Generator-Converter Set for Mobile Power Sources

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Abstract - The feasibility of the mobile power source for speed with diesel generator (~3000 rpm) and high speed with gas generator (~30000 rpm) and permanent magnet synchronous generator is investigated. Three different configurations of power converter are considered. The natural question arises: should be a full controlled rectifier employed or a version with diode rectifier is satisfactory? Does the high speed generation change anything in the investigation? Different current forms for the three defined configurations with their harmonics and influence on generator are given. The efficiency of the overall system is here investigated and an optimal topology is selected. Since the EGS operates very often under low load which does not exceed in average more than 20 % of the rated permanent load, a new hypothetical topology of converter of EGS with high efficiency and low cost is suggested and studied theoretically and experimentally in the paper.

I. INTRODUCTION.

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 main priority 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 3x 400V, 50 Hz). Therefore it is necessary to introduce a power electronic converter to the new EGS structure to allow for variable speed. Such a structure is depicted in Fig. 1.

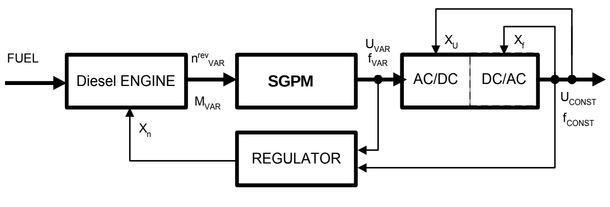

Fig. 1. Flow diagram of EGS new concept

Resulting function of relation between specific fuel consumption of generation EGS with constant speed of engine and new generation of EGS with optimum variable speed of engine is shown in Fig. 2. The biggest improvement of the fuel economy is achieved at low-load.

EGS very often operates under low load which does not exceed in average more than 20 % of the rated permanent load. So new concept with optimum variable speed of EGS can operate with bigger efficiency then EGS with constant speed most of the operating time.

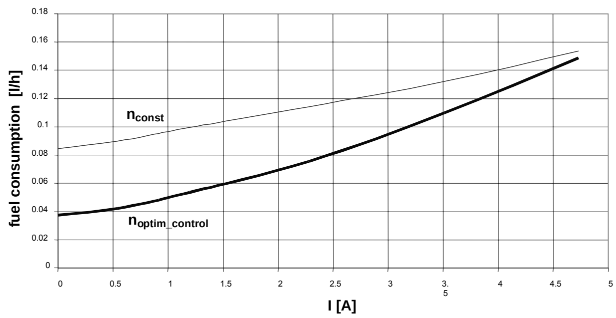

Fig. 2. Comparison of the fuel economy of EGS with constant speed and optimum variable speed

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 EGS concept is higher initial costs in comparison with EGS operating with constant speed. These initial costs can be higher by 30 % according to the kind of power electronic converter which must be used in the concept EGS with variable speed to be stabilized output voltage and frequency of EGS.

II. SYSTEM VARIATIONS

Fig.1 shows the system configuration with diesel engine, synchronous generator with permanent magnets (SGPM), AC/DC/AC converter and speed control unit. The synchronous generator is connected to the rectifier. The natural question arises: is version with diode rectifier satisfactory or should be a full controlled rectifier employed? Does the high speed generation change anything in the investigation?

The losses in the generator and converter depend on the selected type of converter. Three different configurations of power converters are investigated in this paper. The first type is the fully controlled PWM transistor rectifier drawing sinusoidal current (configuration A, Fig.3). The second type (B) is uncontrolled diode rectifier with a large capacitor filter at the output. This topology draws non sinusoidal current from the generator with large current peaks. The third type (C) is uncontrolled rectifier with an inductive filter at the output of rectifier.

