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AN APPLICATION OF THE HEAT ACCUMULATOR AND IMPROVEMENT OF THE DC-DC CONVERTER FOR HYBRID-ELECTRIC VEHICLES

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Abstract

In this article, both problems of the internal combustion-engine's thermal equilibrium as well as improving the DC-DC converter's operation in the hybrid-electric vehicle's propulsion system. The purpose of the proposed amendments is to increase the energy efficiency of the hybrid-electric vehicle's propulsion system. Such a hybrid-electric vehicle in city traffic is characterized by intermittent operation of the internal combustion engine with long pauses, which causes difficulty in obtaining and maintaining the desired operating temperature of the internal combustion engine, especially at low outdoor temperatures and intensive use of the heating system inside the hybrid-electric vehicle. The result is the increased emission of noxious exhaust gas components and increased fuel consumption. The proposed solution to this problem is to apply heat accumulator in the cooling system. It is stored in the waste heat from the cooling system used to obtain and maintain the internal combustion engine's nominal operating temperature. The paper presents the results of simulation analyses the impact of applying heat accumulator in the hybrid-electric vehicle driving in city traffic, at different ambient conditions, such as: air temperature, internal combustion engine's load and the frequency and length of stops. The proposed algorithm for controlling the circulation of the cooling liquid ensures as soon as possible to achieve and maintain the internal combustion engine's temperature. Furthermore, the temperature of the operating medium can be adjusted depending on the operating conditions of the internal combustion engine. Experimental studies, on the example of the Toyota Prius and Yaris, confirmed the desirability of the use of the proposed solution. Improving the DC-DC converter's current is to change the configuration by the use of a two-phase DC-DC converter – instead of a single-phase DC-DC converter, supplying a DC-AC inverter of the DC motoring the hybrid-electric vehicle's propulsion system. This article also includes waveforms for comparison of the properties of both DC-DC converters.

Keywords: *simulation, road transport, DC-DC converter, propulsion system, heating system, hybrid vehicle*

1. Introduction

Restrictions of urban traffic have many features that significantly discern it from an intercity traffic on highways. It is characterized by the frequent change of a **hybrid-electric vehicle** (HEV) speed, resulting from widely varying road-traffic restrictions. They cause that the HEV is frequently moving off, accelerating, braking and stops.

In addition, the average length of distance travelled by the HEV is relatively small and is up to 10 km, the average speed not exceeds of 30 km/h [5].

The result of such traffic restrictions of the HEV is a relatively low average load of the **internal combustion engine** (ICE) in relation to the total time of the HEV driving on a given distance of the road. As a result, the ICE heating to operating temperature is long lasting, and at low external temperatures and a passenger-space heating turned-on, as well as ICE shutdown cause an ICE hypothermia. As you know, most of the impurities in currently manufactured HEVs are emitted in the ICE warm-up. Hence, the designers' aspiration is reducing it. In addition, due to a large share of the heating phase in a total time of the ICE operation and a frequent ICE starts, the fuel consumption and emissions of CO and HC components in the exhaust are increased as well as the storage battery and starter motor are overloaded [1,2]. For example, Engineering Schatz Thermo is reported that reductions in emissions by 40 and 50% of HC and CO in a heating test of the ICE warming up with an additional heating by a thermal energy of the heat accumulator (with barium hydroxide as a phase change material) was achieved [3]. Moreover, during ICE start-up in the heating test, the ICE's heat accumulator has reduced emission of about 30% of HC and CO [4]. Therefore, all solutions used to shorten the ICE warm-up or to reducing emissions during the journey, are desirable from the viewpoint of an increase in demands for environmental protection.

Proposed by the authors solution is used in the cooling system of an ICE's heat accumulator. It is possible to store thermal energy in the waste heat from the cooling system, which is used to obtain and maintain a nominal operating temperature of the ICE. In addition, the heat capacity of the heat accumulator may be used as a buffer, preventing a drop in the coolant temperature observed during road tests of the Toyota Prius when the ICE off. The heat capacity of the heat accumulator should be chosen to ensure effective heating of the cold ICE. In a phase of the heat transfer, the cooling liquid absorbs the thermal energy from the heat accumulator and releases it in the ICE cooling jacket, especially the ICE head (Fig. 1).

