Dynamic Behavior of Mobile Generator Set with Variable Speed and Diesel Engine

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Abstract—The engine-generator dynamics at a sudden load change (from low load to high load) remains a challenge in case of variable speed diesel generator. The dynamic behavior analysis presented here proves that the introduction of an energy storage element into the EGS with variable-engine-speed concept eliminates this drawback. This paper addresses the identification of the dynamic behaviour of such variable-speed EGS systems and the problems encountered during a sudden increase of load (power and voltage drops).

Index Terms—Electrical GEN-SET, Power Electronics, Efficiency, Dynamic Behavior, Diesel Engine

I. INTRODUCTION

An electrical-generator set (EGS) is an electrical power source intended for any mobile electrical application. A simplified block diagram of an EGS with variable speed control can be seen in Figure 1. As a consequence of varying the engine speed when using the optimum variable speed control, both the output voltage and the output frequency of the generator vary and must be regulated to a constant value as required by the load. Therefore, a power electronic converter is required to regulate the output voltage and frequency. Such an EGS concept uses variable-speed, constant-frequency (VSCF) technology, which is already being used in aircraft generators and in some wind-power generators. The EGS system with VSCF technology is a sophisticated mechatronic system consisting of: a mechanical part (the engine), an electromechanical energy conversion part (generator), power electronics (including voltage and frequency regulation as well as optimum speed control, all implemented in a microprocessor program).

The real drawback of concept with optimum variable speed is the inferior engine-generator dynamics. In case of sudden power output increase, the engine can not deliver the requested torque and the result is further decrease of the speed and torque of the engine until the undesirable stop. The diesel engine has namely the time constant of few second, which is further limited by fuel injection limitation. This problem of the EGS with VSCF is investigated in the paper and a solution with the use of an energy buffer is suggested. To facilitate an investigation into the problems regarding an EGS with variable speed control an experimental set-up, consisting of a driving engine (diesel chosen here), a synchronous generator with permanent magnets, a power electronic converter, an output filter and a control unit, as shown in the block diagram (Figure 1), has been assembled.

Figure 1. Block diagram of an EGS system with VSCF technology

II. THE EXPERIMENTAL MODEL OF EGS WITH VSCF

In military applications using a single type of fuel (diesel) eases the logistical challenges, therefore a modern diesel engine has been chosen to drive the EGS in this investigation. A diesel engine (HATZ 1D40) with an output power of 7.7 kW at 3600 rpm and 3.8 kW at 1500 rpm has been selected for a 6 kW EGS. The engine is slightly oversized (as regards power output) to facilitate dynamic changes of the load. The experimental EGS set-up can be seen in Figure 2.

Figure 2. The EGS experimental model (1: diesel engine; 2: SGPM; 3: ac-dc- dc converter; 4: filter)

The output characteristic of the diesel engine is shown in Figure 3 as a function of engine speed, n (rpm).
Permanent-magnet synchronous generators (SGPM) are used in various applications implementing VSCF technology. In the experimental set-up the 12-pole, synchronous generator is connected to the diesel engine by means of a mechanical clutch. The output voltage of the generator has an unregulated frequency as it is generated by a varying engine speed (see Figure 3). The ac output voltage of the SGPM is in the range of 100V to 450V at a frequency ranging from 100 Hz to 300 Hz (Figure 4).

The unregulated voltage and frequency of the generator must be stabilized by using a power electronics converter to regulate at the constant voltage and frequency on the three-phase ac (400 V/ 50Hz) output. Figure 2 shows the block diagram of the power conversion steps including an ac-dc, dc-dc and dc-ac stage. The dc-dc converter with feedback control steps the voltage up from output variable voltage of uncontrolled rectifier to a constant value of 570 V. All the power generated by the EGS is processed by the power electronic converter in this way. Furthermore, the output voltage of the EGS must be independent of its load and engine speed. The system’s operation can be concluded from the converter’s schematic circuit (Figure 5) and from the output characteristics of the ac-dc, dc-dc and dc-ac converters respectively (Figure 6).

A system comprising of a three-phase ac-dc rectifier and dc-dc converter is commonly used for VSCF applications due to its low cost and no need for high quality of its output voltage. The output voltage of the ac-dc converter ($U_{DC\_AC/DC}$) is also shown in Figure 6. The shape of the $U_{DC\_AC/DC}$ characteristics corresponds to the output voltages of a synchronous generator with permanent magnets (see Figures 4 and 6).

