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Computer Analyses and Practical Solution of Mobile Electrical Power Sources with VSCF Technology

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Abstract: - This paper brings some practical results of research devoted to the new generation of mobile electrical power sources, based on the VSCF technology (Variable Speed – Constant Frequency). In this new generation of mobile electrical power sources 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. Computer analyses can enrich modern design of power electronics and research of new generation of mobile power sources with variable speed. The modern computer tools can bring great benefit for fuller understanding of special effects and characteristics of power electronic circuit. This paper brings some new analysis and is concentrated on control structure with practical measurements on the physical model.

Key-Words: - Electrical Power Generating Set, Power Electronics, Optimal speed Control

1 Introduction

Mobile electrical power sources known as Electrical Generator-Sets (EGS) are used for various machines and appliances to increase their mobility (Fig.1). 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.

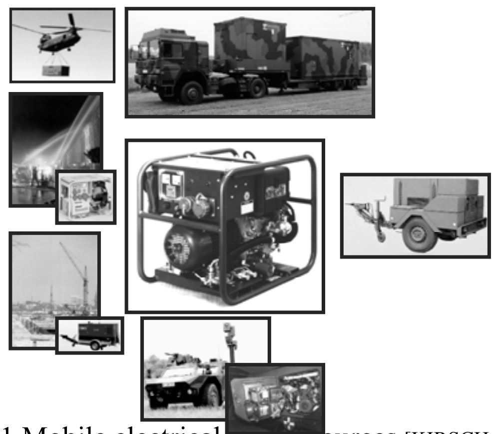

Fig. 1 Mobile electrical power sources [KIRSCH GnbH]

EGS operates very often under low load, which does not exceed in average more than 20 % of the rated permanent load. 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 with VSCF technology.

The new EGS concept (EGSG3- generation 3) is based on the use of diesel engines operating with optimum variable speed according to the EGS load. The diesel engine changes to the speed according to the load of the set. The optimum speed is hereby calculated according to the EGS load with the minimum fuel consumption optimality criterion. In 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. 2.

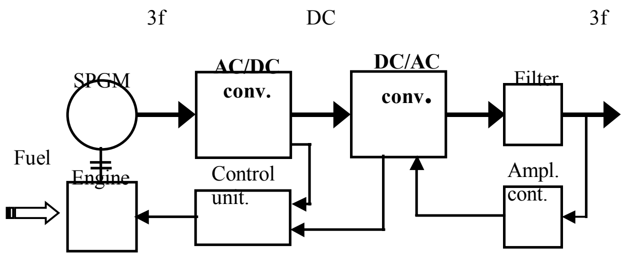

Fig. 2 The simplified block diagram EGS with VSCF technology

The main handicap of new concept with optimum variable speed according to the EGSG3 load are higher initial costs EGS in comparison to the old concepts of

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EGS with constant speed of engine (EGSG1 or G2). 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.

2 Computer Tools of Power Electronics

The EGSG3 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. Computer analysis can enrich modern design of power system and research of new generation of mobile power sources. It is possible to do all simulation of mechatronics systems. And so the computer tools can bring great benefit for fuller understanding of special effects and characteristics of power system. Contemporary simulation programs derive benefits from powerful of computers.

Typical power electronics system analyses consist of many aspects and are multidisciplinary. These are, for example, parameters of magnetic actuators, parameters of semiconductors switches, electrical machine parameters, thermal effects, different control issues, packaging and parasitic effects. Well known simulation packages are Spice and MATLAB-Simulink. Other typical programs for modeling mechatronics system are Vissim and Dynast.

Software for simulation and analyses of electronics circuit are for example: SPICE, MicroCAP, Saber and Electronics Workbench. ¨

Special simulation packages for Power Electronics and electrical drives are CASPOC, Krean, ATOSEC, PSIM and Simplorer.

