POWER MANAGEMENT IN MOBILE ELECTRICAL POWER SOURCES WITH SUPERCAPS AS ENERGY BUFFER

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Abstract. The paper brings some practical results of research devoted to the new generation of mobile electrical power sources (EGS-Engine Generator Sets), based on the VSCF technology (Variable Speed – Constant Frequency). In this EGS the driving motor is optimally controlled in accordance with the load power thus decreasing the fuel consumption. The output voltage and frequency of generator are stabilized by means of power electronics. This paper brings some new analysis and results of the problems with power and voltage drops at sudden increase of the load. The analysis of dynamic behaviour proved, that the disadvatnageous dynamical properties of new concept EGS with VSCF technology could be improved by supercapacitor based energy storage element.

1. Introduction

The mobile electrical power generating sets (EGS) are usually based on the synchronous generator driven by combustion engine. The engine speed is stabilized on the value, corresponding to the required output voltage frequency. The output voltage is usually controlled by means of the generator or its exciters magnetic field exciting current. Such concept of EGS operates with constant engine speed. That can be disadvantageous because the output power of engine *P* [W] and fuel consumption *s* [g·kWh^{-1}] is speed-dependent, as it is shown in Fig. 1. EGS with constant speed concept operates with low efficiency and high fuel consumption on the low loads of EGS.

The 3rd EGS generation (EGS3G) is based on some new technologies [1]. The fundamental difference consists in the optimally changed engine and generator speed in contrary to a constant speed. The optimality criterion secures the minimum fuel consumption in correlation with the instantaneous EGS load.

The historical change from constant speed in EGS to optimally variable speed in EGS3G is based on the analysis of the EGS loading regimes. Due to the low average the EGS load the engine operates often at the superfluous high constant speed (3000 RPM) in uneconomical and from the point of view of the environment undesirable condition. The simplified block diagram of EGS3G can be seen in Fig. 2.

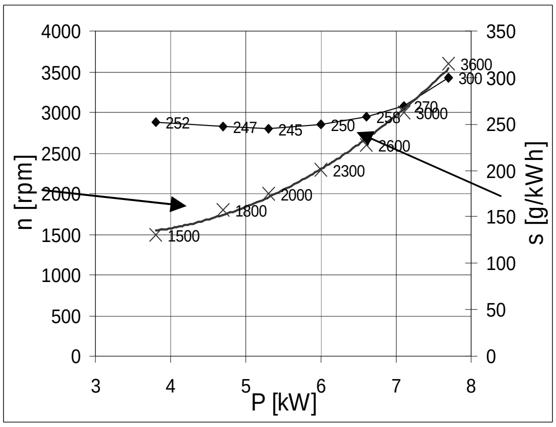

Fig. 1. The fuel consumption and speed as a function of output power of diesel engine

Instead of field excited synchronous machines, the synchronous generators with permanent magnets (SGPM) proved to be the most suitable source of electrical energy in the new concept of EGS. The constant frequency and required output voltage value at variable speed and load is then achieved not by means of the engine speed stabilization and the change of generator exciting current, but by means of power electronics voltage and frequency converters.

The EGS3G can be considered as comparatively sophisticated mechatronic system, consisting of mechanical part, electromechanical energy conversion part, power electronics output power, voltage and frequency transformation and stabilization part including the optimum speed control part based on the microprocessor program.

