Vanadium Energy Storage System Concepts for Telecommunications Applications

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Abstract - The Vanadium Redox Battery (VRB) is a flow battery technology that has technical performance characteristics which are attractive for a number of industrial energy storage applications, including diesel-abatement concepts in Remote Area Power Supply (RAPS) applications, standby power plant, medium and large-scale grid-connected load-leveling, and distributed power conditioning. VRB technology is currently undergoing commercialization. The VRB exhibits considerable cost competitiveness against many conventional energy storage technologies, and has a number of unique design attributes well suited for applications within telecommunications powering infrastructure. This paper describes concepts to integrate the basic VRB into a new and unique energy storage technology - *the Vanadium Energy Storage System (VESS)* - for use in telecommunications powering applications.

I. Introduction

The Vanadium Redox Battery (VRB) is a relatively new flow battery technology that is currently undergoing commercialisation. The basic principles of design and operation, the electrical performance, and the product cost projections have been previously reported [1].

The VRB is a chemical energy storage technology that has a number of unique design attributes and technical performance characteristics that are attractive for a number of industrial energy storage applications. These applications include diesel-abatement and diesel-replacement opportunities in Remote Area Power Supply (RAPS) systems and standby power plant, medium and large-scale grid-connected load-leveling, and distributed power conditioning.

There are many aspects of the VRB compared with conventional chemical energy storage such as lead-acid and Nickel-Cadmium (NiCd) technologies that allow for totally new approaches in terms of energy packaging and utilisation. This utilisation is reflected in the Vanadium Energy Storage System (VESS) concept, where the design and operating characteristics of the VRB are optimized and integrated with automated intelligent control and operational management electronics.

While the VRB itself exhibits considerable cost competitiveness against many conventional secondary battery technologies, the VESS allows practical energy storage for new applications not before thought cost-effective or achievable with lead-acid technology, as well as providing beneficial replacement options for existing DC power infrastructure.

This paper considers the attributes and characteristics of the VRB as the core storage element of VESS, and describes a number of VESS concepts in various telecommunications powering applications.

II. VESS Overview

The battery

The vanadium redox battery, in simple form, converts energy stored in liquid electrolyte to electricity. This occurs as a result of an electron transfer between two different ionic forms of vanadium separated by a membrane. The electrolyte is a solution of vanadium mixed with sulphuric acid, with about the same acidity as in a conventional lead-acid battery. The electrochemical reaction is reversible, so the VRB can be charged and discharged. The concentration of each ionic form of the vanadium electrolyte changes as the battery is charged and discharged, with electrical energy being converted to chemical energy and vice-versa.

An idealised view of the VRB is shown in Figure 1. The battery is made up of two reservoirs, to house the two different electrolyte solutions, and a “stack” of cells. Each cell has two half–cells, separated by a special membrane, and two current-collecting electrodes. One of the two different ionic forms of the electrolyte is in each half-cell. A pump supplies electrolyte to each half-cell, in a closed loop with the half-cell reservoir. When charged electrolyte solution is allowed to flow through the stack, electrons can be forced to flow into an external circuit and so complete the electrochemical path for discharge. Forcing current into the stack from an external source reverses the process and recharges electrolyte in the stack, which is then pumped back into the reservoirs.

In the VRB, the electrolyte flows though the cells in a parallel fashion, and the voltage is developed across the cells in a series fashion. The nominal cell voltage is 1.2V. The current density is determined by the surface area of the current collectors within the cell, but the supply of current depends on the electrolyte flow through the cells, and not on the stack itself. One of the most significant aspects of the VRB technology is that the power (peak power) of the VRB depends on the total flow surface area of the stack, while the available stored energy depends on the volume of charged electrolyte. For conventional lead-acid or NiCd battery technology, the electrodes and electrolyte have to be co-housed, and the power and energy performance is tightly coupled to the dimensional interdependence of the plates and electrolyte volumes. This is not the case with the VRB, where the electrodes and electrolyte do not have to be co-resident. This means that ideas about energy storage need not be limited by the packaging constraints that apply with lead-acid battery technology.

