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Method of Calculating the Main Parameters of the Generator in Various Modes of the Car Regenerative Braking

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Abstract

Improving the method of regenerative braking of a car with a start-stop system by installing an additional generator is offered. An option of the optimal control of the brake torque of an additional generator is offered. The regenerative braking under consideration required an appropriate method of calculation. This technique makes possible to obtain the dependence of the braking moment on the angular velocity of the generator in various modes, the dependence of the allowable maximum generator power on the speed and load, the dependence of efficiency and the braking moment on the speed. Redistribution of energy generated by an additional generator for charging the battery and heating the engine coolant has been introduced. The brake torque of the electric machine G290 is calculated in the mode of regenerative braking. The obtained results are of practical importance for the transport industry. Calculated N at which the current 150 A is reached. According to factory data the ultimate current is reached at 1450 rpm (discrepancy of less than 3%). So, there is a good coincidence of calculated data. This method does not require a great number of experimental points. The obtained results are of practical importance for the transport industry.

Keywords: start-stop system, mathematical model of synchronous generator, regenerative braking, hybrid car, ecological safety, valve electric drive.

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1. Introduction

Fuel and resource problems and global ecological problems are the result of development of modern technologies [1]. Automobile transport is directly related to this [2–4]. The research shows that exhaust gases are responsible for 70% of harmful emissions to the atmosphere. The level of pollution increases annually by an average of 3.1% [5]. Every year 22 million tons of pollutants are emitted in the air throughout the world [6]. All these caused the necessity to create energy-efficient technologies and development of new, more environmentally friendly and cheap types of vehicles, namely, hybrid vehicles, plug-in hybrid vehicles and electric vehicles [7–10]. Compared with the electric vehicles, hybrid vehicles and plug-in hybrid vehicles have a significant advantage, namely there is no direct dependence of the run on the battery charge because they can work like regular gasoline cars. But in spite of this hybrid vehicles also need enhancement aiming at increasing their efficiency and ecological compatibility [11, 12]. Advantages of hybrid vehicles directly depend on the amount of generated brake energy and efficiency of its use. The task of the developers of the strategy of hybrid vehicles control lies in search for optimal decisions connected with economy of fuel, performance and controllability [13–16]. The proper combination of these three criteria is a topical and requested task. In order to optimize distribution of energy between the engine-generator, battery and ultracapacitor of a plug-in hybrid electric vehicle, the authors of paper [14] suggested a new adaptive strategy of energy control, which has more fuel efficiency than the traditional control strategy based on the dynamic programming.

Besides, engineering solutions can improve hybrid vehicles characteristics significantly. For example, the authors of [17] developed a new hybrid transmission with dual planetary gear sets for transit buses. The developers claim that it can reduce fuel consumption by 39% as compared to the common transmission.

Article [18] presents the braking system for hybrid vehicles with automatic gearbox and the algorithm of controlling regenerative braking, which can increase regeneration of regenerative braking energy at the expense of increasing the gradient of the required braking effort against the pedal stroke.

The start-stop system is used not only in hybrid vehicles. One of the possible ways of improving engineering, economic and ecological characteristics of traditional cars is the usage of a start-stop system [19–21]. The cars with more advanced start-stop systems are called micro-hybrid cars. Today many leading car manufacturers have cars equipped with such a system in their range [22]. However, such systems have some drawbacks [23].

The principle of operation of a start-stop system is the following: when the car stops, the engine switches off. In case of the mechanical gearbox, the engine starts when the clutch pedal is depressed (sometimes the accelerator pedal, as well), and with the automatic gearbox the engine starts when the brake pedal is released.

Multiple start of the engine can be realized with the help of the heavy-duty starter motor, reversing generator (starter-generator), hydraulic starter, fuel injection in the cylinders and ignition of the mixture [24–27].

In the developed start-stop system, the improvement of economic and environmental characteristics, in contrast to existing analogues, is achieved due to the fact that:

– when the car is standing or moving at low speed, the engine starts using a starter. At a sufficiently high vehicle speed, the engine starts without a starter, i.e. from the kinetic energy of a moving car;

– to increase the time of regenerative braking, an additional generator (AG) is introduced that is connected to the wheels of the vehicle;

– the engine is stopped not only on a standing car, but also on a car with an open transmission, moving by inertia or downhill;

– the concept of saving regenerative braking energy is used not only in the battery, but also in the form of electrical heating of the cooling fluid. This provides the necessary braking moment when the traction battery is sufficiently charged, and also improves the thermal balance of the engine.

The purpose of this work is introduction of new regenerative braking modes and the development of methods for calculating the main parameters of AG in these modes. Its load can be charging battery or active resistance of the heater cooling fluid. To control the regenerative modes in a wide range of speeds, excitation control is applied and pulse voltage converters are used.

To achieve this goal, it is necessary:

– to consider the features of regenerative braking in a car with a start-stop system;

– to justify the methods of efficient use of stored kinetic and potential energy in a car with an improved start-stop system;

– to foresee the redistribution of the energy produced by the AG for charging the batteries and for heating the coolant of the internal combustion engine;

– to develop a mathematical model of the generator and calculate the braking torque, power and efficiency of the generator in various modes of regenerative braking.

The results obtained are of practical importance for the transport industry.

2. Redistribution of energy of the additional generator

The improved start-stop system allows improving the economic, ecological and performance characteristics of the car due to [7, 28]:

– increased regenerative braking time. For this purpose, an additional generator (AG) connected with the wheels of the car was introduced;

– the reduced load on the starting system due to the fact that at the speed of a car larger than 40 km / h, the internal combustion engine starts without a starter (by the kinetic energy of a moving car);

– the reduced operating time of ICE. The stoppage of the internal combustion engine is carried out not only on a standing car, but also on a car with a disengaged gear, moving on inertia or down the slope;

– implementation of the concept of saving energy of regenerative braking not only in the AB, but also in the form of electric heating of the coolant, which provides the necessary brake torque and improves the thermal balance of the internal combustion engine [28].

Introduction of an AG of up to 10 kW capacity makes desirable its kinematic link with the driving wheels through a belt drive from the shaft of the AG to the secondary shaft of the mechanical gearbox with the required gear ratio.

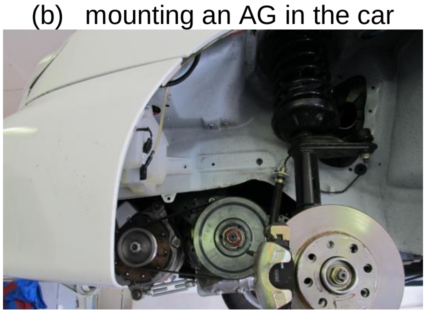
The AG is located in the engine compartment above the gearbox and transmits the rotation to the secondary shaft of the gearbox (to the main transmission). The transmission of the torque of the valve electric engine (VEE) is carried out through the polychain belt, as shown in Fig. 1 [29].