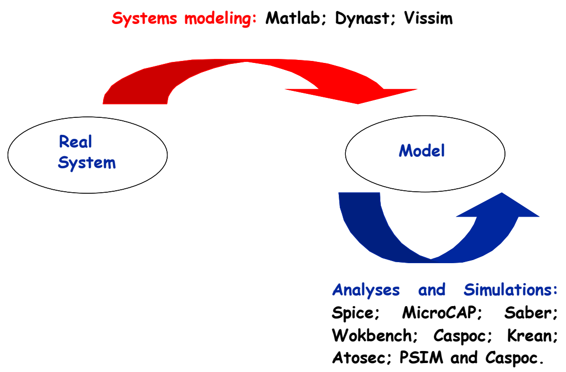

Fig. 3 Computer Tools of Power Electronics

In view of my good previous practical experience with Matlab and Caspoc this paper is directed towards the simulation and analyses by software Matlab and Caspoc.

3 Concept of EGS with Variable Speed

The simplified block diagram of EGS with variable speed was shown in Fig. 2 with diesel engine, synchronous generator with permanent magnets (SGPM), indirect-type converter (AC/DC/AC), output filter and speed control unit.

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. Preliminary calculations and simulations of the 6kW EGSG3 driving part resulted in the choice of diesel engine with the power output 7.6 kW (single cylinder 462 cm^3, 7,6 kW at 3600 RPM, 3,6 kW at 1500 RPM, maximum torque 25 Nm at 2000 RPM). This relation of engine and generator power output corresponds to the required engine ability to cover sudden increase in EGS load at economical optimum low speeds.

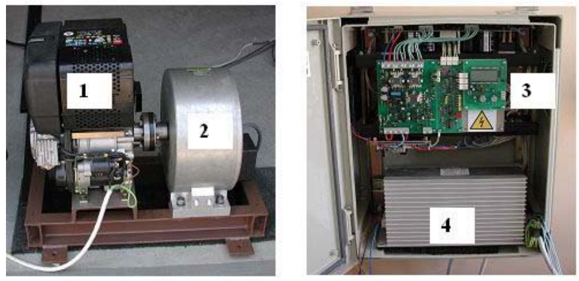

Fig. 4 The photo of experimental model (1-diesel engine; 2-SGPM; 3-indirect converter; 4-filter)

Synchronous generators with permanent magnet (SGPM) without electromagnetic exiting system are used in many modern applications with VSCF technology. SGPM have high efficiency, reliability and high speeds can be reached. Output voltage and frequency of synchronous generator with permanent magnets corresponds with variable speed of diesel engine. Provisionally the generator is the 12 pole synchronous generator with permanent magnets. The output characteristic of our SGPM is shown in Fig. 5.

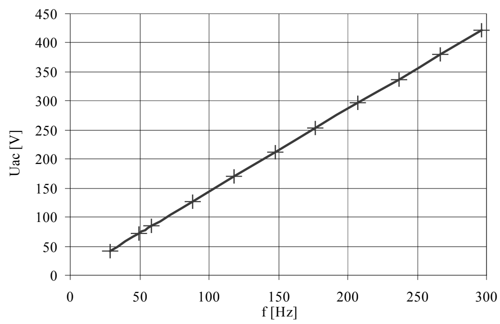

Fig. 5 I/O characteristic of SGPM

All the power passes through the power electronics converters to the EGSG3 power output. The SGPM output voltage, varying in the range of about 200 to 400 V at the variable frequency 100 to 300 Hz is to be converted to stabilized 400/230 V, 50 Hz. The converter part consists as AC/DC; DC/DC and DC/AC converter. These type converters (AC/DC/AC) are very often used on the whole applications of power converters up to a hundred kW of power. Indirect-type converter usually consists of diode rectifier AC/DC, DC/DC converter with transformer and DC/AC inverter. The function of DC/DC converter is stabilizes output DC voltage to the required level U_{DC}=570V. Our solution od DC/DC converter is shown in Fig. 6. It is step-up chopper (type FORWARD). If the output voltage of the diode rectifier is less than 570 V then chopper increases the voltage.

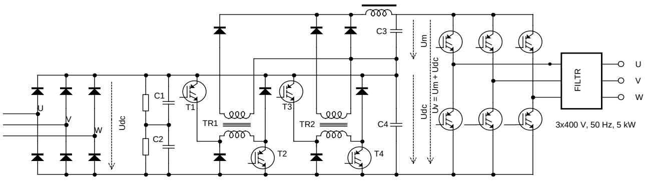

Fig. 6 The schematic diagram of AC/DC/AC converter

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.

