept of EGSG3 with AG

If we use PWM rectifier we can use conception of EGSG3 with asynchronous generator (AG). Schematic diagram of this possible variant EGSG3 is shown in Fig. 4. Asynchronous generator brings smaller price for generator, but greater dimensions, weight and more expensive power electronics converter with PWM transistor rectifier.

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

4. The Optimum Speed Control of EGSG3

The objective of an optimal control is to adjust such a speed of the engine and generator with corresponds to the required power output at optimum speed and at the same time it ensures the minimum of fuel consumption. Analysis of EGSG3 was shown 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.

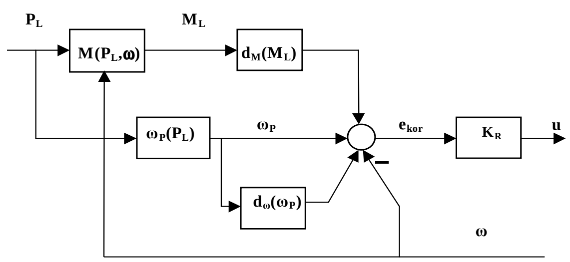


Fig. 5. EGSG3 control system structure

One of the variants of EGSG3 control system structures including three above mentioned control components are given in Fig. 5. This structure corresponds to the chosen control law, given by the relation (1).

$$u = R(\omega, P_L) = K_R\{\omega_P(P_L) + d_\omega[\omega_P(P_L)] + d_M[M_L(P_L,\omega)] - \omega\} \quad (1).$$

Here K_R is the controller gain and d_ω, d_M is 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.

The results of simulations optimum control with respect to the minimum fuel consumption bring following text. Efficiency of EGSG2 for 20 % nominal load is 11 % and efficiency of EGSG3 with optimum speed control is 32 %. Efficiency of both EGSG2 and EGSG3 for 100 % nominal load is 32 %. So maximum efficiency of system EGS is about 32 %, if power output on the load is the same like power generated of diesel engine. This is the primary idea of EGSG3 with optimum speed control.

It is necessary to say that the efficiency of system EGSG3 for 100 % nominal load is lower then efficiency of system EGSG2 for 100 % nominal load. This decrease of efficiency brings additional losses caused by electronics converter in the EGSG3. This decrease is not inconsiderable and therefore it is important to design the converter with highest possible efficiency.

The next results of simulations EGSG3 are given Fig. 6. There is shown the relation between specific EGSG3 fuel consumption and power output for EGSG2 with constant speed (3000 rpm) and for EGSG3 with optimally controlled speed. Values obtained by measurements and experiments on the experiment model of the 3rd generation EGS and on the series of the 2nd generation of generating sets correspond to the expectation and simulation. The maximum fuel economy is for low-load about 40 %.

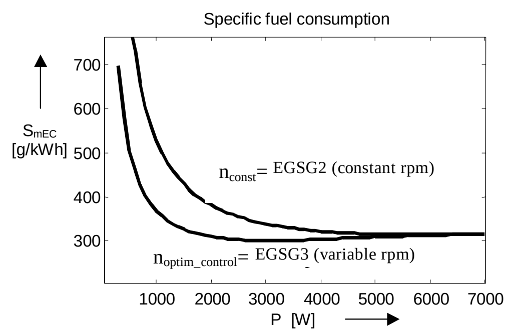


Fig. 6 Fuel economy of EGSG3

5. Experimental Model of EGSG3 with Synchronous Generator

In order to solve fundamental theoretical and research problems of EGSG3 it was decided to build an experimental model, consisting of the chosen driving diesel engine, SGPM, indirect-type converter (AC/DC/AC) and output filter. The photo of experimental model of EGSG3 can be seen in Fig. 7.

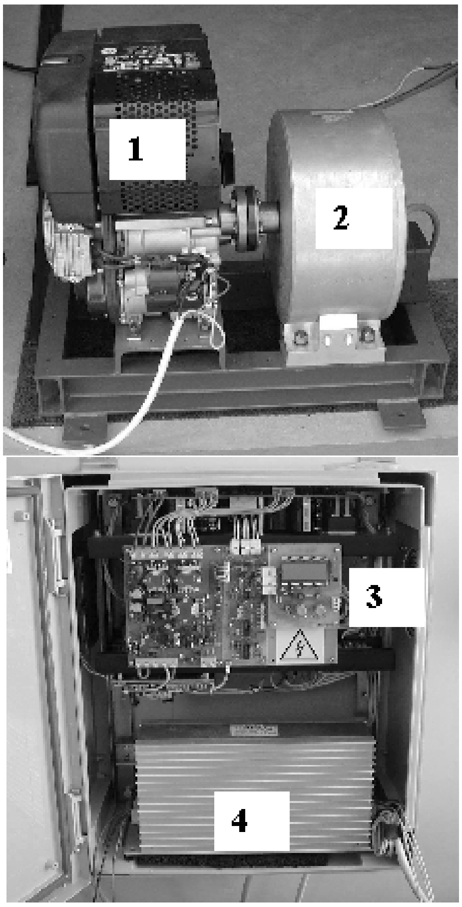
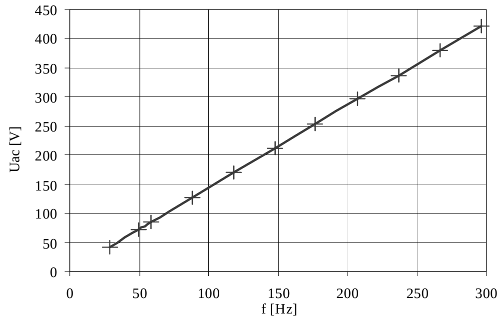


