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Energy analysis of automobile electric energy sources in vehicle braking energy recuperation systems

JERZY OCIOSZYŃSKI

Warsaw University of Technology
Faculty of Automobiles and Heavy Machinery Engineering

The paper presents the possibility of application of recuperated vehicle braking energy, that is converted by AC generator into electric energy and fed to heating resistors for particle filter to increase the temperature of carbon deposits. The final result is burning of soot. Selected AC generator properties, resulting from its current-rpm characteristics as well as its operation under controlled overload are provided. The results of the tests on recovered electric energy transmission to load resistors were compared to the results of the tests with DC generators applied. The tests analysis was based on a city bus driving cycle.

Notation

E — electromotive force;
U_0 — alternator off-load phase voltage;
c — AC generator proper (construction) constant;
Φ — magnetic flux;
n — alternator rotational speed;
I_{abc} — alternator phase current;
R_s — alternator stator coil resistance;
R_{abc} — receiver resistance;
x_L — inductive reactance of stator coil;
f — frequency;
p — pole couple number of alternator;
L — inductance of x_L reactance coil;
$k(t)$ — co-ordinates of cycle velocity trajectory;
$W_{k(t)}$ — test stand co-ordinates;
k — breaking phase factor;
V — vehicle speed.

1. Introduction

Typical for vehicle driven under urban driving cycle conditions is high stopping frequency. During braking phase it is possible to recuperate drive energy and this can be done for every kinds of vehicle powering systems: electric, hybrid or classic.

Up to know, energy savings are usually related to vehicles driven electrically or with hybrid electromechanical drive systems. These systems give the possibility for energy savings by electric means. The recovered energy [1, 2] passed to the electrochemical batteries increases their capacity what insignificantly extends the vehicle driving distance. The possibilities to recover and accumulate braking energy of hybrid electromechanical and electric vehicles put forward and idea to use this energy in classically powered vehicles. In combustion engine driven vehicles, efforts are made to utilise braking energy which is converted by installed electric generators into electric energy. The recuperated energy may be fed to machine load resistors that can be treat as an additional thermal energy sources. It is only last few years that this additional energy is taken into consideration in energy balance of classically powered automobiles. This energy can be used for powering heating resistors of particle filters, for example, to increase the temperature of filter monolith and consequently the temperature of carbon deposits and initiate the burning process of soot.

Particle filters are ecology devices restraining emission of solid substances contained in exhausted gasses produced by combustion engines especially by the Diesel engines. The main ingredient that fortunately makes no danger for people is a soot. However, it adsorbs benzopyrene (3,4-benzopyrene is cancerigenous exhausts component) and converts into cancerigenous substance. The filters should be regenerated periodically by burning out the soot. The spontaneous process cannot occur, as the exhaust system temperature is not high enough. That is why the burning processes with external energy supply are often used. The paper proposes replacing classic methods used to regenerate soot filters with unconventional methods with thermal energy obtained from filter heating resistors, powered by electric energy.

The heat energy initiates soot burn out. However, the installation of mechanical-into-electrical energy converters such as current generators is necessary for the process. The filter regeneration consists of periodic soot burn out. It is necessary to reach the temperature of soot self-ignition equal to 900 K and hold up the burning process till the filter is empty. For this purpose the heating resistors of the filter are used, that during braking phase of actual driving cycle should produce energy at the level of $3 \div 5$ MJ. During experiments discussed in [3] temperature was measured at selected points of model particle filter. Heating resistors were powered at constant level. Oxidising agent (air) was fed at certain flow. Figure 1 presents the test results. The highest temperature rise (900 K) was sensed by the thermoelement no. 1, located on the filter axis close to the air inlet. Supplied energy was about 5.5 MJ. Because of high overestimation of energy supplied from outside, test-stand experiments may have comparative significance only.