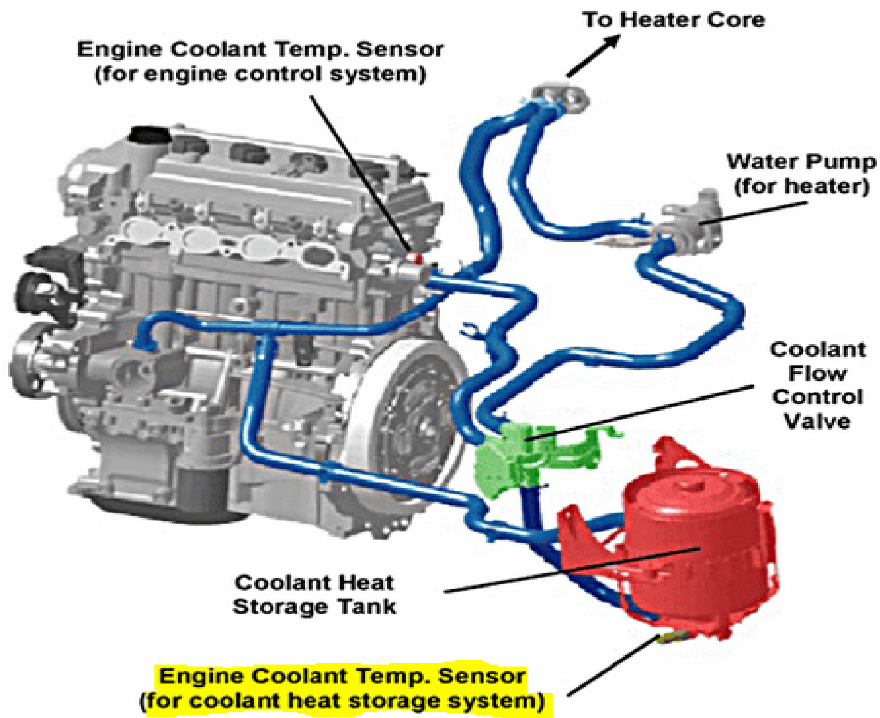

Fig. 1. The ICE cooling system with the coolant heat storage system [brochures Toyota motors]

When the temperatures at the outlet of the heat accumulator and the ICE output, an electric coolant pump is switched off and three-way fluidical valves are switched so as the fluid circulates in an ICE-air cooler.

Too low heat capacity will be not achieved the intended increase in ICE temperature during warm-up. At the same time, oversizing of the heat accumulator may lead to a situation of stop the insufficient charge after the ICE stop.

2. Methodology of Research

The first stage of the study was to analyse the share of the heating phase when the city traffic in the Toyota Prius. To test the temperature of the cooling liquid ICE warm-up phase of it is familiarized with the structure and parameters of the cooling system of the HEV tested and the location of the factory temperature sensors. It was read measured values by the OBD connector to be sufficiently accurate and fast. The measurements were carried out from the moment of readiness HEV when driving in the urban area of Krakow. The HEV defeated the same route, and the temperature is in the range 8-18 °C. Measurements continued until the stabilization of temperature of the working medium to the value specified by the manufacturer. During the tests, the value recorded speed calculated by the controller of the ICE load, the ICE operating time and the temperature of the coolant in the head. Reading measured values held by the OBD connector using DIAGNOSKOP CDIF/3 with a frequency of 3 Hz reading. In order to reduce the influence of ambient conditions, such as traffic or speed, several test drives and defines the average temperature. These measurements allowed to estimate the time elapsed from the start of the vehicle to achieve the ICE operating temperature, as well as the percentage of the heating phase. Moreover, based on studies, the distance and time that overcomes the HEV move off to the launch of the ICE.

