Limitations for lithium-ion batteries application in engine cold cranking

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**Abstract.** This research is devoted to the possibilities of using lithium-ion (Li-ion) batteries operation in engine cold start systems. Down-scale test specimen of LiC<sub>6</sub>–LiNiMnCo (NMC) and LiC<sub>6</sub>–LiFePO<sub>4</sub> batteries coupled with supercapacitor module were tested in cold cranking mode. The charge currents between Li-ion battery and supercapacitor module are experimentally determined. The actual operating temperatures ranges of such batteries are determined in relation to local climate condition and compared with single lead–acid (Pb–acid) battery. The test results showed that significant limitations exist for current value both for Pb–acid and Li-ion battery. Coupling of supercapacitor module with Li-ion battery slightly improves the situation, but does not guarantee reliable three attempts for engine cold cranking.

1. Introduction

Starting an internal combustion engine is a big problem for the use vehicles running on liquid fossil fuels operation in regions with a low average annual temperature [1]. The engine starting torque in traditional vehicles is provided by an integrated electrochemical battery, which is usually lead–acid (Pb–acid) or, not so often, nickel–cadmium (Ni–Cd) battery [2]. Different electrochemical energy storages systems operate in different ways at low temperature, respectively, loss of power output and energy capacity occurs in different ways. Due to the drastically increasing electrolyte resistance and the electrode processes slowdown, the voltage drop on the battery to the lower operating voltage occurs faster that the battery gives the required energy. For electrochemical double-layer supercapacitors (SCs), power loss at temperatures up to −45 °C is negligible [3]. A large number of factories, mines, and mineral deposits in Russia are located in regions with a low average annual temperature. Millions of people use public transport, a large amount of heav equipment is used at the objects located in the northern territories, so the problem of guaranteed engine starting at low temperatures is of great interest in Russian Arctic Zone [4].

Despite the cheapness and widespread use, lead–acid batteries have several disadvantages, such as reduced output energy at low temperatures [5] as well a limited service life, which significantly dependent on charge-discharge currents, depth of discharge and operating temperature [6]. The above problems encourage the use of other electrochemical battery types, for example, a lithium-ion (Li-ion) battery. So this paper is devoted to studies of different
electrochemical energy storage devices, operating at low temperatures and high power. The purpose is to define the optimal storage devices combination for engine cold cranking from weight and cost and efficiency point of view.

2. Calculation and experimental studies
Taking into account low currents and high energy capacity of Li-ion batteries, it seems useful to combine them with SCs high power output at low temperatures. Another reason is SCs high relative price and specific weight. Calculation for optimal combined storage device is taking. One suppose, that SC module will give the cranking current while electrochemical battery provide SCs charge at low current between cranking attempts. Lead–acid battery 6ST-190 (12 V, 190 A h) is typically used as starter battery in Russia. To allow physical experiment of cold cranking with battery, SC module or their combination using ASK150.24.1750.1 test station and KHT450M climate chamber one should down-scale the system from power and currents point of view. Energy capacity of Pb–acid battery is chosen equal 19 A h instead of 190 A h. The lithium-ion battery capacity will be compared with a lead–acid battery. The hybrid energy storage must provide a 3 $C$ ($C$ is value that shows how many times the discharge current exceeds the nominal capacity of the battery also shows the rate of discharge of the battery 1/h).

2.1. Initial data
Figure 1 shows a real experimental sequence diagram of starting a diesel generator set, the starter battery of which includes two Pb–acid batteries, serial connection. This starting cyclergram is quite complex and has steps of less than one second that can not be implemented by test bed. Therefore, we average the starter current over the interval, the time-step $T_s$ is three second

$$I_{\text{start}} = \frac{1}{T_s} \int_0^{T_s} I(t)dt.$$  

(1)

Thus, it is assumed that the starting current is the same for three seconds and is equal to 1330 A. The energy spent on the start can be estimated as

$$W_{\text{start}} = I_{\text{start}} U_{\text{sys}},$$  

(2)

where $U_{\text{sys}}$ is the voltage in the dc bus of the hybrid energy storage, due to the presence of a lithium-ion battery with LiNiMnCo (NMC) as cathode. The energy used to start the engine is 17.8 Wh.

