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Modeling and Operation of a Vanadium Redox Flow Battery for PV Applications

Amjed Hina Fathima[a,b,*], Kaliannan Palanismay[a]

[a] *School of Electrical Engineering, VIT University, Vellore Campus, Vellore, Tamil Nadu,India – 632014.*
[b] *Department of EEE, Adhi College of Engineering and Technology, Walajabad, Kancheepuram District, Tamil Nadu, India - 631605*

Abstract

Energy storage has become an absolute necessity for the growth of renewable power systems today. Vanadium Redox Battery is rapidly gaining popularity in integrated hybrid renewable power systems due to its high life cycle count, modularity and flexible capacity. This paper puts forth an electrical model of a vanadium battery to study its operation while integrated with a standalone photovoltaic power source. The model includes evaluation of cell stack voltages and the state of charge of the storage capacity. A simple energy management strategy is included by modeling a charge controller to avoid any instances of overcharging/discharging. The solar panel is modeled using solar cells which act as the primary source to supply a purely resistive domestic load. The entire work is simulated in a Matlab/Simulink environment and the results investigated for constant and varying irradiation cases. The results obtained prove efficient operation of the battery as per requirements.

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Keywords: battery; flow battery; solar; vanadium redox; model; photo voltaic.

1. Introduction

Energy systems of the future are to be designed for guaranteed reliability and uncompromising energy security to ensure dynamic sustainability of the grid systems. Increased penetration of renewable systems poses a great challenge to the grid functioning due to their intermittent nature. However, due to increased global awareness of pollution and ozone depletion, most countries are opting for green energy policies forcing technology providers to look for options to operate and manage renewable sources without affecting the grid security.

Corresponding Author : *ahina.fathima2013@vit.ac.in*

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Nomenclature

k	Boltzmann constant
n	Number of cell stacks in the VRB battery
q	Elementary charge on an electron
E_{max}	Energy capacity of VRB at SOC_{max} in Wh
F	Faradays constant
I_{ph}	Solar induced current in Amps
I_{ph0}	Solar induced current at I_{r0} in Amps
I_{pump}	Current drawn by circulating pumps in VRB in Amps
I_r, I_{r0}	Incident and Standard irradiation in W/m2 in Amps
I_s, I_{s2}	Saturation current of first and second diodes in Amps
I_{stack}	Battery Stack current in Amps
N, N_2	Quality factors of first and second diodes
R	Gas constant
R_s, R_p	Series and Parallel resistance of PV cell in Ohms
R_{int}	Intrinsic resistance of VRB in Ohms
R_{par}	Parasitic resistance of VRB in Ohms
SOC	State of Charge of VRB in %
T	Temperature in ºC
V_{cell}	Standard cell potential in Volts
V_{eq}	Equilibrium cell voltage for VRB in Volts
V_{stack}	Stack voltage of VRB in Volts
V_t	Thermal voltage of PV cell in Volts

Energy storage Systems (ESS) has become indispensable partners of renewable power sources to enable storage of energy at the time of availability to be delivered at the time of load demand. Many forms of energy storages have been developed but Battery Energy Storage Systems (BESS) have been the most mature and developed technology available for many decades now [1]. Recent advancements in batteries have led to the development of flow batteries which adopt features like expandability and modularity into conventional electrochemical storage technology. By storing the liquid electrolyte in separate tanks outside the cell body they provide better means of managing their energy capacities. The electrolytes are to be pumped into the cell containing the electrodes when needed. Hence, it enables the system to possess a large energy capacity independent of the power capacities of the cell modules. Different classes of flow batteries are now being proposed like redox batteries, membrane-less batteries and hybrid batteries [2]. Redox batteries, as the name suggests, are characterized by simultaneously occurring oxidation-reduction reactions in the electrodes of the battery cell. Many redox batteries like iron-chromium flow battery, vanadium redox flow battery and zinc-bromide flow battery etc. have been developed. In this study, a Vanadium Redox Flow Battery (VRB) has been selected because it is the most promising of all redox batteries with long lifetime and is appreciable energy capacity without any heating problems. With recent reports claiming extraction of Vanadium from oil sludge [3] and fly ash etc., they have become an attractive option for grid-connected applications.