Tab. 1. The result of road test of the Toyota Prius

Toyota Prius	Engine work time	Vehicle drive time	Percent of all drive time	Percent warm-up phase of all drive time
Cold start	14.7 min	16.8 min	87.5%	57.8%
Warm start	9.7 min	17.2 min	56.4%	-
Driving	7.2 min	17.1 min	42%	-

The next step was to create a mathematical model defining the thermodynamic relationships that occur in the cooling system with integrated heat accumulator. For this purpose, selected model heat accumulator type B production Ritter Fahrzeug-Technik, with a curb weight of 2.3 kg and a thermal capacity of 600 Wh. Based on simulation heat accumulator volume chosen such that the amount of heat energy contained in it allowed the heating and cooling liquid head about 40 °C above the ambient temperature. The simulation was carried out in a temperature range from -20°C to 20°C. As coolant adopted Borygo ECO based on propylene glycol. The volume of coolant was a result of the aggregation of volume of a standard cooling system of the car Toyota Prius and the volume of heat accumulator. Selected parameters of the cooling system simulation subjected to the table:

Tab. 2. Specifications of the cooling system

System volume	3.8 l stock	5.2 l with HS
Specific heat of coolant fluid	3.28 kJ/kgK	
Density coolant fluid	1.065 g/cm^3	
Coolant liquid flow		50 l/min
Heat capacity		2.16 MJ

To simplify the calculation author accepted (1):

1. lack of heat loss between the heat storage and the ICE;
2. ideal heat transfer through the coolant;
3. while heating the ICE does not heat exchange with the environment.

$$Q_e = \int_i^N cw_i\, m_i \Delta T, \tag{1}$$

where:
Q_e – amount of heat stored in the ICE,
cw_i – specific ICE components,
m_i – mass of ICE components,
ΔT – temperature changes.

The specific heat coolant transferred from working heat storage during discharge is defined as (2):

$$q = V\Delta T, \tag{2}$$

where:
V – volume of coolant flow,
ΔT – average-logarithmic gradient:

$$\Delta T = \frac{T_{out} - T_{in}}{ln\frac{T_p - T_{in}}{T_p - T_{out}}}, \tag{3}$$

where:
T_{out} – output temperature of heat storage,
T_{in} – input temperature of heat storage,
T_p – melting temperature of phase change material.

It follows that the amount of heat stored in the heat accumulator:

$$Q_{hs} = Vcw_c\rho, \tag{4}$$

where:
cw_c – specific heat coolant liquid,
ρ – density of coolant liquid.

The ICE temperature as function of time for different values of an ambient temperature is shown in Fig. 2.

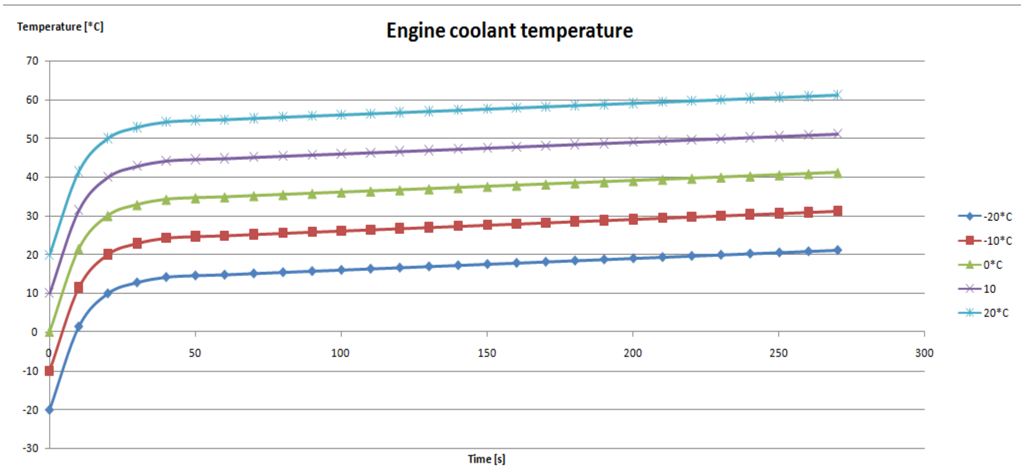

Fig. 2. The ICE temperature as function of time for different values of an ambient temperature

