System Variation of Electrical GEN-SET with Energy Buffer

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***Abstract*-- The new generation of Electrical Generator Sets (EGS) is based on the variable speed generation concept. The diesel engine changes the speed according to the load of the set. The optimum speed is hereby calculated according to the load of the EGS with as the optimality criterion the minimum fuel consumption. The analysis of the dynamic behavior of such new EGS concept shows some new problems with power and voltage drops at sudden increase of the load. The dynamical properties of EGS concept with variable speed technology could be improved by using an Energy Buffer. Solutions of concept EGS with the energy buffer and their advantage or disadvantage are discussed in this paper.**

***Index Terms*—Mobile Electrical Power Sources, Electrical GEN-SET, Supercap, VSCF.**

I. Introduction

Electrical GEN-SET (EGS) are used for various machines and appliances to increase their mobility. EGS initially developed and produced mainly for military purposes. They are used in building industry, agriculture, ground and air transport, health service and in other branches of industry and economy. Quite indispensable are the EGS in civil defence, crisis management forces, and naturally in armed and security forces.

EGS usually operate with constant speed of engine. The constant speed corresponds to the required fixed frequency (50, 60 Hz). The oldest EGS was based on the 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 (Fig. 1). Such an EGS were very heavy, difficult to handle, noisy and with low efficiency.

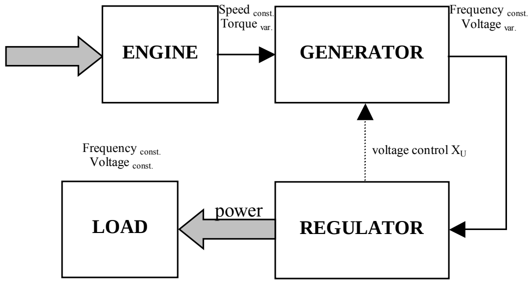

Fig. 1. The system EGS with constant speed of engine.

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Latter generation of EGS with constant speed of engine was characterized by using modern diesel engines, new types of generators (brushless, asynchronous, and synchronous with permanent magnets) and with higher efficiency. Nevertheless these generation EGS operate still on the classical engine-generator concept with constant speed. The relations of efficiency and losses of such EGS systems with constant speed of engine for 7.5 kW system with asynchronous generator are shown in Fig. 2 for 20% of nominal load and Fig. 3 for nominal load.

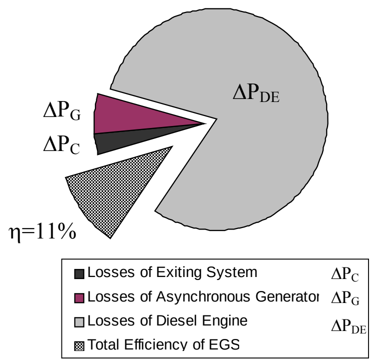

Fig. 2. Efficiency of EGS with constant speed for 20% of nominal load [2].

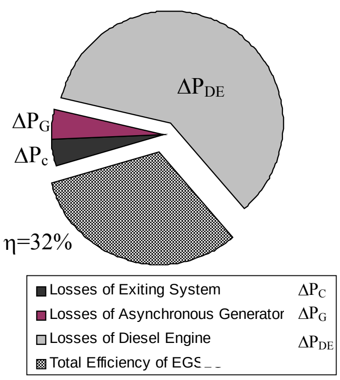

Fig. 3. Efficiency of EGS with constant speed for nominal load [2].

Fig. 2 show that efficiency of EGS for 20 % of the nominal load is cca 11% that is lower then efficiency 32% of EGS for the nominal load (Fig. 3). The losses of a diesel engine are: 80 % for 20 % of the nominal load and 60 % for nominal load. So, the efficiency of EGS as well as fuel consumption is variable according to the load of power. It is possible to say the top efficiency of EGS can be achieved if the engine power is the same as power required by the load. The new concept of EGS with variable speed of engine can achieve better efficiency because the engine with feedback control generates just the right power that is required by the load. Such concept can always operate with efficiency nearly 32 % like EGS with constant speed for nominal load. Fig. 4 shows the system of EGS with optimum variable speed of engine.