Alotto et al. [4] detailed a review on redox flow batteries, sketching their development and future state of the art. Earlier models of VRB [5,6,7] parameterised its stack voltages, voltage losses, and parasitic current losses etc. but each of these studies was either inefficient in modelling transient responses or were complex with extensive parameter measurements. D'Agostino et al. [8] attempted to include the operating modes and start up times in their VRB model and suggested that an efficient management of the electrolyte pumps would minimize losses and improve overall efficiency. Ontiveros and Mercado [9] proposed a new stack model for VRB including stack efficiency along with a mechanical model to improve the accuracy of the VRB model to understand its operation. `Merei et al. [10] attempted to explore aging prediction in VRB battery models. In Barote et al. [11], the VRB was modeled for applications in wind connected systems based on transient behaviour related to the capacitance of the cell electrodes. Wang et al. [12,13] successfully integrated a VRB battery for a PV system to deliver smoothened power output. This paper implements a simplified model of VRB which includes parasitic losses and accounts for the estimation of stack voltages and state of charge of the battery system in view of applications in solar powered applications.

2. Redox Flow Battery

Redox flow batteries are a developing branch of electrochemical energy storage. These batteries have liquid electrolytes which flow into and out of the battery at times of operation and are stored externally in tanks. This allows the battery systems to have high energy capacities and capable of operating at high temperatures. The battery itself is made up of stacked cells each having its own electrode sets separated by an ion selective membrane [4]. Other advantageous features of redox batteries are their high round-trip efficiencies, scalability and modularity, operational flexibility and low emissions. Table 1 presents the characteristics of some redox flow batteries being developed for grid storage applications [14,15]. ZBB is the zinc bromide flow battery using zinc and bromide solutions as electrolytes. It has zero self-discharge characteristics and high recyclability. The Polysulphide Battery (PSB) uses NaBr and Na_2S_X as electrolytes and was built by Regenesys Technologies but the project was abandoned for some economic difficulties. ZEBRA is a sodium-nickel chloride battery using NiCl and liquid Na as the electrolyte solutions and can operate at high temperatures. Its most attractive characteristic is that it is completely recyclable but do suffer from ~15% self-discharge. VRB batteries are the most widely developed and commercially available form of flow battery systems in the energy market.

Table 1. Redox battery storage systems and characteristics

Technology	Capital Cost in $/kWh	Discharge time	Energy Rating (MWh)	Specific Energy (Wh/kg)	Cycling Capability @ %DOD	Life (yrs)	Energy η%	Self dicharge %	Operating temp in °C
VRB	600	Sec-10hrs	2-120	30-50	100-13000@75	10-20	65-85	Very low	0 to 40
ZBB	500	Sec-10hrs	0.1-4	60-85	2000-2500	8-10	65-85	No	0 to 40
PSB	300-1000	Sec-10hrs	0.005-120	>400	100-13000@75	15	60-75	No	0 to 40
ZEBRA	100-200	Sec- few hrs	0.5-4	100-120	>2500	10-14	85-90	15	0 to 40

VRB batteries use vanadium dissolved in sulphuric acid solutions in different concentrations as electrolytes in the VRB. The electrolytes are separated by a proton permeable polymer membrane. Vanadium exists in four oxidation states and this very concept is used in the battery for storing and liberating electrons. Usage of same metal ions reduces the risk of contamination of the membrane and electrodes. The chemical reactions in the battery are as follows:

$$V^{4+} \leftrightarrow V^{5+} + e^- \quad V^{3+} + e^- \leftrightarrow V^{2+} \tag{1}$$

When the VRB is charging electrons are liberated from the positive terminal of the battery and oxidation takes place. In the negative half cell, reduction takes place and electrons are absorbed. These reactions are reversed when the VRB battery starts to discharge causing current to flow in reverse direction. The capacity of electrolyte holding tanks gives the energy capacity of the battery. The battery can be instantly charged by simply filling up of electrolyte liquid into the tanks. The power capacity will, however, depend on the area of electrode contact available within the cells. Hence, the inter-dependability between energy and power capacities is reduced making them flexible to design and operate.

