Cold engine cranking by means of modern energy storage devices – physical simulation

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Abstract. Diesel or gasoline engine cold cranking is a serious problem for different vehicle operation in northern countries. The engine starting torque is usually provided by an on-board electrochemical battery represented by a lead-acid unit. Modern energy storage devices, such as supercapacitors (SCs), lithium-ion, nickel-cadmium (NiCd) and nickel-metal hydride (NiMH) batteries react differently on low temperatures. Moreover, capacity losses also occur. Considering wide applications of such storage devices in electrical vehicles, their behaviour at low temperatures is of interest. Physical simulation of storage battery cold cranking was carried out using a climate chamber. Lithium-ion, NiCd, NiMH and lead-acid batteries were tested individually and paired with a SC unit to generate a power impulse for engine cranking. A number of experiments (up to five) for each type of storage devices were taken. The best performance results both for direct and hybrid cranking simulation were showed by LiFePO4-based and Ni-Cd batteries. The SC module itself showed the best performance, but its specific energy capacity cost is too high to have a large battery system based on SCs only. In this case a combined storage could give enough power to fulfill cranking demands.

1 Introduction

Diesel or gasoline engine cold cranking is a serious problem for different vehicle usage in northern countries [1]. Electric and electrochemical issues, concerned with the cold battery capacity loss phenomenon are described in [2]. The engine starting torque is usually provided by an on-board electrochemical battery, usually lead-acid (Pb-Acid) or nickel-cadmium (NiCd). At the same time, modern energy storage devices, such as SCs, lithium-ion, nickel-cadmium (NiCd) and nickel-metal hydride (NiMH) batteries react differently on low temperatures; capacity losses also occur. Considering wide applications of such storage devices in electric vehicles, including unmanned aerial vehicles [3], their behaviour at low temperatures will be of interest in the future. A hybrid system for engine launching at low temperatures, presented in [2], consists of SC and battery. The SC provides necessary high currents for cranking while the battery can charge the SC with small currents. The main

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purpose of this paper is to estimate real possibilities of different storage devices to be applied for the cold engine cranking both in direct and hybrid modes.

2 Experiments and methods

In [4] experimental charge-discharge measurements for different storage devices at different temperatures and relative currents are given (Figure 1). Authors define the relative current as:

$$I_r(C) = \frac{I * 1\ h}{Q_{nom}} \qquad (1)$$

Where I (A) – operational current, Q_{nom}(Ah) – nominal energy capacity of a battery.

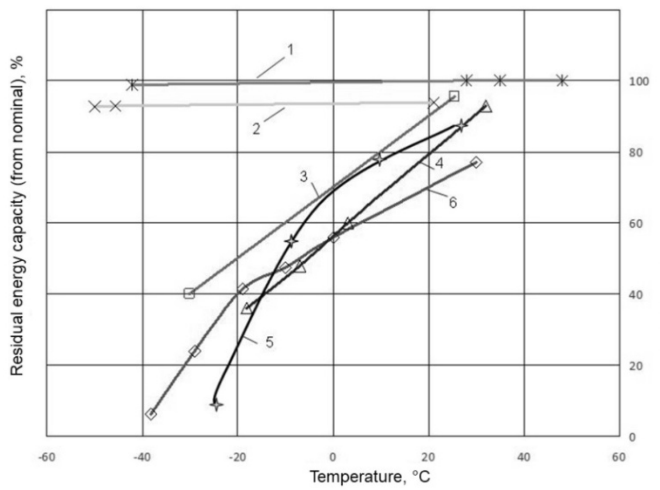

Fig. 1. Residual energy capacity for different relative currents and operation temperatures.
1 – SC battery TPS-16-500 (based on Nesscap cells), relative current 105 C; 2 – SC battery LSMtron 500 F 16 V, relative current 105 C; 3 – $LiFePO_4$ battery Sinopoly 200 AHA, relative current 0,05 C; 4 – $LiFePO_4$ battery Sinopoly 200 AHA, relative current 0,5 C; 5 – Li4Ti5O12-based battery Tiankang 16 Ah, relative current 0.25 C; 6 – Ni-Cd battery Ni-CdKGL 200 P, relative current 0,2 C.