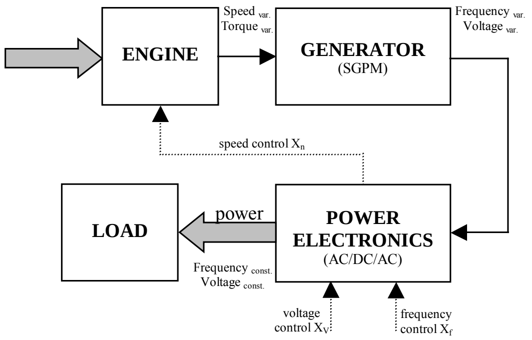

Fig. 4. The system EGS with optimum variable speed of engine

The concept of EGS with variable speed can brings some primary benefits:

- the fuel consumption savings for low and middle load (Fig. 5) and so increasing of EGS efficiency 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.

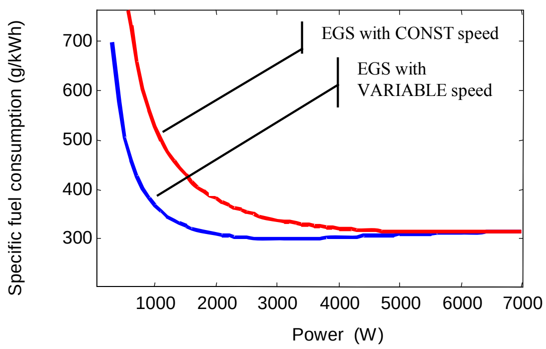

Fig. 5. The fuel economy of concepts EGS

The main disadvantage of concept EGS with variable speed are:

- higher initial costs (according to the kind of power electronics converter);
- higher requirements of maintenance;
- decreasing of efficiency for nominal load [1,3];
- higher weight and dimension;
- the worse dynamic behavior of system with variable speed than concept with constant speed [2].

II. Dynamic Behavior of EGS with Variable Speed of Engine

The control of the engine-generator set speed in the dependence on the instantaneous EGS load can decrease the fuel consumption at low loads, as shown in Fig. 4. The engine speed of rotation is to be optimally controlled in such a way, as to adjust the operating regime for every load to the corresponding power output and torque with the minimum fuel consumption optimality criterion. The real drawback of this approach is the engine-generator dynamics at sudden transient from low load to high load. The following results of experiments (Fig. 8 and 9) show the oscilloscopic records of dynamic behavior of the EGS with variable speed of engine of experimental model that is consisted of the modern diesel engine with power output 7.7 kW for 3600 rpm and 3.8 kW for 1500 rpm (Fig. 6) and 12 poles of synchronous generator with permanent magnets (SGPM). The output characteristic of generator is shown in Fig. 7.

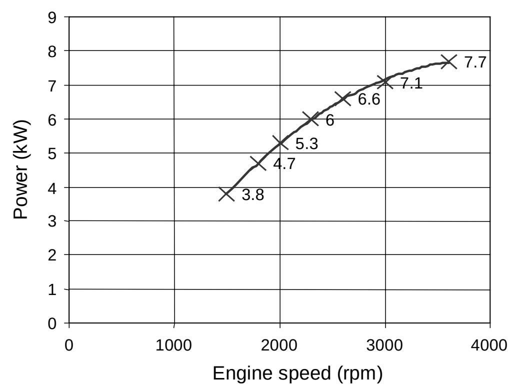

Fig. 6. The power output of engine as function of engine speed

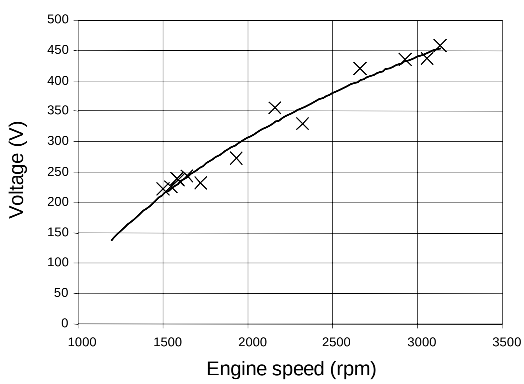

Fig. 7. The power output of engine as function of engine speed

The output voltage of generator is varying in the range from 150 V to 450 V at the frequency 100 to 300 Hz that must be converted by means power electronics that are set up from AC/DC, DC/DC and DC/DC converter (AC/DC/AC) to the three-phase 400 V/ 50 Hz. More details will be shown in chapter III and Fig. 13.