Electrically, different levels of energy may be drawn from different cells or groups of cells within the stack merely by maintaining sufficient electrolyte flow into the cells demanding the higher power. The stack does not have to be charged and discharged at the same terminal voltages. For instance, the VRB may be discharging at one voltage tapped off the series stack voltage, yet be charging across another portion of stack at a different voltage.

In telecommunications applications, the lead-acid battery is typically the technology of choice for energy storage. As a battery technology, the VRB has a number of advantages over the conventional lead-acid battery technology:-

- higher cyclic energy efficiency
- no life degradation from deep discharges
- no chemical degradation due to corrosion
- indefinite life of electrolyte (no disposal issues)
- indefinite cycle-life (limited by membrane)
- energy storage is accurately measured using a direct electrical reading (*i.e.* fuel gauge)
- lower environmental impact during life cycle [2]

These characteristics provide substantial foundation for development of new energy storage system architecture for dc-power infrastructure in various tele-communications applications.

VESS concepts

The Vanadium Energy Storage System (VESS) integrates the VRB into a practical energy storage system. Expert control technology is used to automate the tasks of operational management, capacity management, routine maintenance and correction processes, system status monitoring, and external communication.

A VESS concept abandons the traditional approach to standby energy storage in terms of charge and discharge line voltages, and considers storage in terms of energy and power transfer. To do this, VESS concepts optimise the series-parallel options presented by the stack design and the opportunities presented by decoupling the electric performance of the stack and energy storage role of the electrolyte.

A primary feature of the VESS for telecommunications applications is that it allows for more advantageous utilization of the existing telecommunications powering infrastructure as well as allowing consideration of the introduction of energy storage infrastructure into new green-field applications.

A general outline of a VESS is shown in Figure 2. As shown, with a single energy storage component, VESS has the ability to provide multiple output power capabilities to service different line voltage requirements at the one installation.

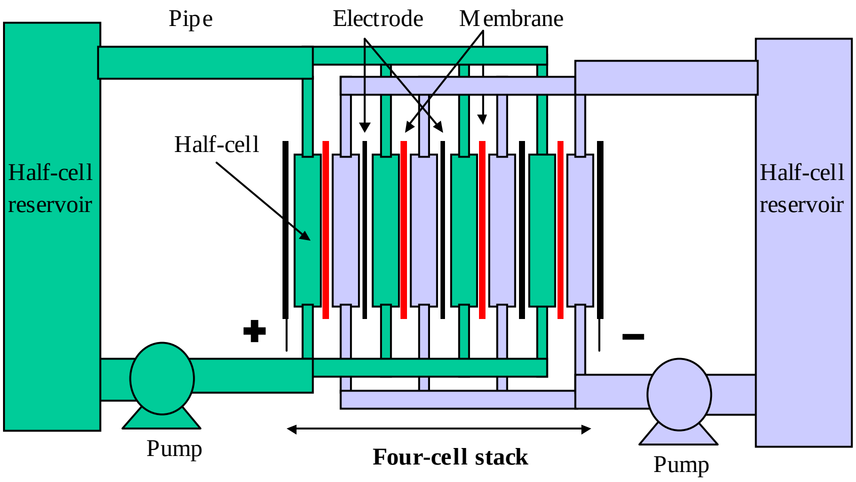

Figure 1: Schematic of the Vanadium Redox Battery (VRB)

This provides considerable advantage over traditional approaches to energy storage architecture that use series-connected strings of lead-acid or NiCd cells. From a storage perspective this is because:-

- all stored energy is in the volume of electrolyte,
- deliverable power is determined by the electrode (stack) dimensions,
- the power density of the system can be physically separated from the energy or stored capacity of the system,
- stable stored capacity.

