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Operation of Hybrid Propulsion Systems in Conditions of Increased Supply Voltage

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Vehicles with hybrid drive systems, are increasingly more often being equipped with solutions that increase the drive systems efficiency. One of such solutions is to use an increased supply voltage for electric motors of such vehicles. The battery voltage is increased several times in the inverter system in order to increase the electrical power supplied to the electric motor. This article presents possible uses of such voltage amplification (called boost) in urban traffic conditions. The tests used the latest models of vehicles with hybrid drive systems equipped with the same drive units: Lexus NX 300h and Toyota RAV4 Hybrid. The study analyses the conditions of starting such a system and the characteristics of its operation. It has been shown that the amplification of the voltage powering the electrical machinery in both vehicles occurs at high torque values. The maximum voltage amplification – almost threefold (up to 650 V) allows a two-fold increase in the torque of the drive system.

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NOMENCLATURE

E = energy
HEV = hybrid-electric vehicle
I = current
Li-Ion = lithium-ion battery
MPG = miles per gallon
n = speed
Ni-MH = nickel-metal hydride battery
Ne = power
RDC = real driving conditions
S = distance
SOC = state of charge
t = time
Torq = motor torque
U = voltage
Ui = share
V = vehicle speed
V_H = voltage after boosting
V_L = voltage before boosting

1. Introduction

Development of hybrid drive systems of vehicles is mainly associated with the possibility to increase their efficiency and to reduce fuel consumption of vehicles (also indirectly affecting the reduction in carbon dioxide emissions into the atmosphere).[1-4] Although the hybrid drive systems of mild hybrid type are technologically simpler, the full hybrid drive systems have the largest share in the reduction of exhaust gases emissions.[5,6]

Vehicles with full hybrid drive systems are equipped mainly with nickel-metal hydride (Ni-MH) batteries, but increasingly also the lithium-ion (Li-Ion) batteries are used. Their advantage over the nickel-metal hydride (Ni-MH) batteries is the ability to obtain a much higher volumetric energy density. This parameter is particularly important with regard to the limited battery space in a vehicle. The maximum volumetric energy density of Ni-MH batteries is around[7,8] 150 Wh dm^{-3}. For the lithium-ion batteries this value currently exceeds 200 Wh dm^{-3}. Modern hybrid drive systems in the so-called Class 3 vehicles (hybrid and electric vehicles of plug-in type) use batteries with parameters shown in Table 1.

The high values of power and energy of batteries in vehicles with hybrid drive systems presented above allow the use of electric motors

Table 1 Characteristics of common batteries used in vehicles with hybrid and electric drive systems[8]

Value	Unit	Ni-MH	Li-Ion
Power density	W kg^{-1}	150	300
Energy density	Wh kg^{-1}	66	110
State of discharge	% per month	15-20	5

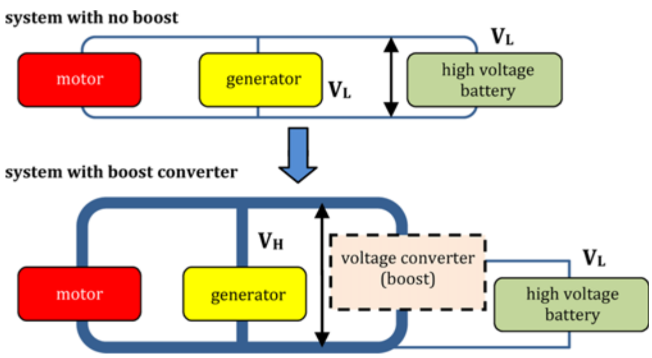

Fig. 1 Wiring diagram of supply systems of electrical motors: (a) without increasing the voltage; (b) with a system of voltage amplification – boost system[9,10]

with high operating indicators.

Increase of the electric motors power in hybrid drive systems can be achieved by increasing the voltage and the current intensity drawn from the battery; however, there it is more common to reduce the battery voltage and to use voltage amplifiers – boost converters instead. The Toyota Company already uses the third generation of such a solution in its hybrid vehicles. Originally batteries with a voltage of 274 V were used, without any voltage amplifiers added. In another system converters capable of achieving a voltage of 500 V at lower values of battery voltage (201 V) were used. Currently a method of increasing the voltages of electrical systems up to 650 V is used (battery voltage in these systems is about 245 V).