As mentioned above the Fig. 8 shows the results of dynamic behavior measurements of EGS with a variable speed of engine. The yellow curve (CH 1) is current of AC/DC rectifier and the ret curve (CH 4) shows engine speed. The output power is calculated from output DC voltage and DC current. The result of calculation is shown as violet curve (MATH). The load change from low load to higher load is given by point *A* in the figure. In time t_1 system was loaded by load power 640 W at the speed of 1560 rpm. In time t_2 the power load was change from 640 W to 2480 W. During this time (580 ms) the transient process is in progress. Time t_3 show steady state of system. The speed drop Δn that is 160 rpm is a so-called static error e_s of the inter-regulator of diesel engine. Time constant of a diesel engine T_C is cca 0.6 s.

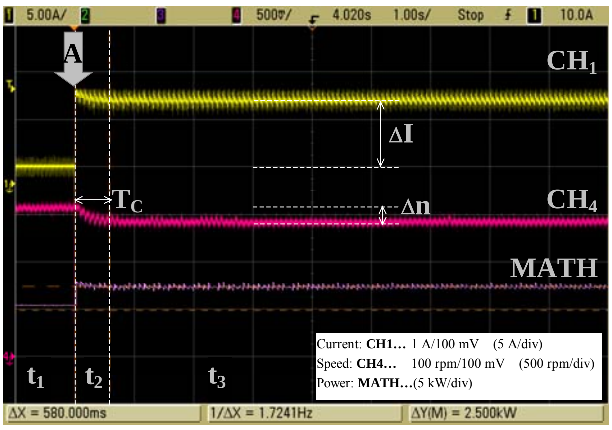

Fig. 8. The low load change at the speed of engine of 1560 rpm

Fig. 9 shows the main results of dynamic behavior measurement of load power change from 448 W to the 5.6 kW at the engine speed of 1460 rpm. Such power load change stops the diesel engine, as shown in time t_2. The engine is namely not able to make sufficient torque and EGS source cannot deliver energy to the load.

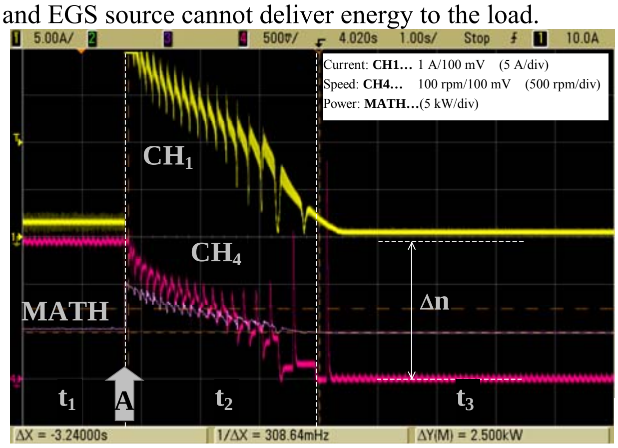

Fig. 9. The load change of EGS from 0.6 to 6 kW at 1440 rpm

The previous measurement from Fig. 9 indicates that the main disadvantage of a concept EGS with variable speed are dynamic behavior properties. The real weak point of EGS with variable speed can be defined as an unsatisfactory reliability of power transfer from engine to the load because of the low dynamic behaviors of EGS. So, the dynamic behavior of EGS with variable speed is limited that is very serious. The diesel engine cannot operate with optimum speed for every load and it is not possible to have enough power for every load for every optimum speed of engine and EGS must be accomplished with energy storage buffer like system UPC.

III. Energy Buffer Used to Improve Dynamic Behavior

Energy buffer must be used to improve dynamic behavior of concept EGS with variable speed of engine at sudden transients from low load to high load. Energy buffer connected via an electronic converter can improve the dynamic behavior of EGS system by means of inserting accumulated energy to the voltage link of the DC/DC converter, Fig. 10. This concept is based on the delivery of peak power from energy buffer to the link capacitor of DC/DC converter during the change of engine speeds.