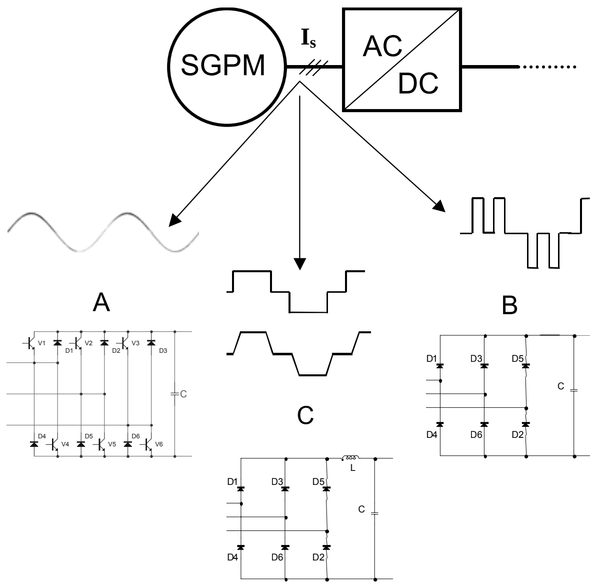

Fig. 3 Different configuration of power electronic converter

Different converter configurations have different losses. The shape of the current drawn by the power converter has influence on the losses of the generator. Therefore the efficiency of the overall system is here investigated and an optimal topology is selected.

III. LOSSES IN THE POWER CONVERTER AND PRODUCED HARMONICS

To solve fundamental theoretical and research problems of losses in the power converter it was decided to build an experimental model, consisting of the chosen driving diesel engine, synchronous generator with permanents magnet, indirect-type converter (AC/DC/AC) and output filter. The photo of experimental model of new generation EGS can be seen in Fig. 4.

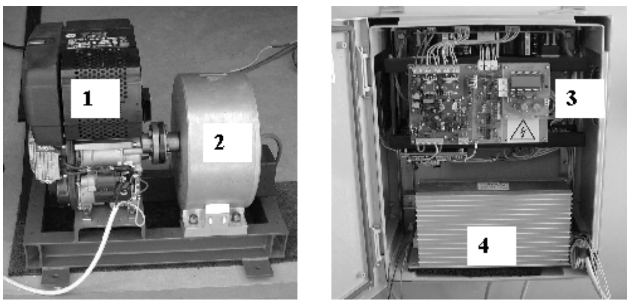

Fig. 4. The photo of EGS experimental model (1-diesel engine, 2-SGPM, 3- indirect converter, 4-filter)

The range of output voltage and frequency of our 12 poles SGPM connected to the diesel engine by means of mechanical clutch are from 200 to 400 V_{ac} and 150 to 300 Hz. This voltage and frequency of the generator has to be converted to 3x400 V/ 50 Hz using AC/DC/AC converter. The schematic diagram of the power AC/DC/AC converter is given in Fig. 5.

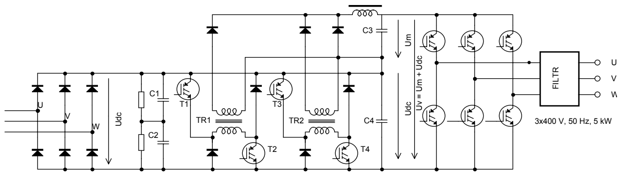

Fig. 5. The schematic diagram of indirect converter AC/DC/AC

As shows in Fig. 5, as AC/DC converter is used three-phase diode rectifier. DC/DC converter is designed as STEP-UP converter (FORWARD). If the output voltage of the diode rectifier is less than 570 V then STEP-UP DC/DC converter increases the voltage. Measured efficiency of AC/DC and DC/DC is shows in Fig. 6 as function of load at the output and speed of the diesel engine.

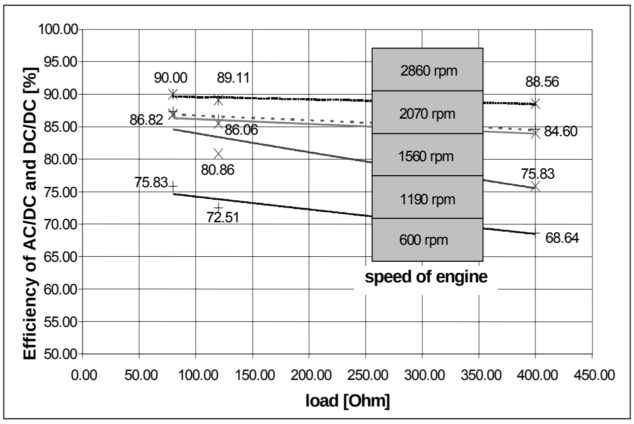

Fig. 6. Efficiency of AC/DC and DC/DC

Our solution of electronic converter of EGS has total efficiency 81% and the losses in the power converter are distributed as follows:

- AC/DC - 5%;
- DC/DC - 7%;
- DC/AC - 5%;
- controls components and others – about 2%.

