

Article

Tests of Acid Batteries for Hybrid Energy Storage and Buffering System—A Technical Approach

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Abstract: Many armies around the world showed an increasing interest for the technology of renewable energy sources for military applications. However, to profit fully from solar or wind energy, an energy storage system is needed. In this article, we present an energy storage system based on acid-lead batteries as a component of a modular generation-storage as a model of military “smart camp”. We proposed a technical approach to study four different types of batteries: DEEP CYCLE, AGM, WET and VRLA in laboratory and real conditions typical for military equipment. It was observed that the best performance was observed for AGM battery in terms of the highest cold cranking amperage equal to 1205 A combined with the most compact construction and resistance to varying thermal conditions from $-25\text{ }^{\circ}\text{C}$, $25\text{ }^{\circ}\text{C}$ and $50\text{ }^{\circ}\text{C}$. Additionally, a 12-month long-term testing in real conditions revealed that AGM and VRLA showed decrease in capacity value maintaining only approx. 80% of initial value.

Keywords: battery; energy storage system; photovoltaics; hybrid power source



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1. Introduction

The current development and wide accessibility of renewable energy systems made them a very good alternative to conventional power sources. However, due to the fact that the supplied energy is highly dependent on external conditions, such as solar irradiation, wind speed or the water level in rivers, a need for using power fluctuation compensation systems as a buffer is created [1]. Additionally, electricity has to be transmitted over long distances and the related losses and disruptions affect the search for new solutions in the field of energy. The answers that seem to be the most rational are environmentally friendly renewable energy sources (RES). Understandably, the issue of energy storage remains, however, a strategy to use a distributed energy storage is a possible solution. These energy storage units can be built together with RES systems, which seems to be the most advantageous [2]. Therefore, the need to store energy forces the use of an additional supporting system based on: pumped storage power plants [3], grid-based energy storage, as well as more dispersed energy storage systems [4]. Both of these systems can coexist with renewable energy source generators; as for the individual end user, having access to energy stored gives the possibility to be partially independent in times of temporary energy shortage from the energetic grid. Such a solution, in which the individual energy generator will also store energy, opens up almost unlimited possibilities, offers great flexibility and is of high interest to both the civilian and military users [5]. It can be compared to the

solutions adopted in computer science, a kind of “energy cloud” or even the Internet of Things [6]. In this case, the energy storage system will collect, equalize and work as a buffer stabilizing the energy.

All the armies in the world are interested in innovative technologies, allowing the troop to survive under field conditions [5]. Already in 2015, the notion of “smart energy” within the NATO structure included an international collaboration of 14 private companies and two government agencies to contribute over 50 different pieces of equipment to provide “Smart Energy Production” during the Capable Logistician Exercise. The “smart energy” during the exercise included production in the form of photovoltaic panels or wind generators, smart energy storage in the form of rechargeable batteries, energy management systems equipped with sensors and controlled by intelligent software. Hence, the adjective “smart” stands for efficient use of energy as a limited resource, applying energy-saving technologies. The wind and solar panel generator are supposed to provide approx. 5 kWp each, connected to a battery storage equal to 60 kWh. As for the industry, it offered various solutions, starting from energy-efficient lighting systems to entire smart energy camps [7].

One of the thriving technologies studied for storing electrical energy are lithium ion batteries. The main advantages of this technology are high energy efficiency, relatively high energy density and long lifecycle [8]. Lithium ion batteries are present in many applications such as mobile devices (i.e., smart watches, smartphones), drones, electric vehicles, satellites, medical devices and many more [9]. Despite its wide applicability, it cannot be used for long-term storage of energy mainly due to its degradation. The degradation can be caused by unsuitable charging-discharging parameters which resulted in the need for a protection circuit ensuring its safe operation. Each cell needs to contain the protection circuit resulting in reduction of the peak voltage value during charge and disconnects the cell when the voltage drops too low on discharge. Maheshwari in its work discussed the importance of degradation process in lithium ion batteries and presents a study based on non-linear degradation model which allows predicting a certain scale of degradation in two steps reducing the degradation of approx. 82%. The study case tried to demonstrate the possible financial outcome in terms of reduction of losses by almost 20% in the case of small portable devices [10]. Another approach aiming in prolongation of lithium ion batteries life span in the case of battery packs focuses on the splice Kalman filtering algorithm. This algorithm uses the open circuit voltage characteristic in functions of different charged state levels to estimate the charged state value. Combined with equivalent circuit model gave a 1.38% of an error of predicted battery charged state. A strategy in predicting the behavior of batteries in the pack can be useful as a tool to monitor and verify the performance of energy storage based on lithium ion technology [11].