3. Modeling of the PV-VRB HRES S*ystem in Matlab/SIMULINK*

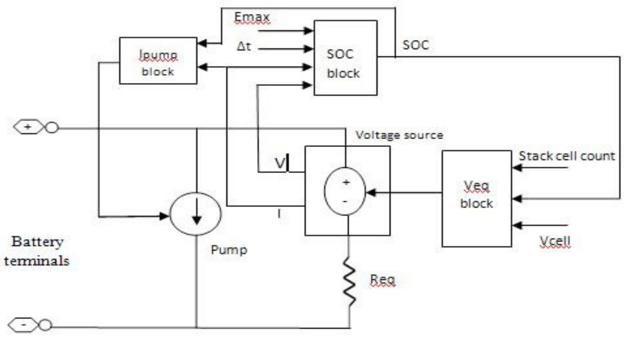

Fig.1. Block diagram of VRB battery

3.1 Modeling of a VRB Battery: A VRB battery is modelled as shown in Fig.1. The model evaluates the stack voltages, currents and parasitic and internal resistances of the battery. These parameters determine the operating characteristics of the VRB system. Internal losses are all current losses occurring inside the battery cell due to electrolyte contamination, electrode and membrane resistance and losses in electrons during passage between cells. Parasitic losses, on the other hand, are more concerned with external resistances in electrolyte circulation system. The following equations are used in modeling of the VRB system. The battery is modelled as a controlled voltage source by evaluating its cell stack voltage given by

$$V_{stack} = V_{eq} + 2\frac{RT}{F}\ln\left(\frac{SOC}{1-SOC}\right); \; V_{eq} = n.V_{cell} \tag{2}$$

The voltage of the VRB cell is modeled as a controlled voltage source using eq. (2). V_{eq} is calculated as product of number of stack cells and the individual cell voltage. The SOC of the battery is then evaluated using eq (3)

$$SOC(t) = SOC(t-1) \pm \frac{V \times I \times \Delta t}{E_{\max}} \tag{3}$$

The battery model also includes internal (R_{int}) and parasitic resistances (R_{par}) to account for the intrinsic and extrinsic losses as in eq (4). Intrinsic losses include mass transport resistance, kinetic resistance, resistance offered by the membrane, electrodes and conduction plates. Extrinsic losses are fixed losses occurring in the external circuitry and the pumps. Equivalent resistance is

$$R_{eq} = R_{\text{int}} \parallel R_{par} \tag{4}$$

The current to the circulating pumps is modeled as per the below equation [10].

$$I_{pump} = 1.011\left(\frac{I_{stack}}{SOC}\right) \tag{5}$$

3.2 *Modeling of PV panel:* The two-diode Solar cell model available in simulink library is considered in this study. The five parameter model is adopted which includes a current source, two diodes, series and parallel resistances. The net output current generated by the solar cell is given by eq (6) [10]

$$I = I_{ph} - I_s * (e^{\frac{V+I*R_s}{N*V_t}} - 1) - I_{s2} * (e^{\frac{V+I*R_s}{N_2*V_t}} - 1) - \frac{V + I * R_s}{R_p} \quad (6)$$

where

$$I_{ph} = I_{ph0} \times \frac{I_r}{I_{r0}} \quad (7)$$

and

$$V_t = \frac{kT}{q} \quad (8)$$

The solar cell thus modeled has an open circuit voltage of 0.6V and short circuit current of 7.34 amps. These cells are connected in an array form to get the desired voltage and current.