The losses are created mainly in the switching elements and transformers of the DC/DC converter. Total efficiency of EGS is decreasing from 32% to 28% by losses in the electronic converter.

Converter also adds extra losses in the synchronous generator of the EGS system. Current harmonics of electronic converter create extra losses injected into generator. The effect and results of the analyses are shown below.

Harmonics of different current waves are expressed analytically. To simplify the solution (e.g. from the Fig. 3, eventuality C without neglecting the commutation) the current is expressed by Fourier analysis equation (1).

$$i_s(t) = \frac{2\sqrt{3}}{\pi} \cdot i_{dc}(\sin\omega_1 t - \frac{1}{5}\sin 5\omega_1 t - \frac{1}{7}\sin 7\omega_1 t + \frac{1}{11}\sin 11\omega_1 t + ... \quad (1)$$

In this case the produced harmonics are of order (2) :

$$(k \cdot 6 \pm 1), \tag{2}$$

where k = 1, 2, 3...
If the commutation is not neglected the current form from Fig.3 C is expressed by equation (3):

$$i_s(t) = \frac{2\sqrt{3}}{\pi} \cdot I_d \cdot \left(\begin{array}{l} \frac{\sin\frac{\mu}{2}}{\frac{\mu}{2}} \sin(\omega_1 t) - \frac{1}{5^2} \frac{\sin\frac{5\mu}{2}}{\frac{\mu}{2}} \sin(5\omega_1 t) - \frac{1}{7^2} \frac{\sin\frac{7\mu}{2}}{\frac{\mu}{2}} \sin(7\omega_1 t) \\ + \frac{1}{11^2} \frac{\sin\frac{11\mu}{2}}{\frac{\mu}{2}} \sin(11\omega_1 t) + \ldots \end{array} \right) = \tag{3}$$

$$= \frac{2\sqrt{3}}{\pi} \cdot I_d \sum_{h=1,5,7,11,\ldots}^{\infty} \frac{1}{h} \frac{\sin\frac{h\mu}{2}}{\frac{h\mu}{2}} \sin(h\omega_1 t)$$

Equation (4) describes the influence of diode conduction δ on the current $i_s(t)$ with connection of uncontrolled rectifier and inductor L. (e.g. from the Fig. 3, eventuality B).

$$i_s(t) = \frac{2\sqrt{3}}{\pi} \cdot I_{dc} \cdot \left(\begin{array}{l} \frac{\sin\frac{\delta}{2}}{\frac{\delta}{2}} \sin(\omega_1 t) - \frac{1}{5^2} \frac{\sin\frac{5\delta}{2}}{\frac{\delta}{2}} \sin(5\omega_1 t) - \frac{1}{7^2} \frac{\sin\frac{7\delta}{2}}{\frac{\delta}{2}} \sin(7\omega_1 t) \\ + \frac{1}{11^2} \frac{\sin\frac{11\delta}{2}}{\frac{\delta}{2}} \sin(11\omega_1 t) + \ldots \end{array} \right) = \tag{4}$$

The amplitude of the h-harmonics of the current $i_s(t)$ is described by equation (5). This equation is showing functional relation between amplitude of h-harmonic current $i_s(t)$ and the first harmonic of current $i_s(t)$.

$$i_h = \frac{1}{h} \cdot I_1 \cdot \frac{\sin\frac{h \cdot \delta}{2}}{\sin\frac{\delta}{2}} \tag{5}$$

Diode conduction angle δ is dependent on size of the capacitor and amount of energy. Therefore it is important for diodes to keep flowing current for the longest time.