Increased voltage applied to electric motors at the same power reduces the current flow value. The current flow causes heat losses, the value of which is directly proportional to the square of the current intensity and the resistance present in the circuit.

Therefore, limiting the current intensity in such systems results in a reduction of power loses, and thus allows for greater efficiency of such electric systems. As a result, it is possible to achieve higher efficiency of the hybrid drive system.

The degree of the battery voltage amplification is defined as the quotient of the so-called low voltage (voltage before boosting – *VL*) and the voltage after amplification (voltage after boosting – *VH*):

$$\text{boost} = VH/VL \tag{1}$$

The voltage amplification systems are used mainly in vehicles with hybrid drives (not in electric vehicles), subsequent generations of which are shown in Fig. 1.

From the presented configuration it follows that also operation of the system at high voltages during regenerative braking is possible. This allows for obtaining high braking powers, and thus high values of braking energy recovery.

Table 2 Technical specification of the tested vehicles[10]

Parameter	Unit	Toyota RAV4 hybrid	Lexus NX 300h
Engine			
Displacement	dm^3	2,494	←
Torque	Nm @ rpm	206 @ 4400-4800	←
Power	kW @ rpm	114 @ 5700	←
Electric propulsion – front			
Torque	Nm @ rpm	270 @ 0-1800	←
Power motor	kW @ rpm	105 @ 4500	←
Electric propulsion – rear			
Torque	Nm	139	←
Power motor	kW	50	←
Energy storage			
Battery	–	Ni-MH	←
Energy	kWh	1.59	←
Battery voltage	V	244.8	←
Max inverter voltage	V	650	←
Vehicle			
Mass	kg	1735	1860

As it can be observed in Eq. (1), the voltage amplification value will depend on the battery voltage and the final value of supply voltage at the electric motor.

Analysis of the data contained in Table 1 indicates that the amplification of the voltage supplied to the electric motor (or motors) is not used in the drive systems of electric vehicles. The voltage values of the battery supplying the electric motor are almost twice as high for electric vehicles compared to the voltages in vehicles with hybrid drive systems.

2. Motivation

In the last few years there has been a significant reduction in carbon dioxide emissions from new passenger vehicles. The preferred method of meeting the stringent emission standards by manufacturers of passenger cars became the downsizing of internal combustion engines and increasing the share of alternative fuels in vehicles, such as electric drives.[11] The authors' previous studies were primarily focused on the operating parameters evaluation of the hybrid vehicle drive in real driving conditions (RDC) and on chassis dynamometer.[12,13] Hybrid vehicles research is described extensively in the literature. Alzorgan et al. presents in paper[14] different control strategies for HEVs that take into consideration the impact of road grade on the vehicle and the possibility to utilize look ahead control strategies in order that minimize the fuel consumption and maximize miles per gallon (MPG) over multiple routes. Most of the recent studies[15-22] are focused on the hybrid development and control analysis that allows for efficient energy use.

The known values of voltage amplification of electric motors do not indicate the degree of utilization of this amplification. They also do not indicate the value of the voltage generated in different urban traffic conditions. Therefore, the aim of the article is to indicate the conditions of driving vehicles with hybrid drive system, in which an increased voltage supply to an electric motor is used. An additional objective is

