Storage Devices in PV System: Latest Developments, Technology and Integration Problems.

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Abstract

This paper considers some of the issues and aspects associated with the use of lead-acid batteries for energy storage in small PV systems. Battery performance depends on the PV system design and operation and the type of battery technology employed. New and emerging energy storage technologies such as the vanadium redox battery and high-speed flywheel are considered as possible alternative energy storage systems in PV applications.

1. Introduction.

PV systems are now used in a range of powering applications. These range from simple water pumping and remote gate control on farms, to highway traffic flow metering and railway control signaling, to remote-area homestead powering, to powering critical telecommunications networks, through to village lighting and power. Typically, PV systems are used in circumstances where it is not cost effective (or acceptable) to provide power through conventional ac-power reticulation systems.

Energy storage is a fundamental and critical part of any practical PV system, and involves the storage of excess PV-generated energy in a form suitable for use during periods of when the solar input is insufficient to support load demands. Traditionally, the lead-acid battery has been the technology of choice in PV-systems. This is primarily due to the comparative technical simplicity and the substantial capital cost advantage of the lead-acid battery over other possible energy storage technologies. However, the performance of the lead-acid battery compared to other components of contemporary PV-systems is varied, and on a life cycle basis, the lead-acid battery becomes a significant element of total system costs. Experience with lead-acid battery storage systems varies with battery type and type of PV application, system sizing design and control scheme.

This paper considers some of the issues associated with the use of lead-acid batteries in PV systems and describes some of the latest approaches to energy storage in Telstra's extensive solar-powered telecommunications networks. Two new and emerging energy storage technologies currently under development – the vanadium redox battery (VRB) and the high-speed flywheel – are also considered as emerging practical alternatives to the lead-acid battery in many PV applications.

2. Lead-acid batteries.

The lead-acid battery is the most widely used secondary battery and is still the technology of choice in most PV systems [1]. It involves the reversible electrochemistry between lead and lead oxide in sulphuric acid. Lead-acid battery technology is more than 100 years old, and in this context, it is "proven" technology. However, the energy storage capability of the lead-acid battery varies with battery design and use, and in all cases, the practical discharge capacity is at best only about 60%-70% of the theoretical capacity. None of the theoretical capacity is actually wasted, it is just unavailable due to a combination of polarization (voltage drop) factors which affect the degree of utilization of active material in the plates. Traditionally, lead-acid batteries are categorized as a function of application, design and performance requirements into three general areas as listed in **Table 1.**

The service-life performance of the lead-acid battery is primarily affected by the intended application. The lead acid battery suffers from a number of short-comings as an energy storage device (undergoing charge and discharge events) which originate from the basic nature of the lead-acid chemistry. In short, they are :

1. Lead naturally corrodes in sulphuric acid

All lead-acid batteries therefore have continuous and unavoidable life-reducing "wear and tear", which limits the useful service life of the battery. Many applications actually aggravate this "wear and tear", and thus reduce service life. Various alloys of lead are used to increase corrosion resistance, but all of these tend to have some consequence on some other aspect of the lead-acid chemistry

2. Overcharging

Thermodynamically, water electrolysis (gassing) is preferred to active material conversion during charge, but it is kinetically hindered to varying levels depending on the state of charge (SOC) of the battery. For a SOC less than 70-75%, there is close to 100% coulombic efficiency during charge. Above 75% SOC, a greater proportion of the charging current produces gas, and the charge efficiency rapidly decreases. A degree of overcharge is therefore necessary to fully re-charge the battery. The amount of overcharge required varies with battery technology and design. Uncontrolled, this "necessary" overcharge is destructive and will chemically corrode the positive plate, and the action of gas bubbles may dislodge active material from the plates (shedding). Both of these processes effectively removes material contributing to the cell capacity. Positive plate growth arising from corrosion is a primary failure mode of the lead-acid battery.

3. Deep discharging

Although lead is converted into lead sulphate in the normal discharge reaction, excessive discharge will result in sulphation of the negative plate, which effectively removes active material and thus again irretrievably reduces plate capacity. The active material in the plates undergoes volume changes during charge and discharge. Deep cycling imposes considerable mechanical stress on the plates and increases shedding. The physical contact between the active material and the lead grid conductors is also reduced. This increases the conduction resistance of the plate, introducing additional voltage drops across the plate (polarization) and thus effectively reduces the available cell capacity.

