Recent Progress in Vanadium Redox-Flow Battery

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1. Introduction

Vanadium Redox Flow Battery (VRB) is an energy storage system that employs a rechargeable vanadium fuel cell technology. Since 1985, Sumitomo Electric Industries Ltd (SEI) has developed VRB technologies for large-scale energy storage in collaboration with Kansai Electric power Co. In 2001, SEI has developed 3MW VRB system and delivered it to a large liquid crystal display manufacturing plant. The VRB system provides 3MW of power for 1.5 seconds as UPS (Uninterruptible Power Supply) for voltage sag compensation and 1.5MW of power for 1hr as a peak shaver to reduce peak load. The VRB system has successfully compensated for 50 voltage sag events that have occurred since installation up until September 2003.

2. Principle of VRB

The unique chemistry of vanadium allows it to be used in both the positive and negative electrolytes. Figure 1 shows a schematic configuration of VRB system. The liquid electrolytes are circulated through the fuel cells in a similar manner to that of hydrogen and oxygen in a hydrogen fuel cell. Similarly, the electrochemical reactions occurring within the cells can produce a current flow in an external circuit, alternatively reversing the current flow results in recharging of the electrolytes. These cell reactions are balanced by a flow of protons or hydrogen ions across the cell through a selective membrane. The selective membrane also serves as a physical barrier keeping the positive and negative vanadium electrolytes separate. Figure 2 shows a cell stack which was manufactured by SEI. It consists of 100 single cells. Dimension of cell stack is approximately 1m in cube.

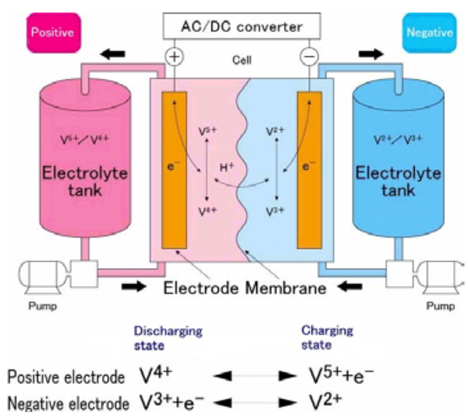

Fig.1 Schematic configuration of VRB system

Fig.2 Photograph of cell stack

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3, Operating characteristic of VRB

In designing of the VRB system, overload capacity and fast response are applied. Those unique features are well suited to the application for UPS, bridging-power system for black out, and the voltage and frequency stabilization system for the renewable energy sources.

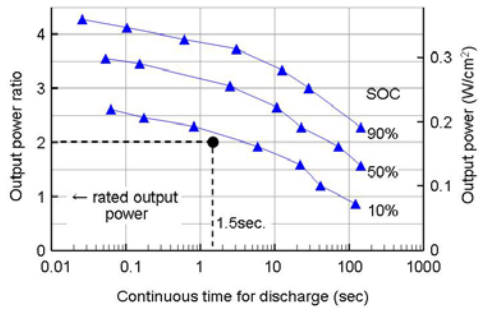

Fig.3 Experimental results of the overload capacity of cell stack.

For short time charge/discharge cycles (in the order of seconds), the VRB can supply more than twice the continuous rated power. This unique feature of the VRB system is referred to as the "overload capacity". This feature makes it possible to reduce the number of the cell stacks in case of systems having short discharging time. Figure 3 shows the experimental results of the overload capacity of the standard cell stack [1]. Horizontal and vertical axis mean the continuous time for discharge and output power ratio, respectively. State of charge (SOC) in the electrolyte is chosen to be parameter. For the short time discharge of 1.5 sec, the cell stack can generate than twice the continuous rated power even if SOC is only 10%. The VRB's maximum overload capacity was measured as 4.6 for SOC 90%, 3.9 for SOC50%, and 2.9 for SOC 10%.

In Fig.3, the upper bound of the output can be considered to appear in three domains. Based on the principle of the electrochemical reaction, we recognized that dominant factor in the battery characteristics is quite different in the time range of the discharge. For the long-range discharge (e.g. more than 300 sec), the internal capacity of the battery is thought to be the dominant factor in the battery characteristics. For the medium-range discharge (e.g. more than 3 sec and less than 300 sec), the resistance of the mass transfer process is the dominant factor. And for the short-range discharge, the resistance of the charge transfer process is the dominant factor.

Based on the above-mentioned recognition, the equivalent circuit for the VRB's cell stack is clarified as shown in Fig.4 [2]. C_0 is the internal capacity of the battery, R_3 and C_2 are for the resistance of the mass transfer process, R_2 and C_2 are for the resistance of the charge transfer process, R_1 is the balk resistance which consists of the resistance of the membrane, electrolyte, contact resistance and so on. I_0 means the self-discharge current. We developed simulation program based on the equivalent circuit model in order to figure out the electric characteristics of the VRB's cell stack.