From a system operation perspective this is because:-

- every cell is in the same state of charge,
- systems can be charged and discharged simultaneously,
- can be charged at higher rates than the lead-acid battery,
- operates with one or more electrical inputs, and outputs, at multiple voltage levels,
- ability to be self-controlled to provide automated self-regulation and self-protection,
- true set and forget operation.

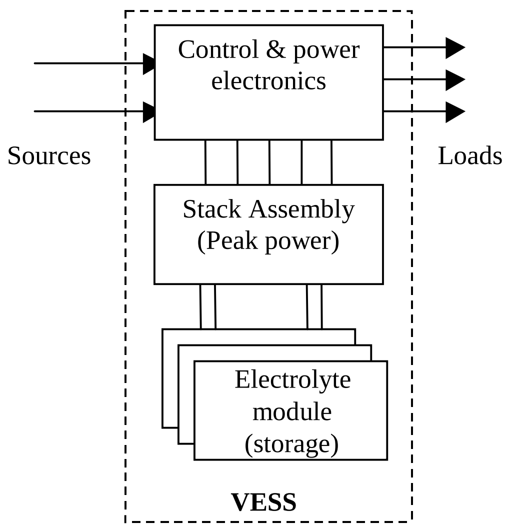

Figure 2: General VESS arrangement

From a system maintenance perspective this is because:-

- autonomy time can be instantaneously increased by the introduction of additional charged electrolyte,
- energy storage can be incrementally added at any time, with a cost of about 20% of lead acid,
- longer life, with partial replacement of some components after 5-10 years,
- extremely low level of maintenance.

III. TELECOMMUNICATIONS APPLICATIONS

VESS is generally attractive in telecommunications applications due to its state-of-charge determination (fuel gauge) and low-cost storage (resulting from increased cost effectiveness with high energy-to-power ratios, kWh/kW). VESS also introduces new concepts, using its novel attributes of energy storage portability and the independence of the energy store to the energy use (*ie.* load and operating voltage), that may be very attractive for certain telecommunications applications.

Two telecommunications applications have been identified where the advantages of VESS are worthy of further consideration. These are in:-

i. diesel replacement opportunities
ii. remote area solar power applications.

Diesel replacement opportunities

Telecommunications power systems often include diesel-engine AC generators to provide long-duration powering autonomy from the AC mains supply. For systems using a diesel, a battery is also required to provide short-duration continuity in supply while the diesel starts and warms up. A telecommunications site typically includes a UPS to supply uninterrupted AC, and an uninterrupted DC supply, both of which use a separate battery. Some small sites only include one battery to supply uninterrupted DC, with uninterrupted AC being derived through an inverter. The diesel component of the standby system represents a significant proportion of the capital cost of the power system and requires an on-going commitment to regular mechanical maintenance schedules to ensure reliability. In practice, the operational duty cycle of the standby diesel is often very small. In this context, the diesel is comparatively very expensive on the basis of cost per time unit of utilisation. New system concepts based on a VESS have the potential to replace the diesel component of a power system, as well provide a total and multi-functional energy storage solution to service existing UPS and high reliability DC supply requirements.

Remote solar applications

Some telecommunications operators maintain large and geographically diverse photo-voltaic (PV) powered networks. Remote area solar powered systems for telecommunications networks have evolved to be robust and reliable, although they are characteristically expensive on both a capital cost and a life-cycle basis. The storage element in PV systems is typically lead-acid battery technology, which demands considerable intervention maintenance and life-cycle support. However, in the current trend towards deregulation and increased competition, there is strong business emphasis on reducing maintenance activity to cut operational costs and staff resource levels. The VESS has potential to replace the lead-acid battery in PV-powered applications with a more cost-effective and maintenance productive alternative.

IV. DIESEL REPLACEMENT APPLICATIONS

Diesel-battery power systems are a very common and effective means of providing high-reliability power systems.

