A field trial of a Vanadium Energy Storage System

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ABSTRACT

This Paper describes the establishment of a User-based field trial of a Vanadium Energy Storage System (VESS) incorporating a 250 kW/520 kWh Vanadium Redox Battery (VRB). The trial is significant in that the system is the first commercial-scale VRB installation outside Japan.

INTRODUCTION

The Vanadium Redox Battery (VRB) is a flow battery, which in simple terms, produces electricity electrochemically by flowing charged electrolyte through a specially designed flow frame. The electrolyte is an acidic solution of vanadium, and electron transfer is effected by the flow of two different and separated ionic forms of vanadium across a proton exchange membrane. The battery operates on the V(4+)/V(5+)//V(3+)/V(2+) redox couples and produces a nominal cell potential of approximately 1.25V, depending on the concentration of the vanadium. As with other flow batteries, useful terminal voltages are achieved by series connection of many cells into a "stack." The amount of power available is related to the stack voltage and the current density established across the membrane, while the time (or ampere-hours) available depends only on the supply of charged electrolyte to the stack. The VRB has advantages over other flow battery technologies (sometimes called regenerative fuel cells) in that the operation involves only vanadium ions in the liquid phase. The attributes and characteristics of the VRB have been previously described [1,2].

In comparison with traditional secondary batteries, flow batteries allow new modes of operation for energy storage applications. Electrically, the VRB stack does not have to be charged and discharged at the same terminal voltages, and 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.

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In terms of an energy storage system, the VRB is particularly useful in that the power function is independent from the energy function. That is, the stack, which dictates the available power, can be decoupled and physically dislocated from the electrolyte volume, which dictates the total amount of stored energy. These system-based advantages of the VRB are exploited in the Vanadium Energy Storage System (VESS) where the design and operating characteristics of the VRB are optimized and integrated with automated intelligent control and operational management electronics.

VESS allows very flexible and cost-effective adoption of the VRB for a wide range of applications, including *telco* standby and UPS. VESS concepts have been previously presented in the INTELEC forum [3].

VRB technology has been under development for some time, particularly in Japan, and the manufacture of the power stack and electrolyte is now sufficiently mature to allow commercial exploitation. As with any new technology, technical credibility and performance against existing technologies must be established. To date however, demonstration of the industrial use of the VRB has been largely limited to on-grid load-leveling and peak-shaving applications in Japan. VRB technology is currently undergoing commercialization for broader applications outside of Japan and VESS technology is being developed to introduce versatile and highly reliable energy storage capabilities for power infrastructure. As such, field trial demonstrations are currently being established to allow technical and industry scrutiny of the features and capabilities of VESS.

The VRB/VESS is now emerging as a strong energy storage candidate for distributed power architectures on the AC supply side, and it is particularly attractive as a diesel abatement option in high reliability DC back-up applications in data centers and data warehouses. This Paper describes the establishment of a User-based field trial of a VESS incorporating a 250 kW/520 kWh VRB in South Africa. The trial has been established to show the versatile configuration and operation of VESS, with the single installation demonstrating applications ranging from sub-second UPS ride-through capabilities through to power quality and emergency power back-up. It is significant in that it is the first large-scale commercial trial of User-based applications for the VRB outside Japan.

THE TRIAL

The trial is an international effort, and it is appropriate to briefly explain the participants. The trial is a tri-party initiative between Vanteck (VRB) Technology Corporation, of Canada, who have rights to the VRB technology for the continent of Africa; Highveld Vanadium and Steel Corp, who have access to significant reserves of vanadium needed for the electrolyte manufacture; and Eskom, the national electricity utility in South Africa. The venture is to create and develop a new energy storage industry based on the VRB/VESS. The drivers for the venture are obvious and timely. Low cost, large-scale energy storage is seen as a critical element in the improvement path for high reliability AC and DC supply. Eskom is the fifth largest electricity generator in the world and generates about 60% of continental Africa's entire electricity demand. Power quality and reliability are increasing strategic concerns for Eskom, and a daily practical consideration for Highveld, one of Eskom's large customers. The trial, now known as the the Stellenbosch VESS Trial, is part of an evaluation of options and solutions for power quality issues currently under consideration by Eskom [4].