Even now, with the ongoing development of different battery technologies [12,13], it is recognized that for military use, the most robust, low-cost devices (USD 150–500/kWh), the efficiency of which ranges from 65 to 80%, are lead-acid batteries [14,15].

Extensive research has been done to study the possibility of using lead-acid batteries as elements of energy storage systems.

Lead-acid batteries are a relatively simple type of battery which have been widely used, mainly in the automotive sector. The theoretical model, including decrease of the level of energy storage with the high rate of charge-discharge, temperature and capacity recovery, allows, together with information provided by the manufacturer, for highly reliable (ca. 98% certainty) predictions to be made on the behavior of energy storage systems containing these type of batteries [16].

Based on the case study described in their work, Lujano-Rojas and others describe an energy-generating system based in Zarragoza, Spain. The authors used a typical generic algorithm (GA) method to optimize the operation of the system. It was noticed that the lead-acid based energy storage system will have to be replaced every 4.2 years, due to operation on a medium to high state of charge (SOC) most likely. The authors also stated that more research is required to improve the hybrid energy-generating system and to optimize its components [17].

In another paper, a solar battery system operating at 24 V and 55 Ah using maximum power point tracking and three-stage-charging-cycle was studied. The component crucial for the energy storage system was the three-stage-charging-cycle charge controller, which regulated adaptation of charging speed. The technology applied resulted in maintaining the health of lead-acid batteries on a stable level of 95%, extending their performance, as well as safety longevity. It was also proved that, for off-grid PV systems, the lead-acid batteries are the favored energy storage solutions [18].

Other researchers have studied the aging process in lead-acid batteries. It was highlighted that prior to the construction of a real hybrid energy-generating system that it is crucial to perform a simulation studies based on the Rain Flow method, in which counting cycles at consistent depth of discharge (DOD) for energy storage elements combined with average temperature conditions will be taken into account. The proposed methodology allows prediction of a lifetime of lead-acid batteries and its extension, when an important factor, such as reasonable balance between DOD and the number of cycles, tubular structure of the battery and oversized housing is considered [19].

In this work, a model of “smart camp” was devised, assuming the implementation of a renewable energy installation based on photovoltaic (PV) modules and wind turbine (WT) infrastructure [5]. Renewable energy systems will generate direct current, which must be converted to the mains voltage of 230 V single-phase alternating current. For this purpose, a hybrid inverter with a charge regulator function will be connected to the system containing PV and WT cells. The main focus of this article will be on tests of acid batteries commonly used in military equipment as the main energy storage systems in a model camp. In this work, the individual cell modules will be electrically tested. The tests will begin with measurements of a representative group of cells for which the following parameters will be plotted: dependence of electric capacity on discharge current, instantaneous peak currents, short-circuit current, internal resistance, effects of overcharging/over-discharge and cyclically applied resistance.

2. Materials and Methods

The individual cell module for the assumed military variant includes 12 V 100 Ah lead-acid batteries representing several types: an Absorbent Glass Mat (AGM)—the electrolyte soaks glass mats in the battery; a DEEP CYCLE—it is an AGM battery utilizing enhanced lead electrodes with greater surface; a valve regulated lead-acid (VRL) type—where precipitation of the formed gases is allowed and which, in principle, do not require that the electrolyte level is maintained and lastly, a wet-cell battery that contains liquid electrolyte. The above is dictated by both the specific military technology requirements (resistance to bullet penetration and possible explosion) and the fact that in the armed forces, lead-acid and alkaline batteries are the most common. The system can use different energy-generating systems. Taking into account the previously mentioned conditions, polycrystalline photovoltaic modules with a power of 270 W and an inverter-generating set with a rated power of 1 kW and a voltage of 230 V AC were used (Figure 1).



Figure 1. A set of photovoltaic modules.

The energy conversion block includes a charge controller and a hybrid inverter with a power of 5 kW, adapted to work autonomously (off-grid) and in prosumer mode (on-grid). In the tested military version, the system operates in the autonomous version only.

The commutation and control block consists of sets of connectors and connecting cables enabling communication between all other blocks of the system. The communication and control block consisted of a central control panel, displaying the most critical parameters of the entire system. The setup was also designed in a way that allowed the signal to be transmitted over a distance of 10 km, that is, between the experimental plant and a main building of the institution facility. Depending on the range, data transfer is based on a number of data transmission channels: LAN (Ethernet) network—local wireless on the test stand; WiFi network—remote control and monitoring; GSM network—remote backup control and monitoring; WiMAX network—basic remote communication network for military applications. The WiMAX network safeguards not only the security of the data being transmitted, but also makes it independent of the Internet providers' infrastructure.

