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Development and validation of a real time flow control integrated MPPT charger for solar PV applications of vanadium redox flow battery

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ABSTRACT

In this paper a real time flow control integrated solar PV Maximum Power Point Tracking (MPPT) charge controller for Vanadium Redox Flow battery (VRFB) is developed and its performance is demonstrated under practical dynamic insolation profiles. Unlike the conventional Lead acid and Li-ion batteries the major challenge in designing the solar MPPT charger for VRFB lies in simultaneous control of charging current and corresponding flow rate for maintaining the maximum overall system efficiency of the VRFB besides achieving the maximum charging efficiency. In this work, the usual Perturb & Observe (P&O) algorithm for designing MPPT charger for conventional batteries has been significantly modified in case of VRFB charge controller by including the real time control of flow rate along with the charging current. The proposed charging algorithm has been validated by a practical 1 kW 6 h VRFB system operation. The modified MPPT based three stage constant current constant voltage (CC-CV) charging topology is found to be the most efficient for VRFB charging from solar PV. Solar MPPT charging of VRFB with a constant flow rate leads to premature thermal shut down of the charge controller resulting incomplete charging of VRFB which is prevented by the use of dynamic flow control integrated solar PV MPPT charging. Two practical case studies of sunny weather and cloudy weather conditions have been adopted for validation of the integrated MPPT charge controller. The proposed VRFB charging system is a generalised one and thus can be very useful for large scale VRFB application in solar PV power systems.

1. Introduction

Battery energy storage systems (BESS) are drawing great interest in the field of renewable energy applications such as solar PV, wind etc. For large-scale renewable power systems, Vanadium Redox Flow Battery (VRFB) is being considered as one of the most potential BESS because of its several merits; such as, independent scalability of its power and energy capacity, deep discharge capacity, free from cross-contamination and above all its very long life cycle, closely matching to that of a solar PV power plant [1]. The VRFB technology was developed by Maria Skyllas-Kazacos [2] and her research group at University of New South Wales (UNSW) in the mid-1980s. Over the years, efforts to make the VRFB technology [3–5] more efficient has led to several avenues of research like stack design [6], modifications to the electrode [7,8], membrane [9,10] and electrolyte [11–13] materials. The realisation of practical VRFB operation and performance remains incomplete without an electrical equivalent model [14–17]. A recent work published by Bhattacharjee et al. [18] proposed a generalised electrical equivalent model of VRFB system where the dynamic optimal flow rate was estimated to improve the VRFB overall system efficiency. The model performance was demonstrated by a hybrid micro-grid system [19]. The dynamic internal parameters of VRFB was extracted and flow rate was optimized considering both stack loss and pump loss simultaneously in the work of Bhattacharjee et al. [20]. The necessity of dynamic impedance matching between solar PV source and VRFB while designing efficient battery management system (BMS) was reported in their paper. The performance analysis of VRFB in photovoltaic micro grid was addressed by Nguyen et al. [21]. Qiu et al. [22] described the field validated model of VRFB for microgrid application. Turkar et al. [23] introduced a VRFB model for large scale applications. Hosseina et al. [24] discussed an optimal scheduling for distribution network with redox flow battery storage to satisfy the peak shaving, load levelling etc. Turkar et al. [25] described the utilization of VRFB to avoid wind power fluctuation penalties in an electricity market. Considering these practical applications, BMS for VRFB is very much essential for its efficient interfacing with renewable energy sources. Design of a proper charge controller [26] is one of the crucial requirements of an efficient BMS for on-grid and off-grid solar PV, wind power applications. Karami et al. [27] demonstrated the analysis and implementation of an adaptive PV based battery floating charger. Considering the intermittency

