Understanding the Redflow Battery

Introduction

Flow batteries are a well understood class of energy storage technology. To date, production flow batteries have been relatively large in terms of both physical size and storage capacity. Redflow has successfully designed and commercialised a small, modular, flow battery based on zinc-bromine reactants — referred to as a ZBM2 (Zinc-Bromine Module). Redflow's 10 kilowatt-hour (kWh) ZBM2 battery has proved very versatile and is successfully used for a variety of energy storage applications. This White Paper describes the Redflow zinc-bromine flow battery technology to highlight the advantages of flow batteries, including their resilience and robustness. After introducing the battery, it discusses the underlying composition and lists key advantages of this technology. This paper also outlines Redflow's design choices that made the ZBM2 battery a reliable and robust energy storage system with unique advantages over legacy battery chemistries including lead-acid and lithium-based batteries. The paper concludes by broadly addressing the topic of ZBM2 battery integration and installation, while noting that specific application notes and design guidelines can be found on the Redflow website www.redflow.com.

The Redflow ZBM2 at a Glance

From a strictly electrical point of view, Redflow's ZBM2 battery presents very good characteristics. In its base configuration, addressed as ZBM2, it is a 220 ampere-hour (Ah), 48-volt (V) nominal battery - a nominal energy storage and delivery capacity of 10kWh at a typical roundtrip efficiency of 80 per cent - with a voltage ranged between 40V and 58V. With no ageing effect caused by usage, the ZBM2 can be charged and discharged completely at rates up to 3kW (kilowatts) and operated in a wide range of ambient temperatures if the electrolyte temperature remains between 10°C and 50°C. Beyond these limits, the ZBM2 automatically suspends operation to protect itself. The roundtrip efficiency of the battery is around 80 per cent with performance warranted for a minimum of 3650 cycles at 100 per

cent depth of discharge (DoD) for a total of 36.5MWh of energy throughput or for 10 years – whichever comes first.

As a flow battery, the Redflow ZBM2 contains about 100 litres of a water-based solution of zinc-bromide salt, flowing around in two separate hydraulic circuits. During the battery charge phase, zinc is extracted from the liquid phase and plated onto carbon-based electrodes. During the battery's discharge phase, zinc is 'de-plated' and restored to the solution. The ZBM2 is managed entirely by an on-board Module Management System (MMS) while multiple ZBMs are managed by Redflow's proprietary Battery Management System (BMS). The MMS controls battery operations and protects the battery against misuse. The MMS also provides access to the battery status, real-time data, event log, alarms, warnings, etc. An image of the ZBM2 battery is shown in the following figure.

The L-shaped tanks containing the electrolyte are visible at the base while you can see the electrode stack and the MMS box at the top.

Flow Battery Characteristics

In its general definition, a flow battery features an electrolyte flowing continuously between a storage compartment (i.e. one or more tanks) and a reaction chamber where the electrodes are placed. Compared to a lead-acid battery, a flow battery contains more components and greater design complexity, with moving parts and sophisticated chemical containment. These batteries are typically deployed in stationary energy storage applications as changes to the system vertical alignment or changes in momentum or inertia

can negatively affect the electrolyte flow, and thus the battery's electrical performance. The ZBM2 on-board Module Management System (MMS), which controls and safeguards the battery, adds an active element to each battery that is not present in standard batteries. While it increases the battery's complexity, the MMS provides advantageous functions that enable the ZBM2 to be self-managing and to protect itself against potential environmental or operational damage risks. Where a ZBM2 replaces a conventional battery in a system design, its charge cycle is started by simply presenting an appropriate charging voltage and current to the Redflow battery. The MMS responds to this voltage by commencing a charge cycle. Likewise, a discharge cycle is commenced by simply drawing power from the battery, with the MMS managing the underlying active components to deliver the energy to the external load as required. A common characteristic of flow batteries, including the ZBM2, is that the battery can completely discharge during normal operation without incurring any damage or performance degradation. Unlike a conventional battery, a complete discharge is harmless to a ZBM2. However, this 100 per cent discharge capability results in the battery output voltage falling to zero volts and the on-board MMS halting operation. This is a circumstance that a conventional battery management system may report as an alarm or may respond by halting system operations. As noted above, after a complete discharge, the ZBM2 operation is re-commenced by simply applying an appropriate charge voltage to the system. In response, the MMS re-starts and commences a ZBM2 charging cycle. Consequently, the design of a system incorporating a ZBM2 battery or batteries needs to accommodate this 100 per cent discharge and re-start scenario as a normal part of battery operations.