4. Simulation Results and Discussion

A Solar-VRB battery power system is considered for this study as shown in Fig.2. The Solar panel receives irradiation and generates the current to power a purely resistive domestic load. The VRB battery is connected in parallel to the PV system and its connections are managed through a charge controller. A 1kW PV model was built using Simulink solar cell model connected in an array to deliver 72V. The I-V and P-V curves obtained from the solar model thus designed is shown in Fig.3.

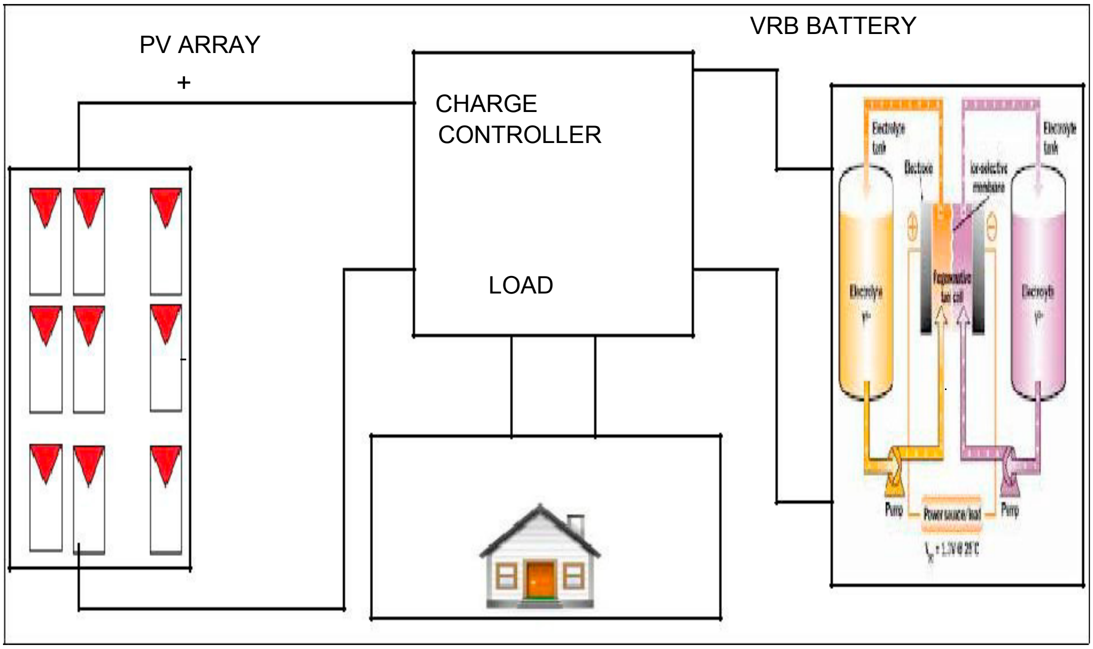

Fig.2. PV-VRB model

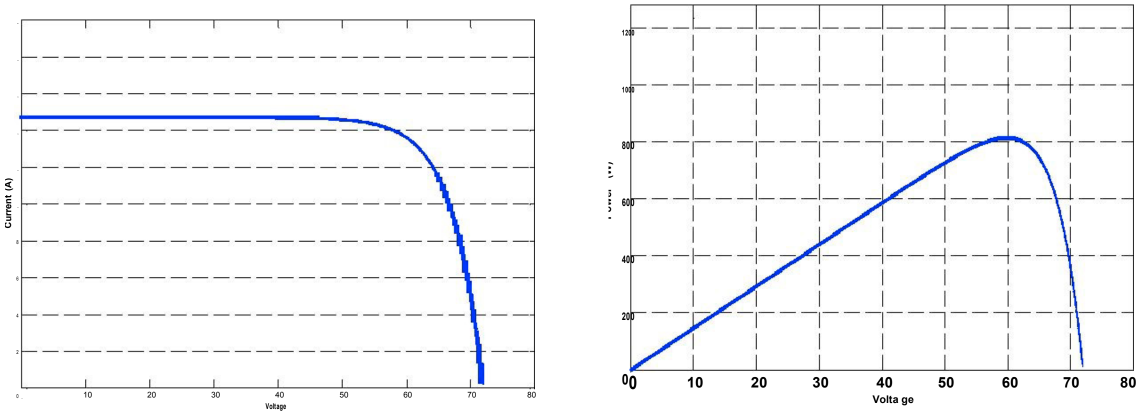

Fig.3. (a) I-V curve; (b) P-V curve

A 1.5kWh VRB battery has been modeled using eq. (1)-(3) in Simulink as shown in Fig.1. The cell stack voltage V_{cell} has been assumed to be 1.5 V and about 40 cells are stringed together in series to build up V_{eq} to about 60 V. R_{eq} has been evaluated to be about 0.75 ohms and was included in the battery model [11].The battery operation has been examined by connecting it in parallel with the PV system and a 500 W resistive load. A charge controller block has also been included which prevents over charging/discharging of the battery. It monitors the battery SOC continuously and generates control signals C1 and C2 which are complementary in nature so that when C1 is 