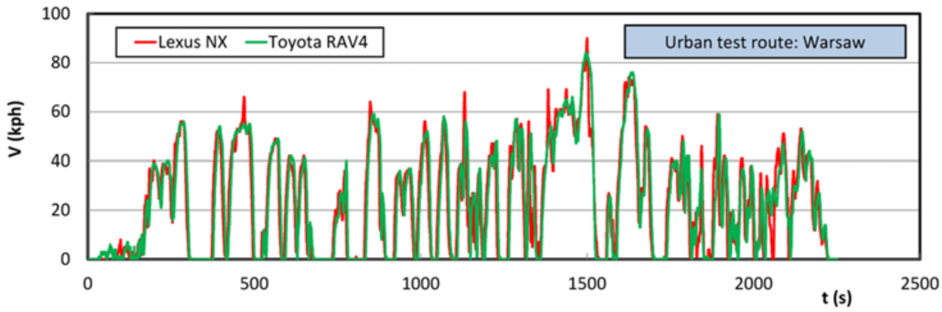

Fig. 2 Speeds comparison for the tested vehicles in urban traffic conditions

to indicate this amplification (boost) and absolute values of the voltage supplying the electric motors. The analysis also included the conditions of using the increased voltage in vehicle propulsion and in conditions of recovering energy during braking. The values and parameters described in the article can be useful for further research and modification of systems to increase the alternative propulsion efficiency.

3. Research Methodology

For tests in urban traffic conditions two vehicles with hybrid drive systems were used: Toyota RAV4 Hybrid and Lexus NX 300 h. The conditions for use of the voltage amplification system were determined during simultaneous driving of the two vehicles in urban traffic. The technical specification of the hybrid vehicles used for tests is shown in Table 2. It should be noted that both vehicles were equipped with the same drive systems. The main difference is the complete vehicle weight, which (apart from the driving techniques) can affect the differences obtained in test drive conditions. However, any acceptable non-repeatability of the results is inscribed in the current trend of vehicles road tests as far as traffic conditions and emissions of exhaust gases are concerned.

The tests were performed in urban driving conditions within the city of Warsaw on a typical working day. The test route led through the streets of the city center. The length of the route was around S = 14 900 m, and the duration of test run was about 2250 s. The average vehicle speed when driving in urban conditions was about 24 kph.

The analysis of the voltage amplification system operation supplying an electric motor was conducted in several variants. The first was to determine the degree of voltage amplification specified using Eq. (3). The value was determined for three boost value ranges:

a) lack of amplification ($VH = VL$)
b) 1 < boost < 2
c) boost > 2

The second variant of the tests was specified based on the value of the voltage amplification and was divided into the following ranges (during operation of the electric machine as an electric motor or as an electric generator): a) $U < 300$ V, b) 300 V < U < 400 V, c) 400 V < U < 500 V, d) 500 V < U < 600 V, e) $U > 600$ V.

4. Test Results

The tests were conducted with simultaneous recording of parameters of the vehicle motion and parameters of the hybrid drive system. The speed characteristics of both vehicles indicate a high repeatability of the test runs – Fig. 2. Maximum speed differences amounted to 17 kph. After approximately 2000 s since the start of the measurement, much greater differences were observed, resulting from the operation of traffic lights in the city. It was the only significant speed difference in both test runs.

5. Analysis of the Use of the Boost System While Driving

The analysis of the voltage amplification system use was conducted by determining the conditions in which it was used. Analysis of the data presented in Fig. 3 shows – in addition to the similarity of the test runs – also the similarity of conditions when using the boost system. The analysis of the time of the test run shows a slightly higher share of operation of the Toyota hybrid drive system without voltage amplification – 81.4% (Lexus: 77.5%).

The operating time density with amplification below 2 for the Toyota vehicle came out to 16.1% (Lexus: 17.6%). The analysis of the share of the route in the two test runs points to analogous values: lower time density of voltage amplification use in Toyota vehicle obtaining the value of 29.1% (Lexus: 33.7) and 3.5% (Lexus: 8.3% – amplification above the value of 2). Analysis of the change of the time density of boost system usage indicates a maximum difference of 3%, and with regard to the travelled route – a difference of 5%.

Also the analysis of the boost system was conducted for both, constant and variable acceleration. The obtained differences are even lower and are as follows: during the constant driving speed: 5%, when accelerating – 1%, when braking – 0.6%.

Therefore, the test runs of the two vehicles should be considered similar (similar are also the operating conditions of the voltage amplification system). Obtaining similar operating conditions of this system allows further analysis of its use in hybrid drive systems of the vehicles analyzed.

