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ONLINE ASSESSMENT OF THE LEAD - ACID BATTERY ELECTRICAL CAPACITY ON SUBMARINES

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Abstract

Despite the invention of new chemical sources of electricity, acid batteries, due to their price, are still widely used. They are also used on conventional submarines as the primary source of power. Due to their properties, lead-acid batteries require a lot of attention during their operation, including charging according to fairly rigorous rules. Because of their special operating conditions on submarines, it is not possible to maintain optimal conditions for such batteries. The battery's integrated management system allows for remote and online monitoring. However, it gives only general information about how much energy remains in the battery for the use in operating conditions. The submarine's operational capabilities, such as range and operation time, depend to a great extent on battery capacity, therefore, the information of its condition and status is very important.

The proposed method of evaluating the capacity of lead-acid batteries allows them to be processed during their operation, without the need of a time-consuming and expensive capacity test. The authors proposed an original algorithm for evaluating the battery capacity, based on measurement data from a typical monitoring system, assembled with a battery on a ship. The measurements needed to implement the proposed algorithm are already implemented in the existing battery monitoring system – no additional equipment is required. Based on the results of the proposed method, it will be possible to easily determine how much energy is available for the submarine, what is crucial in planning combat missions at the sea.

Keywords: battery, lead - acid, submarines, capacity

OCENA ONLINE POJEMNOŚCI OKRĘTOWEJ BATERII OŁOWIOWO - KWASOWEJ

Streszczenie

Pomimo powstawania nowych chemicznych źródeł energii elektrycznej, akumulatory kwasowe, ze względu na swoją cenę, są nadal powszechnie stosowanym rozwiązaniem. Stosuje się je również na konwencjonalnych okrętach podwodnych jako podstawowe źródło zasilania. Ze względu na swoje właściwości akumulatory ołowiowo – kwasowe wymagają dużej uwagi podczas ich obsługi między innymi ładowania według dość rygorystycznie określonych zasad. Ze względu na szczególne warunki ich eksploatacji na okrętach podwodnych, nie jest możliwe zachowanie optymalnych warunków pracy dla takich akumulatorów. Dołączony do baterii system pomiaru i akwizycji jej parametrów, umożliwia ich zdalne i automatyczne monitorowanie. Daje on jednak zbyt ogólną informację na temat tego, ile pozostało w akumulatorach energii, którą w warunkach operacyjnych możemy wykorzystać. Możliwości operacyjne okrętu podwodnego takie jak zasięg czy czas działania zależą w dużej mierze od pojemności akumulatorów, dlatego informacja o jej stanie jest bardzo istotna.

Zaproponowana metoda oceny pojemności akumulatorów kwasowo – ołowiowych umożliwia kontrolę stanu baterii w trakcie jej eksploatacji, bez konieczności przeprowadzania czasochłonnej i kosztownej próby pojemności. Autorzy zaproponowali oryginalny algorytm oceny pojemności baterii, bazujący na danych pomiarowych z typowego systemu monitoringu, montowanego wraz z baterią na okręcie. Dzięki temu pomiary konieczne do realizacji zaproponowanego algorytmu realizowane są przez istniejący już system – nie jest konieczne montowanie dodatkowych urządzeń. Na podstawie wyników zaproponowanej metody, będzie można w łatwy sposób określić jaką ilością energii dysponuje okręt, co jest kluczowe podczas planowania zadań bojowych w morzu.

Słowa kluczowe: bateria, ołowiowo – kwasowa, okręty podwodne, pojemność

1. INTRODUCTION

The only source of power supplied to the propeller on conventional submarines during immersion are batteries. Submarines operate under water, where it is only possible to use electric propulsion to move the ship. During this time, the batteries are systematically discharged. The speed of this discharge depends on many factors: speed, trajectory of manoeuvres, sea currents, etc. At the same time, a major operational problem is to charge this batteries. Battery charging can only be done when ship stays on surface or on periscope depth with lifted snorkel, where the air form above the water comes through a special tube to the inside of the ship, enabling the operation of internal combustion engines. In both cases, battery charging is a process, while ship is an easy target – during this time she loses her ultimate attribute – being difficult to locate[12], [15].

