Research of the alternator on the stand – efficiency aspect

M Adamiec M Dziubiński and E Siemionek

Lublin University of Technology, ul. Nadbystrzycka 36, 20-618 Lublin, Poland

E-mail: m.adamiec@pollub.pl, m.dziubinski@pollub.pl, e.siemionek@pollub.pl

Abstract. The article discusses the methodology of testing an alternator at a stand to determine its energy efficiency. The efficiency was calculated on the basis of the measurement of the electric power supplied to the drive motor and the power generated by the alternator, taking into account the mechanical and electrical losses of the motor and the belt drive. The efficiency of the machine as a three-phase synchronous generator, without rectifier and voltage regulator, was also determined in order to assess the influence of electronic components on the overall efficiency of the machine. The tests were performed for various rotational speeds and loads. Various physical factors and phenomena that have a negative impact on the efficiency of energy conversion in the vehicle electrical supply system are discussed.

1. Introduction

The determination of the efficiency of a technical object shall be carried out in order to assess the correctness of its built, repair, reconditioning and comparison with other devices of similar design and purpose. The practical effects of the performance calculation are to improve existing solutions or to develop a control algorithm in order to make optimal use of the device or system, taking into account other aspects of its operation. Machines and drive systems are subject to electrical, mechanical and magnetic phenomena, as well as the associated energy transformations and energy losses. The easiest thing to do is to measure and calculate electric quantities, more difficult is to measure and calculate mechanical and magnetic quantities, which are subject to a higher level error and which for this purpose are converted into voltage signals. Depending on the measurement possibilities, as well as the objectives and expected effects, the efficiency is determined in the actual operating conditions of the device or on the bench and in a more complicated or simplified way [1, 2].

In automotive vehicles, the generator can be used as a separate machine or in combination with a starter. In the first case, it is a three-phase synchronous generator with a specifically designed rotor, which cooperates with an electronic rectifier system and a voltage regulator. A set of these elements in one housing is called an alternator. The most important changes that have been made to its design due to the increase in electric power of automotive vehicles are listed below [3, 4]:

- improvement of the cooling system,
- optimization of the magnetic circuit,
- modernization of the transmission system,
- use of multifunctional voltage regulators.

These changes show that even well-proven and long-used devices are being successively improved. In particular, the last two aspects of the above have a strong relationship to the efficiency of the machine. Changes in the power transmission can reduce significant mechanical power losses, while in addition to controlling the energy distribution in the vehicle the multifunctional regulators can also make optimum

use of the efficiency of the generator. It is connected with voltage regulation by means of rotational speed changes, but first of all with excitation current formation, the value and course of which are closely connected with energy conversion efficiency [2]. To improve machine performance and efficiency, rotors with permanent magnet and an additional coil are also used, the current of which can more effectively regulate the magnetic field strength [5, 6]. The maximum alternator efficiency value given in the literature, depending on the rated voltage, power and type of excitation control, is in the range of 50 - 65% [4, 7, 2]. In practice, the most important thing is to analyze its variability as a function of load and rotational speed.

2. Power losses in rotating electric machines

Practically all power losses in rotating machines are related to the generation of heat, only the causes of this phenomenon are different [8]. The basic power losses are generated in the windings with resistance R, through which current of I intensity flows:

$$\Delta P_{Cu} = RI^2 \tag{1}$$

In this case it is also possible to take into account the variability of resistance as a function of temperature and the flow of alternating current (skin effect) and for this reason to calculate additional losses caused by the increase of temperature and current frequency. Power losses in ferromagnetic cores are caused by an alternating magnetic field, which cyclically changes polarity of the core (magnetic hysteresis) and induces eddy currents in it. The hysteresis losses ΔP_h and eddy current losses ΔP_r are calculated from the following equations:

$$\Delta P_h = c_h B^2 f \tag{2}$$

$$\Delta P_r = c_r B^2 f^2 \tag{3}$$

where:

c_h – hysteresis loss coefficient,
c_r – eddy current loss coefficient,
B – magnetic induction in the core,
f – current frequency (of magnetic field).