It is important to note that for hybrid vehicles, the quality of the generator / electric motor plays an important role [30, 31].

The AG is turned on together with the "stop signal", i.e. when you press the brake pedal. This allows the driver to turn on only electric braking with a slight pressure on the brake pedal, while the braking system of the car is not working yet. Such periodic activation of electric braking ensures effective use of the kinetic and potential energy of the car, since it provides sufficient deceleration for service braking with the engine off, including driving on long descents.

(a) belt drive

(b) mounting an AG in the car



(c) Installing an additional generator in the car

Figure 1. Additional generator

Usually only battery is charged in the mode of regenerative braking of the car. But a relatively low capacity of battery does not make possible to provide the necessary efficiency of electric braking in all conditions, for example, when the battery is sufficiently charged and the charge current is small. This problem can be solved by pressing the brake pedal, when the electric energy generated by the AG is saved:

– by charging the battery;

– by heating the coolant of the ICE cooling system (Baginov et al., 2009).

That means that the generator can be loaded either directly on the battery, or on the battery through the boost DC-DC converter, or to the active resistance of the starting pre-heater (SPH). The SPH warms the ICE coolant. This principle of regenerative braking helps maintain the thermal balance of internal combustion engines and saves hydrocarbon fuel. It also provides a wide range of vehicle deceleration modes.

In order to achieve the most efficient distribution of regeration energy, it is necessary to select the AG, which is the most suitable by technical characteristics. To do this, a method for calculating the basic parameters of the generator in various modes of regenerative braking of a car has been developed. In this case, the system of automatic control of the generator phase current must maintain the current mode. In addition, when calculating, it is important to take into account the current limiting modes that arise in the area of the working revolutions of the AG.

The source data are necessary for the calculation of the generator. Moreover, the manufacturer of the generator does not provide many of the necessary parameters, and their direct measurement is not always possible or is rather difficult. In order to solve this problem, in this work, the parameters of the idle speed experience of a generator operating in the valve electric engine are available for easy measurement, and the missing parameters are calculated on their basis.

3. Calculation of regenerative generator

The mathematical description of the generator operation is a rather complicated problem because the magnetic flow near the saturation (or the “knee” of the hysteresis loop) is nonlinearly dependent on the current in the windings. In many cases, we can assume that an independent excitation generator operates in a static mode [32].

Calculation in a static mode imposes certain restrictions on the operating conditions of the generator. These are conditions under which there are no transient processes in the generator or the conditions when the phase currents do not exceed the values at which the stator ferromagnetic material is saturated. These conditions are met almost all the time of the generator operation in the presence of a system for automatic regulation (limitation) of phase currents, as well as with the correct choice of the additional generator power, sufficient for all modes of service braking. In the emergency braking mode, there will be no power overload of the generator, because the braking system of the car comes into operation, providing the necessary rapid deceleration of the car.

Then, since the zones of short-term overload over armature current are excluded from consideration, the mathematical description of the energy conversion processes is simplified.

Synchronous electric machines (SEM) are used as automotive generators. They work with a rather small difference in the shape of the generated phase of electro-moving force (EMF) from the sinusoid. This is facilitated by the use of cranky (claw-like) pole rotors in automobile generators. For such SEMs a standard model of a generalized electric machine can be used [33].

The consideration of the SEM in the generator mode is made with respect to the conclusions of the generator's three-phase diode bridge, or the bridge formed by the reverse diodes of the inverter's controlled power switches, if SEM is used more in the mode of the electric machine (EM). In the latter case, all power control keys are in the "off" position. The equation of the voltage balance for the excitation winding and the voltage equation for a loaded armature chain will in general have the following form:

$$u_{ew} = i_{ew} \cdot R_{ew} + L_{ew} \frac{di_{ew}}{dt}; \quad (1)$$

$$e - u_g - i_a \cdot R_a - L_a \frac{di_a}{dt} = 0, \quad (2)$$

where: u_g – voltage on the generator's terminals, the load can be connected to them; u_{ew} – feeding voltage of the EM excitation winding excitation winding; e – EMF of rotation; R_{ew} – cumulative resistance of the excitation winding chain; i_{ew} – instantaneous value of the excitation winding current; i_a – instantaneous value of the armature current. L_a – cumulative inductance of the armature chain; L_{ew} – cumulative inductance of the excitation winding chain; R_a – cumulative resistance of the armature chain.

The value of the cumulative resistance of the armature chain R_a must include: the measured resistance between any two phase terminals of a synchronous electric machine (SEM) (considering the temperature); resistance of two diodes of a three-phase bridge with an armature current.

Mathematical modeling in system engineering of automobile transport often uses reduction of dynamic tasks to static problems. As it is known, powerful transient processes require the solution of a dynamic task. In our case, the transient processes are practically completely omitted by the need for a powerful SEM protection. This protection is made in the form of fast-acting systems of automatic regulation (SAR) of phase currents. Therefore, we will consider the mathematical model of SEM in the static mode.

As in the case of static (steady state) mode, there is a constant excitation stream, then ($L_{ew} \frac{di_{ew}}{dt} = 0$) and there is an armature direct current rectified by a three-phase diode bridge, then $L_a \frac{di_a}{dt} = 0$.

Determination of the excitation stream for the calculations is carried out by the indirect method described below. In the case of a steady-state generator mode, the static equation of the balance of voltages of the EM armature circuit takes the form:

$$E - U_g - R_a \cdot I_a = 0, \quad (3)$$

where U_g – voltage on the generator terminals; I_a – armature current; R_a – resistance of the generator armature chain; E = EMF of rotation.

We determine EMF of rotation E for every SEM. EMF of every conductor of stator winding e_c, crossed by rotating magnetic field of the rotor is determined by the law of electromagnetic induction:

$$e_c = B \cdot l \cdot v, \quad (4)$$

where B – magnetic induction; l – conductor length; v – relative speed of conductor shift.

An average value of EMF of a conductor $e_{c.av}$ at a relative shift of the rotor within the pole pitch is determined via the average value of magnetic induction B_{av}:

$$e_{c.av} = B_{av} \cdot l \cdot v. \quad (5)$$

If the armature winding has N active conductors and $2a$ parallel branches, then the number of sequentially connected conductors in each parallel branch will be $N/(2a)$. Then the average value of IMF of the machine will be:

$$E = B_{av} \cdot l \cdot v \cdot \frac{N}{2a}. \quad (6)$$

The speed at which the conductors cross the magnetic field will be:

$$v = \omega \cdot r, \quad (7)$$

where: ω – angular speed of the SEM rotor; r – radius of the stator counterbore.

Magnetic excitation flow F equals:

$$\Phi = B_{av} \cdot \frac{2\pi \cdot r \cdot l}{2p}, \quad (8)$$

where p – the number of pairs of poles.