ZBM2 Battery Advantages

The various flow battery characteristics discussed in this section can be leveraged to deliver unique advantages in an energy storage system using the ZBM2 zinc-bromine flow battery.

Stack and tank separation

As with most flow batteries, the Redflow ZBM2 features a separation of the energy section - the tanks filled with the electrolyte - and the power section - the stack composed by electrodes. This separation enables unique advantages for flow batteries, such as flexibility

in design and recycling of the battery parts at the end of life. Thus, the Redflow ZBM2 is one of the most sustainable and cost-effective batteries available today.

Decreased likelihood of theft

Another advantage of the ZBM2 battery over legacy technologies such as lead-acid batteries is the reduced risk of theft in the field. Conventional battery banks, which contain several 2V, 6V or 12V batteries, are attractive targets for theft as these single elements can be sold or reused. The uniqueness of the ZBM2 design and components mean that the battery is of little value to a potential thief outside of the application for which it has been designed. Also, with a total weight of about 240kg, the ZBM2 is too heavy for routine incidents of opportunistic theft to which conventional batteries are prone in remote field applications.

Control of immediate shut down

The separation of power and energy components in the ZBM2 battery also permits a shutdown within seconds by interrupting power supply to the flow pumps. Since no reactants are supplied to the electrodes after the pumps stop running, no electrical energy is transferred, so the system becomes still and safe. This enables the safe transport of ZBM2 batteries in this shutdown state. Also, a ZBM2 suffering mechanical damage does not risk explosion, dangerous high current output from short-circuit, or “thermal runaway”.

Inherently safe characteristics

These characteristics, along with its water-based electrolyte, makes the ZBM2 flow battery inherently safe, reducing to a minimum the risk of fire and “thermal runaway” in small, medium or large energy storage systems. Additionally, the electrolyte flow distributes heat across the battery, contributing to easier thermal management of the battery and more effective cooling capabilities.

Module Management System (MMS)

The ZBM2 battery is equipped with the Redflow Battery Management System (BMS) and data communication, which offer multiple advantages.