From Figure 1 one can see that energy capacity losses are significant at low temperatures and high relative currents for all the units tested (see curves 3 and 4 – the relative current increase leads to the energy capacity loss, especially at low temperatures) excepting SCs, as they can be operated down to -45°C with small efficiency losses. But the main problems of SC applications are small energy capacities and relatively high specific energy costs [5]. So, to make 5 cranking attempts, a hybrid system consisting of a SC and an electrochemical battery is needed. In [6] several system configurations with SCs and batteries coupled are given. All of them include DC/DC or DC/AC converters as SCs and batteries have different operation voltage ranges and batteries are more prone to degradation at high currents.

DC/DC converter here is also needed to limit currents from batteries in the SC charging mode and provide the proper voltage level for the SC battery charge, especially in case of the low battery state of charge. So, a realistic scheme of such hybrid system is close to one in Figure 2. This scheme is very important from energy loss point of view. In further calculations a converter efficiency is considered as a constant and equals to 92%. A SC efficiency is also constant and equals to 96%. Some additional energy must be extracted from a battery to cover these losses.

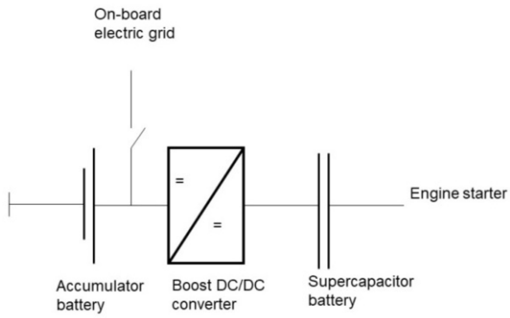

Fig. 2. A realistic electric scheme of SC-battery hybrid storage for cold engine cranking.

So, two versions of the engine launch were physically simulated in this research – a direct (from a battery) and a hybrid (simulating SC battery charge). To evaluate cranking currents and cranking cycles, Hyunday Solaris car technical parameters from the manufacturer were taken. This car has an on-board Pb-Acid battery system (12 V, 60 Ah). The Exide battery manufacturer declares 180 A or 3C as a recommended cold cranking current. A quite hard cranking mode (using relative currents of 3C for 4 seconds) was carried out in experiments for the direct cranking. Five attempts of the direct cranking were taken with 20-50 sec intervals allowing the battery voltage to reduce. The direct cranking energy can be estimated as:

$$W_{dcr} = U_{dcr} * I_{dcr} * t_{dcr} \quad (2)$$

Where U_{dcr} – average battery voltage during cranking (assumed to be 12 V), I_{dcr} – direct cranking current (3C) and t_{dcr} –direct cranking duration (4 sec). To estimate energy needed for the hybrid cranking, losses in the converter and the SC battery must be introduced as:

$$W_{hcr} = \frac{W_{dcr}}{\theta_{dc} * \theta_{sc}} \quad (3)$$

Where θ_{dc} stands for the DC/DC converter efficiency and θ_{sc}– for the SC efficiency. The hybrid cranking is supposed to be performed with a low battery discharge relative current (0,1 C) to extract more energy according to Figure 1. So, the duration of a hybrid cranking could be calculated as:

$$t_{hcr} = \frac{W_{hcr}}{U_{hcr} * I_{hcr}} \quad (4)$$

Wherein U_{hcr}=U_{dcr} as it is very difficult to estimate the voltage loss before performing experiments.

NiCd and Li-ion batteries showed the best performance results while being coupled with the SC unit. The SC unit itself showed the best performance, but its specific energy capacity cost is too high to have a large battery based on SCs only. In this case a combined storage can give enough power to fulfil cranking demands.

Several batteries were assembled to be tested (Table 1). Battery management systems were not used because of their high cost and complexity. To improve the performance of every battery system, Li-ion, NiCd and NiMH-based batteries were oversized and tested preliminary using ASK 2.5.10.8 multichannel chemical power sources analyser made by Yarostanmash LLC [7]. Three charge-discharge cycles with the 0.1C current were taken for each battery to estimate the energy capacity and the equivalent series resistance (ESR) for each unit during the third cycle. Units with similar parameters (the difference between ESR values is less than 30% and between energy capacity values is less than 10%) were assembled in batteries. The fact that Li-ion battery parameters differ depending on cathode material types is well-known [8], so two types of Li-ion batteries were tested – with lithiated irin-phosphate cathode from A123 Systems and with lithiated mixed oxides of Ni, Co and Mn (LiNMC) from Sanyo. Ni-metallohydride batteries are known to their poor performance under low-temperature conditions, but sometimes they are considered to be used inelectric vehicles [9], so they were included in the test program.