For some telecommunications applications, new concepts of powering based on VESS have the potential to replace the diesel component of a power system. The replacement of diesel generators is generally attractive due to a reduction in infrastructure cost, and due to the operational and maintenance impositions of diesel generator components, with their requirements to:

- meet ventilation and noise regulations (which have generally become more onerous in recent times, especially in city environs),
- operate periodically for a certain number of hours and with a certain level of load,
- have short-duration battery back-up of at least 15 minutes (although battery back-up of the order of a few hours is often implemented in order to allow time to respond to a failed start condition),
- have staff in attendance during operation.

Concept #1

Operators often utilise a diesel generator for non-critical sites where long duration AC outages are known to occur. Standard battery storage exceeding 8 hours back up can become prohibitively expensive. In this situation, the VESS offers low cost storage, where the incremental addition of hourly back up is about 20% that of standard battery costs.

For these type of sites it is also considered more cost-effective to have portable AC generating plant available at-call, and deployable within a guaranteed time, especially where the plant is not owned by the operator. Similarly, the VESS offers the opportunity to have mobile electrolyte tankers renew the energy storage within a guaranteed time, providing an extra level of availability against lengthy AC outages.

These portable energy concepts, when coupled with the VESS, are likely to provide the operator with a population of telecommunications sites having a very reliable and cost effective method of energy back-up to cope with long-duration AC outages.

Concept #2

Operators often utilise a UPS to supply uninterrupted AC, as well as using a 48V battery for uninterrupted DC supply. VESS provides the opportunity to join the two energy storage elements into one system. This energy store unification concept lends itself to diesel replacement strategies such as those outlined in *Concept #1*.

This concept is very fluid in its practical implementation (pun intended). For example, the cells that provide the DC supply could be part of a longer string of stack cells that provide uninterruptible AC, or they could be a completely separate stack of cells. Redundant parallel stacks can be implemented easily, and taking one stack off-line does *not* reduce the available capacity. A and B type power feeds can originate from different stacks, but still use the same energy store with no loss of inherent reliability.

A diagrammatic comparison of the traditional energy storage approach for high reliability with an implementation of a VESS which utilises existing infrastructure is shown below in Figure 3.

Another example is that the UPS's AC-to-DC converter could provide the energy to run both the AC and DC uninterruptible supplies, with no specific 48V rectifiers being needed. This is practical, as the battery can be discharging through a set of cells (ie. supplying the 48V DC), whilst charging though a completely separate set of cells (*ie*. the larger number of cells used by the UPS).

It does not matter that the charging current has high ripple, as the ripple does not impact on either the battery life or the quality of the 48V DC generated by a separate set of cells using the same electrolyte store.