Table 1. Typical categorization of lead-acid battery uses

Generic category	Typical application	Typical operational characteristics
SLI	Automotive engine starting and lighting and ignition (SLI)	Frequent high current demand for short periods. Low capacity (20 hr) demand Wide operating temperature range Life measured by starting DCH cycles
Stationary	Standby power Emergency power supplies Telecommunications systems Emergency lighting UPS Computer back-up	Infrequent (unpredictable) demand Deep discharge demand. Wide reserve time range (30 min – 20 hrs) Always needs to be fully charged Long service life Years, not number of DCH cycles. Long strings of series-connected cells
Motive power	Traction Fork-lifts Golf-carts Prime moving Submarines Locomotives Electric vehicles	Peaky high power demand for relatively short periods (longer than for SLI). Continuous high power demand for extended periods (prime movers) Deep (100%) discharges Long cycle life Service life measured in number of DCH/CH cycles Fast charge capabilities

3. Lead-acid batteries in PV systems.

The lead-acid battery is a relatively simple secondary cell, and in principal, any lead-acid battery can be used in any power supply situation. In practice, of course, it becomes a matter of performance and system optimization, and issues of cost, service-life and serviceability requirements dominate appropriate “fit for purpose” considerations. Lead-acid batteries for PV systems therefore need to be a hybrid of a number of characteristics listed in Table 1 and should be matched as far as possible to the energy supply and demand profile of the application.

Historically, flooded (wet) lead-acid batteries have been used in PV systems. Service-life experience varies from 1-2 years in deep-cycling homestead RAPS environments through to 10-12 years in shallow cycling regimes powering telecommunications equipment or railway signaling systems [2]. Homestead RAPS typically exposes the battery to a wide range of capacity demands and considerable deep discharging. Service life similar to the deep cycling profiles of traction batteries is to be expected, but battery performance has been shown to vary widely and depend on battery design and construction technology [1]. On the other hand, in the shallow cycling regimes used in Telstra’s solar-powered communications network, the experience more closely resembles that achieved in traditional standby applications.

In recent years, there has been development of solar “specific” lead-acid batteries claimed to give better cycling performance in typical, variable load RAPS applications. Generally, these types of batteries are modifications of traditional traction-type cells designs, but enhanced with a lower level of antimony (1 - 3%) to retain good grid cycling behaviour, plate wrapping techniques to avoid the consequences of plate shedding, and additional electrolyte volume to reduce the frequency of water top-up. Rarely do these particular types of solar batteries achieve greater than 5-7 years life, which is an improvement for many RAPS applications, but still far short what can be achieved with other types of cells in shallow cycling regimes. The range reflects the basic limitations of the lead-acid battery and highlights the fact that to date, there is no “universal” lead-acid battery that is optimized for all PV applications.

The variation in performance also reflects the cost basis of the system and the degree to which operational effort might need to be applied to achieve a particular level of system performance. While photovoltaic array costs have steadily fallen in recent years, the cost of the storage battery, as a proportion of the total systems capital cost, has steadily increased. For example, in Telstra, which operates one of the world’s largest PV-based telecommunications networks, the lead-acid battery cost for a PV system designed for a 100W load and a 8-10 day reserve is now beginning to approach 50% of the power equipment capital costs. Unlike other energy storage systems, the lead-acid battery cost is virtually linear with system capacity, so larger systems with longer reserves are expensive. Thus, while longer battery service life can be achieved with systems designed for shallower cycling regimes (*ie* more battery), there is a cost penalty to do so. For an operator of an extensive, high reliability PV-powered network like Telstra, this cost is further aggravated by the significant maintenance overhead of water additions, SG measurements and equalization charges required with the use of flooded batteries. More recently, the hidden cost associated with the handling and containment of flooded lead-acid batteries mandated under dangerous goods legislation must also be considered.

The primary purpose of energy storage is to replace expensive energy for less expensive energy, and cost drivers have forced Telstra to consider new ways to design, deploy and-maintain their PV systems. Deregulation and competition has altered the engineering perspective for Telstra, and three generic business drivers :-

(1) system standardization (not optimization),
(2) reduction in skilled labour (specialist knowledge forfeited), and
(3) maintenance (life-cycle) schedules (risk management)

have identified the need to achieve “set-and-forget” approach for PV-systems in Telstra. “Set-and forget” involves a deliberate trade-off between optimized battery service-life and maximum system reliability with minimized on-going maintenance responsibility and programmed replacement strategies.