SPECIFICATION & DESIGN

The Stellenbosch VESS Trial was nominated at the nominal 250 kW level for a number of reasons, *viz*:-

1. at the time, the power rating was consistent with VRB component manufacturing capabilities
2. it aligned with Eskom's own development of Power Conditioning System equipment, particularly the Shunt connected Dynamic Power Quality Compensator (DPQC-P-250), an advanced bi-directional inverter.
3. it complemented Eskom's evaluation of other energy storage options including lead-acid batteries and flywheels.

For the purposes of the trial and demonstration, the system supports a 3-phase critical load at the 380VAC level in a standard series-connected Dynamic UPS (DUPS) configuration. In the DUPS configuration, the UPS only needs to support the load to maintain quality of supply and hence has low operational losses. The bi-directional inverter is connected to the critical load downstream of a static switch (which isolates the line from the load during an outage).

Since the energy available in a VRB is directly related to the electrolyte condition, the system was specified to provide 250 kW DC power at the battery output when operating between 20%-80% SOC using 1.6M concentration vanadium electrolyte.

A VESS system comprising six, 100-cell, 42 kW VRB stacks, connected in series to provide a nominal operating voltage between 650-850VDC, operating at 400A, was chosen as the preferred design implementation to best meet the operational characteristics of the DPQC-250. The system is calculated to provide sub-second dip (or sag) ride-through, through to 2 hour emergency back-up.

The general specification for the system is summarised in Table 1, and the specific battery details are listed in Table 2.

TABLE 1 - System Specifications

Parameter	Specification
AC output line	380V 3 phase
Rated power	250kVA
Operational run-time	2 hour
DC line voltage	nominal 700V
DC voltage range	650V – 850V
Max DC current	400A

SYSTEM CONFIGURATION

The general outline of the system design is shown in Fig 1 and an illustration of the specific configuration of implementation is shown in Fig 2.

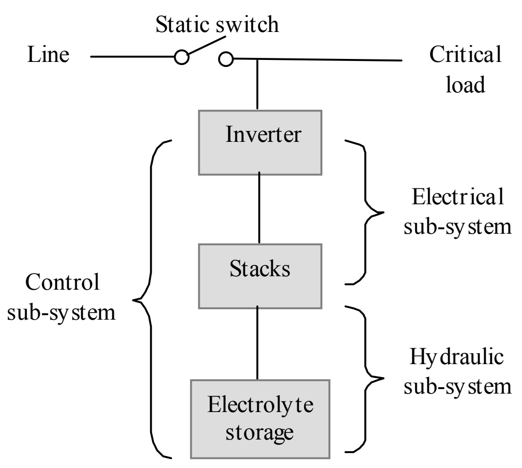

Fig 1. Generalised VESS implementation

The system is designed as an integration of three sub-systems:-

(1) the hydraulic sub-system, comprising the electrolyte storage tanks, piping, pumps, heat exchangers, and control valves, and
(2) the electrical sub-system, comprising the inter-stack connections and the power conditioning system (PCS), which includes a bi-directional inverter, and,