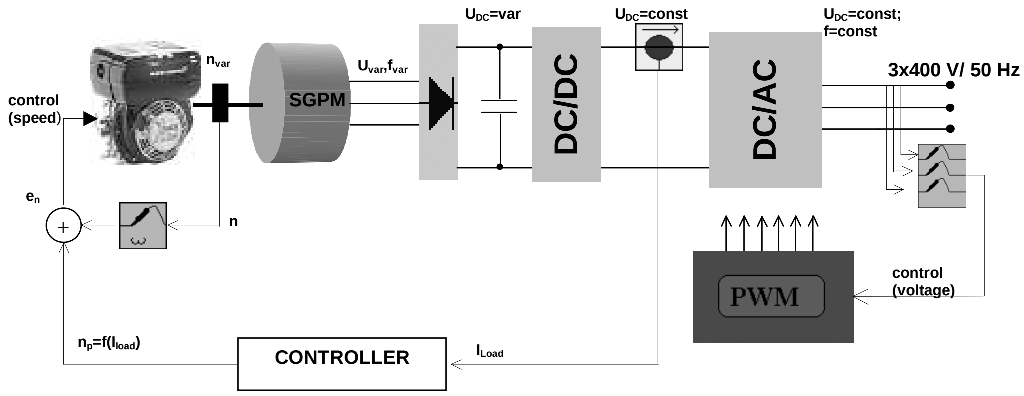

Fig. 2. The simplified block diagram of EGS3G

Fig. 2 shows the system EGS3G with synchronous generator with permanent magnet and AC/DC/AC power electronic converter. In this figure the main control structure of optimum set for every load is shown. Control error e_n is representing difference of required angular speed velocity ω_p of the engine and instantaneous velocity ω. The electrical 3-phase output of generator is connected to the uncontrolled 3-phase 6-pulse diode rectifier. The variable voltage and frequency of generator are function of the engine speed and the output voltage of diode rectifier is function of the engine speed too. The variable output DC voltage must be converted to the constant DC value 570 V by means of DC/DC converter. All power of EGS goes through power electronic converter and output energy is not depending on the EGS load and engine speed.

The main handicap of concept with variable speed of diesel engine is initial costs in comparison with EGS with constant speed. These initial costs can be higher according to the kind of power electronic converter which products output voltage 3x400 V/ 50 Hz. Therefore the choice of the power electronic converter is one of the most important for design considerations of a new concept of EGS.

2. The Analyses of EGS Dynamic Behaviour

Diesel engine, synchronous generator and power electronic converter of EGS has been defined and the system behavior has been simulated in software CASPOC and Matlab-Simulink. The parameters of diesel engine transient responses have been analyzed and identified on the experimental model of EGS consisting of the 7.5 kW driving diesel engine and 12 poles synchronous generator with permanent magnet (Fig. 3).

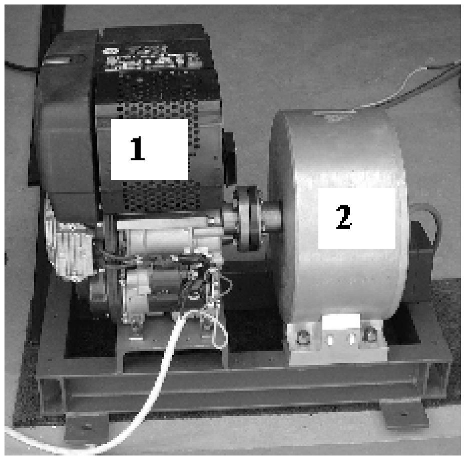

Fig. 3. The photo of EGS experimental model (1-diesel engine, 2-SGPM)

The effect of step change of the load was recorded by an oscilloscope. The change of the load of the generator evokes the change of the torque of diesel engine. Dynamic behaviour of the driving engine in the case of sudden increase of the power output of the generator requires the time about 1 to 7 s to enable the speed change from low to a full speed. The dynamic behaviour of diesel engine can be seen in Fig. 4 and 5.

In Fig. 4 it is possible to see the load change corresponding with change of the power load from 500 W to 1000 W in case of low speed diesel engine (about 1500 RPM). This experiment was done without feedback optimum control speed system during measurement. The change of load evokes changing of engine speed from n_1 to n_2. The load increase creates higher current of generator and consequently higher load torque of diesel engine that is product small speed drop of diesel engine. These drops of speed perform the so-called static error of set inter regulator of diesel engine. In Fig. 4 it is important to notice that current curve was recorded inverted and so load increase evokes decrease of the speed of diesel engine.