A “set-and-forget” regime for lead-acid batteries might be considered a tall order. The primary, and most immediate pathway, has been to consider valve-regulated lead-acid (VRLA) batteries. In recent years, Telstra showed that, contrary to conventional wisdom, a number of commercially available VRLA batteries already being used in the network in standby regimes, could be used in shallow cycling PV applications and achieve service life similar to that being achieved with the “purpose-build” solar flooded batteries [3,4]. Increasingly, VRLA battery technology is being deployed in a variety of PV applications instead of the traditional flooded cell technology. However, from a battery performance perspective, widespread use VRLA batteries in Telstra’ PV powered systems really requires attention to the existing charge regulator scheme. It is now known, for example that even longer life for VRLA batteries can be achieved by allowing open circuit periods rather than trying to “float” the batteries in a fully charged stated as has been the practice in the past with flooded batteries in the PV systems. Furthermore, reduction in maintenance effort suggested by “set-and-forget” implies the need for some improved type of local PV-system diagnostic to interface into the remotely operated network surveillance infrastructure. PV-power system monitoring schemes need to be assessed, and perhaps it is appropriate to now consider integration of control, regulation and remote monitoring functions.

The VRLA batteries currently being used by Telstra in PV applications are relatively expensive, high quality “telco” standby batteries, designed and optimized for very high reliability and long–life on standby in controlled operating environments. It is difficult to extract favourable warranty terms from manufacturers for product is used in applications outside the original design intent. Cost and warranty are important elements in the “set-and forget” approach, and there is a need to use a lower cost battery with warranty and service-life guarantees more suited to the reality facing the end-user. This is no less an issue for homestead RAPS operators.

In an attempt to address this, a few years ago Telstra provided seed funding for the local development and manufacture of a robust, lower cost, long-life VRLA battery specifically suited for Telstra’s PV applications. Ideally, such battery would naturally need to accommodate the existing PV-power system infrastructure, and also address associated work practice issues such as weight restrictions, dangerous goods handling, and low (no) maintenance requirements. However, development evolution focused on low cost, deep cycling performance rather than long life, shallow cycling regimes. To be fair, the battery is still in a manufacturing development cycle, and it is difficult to predict final performance specifications. At the moment, the battery does not appear to offer technical superiority over other VRLA batteries for use in Telstra’s solar powered network. However, it may indeed turn out to be a significant battery development for homestead RAPS applications. Meanwhile, Telstra is left to consider other means to achieve “set-and-forget” energy storage in PV systems.

4. New technology options.

Two emerging alternative storage technologies - one involving chemical energy storage, the VRB, and the other utilizing mechanical energy storage, the high speed flywheel - have now been sufficiently developed to be considered potentially more suitable than lead-acid batteries in some PV applications. A comparison of some characteristics of the lead-acid battery, the VRB and flywheel as energy storage systems is given in Table 2. Trials of these developing technologies in Telstra have been proposed and should be established sometime in the near future.

Vanadium redox battery

An interesting development in chemical storage technology for consideration in PV systems is the vanadium redox battery [5,6]. The VRB involves Vanadium (II)/III and Vanadium (IV/V) redox couples which form the positive and negative half-cells respectively. Electrical energy

Table 2. A comparison of three energy storage systems

Characteristic	Lead-acid	VRB	Flywheel
Storage type	Chemical	Chemical	Mechanical
Energy density Wh/l Wh/kg			300
Power density W/l W/kg	250		1500
Efficiency (%) Overall System	75-80	*ca* 85 *(expected)*	*ca* 95
Service life	< 8 years *(at best)*	5 - 10+ years	20+ years
Technology Maturity	Mature Incremental improvement	Developmental Prototype module stacks under trial	Immature Production units under trial
System packaging	unitary	modular	modular
Charge control	separate	integrated	integrated
Cost relativities			
Capital	1.3 *(VRLA)* 1.0 *(flooded)*	1.5 *(expected)*	3
Operational	1.0 *(VRLA)* 2.0 *(Flooded)*	0.7	0.4
User-based issues	Handling *(flooded)*	Electrolyte handling	System Containment

is supplied as a result of electron transfer between the different forms of vanadium ions across a separating membrane. The VRB is a flow battery and relies on the continuous flow of vanadium electrolytes across an assembly of current collectors (known as a stack) for sustained delivery of power. The stored energy (capacity) is in the concentration of the vanadium ions. Typically, electrolyte is supplied from separate electrolyte tanks, and the charged electrolyte becomes discharged as it passes over the current collectors. The chemistry is reversible, so the discharged electrolyte in each half-cell can be recharged electrically, as is the case with lead-acid cells. A simple representation of the VRB is shown in Figure 1.