3. A Bilateral DC-DC Converter in a Single- and Two-phase System

In the case of **battery electric vehicles** (BEV), **hybrid-electric vehicles** (HEV) or **fuel-cell electric vehicles** (FCEV) exists a need of bilateral electrical energy conversion during regenerative braking when a part of a regenerated energy is stored in the storage battery. Due to the fact that a braking time is short, it is valid to secure a high power on the input electrical energy accumulator, thus a high current on the input of the storage-battery terminals. It simultaneously ensures a higher effectiveness of regenerative braking. However, during a fast-acceleration starting, a normal ride, a high-speed passing or a hill climbing, a stored electrical energy is flowing to the load, and then a sense of current direction has been changed. In some technical solutions, e.g., the railway vehicles, a battery energy store is allowing on an average drive at the crossroads, recrossing of the path section, e.g., with the damaged traction network, or travelling to the nearest stop. In this case is essentially, that a recharging current of the battery have had an appropriately high value for a correctly operation of the propulsion system.

A proposed bilateral DC-DC converter in comparison with a conventional solution – in a single-phase system, ensures:

- higher effectiveness of a faster energy storing in the battery,
- a charging current boosting,
- a discharging current of the battery,
- an electrical energy recovery to the load, particularly at a reduced voltage that is at a partially discharged of the battery.

In Fig. 3 are shown schematic diagrams of the bilateral DC-DC converter's main circuits in a simple single-phase system (a), more often applied in practice as well as in a simple two-phase system (b), proposed by the authors.

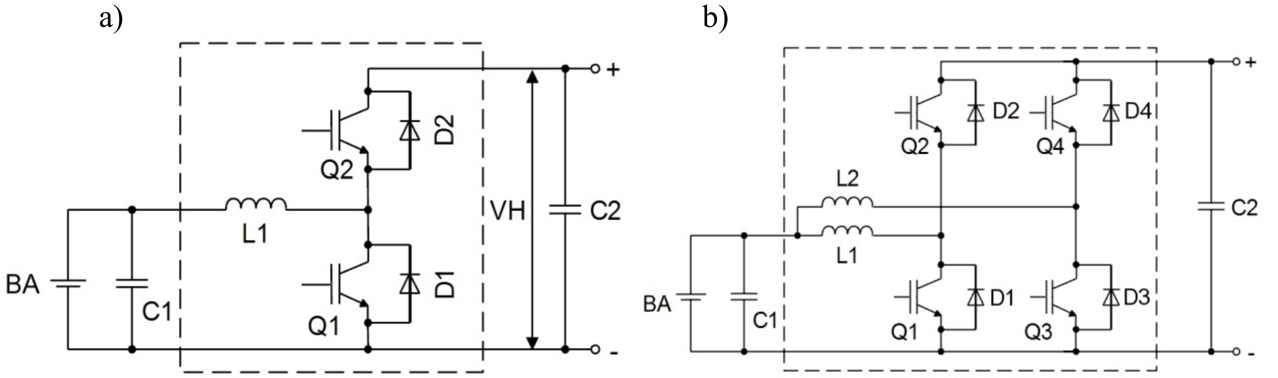

Fig. 3. A schematic diagram of the bilateral DC-DC converter's main circuit in a simple single-phase system [2] as well as in a simple two-phase system (b)

Sometimes, may be also applied a DC-DC converter in a bridge single-phase system, but in this solution is required a considerable greater number of the controlled electrical valves (electronic switches) as well as a two-stage energy conversion in the inverter/rectifier system that reduces a theoretical value of the energy conversion's efficiency coefficient as well as leads to a more considerable complex DC-DC converter system.

In a single-phase system of the bilateral DC-DC converter, shown in Fig. 3a, during charging of the battery from an external energy source (e.g., an external voltage source or electrical machine), first is turned on the electronic switch Q2 – then follows a current flow through the inductance L1 to the battery.

When the electronic switch Q2 has been turned off, then through the shunting diode Q1 undergoes discharging of the stored electrical energy in the inductance L1. In this system of the DC-DC converter storing of an electrical energy in the inductance L1 and its discharging is held in two following after each, operation cycles, alternately. Then, the DC-DC converter acts as a voltage reducing system.