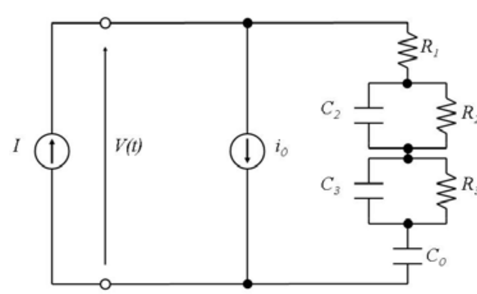

Fig.4 Equivalent circuit model of VRB

The VRB can start the charge/discharge cycle within 1 ms. The VRB is therefore suitable for UPS application. We have confirmed the instantaneous responsiveness of the VRB cell experimentally. Experimental result is shown in Fig. 5. DC part of the VRB system was connected in parallel to both the DC power supply and the electronic load. This applied electronic load was a step current with a rise time of approximately 0.35 ms. Terminal voltage of the DC part of the VRB system was found to be smoothly maintained under the condition s of excess or insufficient voltage. The instantaneous responsiveness of the VRB cell was faster than the load transition time (0.35 ms) and the charge/discharge current change transition was able to follow the load.

<u>4, Three mega-watt UPS system</u>

The VRB can be designed as a bulk energy storage system for peak shaving, but it also has fast enough response characteristics to perform in a wide range of other applications. For example, currently installed VRB systems are providing wind-turbine output stabilization, as well as grid support functions including voltage sag compensation.

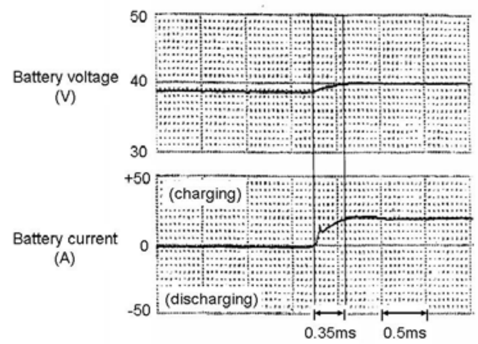

Fig.5 Experimental result of response characteristics of VRB cell stack.

One commercial VRB system in Japan is operating as a combination UPS for voltage sag compensation and a peak shaver to reduce peak load. Figure 6 shows the outline of the VRB system. The upper photograph shows the battery cubicles.
The cell stack is installed in the battery cubicles. The lower photograph shows the electrolyte tanks and pumps.

The VRB system provides 3MW of power for 1.5 seconds in UPS-mode and 1.5MW of power for 1hr in peak-shaving mode. The system has been operating in a large liquid crystal display manufacturing plant since 2001. The VRB system operates in peak shaving mode on a daily basis and provides 24 hour protection against instantaneous voltage sag caused by lightning or other causes. The VRB system maintains constant voltage and prevents the high-tech manufacturing line from stopping. The VRB system has successfully compensated for 50 voltage sag events that have occurred since installation up until September 2003.

Table 1 shows the main parameters of the VRB system. It mainly consists of 36 cell stacks, electrolyte of 180m^3, and power conversion system using a double conversion system with three parallel lines.

Figure 7 shows the schematic diagram of 3MW VRB system. It consists of 3 parallel circuits. This shows only one parallel circuit corresponding to 1MW system. This is the double conversion system. In ordinary situation, electricity converts AC to DC by the rectifier. At the end of the DC-bus line, DC electricity reconverts to AC by IGBT-based inverter. Once voltage sag or blackout within 1.5sec occur, VRB discharges immediately in order to supply electricity to the load without interruption. There are two bypass circuits, one is mechanical bypass circuit which will use in maintenance of VRB system. The other is high-speed bypass circuit using thyrister. When VRB system stops to operate due to failure, high speed switch will close the circuit immediately so as to continue to supply electricity to the load.

Fig.6 Photographs of the VRB system installed in the liquid crystal display plant.

Table 1, Main parameters of the VRB system installed in the liquid crystal display plan.