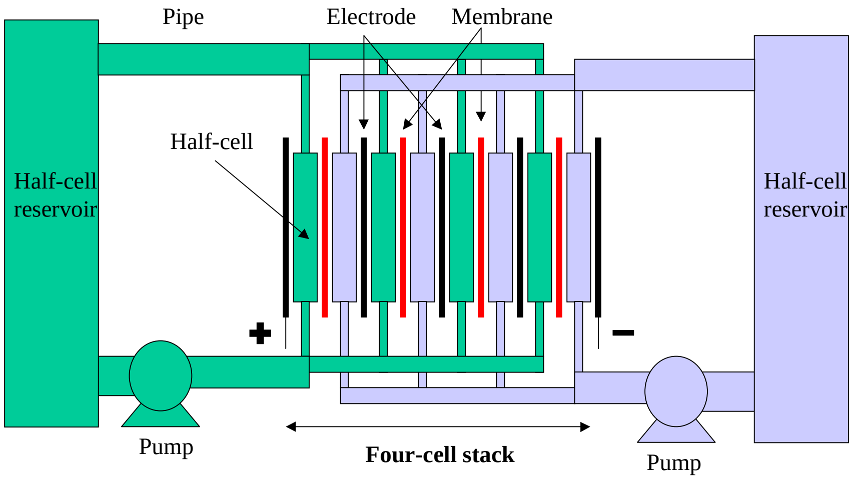

Figure 1. Simple representation of the vanadium redox battery

There are a number of advantages of the VRB compared to lead-acid battery technology for energy storage. One advantage of the VRB over traditional secondary cells is the electrochemistry does not involve a solid-liquid phase transition at the electrode interface (as is the case with lead-acid system), and the electrodes are only functional as current collectors. In principle, this means that the VRB can undergo an unlimited number of charge-recharge cycles. In practice, the cycle life behaviour will depend on the life characteristics of the membrane separating the two electrolyte solutions.

A second very important feature of the VRB is that it allows opportunity charging. This is where the capacity can be increased instantaneously by addition of more charged electrolyte. This is simply akin to refueling the fuel tank in a diesel generator. (All redox flow batteries offer this feature). This characteristic is not possible with the lead-acid battery since the chemical energy is stored in both the electrodes (battery plates) and the electrolyte, and once expended, they must undergo electrical recharge. More importantly, however, is that the bulk electrolyte need not be co-resident with the electrode stack. This means that the packaging need not be the same as with the lead-acid battery where the unit weight is dictated by the cell capacity and the requirement that the battery plates and electrolyte have to be co-housed. With the VRB, the electrolyte can be simply pumped to the stack assemblies. Thus, the capacity-dictating electrolyte volume could be housed underground, in the analogy of petroleum fuel storage. Of course, the VRB does not have anywhere the energy density of diesel fuel, but it is environmentally clean, and has considerably less mechanical complexity than diesel generators.

From a system point of view, the VRB has a number of attributes. As with lead-acid battery technology, the terminal cell voltage of the VRB depends on state of charge and the concentration of electrolyte. Nominal cell voltage for use in system dimensioning is 1.5 V. Therefore, more cells are needed for the same operating voltage than for lead-acid cells. However, the VRB systems can be recharged at a different voltage to the system discharge voltage.

The VRB is an Australian invention and has been under development at the University of New South Wales for some time [5]. More recently, the battery has been subject to commercialization efforts, and a number of field trials are currently being established. To be fair, it is important to acknowledge that the VRB is still early in the development cycle. A number of practical issues need to be progressed, not least the fact that the vanadium electrolytes are in sulphuric acid, and thus present issues similar to those which exist with the lead-acid battery. It is, of course, too early to speculate if the VRB will even be practical, let alone successful, in PV applications. However, it a relatively promising new development in the realm of energy storage in renewable systems and may provide a viable alternative to the lead-acid battery.

