Optimization of Maintenance and Use of Gensets in the Armed Forces

Preliminary Communication

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Abstract *– The Armed Forces use a great number of various types of gensets. The aim is to reduce this large number of diverse genset types, that is, to standardize the equipment used with the aim of simplifying maintenance and modes of use. For this reason, tests are conducted which should provide factual conclusions as to the types of gensets which are both most favourable for use and maintenance and also meet the conditions required by international military operations. One of these requirements is the possibility of using the kerosene fuel F-34 for diesel engines. It is well known that diesel engines running on kerosene fuel develop less power, which can result in the direct reduction of generator rotation speed at rated loads. Therefore, we conducted tests on one type of electric genset by using resistor load. The additional goal was to conduct tests on other types of electric motors by using different types of loads. It was particularly important to conduct the tests during the acceleration of an asynchronous motor since gensets are also used in technical workshops to run compressor units and in these instances asynchronous motors often turn on. So, in order to facilitate conductivity, we also developed mathematical models and computer simulations.*

Keywords *– asynchronous motor, genset, mathematical model, modified kerosene fuel.*

1. INTRODUCTION

Due to its continued procurement activities over an extended period of time, the Armed Forces now use a great number of various types of gensets. Some different characteristics of these gensets are indeed necessary, while some need to be reduced to the lowest number possible. This would facilitate maintenance, reduce the need for huge amounts of spare parts and simplify control of technical documentation. It would also result in the reduction of required assemblies used for fault detection, as well as a more simplified employee training program for the purposes of equipment maintenance and use. The aforementioned is particularly important when it comes to international military operations in which it is impossible to always ensure the presence of highly-specialized maintenance mechanics, as well as large amounts of detection equipment and spare parts.

For a quality based selection of gensets, one needs to conduct an analysis which will provide precise information on the type of genset used, its power, power motor and generator. The obtained data should be used in combination with the vast experience of employees working on maintenance of gensets and using them. The resulting assessment of the types of gensets that should be considered should take into account the need for a bigger amount of standardized equipment for which spare parts may be obtained. During selection and standardization of equipment, special attention needs to be focused on requirements related to international military operations. One of these requirements is the possibility of using the kerosene fuel F-34 for running diesel motors [1].

Testing of motor vehicles has shown that diesel motors develop less power when kerosene fuel is used, which could affect the output characteristics of genset. Therefore, tests were conducted on one type of genset under resistor load. The obtained results and comparison with diesel fuel showed visible differences so this brought up the issue of genset behaviour in extreme conditions. One such example is the running and starting of an asynchronous motor under operating load, which often occurs in technical workshops where gensets run compressor units and are also under other types of load (from air conditioners, etc.). In addition to the aforementioned tests, other tests need to be conducted as well – for the purposes of classifying equipment and defining its potential and working modes, as well as for the drafting of a PQ diagram. A mathematical model and computer simulation have been developed to facilitate the analysis of the obtained results.

Chapter 2 displays implementation tests and comparison of results on one type of electric generators with two different fuels. Chapter 3 presents a mathematical model of genset and an asynchronous motor with a simulation of the starting period of the induction motor shown in Chapter 4, that will be used for the implementation of the final examination.

2. CONDUCTING OF TESTS AND COMPARISON OF OBTAINED VALUES

After the analysis of the obtained data, an assessment was carried out with respect to those gensets which could meet the requirements of international military operations. One of the requirements is the possibility of using the kerosene fuel F-34 for diesel engines. The aforementioned fuel type is based on the civil aviation fuel type JET A-1 (JP-8) which is widely available around the world, so the forces have accepted this single-fuel concept [2]. The tests conducted on motor vehicles have shown increased consumption and reduction in power when F-34 is compared to diesel fuel [3]. The discrepancies shown were significant and hence this brought up the issue of genset operation when using the aforementioned fuel. Detailed testing was also carried out for the needs of the US Army, one segment of whom is shown in [4], where, along with other parameters, reduction in torque and engine power when using JET A-1 (JP-8) is evident and corrections to the injection system (PW) are proposed. Power reduction of the power engine could reduce the rotation speed of the generator at rated loads, which would directly affect the drop in the frequency of output voltage. In order to verify the aforementioned, tests were conducted on the genset type P-B40, R1 with power of 25 kVA.