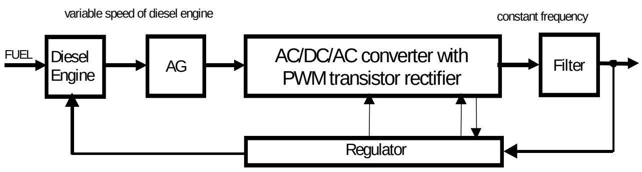

Fig. 7 The Concept of EGSG3 with asynchronous generator

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. 7. Asynchronous generator brings smaller price for generator, but greater dimensions, weight and more expensive power electronics converter with PWM transistor rectifier.

4 The Optimum Speed Control

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.

One of the variants of EGSG3 control system structures including three above mentioned control components are given in Fig. 8. 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.

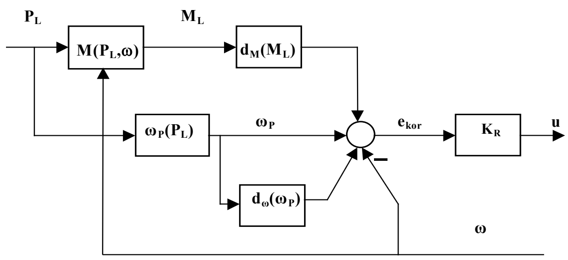

Fig. 8 EGSG3 control system structure

The results of simulations optimum control with respect to the minimum fuel consumption by Matlab bring following text and Fig. 9. Efficiency of EGSG2 with asynchronous generator for 20 % nominal load is 11 %. Efficiency of EGSG2 for 100 % nominal load is 32 %. EGSG3 with optimum speed control can always operate with efficiency 32 % because power output on the load is the same like power generated of diesel engine.

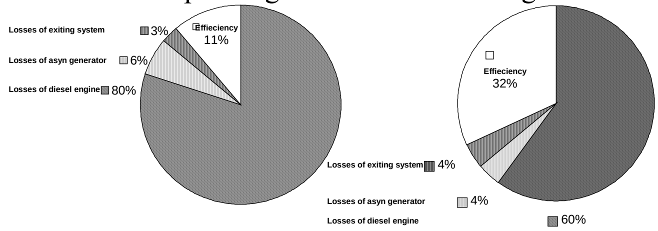

Fig. 9 The Concept of EGSG3 with asynchronous generator

The next results of simulations EGSG2 and 3 are given Fig. 10. There is shown the relation between specific

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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 %.

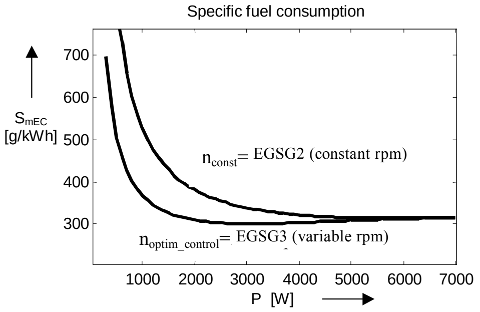

Fig. 10 The fuel consumption of EGSG2 and 3

Fig. 11 presents the detail photo of EGS engine control system. The required speed (ω_p) of the engine is adjusted by actuating lever and instantaneous speed is calculated from position sensor, which measure the instantaneous position of actuating lever. Servo unit is controlled by microprocessor (feedback controller) and adjusts required speed by means of actuating lever. The regulation time from low speed of the engine (low load) to high speed (high load) take about 2 s that is in accordance with computer analysis in MATLAB.

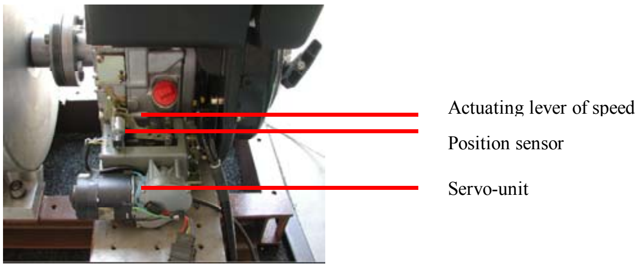

Fig. 11 Photo of EGS control system

The experimental result of our control system of diesel engine is shown in Fig. 12. If we had changed the load of EGS our feed/back control system set optimum speed of diesel engine by control characteristic.