In the laboratory tests, the Climatest ARS-1100 climatic chamber was used to simulate the working environmental conditions. Three different temperatures, $-20\text{ }^{\circ}\text{C}$, $25\text{ }^{\circ}\text{C}$ and $50\text{ }^{\circ}\text{C}$, were selected.

In accordance with the EN standard, the health state test of studied batteries was carried out in voltage range: 9–30 V (DC) with the use of the BT 750 Battery Analyzer (portable version).

The real condition electrical tests were carried out over a period of 12 months. The batteries operated in a quasi-buffer mode, i.e., the discharge cycles were very “shallow” at the level of 20% or of 50% in the low sunlight period. The system (consisting of power generation block, communication and control block, energy storage block and energy conversion block) used for real condition testing, was connected to the power grid system (AC current 230 V and 50 Hz) present at the field site to supply energy for low power-consuming domestic devices. In the case of reaching the above mentioned discharge level, the system was switched off at the moment the photovoltaic system was generating current to charge the power storage module. Such protocol implied single charging-discharging cycle approx. every 24 h.

Apart from the previously mentioned elements of the entire system, the measurement set to control the behavior of a single battery to identify damaged ones included the following components:

- charge regulator (home-made setup, Figure 2);
- DC/AC converter with accessories allowing connection of a load;
- the power generator block consisting of photovoltaic modules (3 kW, 120 V DC);
- load on the “AC side”—load switched on periodically.

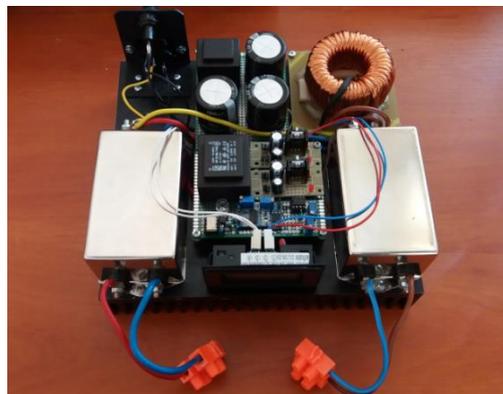


Figure 2. Charge regulator—home-made.

3. Results and Discussion

A prototype hybrid power supply system was devised in order to prepare a military-like installation, where the energy storage block was based on lead-acid batteries. The entire system was divided into individual functional blocks as presented in Figure 3:

1. Power generation block (BWE);
2. Energy storage block (BME);
3. Communication and control block (BK);
4. Energy conversion block (BPE);
5. Data transmission block (BTD).



Figure 3. The concept of a hybrid power system: general arrangement drawing and real image.

The working principle behind the system relies on photovoltaic modules and wind turbines (BWE) that generate direct current, which is converted to the mains voltage of 230 V AC, single-phase. For this purpose, a hybrid inverter with a charge regulator function, adapted to work with photovoltaic and wind turbine systems, was included in the hybrid power system. The designed system can operate in two modes: the prosumer (on-grid) one and the autonomous (off-grid) one. The purpose of block/modular construction was made bearing in mind the philosophy of the LEGO blocks, allowing a tailor-made system in two variants: the civil variant and one for the special (military) use. In this particular iteration, each energy storage block can accumulate 5 kWh and the inverter in the energy conversion block can operate with identical inverters (blocks) in parallel or three-phase modes.

Based on the procedures and standards used in the Polish Army Forces, methodologies were used to study lead-acid batteries as the basic energy storage element. Laboratory tests and long-term testing in real conditions were performed and during the laboratory tests, the following were performed:

- determination of the mass;
- visual inspection;
- measurement of the energy stored in various ambient temperatures;
- assessment of the starting current.

The long-term studies included system operation in the hybrid mode for a period of 12 months.

3.1. Laboratory Testing of the Batteries

In the first step, all tested batteries were sequentially placed on the balance and the measurement results were read out. The average weight of the tested batteries was the following:

- DEEP CYCLE battery—25.7 kg;
- AGM battery—21.92 kg;
- WET cell battery—23.39 kg;

- VRLA battery—29.30 kg.

VRLA battery was characterized by higher mass due to material used to seal the entire whole battery. The second heaviest battery, the DEEP CYCLE one, had a larger amount of lead use to construct it. This kind of battery is supposed to have the largest electrode surface. The WET cell battery mass could be explained by the use of liquid electrolyte with the AGM type being lightest, most likely due to the use of glass fiber soaked with electrolyte in its construction which would result in the volume and the amount of electrolyte being reduced relative to the electrodes.