1, C2 is zero and vice versa. These signals drive the connectivity switches of the battery with the PV system and the load. The depth of discharge of the VRB was assumed to be 80% in the simulation with initial SOC of 60%.

The simulation was run for a total of 72 hours. The battery charges through the PV during the day time until it reaches SOC_{max} after which the control block makes the signal C1 to 0 and C2 as 1. As C1 goes to 0 it disconnects the battery from the PV to avoid over charging. After sunset, the battery then discharges through the load until SOC_{min} condition is reached. This drives C1 to 1 and C2 to 0 and the battery is again connected to PV for charging. See Fig.4. The VRB current and voltage are plotted in Fig. 5. The aim of the proposed system is to deliver constant power to the resistive load. Thus, the battery operates about 4 complete charge-discharge cycle during this simulation. Approximating this value it can be concluded the annual charge-discharge cycles to about 480. Assuming the VRB battery to deliver 10,000 cycles, this count proves that a safe operation of battery with effective management can result in a service lifetime of 20.8 years which is deemed to be very good.

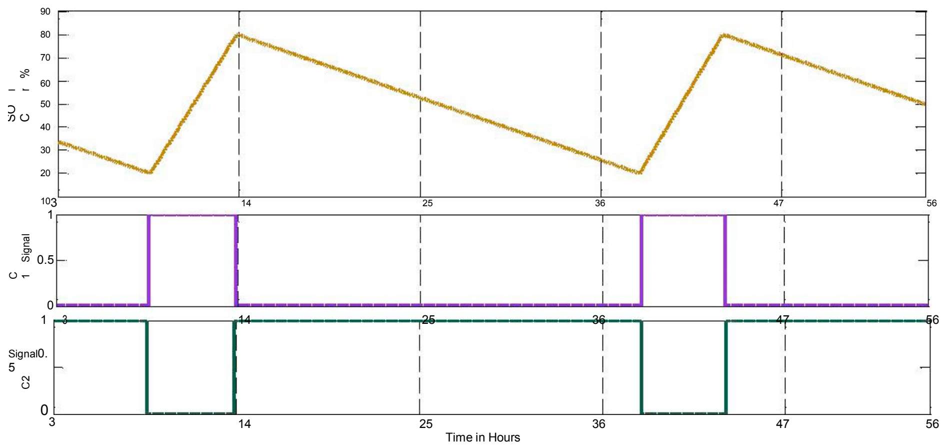

Fig.4. VRB simulation results (a) SOC (b) Control Signal C1 (c) Control Signal C2