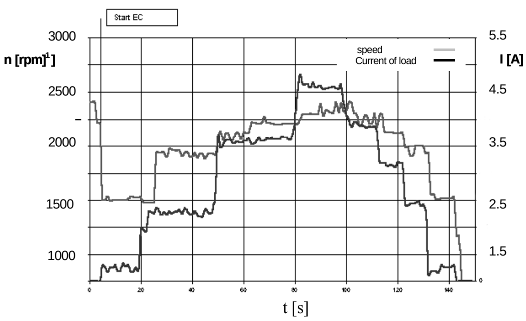

Fig. 12 Experimental result of control EGSG3

The experimental results of relation between specific fuel consumption and power output for constant speed and for optimally controlled speed correspond to the Fig. 10 obtained by simulation in MATLAB.

Analyses and experiments of control system show that the major drawback of this new generation of EGS with variable speed of engine is the engine-generator dynamics at sudden transient from low load to high load in a very short time. Electronic converter can improve the dynamic behavior of whole EGS system by means of inserting accumulated energy to the inter-circuit of DC/DC converter.

5 The Variations of Power Converter

The schematic diagram of power electronic converter AC/DC/AC designed at the University of Defence in Brno can be seen in Fig. 6. This concept of power electronic converter brings the problems with dynamic behaviors of mobile electrical power sources with VSCF technology. Our solution has total efficiency 81% and the losses in the power converter are distributed as follows figure.

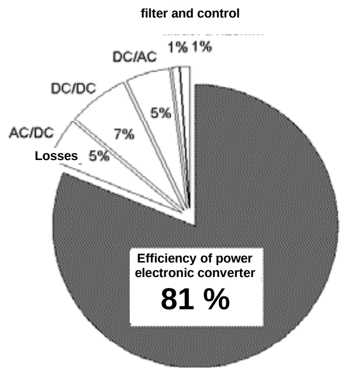

Fig. 13 Losses diagram of power electronic converter

The losses are created mainly in the switching elements and transformers of the DC/DC converter. It is necessary to say, the 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. Results of capacitor effect for harmonics current spectrum are shown in Fig. 14. Bigger capacitor results in higher harmonics distortion and the worse current spectrum of generator. The current is expressed by Fourier analysis equation (2).

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

In this case the produced harmonics are of order (3)

$$(k \cdot 6 \pm 1), \qquad (3)$$

where k = 1, 2, 3... . Diode conduction 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.

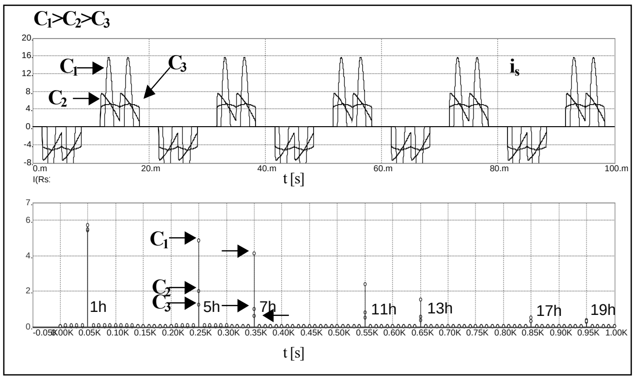

Fig. 14 Capacitor effect for harmonics spectrum of current)

As mentioned above, one of serious problems not yet satisfactory solved is the system behavior at high sudden increasing of loads from low loads at low speed (close to the idle run) to high loads demanding maximum speed. Our computer analysis of engine and system control requires the control time about 2 s. And so, power electronic converter must operate with energy storage like UPC sources. This solution of UPC EGS can be solved by means of converter with accumulators or with super-capacitors. The simplified block diagram of UPC converter is shown in fig. 15 where high cost is the main handicap of this concept.