Life span and operational ability like range or time at sea, mostly depends on capacity of batteries. That is why the information about its condition is very important. The condition of batteries is one of the most substantial parameters in evaluation of ship capabilities.. [5], [7], [11].

2. LEAD-ACID BATTERIES USED ON SUBMARINES

In spite of creating batteries which have much greater energy density – like Li-Ion batteries and the new market innovation in the area of this power source, the lead-acid batteries, due to their low price and longstanding experience in operation, are still applied in ship building, especially on submarines.

The height of used lead-acid cells is greater than one meter and base area exceeds 0,3m^2. The weight of that cell is approximately 1 ton. Every cell with rated voltage 2V can be single or few can be included in one case. Irrespective of the construction solution, every cell has accessible poles' connections and maintenance plugs. The size of those cells allows to collect a lot of energy (greater than 20kAh), simultaneously allowing to control and maintain every single one. On submarines, cells are separated in groups, in which they are serial connected which increases the voltage of the group to rated voltage of the ships' power network. Individual groups can have series or parallel connection or even work individually, but only in special situations [5].

Due to their size and changing temperatures, the cells require a cooling system, which allows to equalize temperatures in single cells in batteries and cool them if they exceed 40^{o}C. The agitation system is based on blowing fresh air into the bottom part of the cell, causing movement of the electrolyte. This causes more equal utilization of active mass of cell plates [14].

During operation of batteries, especially while charging, the cells exhale hydrogen [3], which is highly flammable. To avoid dangerous situation, the batteries' compartments are continuously ventilated.

Battery Monitoring System allows to keep continuous surveillance of batteries condition on submarines. BMS stores information about voltage, current and temperatures of each batteries' cells, with user defined frequency of measurement. The actual temperature parameter allows the user to compare the actual voltage of the cell to the voltage of the cell in temperature 30^{o}C. This is the reference temperature established by the producer of batteries.

BMS is the only source of information about battery condition. Based on counted discharged Ah, it gives the user only general information about the amount of energy still available in the batteries.

3. BATTERY CHARGING STAGES

Figure 1 presents three stages of lead – acid battery charging.

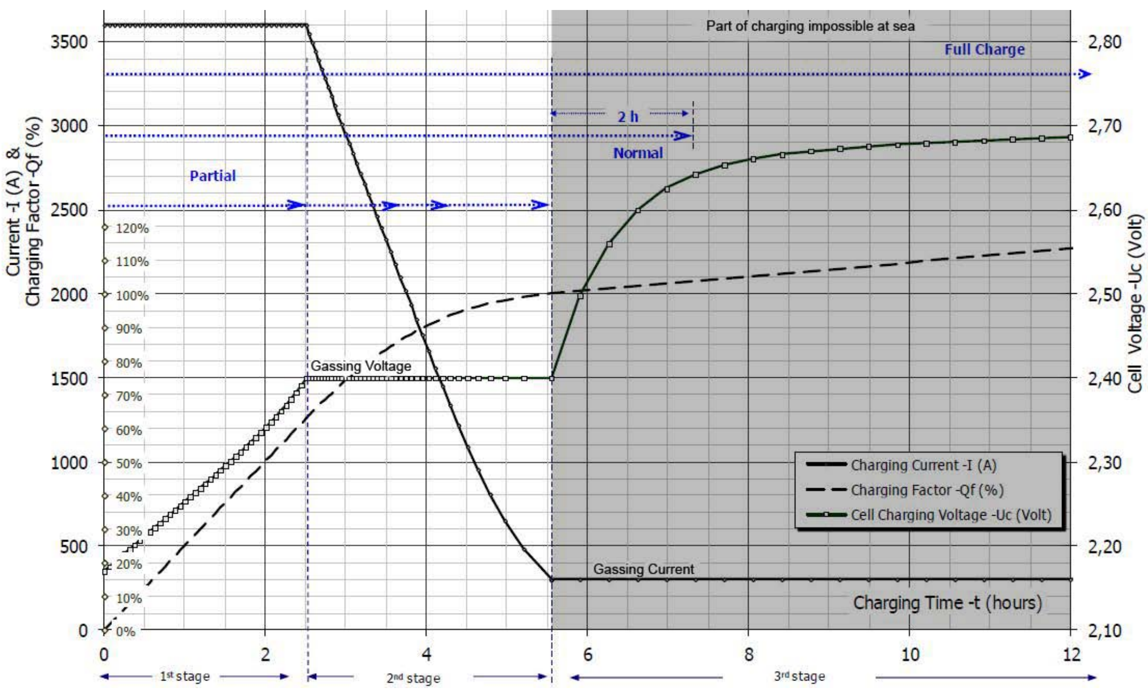


Fig. 1. Charging methods and charging stages of submarine lead-acid batteries [14]