2.2. Specification of lithium-ion battery
Due to high SC specific cost and low specific energy it is necessary to minimize the capacity of the SC battery in the combined energy storage unit. The Li-ion part of the hybrid energy storages unit is equipped with LiitoKala cells. The single cell has an operating voltage range from 2.8 to 4.2 V and rated capacity 3.5 A h. The recommend discharge current of such a battery is 0.5 $C$ and depth of discharge (DOD is maximum discharge ratio, when DOD is 1 that means the battery will be completely discharged during operation) is 0.8. $Q_{\text{max}}$ is maximum energy density of battery A h, $DOD_{\text{Li}}$ is depth of discharge of battery (dimensionless quantity) and $Q_{1}^{\text{Li}}$ is rated capacity of single cell in A h. Now it is possible to estimate amount of single unit Li-ion batteries

$$N_p = \frac{Q_{\text{max}}}{DOD_{\text{Li}} Q_{1}^{\text{Li}}}. $$  

(3)

The maximum load current of the assembled battery is determined by the following expression, where $i_1^{\text{Li}}$ is recommended current of one single cell in units of energy intensity $C$

$$I_{\text{Lib}} = N_p Q_{1}^{\text{Li}} i_1^{\text{Li}}. $$  

(4)
Figure 1. Current and voltage of the starter Pb–acid battery during a 7 C discharging at room temperature: red line—discharging current; black line—voltage during discharge.

2.3. Specification of SC battery

Since the lithium-ion battery has a discharge current limit, the SCs will take the most part of the discharge current, which exceeds the limit, the discharge current that the SC will take on is defined as

$$I_{scb} = I_{\text{start}} - I_{\text{Lib}}.$$  \hspace{1cm} (5)

The upper voltage of a single SC cell is 2.7 V, so to achieve 16 V it is necessary to have 6 single elements connected in series. Due to the absence of a converter between the lithium-ion battery and SC module, the discharge will occur in the voltage range from 9.8 to 14.8 V. Introduce the notation of the upper limit as $U_{\text{up}}$ and the lower limit as $U_{\text{down}}$; $N_{\text{sc}}$ is the amount of SC single elements connected in series. The capacity of the SC must satisfy two criteria. The first criteria is $C_{11}$ it should be enough energy to start the engine, if $C_{11} < W_{\text{start}}$, the engine will not start. The first criterion can be determined by the following expression:

$$C_{11} = N_{\text{sc}} \frac{2W_{\text{start}}}{U_{\text{up}} - U_{\text{down}}}.$$ \hspace{1cm} (6)

The second criterion is $C_{12}$, by the second criterion the ratio of the operating current to the capacitance ($C_F$), if $C_{12} \leq 0.66$ the engine will not start and SC will break down. This is due to the experimental current limit for TEEMP LLC produced SCs, used in the experiments:

$$C_{12} = \frac{I_{scb}}{C_F N_{\text{sc}}}.$$ \hspace{1cm} (7)

3. Results and discussion

For physical modeling 6 SC cells in series have been selected, with a single cell capacity of 350 F, one 12 V Pb–acid battery with a rated capacity 10 A h (reference specimen, tested in the same
Table 1. The successful of attempts to start the engine at different temperatures.

| $t_a$ (°C) | $C$ (1/h) | LiFePO$_4$ with SC | NMC with SC | Pb–acid | Pb–acid with SC |
|------------|-----------|-------------------|------------|---------|-----------------|
| −40        | 7         | 0                 | 0          | 0       | 0               |
| −40        | 3         | 1                 | 0          | 0       | 1               |
| −30        | 7         | 0                 | 0          | 0       | 1               |
| −30        | 3         | 1                 | 1          | 3       | 3               |
| −20        | 7         | 0                 | 0          | 2       | 3               |
| −10        | 7         | 1                 | 1          | 2       | 3               |
| −10        | 3         | 1                 | 1          | 3       | 3               |
| 0          | 7         | 3                 | 2          | 3       | 3               |
| 0          | 3         | 3                 | 2          | 3       | 3               |
| 15         | 7         | 3                 | 3          | 3       | 3               |
| 15         | 3         | 3                 | 3          | 3       | 3               |