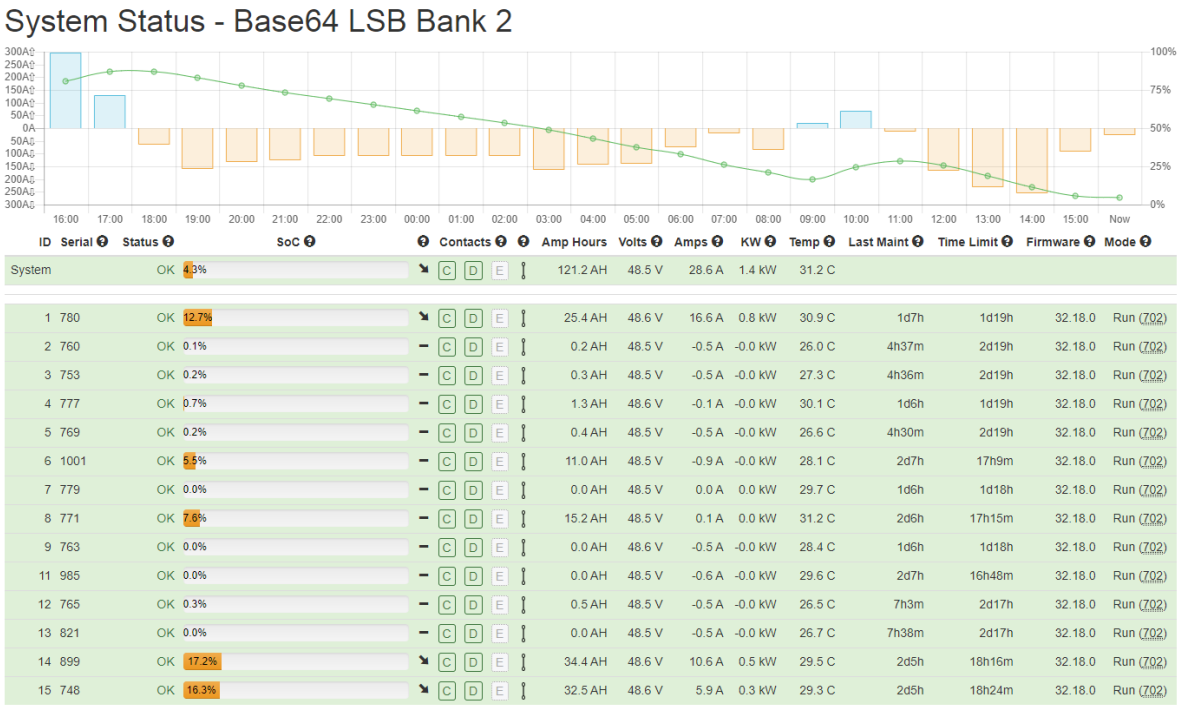
Real time data, diagnostics and event history

Firstly, the ZBM2 can be accessed securely at any time to provide information about the battery status, real time data, diagnostic and event history. This access improves control of the system, both local or remote, and its performance. These “smart battery” capabilities also improve its reliability and fault tolerance.

MMS and BMS active battery protection

The ZBM2 MMS provides active protection for the battery and the system against misuse, damage or extreme operating conditions, such as fluctuations in voltage or temperature. This improves safety and longevity of both the system and the battery by minimising failures and early replacements.

In addition, the Redflow BMS can interface multiple batteries to provide functions like data logging and “clouding”, self-maintenance scheduling, event response, charge and discharge optimisation, fault diagnostics and signalling, auxiliary software-controlled I/Os (Input/Output), inverter control, etc. A BMS interface screen shot appears below.



ID	Serial	Status	SoC	Contacts	Amp Hours	Volts	Amps	KW	Temp	Last Maint	Time Limit	Firmware	Mode
System		OK	4.3%	C D E	121.2 AH	48.6 V	28.6 A	1.4 kW	31.2 C				
1	780	OK	12.7%	C D E	25.4 AH	48.6 V	16.6 A	0.8 kW	30.9 C	1d7h	1d19h	32.18.0	Run (702)
2	760	OK	0.1%	C D E	0.2 AH	48.5 V	-0.5 A	-0.0 kW	26.0 C	4h37m	2d19h	32.18.0	Run (702)
3	753	OK	0.2%	C D E	0.3 AH	48.5 V	-0.5 A	-0.0 kW	27.3 C	4h36m	2d19h	32.18.0	Run (702)
4	777	OK	0.7%	C D E	1.3 AH	48.6 V	-0.1 A	-0.0 kW	30.1 C	1d6h	1d19h	32.18.0	Run (702)
5	769	OK	0.2%	C D E	0.4 AH	48.5 V	-0.5 A	-0.0 kW	26.6 C	4h30m	2d19h	32.18.0	Run (702)
6	1001	OK	5.5%	C D E	11.0 AH	48.5 V	-0.9 A	-0.0 kW	28.1 C	2d7h	17h9m	32.18.0	Run (702)
7	779	OK	0.0%	C D E	0.0 AH	48.5 V	0.0 A	0.0 kW	29.7 C	1d6h	1d18h	32.18.0	Run (702)
8	771	OK	7.6%	C D E	15.2 AH	48.5 V	0.1 A	0.0 kW	31.2 C	2d6h	17h15m	32.18.0	Run (702)
9	763	OK	0.0%	C D E	0.0 AH	48.6 V	-0.5 A	-0.0 kW	28.4 C	1d6h	1d18h	32.18.0	Run (702)
11	985	OK	0.0%	C D E	0.0 AH	48.5 V	-0.6 A	-0.0 kW	29.6 C	2d7h	16h48m	32.18.0	Run (702)
12	765	OK	0.3%	C D E	0.5 AH	48.5 V	-0.5 A	-0.0 kW	26.5 C	7h3m	2d17h	32.18.0	Run (702)
13	821	OK	0.0%	C D E	0.0 AH	48.5 V	-0.5 A	-0.0 kW	26.7 C	7h38m	2d17h	32.18.0	Run (702)
14	899	OK	17.2%	C D E	34.4 AH	48.6 V	10.6 A	0.5 kW	29.5 C	2d5h	18h16m	32.18.0	Run (702)
15	748	OK	16.3%	C D E	32.5 AH	48.6 V	5.9 A	0.3 kW	29.3 C	2d5h	18h24m	32.18.0	Run (702)