First charging stage – charging with constant current or power until the average voltage reaches the gassing voltage – after which intense gas development begins (oxygen and hydrogen), coming from the electrolysis of the acid water. For fast charging, the applied current of first charging stage (or power) is the maximum available that the charging equipment can provide.

Second charging stage – follows directly after the end of the first charging stage. The current is being reduced while the average voltage is being kept below the gassing voltage. The stage end comes when the average voltage reaches the gassing voltage while the charging current reaches a low value referred to in the manual – a gassing current.

Third charging stage (gassing stage) – the charging with constant current (gassing current) while the battery voltage exceeds the gassing voltage. This stage is used to achieve the full charge condition in the shortest possible time. Another use is the refresh charging of a battery in storage condition.

The hydrogen evolution during gassing is high because the larger part of the current is consumed in electrolysis. The charges that include part of the gassing stage can be carried out only at the naval base. Gassing charge at sea is not possible.

The third charging stage ends when voltage on each cell does not increase more than as specified by the manual value [14].

Figure 1 shows which charging methods consist of which charging stages.

4. BATTERY OPERATION ON SUBMARINES

The 100% of battery capacity can be acquired at the end of the second stage of charging (Figure 1). The third stage of charging is aimed at fully restoring the capacity of batteries [10].

The most frequent charging method during cruising operations is partial charge. A partial charge begins with the first charging stage, which can either be interrupted or run until the end of the second charging stage. It is recommended that charging should last until the end of the first charging stage. The duration of partial charging depends on the former discharge condition of the battery, the amount of current flowing into battery and the time available on board at the moment when the partial charge is being performed (operational conditions).

Except for charging methods shown in Figure 1, the equalizing charge is also performed (Figure 2).

The equalizing charge guarantees that all cells are fully and uniformly charged [10].

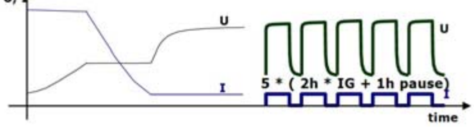


Fig. 2. Equalizing charge [14]

The equalizing charge starts about one hour after the end of the full charge. It consist of three cycles at minimum, each one consisting of two hours charging with gassing current and one-hour rest in between. This charging can be carried out only at the naval base.

During charging batteries submarine loses her ultimate attribute – being difficult to locate. That is the reason why charging, while submarine is operating at sea, is made least often and as quick as possible. It leads to deep discharges of batteries and charging them with maximum available for submarine power network currents [5]. This factors impacts battery capacity very adverse, decreasing it in short period of time [9].

5. CAPACITY TEST

The capacity test is performed to define true capacity of batteries mounted on submarine.

Properly conducted capacity test requires adequate prior preparation of batteries. This preparation involves performing specific charges and discharges.

The preparation begins with a conditioning discharge consisting of unloading from battery 40% of its nominal capacity using specified current. Then, a full charge is performed. The next step is to discharge 80% of the nominal capacity of the battery, also with the specified current. Then, again the full charge is performed and after that the equalizing charge.

Only after carrying out these activities the capacity test shall be performed, which is discharge of 100% of nominal capacity or if voltage drops faster – the current full capacity of battery.

After the capacity test, the battery should be recharged by performing the full charge.

The entire procedure of preparing batteries and carrying out their capacity test takes about a week. This is the time when a ship is completely excluded from operational activities.

Such deep discharge is very harmful to the battery and therefore is used no more than once a year [14].

However, today's capacity test gives the most accurate information about battery state and its actual capacity.

6. PROPOSED METHOD

The manufacturer and supplier of ship's batteries is obliged to deliver batteries with strictly specified parameters in the buyer's requirements. This also applies to documentation, that, in addition to a detailed technical description, operation and maintenance of the supplied batteries, must have a number of characteristics that demonstrate how the battery behaves under different conditions. Using these characteristics, the new algorithm was developed to assess the total capacity of batteries while they are used at sea.