conditions, as the combined start system), Li–NMC battery consisting of 4 series-connected LiitoKala single cells with a rated capacity of 3.45 A h and Li–FePO$_4$ with a rated capacity of 1.5 A h. According to calculations, in order to reliably start the engine with an overload current of 7 C for a lead–acid battery of 12 V and with a rated capacity of 7 A h, it is enough to replace it with a parallel connected Li-ion battery and SC module with 16 V and 57 F. The lithium-ion battery is represented by two types of cathode materials, it is Li–NMC which have a 14.8 V as operation voltage and 3.45 A h and Li–FePO$_4$ with a 13.2 V and 1.5 A h. At the anode both battery types have LiC$_6$. The engine cranking attempt imitation was considered as successful provided that the combined energy storage has been operated at the cranking current for three seconds and has not reached lower voltage limit. In a series of experiments, attempts were made to start the engine three times with an interval of twenty seconds. Typical cranking currents are considered 3 and 7 C. The results of attempts to start the engine are presented in table 1. In table 1, $t_a$ is ambient temperature (°C).

Also, during the experiment, charging currents have been determined between the lithium-ion battery and SC module, which are connected in parallel, without converters. The charging current occurs due to the fact that the internal resistance of the SC is several times less than that of a lithium-ion battery. With a high load current, the voltage drops on the SC, the Li-ion battery begins to charge it with small currents until the voltage between them is equal. The charging current was from 0.9 A at 15 °C to 5.4 A at −10 °C. The reliable operation of combined hybrid energy storage was confirmed only at 0 °C and higher. At −10 °C the reliability drops sharply, three successful cranking attempts are impossible. LiFePO$_4$ could provide one the successful attempt to start the engine already at −40 °C. However the first successful start attempt at Li–NMC battery just at −30 °C.

Combined energy storage starter load currents with LiFePO$_4$ battery inside shown in figure 2. Combined energy storage voltage change while cold cranking with LiFePO$_4$ battery inside shown in figure 3.
Figure 2. Cranking current of combined energy storage with LiFePO$_4$, during a 7 $C$ discharging at $-40$ °C: blue line—LiFePO$_4$ battery voltage; orange line—SC module voltage.

Figure 3. Voltage change while cranking is going on of combined energy storage with LiFePO$_4$, during a 7 $C$ discharging at $-40$ °C: blue line—LiFePO$_4$ battery voltage; orange line—SC module voltage.
4. Conclusions
Calculation to estimate optimal composition for internal combustion engine has been carried out. Calculation technique is proposed. Experiments to verify calculation results have been taken. Experiments showed that combined energy storage estimated composition can be successfully operated only at temperatures above zero providing higher cranking currents than standard lead–acid battery. But system with Pb–acid battery and SC can work at high discharge currents and extremely low temperatures. For stable operation at subzero temperatures, lithium-ion batteries are required, providing higher discharge currents (about 0.1–0.8 $C$) and energy output in this temperature range.

References
[1] Popel O S, Frid S E, Kolomietz Y G and Tarasenko A B 2015 ISJAEE 10 98–106
[2] Glebke M and Mondoloni C 2017 Lead–Acid Batteries for Future Automobiles (Elsevier) chapter 2 pp 149–84
[3] Popel O S and Tarasenko A B 2018 Therm. Eng. 65 266–81
[4] Beliakov A I 2003 Starting of locomotive diesel engines using electrochemical capacitors Proc. of Advanced Capacitor World Summit (Washington: Academic) p 122
[5] Tarasenko A B, Gabderakhmanova T S, Kiseleva S V and Suleymanov M J 2018 MATEC Web Conf. 178 9–12
[6] Schaeck S, Stoermer A O, Kaiser F, Koehler L, Albres J and Kabza H 2011 J. Power Sources 196 1541–54