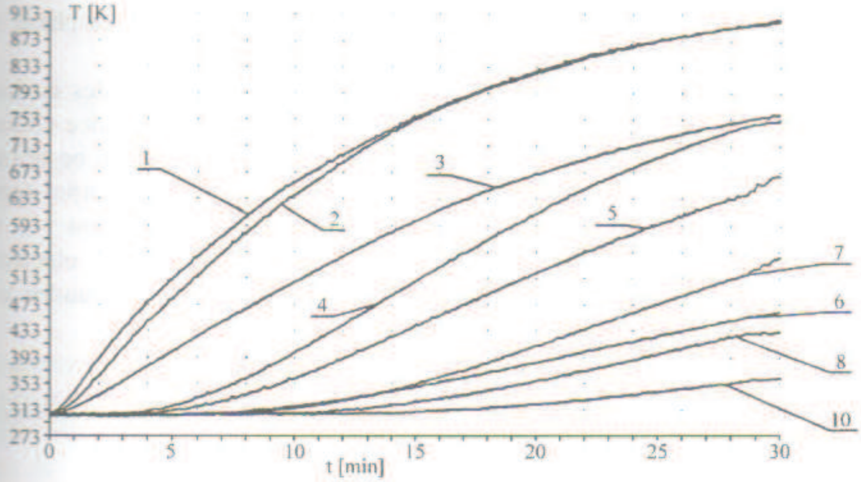

Fig. 1. Temperature changes at selected points of filter monolith versus heating time (heating power 3.2 kW, oxidizer flow 40 dm^3/min).

Rys. 1. Zmiany temperatury w określonych miejscach monolitu filtra w zależności od czasu nagrzewania (moc grzania 3,2 kW, wydatek utleniacza 40 dm^3/min)

Basing on design properties analysis of modern automobiles one can say that they are usually equipped with alternator, which is a vehicle electric energy source. The combustion engine, the primary energy source, is the main supplier of energy for the alternator. In classic applications alternator supplies energy to all electric devices of the vehicle with a battery charge included. Its proper output is controlled by energy balance in which two components: energy transmitted to receivers and energy produced by the source is critical for proper operation of the whole system.

Additionally installed AC generator as a converter of mechanical into electrical energy has a certain output during vehicle braking energy recuperation process. Actually, the output of generators installed in city buses should be 30÷50 kW. Braking phase during real driving cycle last a few up a dozen or so seconds. Actual energy recuperation time is even shorter. Overload ability is a possibility to increase generator's nominal output for such time, that temperature of stator and rotor coil as well as rectifier body will not exceed permissible value. So generator was tested under controlled overload operating conditions to make use of this characteristic, in case of positive results, by installing in real object a generator with lower output.

2. Selected properties of vehicle alternators

A vehicle AC generators [4] are made as three-phase synchronic generators were rotor is a field magnet and stator works as armature. The electromagnetic activation coming from excitation coil located on rotor with „claw" type poles. The semiconductor rectifying diode system made as three-phase bridge rectifies the three-phase current produced in stator coil.

The electric scheme of the tested alternators with 9 rectifying diodes is shown on Fig. 2. The current-rpm characteristic is the basic alternator performance characteristic. This relation (Fig. 3) informs the user about the current amount to be obtained at a certain rotational speed of the alternators and constant voltage on output terminals. The analysis of shape and run of very beneficial generator current — voltage characteristic should be based on assumption of relation describing electromotive force as the key characteristic which is equal to machine voltage under off-load condition:

$$E = U_0 = c \cdot \phi \cdot n, \tag{1}$$

where U_0 — alternator phase — voltage under off-load phase voltage, c — construction constant, ϕ — magnetic flux, n — alternator rotational speed.

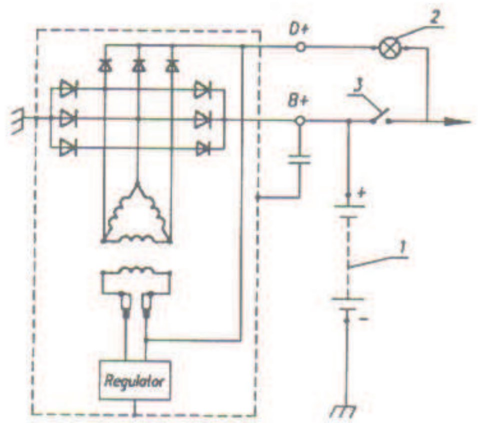

Fig. 2. Electric scheme of the tested alternator: *1* — battery, *2* — control bulb, *3* — load switch, D+, B+ — external clamps, W — rpm indicator switch.