Due to its size and variable climatic conditions, the battery temperature is not constant.

Operating temperatures above 30°C reduce the expected life time of the battery. A general rule of thumb is: for every 10°C increase in the average operating temperature above 30°C, the expected life time is halved [1], [2], [4].

Operating temperatures lower than 20°C does not improve considerably the life time while resulting in reduced capacity, especially for the fast discharge rates.

Operating temperatures between 20°C and 25°C is considered ideal for both life time expectancy and electrical performance.

Excessive temperatures over 45°C, even short lasting, may reduce drastically the life of the battery. The main disadvantages of the high temperatures are the following: increased H_2 development, increased water evaporation, increased attack on the spongy lead of the negative plates (sulphation), increased corrosion rate of the lead parts inside the cell [8],[13].

Practically, in moderate climate, the temperature of cells stays in range 20-30°C. During a longer stopover in the port, in winter months, it drops to 10°C, but exceeds 45°C only in the case of a cooling system failure.

The characteristics provided by the manufacturer illustrate the voltage dependence of the battery at nominal temperature of 30°C. To be able to refer to them as measured at other battery temperatures, they must be corrected. As the electrolyte temperature increases by one degree Celsius, the cell voltage decreases by 5mV. For voltage of whole one group of batteries (120 cells) its 0.6V. The corrected voltage is calculated in accordance with the following formula:

$U(30^oC) = U(T) + 0,005 * (T-30)$ per cell
$U(30^oC) = U(T) + 0,6 * (T-30)$ per battery

where:
U(T) : measured value of the charging voltage
$U(30^oC)$: charging voltage [V] corrected to the temperature of 30°C
T : average temperature [°C] of the cells

The main assumption of the proposed method is the variation of the discharge current during the analysis. It is conditioned by the fact, that under marine conditions, it is difficult to ensure a steady discharge current for a long period of time, as the operation of the submarine mechanisms is not continuous and even the setting of the main engine often changes as a result of the ship manoeuvres.

In order to calculate the energy that is discharged from the batteries, it is also assumed that the operation of the algorithm starts when the batteries are fully charged. The above condition may change after the test on real data.

The presented characteristics (Figure 3) show the dependence of the capacity of submarine batteries from their discharge current. It can be seen that the capacity for one hour unloading current is more than two times lower than for a hundred hours current. It follows that, when discharging battery with not constant current, we can not sum up the unloaded energy, since too much error would result from difference capacitance for each current. In presented method, it is proposed to relate discharged energy to nominal capacity (for a given discharge current) and to present it as a percentage of the discharge of the battery.