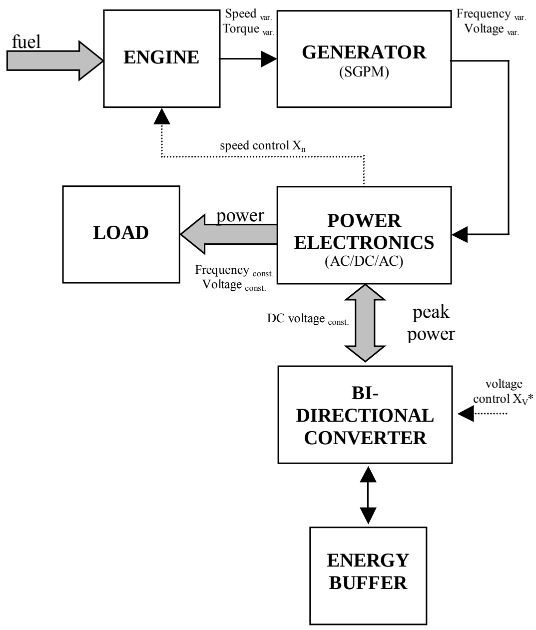

Fig. 10. The system EGS with variable speed and with energy buffer

The requested energy W is given by maximal required power P and average time of the regulation T_R. According modeling [2] it is necessary to cover energy of 6 kW during cca 2 s, see Eq. 1. T_R is time that is required by means of the most disagreeable mode of EGS [3].

$$W = P \cdot T_{Reg} \doteq 6000 \cdot 2 = 12\ kJ \qquad (1)$$

According eg. 1 the system of EGS with energy buffer must include extra energy of 12 kJ for overlap of peak power during speed change.

Energy buffer can be feasible with electrolytic capacitors but 12 kJ of energy is too high for series connection of electrolytic capacitors that products high cost of such energy buffer. Advantage of using the electrolytic capacitors is its easy implementation insertion directly to the link without additional of power Bi-directional converter.

Solution of energy buffer with accumulators can bring a lot of storage of energy, much more than is hereby necessary (12 kJ) [2], but on the other side the EGS with accumulators brings weight increase that is unadvisable.

Energy buffer with Supercaps can bring ideal solution because the efficiency of charging and discharging is much higher than solution with accumulator. Supercaps represent one of the newest innovations in the field of the electrical energy storage. The capacity of Supercaps that can store energy of 12 kJ for delivery of the peak power for nominal voltage e.g. 100 V is 3.2 F (Eg. 2.) that is possible to realized without any technical problems.

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

Fig. 11 shows [2] some selected individual aspects of comparison of energy buffer in the relation to the price, weight and value of energy storage. Solution of energy buffer with electrolytic capacitors is the worst in the all aspects. Accumulators can bring very good relationship between stored energy and price. Accumulator storage unit however brings weight increasing of EGS as much as 60 kg. Supercaps bring better relationship between weight and price in comparison with accumulators. It is necessary to notice that, this figure is only approximately because the price of element is changing.

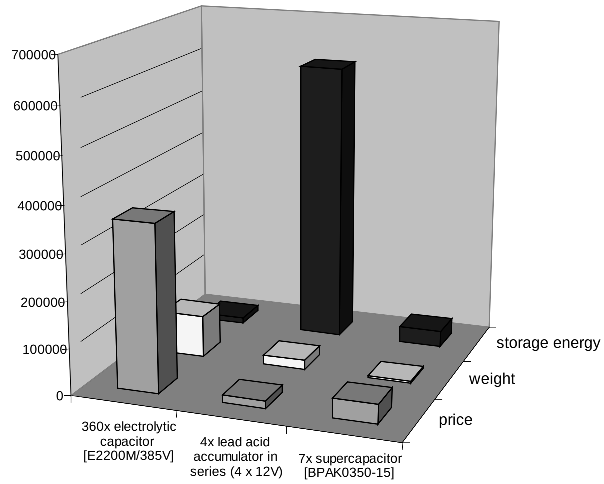

Fig. 11. Comparison of energy buffers solution

IV. Bi-directional DC/DC Converters for Energy Buffer

As mentioned above the energy buffer and bi-directional converter created a peak power for delivery scare energy during changing speed of engine. The output characteristics of engine and generators were shown in the Fig. 6 and 7 as a function of engine speeds. Output variable voltage of generator corresponds to the variable engine speed. Output variable AC voltage must be converted to the constant AC voltage by means of power electronics. A lot system with variable speed technology (VSCF - Varieble Speed - Constant Frequency) is used as concept AC/DC/AC converter. Output voltage of generator is rectified by means of three-phase AC/DC diode rectifier. If the output voltage of a three-phase diode rectifier and generator is less than 570 V than DC/DC converter increases the voltage that DC/AC converter may to transformed DC voltage to the constant three-phase AC voltage (400 V/ 50 Hz). Detail of our EGS power electronics converter can be seen in Fig. 12.