Before tests with various types of fuel were conducted, technical documentation and factory test lists were obtained [5, 6], in which only diesel fuel was used, which was the then requirement from the Regulations on Product Quality/RPQ (in Croatian: *Propisi o kvaliteti proizvoda*) [7].

The shown values [6] indicate that first the genset was not under any load and then a load of up to 110 % of the rated power was applied by using two different loads. The voltage dropped from 400 V to 388 V. According to the RPQ, the change of voltage at change of load from 0 to rated load (the static characteristic of voltage) for power factors between 0.8 and 1 should be within ±3% in comparison with the median value.

Verification of the static characteristic is done in the following way:

a) when the genset is not under any load, the frequency is set such as to meet the RPQ requirement which states that the change of frequency at change of load from 0 to rated load (an outer characteristic of frequency) needs to be within 6 % compared to the initial frequency value, while the frequency at rated load needs to be between 49 and 50.5 Hz,

b) then the genset is under load of 0%, 25%, 50%, 75% and 100% of the rated power, while cosφ=0.8 and 1. The corresponding voltage values are measured for each of the aforementioned load levels. The discrepancy in voltage is calculated according to the following expression

$$\Delta U(\%) = \pm \frac{U_{max} - U_{min}}{U_{max} + U_{min}} \cdot 100 ,$$

where U_{max} is the maximum voltage value, while U_{min} is the minimum voltage value within the measuring range. If the discrepancy in voltage ΔU is within ±3% in comparison with the median voltage value, the requirement is met.

By analyzing values [6] it can be concluded that the genset meets the RPQ requirements. Further analysis of such conditions leads to other significant conclusions. One of these is that that the voltage regulator maintains the right amount of voltage within the set range via the excitation circuit [8], which points to the conclusion that the installed assemblies operate correctly. The second very important conclusion is that the frequency is maintained within the set limits, which indicates that the generator, i.e., the power diesel engine, rotates at the correct speed. This in turn points to the correct operation of the regulator for high-pressure pump rotations, as well as to the appropriate amount of power for generator needs in the diesel power engine [9].

Tests of this type can be very useful for gensets used, which often have a problem with power engines used making it impossible to obtain rated power, meaning that in such cases there is a significant reduction in rotation speed at bigger loads. Consequently, the level of frequency can be one crucial piece of information when assessing how much a genset, i.e., a diesel power engine has been used up. A similar test procedure was carried out with kerosene fuel F-34 [10], which showed greater consumption in comparison with diesel fuel, with the same cost of produced electric energy. There were no significant drops in rotation speed when below the rated load; however, above the rated load, there was less power to the power engine when kerosene fuel F-34 was used.

Fig. 1 indicates that diesel fuel ensures operation with approximately 10 % more load and no stopping of the power engine [10].

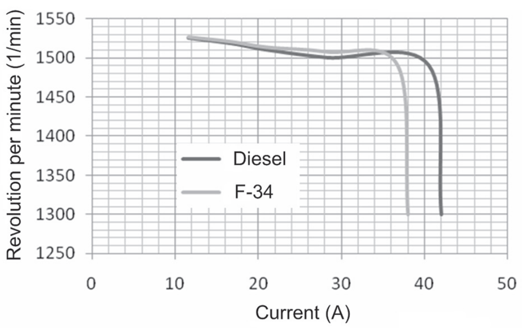

Fig. 1. Rotation Speed Dependency on Load Level [10]

Bearing in mind all of the aforementioned, our suggestion is to test and define procedures on other types of gensets so as to determine if they would operate correctly and under what kind of load when kerosene fuel F-34 and various loads are applied.

3. MATHEMATICAL MODEL OF THE GENSET AND THE ASYNCHRONOUS MOTOR

The results obtained show that diesel engines running on kerosene fuel develop less power than those running on diesel fuel. The tests with kerosene fuel were carried out only under operating load and without recording transitory processes; hence, this type of testing alone cannot establish without doubt that this type of genset running on kerosene fuel meets all RPQ and ISO 8528 requirements. In order to confirm the aforementioned, additional tests need to be carried out as well. We suggest first to record the output characteristics of a genset when starting an asynchronous motor. In what follows we give a mathematical model for the genset and the asynchronous motor [11] to serve as a basis for the testing and simulation procedure.