$2\pi rl/(2p)$ – the surface of the armature core for one pole.

The average value of magnetic induction will be:

$$B_{av} = \frac{p \cdot \Phi}{\pi \cdot r \cdot l}. \quad (9)$$

Substituting (7) and (8) in (6) we obtain the following expression:

$$E = k \cdot \Phi \cdot \omega, \quad (10)$$

where k – constructive coefficient.

$$k = \frac{p \cdot N}{2\pi \cdot a}. \quad (11)$$

In order to obtain the equation of balance of powers we multiply the equation (1) by I_a:

$$E \cdot I_a - U_g \cdot I_a - R_a \cdot I_a^2 = 0 \,, \qquad (12)$$

where: $E \cdot I_a = P_s$ – full electric power of generator which is a sum of power on the generator load and the power of heat losses in generator; $U_g \cdot I_a = P$ – electric power from the generator to the load.

Rewriting the obtained balance of powers (12) we have:

$$P = E \cdot I_a - R_a \cdot I_a^2 \,. \qquad (13)$$

Hence, the magnitude of power at the output of the generator P is the difference between the total electric power of the generator and the electric losses that turn into heat inside the generator. The total electrical power is equal to the mechanical power supplied to the generator (if not taking into account bearing losses, fan losses and losses in the SEM magnetic trains).

The mechanical power can be written as $\omega \cdot M$, where M is a mechanical moment applied to the generator shaft. So, taking into account expression (10) we have:

$$E \cdot I_a = k \cdot \Phi \cdot \omega \cdot I_a = \omega \cdot M \,. \qquad (14)$$

Thus, for a mechanical moment, rotating the generator rotor, we have an expression:

$$M = k \cdot \Phi \cdot I_a \,. \qquad (15)$$

In practice, for mathematical modeling of SEM, the determination of the magnetic flow of excitation Φ and the values of the constructive coefficient k is a significant difficulty. As they always occur in the form of a product, we consider it expedient to determine the product of $k\Phi$ by the following computational-experimental way. We use the fact that, in the framework of accepted assumptions, the value $k\Phi$ is the same in the mode of EM, and in the generator mode. We write the equation of the balance of voltage of the armature chain for the motor mode of SEM [34]:

$$U - E - R_{a.eng} \cdot I_a = 0. \qquad (16)$$

where U – constant voltage of EM supply; $R_{a.eng}$ – cumulative resistance of an armature chain in the electric engine mode, i.e. considering the resistance of the channels of two open power keys of the controlled three-phase bridge.

Using the expressions (16) and (10), which are correct for the motion mode of SEM as well, we express the value $k\Phi$ necessary for further calculations:

$$k\Phi = \frac{U - R_{a.eng} \cdot I_{a.idl}}{\omega_{idl}}, \qquad (17)$$

where $I_{a.idl}$ – an armature current in the engine idling of the EM; ω_{idl} – angular speed of the rotor in the engine idling of EM.

In order to determine $I_{a.idl}$ и ω_{idl} an experimental research should be conducted.

Experimental determination of $I_{a.idl}$

We switch on the improved generator AG with the sensors of the rotor position and the block of inventor as an electric engine in engine idling.

Measurement of the armature current in engine idling $I_{a.idl}$, supply voltage of EM U and full active resistance of the armature $R_{a.eng}$ do not cause any difficulties. We calculate the speed of rotation of the shaft on engine idling $n = f/p$ (revolutions per second) by the measured frequency of the signal f from one of the sensors of the rotor position considering the number of pairs of poles and then obtain the value of the angular speed ω_{idl} on engine idling of the EM, $\omega_{idl} = 2\pi n$.

In Fig. 2. the experimentally taken in the engine idling values of the current and speed of rotation from the voltage of the battery for the EM are shown. EM is taken on the basis of the automobile generator G290B at the supply voltage of the excitation winding of 28 V. Also, Fig. 2. shows the dependence of idle power consumption P_{idl}, which will be needed to calculate the efficiency. To determine the value of $k\Phi$, it is advisable to choose an allowable maximum voltage, the efficiency will be maximum, and hence, the error will be minimized.

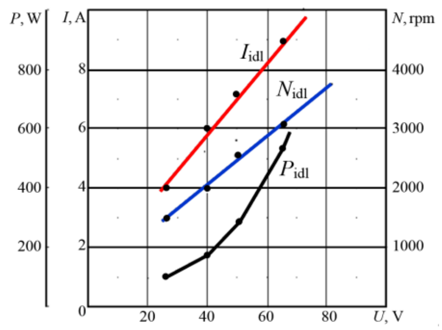


Figure 2. Experimental dependencies of the current I_{idl}, power P_{idl} and speed of rotation N_{idl} on voltage U for the engine idling

4. Calculation of efficiency of valve electric engine in generator mode

As generated electric power of a generator is known as $P_{el} = U_g \cdot I_a$, the efficiency η can be calculated without considering mechanical losses in bearings, losses for ventilation and magnetic losses.

If $P_{mech} = \omega \cdot M$ – mechanic power, supplied to the generator shaft, then:

$$\eta = \frac{P_{el}}{P_{mex}} = \frac{U_g \cdot I_a}{\omega \cdot M} = \frac{U_g \cdot I_a}{\omega \cdot I_a \cdot \kappa \cdot \Phi} = \frac{U_g}{\omega \cdot \kappa \cdot \Phi} = \\ = \frac{U_g}{E} = \frac{1}{E}\left(\frac{E - R_a E}{R_a + R_n}\right) = 1 - \frac{R_a}{R_a + R_n} = \frac{R_n}{R_a + R_n} . \quad (18)$$

In such approximation the efficiency of a generator G290 is 0,806.

Taking into account the losses for ventilation P_v and magnetic losses obtained from the experience of the idle motion of SEM in the EM mode, we have:

$$\eta = \frac{EI_a - R_a I_a^2 - P_v}{E \cdot I_a + P_{el.idl} - P_{a.idl} \cdot I_{a.idl}^2} = \\ = \frac{\omega \cdot k\Phi \cdot I_a - R_a I_a^2 - P_v}{\omega \cdot k\Phi \cdot I_a + U \cdot I_{a.idl} - P_{a.idl} \cdot I_{a.idl}^2} , \quad (19)$$

where $R_{a.idl}$ – cumulative resistance of the armature chain in the mode of idling engine.

Expression (19) takes into account that the power of losses determined by expression $R_a I_a^2$ in the numerator considers the full power of losses on electric heating, so the losses on electric heating $R_{a.idl} I_{a.idl}^2$ must be subtracted from experimentally obtained electric power of idling.

