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Industrial batteries in the electric power system of 'Electricité de France'

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Abstract

More than 5000 industrial batteries are operating in the different power plants, substations and distribution centres of 'Electricité de France' (EDF). 2 V lead/acid and 1.2 V alkaline systems are used for different stationary stand-by applications: power station control, communication, etc. In nuclear plants, these batteries are part of the ultimate safety system ensuring the safe control of the reactor. The operating conditions of the industrial batteries at EDF, the different related battery technologies and the testing methods used to assess their operating ability are described. For selection, batteries undergo electric, seismic and ageing tests. Ageing sequences involve successive floating phases at a high temperature. Results on absorptive glass mat valve-regulated lead/acid battery testing are given. On-line monitoring methods are studied in order to evaluate the remaining available autonomy of the battery according to its state of ageing. In addition to these stand-by applications, EDF is also investigating the potential of future energy and quality applications of stationary batteries such as load levelling or storage of energy produced from renewable sources.

Keywords: Power systems; Lead/acid batteries; Hydrogen evolution; Sizing; Industrial batteries

1. Introduction

Roughly 5000 batteries are operating in the different power plants, transmission and distribution centres of 'Electricité de France' (EDF). Industrial batteries are mainly used to supply emergency d.c. power (or a.c. power through inverters) in case of mains or power generation failures. They are an essential component of the safety and reliability system of nuclear plants. In case of charger or grid failures, energy back-up provided by batteries allows procedures for shutting down the reactor to be carried out. Batteries are designed to undergo earthquakes without being affected on duty.

In power plants, power supplies are generally composed of a charger (a.c./d.c. rectifier) supplying d.c. power in parallel to a battery and to d.c. 'users' or a.c. 'users' through an inverter (Fig. 1) [1]. In case of emergency, d.c. power is automatically supplied by batteries to the main 'user' devices (computers, control and instrumentation systems, emergency diesel generator start, etc.). Due to the parallel on-line connection of the stand-by battery to 'users', no power interruption is encountered.

One of the basic principles of nuclear safety is redundancy. Two independent circuits, called A and B divisions, must always be available and ready for operation. In EDF's plants, A and B divisions are equipped with lead/acid and Ni–Cd batteries, respectively.

2. Industrial batteries in EDF's power plants

More than 1700 industrial stand-by batteries are used in EDF's power plants as emergency power supplies. About 12 lead/acid and 5 to 6 Ni–Cd batteries are installed per nuclear plant unit. Nominal voltages range from 24 to 230 V, nominal capacity from 40 to 2000 Ah. In thermal and nuclear power stations, roughly 800 tubular lead/acid batteries (≈40 000 2 V cells) and 260 Ni–Cd ones (≈18 000 1.2 V cells) are in operation. In hydroelectric plants, 300 lead/acid and 300 Ni–Cd batteries are used. Table 1 depicts an example of a battery installation in a 1400 MW nuclear plant.

Due to service and reliability constraints, the mean time before replacement, today, is 8 to 10 years for lead/acid batteries and 13 to 15 years for Ni–Cd ones. From the beginning of nuclear production in France in 1997, 25% of Ni–Cd batteries have been replaced. In 1994, 69 lead/acid batteries (4280 cells) and 18 Ni–Cd ones (1174 cells) were replaced, which means a replacement cost, respectively, of 4.5 millions FF and 1.6 millions FF. In 1993, 49 lead/acid batteries (3288 cells) and 12 Ni–Cd ones (1174 cells) were changed, for a replacement cost of 4.5 millions FF and 1 millions FF, respectively.

Few data are available on battery back-up for computer protection in EDF's power system. However, a statistical feedback study, carried out on about 120 UPSs