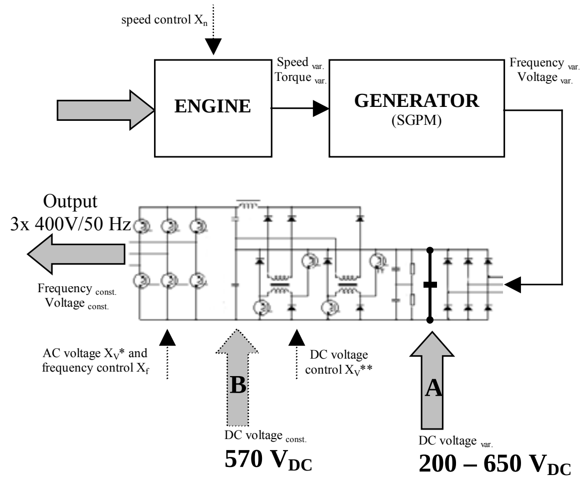

Fig. 12. The system EGS with optimum variable speed of engine and detail of power electronics converter

The function of AC/DC/AC converter is apparent from figure. The output voltage of diode rectifier corresponds to the output voltages of generator, see Fig. 7 and 13 (U_{DC}_AC/DC). The output voltage of diode rectifier is varying too as varying output voltage of generator according engine speeds.

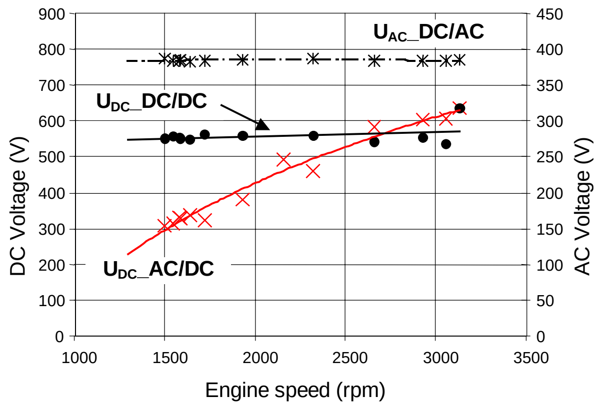

Fig. 13. Output voltage of AC/DC/AC as a function of engine speed

DC/DC converter is designed as a step-up chopper (FORWARD). If the output DC voltage of the rectifier is less than 570 V then the chopper increases the voltage.

The output characteristic of DC/DC converter (U_{DC}_DC/DC) is shown in Fig. 13. Figure shows that the output DC voltage of DC/DC converter is stable. Output EGS voltage (3x 400 V/50 Hz) is made by using a frequency DC/AC inverter. The output voltage of inverter (UAC_DC/AC) is shown also in Fig. 13.

In the Fig. 12 was shown the system of EGS electronics with two possibilities (A or B) of using a bi-directional converter wish supercaps to the DC link of AC/DC/AC converter. The fist connection (B) requires DC link of rectifier and the second (A) require DC link of DC/DC. Both cases are possible to use for connection with energy buffer according Fig. 10. As mentioned below, connection (B) required lower value of output voltage of bi-directional converter because the problems of dynamic behavior are series only for low speed up to the 2000 rpm that is presented cca 400 V on the rectifier output. The connection (A) requires always 570 V on the output of bi-directional converter. In the Fig. 14, 15 are shown two main topologies of bi-directional converters.

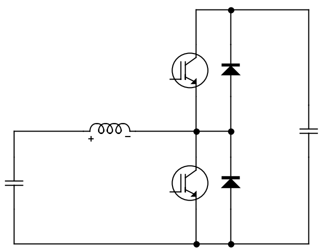

Fig. 14. Bi-directional converter with inductor

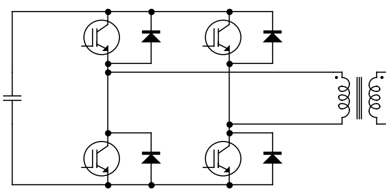

Fig. 15. Bi-directional converter with transformer (full-bridge)

The first topology is widely known non-isolated bi-directional converter topology that is good at price. The main disadvantage of this topology is that the voltage gain is limited (max 3x). Second topology of bi-directional converter with transformer is used as a topology *full-bridge.* Full-bridge topology makes it possible high voltage gain between input and output. Disadvantage of full-bridge topology can be high number of transistors and thereby the cost of converter is increasing. Cheaper solution with transformer is topology *half-bridge* or *push-pull* (Fig. 16). Disadvantage of push-pull is his transformer that is complicated and this topology is preferred for low power application.

