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Impedance source converter for photovoltaic stand-alone system with vanadium redox flow battery storage

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Abstract

Photovoltaic stand-alone systems require an energy storage component to provide continuous energy to the load when the solar intensity is inadequate. A vanadium redox flow battery has many prominent attributes which make its integration with a photovoltaic stand-alone system highly attractive. This paper investigates a 3kW photovoltaic stand-alone system including solar panels, impedance source converter and vanadium redox flow battery. Impedance source converters are new type of DC-DC converters with buck and boost operating capability, offer greater range of DC output voltage, high reliability and reduce ripple currents. The equivalent circuit and the charging characteristics of the vanadium redox flow battery are provided. Impedance source converter acts as the power conditioning converter which receives the maximum power from the photovoltaic panel and maintains the constant voltage across the battery by controlling its duty cycle. The results are provided to study the charging behavior of the battery and to validate the advantages.

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Keywords: Energy storage; impedance source converter; photovoltaic; vanadium redox flow battery;

1. Introduction

World's energy consumption is forecasted to more than twice by 2050 and more than three-fold by the end of the century. Incremental improvements in conservation and energy efficiency measures in present energy system will not be sufficient to render this demand. Fossil fuels are the major source of energy that are being utilized today. But

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their continuous consumption leads harmful environmental effects such as pollution that endangers health of all creatures and greenhouse gases associated with climate change. Finding out of clean energy with adequate supply for the future is the most daunting challenge.

Nomenclature

V_{eql}	equilibrium cell voltage (cell potential at 50% SOC)
F	Faraday constant = 96485 C/mole
T	temperature impact on VRFB
R	universal gas constant = 8.314510 J/k.mole
n	number of cell stacks

The contribution of alternative renewable energy sources is being increased worldwide. Our ultimate source of clean, inexhaustible and abundant energy is the sun. But the major problem in solar power generation is the fluctuation in its output. Efficient electrical energy storage technologies, amongst which energy storage batteries are giving solutions to this problem especially for stand-alone or micro grid applications. The lead acid battery is the dominant energy storage technology for stand-alone photovoltaic system due to its relatively low cost. However, this battery is limited by the life cycle under deeply discharging conditions. The nickel cadmium batteries have drawn great attention due to its low self-discharge and non-freezing characteristics, but they are very expensive, highly hazardous, and low efficient. Another battery is nickel iron. It has very long life, but it has low efficiency, very high rate of self-discharge and high specific weight [1]. The vanadium redox flow battery (VRFB) has received considerable attention recently for the storage unit of photovoltaic stand-alone system. VRFB offers almost unlimited energy capacity using larger electrolyte storage tanks and it can discharge for long periods with no ill effects. VRFB technology has many advantages including long lifecycle, high storage efficiency, scalability, high round trip efficiency, rapid response, and low maintenance costs. Operation under rapidly changing conditions is possible without impact on efficiency, because the integrated pump ensures the availability of electrolyte at all times near the electrodes [2,3].

2. Vanadium redox flow battery

VRFB is an electrochemical cell used for electricity storage systems. Like other flow batteries, VRFB stores chemical energy and converts it into electrical energy by a reduction-oxidation (redox) reaction between vanadium ions dissolved in the electrolytes. VRFB cell has two compartments separated by a cation permeable polymer exchange membrane with electrolytes of vanadium dissolved in sulfuric acid solution in each compartment as shown in Fig. 1. The electrolytes are stored externally from the battery and must be pumped through the cell for all the chemical reactions. In the VRFB, two reactions are taking place simultaneously on both sides of the membrane. During the discharge cycle, $V^{2+}$is oxidized to V^{3+} with the release of electrons in the anolyte. These electrons are removed from the negative electrolyte and transported through the external circuit (either DC or AC) to the positive electrolyte. In the catholyte, V^{5+} in the form of VO_2^+ takes an electron from the external circuit and is reduced to V^{4+} in the form of VO^{2+} . Hydrogen (H+) ions are exchanged between the anolyte and catholyte to maintain charge neutrality. During the charging cycle the reduction occurs in the anolyte and the oxidation in the catholyte and the electron flow is reversed [4].
The reactions of the VRFB electrodes can be expressed by the equations (1) and (2).
Positive Electrode Reaction:

$$VO^{2+} + H_2O + e^- \leftrightarrow VO_2^+ + 2\ H^+ \qquad (1)$$

Negative Electrode Reaction:

$$V^{3+} + e^- \leftrightarrow V^{2+} \qquad (2)$$

Total cell reaction can be expressed in equation (3).

$$VO_2^+ + 2H^+ + V^{2+} \leftrightarrow VO^{2+} + H_2O + V^{3+} \quad (3)$$

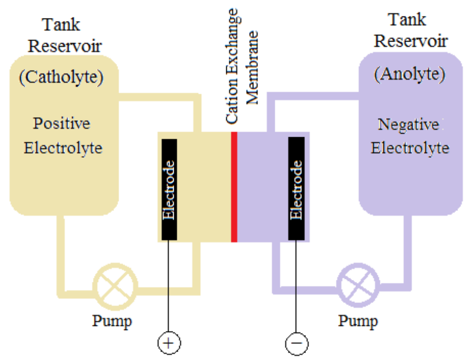

Fig. 1. Configuration of VRF battery.