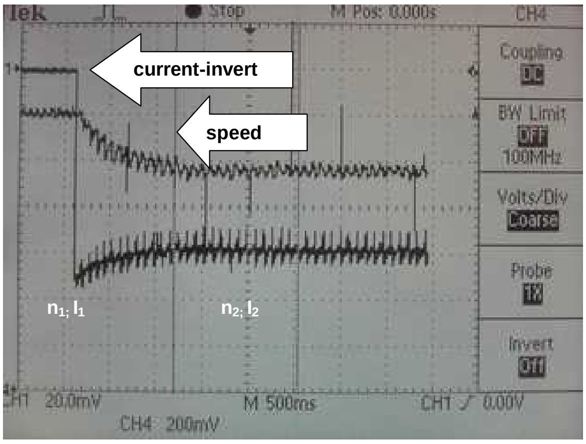

Fig. 4. The low load change at the speed of engine 1650 rpm

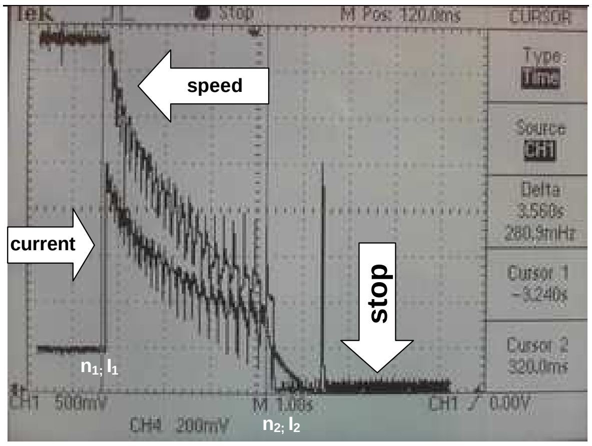

Fig. 5. The load change of EGS from 66 Ω to 14 Ω at the speed of engine 1530 rpm

Fig. 5 shows measurement of sudden load change applied from low load to a high load. During this time required output power is not in balance. The main problem of dynamic behavior of diesel engine can defined as transient from low load to full load. This change can cause stop of the diesel engine. The engine is namely not able to make sufficient torque and EGS source cannot deliver energy to the load.

The mathematical model of EGS system with variable speed and its feedback control was presented in publication [1],[2]. This paper derives mathematical model used in simulation and introduces some interesting results of analyses. As mentioned above the optimal feedback control is to adjust such a speed of the engine and generator which corresponds to the required power output at optimum speed and at the same time it ensures the minimum of fuel consumption. Analysis of EGS3G control system was shown it follows:

- the required course of transient process will be ensured by the feed-back controller;
- steady-state errors will be eliminated by the integral part of the controller;
- 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.

The complete model of EGS in Matlab-Simulink is shown in Fig. 6. Model consists of two parts: the engine and the generator. Generator loads engine by torque MZ. Behind generator there is a model of converter ZM-1 that converts variable AC voltage to the constant DC value of 600 V. The engine is feedback control by regulator RS-2 and calculation of optimum speed for every load is product by RS-1.

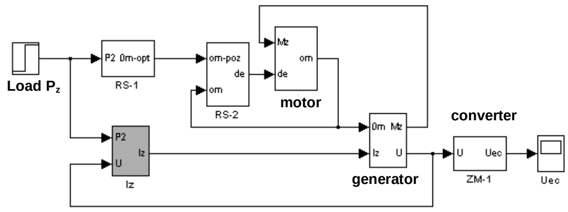

Fig. 6. The model of EGS in Matlab-Simulink for identification of power area

The main characteristics of dynamic behavior of EGS system are characterized by transient process of engine speed and power output, respective current output. Simulation was made with feedback control of diesel engine. Resulting mathematical solution of simplified engine corresponds to the first system order [1],[2] and for periodic transient response can be used P.I.D.-controller with gain at intervals K_ω= 1 to 10. In the Fig. 7 is shown result of simulation for gain K_ω=1. Model was exited by two jumps: the first jump is exited by changed speed of engine from 200 to 300 rad·s^{-1} and second jump presents change of load.

In Fig. 7 is possible to see static error of set speed of engine as in previous fig. 4. The static error can be decreased by means of higher gain of controller.

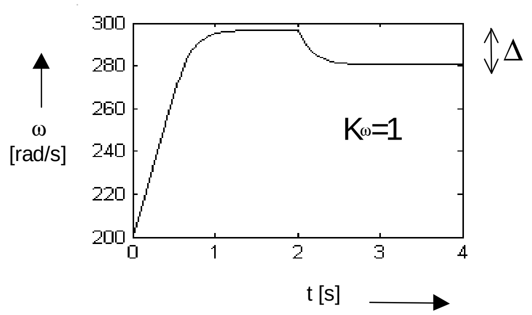

Fig. 7. Transient state of feedback control

The following figures (8; 9; 10) show transient response of loading for various power output (current) with minimum static error. Static errors are eliminated by the integral part of the controller.

The first figure (Fig. 8) was made by means of load change that is required the change of output power from 500 W to 1000 W. This change of the load evokes the change of angular velocity of engine from 102 to 118 rad·s^{-1} by means of feedback speed control.