During discharging of the battery, follows a stored electrical energy flow to a load, i.e., a DC-AC commutator electrical machine, or a traction storage battery. Then, the electronic switch Q1 is turned on, and owing to a current flow through the inductance L1, follows in it, storing of an electromagnetic field energy, then in a second cycle, the electronic switch Q1 has been turned off, and an electrical energy stored in the inductance L1 is discharged to a load through the shunting diode Q2. In this operation mode, the DC-DC converter acts as a voltage increasing system and a sense of energy-flow direction has been changed.

However, in a two-phase system, shown Fig. 1b, owing to the DC-DC converter's two parallel commutating branches, in the same time, follows storing of an electrical energy in the DC-DC converter's first branch, as well as discharging – in the DC-DC converter's second branch, namely, during charging of the battery.

In the first operation cycle follows turning on of the electronic switch Q2 in the DC-DC converter's first branch and current flow to the battery, as well as an electrical energy discharging, stored in the inductance L2, and owing to a current flow through the shunting diode Q3, due to this, the currents of both DC-DC converter's branches are added in the battery.

In the second cycle of discharging of the battery, the electronic switch Q4 has been turned on of the DC-DC converter's second branch, what causes flowing of the current to the battery, as well as, discharging of an electrical energy stored in the inductance L1, owing to a current flow through the shunting diode Q1.

During discharging of the battery, in a two-phase DC-DC converter, in the first operation cycle, the electronic switch Q1 has been turned on, and follows storing of an electromagnetic field energy in the inductance L1, and simultaneously, through the shunting diode Q4 follows discharging of an electrical energy stored in the inductance L2.

In the second cycle of discharging of the battery, the electronic switch Q3 has been turned on, and an electrical energy is stored in the inductance L2, and simultaneously through the shunting diode Q2, an electrical energy stored in the inductance L1 is discharged.

Advantages of the DC-DC converter, resulting with a two-phase system application are as follows:

- increasing of a charging current of the battery, as well as – a discharging current, and therefore increasing of an energy conversion's power, what ensures an improvement of a practice effectiveness of the battery in an automotive propulsion system,
- decreasing of a charging current as well as a discharging current variations (decreasing of alternating components of the both currents),
- improvement of the operation effectiveness during charging of the battery at a decreased voltage, what improves a regenerative braking effectiveness,
- increasing of a theoretical DC-DC converter efficiency, owing to a lack of the transformer, and lower complexity, what combines with a lower cost and higher reliability in comparison with a bridge system.

4. Laboratory Tests of the Bilateral DC-DC Converter in a Two-phase System

4.1. Charging of the storage battery

In Fig. 4 and 5 are show waveforms of the storage battery's charging current in the DC-DC converter's simple single-phase (a) as well as simple two-phase systems (b). A vertical scale of the current yields 2 A/plot.

As well for low values of the storage battery's charging current (Fig. 4) as for high values (Fig. 5) – is visible an improvement in operation of the DC-DC converter in a two-phase system, particularly, at higher values of the charging current when is presented a higher direct component, and decreases an alternating component, what causes as well as lower emission to an environment of magnetic field harmonics in the commutation circuit's inductance.

a) b)

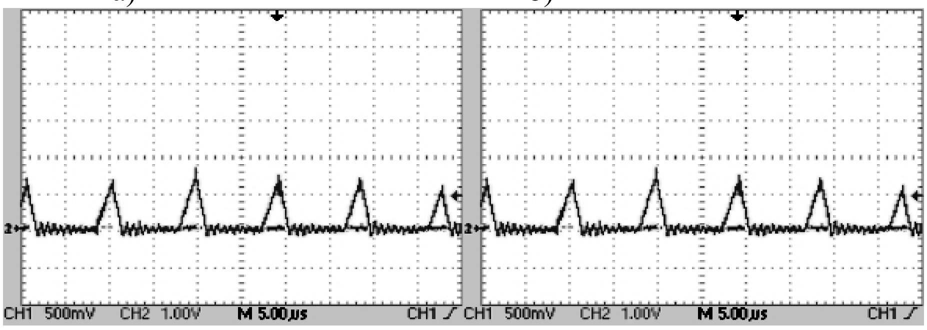

Fig. 4. Low charging current of the storage battery in single-phase (a) and/or two-phase (b) systems

a) b)