100 per cent depth of discharge

The zinc-bromine flow battery's 100 per cent depth of discharge delivers advantages in many energy storage applications where other batteries struggle. As the battery can stay fully or partially discharged for an indefinite time without degradation, it offers the best choice for applications that schedule the use of stored energy or often have idle periods.

Zero state of charge advantages

In solar applications, the battery can be started from a zero per cent state of charge every morning and used to store the excess energy supplied by the sun during the day. The entire battery capacity is available to store solar-generated energy. At any time during the day or the night, the battery can be discharged partially or fully down to zero per cent state of charge and left safely in this condition overnight. If no solar energy is supplied to the battery the next day, the flow battery incurs no "ageing" or performance degradation.

This capability contrasts with other common battery chemistries that must start the day at a higher state of charge (for example 50 per cent) to avoid deep discharge states that could age the battery faster. This limits their useable daily energy storage capacity. When stored energy is needed, these batteries can be discharged only back to 50 per cent - no further discharge is allowed. If no solar energy is available the next day, the battery life and capacity is negatively affected by deep discharge conditions leading to sulfation.

The capability for safe and complete discharge of the ZBM2 battery also proves advantageous in diesel backup generator minimisation applications.

Increased capacity

The ZBM2 flow battery's ability to use 100 per cent of its stored energy also enables better sizing of the energy storage system compared to other battery technologies. It is essential to factor this difference in **useable** capacity for a ZBM2 into comparisons of battery system capacity. A conventional battery must reserve a large proportion of its theoretical energy

storage capacity to protect the battery from the damage or reduced useable life that result from 100 per cent depth-of-discharge conditions. A conventional battery can also take a long time to charge fully, with charge-rates slowing as the battery approaches its completely full state. This means that even more *theoretical* battery capacity is often reserved from the application *in practice*, to accommodate this characteristic. By contrast, a ZBM2 can routinely operate from zero per cent to 100 per cent state-of-charge and back to empty for ***every*** operational cycle without loss of performance or risk of battery damage.

Linear voltage

Another advantage is that ZBM2 charge and discharge cycles operate at a near linear voltage and current levels across the entire range of charge states. This allows a ZBM2 to be charged on a near-linear basis. It also allows the entire ZBM2 capacity to be usefully delivered to the required system load, with output current and voltage also remaining consistent and stable across the entire discharge phase. ZBM2 flow batteries are preferable in the case of remote applications where site access is difficult - for example, seasonal impediments or transport difficulties, etc. - because they can tolerate long power outages.

Complete cell tested performance and reliability

The ZBM2 physical and mechanical characteristics also deliver benefits. For example, each standard ZBM2 battery contains 30 cells in series directly interconnected to reach 48V nominal voltage. Redflow tests every ZBM2 for the battery's lifetime performance and reliability. Other technologies test only the individual cells - for example the 2V cell in the lead-acid chemistry - but provide no information on the performance of the interconnected 24 cells that are needed to reach the full 48V.

