Peak Power Shaving Using Vanadium Redox Flow Battery for Large Scale Grid Connected Solar PV Power System

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***Abstract*—This paper presents a demand side power management scheme for large scale grid connected solar PV power system with optimized penetration of battery energy storage system (BESS) under intermittent solar irradiance. Vanadium Redox Flow Battery (VRFB) claims to be a promising energy storage to improve the power supply reliability for large-scale PV applications due to its scalability, independent power and energy capacity, deep discharge capacity and very long life cycle compared to other conventional battery energy storages. In this work, the storage integrated solar PV system will supply the required load demand and the surplus power will charge the battery and export the remaining power to the grid after satisfactory charge completion. During PV Power generation deficiency, the battery will be in discharging mode and thus shaving the peak load demand during that period. It is observed that at a very low available state of charge (SOC) less than 10% of VRFB storage and inadequate power generation from solar PV source together causes peak load demand dissatisfaction which can be managed by importing power from the AC utility grid. Considering AC local loads of 50kW, a suitable bi-directional inverter along with necessary filter is designed between the Point of Common Coupling (PCC) and the grid. The entire power management scheme has been designed by developing an electrical equivalent model of 10kW 5hr VRFB storage and 80kW$_P$ solar PV array with electrical interface modules and converters in MATLAB/Simulink environment. The battery SOC prediction algorithm is also implemented to lengthen storage lifetime and the demand side power supply reliability. The penetration of utility grid is executed only in the worse situation of poor solar PV power output and very low SOC of VRFB storage thus making the overall PV power system cost effective and efficient. The presented research work has dealt with the simulation work to smoothen the peak load demand the results are very useful for field validation.**

Keywords- Solar PV;Vanadium Redox Flow Battery;Peak Load;Bi-directional inverter;grid.

I. Introduction

Utilization of renewable energy sources such as solar, wind etc. for electric power supply has drawn much attention in recent years due to global environmental concerns associated with conventional energy generation and potential worldwide energy crisis. Solar PV energy systems have leading potential among the renewable energy sources but face practical challenges in implementation because of intermittent nature. Integrating appropriate energy storage with solar PV power system helps in smoothening the power fluctuation and improves the reliability of power supply at the load end. Vanadium Redox Flow Battery (VRFB) is a promising energy storage option for large stationary electricity storage systems because of its very long life cycle, scalability of power and energy capacity and deep discharge capability. Considering the availability of PV power and battery state of charge (SOC) the load demand matching reliability of a solar PV system undergoes a challenge. To mitigate this difficulty a VRFB storage integrated grid [1-4] connected solar PV system model is introduced in this paper with an efficient power management algorithm. The power conditioning unit (PCU) including the dc-dc boost converter and a bi-directional inverter play an important role to allow power flow to and from the grid as and when required. In this paper an 80kWp solar PV array, a 5kW 10hr VRFB storage [5-8] are designed in MATLAB/Simulink and the power flow is optimized by the proposed algorithm to satisfy demand side requirement under dynamic irradiance and temperature profile.

II. Proposed System Topology

A. Block diagram representation

The proposed grid connected solar PV VRFB hybrid power system [9-11] has been designed based on the topology as shown in the following block diagram in figure 1,

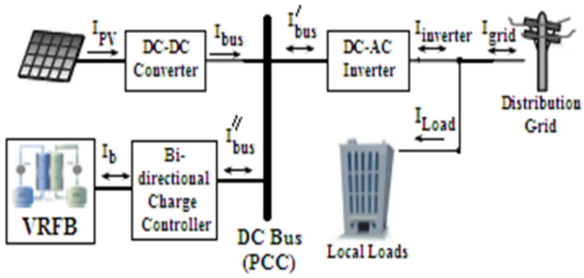

Fig. 1 Schematic of the proposed system

B. *Model description of each subsystem*

The proposed system model comprises of five major subsystems; solar PV array, MPPT controller & DC-DC boost converter, VRFB storage, bi-directional inverter and the proposed power management algorithm. The parameters chosen for modeling and simulation are shown in table 1 below.