5. Checking the developed mathematical model of generator

In order to check we compare the factory data of generator with calculated values. The ultimate long-term current for armature windings of the generator G290 is 150 A, it is reached at voltage of 25 B, so $R_n = 0.166$ ohm. To determine $k\Phi$ we use expression (17) and an experimentally changed speed of rotation of the shaft on idling of EM with the supplying voltage 64.2B ($N_{idl} = 3123$ rpm) $I_{a.idl} = 9$ A, $R_{a.idl} = 0.03$ ohm.

The maximum calculated current can be written considering the full resistance of armature chain:

$$I_{max} = \frac{E}{R_n + R_a} = \frac{\omega \cdot k \cdot \Phi}{R_n + R_a}, \quad (20)$$

where $R_a = R_{a.f} + R_{a.eng}$, $R_{a.f}$ – full active resistance of armature winding (for G290 measured $R_{a.f} = 0.025$ ohm; $R_{a.eng}$ – resistance of two diodes of a three-phase bridge).

Voltage drop on one such diode with the current of 150 A is approximately 1.1 V. It means that for two sequentially switched on diodes it is $R_{a.eng} = 0.015$ ohm. The full active resistance of an armature winding will be:

$$R_a = R_{a.f} + R_{a.eng} = 0.025 + 0.015 = 0.04 \text{ ohm}$$

From (20) we express the angular speed ω, at which the current of 150 A is reached:

$$\omega = I_{max} \frac{R_n + R_a}{k \cdot \Phi} = \frac{2 \cdot \pi \cdot N}{60} . \quad (21)$$

As $\omega = 2\pi N/60$, then the number of revolutions is $N = 60\omega/2\pi$, rpm. We calculate N at which the current 150 A is reached:

$$N = 60 \cdot I_{max} \frac{R_n + R_a}{2\pi \cdot k \cdot \Phi} = 1489 .$$

According to factory data the ultimate current is reached at 1450 rpm. The comparison shows discrepancy of less than 3%. So, there is a good coincidence of calculated data with the Krause of a complicated task of calculating magnetic chain of SEM. This method does not require a great number of experimental points, especially with small currents of excitation winding, where the dependence of magnetic flow on the current is practically linear.

6. Braking modes of SEM with the improved start-stop system

There are three modes of the work of SEM with the improved start-stop system:

Mode 1 – the mode of regenerative braking when the car moves with the speed $V > V_{kr}$, where V_{kr} is a critical speed at which the condition $E = U_{AB}$ is fulfilled, where U_{AB} – is the voltage of the accumulation battery.

Mode 2 – is the mode of rheostatic braking when the car is moving. This mode is possible with any speed of the moving car.

Mode 3 – is the mode of regenerative braking when the car moves at the speed $V < V_{kr}$.

Mode 1

In mode 1 the equation of the balance of the armature chain voltages will be:

$$E - U_{AB} - R_a \cdot I_a = 0 , \quad (22)$$

where $U_{AB} = U_{ch}$ – is the voltage of accumulation battery in the charging mode; U_{ch} – the voltage of the charge of accumulation battery; R_a – resistance of the armature chain of the generator.

The armature current is equal to the charge current $I_a = I_{ch} = I_{ch}(\omega)$:

$$I_a = \frac{\omega k\Phi - U_{AB}}{R_a} . \quad (23)$$

The voltage on the power nippers of SEM is $U_{AБ}$, the charging current is equal to the armature current $I_a = I_{ch}$, at this, the charge is possible only with its positive value. To build the graph $I_{ch} = I_{ch}(\omega)$, we also need the dependence for stabilized (limited) current of the generator: $I_{ch} = I_{max}$. For G290B I_{max}=150 A.

Fig. 3 shows the dependence of the charging current on the terminal of the generator $I_{ch}(\omega)$ on the angular velocity ω of the shaft of SEM.

Charging the accumulation battery at regeration in Mode 1 makes sense only in the zone $\omega > \omega_1$, where ω_1:

$$\omega_1 = \frac{I_{max}(R_n + R_a) - U_{AB}}{k\Phi}. \qquad (24)$$

The zone of current rise in front of this zone is short in time and is not suitable for full service braking, so it needs to be replaced with Mode 3. When approaching the full charge, the battery voltage increases and then reaches a limit value, it is inadmissible to exceed it, therefore, a second loop of SAR voltage battery has been introduced. It also works by controlling the current of the excitation winding. Since the voltage stabilization immediately begins to reduce the charge current, and hence to reduce the brake torque, it is necessary to provide switching to Mode 2.

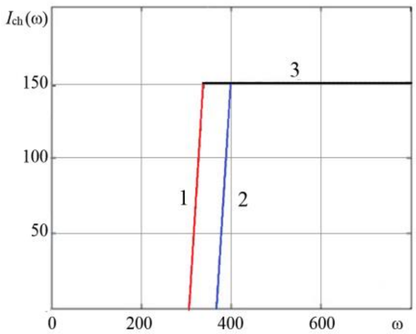


Figure 3. Dependence of the charging current at the generator's terminal on the angular velocity of the shaft of SEM: **1** For U_{AB} = 60 V; **2** For U_{AB} = 72 V; **3** $\omega \in [\omega_1, \omega_{max}]$

Mode 2

In the mode of rheostatic braking (Mode 2), the constant output voltage of the generator after the rectifier is converted by the DC-AC converter into the high-frequency alternating voltage. After this, it is raised by means of a high-frequency transformer (with a transformation coefficient n_{tr}) and fed to the starting preheater. At the same time a brake torque appears on the driving wheels of the car and a rheostatic regenerative braking take place [30]. The energy generated by the generator is used to heat the cooling fluid of the internal combustion engine. In an automobile with a start-stop system, the ICE does not work continuously, the coolant cools, so its heating improves the thermal balance of the ICE and reduces fuel consumption. In this unencumbered fuel the energy of recovery is preserved. The equation of the balance of the armature chain voltage in this mode will be:

$$E - (R_a + R_{in.c})I_a = 0, \qquad (25)$$

where $R_{in.c}$ – input resistance of a DC-AC converter, serving to feed the starting preheater of ICE coolant with the high-frequency AC.

If we determine the cumulative resistance ($R_a + R_{in.c}$) via R_s, then the armature current, and consequently, the current produced by a generator, will be determined by the expression:

$$I_a = k \cdot \Phi \cdot \omega / R_s. \qquad (26)$$

The coefficient of transformation of high-frequency transformer n_{tr} is calculated as the ratio of the working voltage of the staring preheater (220 V) to the optimal (factory) value of the working voltage of the generator G290B (28 V).

From the condition of power preservation of an ideal transformer the equivalent intake resistance from the primary transformer winding, loaded from the secondary winding on the SPH with the resistance R_{sph} will be: $R_{in.c} = R_{sph} / n_{tr}^2$. Considering the efficiency of DC-AC converter $\eta_{dc\text{-}ac}$ we have $R_{in.c} = \eta_{dc\text{-}ac} \cdot R_{sph} / n_{tr}^2$.