On the other hand, additional magnetic losses are caused by pulsations of magnetic field caused by toothing of the armature core, field produced by higher harmonic flows of windings and deformation of magnetic field caused by transverse interaction of the armature [9]. Magnetic power losses in a machine operating as an alternator are also caused by the variable component of the excitation current, which is caused by the cyclical operation of the voltage regulator. For this reason fields rotating asynchronously can produce eddy currents in the rotor core [4, 7]. In a DC motor and a generator operating as a three-phase synchronous generator excitation current hasn't got variable component. Power losses caused by current flow and voltage drops on rectifier diodes and voltage regulator elements (transistors, Zener diode, resistors) must also be taken into account in the alternator. Load and excitation currents of the alternator flow through the two diodes of the rectifier system at any time. A typical voltage drop on a silicon rectifier diode is $0.5 - 0.7$ V. The power losses of ΔP_d can be calculated according to the formula:

$$\Delta P_d = I_{la}(\Delta U_{dp} + \Delta U_{dn}) + I_{ea}(\Delta U_{de} + \Delta U_{dn}) \tag{4}$$

where:

I_{la} – alternator load current,
I_{ea} – alternator excitation current,
ΔU_{dp} – voltage drop on positive diode,
ΔU_{dn} – voltage drop on negative diode,
ΔU_{de} – voltage drop on excitation diode.

Mechanical losses are caused by the friction force of the moving parts against the stationary parts and the surrounding medium. They are calculated in different ways, e.g. according to the following formula [8]:

$$\Delta P_m = (\alpha_1 \mu F + \alpha_2)n^2 \tag{5}$$

where:

μ – coefficient of friction,

F – downforce,

n – rotational speed,

α_1, α_2 – coefficients relating to the construction of the machine.

Power losses in insulation are taken into account only in machines supplied with voltage of several dozen or several hundred kilowatts or operating at frequencies of the order of kilohertz [8]:

$$\Delta P_{in} = cU^2 f \cdot tg\,\delta \tag{6}$$

where:

$tg\,\delta$ – dielectric loss coefficient,

c – coefficient relating to the construction of the machine.

3. Research methodology

A compact alternator with a nominal voltage of U_n=12 V and nominal current of I_n=80 A, equipped with a 9 diode rectifier and a conventional voltage regulator was used in the tests. As a drive motor, a DC commutator machine separately excited with a nominal voltage of U_n=220 V and a nominal power of P_n=2200 W was used. The alternator has been modified in such way that the connection of the armature winding to the rectifier system has been interrupted and the voltage regulator has been connected to the excitation winding, and the contact points have been connected to the outside of the machine using additional wires (Fig. 1). Thanks to these changes, the generator was able to operate as an alternator, with its original or externally connected rectifier and voltage regulator, and as a three-phase synchronous generator. The alternator test was carried out with the use of the original rectifier and voltage regulator. It was not possible to directly measure voltage drops on elements of these systems. In addition to the load and the battery charging currents, it was also possible to measure the excitation current. The rotational speed was measured by means of an inductive sensor and an oscilloscope calculating the frequency of its voltage. The tests were performed at three rotational speeds (3000, 4800, 6000 rpm) at variable load of the generator. Initially, the electric power of a driving motor engine running idle was determined:

$$P_{m1} = U_{a1}I_{a1} + U_{e1}I_{e1} \tag{7}$$

where:

U_{a1} – armature voltage,

I_{a1} – armature current,

U_{e1} – excitation voltage,

I_{e1} – excitation current.

The electrical power of the motor transferring the torque to the alternator operating at idle state P_{m2} and the power of the motor driving the alternator operating at load state P_{m3} were calculated similarly (according to the formula 7).

The output power on the drive motor shaft, connected by means of a belt transmission with an idling alternator, was calculated on the basis of the following:

$$P_{m4} = P_{m2} - P_{m1} - (I_{a2} - I_{a1})^2 R_a \tag{8}$$

where:

P_{m2} – electrical power of the motor driving the alternator in the idle state,

I_{a2} – armature current of the motor driving the alternator in the idle state,

R_a – resistance in the armature circuit of the motor.

For higher accuracy, the power of P_{m4} was determined in the initial phase of the powertrain operation and after the measurements (at a higher temperature) and the mean value was calculated. Formula (8) takes into account the load losses in the armature circuit of the drive motor, which occur due to an increase of load and armature current.