Output and Capacity	for UPS	AC 3,000kW - 1.5sec
	for peak-shaving	AC 1,500kW - 1h
Rated voltage	AC output	6,600 V
	DC bus	400 – 620 V
Equipments	Cell stacks	36 stacks
	Power conversion system	-Double conversion system -3 parallel lines
	Electrolyte	-Vanadium sulfate solution -180m^3
	Tank	-Polyethylene -8 tanks
	Others	-Electrolyte circulating system -Water cooling system -Battery controllers -Remote monitoring system

Figure 8 shows the experimental results of voltage-sag compensation. The upper waveforms are the input voltage to VRB system. Blackout occurred for 1.5sec. During blackout , VRB discharges to compensate electricity. There is no interruption in the voltage and current waveforms measured at the load. Therefore, this system can completely compensate voltage sag.

Figure 9 shows an experimental result of the performance of the bypass system. This breaking down was made by artificial procedure. The plug of optical fiber for data communication was disconnected intentionally for test purpose. The thyrister-based bypass circuit was installed in the power conversion system. Just after breaking down, the thyristor switch turns on immediately. After that, power source of electricity changed from battery to grid. Its transition time is less than 2msec. In our client’s case, all equipment continued to operate even though this transition occurred.

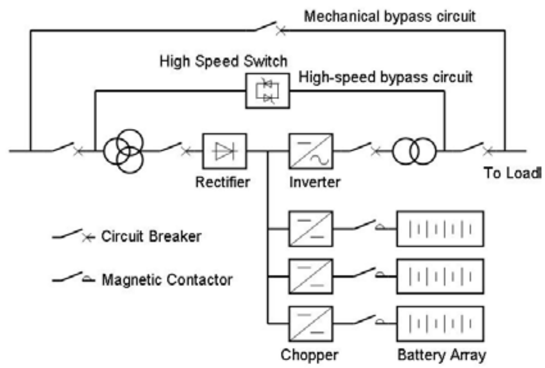

Fig 7, Schematic diagram of the VRB system. The 3MW VRB system consists of three parallel circuits. This shows schematic diagram of 1 parallel circuit. Two bypass circuits was installed in it.

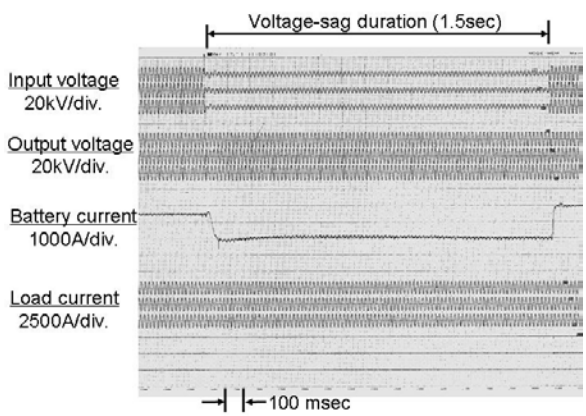

Fig8 Experimental results of voltage-sag compensation

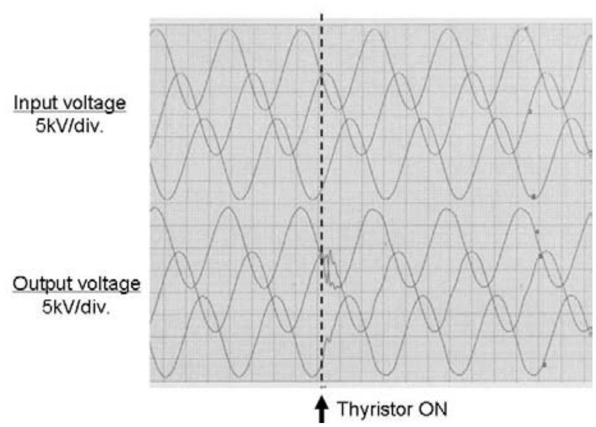

Fig.9 Experimental results of the bypass-system performance.

5, Conclusion

Sumitomo Electric has developed 3MW VRB system and delivered it to a large liquid crystal display manufacturing plant. The VRB system provides 3MW of power for 1.5 seconds as UPS for voltage sag compensation and 1.5MW of power for 1hr as a peak shaver to reduce peak load. The VRB system has successfully compensated for 50 voltage sag events that have occurred since installation up until September 2003. In designing of the VRB system, overload capacity and fast response are applied. Those unique features are well suited to the application for UPS, bridging-power system for black out, and the voltage and frequency stabilization system for the renewable energy souses.

Reference

1) H. Deguchi, T. Shigematsu, T. Hara, H. Inaba, T. Kaizuka and T. Sakai, “Assessment of the Application of a Redox Flow Battery to Load Frequency Control and Power Quality Maintenance”, SEI Technical Review, No. 52, June, 2001
2) K. Enomoto, T. Sasaki, T. Shigematsu and H. Deguchi, “Evaluation Study about Redox Flow Battery Response and Its Modeling”, Trans. IEE Japan, Vol. 122-B, No.4, 2002