Fig. 8 is representing difference of required angular speed velocity ω_p of the engine and instantaneous velocity ω. As possible to see the transient process is linear because fuel injection of diesel engine is limited and the regulation time take about 0.3 s.

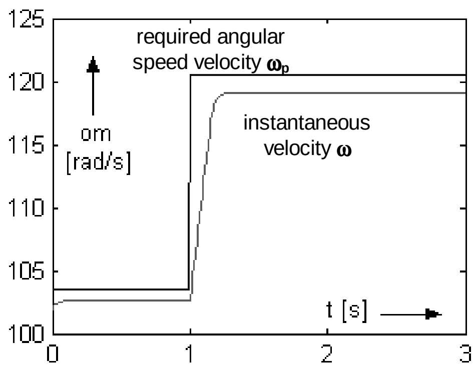

Fig. 8. The transient response for the power jump from 500 W to 1000 W

Figure (Fig. 9) was simulated for load change from 500 W to 2000 W (102 to 150 rad·s^{-1}) and time of regulation is 0.9 s. This transient response is longer then previous from fig. 9.

And so, it is possible to see from Fig. 8 and 9 that higher load change evokes extension of transient responds and so the transient process is function of load. Both example of load change is possible and EGS with variable speed of engine can work safely.

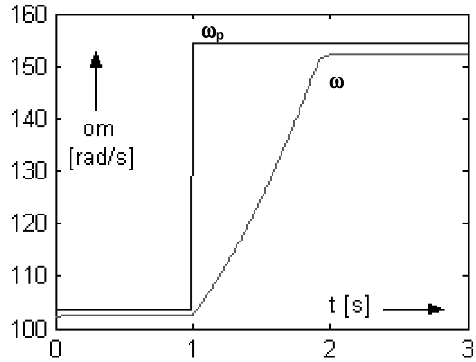

Fig. 9 The transient response for power jump from 500 W to 2000 W

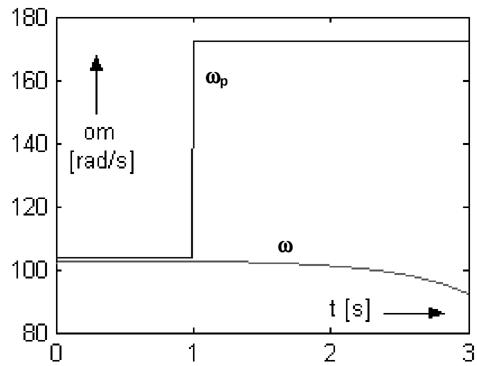

Fig. 10 The transient response for the load change from 500 W to 2700 W

Fig. 10 is shown further result of power load change from 500 W to 2700 W. Results of engine behavior is similar as was shown in fig. 5. In case of increasing of loads from low loads at low speed to high loads the engine cannot products torque that is required by the load and so EGS cannot make enough energy for the load requirement and so EGS cannot operate with this load change.

As mentioned above, the time of speed change is limited and so the dynamic behavior of EGS is limited too. Result of identification possible load change is shown in fig. 11. Figure shows operating power area of EGS for every optimum speed of diesel engine. P_{opt} is power that diesel engine products on the optimum speed, P_{rez} is margin of power for every set speed and P_{max} is maximum power that is possible catch it on the actual speed. And so P_{max} shows maximal energy that is possible and the area of power below P_{max} represents power output of EGS with optimum variable speed according to the load where EGS can operate without any problems and safely. For example: if engine operate with angular velocity 150 rad·s^{-1}, output power generated by EGS is about 2000 W and for this mode EGS can be accepted increase power into 4000 W.