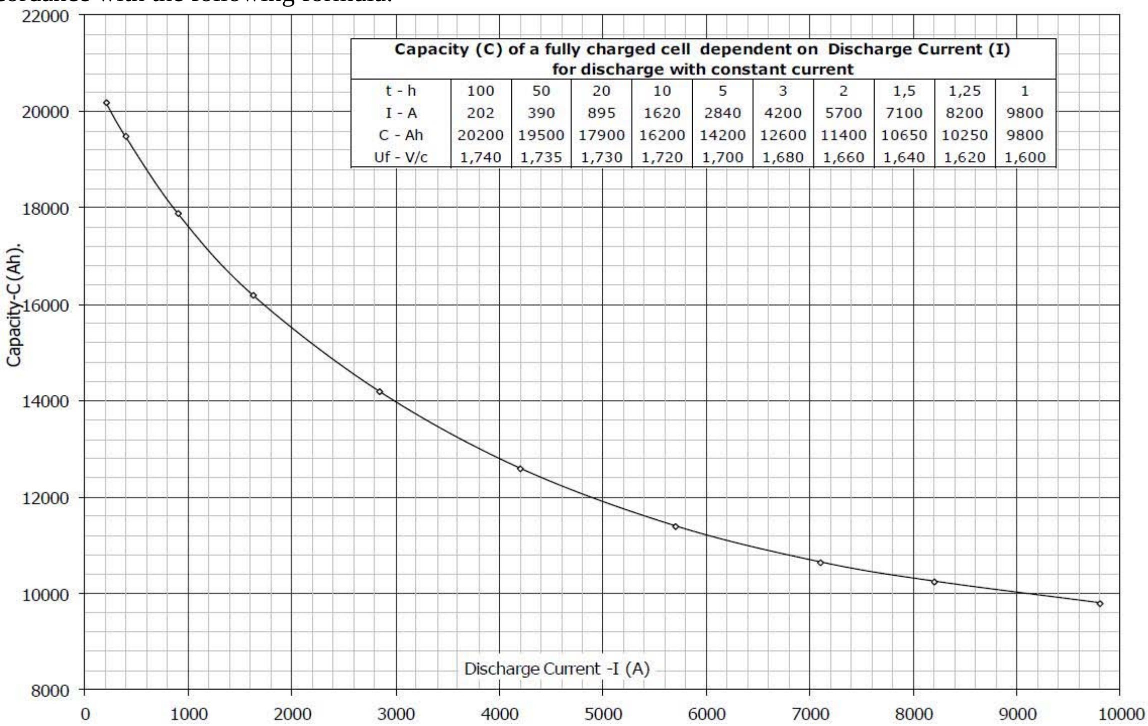


Fig. 3. Dependence of capacity of submarine batteries from their discharge current [14]

Assuming a full charge of battery, as a result of the first assumption, the measurement of the discharge current with a specified frequency is recorded. These measurements for a given time interval are averaged.

I_d – measured discharge current
I_{da} – average of I_d measurements

At the same time, the measurement of the voltages and temperatures of individual cells is recorded with current measurements.

Taking into account the average current value, it is possible to calculate the energy that is discharged from the battery during the time T_{Id}.

$E = I_d * T_{Id}$ [Ah] (1)

Also, with the specified current (I_d), based on characteristic in Figure 3, it is possible to determine the nominal capacity of the battery for this current value.

The next step is to determine the percentage of battery discharge. To determine this, the calculated discharge capacity is divided by the nominal capacity for the discharge current.

$C_{\%} = E/C_N$ (2)

where:
$C_{\%}$ – percentage discharged capacity for T_{Id}
E – energy discharged from battery [Ah]
C_N – nominal capacity for given current

The calculated $C_{\%}$ are summed for each successive T_{Id} time interval, receiving a total percentage of battery discharge.

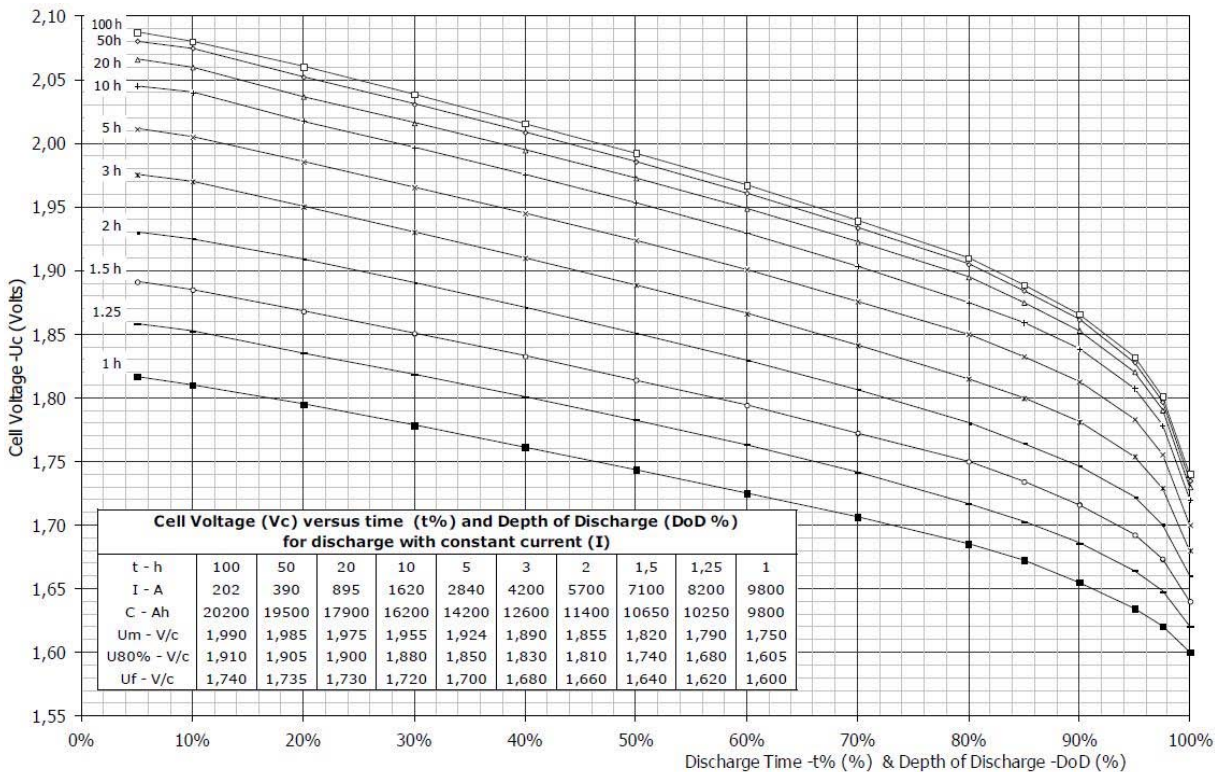
The following family of characteristics (Figure 4) represents the relationship of the voltage of a single cell from its discharge state for specific discharge currents. Characteristics are specified for ten current values. In the implementation of the algorithm, the calculated mean discharge currents (I_{da}) will not overlap with the current values shown in the characteristics.