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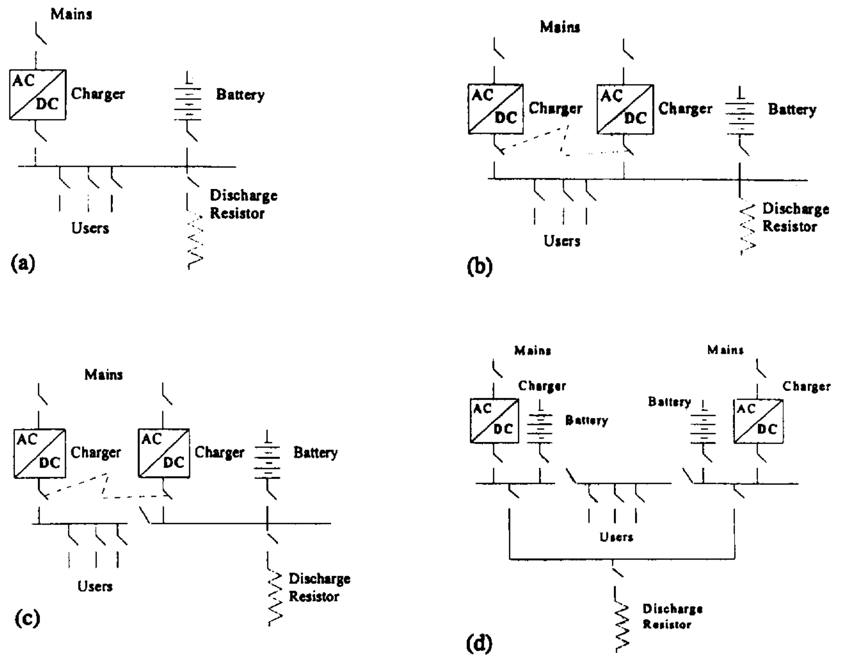

Fig. 1. Configuration of a d.c power supply in power plants: (a) one charger/one battery/one bus bar; (b) two chargers/one battery/one bus bar; (c) two chargers/one battery/two half bus bars, and (d) two chargers/two batteries/one bus bar.

Table 1
Data of d.c. UPSs in a 1400 MW nuclear plant

Supplied d.c. voltage (V)	A division battery Pb-Ca		B division battery Ni-Cd		Powered 'user'
	$I_{\text{discharge}}$ (A)	I_{capacity} (Ah)	$I_{\text{discharge}}$ (A)	I_{capacity} (Ah)	
230	390	1500	150	380	220 V a.c. (inverter): control and instrumentation protection, computers, telecommunication, television, etc.
125	290	1000	75	250	Equipment (circuit breakers, contactors, etc.), actuators (valves, etc.)
48	200	660	150	380	Reactor protection
48	320	2000	300	760	Mutiplexers, relaying circuitry, etc.
	260	880			
30	520	2000	300	760	Automated control devices, switching devices

(charger + battery + rectifier) used in EDF's distribution centres, shows that 25% of UPS failures are related to batteries [2]. The mean time between failure appears to be 7.5 years. Installed UPSs range from 2 to 200 kVA. 30% of them supply more than 80 kVA, 40% of them less than 10 kVA.

3. Sizing parameters

Except in case of emergency or maintenance, stand-by batteries are not discharged. They are always connected to the charger in floating conditions. Their stand-by voltage is then maintained high enough to compensate self-discharge in order to keep cells fully charged.

Four main parameters are used to design and select batteries for stationary applications. Selecting criteria match actual operational constraints and service:

(i) *Minimum requested autonomy under constant current discharge* (*Am*). This parameter refers to the minimum requested operating duration of the emergency power supply in case of a.c. power loss. It must last at least for 60 min in thermal and nuclear power plants, from 4 to 8 h in hydroelectric production centres, transmission and telecommunication facilities.

(ii) *Maximum requested discharge current* (*Id*). This is related to the maximum current likely to be drawn from the battery by all the 'users', working together in the same time, in proper operating conditions.

(iii) *End-of-discharge voltage* (*Ueod*). This value corresponds to the lowest authorized operating voltage bearable by 'users' before any damage or operating inability. Transmission losses are taken into account.

(iv) *Maximum charging voltage* (*Um*). This value is linked to the maximum normal operating voltage bearable by 'users' before any damage or operating inability. Exceptionally, higher special voltage (*Ue*) can be applied for a short period of time in case of special charging.