The output power of the motor shaft driving an alternator operating at load state was calculated from the following equations:

$$P_{m5} = P_{m3} - P_{m1} - (I_{a3} - I_{a1})^2 R_a \qquad (9)$$

where:

P_{m3} – electrical power of the motor driving the alternator at load state,

I_{a3} – armature current of the motor driving the alternator at load state.

The electrical output power of the alternator was calculated on the basis of the following equation:

$$P_a = U_{B+}(I_l + I_{ac}) \qquad (10)$$

where:

U_{B+} – alternator mains voltage,

I_l – alternator load current,

I_{ac} – battery charging current.

The efficiency of the alternator was calculated as the ratio of the power P_a to the power P_{m5}. Then the configuration of connections was changed and the efficiency of the same machine was determined, but this time working as a three-phase synchronous generator with a resistance receiver Y connected. The load was changed symmetrically in all phases and the excitation current was supplied via power supply. Active power, current and voltage were measured in individual phases with the clamp power meter. Measurements were made at the same rotational speeds and at a constant excitation current of I_e=2 A. On the basis of tests it has been established that the current of such value provides the lowest braking torque of the rotor of the generator in relation to the range of changes in the output power of the machine.

Although a large range of efficiency changes have been achieved, it has not been possible to compare these results with those of an alternator machine. Therefore, an attempt was made to determine the efficiency of the generator again by selecting such excitation current values that were set by the voltage regulator when loading the generator. For each selected excitation current value, at constant rotational speed, the load on the generator was adjusted to obtain a similar active power of the three-phase receiver to the power of the receiver which loaded generator in the first part of the test. In this way, the efficiency variability of the alternator and the three-phase generator were determined under similar operating conditions. The electrical and mechanical power of the drive motor was calculated in the same way as that of the alternator, but to calculate the input power of the generator P_{in3f}, the excitation power supplied by the PSU (power supply unit) is still taken into account:

$$P_{in3f} = P_{m3} - P_{m1} - (I_{a3} - I_{a1})^2 R_a + U_e I_e \qquad (11)$$

where:

U_e – generator excitation voltage,

I_e – generator excitation current.

On the other hand the output power of the three-phase generator P_{out3f} was calculated as the sum of the active power in the individual load phases, and the efficiency was calculated as the ratio of P_{out3f} to P_{in3f}.
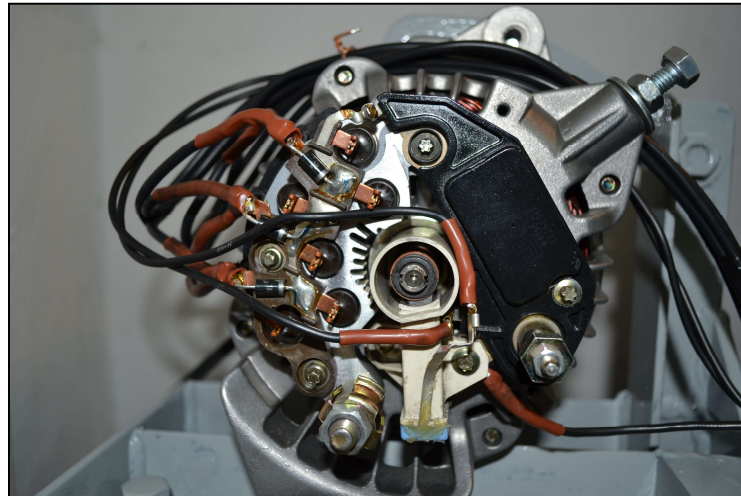
Figure 1. Modifications in the tested alternator's

4. Results of the research

The measurement results are presented in the diagrams, on which the efficiencies of the alternator and three-phase generator as a function of output power, determined at constant speed, are presented (Fig. 2-4). The efficiency determined for the same excitation currents and similar power is greater for a machine operating as a three-phase generator, throughout the entire range of power changes at a rotational speed of 3000 rpm (Fig. 2).

At a higher speed of 4800 rpm, the two efficiencies are already very slightly different, at most of the measuring points the efficiency of the three-phase generator is slightly superior, at several points the values are almost equal and only at maximum power is the difference more pronounced (Fig. 3). However, for the highest rotational speed of 6000 rpm, in the range of lower power output, the efficiency of the three-phase generator is slightly higher, and for higher power values, the efficiency of the alternator gains an advantage (Fig. 4). The point of intersection of the characteristics, i.e. equalization of the efficiency values for two variants of operation, occurs just below half of the whole range of power changes, for its value equal to 300 W.