Mode 2 must obligatory have the SAR – by voltage on the SPH. We assume that the current is limited by the armature limit current $I_{a.max}$. Then, on the base of (26) we have the equation:

$$I_{a.max} = \frac{k \cdot \Phi_{max} \cdot \omega_1}{R_s}, \qquad (27)$$

where Φ_{max} – is a full (non-weakened) excitation flow.

Consequently, in point ω_1 on the interval $\omega \in [\omega_1, \omega_{max}]$ we have:

$$\omega_1 = R_s \cdot I_{a.max} / (k\Phi_{max}), \qquad (28)$$

where $(k\Phi_{max})$ – is the product at full excitation flow.

Next we write the condition for current stabilization:

$$I = \omega \cdot k \cdot \Phi(\omega) / R_s = \text{const} = I_{a.max} = \\ = k \cdot \Phi_{max} \cdot \omega_1 / R_s, \quad \omega \in [\omega_1, \omega_{max}] \qquad (29)$$

$$\omega \cdot k \cdot \Phi(\omega) / R_s = k \cdot \Phi_{max}\, \omega_1 / R_s;$$

$$\text{from where } \omega \cdot k \cdot \Phi(\omega) = k \cdot \Phi_{max}\, \omega_1, \ \omega \in [\omega_1, \omega_{max}] \qquad (30)$$

We must note that functional dependence $\Phi(\omega)$ is introduced to ensure the possibility of SAR work. As the angular frequency increases, the current, produced by the generator, also increases. To make this current constant and, taking into account that values k and R_s are constant, we must reduce (weaken) the flow by some law. From (30) we have:

$$\Phi(\omega) = \Phi_{max}\,\omega_1 / \omega\,,\ \ \omega \in [\omega_1, \omega_{max}]$$

$$k{\cdot}\Phi(\omega) = (k{\cdot}\Phi)_{max}\,\omega_1 / \omega\,,\ \omega \in [\omega_1, \omega_{max}] \qquad (31)$$

Using the experimental-calculation method as before, we obtained value $k\Phi$. Similarly, using the SEM in engine idling, the dependence $k\Phi(\omega)$ required for further calculations should be obtained. The number of experimental points can be relatively small, especially at low currents of the excitation winding.

It is also convenient to adjust the power supply voltage of SPH in the process of SAR operation for the SEM with electromagnetic excitation in the generator mode by changing the current of the excitation winding.

We will use the power reserve of the generator and the fact that there is a limitation on the ultimate current of the generator and the maximum voltage of the SPH. That is, we will make service braking at low speeds more efficient. To do this, we will introduce the possibility of regulating the "degree of regeration". This is achieved by decreasing (for example, by increasing the transformation coefficient n_{tr}) the total resistance of the armature chain $R_s = R_a + R_{in.c}$. At the same time, as follows from expression (11), the efficiency also decreases. However, the thermal mode of the SEM does not deteriorate, as the armature current stabilization is still maintained.

For the SPH power consumption, we will take two values of the SPH power $P_n = 1500$ W (resistance 32 ohm) and $P_n = 3000$ W (resistance 16 ohm), which corresponds to the power of the serial SPH "Severs-M1" and "Severs-M3". We will make the corresponding choice of the SPH for the car according to the results of calculating the parameters of service braking, taking into account the conditions of the car operation.

Fig. 4 shows the dependence of the armature current $I_a(\omega)$ on the angular velocity of the SEM shaft (SPH of 1500 W) for four values of the total resistance $R_s = R_a + R_n$, taking into account the ultimate current limitation of the armature at 150 A (line 5).

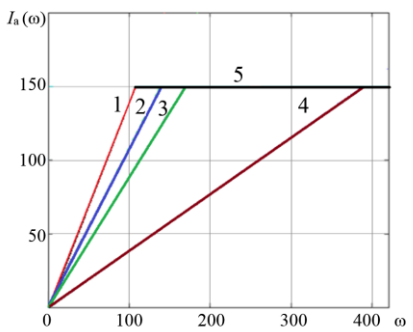


Figure 4. Dependence of the armature current on the speed in Mode 2 for the SPH of 1500 W:
1 – R_{n1} = 0.14 ohm; 2 – R_{n2} = 0.18 ohm;
3 – R_{n3} = 0.22 ohm; 4 – R_{n4} = 0.506 ohm;
5 – coincidence of lines 1-4 due to the limitation of armature ultimate current at level 150 A

Fig. 5 shows the dependence of the armature current I_a on the angular speed of the SEM shaft for a SPH of 3,000 W, respectively, the values of the four input converter resistances are selected to be two times smaller.

Value ω = 400 rad/s corresponds to the movement of Daewoo Lanos Pickup at the speed of 58 km/h, the first bend point on Fig. 3 corresponds to the speed of 15.8 km/h. In this point, the generator voltage is 15.4 V, the power on the generator output is 2310 W. This value corresponds to the voltage of the SPH equal to 272 V. However, it is too much for the SPH calculated as at 220 V. The SPH will have the required voltage of 220 V due to introduction of SAR by voltage on the SPH, which influences the excitation winding.

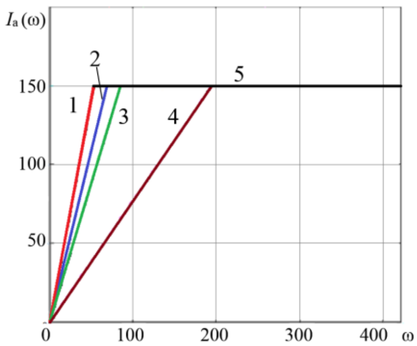


Figure 5. Dependence of the armature current on the speed in Mode 2 for SPH of 3000 W:
1 – R_{n1} = 0.07 ohm; 2 – R_{n2} = 0.09 ohm;
3 – R_{n3} = 0.11 ohm; 4 – R_{n4} = 0.253 ohm;
5 – Coincidence of lines 1-4 due to the limitation of armature ultimate current at level 150 A

Optimization of input resistance of a DC-AC converter at the service rheostatic regenerative braking

The power of braking on the car wheels P_{wh}, at the moment of service braking is determined as:

$$P_{wh} = \frac{P_n}{\eta_{tr} \cdot \eta_{bd} \cdot \eta_{dc-ac} \cdot \eta_g}\,, \qquad (32)$$

where η_{tr} – efficiency of transmission (η_{tr} = 0.91); η_{bd} – efficiency of the belt drive (η_{bd} = 0.92); $\eta_{dc\text{-}ac}$ – efficiency of a DC-AC converter. η_g – efficiency of a generator.