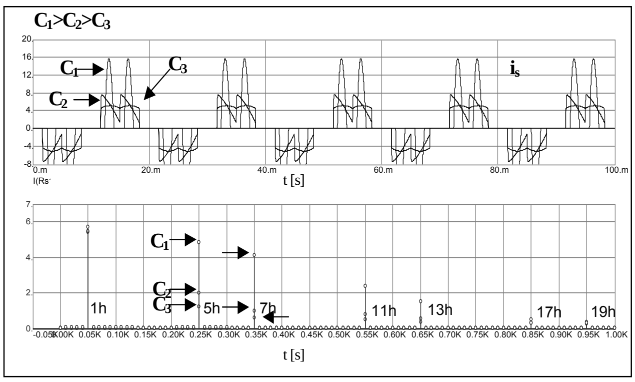

Fig. 7 Capacitor effect for harmonics spectrum of current $i_s(t)$

Results of capacitor effect eventuality C for harmonics current spectrum are shown in Fig. 7. Bigger capacitor results in higher harmonics distortion and the worse current spectrum of generator.

IV. ANALYSIS OF LOSSES IN SYNCHRONOUS GENERATOR

It is necessary to do the loss analysis of synchronous generator based on the current wave drawn by the electronic converter as expressed by equations (1),(3),(4). Different circuit of electronic converters can draw different current of generator $i_s(t)$ with different content of harmonics and different losses in the generator too. The waveforms of the current drawn from generator are given in Fig. 3. To calculate the losses in high-speed PM generator with rectifier a model of a generator (in Fig. 8) is suggested and verified [2],[8].

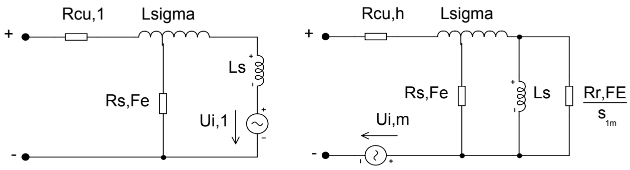

Fig. 8 The equivalent circuit of SGPM for
a) fundamental time harmonic b) higher time harmonics [2]

The cupper losses ΔW_{CU} of generator are expressed by resistor $R_{s,CU}$, where $R_{CU,1}$ express cupper losses by first harmonic and $R_{CU,h}$ express cupper losses by h-harmonics. The cupper losses are calculated only for the stator.

The iron losses ΔW_{FE} of generator are expressed by resistor $R_{s,FE}$ connected in parallel with inductance L_s and leakage inductance. Iron losses ΔW_{FE} of stator are expressed by $R_{s,FE}$ and iron losses of rotor are expressed by $R_{r,FE}$.

This model of SGPM allows to analyse the influence of a different circuit of electronic converters on the overall efficiency of generator for every speed of the engine.

The cupper losses ΔW_{CU} of generator are not function of the generator speed ω and results of relation $R_{s,CU}$ and ω are given in Fig. 9. Therefor the value of $R_{s,CU}$ is constant.