Table 1. Tested batteries' parameters.

Battery	Li-ion ($LiFePO_4$)	Li-ion (LiNMC)	Ni-MH	Ni-Cd	Pb-Acid
Supplier	A123 Systems	Sanyo	Camelion	Camelion	Delta Battery
Nominal energy capacity Q_{nom}, Ah	1.1	3.4	0.6	0.6	7.2
Battery nominal voltage, V	12.8	14.8	14	14	12
Battery recommended charge voltage	14.5	16.8	15	15	14.6

Parameters from Table 1 were used to calculate the relative current, the direct and hybrid cranking energy and the duration of a hybrid cranking values for experiments using (2)–(4). Every time before testing, battery was charged up to initial voltage with 0.1 C current and stored in the KHT 450M climate chamber for 2 days. Two temperature modes were considered – (from -0.5 C to -2°C) and (from -20 C to -22°C). After the time period direct or hybrid discharge modes were simulated. Then each battery was kept at the room temperature during one day and then charged again up to the initial voltage level. First of all, a series of direct discharge experiments were carried out with fully charged Pb-Acid and LiNMC batteries using the ASK150.24.1750.1 chemical power sources analyzer. Its internal registrators were also used to perform experimental data analysis and calculations. Figure 3 shows that a fully charged Pb-Acid battery faced 5 direct cranking attempts with the operation voltage of up to 10.2 V. Quite similar results (the operation voltage is above 11.5 V) were obtained for LiNMC and $LiFePO_4$ batteries. So it can be seen that a fully charged new battery can perform the direct engine cold cranking.

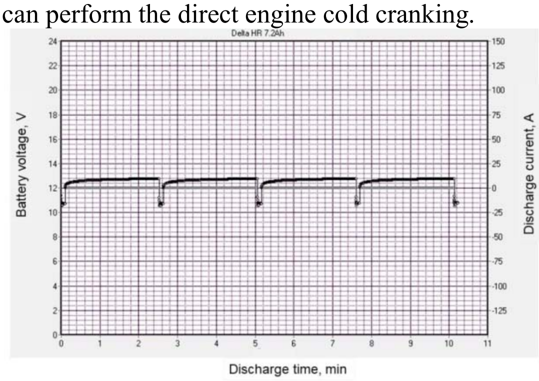

Fig. 3. Pb-acid battery direct discharge after 2-days handling at the temperature of -22°C.

Further experiments were continued using partly discharged batteries which is a more realistic situation. Thus, the Pb-Acid battery had a voltage of 12.8-13 V, while alkaline batteries – 13.6-13.8 V and $LiFePO_4$ battery 2.9-13.1 V. Due to low currents for the alkaline batteries a simple measurement scheme was used in all the following experiments. A preliminary charged battery kept during two days in the climate chamber was discharged with a rheostat with a resistance value, corresponding to the current demanded (which is equal to 3C for the direct cranking and 0.1C for the hybrid cranking simulation) during a fixed time (equals to 4 sec for the direct cranking and t_{hcr} – for the hybrid cranking simulation). The Currents were measured using shunt resistors and voltage dividers by means of the MB110-224.2A analog-to-digital converter) and the MSD-200 registration unit (both are from OWE N LLC) [10] that provides data collection on a SD-card.

3 Results and discussion

Voltage values measured during all the experiments are given in Figure 4. It can be seen that LiNMC and NiMH batteries showed the worst performance, as the direct cranking leads to lower battery voltages, which in turn affects the engine torque and battery lifetime.