The same drive systems in both vehicles and similar initial level of the battery charge (about 45%) resulted in a very similar flow of energy in both vehicles while driving. It was observed that the Lexus vehicle, in initial phase of motion, operated in electric mode (the drop in the

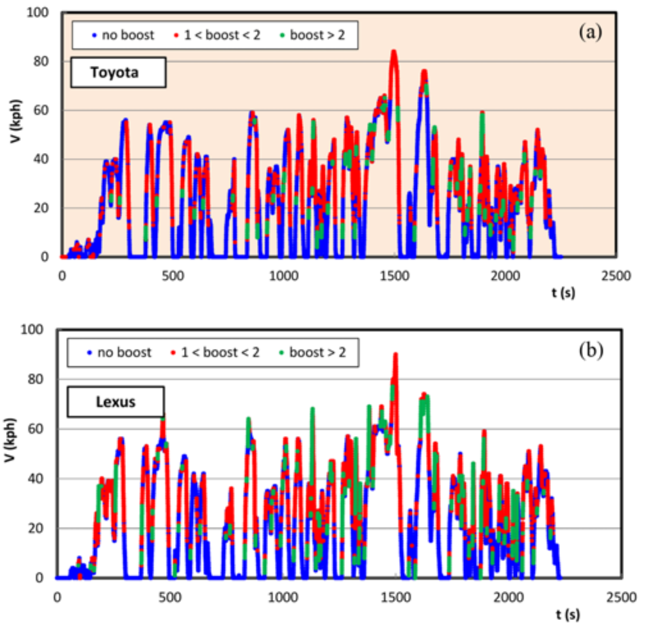

Fig. 3 A comparison of the conditions of using the increased voltages (boost) during the urban test runs a) Toyota RAV4, b) Lexus NX

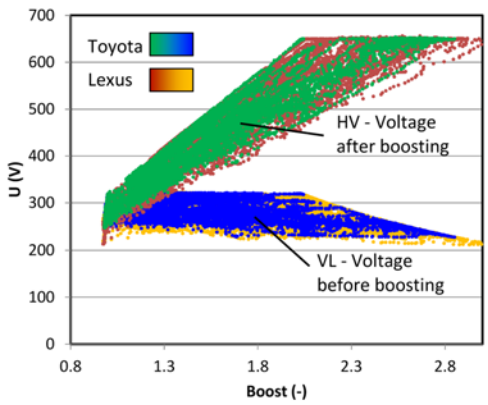

Fig. 4 The operating conditions of the battery voltage in hybrid drive system of the analyzed vehicles

battery charge level); however, the end of the test run showed the same level of charge (*SOC*) of the batteries. The nature of the energy flow (charging/discharging) indicates the same mode of driving and the initial differences may result from differences in the thermal conditions of the combustion engine.

Due to the limited value of the maximum voltage amplification of about 650 V, the change of the voltage from *VL* to *VH* occurs linearly within a certain range of tolerance. The analysis of voltages shown in Fig. 4 indicates the existence of voltages ranging from 244 V (standard voltage of the battery) to the value of the more than 300 V for *VL*. Voltages after amplification are in accordance with the determined equations. It should be noted that the maximum voltage amplification requires limiting the voltage within *VL*. For this reason, in order to limit the maximum voltage to 650 V, it is necessary to limit low voltage (*VL*).