Rys. 2. Schemat elektryczny badanego alternatora: *1* — akumulator, *2* — żarówka kontrolna, *3* — wyłącznik obciążenia, D+,B+ — zaciski wyjściowe, W — zacisk do łączenia miernika prędkości obrotowej

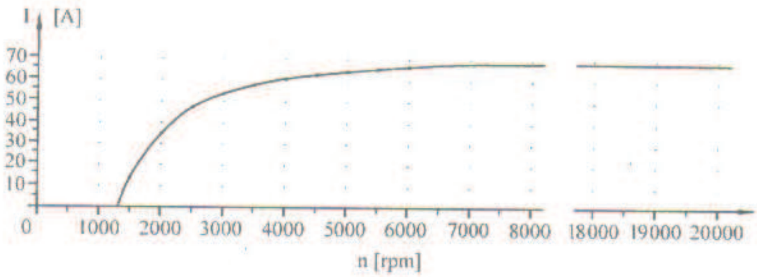

Fig. 3. The current — rpm characteristic of the tested alternator.

Rys. 3. Charakterystyka prądowo-prędkościowa badanego alternatora

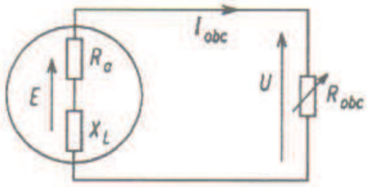

Fig. 4. The substitution scheme of the alternator loaded by a resistor.
Rys. 4. Schemat zastępczy alternatora obciążonego rezystorem

A substitution scheme of a resistor-loaded alternator is shown at Fig. 4. For the sake of simplicity the interface of armature reaction to coil internal flux upon the main flux was neglected in the analysis. According to Fig. 3 the value of load phase current may be given as:

$$I_{obc} = \frac{U_0}{\sqrt{(R_a + R_{obc})^2 + X_L^2}}, \tag{2}$$

where R_a — alternator stator coil resistance, R_{obc} — receiver resistance, x_L — inductive reactance of stator coil.

The inductive reactance of stator coil depends on frequency in the following fashion:

$$X_L = 2\Pi \cdot f \cdot L = 2\Pi \frac{p \cdot n}{60} L = c_1 \cdot n, \tag{3}$$

where f — frequency, p — pole couple number of alternator, L — inductance of x_L reactance coil.

Then it can be stated:

$$I_{obc} = \frac{c \cdot \phi \cdot n}{\sqrt{(R_a + R_{obc})^2 + (c_1 + n)^2}}. \tag{4}$$

On the base of the following inequality valid for small rotational speed of the rotor:

$$C_1 \cdot n << R_u + R_{obc} \tag{5}$$

and assumption of constant flux the formulation given in (4) may be simplified:

$$I_{obc} = \frac{c \cdot \phi \cdot n}{\sqrt{(R_a + R_{obc})^2}} = c_2 \cdot n. \tag{6}$$

It follows from the mentioned above that at the first stage of characteristic the load current is proportional to rotor rotational speed. The consecutive increase of rotor rotational speed brings the inductive reactance to higher level ($X_L > c_1\ n$) and at a certain n value threshold the inequality may be stated:

$$R_a + R_{obc} << c_1 \cdot n \tag{7}$$

which substituted to formula (3) yields:

$$I_{obc} = \frac{c \cdot \phi \cdot n}{\sqrt{(c_1 \cdot n)^2}} = \frac{c}{c_1} \cdot \phi = \text{const.} \quad (8)$$

The above analysis brings the conclusion that the value of loading current is constant at high angular velocities of the rotor. The possibility to reach the rotational speed of 20000 rpm enables to use this property of alternator for energy recuperation in braking phase of a vehicle motion. So, a constant output may be transmitted to resistance receivers at a wide range of braking velocities of the vehicle.