The initial condition applied to the model is:

$$\frac{di_d}{dt} = \frac{di_{dA}}{dt}$$
$$\frac{di_q}{dt} = \frac{di_{qA}}{dt} \quad (1)$$

By applying the asynchronous model in the *abc* coordinates and the corresponding transformations we arrive to the mathematical model in *dq* coordinates, which encompasses two static and two rotor equations

$$u_{dA} = R_s \cdot i_{dA} + \frac{d\Psi_{dA}}{dt} - \omega \cdot \Psi_{qA}$$
$$u_{qA} = R_s \cdot i_{qA} + \frac{d\Psi_{qA}}{dt} + \omega \cdot \Psi_{dA} \quad (2)$$

$$0 = R_r \cdot i_{DA} + \frac{d\Psi_{DA}}{dt} - (\omega - \omega_A) \cdot \Psi_{QA}$$
$$0 = R_r \cdot i_{QA} + \frac{d\Psi_{QA}}{dt} - (\omega - \omega_A) \cdot \Psi_{DA} \quad (3)$$

The chained flows of stator and rotor winding are as follows:

$$\Psi_{dA} = L_s i_{dA} + L_m i_{DA}$$
$$\Psi_{qA} = L_s i_{qA} + L_m i_{QA}$$
$$\Psi_{DA} = L_r i_{DA} + L_m i_{dA}$$
$$\Psi_{QA} = L_r i_{QA} + L_m i_{qA} \quad (4)$$

By including (4) in (2) and (3) we get a system of voltage equations:

$$u_{dA} = L_s \frac{di_{dA}}{dt} + L_m \frac{di_{DA}}{dt} - \omega(L_s i_{qA} + L_m i_{QA}) + R_s \cdot i_{dA}$$
$$u_{qA} = L_s \frac{di_{qA}}{dt} + L_m \frac{di_{QA}}{dt} + \omega(L_s i_{dA} + L_m i_{DA}) + R_s \cdot i_{qA} \quad (5)$$
$$0 = L_r \frac{di_{DA}}{dt} + L_m \frac{di_{dA}}{dt} + s \cdot \omega(L_r i_{QA} + L_m i_{qA}) + R_r \cdot i_{DA}$$
$$0 = L_r \frac{di_{QA}}{dt} + L_m \frac{di_{qA}}{dt} + s \cdot \omega(L_r i_{DA} + L_m i_{dA}) + R_r \cdot i_{QA}$$

The equation of motion:

$$T_{mA} \cdot \frac{ds}{dt} = m_{TA} - m_{elmA}$$
$$m_{elmA} = \frac{L_m}{\sigma \cdot L_s \cdot L_r} \cdot (\Psi_{DA} \cdot \Psi_{qA} - \Psi_{QA} \cdot \Psi_{dA}) \quad (6)$$
$$\sigma = 1 - \frac{L_m^2}{L_r \cdot L_s}$$

By solving the system of equations (5), along with the equation of motion (6) expressed through current, we get a system of differential equations of the asynchronous motor which is suitable for numerical solving:

$$
\begin{aligned}
\frac{di_{dA}}{dt} &= \frac{1}{\sigma\cdot L_s}\cdot\left[u_{dA}+\omega(1-s)L_m\cdot i_{QA}+\omega i_{qA}\left(L_s-s\frac{L_m^2}{L_r}\right)-R_s\cdot i_{dA}+\frac{L_m}{L_r}\cdot R_r\cdot i_{DA}\right]\\
\frac{di_{qA}}{dt} &= \frac{1}{\sigma\cdot L_s}\cdot\left[u_{qA}-\omega(1-s)L_m\cdot i_{DA}-\omega i_{dA}\left(L_s-s\frac{L_m^2}{L_r}\right)-R_s\cdot i_{qA}+\frac{L_m}{L_r}\cdot R_r\cdot i_{QA}\right]\\
\frac{di_{DA}}{dt} &= -\frac{L_m}{\sigma\cdot L_s\cdot L_r}\cdot\left[u_{dA}+\omega(1-s)L_s\cdot i_{qA}+\omega i_{QA}\left(L_m-s\frac{L_s\cdot L_r}{L_{mr}}\right)-R_s\cdot i_{dA}+\frac{L_s}{L_m}\cdot R_r\cdot i_{DA}\right]\\
\frac{di_{QA}}{dt} &= -\frac{L_m}{\sigma\cdot L_s\cdot L_r}\cdot\left[u_{qA}-\omega(1-s)L_s\cdot i_{dA}+\omega i_{DA}\left(L_m-s\frac{L_s\cdot L_r}{L_m}\right)-R_s\cdot i_{qA}+\frac{L_s}{L_m}\cdot R_r\cdot i_{QA}\right]
\end{aligned} \tag{8}
$$