The efficiency of a machine operating as a three-phase generator, at a constant excitation current of 2 A, is less than two previously discussed efficiencies at lower power levels and more for its higher power levels. The differences are much greater for rotational speed of 4800 and 6000 rpm, and in these cases it can be seen that greater efficiency is achieved in the final power range of a machine operating at different excitation currents. In addition, the entire characteristic is shifted because machine operation at a constant excitation current of 2 A starts at higher power and efficiency and the maximum power value is greater.
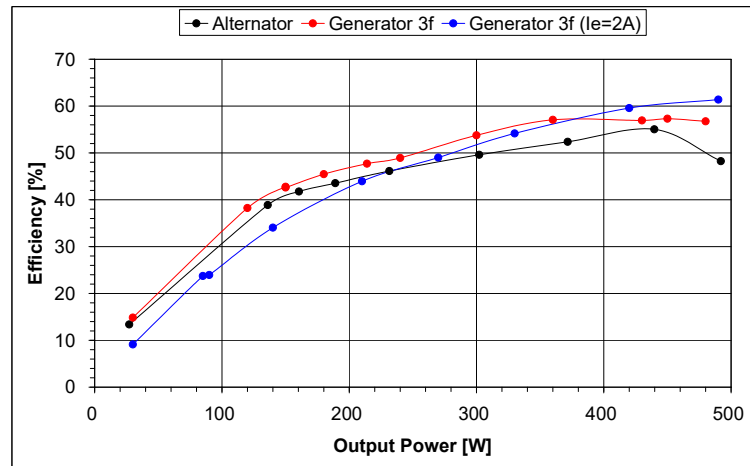
Figure 2. Efficiency of machine operating as an alternator and three-phase generator according to output power at 3000 rpm
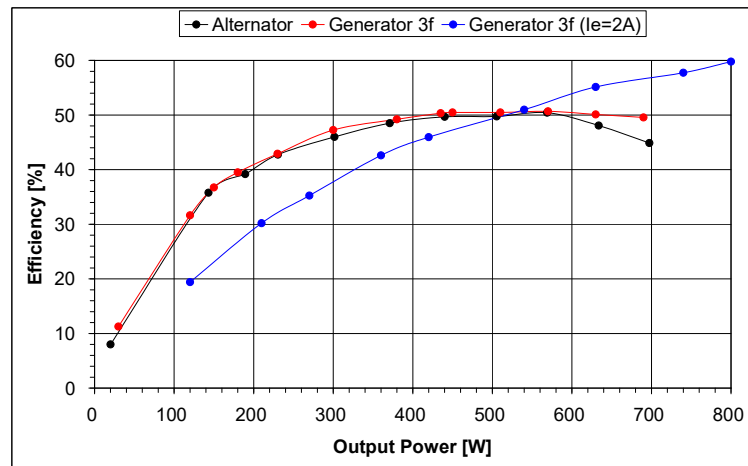

Figure 3. Efficiency of machine operating as an alternator and three-phase generator according to output power at 4800 rpm
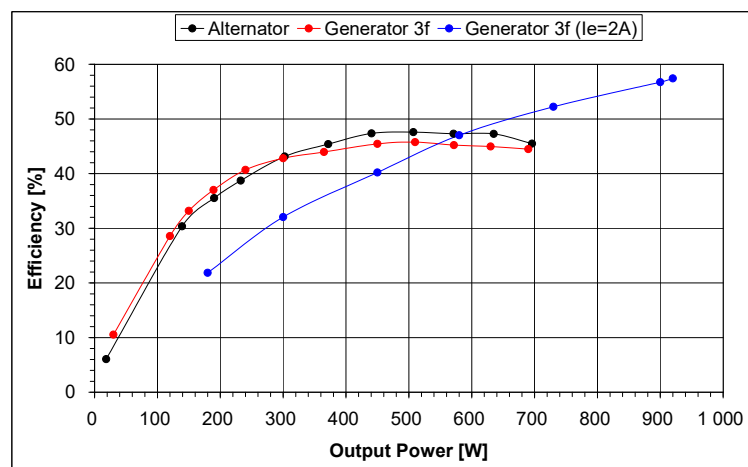

Figure 4. Efficiency of machine operating as an alternator and three-phase generator according to output power at 6000 rpm

5. Summary and conclusions

In order to calculate the efficiency of the alternator and the three-phase generator, a simplified method was used, consisting in determining the difference in power between the drive motor operating at load and idle, and load losses power in its winding and components of the armature circuit. The values of voltages, currents, power and resistance of individual elements of the drive system, necessary to calculate the input and output power of the machine were measured and, as a result, its efficiency achieved at different rotational speeds and loads, were measured.