Modeling of VRFB is necessary to make the analysis, simulation and characterization of the battery unit for photovoltaic stand-alone system. The electrical equivalent circuit model of the VRFB is shown in Fig.2. The VRFB model has two parts: the electrochemical model and the mechanical model. In the electrochemical model, stack voltage (V_{stack}), stack current (I_{stack}), and state of charge (SOC) of the electrolyte are determined by the battery terminal current (I_b). The pressure drop produced by the flow rate in the hydraulic system is determined in the mechanical model. There are two resistances in this model, the internal resistance and the parasitic resistance. Battery's losses such as membrane resistance, solution resistance, electrode resistance and etc., account for internal resistance. Power consumption by the system controller, recirculation pumps, and power loss from cell stack by-pass currents accounts for parasitic resistance [5,6].

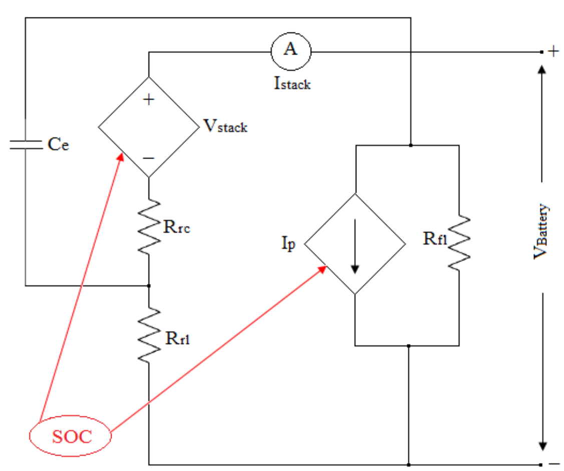

Fig. 2. Equivalent circuit of VRF battery.

The individual cell voltage of VRFB is directly related to the SOC of the battery and is given based on Nernst formula in equation (4),

$$V_{cell} = V_{eql} + 2\frac{RT}{F}\ln\left(\frac{SOC}{1-SOC}\right) \quad (4)$$

Equilibrium cell voltage is calculated as given in equation (5).

$$V_{eql} = n\, V_{cell} \tag{5}$$

In this model the controlled voltage directly depends on the SOC and the number of cell stacks. The stack voltage V_{stack} is modeled as a controlled voltage source whose value is also decided by the number of cells and the SOC. Thus V_{stack} is expressed as,

$$V_{stack} = n\left[V_{eql} + 2\frac{RT}{F}\ln\left(\frac{SOC}{1-SOC}\right)\right] \tag{6}$$

The battery output terminal voltage $V_{Battery}$ is thus depending on the stack voltage and the operational losses. In steady state, if I_{stack} is the input stack current, then $V_{Battery}$ can be expressed as,

$$V_{Battery} = V_{stack} + I_{stack}\,(R_{rc} + R_{rl}) \tag{7}$$

SOC of VRFB is estimated using the system SOC and the previous SOC.

3. Impedance source DC-DC converter

A new buck-boost converter known as impedance source converter are recently developed with added features of low ripple input current and high value of voltage gain [7]. These advantages make use of this converter for photovoltaic power generation with high tracking efficiency and better performance. Impedance source converter as shown in Fig.3 has two inductors and two capacitors in X-shape form at the input side. Switching positions of S_{w1} and S_{w2} give two operating modes: Non shoot-through mode and shoot-through mode [8,9].

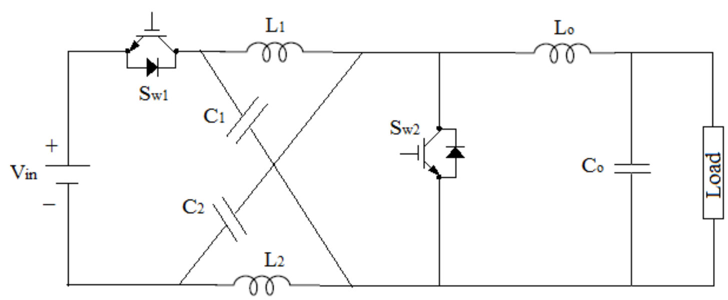

Fig. 3. Impedance source DC-DC converter.