Fig. 7. The photo of EGSG3model (1-diesel engine, 2-SGPM, 3- indirect converter, 4-filter)

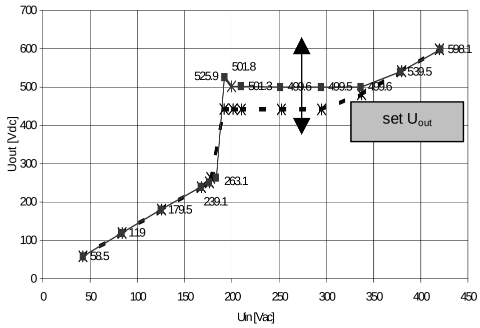
Preliminary calculations and simulations of the 5.5 kW EGSG3 driving part resulted in the choice of the diesel engine with power output 7 kW at 3000 rpm and 3 kW at 1500 rpm. Output characteristic of our 12 pole SGPM connect to diesel engine by means of mechanical clutch can be seen in Fig. 8a. The SGPM output voltage, varying in the range of 200 to 400 V at the frequency 100 to 300 Hz is to be converted to stabilized 570 V_{DC} by AC/DC and DC/DC converters.

Converter (DC/AC) stabilizes the output voltage and frequency (3 x 400 V/ 50 Hz).

Our DC/DC converter is designed as STEP-UP chopper (FORWARD) with two switches connected in serial with diode AC/DC rectifier. If the output voltage of the diode rectifier is less than 570 V then STEP-UP chopper increases the voltage. The output characteristic of DC/DC is shown in Fig. 8b. DC/DC converter must be designed for diesel engine speed region.



a)



b)

Fig. 8a. I/O characteristic of SGPM;
8b. I/O characteristic of DC/DC converter

The schematic diagram of all circuit of indirect converter AC/DC/AC is seen in Fig. 9, which was designed at the Military academy in Brno. It seems our solution is not bed for realizing EGSG3.

Next configuration which is preparing at the Military academy in Brno is based on the configuration of power electronic converter with accumulator (energy storage) between the DC/DC converter. The generator is designed for 42 V and this concep of mobile electrical power source is very like UPC systems (ON-LINE). There brings better solution of EGSG3 then above-mentioned conception, because one of serious problems not yet satisfactorily solved is the system behaviour at high sudden increasing of loads from low loads at low speed close to the idle run to high loads demanding maximum speeds. Configuration with accumulator is viable only for low power EGS.

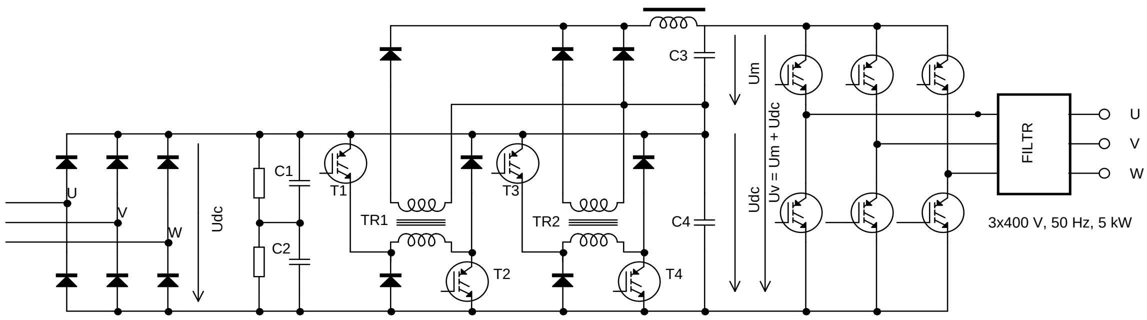


Fig. 9. The schematic diagram of indirect converter AC/DC/AC

6. The Effect of Power Electronic Converter on the Efficiency of EGSG3

Experimental model with indirect-type converter (AC/DC/AC) and synchronous generator with permanent magnets shows us same problems of system is important to solve.

The decrease of efficiency is caused by the power electronic itself and by the effect of power electronic converters on the permanent magnet synchronous generator. This efficiency decrease is not inconsiderable and it is important to design the suitable converter structure with its own high efficiency and with low effect on the generator efficiency. The losses in the generator and converter depend on selected type of converter. Different circuits of power electronic converters can have different generator currents with different harmonics and respective different generator losses. Results of simulation efficiency of synchronous generator with permanent magnets as a function of the speed engine and electronic converter configuration are shown in Fig. 10. The simulations were done by MATLAB with the use of model of high-speed synchronous generator, which was published [2].