According to the results of generator tests under controlled overload condition [5] the power — rpm characteristics for machine certain voltage were shown at Fig. 5.

The Table 1 summarises self-excited operation tests results of the alternator operation under different voltage (controlled overload condition). The following values

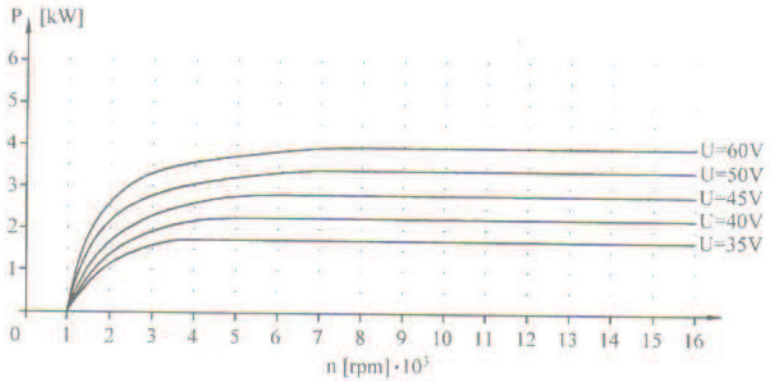

Fig. 5. The alternator power — rpm characteristic for different external voltage.
Rys. 5. Charakterystyka mocy w funkcji prędkości obrotowej alternatora, dla różnych wartości napięć na zaciskach maszyny

Table 1. The tests results of the alternator working in self-exciting system for different values of external voltage.
Tabela 1. Zestawienie wyników badań alternatora w układzie pracy samowzbudnej dla różnych wartości napięć na zaciskach zewnętrznych

n rpm	P_{max} kW	R_{obc} Ω	U_{reg} V	I_{obc} A
1	2	3	4	5
4000	1.732	0.70	35	49.5
5000	2.252	0.71	40	56.3
6000	2.812	0.72	45	62.5
7000	3.400	0.73	50	68.0
8000	3.960	0.91	60	66.0

are presented in the consecutive columns: w1 — rotational speed coupled to alternator maximum output, w2 — maximum output of the alternator, w3 — loading resistance applied in the experiment, w4 — voltage regulated in the experiment, w5 — loading current.

Test results proved the possibility of generator operation under controlled overload. Such unconventional operation demands certain limitations, mainly concerning the operation time under such non-typical conditions. The whole range of experiments described in [3] confirmed the possibility of generator operation under load several times increased above nominal output within 120 s while maintaining admissible temperatures of its components. Because the alternator with output of 0.9 kW was used in the tests, above states exceeding nominal output 1.9 up to 4.4 times for selected load range. This overload ability also applies to generators with grater output. Such characteristic could be referred to energy transformation machines that DC generators are. To summarise, assuming application of discussed generator properties it is possible to obtain braking energy recuperation in real objects by utilising transformation machines with lower nominal output.

3. Alternator as an electric energy source in braking energy recovering systems

In classically powered vehicles mechanical energy of braking transformed into electric energy may be used to supply heating resistors which turn out as and additional heat source. In order to transform mechanical energy into electric energy DC or AC generators should be used. The tests results obtained at model stand were transformed to real conditions.

The graph showing city bus speed versus time built in accordance to so called Warsaw driving cycle [6] treated as a real traffic cycle is presented at Fig. 6. The alternator with power output of 5 kW (operation under controlled load) was tested. According to the current — rpm characteristic (Fig. 2) power output was kept on constant level at the rotational speed change from 16 000 to 8000 rpm. Theoretical calculations of braking energy recover were made by using driving cycle of a city bus. The driving speed of the city bus equal to 50 km/h was related to alternator speed equal to 16 000 rpm.