If switch S_{w1} is closed switch S_{w2} is opened, the non shoot-through mode operation is obtained and the energy stored in L_1 and L_2 is transferred to the load. The load side inductor L_o is energized. Simultaneously, the capacitors C_1 and C_2 are charging. Shoot-through operation is obtained by reverse switching. Here C_1 and C_2 deliver their charges to L_1 and L_2. The input side is disconnected because the diode in S_{w1} is reverse biased.

Consider identical inductors and capacitors in the circuit. (L_1=L_2=L and C_1=C_2=C). So the voltage equations can be written as,

$$V_{C1} = V_{C2} = V_C \quad \text{and} \quad V_{L1} = V_{L2} = V_L \tag{8}$$

When the circuit operates in non shoot-through operation for a duration T_{nst}, the inductor voltage and the voltage across the switch S_{w2} can be written as

$$V_L = V_{in} - V_C \tag{9}$$

$$V_d = V_C - V_L = 2V_C - V_{in} \tag{10}$$

During shoot-through operation for a duration T_{st}, S_{w2} is short circuited. Hence voltage across S_{w2} is zero. The inductors and capacitors are connected in parallel. Thus inductor voltage equals the capacitor voltage.

The total switching time is $T_s = T_{nst} + T_{st}$. Now considering the average value of inductor voltage is zero over one switching time T_{st}, the voltage across the capacitor V_C is obtained as

$$V_C = \left(\frac{T_{nst}}{T_{nst} - T_{st}}\right) V_{in} = \left(\frac{1-D}{1-2D}\right) V_{in} \tag{11}$$

where $D = T_{st} / T_s$ is the shoot-through duty cycle.
The average output voltage is determined as

$$V_o = \frac{1}{T_s}\int_0^{T_s} v_d(t)dt = \frac{T_{st}.0 + T_{nst}(2V_C - V_{in})}{T_s} = \left(\frac{T_{nst}}{T_{nst} - T_{st}}\right) V_{in} = \left(\frac{1-D}{1-2D}\right) V_{in} = V_C \tag{12}$$

4. System configuration and results

A 3 kW photovoltaic residential stand-alone system is considered in this configuration. It includes PV panel, impedance source converter with maximum power point tracking technique (MPPT) technique, bidirectional charge controller and VRFB storage device. Only the charging behavior of VRFB is studied in this work. To study the discharging behavior an inverter, transformer and AC loads should be connected. The SHARP-A215A2 photovoltaic panel is taken for modeling and simulation, because this panel is commercially suitable for residences, office buildings and solar power stations. This panel has 60 series connected polycrystalline PV cells and provides 215W of nominal maximum power, 36.7V of open circuit voltage and 7.82A of short circuit current. To achieve a minimum 3 KW power, 14 such panels are required to be connected in series/ parallel combination. A 3kW, 40 V residential VRFB is modeled in this work for storage. The VRFB parameters are calculated based on 15 % internal losses and 6% parasitic losses. According to this estimation, the internal resistance is divided as R_{rc} (0.025 Ω) and R_{lc} (0.0915 Ω). There are 39 cells in VRFB stack in series and each cell has a capacitance of 6 F. Thus the capacitance of electrode C_e is calculated as 0.154 F. The equivalent circuit of VRFB battery shown in Fig.2 is simulated in MATLAB to study its charging characteristics and its voltage and current are shown in Fig.4.

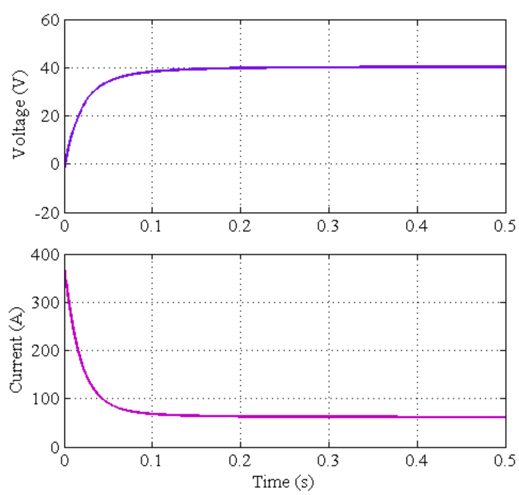

Fig. 4. Voltage and current waveforms of VRFB.

The output voltage and power of the PV panel is continuously varying based on solar intensity and temperature. A variable DC voltage is unsuitable for VRFB charging and it can damage the battery. The impedance source converter with MPPT technique is integrated to extract maximum power from the PV panel and to provide a constant voltage to VRFB. Here the perturbation and observation method of MPPT is applied [10]. The shoot-through duty cycle control of impedance source converter, connecting the PV panel and the VRFB, consists of PI controller providing the required voltage gain for the converter. The input voltage to the impedance source converter is obtained from PV panel which varies with the solar intensity and temperature, but the output voltage is kept constant to the VRFB. The impedance source converter is designed with the following values: $L_1 = L_2 = 1.2$mH and $C_1 = C_2 = 470\mu$F. The switching frequency is 10 kHz. The complete system consists of PV panel, impedance source converter and VRFB is developed in MATLAB and is shown in Fig.5. This model is simulated and waveforms of the PV panel power, PV panel voltage and the output voltage of the converter which is given to VRFB are obtained and are given in Fig.6. From the waveforms, it is clear that the charging voltage to VRFB is kept constant under varying solar intensity (from 0.2kW/m^2 to 1.0kW/m^2), but with temperature constant.