Applying expression (18), we calculate efficiency for a SPH of 1500 W:

$$\eta_{g11} = R_{n1} / (R_a + R_{n1}) = 0.14 / (0.04+0.14) = 0.77$$
$$\eta_{g12} = R_{n2} / (R_a + R_{n2}) = 0.18 / (0.04+0.18) = 0.82$$
$$\eta_{g13} = R_{n3} / (R_a + R_{n3}) = 0.22 / (0.04+0.22) = 0.85$$
$$\eta_{g14} = R_{n4} / (R_a + R_{n4}) = 0.506 / (0.04+0.506) = 0.92.$$

We calculate efficiency in four points for a SPH of 3000 W. As the load of a DC-AC converter has a twice smaller resistance, we take R_{n1} = 0.07; R_{n2} = 0.09; R_{n3} = 0.11 and R_{n4} = 0.253 ohm:

$$\eta_{g\,21} = R_{n1} / (R_a + R_{n1}) = 0.07 / (0.04+0.07) = 0.64$$
$$\eta_{g\,22} = R_{n2} / (R_a + R_{n2}) = 0.09 / (0.04+0.09) = 0.69$$
$$\eta_{g\,23} = R_{n3} / (R_a + R_{n3}) = 0.11 / (0.04+0.11) = 0.73$$
$$\eta_{g\,24} = R_{n4} / (R_a + R_{n4}) = 0.253 / (0.04+0.253) = 0.88.$$

For a SPH of 1500 W only limitation of resistance on SPH takes place, as the power, taken from the generator, is less than its maximum electric power, $P_{g.max}$ = 4200 W. We take into consideration that the ultimate power of the generator G290B at the voltage 28 V is 4200 W, and efficiency is η_g = 0.797, the power of loss at this will be:

$$P_{l.g.\max} = P_{\mathrm{g.max}}(1-\eta_g) = 852.6 \text{ W}$$

At any electric load, the power of electric losses, that heats the generator $P_{l.g.max}$, must not exceed this value, so we can write the equation:

$$(1-\eta_g)\cdot P_{\mathrm{g.max}} = P_{l.g.\max} \tag{33}$$

Hence, we will obtain the maximum permissible power. We take the smallest efficiency (η_{g21} = 0.64) from the obtained for the load 3000 W and resistance 0.07 ohm, then the power of the generator at braking must not exceed:

$$P_{g.\max} = P_{l.g.\max} / (1-\eta_g) = 852.6/(1-0.64) = 2368 \text{ W}$$

Such power of the generator is obtained because of the SAR action in limiting the ultimate current of the generator (150 A for the generator G290B). Similarly, for the SPH of 3000 W with a load resistance of 0.09 ohms, we have an ultimate power of the generator of 2750 W, also supported by the SAR. With load resistance of 0.11 ohms and 0.253 ohms, the ultimate power will be greater than the power of the SPH (3000 W) and the current SAR will not work. Finally, we will calculate the brake mechanical power on the wheels by the formula (32), consequently, we have:

$$P_{wh11} = 1500\text{W} / (0.753\cdot\eta_{g11}) = 2585 \text{ W}$$
$$P_{wh12} = 1500\text{W} / (0.753\cdot\eta_{g12}) = 2427 \text{ W}$$
$$P_{wh13} = 1500\text{W} / (0.753\cdot\eta_{g13}) = 2342 \text{ W}$$
$$P_{wh14} = 1500\text{W} / (0.753\cdot\eta_{g14}) = 2163 \text{ W}$$

The average braking power on the wheels with SPH of 1500 W will be P_{wh1a} = 2379 W.

For a SPH of 3000 W we have:

$$P_{wh21} = 2368\text{W} / (0.753\cdot\eta_{g21}) = 4913 \text{ W}$$
$$P_{wh22} = 2750\text{W} / (0.753\cdot\eta_{g22}) = 5292 \text{ W}$$
$$P_{wh23} = 3000\text{W} / (0.753\cdot\eta_{g23}) = 5457 \text{ W}$$
$$P_{wh24} = 3000\text{W} / (0.753\cdot\eta_{g24}) = 4573 \text{ W}$$

The average braking power on the wheels with the SPH of 3000 W will be P_{wh2a} = 5059 W.

We calculate the brake torque on the wheels in point ω_1 for the smallest resistance of the load for a SPH of 1500 W and 3000 W. For this, we will write the expression for determining the mechanical power on the wheels:

$$P_{\mathrm{wh}} = M_{\mathrm{wh}}\cdot\omega_{\mathrm{wh}}, \tag{34}$$

where ω_{wh} – is an angular velocity of the wheel ($\omega_{wh} = \omega/K_{tr}$).

$$M_{\mathrm{wh}} = P_{\mathrm{wh}} / \omega\mathrm{wh} = P_{\mathrm{wh}}K_{\mathrm{tr}} / \omega, \tag{35}$$

where K_{tr} – is a coefficient of transmission between the EM shaft and the wheels.

For Daewoo Lanos Pickup K_{tr} = 6.88. The brake torque on the wheels in point ω_1 for the smallest load resistance for the SPH of 1500 W will be:

$$M_{wh} = P_{wh}K_{tr} / \omega_1 = 2585\cdot 6.88 / 110 = 161 \text{ Н·м}$$

The brake torque on the wheels in point ω_1 for the smallest load resistance for the SPH of 3000 W will be:

$$M_{wh} = P_{wh}K_{tr} / \omega_1 = 4913\cdot 6.88 / 53.6 = 630 \text{ Н·м}$$

For Daewoo Lanos Pickup with the mass of m = 1100 kg, the wheel radius of r_{wh} = 0.275 m in point ω_1 we have the braking effort for the SPH 1500 W: $B = M_{wh} / r_{wh}$ = 585 H. The negative braking acceleration at this will be (–0.53) m/s^2. For the SPH 3000 W we have a braking effort of 2290 H, and a negative braking acceleration will be: (–2.1) m/s^2.

We consider how the force of the armature current changes in case of rheostatic braking with the changing speed:

$$I_a = E / R_s = k\cdot\Phi\cdot\omega / R_s \text{ on interval } \omega \in [\omega_0, \omega_1];$$
$$= I_{a.max} \text{ on interval } \omega \in [\omega_1, \omega_{max}] \tag{35}$$

Fig. 4 and Fig. 5 show the graphs of this dependence for generator G290B at $I_{a.max}$ = 150A for SPH (P = 1500 W and P = 3000 W respectively) at different values of R_s. Horizontal line 5 is common in the areas of stabilization (limitation) of current $\omega \in [\omega_1, \omega_{max}]$. In these areas, the courses of the previous dependencies partially merge.