Table 2
Recommended threshold values in power plants

Nominal voltage (V)	Number of cells Lead/acid	Ni–Cd	End-of-discharge voltage *Ueod* (V)	Maximum normal voltage *Um* (V)	Maximum special voltage *Ue* (V)
24			20.5	26.5	27
28	14	20–22	23	31	32
30			25.5	33	34
48	23	36–38	41	52.5	55
125	59	93–96	105	134	138
230	108	172–179	194	247.5	255

Two charging methods can be used for stationary batteries:

(i) *Single level float charging*. Batteries are charged under a given voltage, e.g. *Um*, during 24 h with current limitation, then automatically placed in floating at the same voltage, e.g. *Um*.

(ii) *Two level float charging*. Batteries are charged under high voltage, e.g. special voltage *Ue*, during 24 h with current limitation, then automatically placed in floating at a lower voltage, e.g. *Um*.

The battery makers should take into account this specification for designing and sizing the proposed batteries.

Table 2 indicates examples of recommended threshold values in power plants and the proposed number of cells for lead/acid and Ni–Cd batteries.

4. Stationary battery technologies used in EDF's power system

Up to now all cells are flooded ones. Watering and maintenance are required at regular intervals.

4.1. Lead/acid batteries

(i) *Planté-type cells*. Only a small number of cells of this type is still in use. They were formaly installed in hydroelectric production sites (40 batteries with an average capacity of 100-200 Ah, ≈ 10% of the present total amount).

(ii) *Pasted alloy plate cells* (*Fauré-type batteries*). This type of battery is used in hydroelectric production (≈ 50% of the installed battery packs).

(iii) *Positive tubular plate cells*. Nowadays, this technology is preferentially selected for replacement and new equipment. Tubular lead/acid batteries represent 33% of the operating batteries in thermal and hydroelectric power plants and 66% in nuclear ones. Low antimony ($Sb < 3\%$) or antimony-free Pb-Ca batteries are used.

4.2. Ni–Cd batteries

Pocket plate Ni–Cd cells represent 33% of the total amount of the batteries in EDF's power plants. A large number of small capacity sealed sintered plate cells are also used for emergency lighting or in electrical equipment cabinets.

5. Assessing and selecting battery technologies

Rules have been edited for assessing, selecting and controlling batteries. For nuclear plant equipment, 'Quality Assurance' procedures cover each essential step in the decision-making process.

5.1. Battery selection

Selection relies on battery testing according to EDF's standards. Testing procedures tend to include international standards, in addition to EDF's particular requests. The R&D division of EDF has set up testing procedures for lead/acid and Ni–Cd stationary batteries. They involve ageing sequences at a higher temperature than the actual operating one. For nuclear uses, the continuous operation of the batteries under and after seismic conditions is checked. Ageing was previously carried out by applying overcharge cycles at 25 °C. Present evaluation procedures are based on several successive floating periods at 45 °C for lead/acid batteries and at 55 °C for Ni–Cd batteries. Sequences of performance measurements at various discharge rates are intercalated. According to previous investigations at 55 °C, the testing temperature for lead/acid batteries was set at 45 °C to prevent non representative ageing of the active mass. At 55 °C, a rapid ageing of the negative plate was observed (expander degradation) in contrast to the positive plate ageing noticed on field. Internal resistance, initial performances, leaktightness, short-circuit current, flame arrester and plug effectiveness are among the different parameters checked.

5.2. Battery assessment

EDF's investigations on stationary batteries focus on two main topics: (i) evaluation of the ability of new battery technologies to meet operational requirements, and (ii) development of appropriate testing procedures, selection criteria and monitoring methods.

5.2.1. Valve-regulated lead/acid battery

For stationnary applications, new technologies as valve-regulated lead acid (VRLA) batteries are interesting for users because their use allows cost reduction, safety improvement or increased operational availability. VRLA batteries show generally reduced lifetime and performances in comparison with flooded cells. To counterbalance these lower performances, reduction of maintenance (no watering needed, easier handling, no electrolyte leakage, etc.) and no need for specific safety infrastructures (mechanical ventilation, hydrogen sensors, special rooms, etc.) in order to prevent hydrogen hazards are good arguments in decision making.

For assessing absorptive glass mat (AGM) VRLA battery technology, six different batteries were tested paying specific attention to recombination efficiency, gas evolution and ageing. Four successive floating periods of 40 days each, at 2.27 V/cell and 45 °C, were applied in order to accelerate the ageing. Afterwards, these batteries were floated at 2.27 V/cell and 25 °C during six months. Their autonomy (discharge duration at the 0.3*C* rate) was checked at the end of this last operation. Evolved gas volumes and gas flow levels were measured during the 25 and 45 °C floating periods.