The data obtained (Fig. 5 and Fig. 6) show that energy recuperation calculations will not be conducted under 25 km/h (corresponding to 8000 rpm of alternator speed). The example of energy analysis related to driving cycle phases 5th to 9th where driving cycle co-ordinates approach values:

$$V_5 = 50\ \text{km/h};\quad V_6 = 42\ \text{km/h};\quad V_x = 25\ \text{km/h}$$

The time of energy supply in driving cycle is equal to:

$$t_{(5-6)} = 8\text{s};\quad t_{(6-x)} = 8\text{s}.$$

Considering total time of braking phase factors 5-6-x equal to 16 s the total recuperation energy comes to the value 80 kJ.

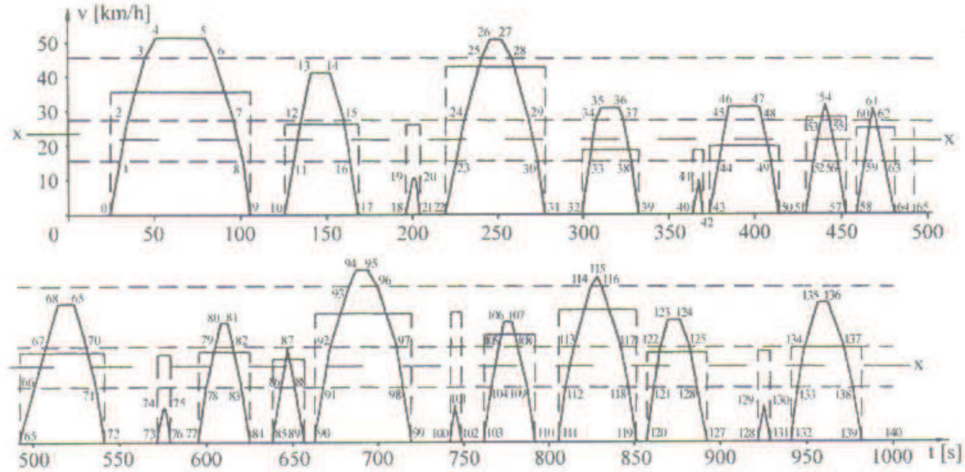

Fig. 6. City buses speed-time characteristic corresponding to Warsaw Driving Cycle.
Rys. 6. Warszawski cykl jazdy przedstawiający zależność prędkości jazdy autobusu miejskiego od czasu