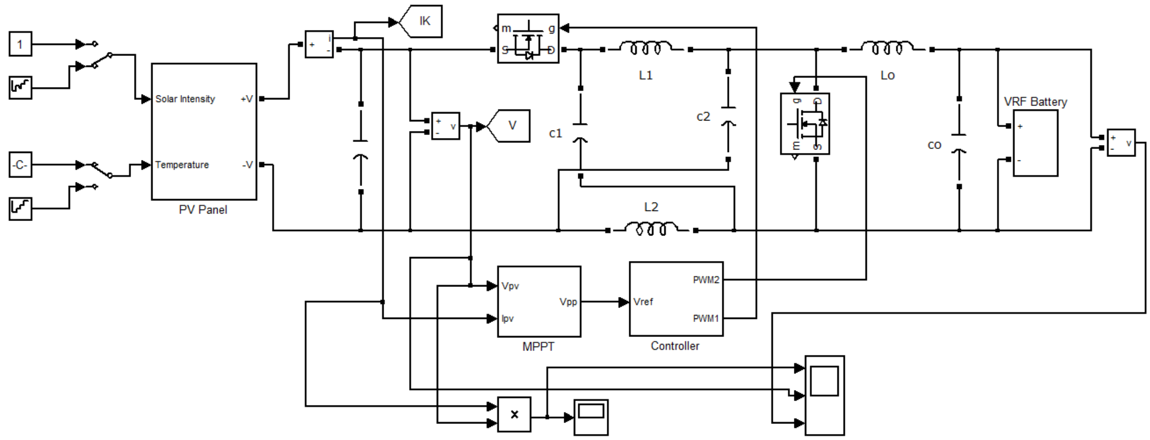

Fig. 5. MATLAB model of PV panel-VRFB system.

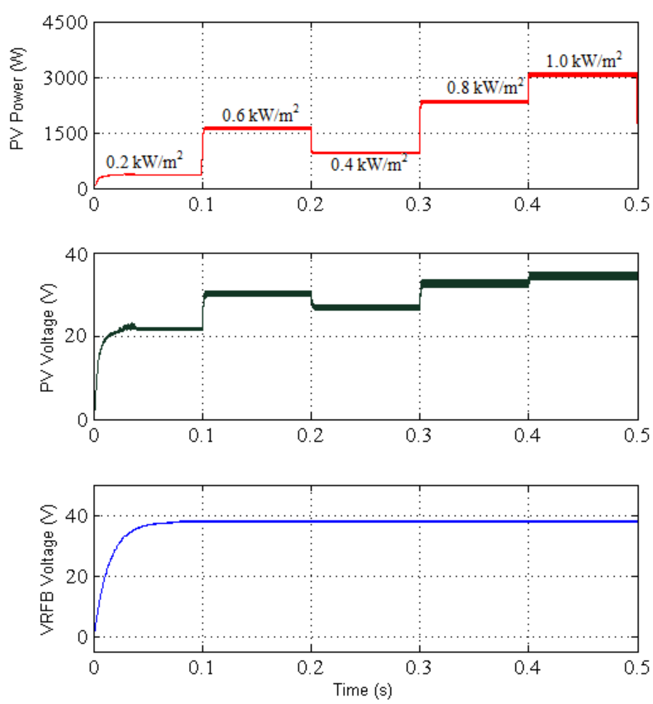

Fig. 6. PV power, PV voltage and battery voltage waveforms.

5. Conclusions

The storage of solar energy by VRFB has been approached for PV stand-alone system. This paper has proposed the integration of PV panel with the VRFB through an impedance source converter in order to smooth the output power fluctuations. The electrical equivalent circuit model of VRFB has been developed using MATLAB to study its characteristics. Impedance source converter can buck or boost the PV voltage and maintain a constant voltage across the battery terminals for charging. Impedance source converter has been preferred over conventional buck boost converter because it can reduce voltage and current ripples to least values and can provide high voltage gain during boost mode of operation. The complete integrated system has been configured and simulated for a 3 kW residential application. Simulation studies show that the maximum power tracking from the PV panel and energy storage in VRFB are satisfied under varying solar intensity. Thus VRFB storage is a promising solution and well suited for PV stand-alone applications because of its high scalability, high efficiency, long life, fast response, and low maintenance requirements.

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