The aim of the research was to determine the real value of efficiency and the range of its changes as well as the influence of such electronic elements of alternator as rectifier system and voltage regulator on the total efficiency. Therefore, this value was determined for the machine operating as a self-excited alternator and a three-phase separately excited synchronous generator. Correct, regular diagrams have been achieved for the three rotational speed values, with small measuring deviations due to the unsimultaneous measurement of several values and the variability of the rotational speed and temperature. The diagrams show that it is not efficient to operate the generator at low load or at high rotational speed in relation to the load. The mechanical power losses associated with the transmission system and the frictional force of the various components are then predominant. The highest efficiency of 55% was achieved for the smallest of the three rotational speeds and almost the maximum load possible under these conditions. For higher rotational speeds the maximum efficiency is lower, but it is maintained within a wider load range. Determining the variability of efficiency under different operating conditions can be useful in vehicle electrical energy flow control systems for optimum control of the generator. The assessment of the power losses in the alternator electronics systems cannot be carried out explicitly as there are additional effects associated with the flow of alternating current during operation of the three-phase generator. This is best illustrated in Figure 4, where due to the higher rotational speed and frequency of the current, the inductive reactance of the receiver increases, resulting in increased energy losses and, as a result, a higher efficiency of the machine operating as an alternator than that of the three-phase generator supplying the receiver with alternating current. For a rotational speed of a test machine rotor of 6000 rpm, its voltage frequency shall be 600 Hz (the number of pairs of magnetic poles shall be six). Correspondingly, at 4800 rpm it is 480 Hz and at 3000 rpm it is 300 Hz. For the lowest rotational speed, when the reactance is small and the receiver is resistive, the current flow conditions are similar to those of direct current and it can be seen that the alternator, which is additionally equipped with a rectifier and voltage regulator, has a lower efficiency than a three-phase generator. For an average rotational speed of 4800 rpm, these differences are already very small.

An additional factor causing magnetic power loss in the alternator is the pulsating nature of the excitation current, rectified by the diodes and interrupted cyclically by the voltage regulator (the variable component is present). It was also noticed that in the idling state of the machine, but after the excitation current is fed to the rotor winding, there is a braking torque which is the result of the magnetic field generated by the excitation winding and amplified by the rotor core and the field generated by the magnetized stator core. The mutual relation of the efficiency of the machine working as an alternator and the three-phase generator is molded depending on various factors and the proportions of several physical quantities. A simplified method of determining the efficiency of the generator enables the calculation of input and output power as well as power losses in the belt drive and machine windings. However, it does not allow to determine the remaining power loss components separately.

References

[1]   Niedworok A and Orzech Ł 2016 Przegląd Elektrotechniczny **8** 246

[2]   Whaley DM, Soong WL and Ertugrul N 2004 Australasian Universities Power Engineering Conference (Brisbane)

[3]   Consoli A, Cacciato M, Scarcely G and Testa A 2004 Industry Applications Magazine IEEE **10/6** 35-42

[4]   Friedrich G and Gimeno A 2004 IEEE **1(1)** 1-6

[5]　　Bonisławski M, Pałka R, Paplicki P and Wardach M 2014 Przegląd Elektrotechniczny **10** 6
[6]　　Popenda A and Chwalba S 2014 Przeglad Elektrotechniczny **12** 265
[7]　　Ivankovic R, Cros J, Kakhki MT, Martins CA and Viarouge P 2012 New Advances in Vehicular
　　　　Technology and Automotive Engineering **6** 169
[8]　　Gross CA 2007 Electric Machines **1 edition**
[9]　　Dziubiński M, Drozd A, Adamiec M and Siemionek E 2016 IOP Conference Series: Materials
　　　　Science and Engineering [WOS] **1/148** 1-11