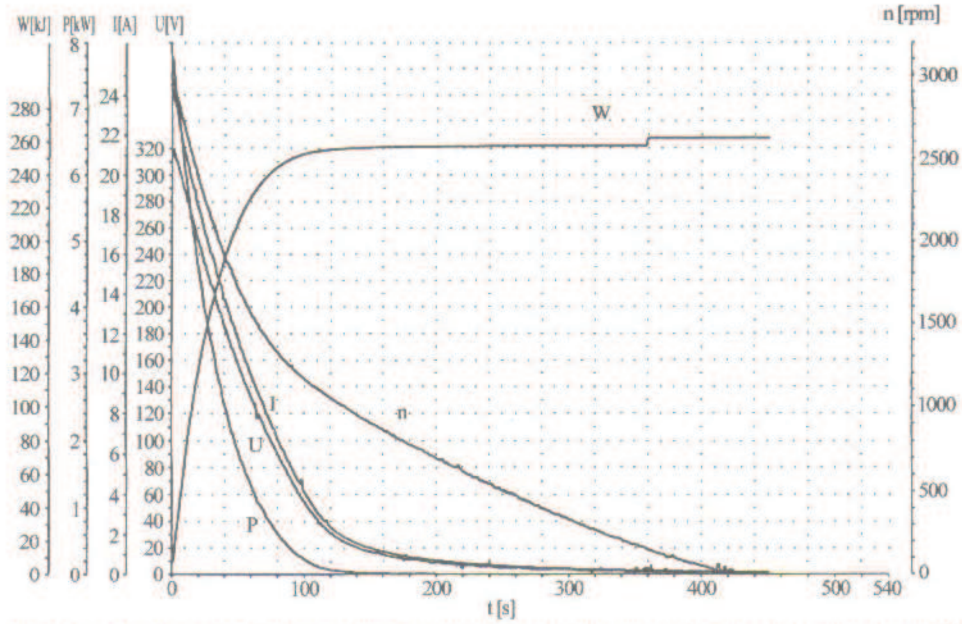

Fig. 7. Graphs of current, voltage, power, rotational speed and recuperation energy versus time for DC generator during braking inertia mass up to 3000 rpm.
Rys. 7. Przebieg prądu, napięcia, mocy, prędkości obrotowej i energii rekuperacji w czasie, prądnicy prądu stałego w trakcie hamowania masy bezwładnościowej od prędkości obrotowej 3000 obr/min

For comparison purposes, the results of experiments with DC generator as a mechanical-into-electrical energy transformer obtained in [7, 8] are presented. The graph presented on Fig. 7, showing current, voltage, power, rotational speed and recuperation energy versus time for DC generator during braking inertia mass from 3000 rpm, was the analysis background. The generator voltage was equal to 320 and load current reached 22 A. For this reason the installed 3.5 kW generator was loaded up to 7.0 kW.

In energy analysis concerning DC generators the relation between the rotational and linear speed versus time was assumed as the linear dependence. The maximum vehicle speed in the driving cycle is 50 km/h, while maximum rotational speed of experimental stand generator reached 3000 rpm. In the experiment the rotational speed of 1250 rpm (corresponding to vehicle speed of 21 km/h) was settled as energy recovery threshold. In order to define minimal real values of energy which still might be recovered the area of triangles in systems of driving cycle co-ordinates $V_{k(t)} = f_{(tk)}$ and the area of triangles in systems of experimental stand co-ordinates $W_{k(t)} = f_{(tk)}$ are proportional. As an example the energy analysis of phases 5-9 of driving cycle was carried out and the results were compared to corresponding experimental results. In the driving cycle for $k = 5$ to 9 (k — braking phase factor) the co-ordinates reach the values:

$$V_{c(5)} = 50 \text{ km/h}, \quad V_{c(6)} = 42 \text{ km/h}, \quad V_{c(7)} = 25 \text{ km/h}, \quad V_{c(x)} = 21 \text{ km/h}.$$

The co-ordinates corresponding to experimental results are as follows:

$$n_{p(5)} = 3000 \text{ rpm}; \quad n_{p(6)} = 2500 \text{ rpm}; \quad n_{p(7)} = 1500 \text{ rpm}; \quad n_{p(x)} = 1250 \text{ rpm}.$$

The time of energy supply in driving cycle is equal to

$$t_{c(5-6)} = 8\text{s}, \quad t_{c(6-7)} = 8\text{s}; \quad t_{c(7-x)} = 4.5\text{s}.$$

The time of energy supply during measurement:

$$t_{p(5-6)} = 15.5\text{s}, \quad t_{p(6-7)} = 49.4\text{s}; \quad t_{p(7-x)} = 17.6\text{s}.$$

According to taken assumptions the energy transmitted to load resistors is equal to:

$$W_{r(5-6)} = \frac{8}{15.5} 98 = 50.6 \text{ kJ}; \; W_{r(6-7)} = \frac{8}{49.4} 134.4 = 21.8 \text{ kJ}; \; W_{r(7-x)} = \frac{4.5}{17.6} 16.6 = 4.2 \text{ kJ}.$$

Total amount of transmitted energy reaches the value: $W_{r(5-x)} = 76.6$ kJ. The energy measured at the experimental stand during the same time was equal to:

$$W_{p(5-6)} = 98 \text{ kJ}; \quad W_{p(6-7)} = 134.4 \text{ kJ}; \quad W_{p(7-x)} = 16.6 \text{ kJ}.$$