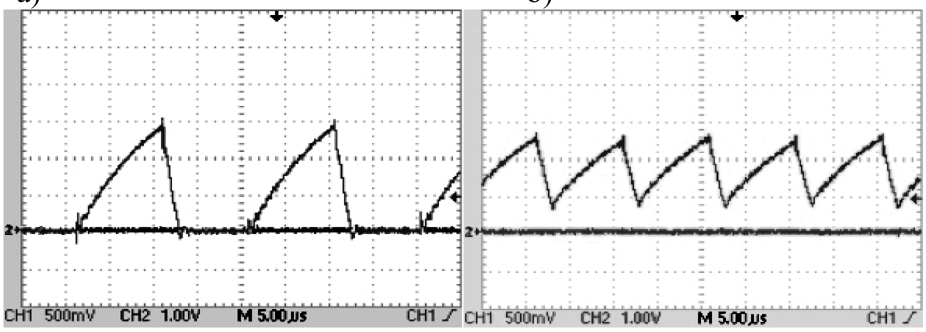

Fig. 5. High charging current of the storage battery in single-phase (a) and/or two-phase (b) systems

4.2. Discharging of the storage battery

In Fig. 6 are presented the discharging current waveforms in as well a simple single-phase (a) as a simple two-phase system.

a) b)

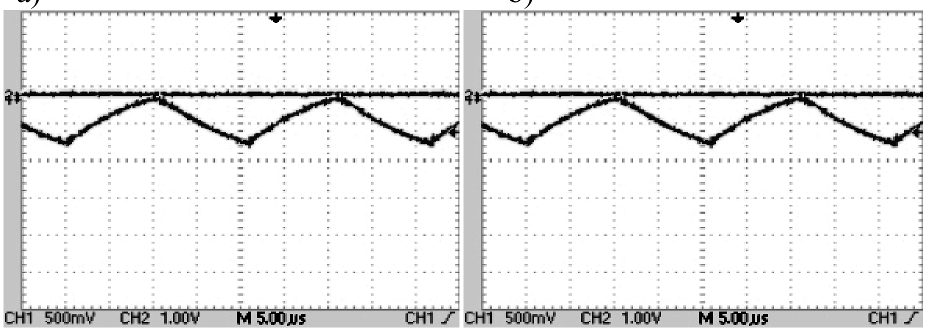

Fig. 6. Charging current of the in the DC-DC converter's single-phase (a) and/or two-phase (b) systems

In the storage battery's discharging-current waveform is visible an improvement in the current shape (increase of a direct component, and decrease of an alternating component) in a simple two-phase (b) in comparison with a conventional (a) system. A sense of the storage battery current was changed, that has why in the waveform of this current has a negative value.

5. Conclusions

The results confirmed a significant share of the heating phase of the ICE during urban-traffic of the HEV. Warming up of the ICE to operating temperature is a long process. Slow achievement of the coolant temperature set by the manufacturer is the result of an ICE in terms of its high thermal efficiency. For tested HEVs, the percentage of time powering up the ICE was amounted to about 67% of the total time required to drive a given section of the ride. Total running time of the ICE while overcoming a designated section of road for the cold start was 87% for the Toyota Prius. The proposed solution to the problem of prolonged warm-up of the ICE is to use a heat accumulator in the cooling system. The heat accumulator is stored the waste heat from the cooling system in order to obtain and maintain a nominal operating temperature of the ICE. In addition, the heat capacitor of the heat accumulator could be a buffer, preventing drops in coolant temperature during off the ICE. The results of simulations in Matlab indicate a significant reduction in the duration of heating the ICE as a result of the recovery of heat stored in the heat accumulator. This allows the driver to start the ICE at temperature conditions of -20ºC to the temperature of the main ICE components at about 10ºC. In the case of a possible short-term to deepen the level of discharge of the traction storage battery it was possible to obtain a higher temperature, by extending the time of heat transfer. As a result of the simulations, there was no significant effect of changes in a coolant-temperature distribution on the ICE. This is due to the high intensity of a heat transfer from the heat accumulator, as a result adopted flow rate of the coolant.

A proposed DC-DC converter in a simple two-phase system, as it was confirmed by the laboratory tests, ensures a better operation as well in a charging mode as a discharging mode of the storage battery, in comparison with a conventional single-phase system.

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