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Nomenclature

SOC	state of charge
I_{stack}	stack current (A)
Q	electrolyte flow rate ($cm^3\,s^{-1}$)
N	electrolyte capacity ($A\,s\,cm^{-3}$)
n_e	no. of electrons transferred per mole
F	Faraday's constant ($96{,}485\,C\,mol^{-1}$)
c	vanadium concentration ($mol\,L^{-1}$)
$P_{pump\_electrical}$	pump electrical power consumption (W)
η_{pump}	pump efficiency
R	universal gas constant ($8.3144\,J\,K^{-1}\,mol^{-1}$)
T	ambient temperature (K)
k	proportionality constant
$E_{Stack\,(OCV)}$	VRFB stack open circuit voltage (V)
n	no. of series cells in VRFB stack
$E_{Cell\_eq\,(at50\%SOC)}$	VRFB cell equilibrium potential (V)
$I_{parasitic}$	parasitic current (A)
R_P	parasitic resistance (Ω)
R_0	electrolyte solution resistance inside the stack (Ω)
R_{ct}	charge transfer resistance inside the stack (Ω)
C_{dl}	double layer capacitor (F)
I_d	diffusion current (A)
C_i	concentration of vanadium species ($mol\,L^{-1}$)
D_m	diffusion coefficient ($m^2\,s^{-1}$)
x	thickness of the membrane (μm)
$E_{self\_discharge}$	self discharge potential drop (V)
$R_{self\_discharge}$	self discharge resistance (Ω)
E^+	positive electrode potential (V)
E^-	negative electrode potential (V)
E^0_+	positive electrode equilibrium potential (V)
E^0_-	negative electrode equilibrium potential (V)
C^+_O	concentration of oxidized vanadium species in the positive electrolyte side ($mol\,L^{-1}$)
C^-_O	concentration of oxidized vanadium species in the negative electrolyte side ($mol\,L^{-1}$)
C^+_R	concentration of reduced vanadium species in the positive electrolyte side ($mol\,L^{-1}$)
C^-_R	concentration of reduced vanadium species in the negative electrolyte side ($mol\,L^{-1}$)
E_{stack}	VRFB Stack terminal voltage (V)
i_{charge}	charging current (A)
$i_{discharge}$	discharging current (A)
η_{max}	maximum VRFB overall system efficiency
P_{Charge}	power consumed by VRFB during charging power (W)
$P_{Discharge}$	power delivered by VRFB during discharging (W)
P_{stack}	power inside the VRFB stack (W)
P_{int_loss}	power lost due to VRFB stack internal resistance (W)
$\eta_{charging}$	VRFB charging efficiency
K	permeability of porous electrode (m^2)
μ	dynamic viscosity of the electrolyte (Pa s)
Δp_{stack}	pressure drop across the stack (Pa)
Δp_{pipe}	pressure drop due to pipes (Pa)
P	density of the electrolyte ($kg\,m^{-3}$)
V_s	velocity of the electrolyte inside the pipe ($m\,s^{-1}$)
Z	height of the pipe (m)
G	acceleration due to gravity ($m\,s^{-2}$)
h_m	minor losses (m)
h_f	friction losses (m)
f	Friction factor
L	length of pipe (m)
D	hydraulic diameter of the pipe (m)
Re	Reynolds' number

and low efficiency of solar PV source, the maximum power point tracking (MPPT) [28–30] technique needs to be applied for improved power conversion while charging the battery storage from solar PV source. The literatures [31–33] described the design and performance of solar MPPT based battery charge controller. The power converters play significant role in efficient conversion of solar PV power to the battery and the load/grid. Fathabadi et al. [34,35] demonstrated a high efficiency DC-DC boost converter based solar PV battery charge controller performance. A dc-dc buck converter operation and control for stand-alone solar battery charge controller was discussed by López et al. [36]. Nguyen et al. [37] proposed a low cost and fast charging topology for solar vehicle applications. With an emphasis on solar PV charge controller, it may be noted that the voltage excursion/cell in VRFB is about 38% as compared to that of same capacity lead acid battery which is about 20%. Thus the role of MPPT in VRFB charging is more important than lead acid or similar battery storage systems. VRFB has a wider range of cell voltage (1–1.6 V/cell) as compared to lead acid (1.95–2.4 V/cell) batteries and therefore it is more attractive to apply MPPT while charging VRFB from solar PV source. For a 48 V lead acid battery the voltage range is 46.8–54.4 V which is equivalent to a 34 cell VRFB stack. Therefore the voltage range for the equivalent VRFB system becomes 34–54.4 V which demands much more application of MPPT algorithm for its interfacing with solar PV source for avoiding loss of solar PV power. Unlike the other conventional batteries like lead acid, Li-ion, etc. the major challenge in designing efficient charge controller for VRFB is its simultaneous control of charging current and flow rate to achieve the maximum VRFB overall system efficiency besides improved charging efficiency. For fast charging operations of VRFB, the high current cause excessive rise in temperature inside VRFB stack which may lead to premature thermal shut down of the charging system in order to maintain safe operation of VRFB. It may be noted that VRFB suffers from thermal precipitation at a temperature above 40 °C as reported by Tang et al. [38] and Yan et al. [39]. Hence the flow rate needs to be dynamically optimized [40–42] in order to overcome the problem of stack temperature rise beyond safe limit and incomplete charging.

In this paper a real time flow control based solar PV MPPT charge controller for VRFB system has been developed and its performance is demonstrated under dynamic solar irradiance profiles. The charging power conditioning unit is the DC-DC buck converter designed for efficient interfacing VRFB with solar PV source. Three different charging algorithms are implemented on the developed charging system using dsPIC (dsPIC33FJ32MC204) controller platform and their performances are compared. Besides the MPPT based CC-CV charging topology for maximizing the charging efficiency, the real time control of flow rate is also incorporated in the charging algorithm in order to achieve maximum VRFB overall system efficiency and controlled temperature rise inside the VRFB stack. The modified charging topology also prevents the possibility of premature thermal shut down of the charge controller due to temperature rise beyond 40 °C and hence ensures complete charging of VRFB. The performance of the charge control algorithm is validated by a 1 kW 6 h VRFB system. The proposed controller is a generalised one and thus very useful for large scale VRFB systems in solar PV applications.

Rest of the paper is organised as follows, Section 2 gives a schematic description of the proposed solar PV charge controller for VRFB system. Section 3 discusses the modelling and simulation of different subsystems of the proposed VRFB charge controller. In Section 4, the design of experimental set up and different subsystems have been described. The model performance and experimental results with two practical case studies are shown in Section 5. Finally, Section 6 includes the conclusion of this paper.