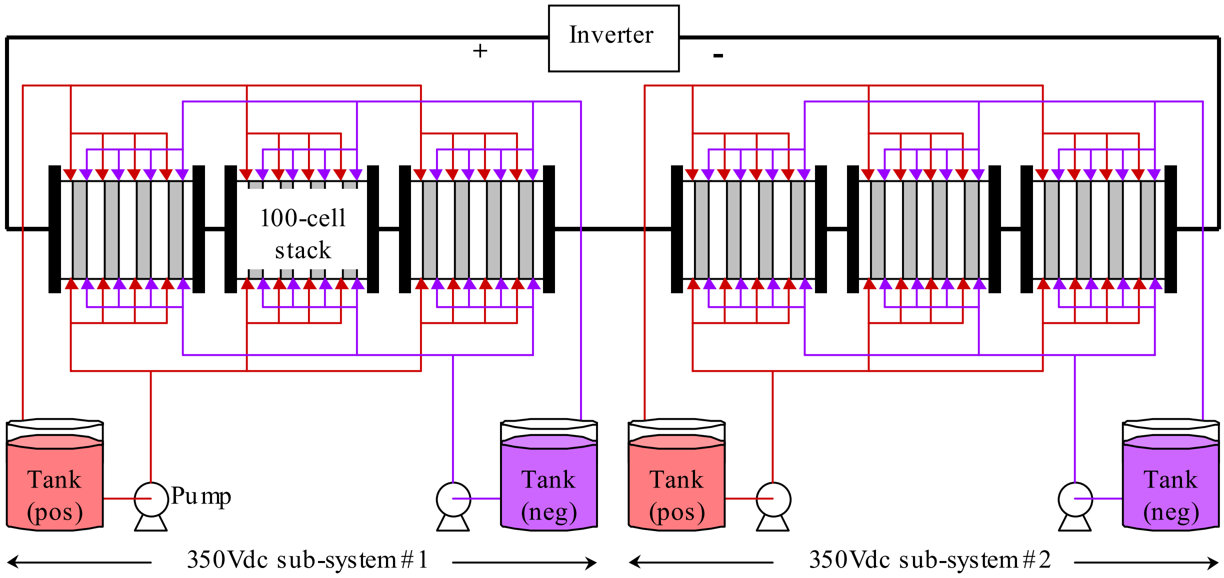

Fig 2. VRB configuration comprising two sub-systems

(3) the control sub-system, including variable speed motor control for the pumps; actuator electronics for the valve control, safety and switching elements; and sensors.

All sub-systems are integrated and co-ordinated by proprietary VESS hardware and software. Flexible operation is implemented through an intelligent monitoring and control facility. VESS performance is optimised and maximised when there is communication between the inverter and the VESS controller.

In flow battery designs using a parallel hydraulic topology, a wasteful shunt current occurs due to the potential that exists across the highly ionic (and conductive) electrolyte. One approach to the management of the extent of the power loss is by increasing the electrical resistivity of the electrolyte outside the stack. As shown in Fig 2, a configuration consisting of two nominal 350Vdc sub-systems was chosen as a practical compromise between reduction of shunt current losses and the cost of additional Balance of System (BoS) components which arise if sub-systems of lower series voltage are used.

TABLE 2 - VRB specifications

Element	Specification
VRB Stack	
Stack power rating	42kW continuous (130 kW peak)
No of stacks	6
Stack dimensions	1.2L x 0.9W x 1.1H (m)
Stack weight	1,400 kg
Electrolyte	
Electrolyte type	1.6M Vanadium in 4.6M sulphuric acid
Ionic ratio	1:1 V(4+):V(3+)
Electrolyte volume	42 m^3 total *(see note)*
Operating SOC	20%-80%
BoS	
Electrolyte tanks	4 x 2.5m^3 HDPE *(see note)*
Piping	uPVC pressure
Pumps & motors	4 x centrifugal pump/2.2kW
Heat exchangers	4 x 6 kW
Valving	Manual and motorised
Control VESS	automated with manual override

Note:
Tank sizing is modular to allow growth in energy storage. At commissioning, only 7.5m3 of electrolyte has been installed.

SYSTEM COMPONENTS

System components were obtained from various sources, and again reflected the international effort to commercial VRB technology. Stacks for the Eskom trial were purchased from one of the two Japanese companies that currently manufacture VRB stacks.[3] Six 42 kW, 100-cell stacks were used. Highveld produced the electrolyte to a purity level specified by the stack manufacturer. Eskom's 250 kVA Shunt connected Dynamic Power Quality Compensator (DPQC-P-250) was used as the PCS bi-directional inverter. The PVC piping and the pump systems were locally supplied. Proprietary VESS hardware and software was provided to Vanteck by Telepower Australia. A local domestic engineering firm carried out the civil works.