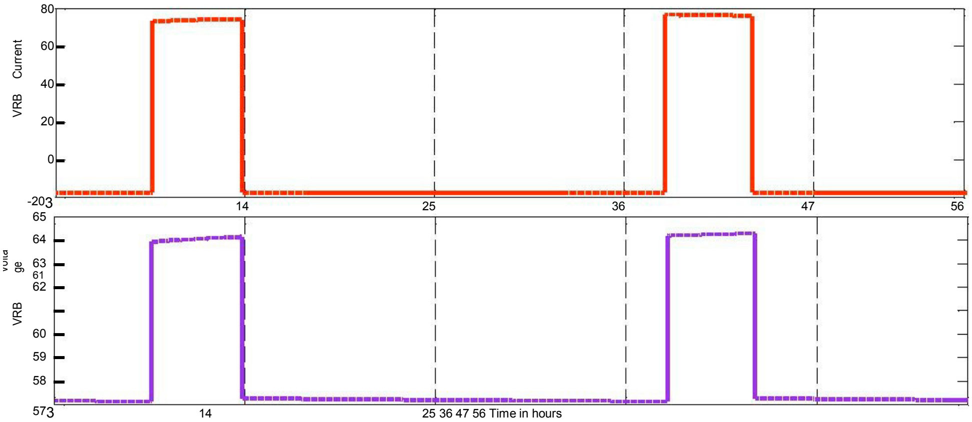

Fig.5. VRB simulation results (a) VRB Current (b) VRB voltage

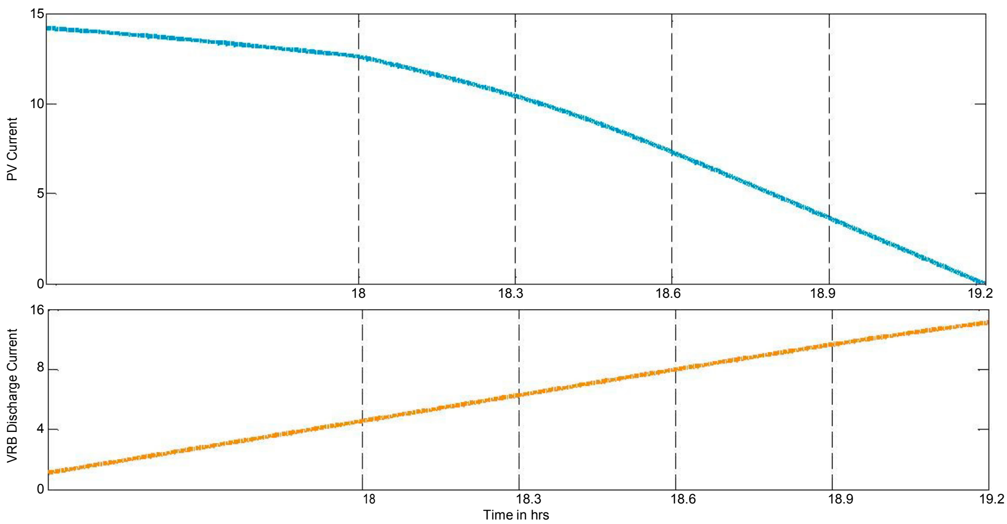

Fig.6. PV and VRB discharge current at decreasing irradiation

The PV-VRB system is then tested for operation to manage the intermittencies in irradiation on cloudy days. A varying irradiance condition is considered by simulating a decrease from 1000 W/m^2 to 0 W/m^2 in evening hours. Fig.6. shows the behavior of the PV and the VRB currents accordingly. It is clear that as irradiation decreases solar current also decreases and the VRB battery starts to discharge power to maintain constant power to the load. This proves that VRB battery modeled as proposed in this study functions as a requirement to balance the load under varying irradiations and helps in improving the reliability of the power system.

5. Conclusion

This paper elaborates the modeling, integration and operation of a PV-VRB battery system where the VRB battery charges during day time and discharges after sunset to power the load. The VRB system is modeled considering the evaluation of stack voltages, parasitic resistances, and state of charge of the battery. The solar power system is modeled using solar cells built as arrays in Simulink environment. The VRB battery model also includes a charge controller which prevents over charging or discharging of the battery storage to ensure its safe operation.

Simulation results prove effective functioning of the battery system thus modeled. The performance of battery under varying irradiation is also studied. VRB battery balances the load when solar power drops to ensure constant power output at the load. Thus, a stable PV-VRB hybrid power system is modeled and tested to enable firm power delivery to the consumers.

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