As mentioned earlier, when using batteries at the sea, it is practically not allowed (only in combat situations) to discharge more than 80% of stored energy from the batteries. The characteristics in this range are almost straight and parallel and it is assumed that for other values of currents than those described in the characteristics, they can be interpolated.

As shown in Figure 4, the earliest battery capacity rating can be started at least at 6% of discharged capacity. It is assumed that, with the increase in discharged capacity, the algorithm will ensure more accurate evaluation of the battery state.

Using total percentage of battery discharge (sum of $C_{\%}$) and corrected voltage of each cell, it is possible to determine a point on characteristic for every single cell. Then, knowing the discharge current (I_d), determine its position relative to the characteristic of the cell with 100% of the nominal capacity.

For example, assuming the percentage of total battery discharge is 14%, and the measured, corrected cell voltage is 1.95V, the point on the Figure 5 is indicated.



t - h	100	50	20	10	5	3	2	1,5	1,25	1
I - A	202	390	895	1620	2840	4200	5700	7100	8200	9800
C - Ah	20200	19500	17900	16200	14200	12600	11400	10650	10250	9800
Um - V/c	1,990	1,985	1,975	1,955	1,924	1,890	1,855	1,820	1,790	1,750
U80% - V/c	1,910	1,905	1,900	1,880	1,850	1,830	1,810	1,740	1,680	1,605
Uf - V/c	1,740	1,735	1,730	1,720	1,700	1,680	1,660	1,640	1,620	1,600

Fig. 4. Dependence of cell voltage from depth of discharge [14]

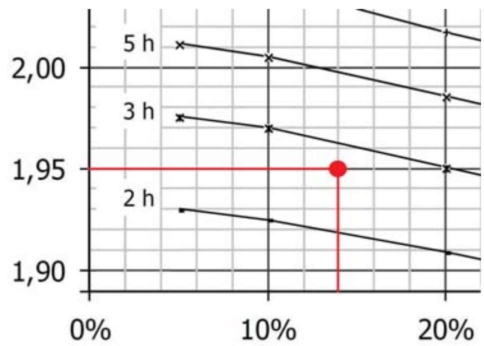


Fig. 5. Example for cell voltage 1.95V and depth of discharge 14%

Assuming that the discharge current (I_d) is 4200A, the next point on the current curve is determined for the measured value of the corrected voltage (Figure 6).

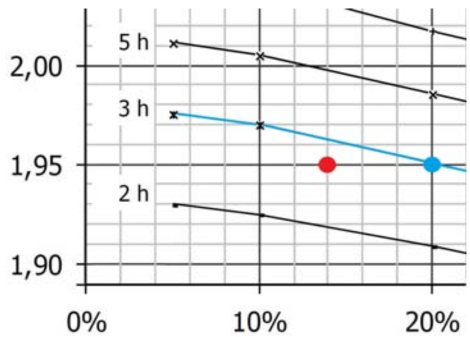


Fig. 6. Example for cell voltage 1.95V and depth of discharge 14% with marked 3h discharged current

By reading the percentage of discharge for the 100% nominal capacity cell (in this case 20%) and referring it to the previously calculated total percentage of battery discharge, the reduction (or increase) of the cell capacity relative to the nominal capacity can be determined.