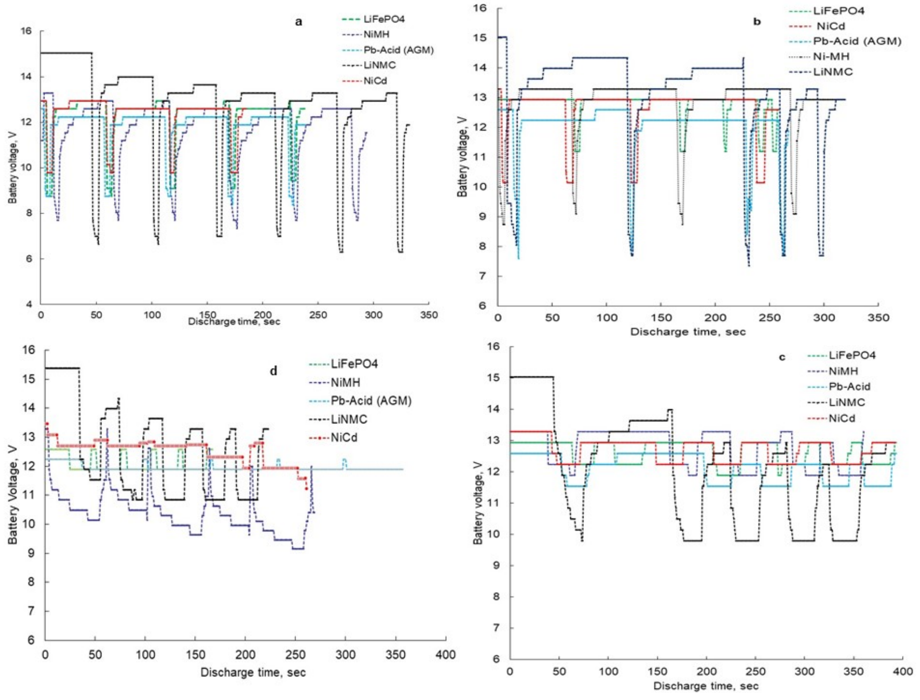

Fig. 4. Batteries voltages during cranking simulations (a-direct cranking at -20°C, b-direct cranking at -2°C, c-hybrid cranking at -2°C, d-hybrid cranking at -22°C).

The detailed analysis of current and voltage behaviour (Figure 5) for direct cranking simulation at -20°C for the LiNMC battery shows, that battery current values during all the cranking attempts was less than 3C (equals to 10.2 A for this battery type). This circumstances and significant voltage loss make proper cranking to be unlikely. During several experiments a battery relaxation time (when current was equal to 0) was decreased by two times compared to 40-50 sec during the direct cranking, however it didn't lead to a significant performance decrease. In these cases 10-20 seconds is enough to recover voltage due to the effect of charge redistribution in an electrode. The further slow voltage increase can be concerned with the electric double layer charging on an electrode-electrolyte interface). The capacity of the layer is quite low and doesn't affect significantly the battery performance. In all cases hybrid cranking allows to increase energy extraction from batteries increasing a probability of a proper cranking to happen. The NiMH battery can be operated in this mode without any dramatic voltage decrease which is typical for the direct cranking simulation. For all the batteries tested the low voltage limit during the discharge process was increased in the hybrid mode which leads to a longer battery lifetime.

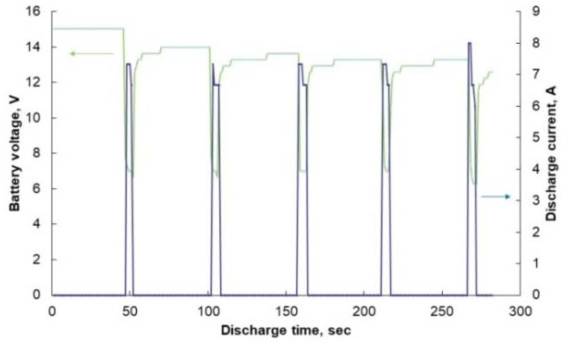

Fig. 5. The LiNMC battery's voltages and currents during the direct cranking simulation (the temperature is -20°C).

4 Conclusions

Physical simulations of direct and hybrid cold engine cranking have been performed using different battery types. Batteries performed better during the hybrid cranking simulations (they had lower battery voltage sag and higher extracted energy value) despite the fact that there were additional energy losses on the SC unit and a DC/DC boost converter. In case of the direct cranking, physical simulations showed that new and fully charged Li-ion or Pb-Acid batteries can perform cranking at low temperatures without the SC, but the battery lifetime and the degradation effect are issues in this case. The best performance both for direct and hybrid cranking simulations was shown by $LiFePO_4$ and Ni-Cd-based batteries, the worst – by LiNMC and NiMH-based batteries. These systems had the largest voltage decrease, implying less torque during cranking and higher battery degradation rate.

The work is supported by the Russian Science Foundation (grant №16-19-10659). Authors also acknowledge Yaroslav A. Men'shikov (Yarostanmash LLC, TEEMP LLC) for his support in planning experiments and discussing the results.

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