The results of the energy recovered by alternators in driving cycle of a city bus corresponding to Warsaw driving cycle were presented in Table 2. As a comparison, the calculation results of energy recovered by DC generator in the same driving cycle are also presented. The results corresponding to 7 kW DC generator and 5 kW AC generator are given in Table 2. The value of energy recovered by an alternator of the same output as DC generator would be equal to $\frac{7.0}{5.0} \cdot 550 = 770$ kJ in comparison to the 379 kJ in case of DC generator. In the case of hypothetical installation in a vehicle a DC generators with expected total output equal to 30 kW the following interpretation may be applied to the calculation results: the total recovered energy transmitted to load resisters would be $\frac{30}{70} \cdot 380 = 1.61$ MJ, and by alternator $\frac{30}{5} \cdot 550 = 3.3$ MJ.

Table 2. Summary of results of the calculation of the energy transmitted to AC and DC generator load resistors during braking phases of Warsaw driving cycle.

Tabela 2. Zestawienie wyników obliczeń energii elektrycznej przekazywanej do rezystorów obciążenia alternatora i prądnicy prądu stałego w fazach hamowania w trakcie realizacji cyklu warszawskiego

N°	Braking phase N°	Braking phase time	Energy recuperation time (DC generator)	Energy recuperation time (AC generator)	Recovered energy (DC generator)	Recovered energy (AC generator)
–	–	s	S	S	kJ	KJ
1	5–9	26.0	20.5	16.0	76.6	80.0
2	14–17	16.0	11.0	9.0	20.0	45.0
3	20–21	2.5	0	0	0	0
4	27–31	26.0	20.0	17.0	76.8	85.0
5	36–39	11.0	8.0	4.0	8.7	20.0
6	41–42	2.5	0	0	0	0
7	47–50	11.0	6.0	3.0	6.5	15.0
8	54–57	11.0	6.0	3.0	6.5	15.0
9	61–64	11.0	6.0	3.0	6.5	15.0
10	69–72	16.0	12.0	8.0	23.0	40.0
11	75–76	2.5	0	0	0	0
12	81–84	13.5	6.0	4.0	9.0	20.0
13	87–89	9.0	3.0	0	2.0	0
14	95–99	25.0	13.0	11.0	67.7	55.0
15	101–102	2.5	0	0	0	0
16	107–110	13.5	6.0	4.0	9.0	20.0
17	115–119	22.5	14.0	12.0	32.0	60.0
18	124–127	13.5	8.0	6.5	12.0	32.5
19	130–131	2.5	0	0	0	0
20	136–139	16.0	11.0	9.5	23.2	47.5
					Σ 379.5	Σ 550

4. Concluding remarks

Presented concept to use AC generator as a mechanical into electric energy transformer during energy recover at braking phase of a vehicle motion brought the following conclusions:

- Alternator properties arising from its current-rpm characteristic make it possible to obtain constant output during braking phase at a wide range of vehicles velocities.
- The difference of recovered energy values at real driving cycle obtained for DC and AC generators of the same output is two times bigger in favour for the alternators.
- The load resistance may be supplied with power up to five times grater than rated power output of the alternators working under controlled overloading for certain time.
- Automobile alternators may be used for particle (soot) filters regeneration process as electric energy sources.

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Analiza energetyczna źródeł energii elektrycznej w systemach odzysku energii hamowania

Streszczenie

W publikacji omówiono możliwości wykorzystania energii hamowania samochodu, która, przekształcona w alternatorze w energię elektryczną, zasila rezystory grzejne filtra cząstek stałych, zwiększając temperaturę nagromadzonej w nim sadzy. Końcowym efektem jest spalenie sadzy. Podano wybrane właściwości alternatora, wynikające z jego charakterystyki prądowo-prędkościowej oraz pracy w warunkach kontrolowanego przeciążenia. Wyniki badań, w których odzyskana energia elektryczna przekazywana była z alternatora do rezystorów obciążenia, porównano z badaniami stanowiskowymi, w których ta energia dostarczona była do rezystorów z prądnic prądu stałego. Analizy wyników dokonano w warunkach rzeczywistego cyklu jazdy autobusu komunikacji miejskiej.