The dc-dc converter is designed to function as a step-up chopper. If the rectified dc-voltage is less than 570V then the step-up chopper increases the voltage by adjusting the duty ratio of the switching element, $D$ (Figure 5). The main goal of this dc-dc converter is to convert and stabilize the unregulated dc-output voltage of the rectifier. The output characteristic of the dc-dc converter ($U_{DC\_DC/DC}$), shown in Figure 6, shows that the output dc voltage is constant. The last measured point in the characteristic falls outside the operating area of the dc-dc converter. Here the duty cycle of the dc-dc converter has already reached one of its limits. The output voltage of the dc-dc converter simply follows the rectified voltage when it increases above 600V.

The three-phase EGS output is adjusted to the constant frequency (50Hz) by using a dc-ac inverter and a voltage control unit (Figure 2). The unit evaluates the three-phase information and makes the amplitude of the rotating output
voltage vector suitable for feedback control. The output characteristic \((U_{AC\_DC\_AC})\), output voltage (rms) versus generator frequency, is shown in Figure 6. Figure 7 shows the measured quality of one of the EGS phase’s output voltage and current. Figure 2 shows the EGS system complete with the main control structure necessary to implement optimum engine speed control to compensate for the EGS load. The required angular speed, \(\omega_p\), of the engine is calculated by using an EGS optimum control strategy. The PID controller receives its feedback information in the form of the instantaneous angular speed, \(\omega\). Figure 8 presents a detail photo of the experimental EGS control system. The required speed of the engine is adjusted by the actuating lever and the instantaneous speed is calculated from the position sensor -- which measures the instantaneous position of the actuating lever. The servo unit is designed as a dc-servo machine and is controlled by means of variable PWM according to the required angular speed, \(\omega_p\), of the engine.

III. EGS DYNAMIC BEHAVIOUR - EXPERIMENTAL RESULTS

The control of the EGS’s speed can reduce the fuel consumption under low-load conditions, as shown in Fig. 1. The engine’s rotational speed is to be optimally controlled by adapting the operating strategy for every load to the required power output and torque, while minimizing the fuel consumption. The engine-generator dynamics, during sudden transients from low-load to high-load conditions, still poses a challenge in this regard. The following experimental results (Fig. 8 and 9) show the oscilloscope reading of the EGS’s dynamic behaviors. The measurements were performed in open-loop mode to show the dynamic behavior of only the generator set with its static speed error \(e_s\) (\(\Delta n\)) and also to determine the engine time constant, \(T_c\).

In Figure 8 the measurements during a load change is shown. The yellow curve (CH 1) shows the output current of uncontrolled ac-dc rectifier (see fig. 5) and the red curve (CH 4) presents the engine speed. The output power is calculated from the output dc-voltage and dc-current. The result of this calculation is shown in Figure 8 as the violet curve (MATH). The exact point where the load is changed from low load to high load is indicated by point A. During time interval \(t_1\) the system was loaded with 640 W at 1560 rpm. During time interval \(t_2\) (580 ms) the load was changed to 2480 W and the transient occurs. Time interval \(t_3\) shows the system operating in steady-state condition. In Figure 10 a drop in speed, \(\Delta n\), of 160 rpm is shown. This drop in speed translates into the static error, \(e_s\), of the diesel engine inter-regulator. The time constant of a diesel engine, \(T_c\), is approximately 0.6s.
sufficient power to the load. The previous measurements indicate the serious nature of the dynamic behavior problem associated with the EGS with variable speed: its unsatisfactory reliability during sudden load changes as a result of the inferior dynamic behavior of the EGS. Therefore the dynamic behavior must be analyzed in detail, by using modeling methods for example, to understand these dynamics and to be able to improve it.

IV. MODEL OF THE EGS

The basic mathematical model of an EGS with variable speed includes the diesel engine (DE), the permanent magnet synchronous generator (SG), the power converter (PC) and two control units (RS-1 and RS-2). The model includes two main system variables: the first is the angular speed, \( \omega_s \), of the diesel engine that is fed into the synchronous generator and the second is the load torque, \( T_L \), with which the generator loads the diesel engine. The resulting model, as implemented in Matlab-Simulink, is shown in Figure 10.