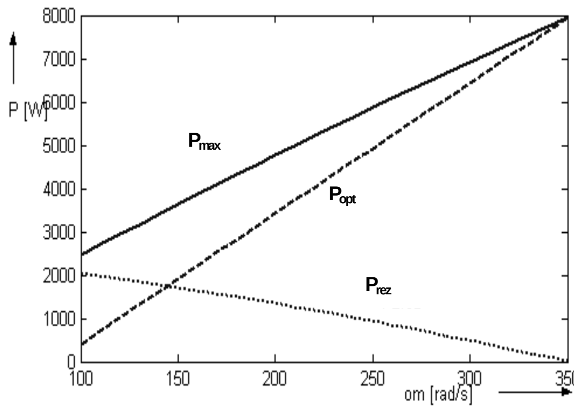

Fig. 11 The identification of power margin

The result of above analyses of dynamic behaviour EGS with optimum variable speed is that EGS cannot by realized as system with optimum speed according to the load that was shown in Fig. 2. The system from Fig. 2 can be realized but diesel engine cannot operate with optimum speed for every load a feed-back of engine must be designed with high speed according to the load that is much more than optimum speed which is uneconomical. The problem is that EGS is not possible to have enough power for every load for every optimum speed of engine and concept EGS must be with energy storage like UPC source (see Fig. 12).

3. The Analyses of used Power Converter

As mentioned in the previous analyses the real drawback of this new EGS concept with optimum variable engine speed is the engine-generator dynamics at sudden transients from low load to high load. Fig. 8 and 9 give transient response of diesel engine from 200 to 300 rad·s^{-1} for various values of the loads. The time of regulation can be much more then results of first (0.3 s) or second case (0.9 s) up to 5 s according to the value of the load and according range of speed change. During this time require power on the load is missing and EGS does not work correctly.

Electronic converter can improve the dynamic behaviour of EGS system by means of inserting accumulated energy to the voltage link of the DC/DC converter (see Fig. 12.). This concept is based on the delivery of peak power from energy storage to the capacitor of DC/DC converter during the regulation time of engine from low to high speed. The equation of storage energy W is given by power P_{max} and average time of regulation T_{reg} (2 s)

$$W = P_{\max} \cdot T_{\mathrm{Re}\,g} \doteq 6000 \cdot 2 = 12\ kJ\ . \qquad (1).$$

The system EGS must include extra energy of 12 kJ for overlap of peak power during speed change from low to a high speed. Three different configurations of energy storage are investigated here. The first type is with the electrolytic capacitor **(A)**, second type is with accumulator **(B)** and the most perspective storage bank is with super-capacitors **(C)**. More information about energy storage is shown in part 4.

Model to simulate EGS with extra source for delivery of the peak energy is shown in Fig. 13. It includes further modules (ZM-2 and ZM-3) that present DC/DC converter and energy storage unit. Module (RS-2) regulates the flow of energy between engine and energy unit.

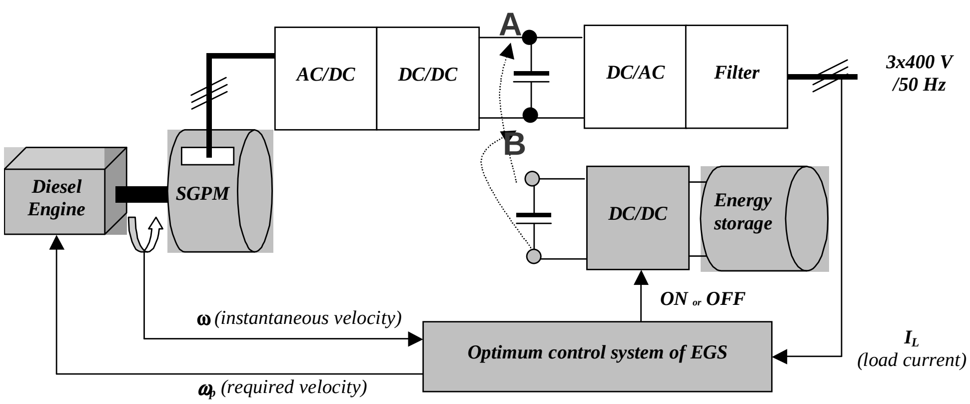

Fig. 12. The EGS system with peak power energy to DC link of AC/DC/AC converter

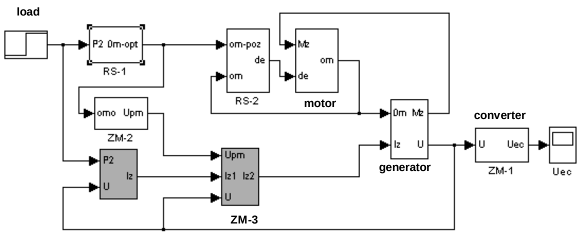

Fig. 13. The model of EGS in Matlab-Simulink with extra source for delivery peak energy

Test of the functionality of extra source for delivery peak energy in EGS was done with load change from minimum to the nominal load that is required the change of output power from 500 W to 7000 W. These change of the load evokes the change of engine angular velocity from 100 to 320 rad·s^{-1}. The result of transient response with extra energy storage unit is shown in Fig.14. The time of optimum speed adjust is about 2 s. During this time is necessary to delivery energy from accumulator or supercapacitor to the load.