Special connections of non-isolated bi-directional converter topology from Fig. 14 are topology of parallel connection (see Fig. 17). Topology makes higher voltage gain possible. Serial connection is possible, but it is not interesting because this solution requires higher number of capacitors that products higher dimension of converter.

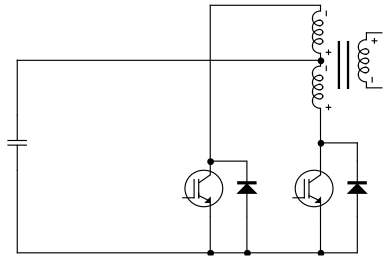

Fig. 16. Bi-directional converter with transformer (push-pull)

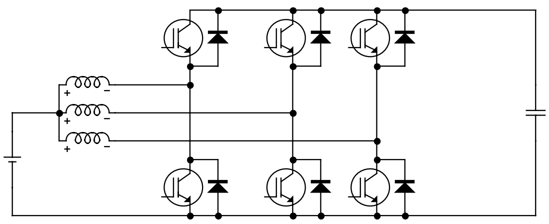

Fig. 17. Bi-directional converter of parallel connection

The system EGS with the cheapest solution of bi-directional converter according Fig. 14 connected to the DC link of rectifier is shown in the Fig. 18.

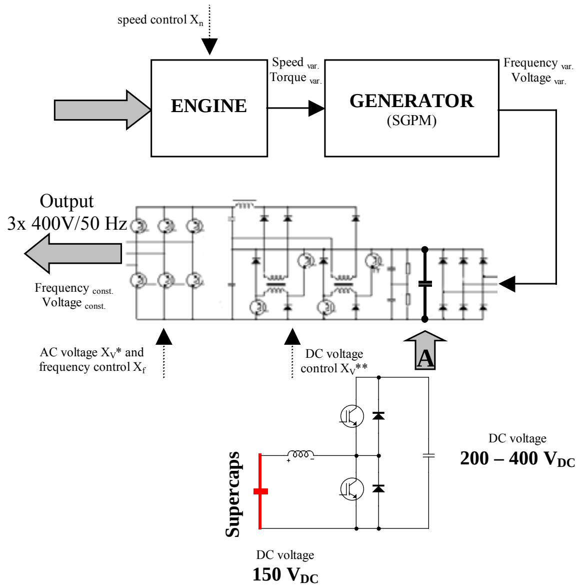

Fig. 18. The system EGS with optimum variable speed of engine and with energy buffer

Bi-directional converter according Fig. 17 can make reduce of nominal voltage of supercaps under 100 V, that bring decreasing of price of supercaps buffer, but the value of current of converter are not profitable. In the Fig. 19 is possible to see the results of optimalization of output supercaps voltage by means of BPAK0350-15 moduls. Figure shows effect of nominal voltage of supercaps 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 supercaps. From the figure can be seen to optimum value of nominal voltage is 100 V. Voltage 100 V can by obtained by series configuration of 7 modules of BPAK0350-15 that can store about 34 kJ according to the formula (2) and can delivery 6 kW during 5 s that is enough.

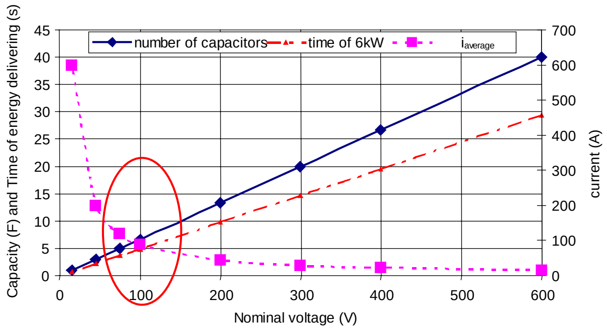

Fig. 19. Optimalization of nominal voltage design of supercaps buffer

Bi-directional converter according Fig. 17 there is set by three parallel branches of converter according 14 can be modified as connection with only two parallel branches of converter for nominal voltage 100 V. This solution can bring optimal topology of power electronic of EGS with energy buffer.