We obtain the dependence of the brake torque on angular speed for interval $\omega \in [\omega_0, \omega_1]$:

$$M_{\mathrm{br}} = k\cdot\Phi\cdot I_{\mathrm{a}} = \frac{k\cdot\Phi\cdot E}{R_{\mathrm{s}}} = \frac{\omega\cdot(k\cdot\Phi)^2}{R_{\mathrm{s}}} \tag{33}$$

We write the dependence of brake torque on the angular speed for the interval $\omega \in [\omega_1, \omega_{max}]$. On this interval the dependence of product $k\Phi$ from ω, obtained before for this interval in expression (16). The armature current on this interval is constant as the result of SAR action on the current: $I_a = \text{const} = I_{a.max}$, hence we have:

$$M_{br} = k\Phi(\omega) \cdot I_{a.max} = I_{a.max} \cdot (k\Phi)_{max}\ \omega_1 / \omega,\ \omega \in [\omega_{1,}\omega_{max}] \tag{34}$$

Fig. 6 gives a graph of this dependence for generator G290B, having the value $I_{a.max}$ = 150 A. On curve 6 the courses of previous dependencies partially merge. Dependencies 1 and 6 make an ultimate characteristic of the torque of electric braking $M_{br}(\omega)$, and partial characteristics are the result of weakening the excitation flow, i.e. dependencies 2 and 6, 3 and 6, 4 and 6, 5 and 6.

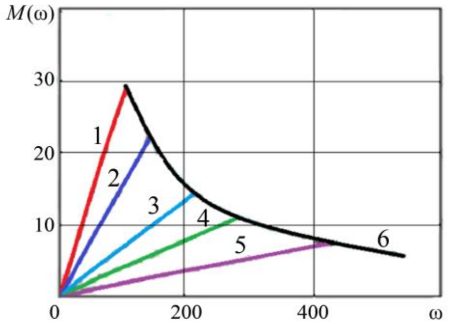


Figure 6. Dependence of the torque on the speed for different values of $k\Phi$: 1 – for maximum value kF = 0.196; 2 – $k\Phi$ = 0.147; 3 – $k\Phi$ = 0.098; 4 – $k\Phi$ = 0.0735; 5 – $k\Phi$ = 0.049; 6 – hyperbole common for all in the areas of stabilization (limitation) of current $\omega \in [\omega_{1,}\omega_{max}]$

The limit characteristic has a narrow area of high values of the brake torque in the range of velocities. As in a car with a start-stop system, the additional generator is of relatively small capacity, it is necessary to have a sufficiently high brake torque in a wide range of speeds for service electrical braking. This can be achieved by increasing the load resistance of the generator in proportion to the increase in speed.

We calculate the dependence of the brake torque on the angular speed with the full excitation flow for several nominals of brake resistors. The graph of this dependence is shown in Fig. 7.

Each of the dependencies 1–4 has a bend point on line 5, i.e. for each value of the braking resistor there is an angular velocity at which a maximum brake torque is reached with this value kF. Horizontal line 5 is given for reference. It corresponds to the maximum brake torque at the maximum permissible current of the armature.

If we increase value R_s at increasing speed, then we can (it is seen from (34)) maintain the high constant torque, corresponding to the maximum permissible current of armature winding, in high range of speeds. For this $R_s(\omega)$ must be proportional to ω, as dependence (31) is inverse to ω. Hence, the dependence $R_s(\omega)$ must be linear. In order to find this dependence we take two points of the graph in Fig. 7, namely, the bend points of dependencies $M_1(\omega)$ and $M_4(\omega)$.

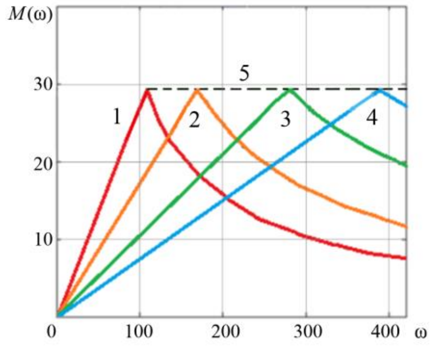


Figure 7. Dependencies of the brake torque on angular speed with the full excitation flow: 1 – R_s = 0.14 ohm; 2 – R_s = 0.22 ohm; 3 – R_s = 0.36 ohm; 4 – R_s = 0.506 ohm; 5 – a maximum brake torque at a maximum armature current

The coordinates of variable ω in the bend point of dependencies $M_1(\omega)$ and $M_4(\omega)$ are marked ω_1 and ω_4 correspondingly. We obtain these values for corresponding bend points from expression (28):

$$\omega_1 = \frac{R_{s1} \cdot I_{a.max}}{k \cdot \Phi_{max}}; \tag{35}$$

$$\omega_4 = \frac{R_{s4} \cdot I_{a.max}}{k \cdot \Phi_{max}}. \tag{36}$$

In coordinates ω and R_s we have points (ω_1, R_{s1}) and (ω_4, R_{s4}). According to these two points we build the dependence $R_s(\omega)$. The equation of this dependence will be:

$$(R_{s1} - R_{s4})\ \omega + (\omega_4 - \omega_1)\ R_s(\omega) + (\omega_1 R_{s4} - \omega_4 R_{s1}) = 0 \tag{37}$$

Taking into account (35) and (36) we have:

$$R_s(\omega) = \frac{\omega(R_{s1} + R_{s2})}{\omega_2 - \omega_1} \tag{38}$$

Dependence (26) for SEM of G290B is given in Fig. 8. It starts from value R_s = 0.14. It is stipulated by the limit armature current and ultimate power of armature winding heating.

The required increase of $R_s(\omega)$ with the increasing speed is accomplished by changing the base duty cycle of the open state of half-bridge keys of the DC-DC or DC-AC converter. If the converter has the maximum duty cycle $\chi_{max} = 1$, at the minimum input resistance $R_{in.min}$, then, the duty cycle of $\chi = R_{in.min}/R_{in}$. is necessary to achieve the increased input resistance.

After introducing variable input resistance of the converter, which is a generator load, we obtain the dependence of a brake torque of different values $I_{a.max}$, Fig. 9. A driver can choose these values by adjusting the degree of regeration". Such adjustment can be necessary, for example, on long descents.