Sealed assembly

The ZBM battery has a sealed assembly and uses corrosion-resistant materials. These features make the battery ideally suited for extreme condition environments. A summary of Redflow battery advantages and challenges is reported in the following Table 1.

ZBM Feature	ZBM Disadvantage	ZBM Advantage
Higher parts count	More complex physical system	Recycle, repair, refurbish
Stationary, 250kg total weight	Unsuitable for some physically mobile applications	Very small potential for theft
Separation of power and energy components of battery	Electrolyte in motion during battery use	Immediate shutdown possible, easy thermal management, intrinsically safe after physical damage, very safe for transport/ delivery, stack can be replaced to extend battery life, extremely long storage life in quiescent state.
On-board MMS	System integration effort	Smart battery
100% Depth of Discharge	System integration effort	100% of energy storage and delivery cycle available
Sealed and corrosion resistant	-	Suited for extreme environments

Table 1

ZBM2 Self Maintenance Cycles

To optimise its performance, the ZBM2 *must* be completely discharged periodically as a self-maintenance requirement to maximise the surface area of the battery electrode surfaces. The ZBM2 MMS automatically engages this 'electrode scrubbing' operation on a periodic basis if the battery has not been recently discharged to a zero state of charge during normal operations. The ZBM2 system design needs to accommodate this typical flow battery characteristic. For single battery systems, the design must therefore accommodate short periods where the ZBM2 is effectively 'off' at the end of a scrubbing cycle. For designs containing multiple ZBM2s, batteries can be scheduled to undergo this cycling process sequentially by accessing a menu in the BMS. The user can specify how to execute this automated self-maintenance sequencing – whether all batteries together or one at a time.

The ZBM2 Design

The large size of typical flow battery designs means that most installations worldwide fall in the category of large-scale systems where the battery is custom-made for the specific energy storage application.

Redflow has commercialised a modular, small-scale battery that enables the deployment of its ZBM2 flow battery for applications previously considered too small for flow batteries, including residential, commercial & industrial (C&I) and telecommunications.

An example of this scalability is the Redflow LSB (Large Scale Battery) reference platform, a shipping-container form factor containing as many as 60 ZBM2 batteries – or 45 batteries and multiple battery inverters – that delivers large-scale energy storage capacity suitable for renewables integration, distributed generation and uninterruptible power supply (UPS) systems applications. In addition, the LSB itself is modular, allowing the deployment of multiple LSB units for grid-scale energy storage and load-levelling applications.

Redflow made key design choices to ensure one battery could match each of those potential deployment scenarios. The following section discusses some of these crucial design choices.

Mechanical design

The ZBM2's physical assembly includes a removable electrode stack placed at the top of the battery. This allows for stack replacement at the end of life and recycling/refurbishment of the battery. Two tanks – using a one-inside-the-other design - provide interstitial space to simplify the battery assembly and contain potential electrolyte spillage. The sealed MMS box is at the front to avoid direct exposure of battery terminals and to allow cabling access.

DC pumps

Redflow has co-developed a role-specific advanced DC pump for the ZBM2, which offers several advantages. Firstly, the battery itself can power the pumps without requiring AC components. Redflow's DC pumps feature brushless motors that offer superior performance in terms of life, noise, torque, reliability and robustness. An important feature is also the capability to dynamically adjust the pump speed, and hence the flow speed, according to

the required charge or discharge rate. This delivers an improvement in overall battery efficiency and extends the life of the pumps. The Redflow MMS monitors the pump flowrate, letting you detect and report pump failure.

Cooling apparatus

The ZBM2 contains an internal cooling apparatus that is designed to extend the operating temperature range of the battery, allowing operations in the electrolyte temperature as warm as 50°C without any negative effect on the battery life.