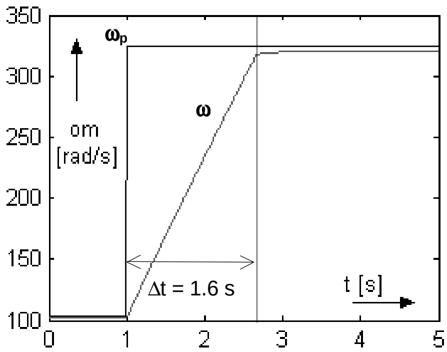

Fig. 14 Transient response of EGS concept with extra energy storage unit for power jump from 500 W to 7000 W

In Fig. 10 was shown because the change of the load from 500 to 2700 W that brought to the stop of engine and EGS couldn't make enough output energy that was request by the load. New behavior of EGS brings satisfactory results for using EGS with variable speed concept.

4. The Analyses of different configurations of energy storage unit.

As mentioned above are possible to used three different configurations of energy storage unit: electrolytic capacitor; accumulator and supercapacitor. This configuration with different energy storage can have same advantageous or disadvantageous properties that are compared in the following text.

A) Storage bank with electrolytic capacitor is feasible but energy of 12 kJ is too high for this solution. Electrolytic capacitor can accumulate very few energy. The equation 2 shows result of capacity value to make energy bank (12 kJ) during 2 s.

$$C = \frac{\Delta t}{\Delta U} \cdot I_d = \frac{\Delta t}{\Delta U} \cdot \frac{P}{U_d} = \frac{2}{50} \cdot \frac{6000}{600} = 0.4\,F \qquad (2).$$

To obtain the figure about the costs of the electrolytic capacitor: Jamicon E2200M/385V cost ±100 Euro (GM electronic, 8.12.2005). Dimensions of this capacitor are 75x105 mm and weight 250 g. Number results of capacitors shows equation 3. Solution of energy bank with 364 capacitors brings radical increasing of weight and price.

$$x = \frac{C_{total}}{C_{cell}} \cdot \frac{U_{nominal}}{U_{cell}} = \frac{0.4F}{2200e^{-6}F} \cdot \frac{800V}{400V} = 364\,[-] \quad (3)$$

B) Solution with accumulator can bring a lot of storage energy. E.g accumulator LONG with (output voltage 12V; capacity 7.2 Ah; dimension is 151x65x94mm; weight 2.68 kg; price 11 Euro) can deliver 6 kW energy with current 125 A during 10 s. The load characteristics of accumulators discharging are shown in Fig. 15.

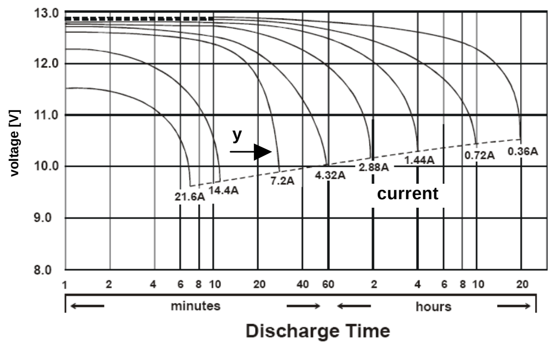

Fig. 15. Discharging of accumulator LONG

Energy of accumulator can be expressed by equation (4). One curve ***y*** of output characteristics from Fig. 15 was approximated by quadratic polynom

$$y = -0.0000012\,t^2 + 0.0006\,t + 12.629$$

and substitution to the equation (4) where we obtained quantity of energy about 158 kJ.

$$W = Q \cdot U = \int_0^t u(t) \cdot I\; dt = I \cdot \int_0^t u(t)\; dt = \qquad (4)$$
$$7 \int_0^{1800} (-0.0000012\,t^2 + 0.0006\,t + 12.629)\,dt \approx 160\,kJ$$

For example: 12 V and 7.2 Ah lead acid accumulator batteries connected in series with output voltage 48 V (4 x 12V) and DC/DC converter with output voltage 600 V_{DC} can accumulate energy cca 640 kJ, see Fig. 15, that is much more than we needed (12 kJ).