Analysis of the energy flow coditions in hybrid drive systems

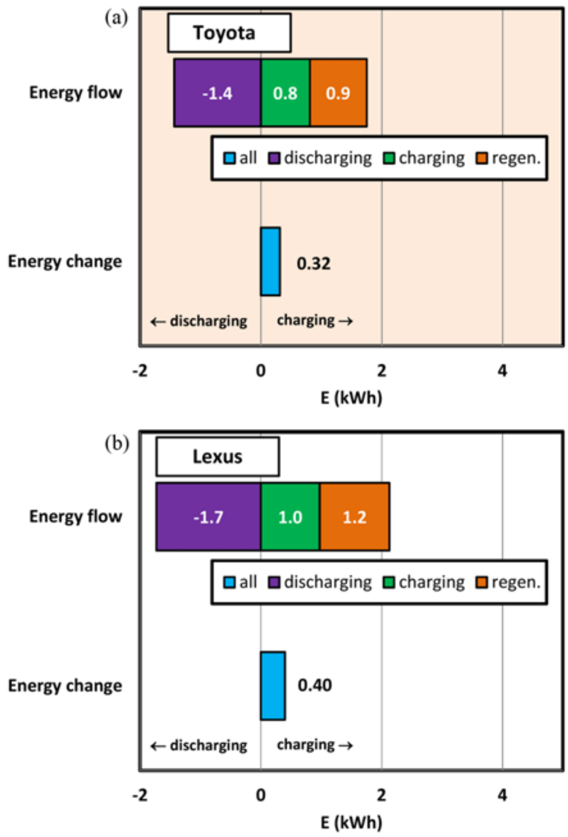

Fig. 5 Analysis of the flow of energy in a hybrid drive, including charging and discharging of the battery during test runs in the urban traffic conditions for (a) Toyota RAV4, (b) Lexus NX

enabled determining of the quantitative indicators of its flow. Indicated increased level of battery charge (in both vehicles), required a numerical definition of that parameter. For this reason, the amount of battery power used to drive the vehicle (battery discharge), the amount obtained during charging (but without the use of regenerative braking) and the amount of energy obtained only during regenerative braking were all determined. Values of these shares are presented in Fig. 5. It shows that despite high values of battery discharge, its recharging in both vehicles increased the level of the battery charge. The final *SOC* value was increased, due to the increased amount of energy gained when charging. It amounted to 0.32 kWh for Toyota and to 0.4 kWh for Lexus. Knowing the increase in *SOC* for each vehicle (Toyota – 2%, Lexus – 3%), the amount of energy for ΔSOC = 1% was determined. This value for Toyota RAV4 test run was 264 Wh, while for Lexus NX – 360 Wh (the difference of the results obtained for both vehicles was 26%). This significant difference in value results from different strategies of the battery operation at the start of the test route. In these studies the values of voltage amplification were also taken into account.

Analysis of the conditions of energy recovery indicates the same share for both vehicles, without voltage increase. This value was 0.3 kWh for both vehicles. When using voltage amplification, in Toyota vehicles 0.6 kWh of energy was recovered (for Lexus it was 0.8 kWh). High voltage amplification was quite rarely utilized in electric machines working as power generators, as both vehicles recovered in these conditions below 0.1 kWh of energy (Toyota – 0.02 kWh, Lexus – 0.03 kWh).