Advanced MMS

As a plug-and-play energy storage device, Redflow's ZBM2 is a "smart battery" that can work independently from the surrounding system. Redflow achieves this by using an advanced MMS that can perform independent operations and act when needed. The Redflow BMS can also start some operations with external commands, allowing the system integrator to adjust or drive the system responses through settings in the BMS interface.

Operational features

The ZBM2 design is optimised for telecommunication applications with these features:

- Voltage range adjusted for standard lead-acid systems with a maximum charging voltage up to 57V and a low voltage disconnect down to 40V,
- Extended high-end temperature range,
- No ageing due to deep discharge and long discharged periods,
- Low maintenance.

Redflow has included additional features for integration with renewables and interfacing with advanced monitoring. For example, Redflow has introduced an electronic protection for overcharge (not affecting the instantaneous discharge) for direct connection to solar panels and renewables. Also, several ZBMs can be connected in parallel without adverse inter-battery current flows due to differences in charge/discharge state. No protection devices are required in this configuration, and no unwanted flow of power can be observed among multiple ZBM2 modules connected to the same DC bus.

ZBM2 can be used with commercially available inverters for residential or industrial applications to provide backup or renewables shifting. It is easy to integrate ZBM2 monitoring in more complex supervisory systems.

For large energy storage applications using the LSB reference platform, ZBM2 modules are connected in series to reach higher voltages. The de-facto standard is the 400-800V range. Redflow has designed a variation of the MMS module for this application to allow for series connection without affecting the ZBM2 protection and access to battery information.

Standby Power Supply mode - ZBM2 as a pre-charged 'electro-chemical' generator

One of the most advantageous operational modes of the ZBM2 is Standby Power System (SPS), a storage mode in which the battery can act as a pre-charged electro-chemical generator. Requiring just 10 per cent of the battery's stored energy to establish, this mode enables you to leave the ZBM2 unattended for months, with no additional self-discharge occurring. This eliminates the need for trickle charge, equalisation or conditioning. During this period, the voltage on the battery terminal can decay to zero volts while the battery will retain as much as 90 per cent of its original state of charge. When required, the battery can restart within 60 seconds - either by an external voltage of at least 36V or by restarting itself. SPS mode enables the battery to self-sustain and supply stored energy - as much as 9kWh from one ZBM2. If extra ZBM2s are connected in parallel, the first battery, once restarted, can power up the others, with the BMS restarting them in seconds.

The ZBM2 in SPS mode can be used in conjunction with other batteries for UPS applications. Today, expensive lead-acid battery banks incur significant costs from ageing, power consumption, weight and maintenance. ZBM2 also considerably reduces operational costs.

Another application of the ZBM2's SPS mode is in areas that experience frequent blackouts. Without requiring any maintenance charge, the ZBM2 can start in the event of an electricity outage to power emergency loads. For example, with just one complete discharge each week, the battery will only perform approximately 500 cycles during 10 years, providing plenty of capacity to supply Standby Power when required. The ZBM2 battery is warranted for 10 years or 36,500 cycles – whichever comes first.

Learn more about Redflow and Zinc-Bromine Flow Batteries

Redflow Limited, a publicly-listed Australian company (ASX: RFX), produces small 10kWh zinc-bromine flow batteries that tolerate daily hard work in harsh conditions. Marketed as ZCell and ZBM2, Redflow batteries are designed for high cycle-rate, long time-base stationary energy storage applications in the residential, commercial & industrial and telecommunications sectors, and are scalable from a single battery installation through to grid-scale deployments. Redflow batteries are sold, installed and maintained by an international network of energy system integrators. Redflow's smart, self-protecting batteries offer unique advantages including secure remote management, 100 per cent daily depth of discharge, tolerance of high ambient temperatures, a simple recycling path, no propensity for thermal runaway and sustained energy delivery throughout their operating life.

Redflow contact details:

Redflow Limited (Head Office)
27 Counihan Road,
Seventeen Mile Rocks, Brisbane
QLD, 4073, Australia

Phone: + 61 7 3376 0008
Fax: + 61 7 3376 3751

Sales: sales@redflow.com
General: info@redflow.com