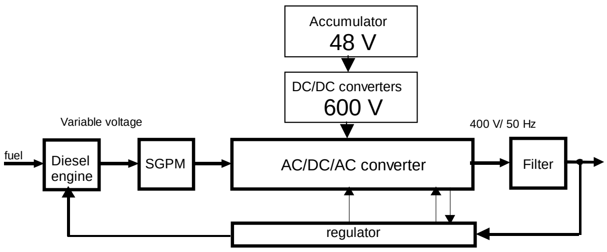

Fig. 14 The EGS concept as UPS source

This concept is based on the delivery of peak power from energy storage to the inter-circuit of DC/DC converter during the regulation time of engine from low speed to high speed. This energy W is given by power P_{max} and time of regulation T_{reg} for extreme case of rated full power.

$$W = P_{\max} \cdot T_{\mathrm{Re}\,g} \doteq 6000 \cdot 2 = 12\ kJ\ . \qquad (4)$$

Output voltage of capacitors must be about 600 [V_{DC}] and resultant equation for capacity of capacitors used is

$$C = \frac{\Delta t}{\Delta U} \cdot I_d = \frac{\Delta t}{\Delta U} \cdot \frac{P}{U_d} = \frac{2}{50} \cdot \frac{6000}{600} = 0.4\ F \qquad (5).$$

Such energy is too high for classical inter-circuit solution with electrolyte capacitors. Accumulator can bring a lot of storage energy. For example: 12 V and 7 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 about 60 kJ for 600 s. That is much more than we needed. Solution of converter with acumulater brings weight increasing of EGS as much as 60 kg.

Further way of energy storage can be achieved by super-capacitors (Fig. 16). Super-capacitors are relatively new and rather expensive. The efficiency of charging and discharging is much higher than in previous solution with accumulator. Energy of electrical field of capacitors can be expressed by equation (6) including the fact that super-capacitors is not discharged fully but only to half of nominal voltage (U_{nom}). Very often the resultant capacity is increased by 30 % as energy reserve.

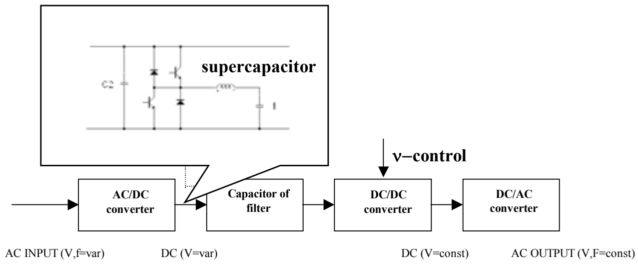

Fig. 16 The EGS concept with supercapacitor

$$W_{sc} = \frac{1}{2} C_{sc} \left(U_1^2 - U_1^2 \right) = \frac{1}{2} C_{sc} \left(U_{nom}^2 - \left(\frac{U_{nom}}{2} \right)^2 \right) = \qquad (6)$$
$$= \frac{3}{8} C_{sc} \cdot U_{nom}^2$$

Resultant capacity is given by formula (7) for nominal voltage 200 V. For nominal voltage 100 V resultant capacity equals up to 4 F. This super-capacitor can store about 15 kJ with better relationship between stored energy storage, dimensions and weight then acumulator.

$$C_{sc} = \frac{8 \cdot W_{sc}}{3 \cdot U_{nom}^2} = \frac{8 \cdot P_{\max} \cdot T_{\mathrm{Re}\,g}}{3 \cdot U_{nom}^2} \doteq \qquad (7).$$
$$\doteq \frac{8 \cdot 6000 \cdot 2}{3 \cdot 200^2} = 0.8 \doteq 1\,[F]$$

6 Conclusion

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.

It is necessary to say that the efficiency of 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 selected type of converter.

The mathematical analysis and simulation of static characteristics and dynamic behavior of the EGS with VSCF structure proved, that the dynamical properties of the system enable the formulation of control laws and thus to solve successfully the control requirements by the use of minimum fuel consumption optimizing criterion. The bad dynamical properties of the system (at high sudden increasing of loads from low loads at low speed to high loads) can improve by power electronic converter with energy storage between the DC/DC converter and DC/AC converter.

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