High current that is not friendly for operating time of accumulator can be decreased by means of voltage increasing e.g. by series connecting of more of a number of accumulators (25 x 12V). This solution can bring with the same type of accumulators (LONG) a lot of energy (cca 4 kJ) that is available for 8 minute with discharge current 20 A. For smaller current EGS with accumulator bank can operate without running diesel engine more than 1 hour that can be useful for army during military action (without any noise and harmful emissions.

Solution EGS with accumulators brings for both concept of voltage proposals weight increasing of EGS as much as 60 kg. Further way of energy storage can be achieved by super-capacitors. The efficiency of charging and discharging is much higher than solution with accumulator and can bring better relationship between stored energy storage, dimensions and weight then accumulators.

C) Super-capacitors are relatively new, rather expensive and represent one of the newest innovations in the field of the electrical energy storage. Supercapacitors found their place in many applications and opening new area of energy accumulation. There are combined advantageous features both previous techniques of energy storage. The supercapacitors can store much more energy then electrolytic capacitors. Today supercapacitors are readily available with capacity 3500 F. Usually, the accumulators have limitation on life cycles and supercapacitors have just those longer life cycles.

Energy of electrical field of capacitors can be expressed by universal equation (5) including the fact that supercapacitors is not discharged fully but only to half of nominal voltage U_{nom}.

$$W = \frac{1}{2} \cdot C \cdot \Delta U^2 = \frac{1}{2} \cdot C \cdot \left(U_{nom}^2 - \left(\frac{U_{nom}}{2} \right)^2 \right) \quad (5)$$

The resultant of required capacity that can store energy 12 kJ for delivery peak energy for nominal voltage e.g. 100 V of supercapacitors is given by formula (6). Final capacity 3.2 F is very much but realization by means of supercapicitors for on the present is possible.

$$C = \frac{2 \cdot W}{\left(U_{nom}^2 - \left(\frac{U_{nom}}{2} \right)^2 \right)} = \frac{2 \cdot 12k}{100^2 - \left(\frac{100}{2} \right)^2} \approx 3.2\,F \quad (6)$$

In Fig. 16 is shown results of effect of nominal voltage of supercapacitors versus number of capacitors that shows results price; value of time that shows energy possibilities for delivery 6 kW to the EGS load and last dependence is on the average current that will be take from supercapacitor.

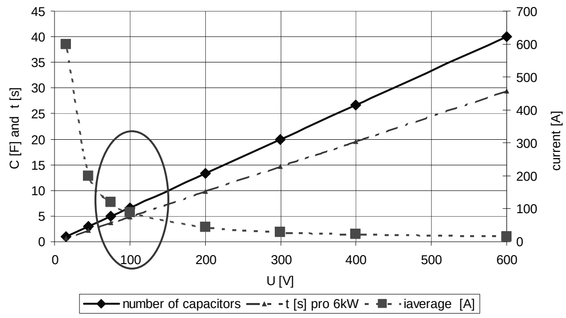

Fig. 16. Optimalisation of design nominal voltage of supercapacitors bank

Every dependence parameters on the nominal voltage of supercapacitors are very important for design supercapacitors bank. I chose modules BPAK0350-15 by company Maxwell and parameters are (58 F; 15 V; DC resistance 19 mΩ; dimension is 216x69x38 mm; weight 0.5 kg; price about 210 Euro). From the figure can be seen to optimum value of nominal voltage is 100 V.

The analyses that were mentioned above shows that the nominal voltage 100 V can by obtained by series configuration of 7 modules of BPAK0350-15. This module can use high charge and discharge current for very fast supercapacitor charge or very quick delivery energy to the load that is very important for concept EGS with extra energy source for delivery peak energy. This concept can store about 34 kJ according to the formula (7) and can delivery 6 kW during 5 s that is enough.

$$W = \frac{1}{2} C \cdot \left(U_{nom}^2 - \left(\frac{U_{nom}}{2} \right)^2 \right) =$$

$$= \frac{1}{2} \cdot \left(C_{cell} \cdot \frac{\#parallel}{\#series} \right) \cdot \left(U_{nom}^2 - \left(\frac{U_{nom}}{2} \right)^2 \right) = \quad (7)$$

$$= \frac{1}{2} \cdot \left(58 \cdot \frac{1}{7} \right) \cdot \left(105^2 - \left(\frac{105}{2} \right)^2 \right) = 34.3\,kJ$$

The main disadvantageous of high nominal voltage is high internal resistance R_i. Internal resistance of single module is 0.002 Ω. Resistance of seven modules is 0.014 Ω that isn't so much in comparison with series combination of 25 accumulators, where the internal resistance is 25x0.06 Ω=1.5 Ω. This internal resistance decline the gain and higher internal resistance decline substantially efficiency of energy storage.