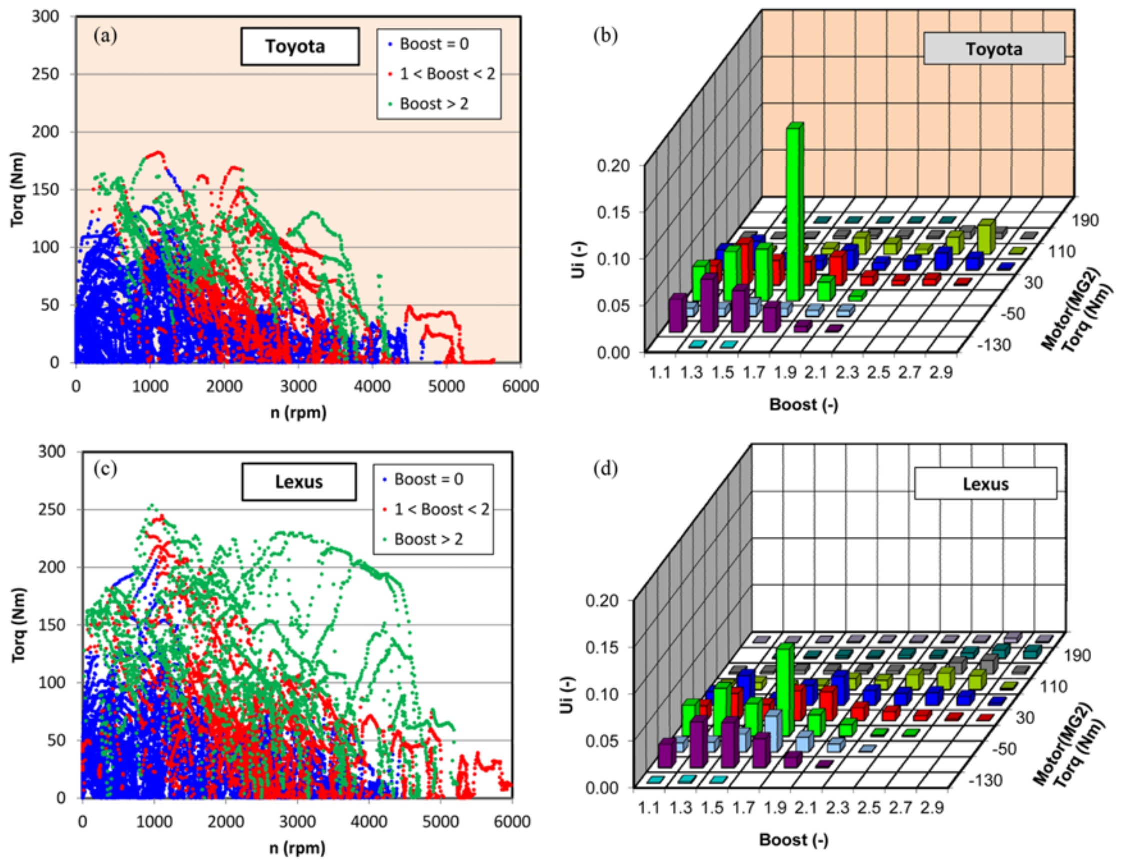

Fig. 6 Analysis of the use of the voltage amplification on the characteristics of the electric motor operation of Toyota RAV4 (a) and Lexus NX (c) and the respective operating time densities of these motors ((b) and (d))

The assessment of the boost system utilization in urban traffic conditions was also carried out in relation to the electric motors of the tested vehicles. Toyota, tested as the first vehicle, was characterized by lower values of torque across the whole range of speed changes – Fig. 6. Although the maximum torque value was 270 Nm, the use of such value was not necessary. Because of the need to maintain the speed for Lexus NX comparable to the previous tested vehicle, the value of the torque of an electric motor was significantly greater. This higher value was mainly observed in the range of 3000-4000 rpm. The motor torque was higher by approximately 50 Nm. Taking into account the changes in amplification of the voltage supplying the motor reflects – on load characteristics – the use of amplification in specific operating conditions of the motor. In the range of medium and high speeds, the share of amplification in range (1, 2) is significant. Obtaining the maximum torque – regardless of speed – requires high values of voltage amplification (above 2).

Analysis of the operating time density of electric motor with different degrees of voltage amplification indicates the similarity of operation of both drive systems. Significantly higher values were recorded for amplification from range < 1.2), than for the range < 2, 3). The characteristics of the share of operating time also indicate that regenerative braking takes place mainly for low values of voltage amplification in the converter system (the value of amplification was 1.3-1.5).

Assessment of the use of voltage amplification indicates (similarly to the amplification value), that the electric motor in urban traffic conditions uses mainly the values of voltage amplification below 400 V (partial amplification or no amplification). Obtaining high values of the torque – regardless of speed – requires high values of supply voltage – Fig. 7. In high efficiency operating ranges of the electric motor, the voltage of 500 V and more are observed. This is one of the reasons for the high efficiency of such motors, thanks to which it is possible to limit losses of the flowing current. Taking into account the characteristics of the electric motor power (not shown in figure) indicates that the maximum values are obtained only for the motor power supply voltages exceeding 600 V.

6. Conclusions

The analysis of operation of the system of voltage amplification shows that the system increases efficiency of the drive system by decreasing current intensity, which, at the same time, reduces the electric power losses. Increase of the voltage supply for the electric motors is used mainly to increase their torque and power. At the same time, this system increases electric braking power, resulting in increase in the amount of recovered braking energy.

The analysis of the use of the voltage boost system indicates the system is more often used when using the electric motor for propulsion rather than as a generator.