After four floating periods at 45 °C, the recombination rates at 25 °C and 2.27 V/cell were all over 96%. Gas flow levels at 25 °C and 2.27 V/cell were measured lower than the IEC 896-2 threshold (100 cm3/(cell per day per 100 Ah), or 4.2 ml/(h per cell per 100 Ah)), as depicted in Fig. 2. The 0.3*C* discharge durations were all checked over 90 min (*Ueod*: 1.80 V/cell) except for one battery, a faulty cell, of which prevented the discharge from being completed properly.

This duration is much higher than the minimum requested autonomy (60 min in nuclear plants) at the end of life of the battery (Fig. 3). It allows to take into account a safety margin of 30 min for a decrease of the discharge duration with ageing. However, at 45 °C and 2.27 V/cell, gas flow levels as high as 20 ml/(h per cell per 100 Ah) and a decrease of the recombination efficency were previously encountered (Fig. 4).

These results underlines that not only the recombination coefficient, but also global gas evolution volumes have to be considered. The gas flow level is obviously of special interest when selecting batteries for applications in non or poorly-ventilated areas (electrical equipment cabinets, etc.). The new IEC 896-2 standard approaches more appropriate the behaviour of VRLA batteries with respect to gas evolution than previous ones.

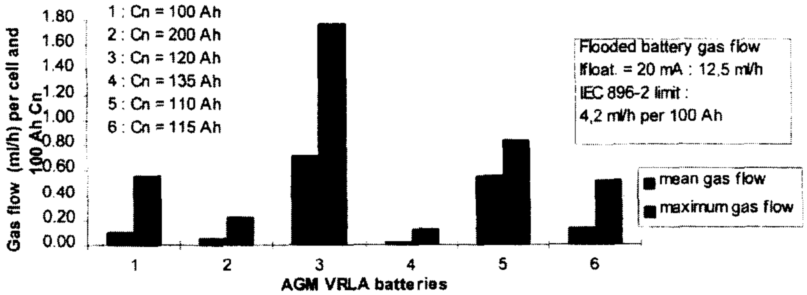

Fig. 2. Gas flow of AGM VRLA batteries in floating conditions at 2.27 V/cell and 25 °C after four ageing periods at 2.27 V/cell and 45 °C.

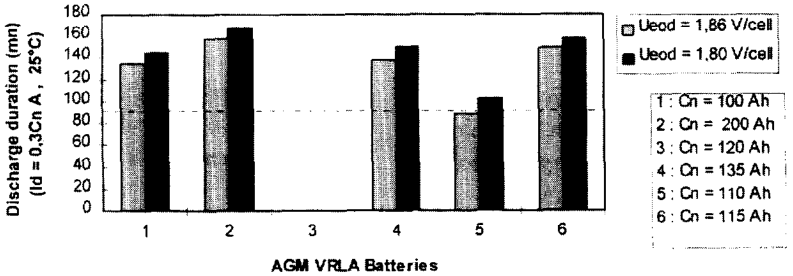

Fig. 3. Autonomy (discharge duration in min) during a 0.3Cn discharge after four ageing periods at 45 °C and 2.27 V/cell and a six-month floating at 25 °C and 2.27 V/cell.

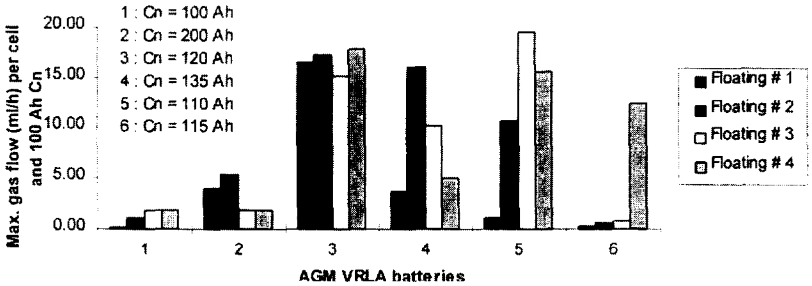

Fig. 4. Evolution of the maximum gas flow of AGM VRLA batteries through four ageing periods in floating conditions at 45 °C and 2.27 V/cell. Increase of the gas flow of the battery no. 6 is related to unintentionial flooding due to a failure in the gas measurement setting and a faulty valve (the AGM separator was partialy saturated with water which led to lower recombination rate).