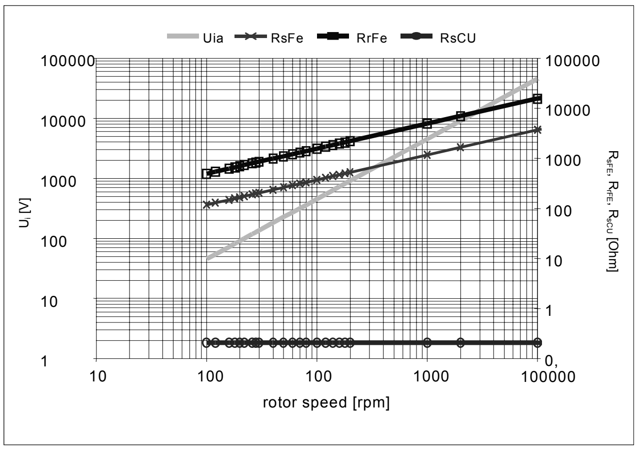

Fig. 9 Calculated losses as a function of the generator speed

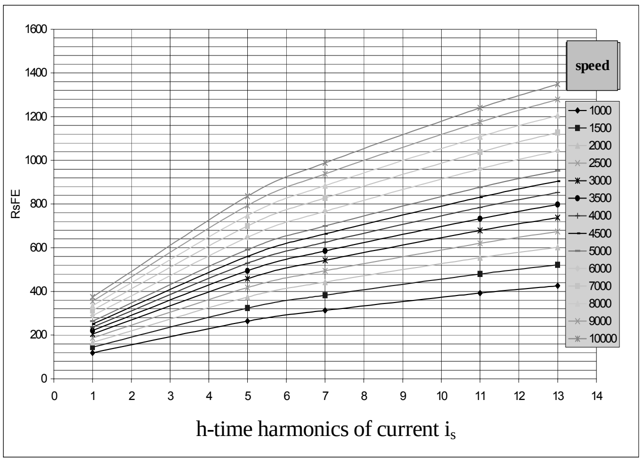

Fig. 10 Calculated losses $R_{s,FE}$ as a function of the speed and h-time harmonics of the current

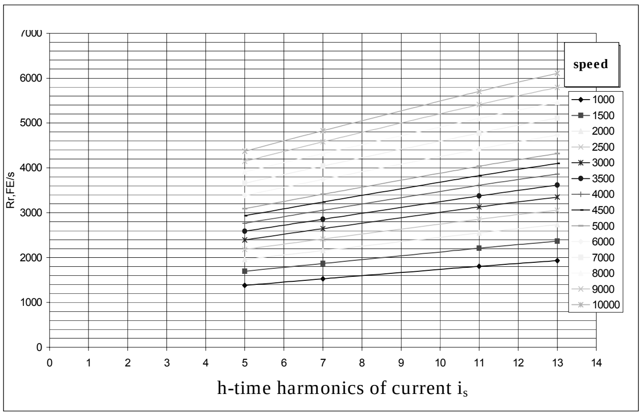

Fig. 11 Calculated losses $R_{r,FE}$ as a function of the speed and h-time harmonics of the current

The iron losses ΔW_{FE} are a function of the speed ω of the generator and therefore the values of $R_{s,FE}$ and $R_{r,FE}$ are varying (Fig. 9). Parameters $R_{s,FE}$ is a function of the speed of the generator and h-harmonics of the current, too. And so relations of stator losses $R_{s,FE}$ is shown in the Fig. 10 as a function of the speed and h-time harmonics of current. The iron losses in the rotor $R_{r,FE}$ are dependent only on the higher time harmonics (Fig. 11).

Results of this analysis are relation losses of generator with permanent magnet and generator speed or relation losses of generator with permanent magnet and h-time harmonics of the current by electronic converter. For example for rotor speed 3000 rpm the losses caused by 5^{th} harmonics of the current are 1.2x higher then losses due to the fundamental time harmonic of the current.

The losses by h-time harmonics of current have influence on decreasing efficiency of the generator by electronic converter, as shown in Fig. 12. The efficiency of generator as a function of the speed and electronic converter configuration (based on produced current harmonics) from the Fig. 3 is calculated. As expected, the efficiency of the generator with circuit C (uncontrolled rectifier) is the lowest. The best efficiency is with controlled rectifier. This converter can improve efficiency of EGS by more then 5 % in comparison with circuit C. Finally the efficiency of the overall system is estimated.

V. SUGGESTED SOLUTION OF ELECTRONIC CONVERTER FOR EGS

As mentioned above, 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 13. Higher efficiency and lower operation costs may be achieved by using new topology of electronic converter of EGS. This new configuration of power electronic converter for new generation of mobile electrical power sources is based on the idea of the efficiency control as a function of the load.

For low load will be used controlled rectifier with high efficiency and low effect on generator losses will be used. For high loads a classical uncontrolled diode rectifier will be used. Diode rectifiers usually operate with low efficiency and their effect on generator losses is higher. Their primary benefit is the price.