$$
\frac{ds}{dt} = -\frac{1}{T_{mA}}\left[\left(i_{DA}\cdot i_{qA}-i_{QA}\cdot i_{dA}\right)\cdot L_m-m_{TA}\right] \tag{9}
$$

The input values are supply voltage and load torque, while the output values are currents and rotation speed. The system rotates at synchronous speed, while stator currents in the *abc* coordinate system are obtained by applying a transformation matrix [11].

In order to simplify the writing of equations (8) new symbols are introduced:

$$
\begin{aligned}
A_{idA} &= \omega\cdot(1-s)\cdot L_m\cdot i_{QA}+\omega\cdot\left(L_s-s\cdot\frac{L_m^2}{L_r}\right)\cdot i_{qA}-R_s\cdot i_{dA}+\frac{L_m}{L_r}\cdot R_r\cdot i_{DA}\\
A_{iqA} &= -\omega\cdot(1-s)\cdot L_m\cdot i_{DA}-\omega\cdot\left(L_s-s\cdot\frac{L_m^2}{L_r}\right)\cdot i_{dA}-R_s\cdot i_{qA}+\frac{L_m}{L_r}\cdot R_r\cdot i_{QA}\\
B_{iDA} &= \omega\cdot(1-s)\cdot L_s\cdot i_{qA}+\omega\cdot\left(L_m-s\cdot\frac{L_s\cdot L_r}{L_m}\right)\cdot i_{QA}-R_s\cdot i_{dA}+\frac{L_s}{L_{mr}}\cdot R_r\cdot i_{DA}\\
B_{iQA} &= -\omega\cdot(1-s)\cdot L_s\cdot i_{dA}-\omega\cdot\left(L_m-s\cdot\frac{L_s\cdot L_r}{L_m}\right)\cdot i_{DA}-R_s\cdot i_{qA}+\frac{L_s}{L_{mr}}\cdot R_r\cdot i_{QA}
\end{aligned} \tag{10}
$$

By including (10) into (8) we get stator currents of the asynchronous motor:

$$
\begin{aligned}
\frac{di_{dA}}{dt} &= \frac{1}{B_A}\cdot\left(u_{dA}+A_{idA}\right)\\
\frac{di_{qA}}{dt} &= \frac{1}{B_A}\cdot\left(u_{qA}+A_{iqA}\right)
\end{aligned} \tag{11}
$$

The equations of rotor current are as follows:

$$
\begin{aligned}
\frac{di_{DA}}{dt} &= \frac{1}{A_A}\cdot\left(u_{dA}+B_{iDA}\right)\\
\frac{di_{QA}}{dt} &= \frac{1}{A_A}\cdot\left(u_{qA}+B_{iQA}\right),
\end{aligned} \tag{12}
$$

where

$$
\begin{aligned}
A_A &= \frac{L_m^2-L_s\cdot L_r}{L_m} = -\frac{L_s\cdot L_r}{L_m}\cdot\sigma\\
B_A &= \frac{L_s\cdot L_r-L_m^2}{L_r} = L_s\cdot\sigma
\end{aligned} \tag{13}
$$

Voltage equations in *d* and the *q* axis are obtained from (1) and by including the equations of synchronous generator currents [11] and asynchronous motor currents (12):

$$
\begin{aligned}
-u_d\cdot a_{id}+A_{id} &= \frac{1}{B_A}\cdot\left(u_{dA}+A_{idA}\right)\\
-u_q\cdot a_{iq}+A_{iq} &= \frac{1}{B_A}\cdot\left(u_{qA}+A_{iqA}\right)
\end{aligned} \tag{14}
$$