In the case under discussion, this illustrates the line, joining both points on the characteristics (Figure 7).

The percentage of discharged cell at the nominal capacity of the cell at three-hour current is 20%. Comparing it to the previously calculated total capacity (14%), the current battery capacity is reduced by 6%.

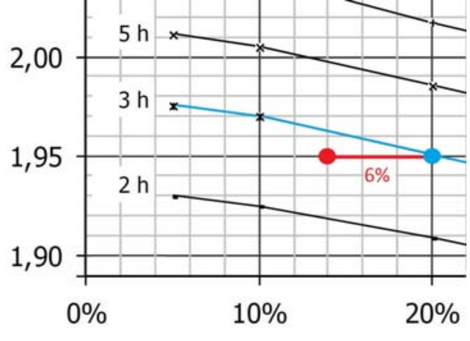


Fig. 7. Illustration of capacity drop for discussed example

7. CONCLUSIONS

The proposed method of evaluating the capacity of lead-acid batteries, based on data obtained from used BMS, allows them to be processed during their operation, without the need for time-consuming and expensive capacity test. The measurements needed to be implemented in the proposed algorithm, are already implemented in the existing battery monitoring systems – no additional equipment is required. Based on the results of the proposed method, it will be possible to easily determine how much energy is available to the submarine, which is particularly important at the end of battery life cycle, when its capacity is dramatically decreasing in time. The proposed algorithm should be checked on the results of the actual object measurements and compare the results with the results of capacity test. On the basis of the experiment, it would be necessary to determine the optimal time intervals in which the current measurement will be conducted and the ranges in which it will be averaged. It would also be necessary to determine which effect the charging batteries applied at the sea would have on the proposed algorithm.

REFERENCES

1. Rand DAJ, Moseley PT. *3 – Lead-acid battery fundamentals*. Lead-Acid Batteries for Future Automobiles 2017: 97-132
2. Lambert DW, Greenwood PH, Reed MC *Advances in gelled-electrolyte technology for valve-regulated lead-acid batteries.* J Power Sources, 2002, 107;(2): 173–179.
3. Detchko P. *Chapter 3 – H2SO4 Electrolite – An Active Material in the Lead-Acid Cell.* Lead-Acid Batteries: Science and Technology (Second Edition) 2017: 133-167.
4. Detechko P. *Chapter 2 – Fundamentals of Lead-Acid Batteries*, Lead-Acid Batteries: Science and Technology (Second Edition) 2017: 33-129
5. *Directing the submarine type 877E*: Naval Command Gdynia 1988. Polish.
6. Chen M, Rincon-Mora GA. *Accurate electrical battery model capable of predicting runtime and I–V performance.* IEEE Trans Energy Convers, 2006; 21(2): 504–511.
7. Zaloga M. *Organization, operation and security of submarine operations* WSMW Gdynia 1967. Polish.
8. M.A. Dasoyan, I.A. Aguf, Current theory of lead-acid batteries, Stonehouse 1979.
9. Hunter PM, Anbuky AH. *VRLA battery rapid charging under stress management.* IEEE Trans Industr Electron, 2003;50(6):1229–1237.
10. Krein PT, Balog RS. *Life extension through charge equalization of lead-acid batteries*. 24th annual international telecommunications energy conference, 2002. INTELEC, IEEE 2002: 516–523.
11. *Rules of combat use of submarines*: Naval Command Gdynia 1990. Polish.
12. *Submarines: Hunter/Killers & Boomers. – Lincolnwood.* Beekman House 1990.

13. Reddy T. *Linden's handbook of batteries*. 4th ed. McGraw-Hill Education; 2010.
14. *Technical manual s/m propulsion battery type 40 ST 35*, Lead Acid Batteries Technical Department Systems Sunlight Factory Xanthi (Greece) 2014.
15. Grabowski Z. *Submarines*. Ministry of National Defense 1965. Polish.

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