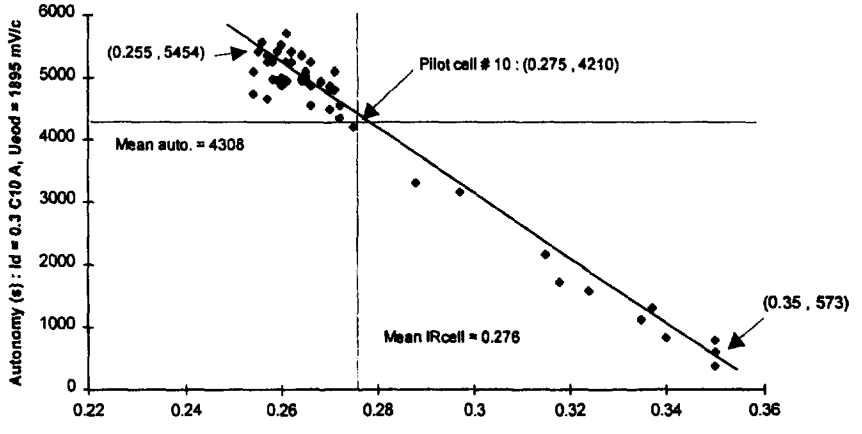

Fig. 5. Correlation between *IR*, measured before discharging, and autonomy for 1000 Ah 81-month-old lead/acid battery cells.

Safety issues for VRLA operation in power plants are essentialy related to hydrogen evolution. As observed, recombination decreases and gas flow increases with temperature if the floating voltage is not adjusted. At 45 °C, the floating voltage should be in the order of 2.20 V/cell instead of 2.27 V/cell for a proper operation. Moreover, if the applied overcharge current is of some orders of magnitude higher than a 'normal' floating current, the recombination efficiency decreases. In case of a faulty charger with its maximum rated current applied on the cells during the overcharge phase, VRLA batteries are likely to behave as flooded ones regarding gas evolution. A secured charger with temperature compensation of the floating voltage is therefore necessary.

In proper operational conditions and considering watering, AGM VRLA batteries are maintenance-free due to high oxygen recombination and low hydrogen evolution. They are likely to need no specific ventilated rooms for safety. But they must not be used in non ventilated or gastight cabinets or areas. However, failure conditions have to be kept in mind in designing new equipments. The need for cell monitoring, the influence of ageing on the hydrogen evolution or the oxygen cycle may help users to assess this new technology to meet their requirements. Operational constraints as temperature compensation, secured chargers, cell monitoring or minimum ventilation rates should be clearly introduced to users by the manufacturers. EDF is about to start investigations on gelled VRLA batteries.

5.2.2. *Battery monitoring*

Another goal is to develop on-line testing procedures avoiding disconnection of the tested battery from the supply system for safety and maintenance cost reduction reasons. Monitoring methods are necessary to check and control proper battery operation. Therefore, EDF has been investigating the correlation between internal resistance (*IR*) and the remaining available autonomy according to the state of ageing of the battery [3–5]. A prototype impedance meter has been designed to carry out field testing. Some encouraging results show a strong correlation between high *IR* values and the autonomy decrease for the flooded cells. Fig. 5 depicts such a relationship on a 1000 Ah 81-month-old stationary lead/acid battery, used in a nuclear plant. A statistical approach is however needed. An absolute conversion *IR*-autonomy should be difficult to establish. The study of the relative *IR* evolution (average, standard deviation, etc.) of the different cells of a battery appears to be a more interesting method for indentifying weak cells.

Other interesting results reveal a strong relationship between the discharged capacity of the cells, and their voltage drops after only 10 min of discharge [6]. This method is already applied on field for autonomy loss evaluation and could gradually replace or help postpone the yearly 60-min discharge. Both methods need further field investigations. However, they should help reduce the off-line time, currently caused by the control discharge during the yearly plant maintenance, or establish replacement strategies. As far as possible for new equipment and replacement, battery cells are being instrumented with measurement wires to allow individual voltage monitoring and recording.