The asynchronous motor is directly connected to the synchronous generator which is not under any load so the following applies:

$$
\begin{aligned}
-u_d &= u_{dA}\\
-u_q &= u_{qA}
\end{aligned} \tag{15}
$$

The voltage on the clamps of the generator under load from the asynchronous motor is:

$$
\begin{aligned}
u_d &= \left(A_{id}-A_{idA}\cdot\frac{1}{B_A}\right)\cdot\left(a_{id}+\frac{1}{B_A}\right)^{-1}\\
u_q &= \left(A_{iq}-A_{iq}\cdot\frac{1}{B_A}\right)\cdot\left(a_{iq}+\frac{1}{B_A}\right)^{-1}
\end{aligned} \tag{16}
$$

The system of equations is completed with synchronous generator equations, the equation of motion, equations of excitation regulation and regulation of rotation speed [11].

4. SIMULATION OF ACCELERATION IN AN ASYNCHRONOUS MOTOR CONNECTED TO A GENSET WHICH IS NOT UNDER ANY LOAD

In addition to powering operating loads, gensets are also used within the Armed Forces to power various electric engine drives, such as training simulators in military camps and compressor units in separate technical workshops and storage spaces. Powering of compressor units results in difficult conditions for operation of gensets due to impact load caused by frequent starting of asynchronous motors. This results in rotational speed drop and voltage dips, depending on the strength of the genset, regulation parameters and power of the connected loads.

Since previous testing established that the power engine develops less power when kerosene fuel is used, this raises the issue of genset behaviour when starting an asynchronous motor. For this reason, we carried out a simulation of the starting of an asynchronous motor connected to a genset which is not under any load. We suggest measuring and comparison of obtained results afterwards. This testing will have a great impact on the decision and defining of suitability of gensets and their meeting of requirements related to international military operations and ISO 8528.

Fig. 2 (from MATLAB-Simulink) shows that the synchronous generator has a power of 25 kVA and is connected via a three-phase switch to an asynchronous motor with the power of 7.5 kW.

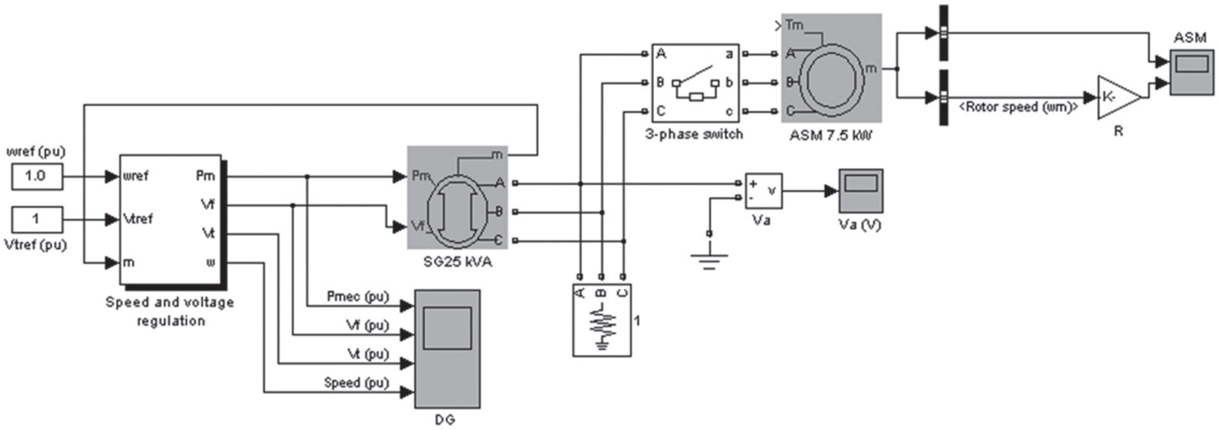

Fig. 2. Block diagram of simulation models in MATLAB-Simulink

Fig 3 (obtained in MATLAB-Simulink) shows the generator voltage response which indicates that after 0.2 s the asynchronous motor turns on, which results in a voltage dip $\delta U_{dyn} \approx 30\%$, which is, according to the standard [12], one of the requirements for defining a class of gensets.