The visual inspection revealed that all the batteries were manufactured with great care; the housings were solid with handles for carrying the battery and the filler plugs equipped with seals protecting against electrolyte leakage in the case of the WET, the DEEP CYCLE and the AGM batteries. The VRLA battery was airtight, allowing it to work in any given position.

Next, all the batteries were discharged with using a 10 A current for ten hours, for a 100 Ah battery. The discharge process was carried out for three temperatures ($-20\text{ }^{\circ}\text{C}$, $25\text{ }^{\circ}\text{C}$ and $50\text{ }^{\circ}\text{C}$) until the limit voltage set at 10.6 V was obtained. Taking into account the environmental requirements, the batteries were tested in an environmental chamber in the original housing (Figure 4), without any additional protective measures. In this work, the temperatures were selected based on those used during the testing of military equipment. These conditions are supposed to simulate harsh field conditions. The batteries were connected to the energy conversion block—the connector between photovoltaic system and energy storage. This module communicates with the power grid and the power generation block, ensuring proper charging and discharging of batteries. During the first step of the charging and discharging cycle, in the case of the VRLA battery type, some models were damaged and replaced with new ones, however, no statistical trends were observed in this matter. In all cases, the damaged batteries suffered from poor workmanship.



Figure 4. Stand for testing battery discharge in the climatic chamber.

A typical current-voltage characteristic of the discharge process for all the battery types had very similar tendency: after a first drop of current, the following points registered during the process showed stable decrease as illustrated in Figure 5 for a single AGM battery.

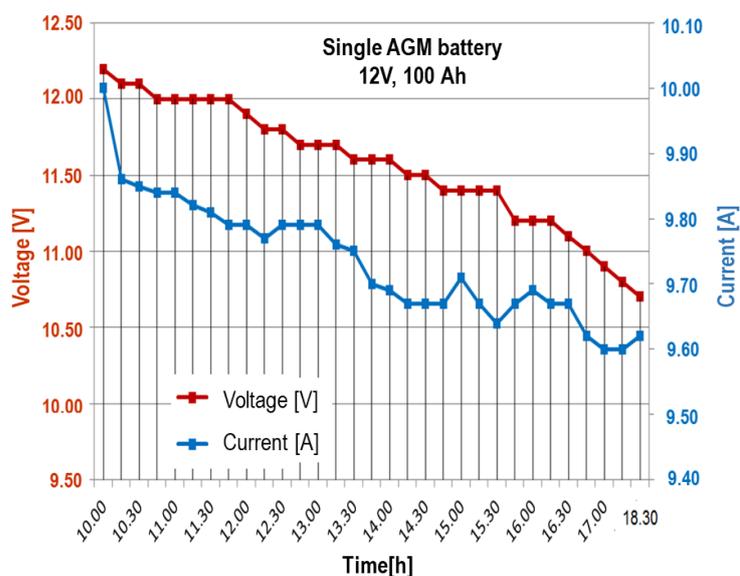


Figure 5. The characteristics of the battery voltage and discharge current as a function of time for an increased temperature T = 50 °C.

The obtained results of stored energy and cold cranking amperage are included in Table 1. The discharge process performed at −20 °C and 25 °C revealed that all the four types of batteries yielded very comparable results, which can be explained by similar behavior of the basic components of the battery, the electrodes, electrolyte and the same electrochemical processes. A difference in the maximal stored energy was observed at 50 °C. It may stem from the difference in the cell construction and distortion of evaporation processes; the lowest energy was registered for battery based on liquid electrolyte (WET) only. The second lowest value was observed for DEEP CYCLE, where the lead electrodes have the largest surface area among all the tested types. Since lead is a good heat conductor, extended electrode surface promotes increased evaporation. Slightly better results were noted for the VRLA type most likely due to the valve regulation system that allows retention of gaseous products, affecting formation of an equilibrium state quicker than in the aforementioned cases. The best results were observed for the AGM battery type. For this case, the use of glass mat soaked in electrolyte works as an insulator, reducing diffusion of heat across the battery interior. Regarding the application of these batteries, the highest obtained values of cold cranking amperage (CCA) suggests use of AGM and WET batteries in vehicles as a starter battery since it is possible to draw higher currents.

Table 1. Data obtained from electrical testing of batteries.