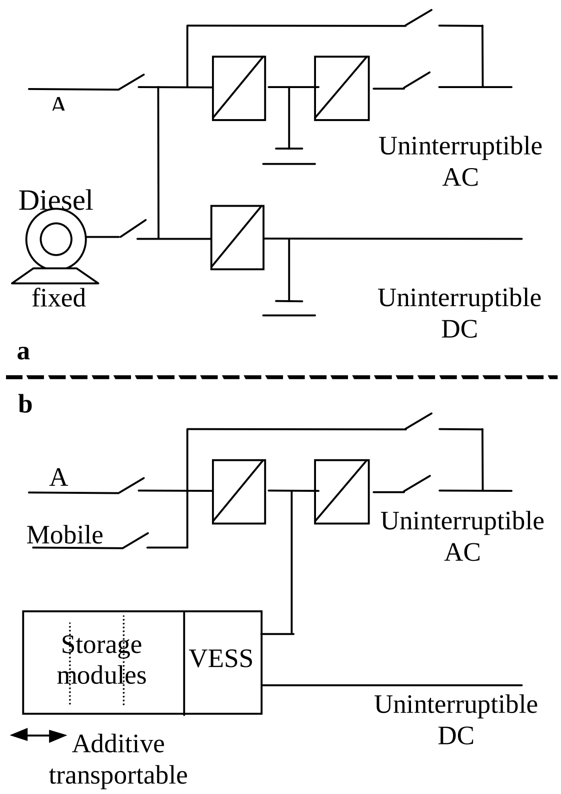

Figure 3: (a) traditional arrangement.
(b) possible usage of the VESS

V. REMOTE SOLAR (PV) APPLICATION

For a country like Australia where there are many thousands of remote PV sites, each separated by many tens of kilometers, the imposition of routine visits is significant. Of more concern is the often unproductive visits that result from attending to power system alarms, especially the "battery low volts" alarm. Indeed the number of kilometers traveled in a diesel-engine four-wheel drive to address these maintenance activities can be truly enormous (as can be the greenhouse emissions).

Typically, remote solar sites use lead-acid battery energy storage. Total power system implementation costs, which includes capital, design, installation and commissioning, are high (about AUD$50/Wp).

Operational (routine site visits and faults) costs vary depending on the site location and relative importance of the site, but life-cycle maintenance costs over the life of the site are very significant, and range from a factor of 0.5 through to 2.5 of the installed costs.

For these networks there is a special need to introduce a PV power system with energy storage that delivers a lower cost basis, improved life-cycle performance, and addresses the performance and maintenance limitations now being faced.

A VESS system can be specifically engineered to meet the operational and maintenance requirements for a remote telecommunications PV power system. The fundamental VESS characteristics provide for the implementation of :-

- maximum input power utilization,
- intelligent energy storage (capacity) management,
- greatly reduced maintenance mechanisms.

The ability of VESS to be engineered with near-zero maintenance mechanisms is one of the key attractions for remote PV systems. The *PV-VESS* implements the zero-maintenance function by automated capacity management, automated (unattended) routine performance and correction processes, and intelligent communication of the status of the system back into centralised network operations surveillance infrastructure. These automated self-maintenance mechanisms are being implemented to allow the system to operate unattended for 3-5 years.

Another key attraction of the *PV_VESS* is the implementation of additional functionality that integrates expert control technology to provide system status and history logging functions, and to assist in total power system fault diagnosis. This added functionality is targeted at the generally unproductive nature of existing alarm-based maintenance visits to remote PV power systems to attend to battery problems.

Productive maintenance effort

When maintenance staff are called to restore energy into a depleted battery at a remote PV site, the common practice is to use a portable generator to provide recharge. The amount of re-charge achieved is limited to the time the staff can remain on site. Lead-acid batteries impose a further practical constraint, as their recharge current needs to be limited during the initial stage of recharge for deeply discharged batteries.

The *PV-VESS* allows a more productive use of maintenance effort in an energy restoration situation. The first attraction is that the staff will know in advance why the battery is depleted (*eg*. poor insolation conditions). The second advantage is that recharge can occur at higher rates than for a lead-acid battery.

The third advantage is that staff can transport a portable modular electrolyte tank with them. Such a "fuel" tank can be exchanged on-site with the depleted tank in a fairly rapid manner. An extension of this practice is to recharge the depleted tank during transit to the next site. Electrolyte energy density levels of about 20kWh/ton and 30kWh/m^3, make the transport of a practical amount of energy for PV sites very realisable.

Life-time cost assessment

A simple cost assessment is used to show the significant cost advantage that is likely to be achieved for a long-life battery system in a remote solar application. The life-cycle assessment uses a common Australian site configuration, comprised of two 48V battery strings of 500Ah flooded lead-acid batteries providing a nominal 10 day reserve with a 200W constant load. The nominal energy stored in both battery strings is 48kWh. The typical installed battery cost is about $50,000 (for valve-regulated lead-acid battery technology) and the expected battery lifetime is 5 years. Yearly maintenance comprises 2 site visits, with each visit consuming one staff day at a nominal labour cost of $400. The simple Net Present Value (NPV) lifecycle cost for the sites lead-acid battery system is about $110,000 using an 8% discount rate and an analysis period of 15 years.