![Figure 10. The mathematical model of the EGS in Matlab-Simulink graphics](image)

The required angular speed, \( \omega_s \), according to the power load, \( P_L \), is calculated by the control unit labeled RS-1. The diesel engine is controlled at the required angular speed, \( \omega_s \), by using a feedback regulator (RS-2). The control error between the required angular speed, \( \omega_s \), and the instantaneous speed, \( \omega_i \), is compensated by adjusting the fuel injection, \( d \) [mg], within the feedback regulator unit (RS-2). The fuel injection, \( d \), can be defined as a quantum of fuel in one injection [mg]. Behind the generator (SG) there is a model of the power converter (PC) that regulates the output dc-voltage. The dc-ac conversion is neglected because the dynamic response of the dc-ac converter is much faster than that of the dc-dc converter, generator and diesel engine. The details on the separate parts of the model are described in the transaction paper [21].

A Results of the dynamic behavior modeling

The main goal of the analyzing and modeling of the EGS is to determine both the dynamic behavior characteristics and steady-state characteristic of the EGS with variable engine angular speed. The dynamic behavior of the EGS system showed that the EGS system is stable and aperiodic and from this point of view the proportional regulator is sufficient. But the system is not astatic therefore its steady-state errors are not equal to zero. The steady-state error \( e_s \) is enforced by both required angular speed \( \omega_s \) and load torque \( T_L \) and it is expressed by (1)

\[
e_s = e_s(\omega_s, T_L) = \frac{\omega_p + K_i(T_s + T_L)}{1 + K_p K_i} = \frac{\omega_p + K_i(T_s + T_L)}{1 + K_p K_i} = \frac{\omega_s + K_i(T_s + T_L)}{1 + K_p K_i}
\]

Figure 11 presents the transient response of the feed-back controlled engine with proportional regulator (for \( K_p = 1 \)). It shows the system response evoked by two step functions, First one, at \( t_1 = 0 \), is the step change of the required engine angular speed from 200 to 300 rad·s\(^{-1}\) and the second one, at the time instant \( t_2 = 2 \), is the step of the load change from 0 to 10 Nm. The steady state error is not negligible and it could be decreased by higher \( K_p \). In general, we have more possibilities how to eliminate the steady-state error. For example the PI regulator could be employed. But because of the relation between the required angular speed and torque load is known the steady-state error is simply eliminated by correcting the course of required control law (1).

![Figure 11. Transient response of feedback control [11]](image)

The main results of dynamic behavior modeling are shown in Figures 12. Figure show the respective transient responses for various loads and for the controller gain \( K_p = 1 \).

Figure 12 (a) shows the system response for power load change from 500 W to 1000 W. This load change brings about a change of the engine angular speed from 102 to 118 rad·s\(^{-1}\). We can notice, that the difference between the required angular speed \( \omega_s \), and instantaneous speed, \( \omega_i \) i.e. steady state error is eliminated by way discussed above. The theoretical value of the time of regulation \( T_R \) is for known engine parameters and it is equal to 0,09 s. Real value of the \( T_R \) is affected by \( d \) limitation and it is \( T_R \), is 0,3 s.

Figure 12(b) shows a power load change from 500W to
2520W. At the initial angular speed the engine is not possible to surmount the instantaneous power load and the angular speed is decreasing. The EGS can not operate with such a load change. Figure 12(b) verifies the experimental results shown in Figure 9.

A summary of the experimental results and observations is shown in Table I.

<table>
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<th>b)</th>
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<th>d)</th>
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<td>6.3</td>
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This table shows the change of load power from $P_{L1}$ to $P_{L2}$, the required angular speed $\omega_p$ and instantaneous speed $\omega$, the load torque $T_L$ and the load current $I_L$. In next columns are maximum values of power. This table shows a power $P_{L\text{max}}$, torque $T_{L\text{max}}$ and the current $I_{L\text{max}}$ that could be provided by engine at level of $\omega_p$. For carrying out the successful transition the $P_{L\text{max}}$ must be higher then $P_{L2}$ i.e. the condition $P_{L2} < P_{L\text{max}}$ must be fulfilled.