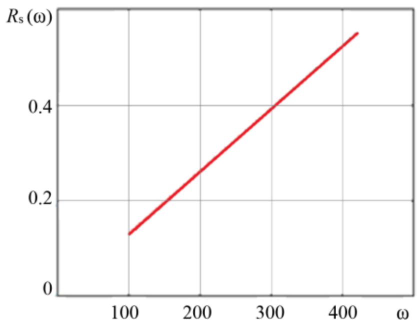


Figure 8. Dependence of the optimal input resistance of a DC-AC converter on the velocity

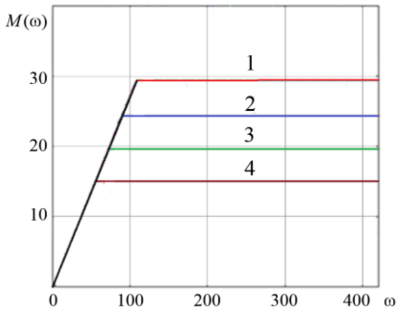


Figure 9. Dependence of a brake torque on the speed at optimal change of input resistance of a DC-AC converter: 1 – $I_{a.max}$ = 150 A; 2 – $I_{a.max}$ = 125 A; 3 – $I_{a.max}$ = 100 A; 4 – $I_{a.max}$ = 75 A

Mode 3

In the mode of regenerative braking, when the car moves at the speed of $V < V_{kr}$ (Mode 3), to store energy in battery (i.e. charging battery), the terminal resistance increases with the help of maximizing DC-AC booster. The equation of resistance balance of the armature chain in this mode will be:

$$E - (R_a + R_{in.br}) \cdot I_a = 0, \qquad (39)$$

where $R_{in.br}$ is an input resistance of maximizing DC-AC booster for battery charging.

The armature current I_a in this mode is $I_a = E / (R_a + R_{in.br})$. The charge current of battery I_{ch} will be:

$$I_{ch} = \frac{I_a \cdot \eta_{DC-DC}}{k_{DC-DC}}, \qquad (40)$$

where η_{DC-DC} – is the converter efficiency; k_{DC-DC} – is the coefficient of increasing resistance of a DC-AC converter.

Mode 3, like Mode 1, must obligatory have two SARs – one on the maximum current of the armature chain and the second on the maximum-permissible voltage of AB.

If there is a probability of exceeding the limit value of charging current, then the charging current of battery can be limited.

Adjusting both current and resistance of the generator in the process of SAR work can be conveniently accomplished by changing the current of excitation winding. However, if there is a necessity to have a maximum brake torque at regeration in this range of speeds (the same as in Mode 2), adjustment must be made by regulating the duty cycle of the open state of the DC-AC converter power keys.

7 Results and discussion

The proposed calculation technique for a generator based on SEM with electromagnetic excitation allows to obtain the basic characteristics necessary for calculating the brake mode of the electric drive of a hybrid vehicle, namely:

- dependence on the angular speed of the brake torque of SEM (mechanical characteristics) in different modes;
- dependence of the braking current of the SEM armature on angular speed (current-speed characteristic);
- dependencies of the permissible maximum power of the SEM in the generator mode on the speed and load;
- dependence of efficiency on the load in the generator mode;
- dependence of the brake torque on the speed at optimal change of the input resistance of the DC-AC converter;
- allows calculating not only external but also partial characteristics of SEM in generator mode.

It is important to note that for making a mathematical description of the generator operation, it was assumed that a generator with an independent excitation operates in static mode [30]. Thanks to this, the mathematical description of the processes of energy conversion is simplified. This allowed analyzing the operation of the generator with accuracy acceptable in practice.

Such a possibility is stipulated by the fact that the transient processes are almost completely extinguished by the powerful protection necessary for SEM. This protection is made in the form of high-speed system of automatic control of phase currents.

SEM work in three modes has been analyzed. The use of all these three modes enables to increase significantly the percentage of electric braking to braking by the braking system of the car. This applies primarily to service braking of the car, which happens much more often than emergency braking.

Mode 1 is the mode of regenerative braking when a car runs at a speed $V > V_{kr}$, where V_{kr} is the critical speed at which the condition $E = U_{AB}$ is fulfilled. In this mode, the charging of battery during regeration makes sense only in the zone $\omega > \omega_1$, Fig. 3. The zone of current rise in front of this zone is short-lived and not suitable for full service braking, so it needs to be replaced with Mode 3. When approaching the full charge, the voltage of the accumulation battery increases and then reaches a limit value, the excess of which is not permissible, therefore, the second SAR loop is introduced on the battery voltage. It controls the current of the excitation winding.

Mode 2 is the mode of rheostatic braking when a car is moving. This mode is possible at any speed of the car. In this mode, the output voltage of the generator, after the rectifier, is converted to the high-frequency variable by the DC-AC converter. After this, it is raised by means of a high-frequency transformer and is supplied to the starting pre-heater. At the same time, a brake torque appears on the driving wheels of the car and a rheostatic regenerative braking takes place [30]. The energy generated by the generator is used to heat the cooling fluid of the internal combustion engine. In an automobile with a start-stop system, the internal combustion engine does not work continuously, the coolant cools, so its heating improves the thermal balance of the internal combustion engine and reduces fuel consumption.

Mode 3 is the mode of regenerative braking when a car is running at a speed $V < V_{kr}$. In this mode, to save energy in AB, the output voltage is raised by using a DC-DC converter.

Mode 3 and Mode 1 must necessarily have two SARs – at the maximum current of the armature winding and at the maximum permissible voltage of AB.

The regulation of current and voltage of the generator in the process of operation of the SAR is carried out by changing the current of the excitation winding. But, if having the maximum brake torque during regeration is necessary in this speed range (as in Mode 2), the adjustment should be made by regulating the duty cycle of power keys of a DC-AC converter.

Generator mode SEM in a car with an advanced start-stop system is in demand because, firstly, to operate service braking with the help of a second generator is convenient and very easy. This braking starts immediately as soon as the brake pedal is pulled from the stop and the stop signal is on, while the braking system is not yet engaged. Secondly, when braking with it, regeration is possible, which enables to save some part of the kinetic or potential energy of the car. This reduces fuel and electricity consumption. When SEM is working in a generator mode, it is necessary to provide a limitation of the maximum phase current with the help of SAR. Consequently, it is necessary to make separate calculation in the area of parameters where there are limitations (stabilization) in current and in the area where there are no limitations in current (stabilization). Thereby the calculation of the brake torque during regeration is different.

The obtained theoretical and experimental results have practical significance for the transport industry.

8 Conclusion

The methods of deceleration of a hybrid car with a mechanical gearbox as well as the features of regenerative braking have been considered and systematized.

The methods of efficient use of kinetic and potential energy for saving hydrocarbon fuel have been proposed and proved.

Redistribution of energy produced by a traction electric engine in the generator mode for charging battery and heating of the cooling fluid of the ICE have been substantiated.

The method of calculation and mathematical model of SEM in the mode of regenerative braking have been developed. The power, efficiency and brake torque of the generator at different modes of regenerative braking have been calculated.

The methods of providing the necessary brake torque of the electric machine G290 in the mode of regenerative braking during the movement of the car at high speed, at low speed and in the mode of rheostatic braking have been proposed.

The problems of optimization of input resistance of DC-AC-converter at the service rheostat regenerative braking to provide the necessary braking torque have been considered. The method for introducing the dependence of the converter input resistance for the starting preheater of the cooling liquid of the internal combustion engine on the angular velocity of the SEM rotor has been suggested.

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