[3] Stacks were manufactured by and purchased from Sumitomo Electric Industries, Osaka, Japan.

As an electrochemical system, the VRB can achieve high voltaic and coulombic efficiencies. Typical voltaic efficiency of 92% and coulombic efficiency of 96% have been reported [1]. The individual stack performance was verified at the place of manufacture prior to shipping. The typical discharge and charge curve for one of the 100-cell stacks is shown in Fig 3. The profile is similar in character to the discharge of a typical lead-acid battery.

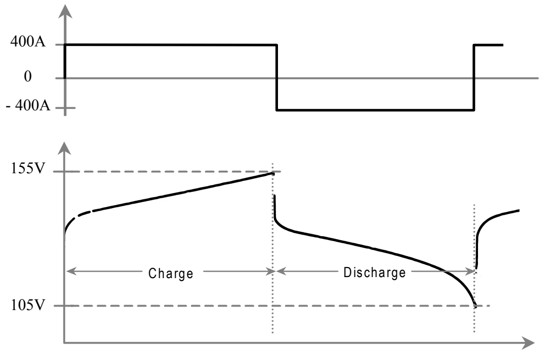

Fig 3. Typical stack charge/discharge profile

The benchmark stack performance of each of the six stacks at the specified 400A operational current measured over three consecutive charge-discharge cycles is listed in Table 3. At a discharge current of 400A, the stacks used in the Stellenbosch VESS Trial all delivered in excess of 42 kW DC power during discharge and exhibited a consistent overall DC energy efficiency of 82%-85%.

TABLE 3 - Benchmark stack performance

	efficiency (%)			
stack	cycle 1	cycle 2	cycle 3	average
#1	82.1	81.7	81.6	81.8
#2	83.2	83.3	83.5	83.3
#3	83.9	84.3	84.4	84.2
#4	84.5	84.7	84.9	84.7
#5	84.5	84.5	84.7	84.6
#6	84.5	84.4	84.4	84.4

CONSTRUCTION & INSTALLATION

This is the first construction and installation of a VRB/VESS site outside Japan, and a degree of collective wisdom had to be developed as the project developed. The site was chosen by Eskom to be at the University of Stellenbosch at the Department of Electrical and Electronic Engineering to best facilitate trial and demonstration purposes.

The general plan and layout of the system is shown in Fig 4, and a summary of some of the site details is given in Table 4. The size of the installation was made generous to allow access during construction and later performance evaluation. While the configuration of the VESS is modular, "standard" fittings for a VRB installation do not yet exist, and many parts associated with the electrolyte piping had to be prepared at site at the time of installation.

TABLE 4 - Site details & civil design

Site	Stellenbosch (near Cape Town), South Africa
Location	University of Stellenbosh
Configuration	Stand-alone structure. Two levels, open decks:- Stacks upper deck Electrolyte storage lower deck
Construction	Structural steel
Site footprint	Approx. 5m x 8m
Max height	4.5m max (including roof)
Containment	$5m^3$ acid-proof concrete bund
Weight bearing	Lower deck 50 ton Upper deck 9 ton