This application's battery requirement is for very low power coupled with very large energy storage. The PV-VESS is well suited to this application as the cost of the stored energy is relatively low. For the cost comparison, the VESS installed cost is assumed to be equal to the lead-acid battery cost. Maintenance consists of a five yearly system overhaul, with a cost estimated at 25% of capital cost (*ie*. $12,000). The *PV-VESS* is projected to have a life of 15 years, and be maintenance free between the 5-yearly overhauls. The simple NPV lifecycle cost for the VESS system is $62,000.

The benefit of a *PV-VESS* can be seen in the plot shown Figure 4.

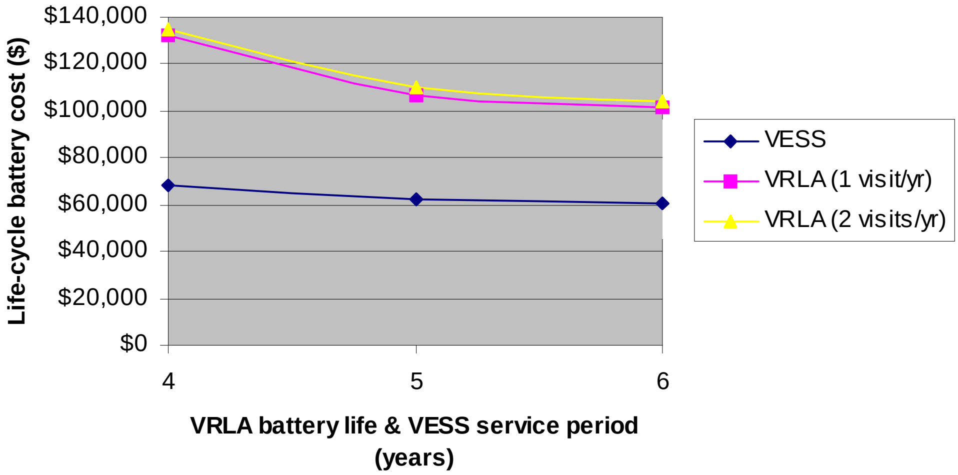

Figure 4: Comparison of life-cycle energy costs in PV applications

This cost assessment indicates that a *PV-VESS* can provide up to about 50% cost saving over 15 years operation. Additional contributors to the real life-cycle cost, such as flow-on effects of more productive maintenance effort, have not been included in this simple assessment.

VI. Conclusions

The attributes and characteristics of the Vanadium Redox Battery have been described in terms of a new integrated Vanadium Energy Storage System (VESS) for use in high reliability dc powering infrastructure. In terms of the typical approaches, the VESS technology has a number of advantages over the conventional lead-acid battery technology used for energy storage applications:-

- automated self-control provides self-protection, self-regulation, and system control interface,
- internal control unit can control other system components,
- energy storage is accurately measured using a direct electrical reading (*ie*. fuel gauge),
- longer life, with maintenance requiring only a partial replacement after ~5 years,
- energy storage can be incrementally added at any time, with a very low cost of ~$200/kWh *(ie*. about 20% of lead acid installed cost). Additional energy storage using lead-acid batteries is typically limited without housing and infrastructure changes that cost between 30%-50% of the cost of the additional battery.

Currently, two 18-months field trials are being established to showcase the technical and operational benefits of using VRB integrated into VESS technology as a cost-effective alternative to conventional energy storage approaches used in DC powering in telecommunications infrastructure. The authors look forward to reporting the results of the trial as they come to hand.

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References

[1] "The Vanadium Redox Battery for Emergency Back-up Applications", M. Skyllas-Kazacos & C. Menictas, International Telecommunications Energy Conference INTELEC'97, pp. 463-471.

[2] "Environmental assessment of Vanadium Redox and Lead-acid Batteries for Stationary Energy Storage", C.J. Rydh, 21st International Power Sources Symposium 10-12 May 1999, Brighton, UK (Pre-print information).