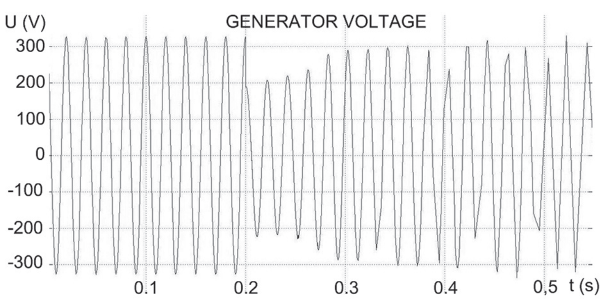

Fig. 3. Generator voltage response during asynchronous motor acceleration

Fig 4 (obtained in MATLAB-Simulink) shows the speed of generator rotation and mechanical power which represents the load on the diesel engine during acceleration of the asynchronous motor.

Rotational speed of the genset has a dip of approximately 3 % of the rated speed, after 100 ms from the beginning of acceleration, when the load on the power unit is at the maximum and the electric engine achieves a breakdown torque. After this, the load drops and the rotational speed of the genset increases and achieves a steady value at approximately 500 ms from the beginning of acceleration.

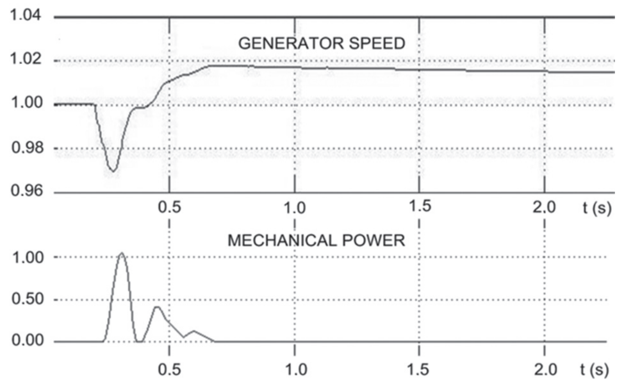

Fig. 4. Rotational speed and mechanical power during acceleration of an asynchronous motor

Rotational speed of the genset has a dip of approximately 3 % of the rated speed, after 100 ms from the beginning of acceleration, when the load on the power unit is at the maximum and the electric engine achieves a breakdown torque. After this, the load drops and the rotational speed of the genset increases and achieves a steady value at approximately 500 ms from the beginning of acceleration.

5. CONCLUSION

This article provides a summary of the activities which need to be carried out in order to improve and simplify maintenance and use of gensets within the Armed Forces. The aim is to reduce the number of various gensets and define which of them meet the requirements related to international military operations. For this reason we have shown the results of tests on one type of electric power unit when kerosene fuel F-34 was used. Since this indicated a reduction in the power of the power engine, additional tests at impact load and during asynchronous motor acceleration need to be conducted. The simulation shown is related to diesel fuel and specific regulation parameters. It can be assumed that the measured values at asynchronous motor acceleration when using fuel F-34 will be somewhat lower, which, according to ISO 8528, can result in a genset classified to a lower class.

Results of final testing that are to be reached through the implementation presented in this paper will be used to make a final decision on the possibility of using funds in international military operations, which is the goal of this paper as well as other works [2, 3, 4] which display implementation of similar tests and the use of fuel JET A-1 (JP-8).

The paper points to the possibility of an uncontrolled decrease in the rotational speed when using fuel F-34, which is essential in the genset, where the frequency of the output voltage is directly dependent on the speed of rotation of the drive motor.

By studying the available literature [2,3,4] it can be seen that the focus was on the impact of fuel changes on the operation of motors, and not on the problems of the genset, or the significant importance of reducing the power and speed of the genset drive. The number of gensets in the armed forces and the importance of their availability in military and civil uses make it important to carry out tests proposed in this paper in order to confirm which types of gensets are subject to significant changes in the rotational speed when using a specified fuel.

The obtained data is important to conduct research and make a decision about future prospects of the unification of equipment which is essential to simplify the maintenance and use of the genset.

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