Battery Type	Stored Energy [kWh]			Cold Cranking Amperage [A]
	−20 °C	25 °C	50 °C	25 °C
AGM	0.64	1.26	0.97	1205
DEEP CYCLE	0.65	1.28	0.85	957
VRLA	0.7	1.29	0.88	704
WET	0.66	1.28	0.84	1135

After the environmental testing, all the samples were tested for cold cranking amperage to reveal and select which of the battery types could withstand fast discharge. The best results were observed for a pair of batteries: the AGM one and the WET one. In all probability, it was linked to the highest mobility of the electrolyte between electrodes. In the case of WET battery type, we deal with pure liquid electrolyte that possess the highest mobility compared to the other types, whereas the AGM has been constructed in a more compact way, so the distance between the electrodes is smaller due to porous structure of

glass mat which performs the role of an electric insulator. However, due to the presence of electrolyte in the pores, it can conduct ions. For the DEEP CYCLE, even though this type has similar construction to the AGM, the extended lead electrode surface precluded a tight construction, resulting in more significant distances, hence mobility reduction. Considering the construction factor for future applications, VRLA, AGM and DEEP CYCLE batteries should be suitable candidates for applications where low maintenance is more important for the user despite CCA values.

3.2. Battery Tests in Real Conditions

Taking into account the findings from laboratory testing, two types of batteries, the AGM and the WET, were selected for the long-term testing.

The mass study after the 12 months of exploitation revealed that only in the case of the AGM type was a reduction in approximately 15% of mass observed, when compared to the starting values. This indicated some serious deterioration of the batteries used.

External inspection after the durability testing revealed that WET battery resembles very careful workmanship of the housing and filler plugs with gaskets protecting against electrolyte leakage. The external appearance was almost the same as the new battery even under the manufacturer's label. In the case of the AGM battery, there were signs of low-quality construction of the housing and inlet plugs, with visible electrolyte leaks (see Figure 6). A large number of labels were used to hide questionable and weaknesses of housing.



Figure 6. View of the filler plug and the charge level indicator: undamaged and damaged, respectively.

Technical condition examination results registered after 12 months of constant use revealed in the case of WET battery, where a drop of the level of stored energy was reduced by about 20% from 1135 kWh to 917 kWh. Additionally, an increase of internal resistance by 20% was registered. The charging-recharging testing proved that the health state was maintained unchanged.

The tests performed on AGM batteries revealed a drastic drop in the stored energy by 86% and almost 10 times greater internal resistance for 1/3 of tested batteries. The other remaining samples showed similar to the above mentioned 20% of loss in initial parameters. The damaged battery was totally discharged and the received values showed only residual value of stored energy. The damaged battery showed signals of leakage and correct charging-discharging process was not possible due to temporal voltage increases followed by sudden drop.

4. Conclusions

This article presents a technical approach in testing lead-acid batteries as a main element of energy storage system in a model of “smart camp” that uses renewable energy installation as the energy source. Four types are available in the market lead-acid batteries: DEEP Cycle battery, AGM battery, WET battery and VRLA battery were tested to find a relationship between manufacturing technology and the performance of the battery. The obtained measurement revealed that all lead-acid battery types presented quite similar behavior given by the same electrochemical principle common for all of them. However, in some cases, the construction of the battery regarding the type of packing of electrodes,

the use of pure liquid electrolyte or soaked mats influenced, sometimes significantly, the battery performance.

Based on the obtained results, the following observation were drawn:

- as a starter battery: AGM and WET battery can be used due to the highest obtained values of cold cranking amperage above 1100 kWh;
- as an energy storage battery, the most suitable ones are VRLA, AGM and DEEP CYCLE type, mainly due to their low maintenance options—differently from WET, they do not require refilling with distilled water to maintain the electrolyte level.

Therefore, AGM or VRLA batteries can be used for on-board networks (24 V) and energy storage (24 V, 48 V or 96 V). Such batteries will be used to design an energy storage in the “acid” technique for the needs of the armed forces due to high CCA value for AGM or low influence of the temperature on the stored energy value. The compact construction of AGM battery makes it the most universal, thanks to the low weight.

Comparing the technical parameters of all the studied types in function of time, it can be concluded that all batteries do not maintain their initial capacity (comparison of currents) and after 12 months of exploitation, showed levels around 80% of the initial value.

This article also presents an insight into crucial factors, such as construction technology, basic physical parameters such as weight and weak point of some types of acid-lead batteries. These can be indicating factors enabling the construction of a tailored hybrid energy generator and storage system depending on the current needs of the customer, with the possibility of expansion without the need to replace the existing equipment (the Lego blocks strategy).

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