High speed fly-wheels

Another promising storage technology for PV systems is the high-speed flywheel [7,8,9]. Mechanical rotation is a very traditional form of energy storage and historically large flywheels have been used as stabilizing and regulation devices. Energy dissipation in catastrophic failure has always been a problem with flywheels, and advances with smaller, high speed devices is now only possible with the advent of carbon-fibre composite materials [7,8].

This new flywheel technology is a likely candidate for smaller systems [8]. Flywheel energy storage systems spinning at 30,000 rpm to store 2kWh have been announced and are under trial as emergency backup power devices in remotely located telecommunications nodes in the USA [9]. As shown in Figure 2**,** the systems under trial are housed underground as an added precaution against mechanical failure of rotating elements. A device operating at 24V and capable of 2 kWh occupies a volume of about 1.5 m^3, but a significant amount of this volume is for specific containment purposes. By comparison, the volume occupied by VRLA batteries providing similar storage can range between $0.2m^3$ to about $1.0m^3$. In many applications, particularly in telecommunications, the actual energy density is often not an important design or selection attribute. The 2 kWh device weighs a total of about 120 kg, which is considerably lighter than the weight of VRLA batteries to do the same task.

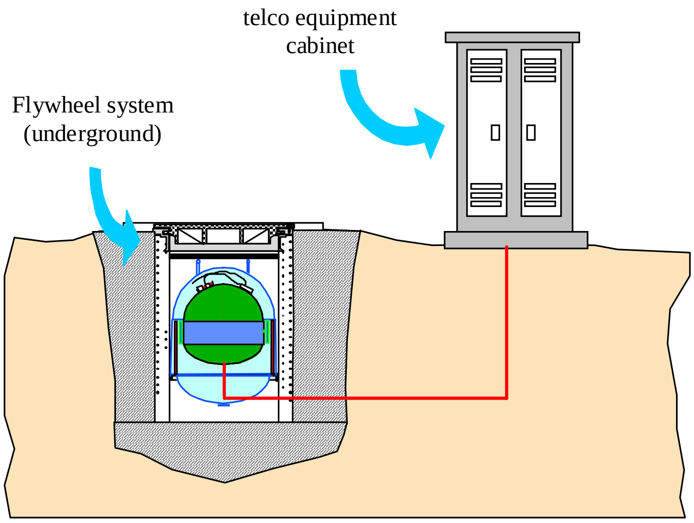

Figure 2 Arrange of flywheel energy storage in telecommunications trial *(from Ref [9])*

It has been reported that these devices have superior energy storage characteristics and are cost-competitive with the lead-acid battery in telecommunications applications [7,8]. These systems are advantageous in that they incorporated integrated conversion and control electronics, thus enabling system packaging as a direct and complete replacement of the lead-acid battery installation and the associated charging systems. A bi-directional inverter allows charging with constant current and discharging in constant voltage mode. With integrated electronics and minimum maintenance requirements, and a preference to be completely house underground, these flywheels systems do offer the potential for “set-and-forget” operation. On this basis, a trial of flywheel energy storage as direct replacement of VRLA batteries in small, 1kW - 5kW systems requiring 1-3 hour emergency backup power has been proposed in Telstra.

The flywheel technology described here has merit in the more traditional RAPS-based PV systems. The commercially available flywheel systems at present are limited in energy capacity. However, the power density and specific power density of the flywheel are significantly higher than for the lead-acid battery (and particularly so if only considering the lower cost, flooded type of lead-acid cells typically used in homestead or domestic RAPS applications.). The use of flywheel for long reserve times may not be all that advantageous, but consideration of a hybrid flywheel/lead-acid battery storage systems may be the pathway to a significant improvement in life cycle performance. A flywheel energy storage system could supply household peak loads, such as washing machines and refrigerators. More constant power demands such as lighting may be supplied by VRLA batteries sized for relatively shallow cycling. This split supply approach could also take advantage of the existing lighting and power circuits in domestic wiring. Of course, there would have to be a little more control electronics than might currently exist, but then given modern inverter and converter electronics, this should not be a particular problem.

5. Conclusions

Lead-acid battery is the technology of choice for most PV applications. However, there are performance limitations which result in excessive replacement costs, work-place OS& H issues and operational maintenance overheads for many end-users. The technical shortcoming of the lead acid battery continues to fuel research and developmental activity for comparative, low cost, alternatives. Two recent developments - the VRB and the high-speed flywheel - have progressed sufficiently to be now considered as possible alternatives to the ubiquitous lead-acid battery in many PV applications.

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