For any value of angular speed some value of $P_{L\text{max}}$ exists. In Figure 13 the curve of $P_{L\text{max}}$ is shown and it is margin of the EGS operating area in plane of $(\omega_p, P_L)$. The second curve designated as $P_{opt}$ represents the power provided by engine working at the optimal angular speed. The third curve $P_{rez}$ is the difference between $P_{L\text{max}}$ and $P_{opt}$ and it indicates the reserve of power of the system operating at optimal angular speed.

For example: if the engine operates with an angular speed of 150 rad·s$^{-1}$ than the output power of engine is 1900W and the power margin of engine is as high as 1700 W. If the power drop is higher, than diesel engine cannot make enough power that is required by the load.

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V. VERIFICATION OF EGS CONCEPT WITH ENERGY BUFFER

The energy buffer selection is in details described in paper [21]. The mathematical model of the EGS including the energy storage element, for delivery of the peak energy, is shown in Figure 15. The model includes the modules EB and RS-3. EB is the energy buffer (EB) including a dc-dc bi-directional converter and RS-3 is a power management controller regarding the energy storage element, which is indispensable for regulation of the buffer voltage level. The module RS-3 controls the flow of energy based on the output voltage, $U_{DC}$, and the load current.

![Figure 15. The model of EGS with energy buffer for delivery of peak power](image)

The energy storage system is controlled in such a manner that current flows out of the EB when it is discharging or flows into the EB when it is charging. The dc-dc converter operates in BOOST mode when power is delivered from the EB to the dc-line. Alternatively, the dc-dc converter operates in BUCK mode when regenerative energy is absorbed into the EB.

Figure 16 shows the results of a feasibility test performed on the energy buffer concept (to deliver the required peak energy) in the EGS. The verification of the EGS concept with energy buffer is summarized in Table II.

![Figure 16. Transient response of EGS with energy buffer for load change](image)

**Figure 16. Transient response of EGS with energy buffer for load change (a) 500 W to 2520 W (b) 500 W to 7000 W**

The energy buffer supports the motor transition from one speed to the new optimal speed value and torque $T_L$ as well as current $I_L$. Figure 16 (b) illustrates the maximal step change from 500 W to 7 kW. Both cases shown in Figure 16 exceed the maximal allowed value of $P_{max}$, as shown in Figure 12. In both cases the regulation time $T_R$ is shorter than 2s (according to the calculation of the energy buffer).

In Figure 17 it is possible to see the experimental verification of the EGS concept with energy buffer as well as feed-back control of the speed. Channel 1 curve (CH 1) is the same as in Figures 10 & 11 and shows the current of the rectifier. The red curve (CH 4) shows the engine speed. The output dc voltage is shown by the green curve (CH 2), while the output power is shown as the violet curve (MATH), which is calculated from the output dc voltage and dc current. In time interval $T_1$ the system was loaded with 1kW at 1500 rpm. In time interval $T_2$ the power load was changed from 1 kW to 5.06 kW. During this time (2.28 s) the transition takes place and power is extracted from the energy storage element. Time interval $T_3$ shows the steady-state condition of the system. It is possible to see that the system is now capable of handling the power load change combined with the feed-back control of the speed.

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<td>$T_R$ [s]</td>
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engine speed (set at an optimal speed of the diesel engine). This proves the feasibility of the EGS with variable speed of engine concept.

![Figure 17](image)

**Figure 17. The verification of EGS concept with energy buffer**

VI. CONCLUSION

Mathematical analysis and simulation of the static characteristics as well as dynamic behavior of mobile electrical power sources with VSCF technology has shown that the bad dynamical properties of the system (at substantial, sudden increases of load (from low loads at low speed to high loads) can be considerably improved by implementing power electronic converters with an energy buffer. This publication includes detailed analysis of an EGS mathematical model as well as identification of its dynamic behavior. Figure 14 shows the proposed concept of the EGS with optimum variable speed used in combination with an energy storage element to improve the dynamic behavior of the EGS. The drawback of the proposed EGS with variable speed and energy buffer concept translates into a higher initial cost when compared to the EGS with constant speed control.

ACKNOWLEDGMENT

The above research work is supported by the Grant Agency of the Czech Republic (project no. 105/05/P001).

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