The less acceptable of EGS concept is system with connecting a bi-directional converter on the output DC/DC conveter (Fig. 20). There is required a voltage gain from 100V to 600 (6x) that is set much greater of requirement on the bi-directional converter and so high requirement on the price.

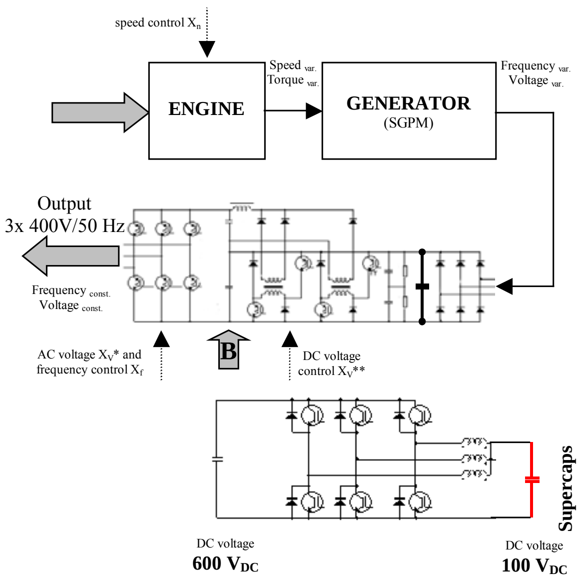

Fig. 20. EGS with variable speed of engine and with energy buffer

V. The Verification of EGS with Energy Buffer

The results of a functionality testing of the energy buffer for delivery peak energy in EGS are shown in Fig. 21. The verification of EGS with energy buffer brings satisfactory results. In Fig. 21 the yellow curve (CH 1) is the same as Fig. 9 and 10 show current of rectifier and the ret curve (CH 4) show engine speed. Output DC voltage shows green curve (CH 2). The output power is shown violet curve (MATH) that is calculated from output DC voltage and DC current. In time t_1 system was loaded by load power 1 kW at the speed of 1700 rpm. In time t_2 the power load was change from 1 kW to 4.5 W. During this time (1.24 s) the transient process is in progress and power is delivered from energy buffer. Time t_3 show steady state of system. Is possible to see the system accepted the change of power load and feed-back control of engine speed set a optimal speed of engine.

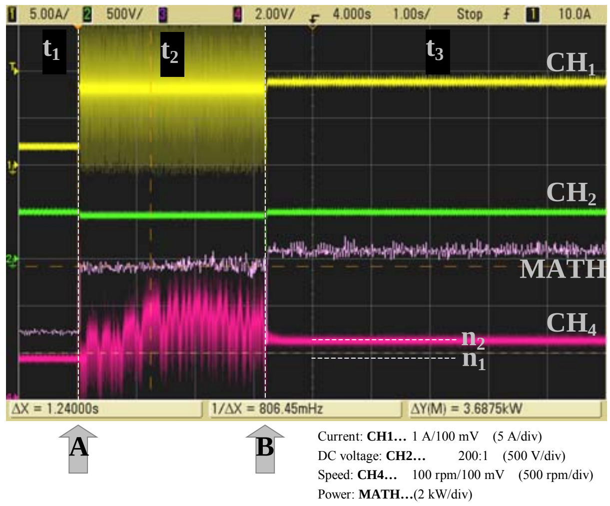

Fig. 21. The verification of EGS concept with energy buffer

VI. Conclusions

The analysis of dynamic behavior of electrical GEN-SET with variable speed of engine proved, that dynamic behavior of diesel engine can affect unfavourable effect on quality of EGS energy. Electronic converter can improve the dynamic behavior of whole EGS system by means of inserting accumulated energy to the DC link of AC/DC/AC converter.

The paper includes detail analyses of system variation of energy buffers and shows bi-directional converters for using in the storage with high efficiency in reference to price. Furthermore in the paper a very important an experimental verification of above described solution of energy buffer of EGS with variable speed of engine. Results: concept EGS with variable speed of engine can be applied. More details of verification of a EGS concept with energy buffer is summarized in [3].

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