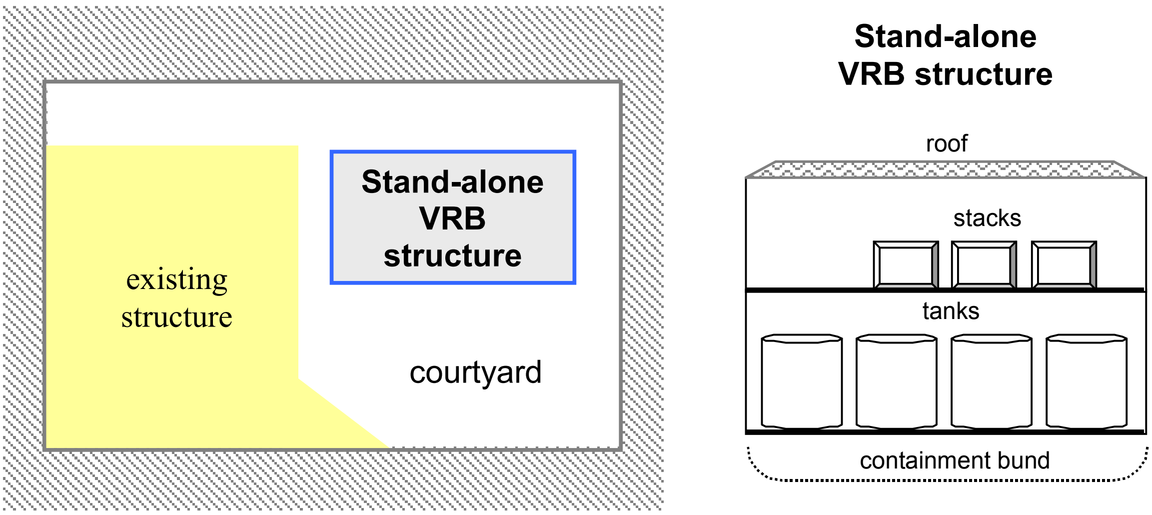

Fig 4. Layout plan of VRB/VESS installation

Fig 5. Lower level of VRB installation

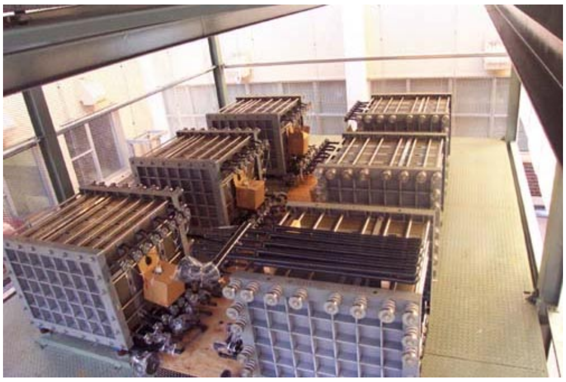

Fig 6. Upper level of VRB

Future installations will exploit the component "standards" which have evolved from this work. Future installation can be more economical in the amount of space consumed, as up to 30% volume savings could be achieved.

Construction involved a considerable degree of civil works, due primarily to the stand-alone structure. For practical installations in End-user premises, the layout may very well be made more space efficient, and hence the degree of civil works required may be reduced. That said, the civil works are relatively simple and uncomplicated, and in principle, the structure only supports the placement of the electrolyte tanks and the stacks. Progress with the installation process is shown in Figs 5 & 6. Fig 5 is a photograph of the lower level plant, showing the electrolyte tanks, heat exchangers and piping. Fig 6 is a photograph of the upper level where the six stacks are positioned.

Construction, installation and commissioning activities were ambitiously scheduled to take no longer than 10 weeks. In reality, construction and installation took a little over three months[4].

CONCLUSION

This paper has reported on the establishment of a trial of a 250 kW/520 kWh VRB/VESS to demonstrate medium to large scale energy storage for power quality and high reliability stand-by power applications. This trial is important and significant in that it is the first commercial-scale demonstration of this emerging new energy storage technology outside Japan. Core competency and new knowledge in the design and installation of VESS has now been developed. The trial is also important as providing means to develop standardised and modular components, which are a critical element in achieving the relatively low unit energy costs expected for this technology as it matures. After commissioning, the trial is scheduled for a 6 month testing and evaluation period. Many specific power quality standby plant applications will be tested. After the completion of the trial, it is expected that the VESS is to be relocated to an End-user premises for integration into an emergency DC power plant infrastructure. The authors look forward to reporting the trial results upon completion of the evaluation period.

ACKNOWLEDGEMENT

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[4] At the time of preparation and submission of this manuscript, the two week commissioning period had just begun.