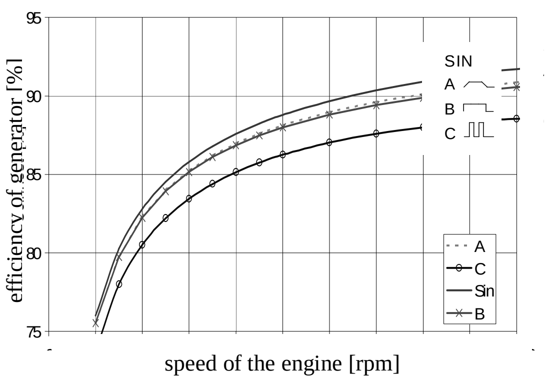


Fig. 10 Calculated efficiency of generator as a function of speed and electronic converter configuration

Two different configurations of power converter are investigated.

The first type of power converter is indirect converter AC/DC/AC with the uncontrolled diode AC/DC rectifier. This topology of converter has nonsinusoidal current from the generator with high current peak containing 1, 5, 7, 11, 13, harmonics. The result of simulation of efficiency SGPM with this connection is mark (A+B+C) in the Fig. 9. The worst efficiency is show by curve (C). This is connection of uncontrolled diode AC/DC rectifier with a large capacitor on the output. Type (A) of converter is the same connection like type (C), but there was an inductor added. Inductor decreases the current peak and gives the better harmonic spectrum. Type (B) shows the effect of neglected commutation of diodes in the circuit.

The second type of power converter is creating a sinusoidal current of SGPM. It is converter with fully controlled transistor rectifier (SIN). And so, the best efficiency of EGSG3 is culminated with controlled rectifier (more 5 % than uncontrolled rectifier). But this solution is more expensive than solution with diode rectifier.

As mentioned above, the main handicap of new concept EGS is higher initial costs EGS then EGS wish constant speed. These initial costs can be higher by 30 % according to kind of power electronic voltage and frequency converter and so it is important to look for a new system topology of electronic converter with high efficiency to take account of results analysis of efficiency and decreasing price. Further solution topology of electronic converter is shown in Fig.11a. This new solution of electronic converter of EGSG3 is based on the idea, to control efficiency of generator as a function of the load [4]. For low load (Fig. 11b, A) is application electronic converter with controlled transistor rectifier and for high load will be used uncontrolled diode rectifier (Fig. 11b, B). As shown above EGS operate often with low load (75%) and so EGSG3 will be operating with highest efficiency for most of operate time. The part of transistor rectifier can be designed for low power to save investment cost. Fig. 11c shows comparison of cost for electronic converter of EGSG3 with controlled rectifier, uncontrolled rectifier and new type of power electronic converter for EGSG3. This configuration will be verified in the near future.

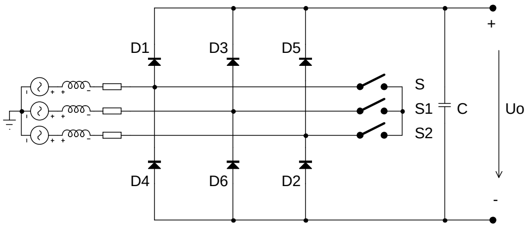


Fig.11a New type electronic converter of EGSG3 as a function of the load

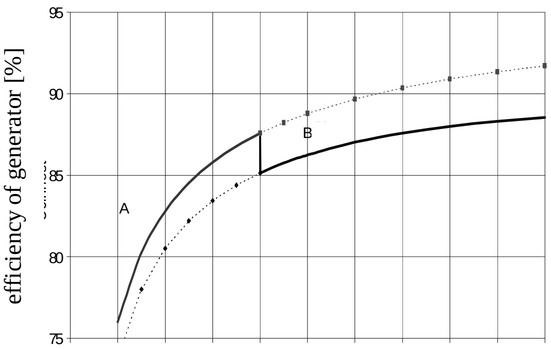


Fig. 11b Output efficiency of generator as a function of the new type of electronic converter

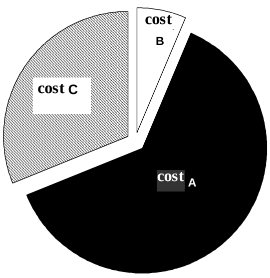


Fig. 11c Comparison of cost for:
A-full controlled rectifier; B-uncontrolled rectifier and C-new type electronic converter of EGSG3

6. Conclusions

The 1st and 2nd generation of EGS operate with constant engine speed corresponding to the required output voltage frequency. Both engine and generator operate often with low efficiency at the low and middle load. Higher efficiency and lower operation costs may be achieved by using new concept of EGSG3 with 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 the minimum fuel consumption optimality criterion. Both the generator output voltage and the frequency are variable and are to be converted to the constant values by power converter.

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

The losses in the generator and converter depend on selected type of converter. Three different configurations of power converter are investigated.

The first type is the fully controlled AC-DC rectifier drawing a sinusoidal current

The second type is connected with the uncontrolled AC-DC rectifier with large capacitor at the output.

The third circuit structure is similar to the previous and combinations the advantage of uncontrolled rectifier (price) and controlled rectifier (efficiency).

7. References

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