Fig. 17 shows easy comparison of energy storage unit in relation to the price, weight and value of energy storage. Solution of storage unit with electrolytic capacitors is the worst in the all aspects. Accumulators can bring very god relationship between stored energy and price. Accumulator storage unit however brings weight increasing of EGS as much as 60 kg. Supercapacitors bring better relationship between weight and price in comparison with accumulators. It is necessary to introduce, this figure is only approximately because the price of element cannot be binding.

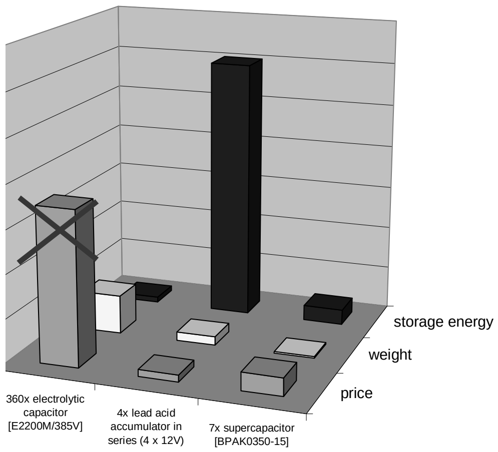

Fig. 17. Comparison of energy storage unit

5. DC/DC Converter for Energy Storage Unit.

Electronic converter in combination with the energy storage unit can improve the dynamic behavior of the EGS system by means of inserting accumulated energy to the inter-circuit of DC/DC converter (was seen in Fig. 12.).

The energy stored in accumulator or supercapacitor must be controlled. This can be realized by means of DC/DC converter. Current of accumulator (supercapacitor) must be controlled so that current flows out of accumulator when the accumulator is discharged or flows into when accumulator is charged. DC/DC converter must be bi-directional and Fig. 18 shows the mode of operation. The DC/DC converter is in BOOST mode operation for delivery of power from accumulator to the capacitor terminals A-B (see Fig. 12). On the other hand, the DC/DC converter is in BUCK mode operation as the regenerative energy comes to accumulator bank. Prototype of 6 kW DC/DC converter is shown in Fig. 19.

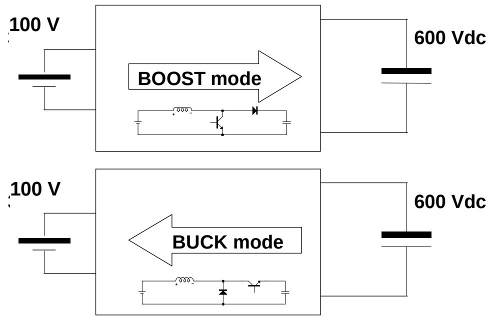

Fig. 18. Concept of bi-directional DC/DC

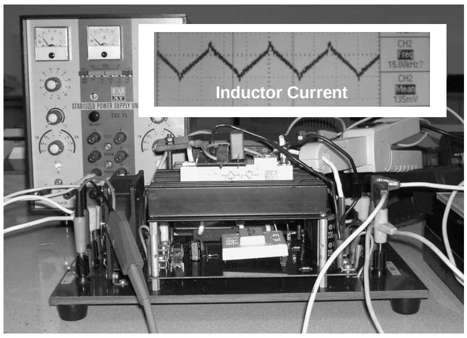

Fig. 19. Prototype of DC/DC converter

6. Conclusion

The mathematical analysis and simulation of dynamic behavior of mobile electrical power sources with VSCF technology proved, that dynamic behavior of diesel engine can affect unfavorable effect on quality of EGS energy. Electronic converter can improve the dynamic behaviour of whole EGS system by means of inserting accumulated energy to the inter-circuit of DC/DC converter. The paper includes detail analyses of solution converter with supercapacitor as energy buffers.

7. References

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