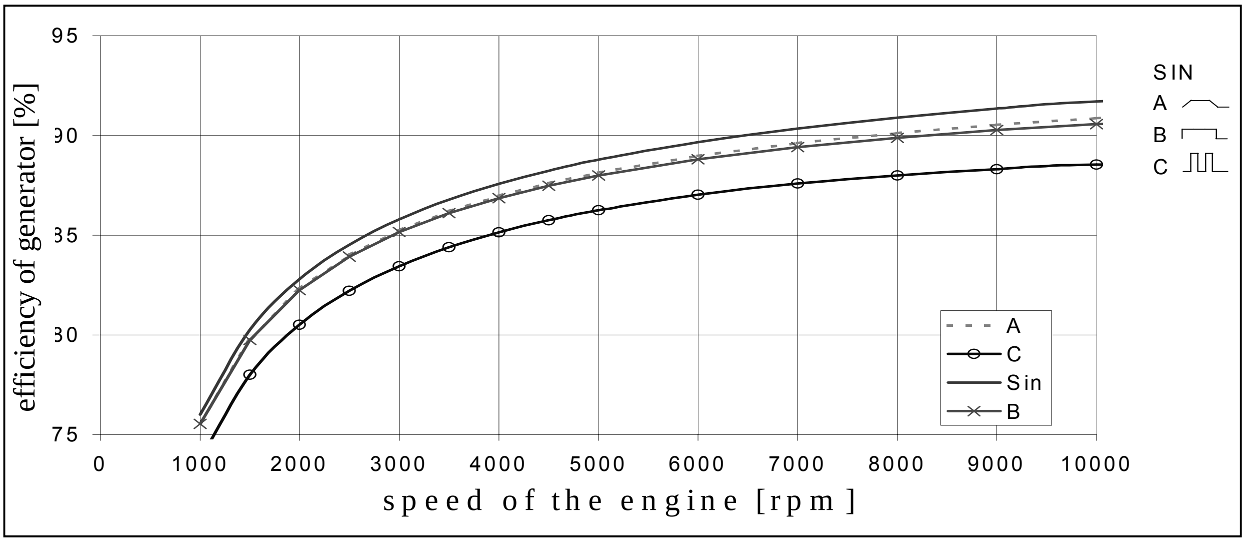

Fig. 12 Calculated efficiency of generator as a function of the speed and electronic converter configuration

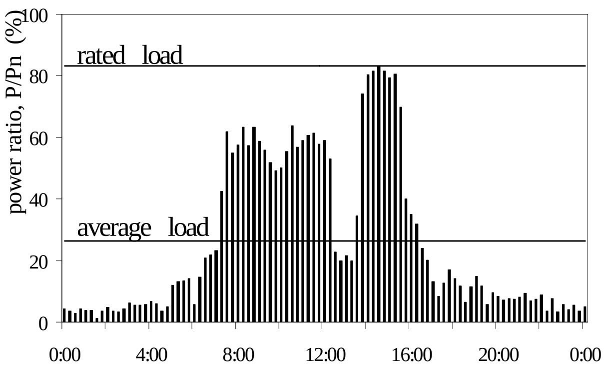

Fig. 13. The average load of classical EGS

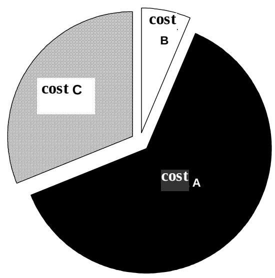

Fig. 16 Comparison of converter cost of EGS with

(A) controlled rectifier; (B) uncontrolled rectifier; (C) suggested solution of new type converter

The hypothetical topology of electronic converter of EGS with variable speed of engine is shown in the Fig. 14 [3],[7]. Result of analysis of efficiency synchronous generator with permanents magnet and with hypothetical new topology of electronic converter of EGS brings Fig. 15. By low load (most of the operational time of the set) the controlled rectifier is active, by full load only uncontrolled diode rectifier gets into operation. This solution has lower cost then a full controlled rectifier, is robust and offers a low cost high efficiency solution for the set. This new topology offers a compromise between the cost and efficiency.