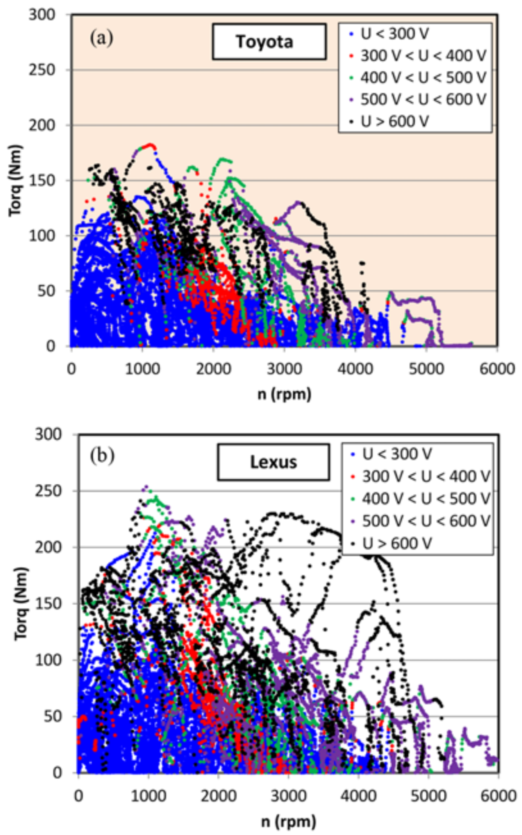

Fig. 7 Analysis of the use of the increased voltage supply for the electric motors on the characteristics of their operation (a) for Toyota RAV4 (b) and for Lexus NX

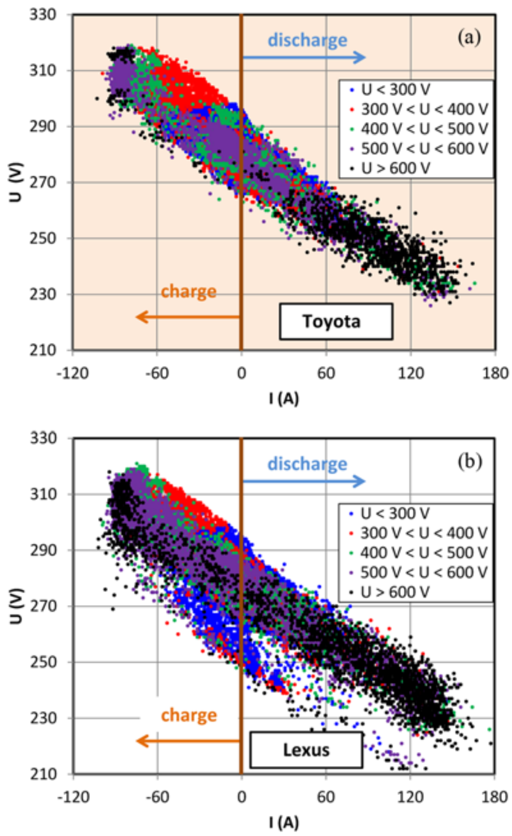

Fig. 8 The characteristics of voltage and current intensity for high-voltage battery for different conditions of voltage amplification

The data in Fig. 8 shows that the voltage exceeding 600 V covers a much larger area within the positive values of current intensity than within the negative values (working as a power generator – regenerative braking). Such conditions are repeated during the test run of Toyota RAV4 (lower torque values result in lower current values) and during the test run of Lexus NX. In this case, higher values of the electric motor load also point to much higher values of the positive current intensity.

The maximum values of voltage amplification are generated in the drive system of the vehicle ainly in the presence of nominal voltage – Fig. 4 (in the tested vehicles, this value was approximately 244 V). During regenerative braking these relations were not preserved – here the highest voltage amplification occurred at high values of current generated in the system and at high values of the battery voltage.

The presented conclusions indicate a greater possibility of using a hybrid drive system in Lexus vehicle in urban traffic conditions (increasing the maximum limits of parameters for controlling the drive system). This is caused, among others, by the increased flow of energy between the battery and the electric motor (Fig. 5), which effectively contributes to the increase of the value of energy stored in the vehicle while driving. In addition, the range of electric motor operation in the conditions of voltage amplification is also larger (Fig. 6). All these factors are aimed at maximizing the flow of energy and thus the operation of the drive system in the conditions of voltage amplification (Fig. 7).

The above relations apply to the voltage amplification controlling system in both cases of the electrical motors use are aimed at maximizing the electric power (consumed or recovered) while minimizing the losses of that power.

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