6. Potential battery energy storage applications

6.1. *Grid back-up*

EDF's R&D department is studying some potential applications of stationnary batteries aiming at a better management of the grid and an appropriate utilization of renewable power sources.

In order to upgrade and manage the production, transmission and distribution facilities, electric utilities are facing nowadays new technical, economical and environmental issues.

Public utilities are generally concerned by increasing costs for not distributed energy, they need more accurate grid management on distribution side; they face also increasing difficulties to build new transmission lines or even reinforce existing power links. In this situation, the interest in battery energy storage applications in power systems has been revived.

Local power installations combining stationnary batteries and electronic power converters can help: (i) regulate the load for short periods with peak shaving and for longer time with load levelling, differing therefore upstream grid reinforcement or upgrading; (ii) manage local energy transmission and distribution, enabling frequency regulation, load factor correction, voltage regulation, and (iii) increase the safety and quality of delivered electricity, avoiding microcuts, voltage sags, loss of upstream supply, etc.

Such battery + converter systems need high capital investment. All added values from different associated functionalities must be taken into account. A preliminary economic approach shows is useful if a tendency to cost reduction is confirmed [7].

This seems to be the case with the large- or medium-size power electronic converters (GTOs or more recently IGBTs) for which a reduction of a factor of two within ten years can be expected. The cost of batteries have to decrease well under FF 1000/kWh. At the same time a good cycleability (1500 cycles or more) must be kept. Integration into very compact systems, and no or very little maintenance are also needed.

Present flooded lead/acid batteries give already interesting technical results which are illustrated by roughly two tenths of large scale experimental, operational, or decided installations in the world, ranging from 200 kW to 70 MW and from 200 kWh to 40 MWh (Bewag, Chino, Prepa). Maintenance-free recombination lead/acid batteries are also interesting candidates. Both technologies need performance and service life improvements. Ways to achieve this can be the reduction of the non active mass amount by scaling-up the battery monoblocs, the development of battery management systems or the use of semi-bipolar or bipolar plate design. The development of integrated modular packages, each combining a maintenance-free storage block and the associated modular electronic converter power module in order to use large series standardized production should also help decreasing the costs and allowing a progressive capacity investment according to a growing storage need.

Other systems, like the compact sodium–sulfur packages proposed by Ngk/Tepco, Japan, or by Silent Power, USA, may also be of great interest if suficient low costs can be reached.

Also some 'outsider' technologies such as zinc–bromine batteries are still developed in the USA with a low cost perspective (US $150/kW).

Theoritical studies are carried out by EDF on stationnary battery applications for grid back-up and quality management on a technico-commercial basis.

6.2. Energy storage from renewable sources

According to the battery operating modes, two fields can be considered for the energy storage from renewable sources:

(i) *Low depth of discharge applications*, e.g. the energy storage from a photovoltaic generator for power line tower signalization. In this case, batteries are oversized to avoid frequent maintenance and energy shortage. They operate at low rate of discharge. Flooded and VRLA batteries are, therefore, interesting technologies. EDF is conducting a feedback study on this application. Major problems are related to frequent maintenance, dictated by the necessary watering, and the stratification of the electrolyte due to insufficient charge coefficients. Particular work is being carried out on charging regulation processes and gas recombination, thanks to extra recombination plugs, to reduce the number of maintenance periods and to maintain performance.

(ii) *High depth of discharge applications*, e.g. the energy production for houses or building in remote areas for which good cycleability and high rate of discharge are necessary. Applications needing daily deep-cycling can be covered. The need of high performance batteries as high cycleability lithium-carbon/metal oxide batteries developed under Libes, Japan, is here stronger. However, flooded and VRLA batteries can also be interesting candidates for low-energy consuming applications. EDF is starting investigations on power generation from photovoltaic generators and wind turbines in remote areas.

7. Conclusions

Knowledge of large stationary stand-by batteries behaviour has now progressed, allowing for either good matching of their performances to specifications or better understanding of the remaining performance gaps.

New issues met by utilities may enhance the use of distributed batteries for quality, technical management and load control applications in large power grids. However, this will need technological evolutions leading to lower cost systems.

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