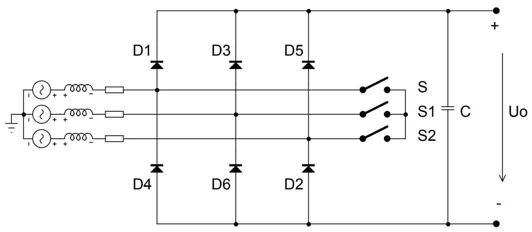

Fig. 14 Electronic converter for new generation of EGS (dependent on the load)

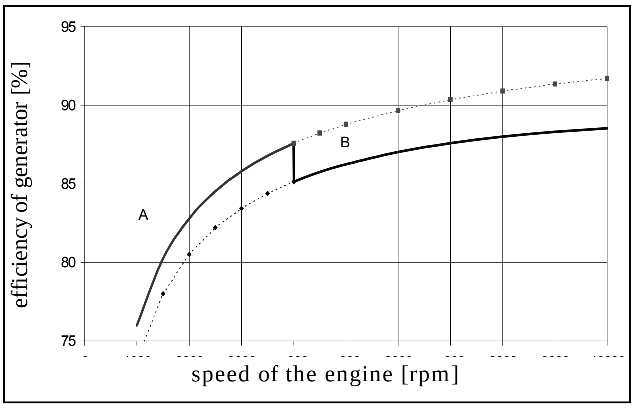

Fig. 15 Output efficiency of generator with new type of electronic converter (dependent on the engine speed)

As given above, EGS usually operate long time under low load. Solution of EGS with control transistor PWM rectifier for every load has virtual efficiency about 32%. Virtual efficiency of EGS shows total efficiency with calculation average operating time of EGS. Solution of EGS with un-control diode rectifier has virtual efficiency about 28%. Our solution can bring increasing virtual efficiency of EGS with variable speed from 28% to 31%.

The suggested solution of electronic converter can brings lower cost than controlled converter and higher efficiency of EGS system in comparison with the uncontrolled rectifier. This new idea will be verified. Hypothetical costs for electronic converter of EGS with controlled, uncontrolled rectifier and new type of power electronic converter are shown in Fig. 16.

VI CONCLUSIONS

Higher efficiency and lower operation costs of EGS may be achieved by means of new concept EGS with optimum variable speed. 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.

The efficiency of the new concept EGS with variable speed at rated load is lower then the efficiency of EGS 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 the selected type of converter. Three different configurations of power converters have been investigated. The first type is a fully controlled AC-DC rectifier drawing a sinusoidal current from the generator. The second type is connected with the uncontrolled AC-DC rectifier. The third circuit structure is similar to the previous one and combines the advantage of uncontrolled rectifier (price, costs) and controlled rectifier (efficiency).

REFERENCES

[1] J. Leuchter, " Power Electronics in New Generation in New Generation of Mobile Electrical Power Sources with Variable Speed, "*Doctor Thesis*, Military Academy in Brno, 2003.

[2] H. Polinder, " On the Losses in a High-Speed Permanent-Magnet Generator with Rectifier, "*Doctor Thesis*, ISBN 90-5651-041-X. TU-DELFT, Delft, Netherlands, 1998.

[3] P.Bauer, K.Bauer: Modern Power Electronics, ISBN 90-9010243-4, 1996

[4] J. Salmont, " Operating a Three-Phase Diode Rectifier with a Low-Input Current Distottion Using a Series-Connected Dual Boost Converter, "IEEE Transactions on Power Elektronics, Vol.11, No. 4. 2001.

[5] H. Knitterscheidt, " Neue Generation SEA füer militärische Nutzung“. Symposium moderne elektrische Energietechnik. Mannheim ", Germany 1998, pp. 14.1 - 14.22

[6] L. Gresiak, W. Koczara, M. Da Ponte, " Application of Permanent Magnet Machine in the Novel Hygen Adjustable - Speed, Load - Adaptive Electricity Generating System”. Proceedings of the conference IEMDC 99, Seattle, USA, 1999, pp. 398-400.

[7] P.Bauer et.al: Low cost converter for renewable energy application, patent application 2004

[8] R.K.Jardan, I.Nagy, N.Schendl: Dynamic Analysis of high speed synchronous machine-turbine system, in press