TABLE I. TECHNICAL SPECIFICATION USED FOR SYSTEM MODELLING

Parameters	**Technical specifications required to model the proposed grid connected solar PV system with VRFB storage**		
	Solar PV Array	***VRFB Storage***	***Load***
Power rating	80 kWp	10 kW 5 hr	50 kW (Peak load)
Voltage rating	1100 Volts at MPP at STC	320V for 200 cells	415V (3-Ph)

1. *Solar PV array model:*

In this work the solar PV array is modeled based on the following practical technical specifications and a MATLAB/Simulink library has been formed.

TABLE II. TABLE FOR TECHNICAL SPECIFICATIONS OF SOLAR PV ARRAY

Parameters	**Values**
No. of series strings	32
No. of parallel strings	10
Module open open circuit voltage (V_{OC})	43V
Module maximum voltage (V_{mpp})	35.2V
Module short circuit current (I_{SC})	7.76A
Module maximum power (at STC)	7.1A
Module Maximum Power (P_{mpp})	250W_P
Temperature coefficient of V_{OC}	-0.3028 (%/deg.C)
Temperature coefficient of I_{SC}	0.0352 (%/deg.C)
Shunt Resistance (R_{sh}) /cell	111.87Ω
Series resistance (R_{Se})/cell	0.42 Ω

* STC: Standard Test Condition (1000 W/m^2 and 25^{0}C)

2. *Maximum Power Point Tracking (MPPT) and DC-DC boost converter:*

To extract maximum power from the solar PV array, Perturb and Observe algorithm is used for its simplicity in implementation. The algorithm performance is tested under a practical irradiance profile. The flow chart of the P&O MPPT algorithm is shown in figure 2.

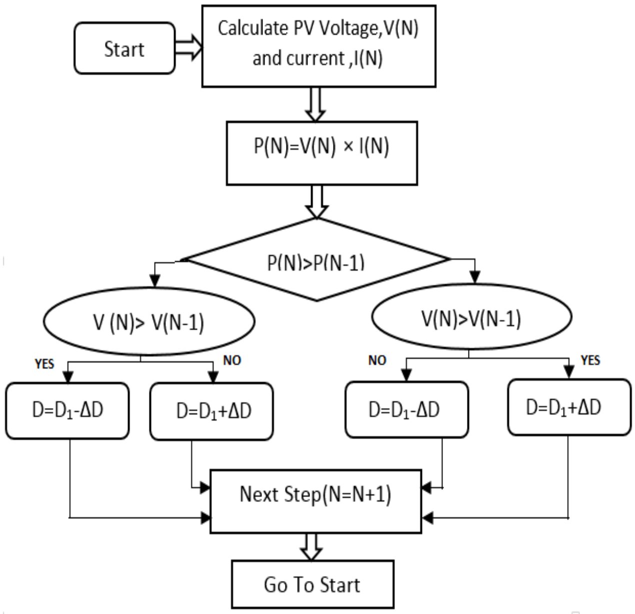

Fig. 2 Flowchart of Perturb & Observe MPPT algorithm

A suitable dc-dc boost converter is designed in MATLAB/Simulink to track the maximum power from the solar PV array. The aim of maintaining high dc link voltage at the PCC (point of common coupling) is to minimize losses. The MATLAB/Simulink model of the dc-dc boost converter is shown in figure 3.

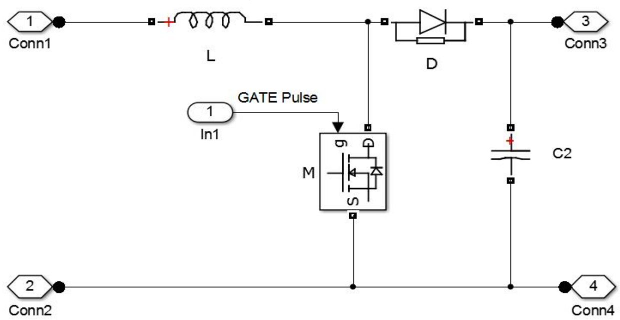

Fig.3 MATLAB/Simulink model of DC-DC boost converter

3. *VRFB storage modeling:*

VRFB stores chemical energy and generate electricity by a redox reaction between vanadium ions dissolved in the electrolytes. The most significant feature of the VRFB is the modularity of their power (Watt) and energy (Watt-hour) ratings are independent of each other and hence scalable independently according to the solar PV and the load capacity. VRFB are essentially comprised of two key major subsystems; the cell stack where chemical energy is converted into electrical energy in a reversible process and the two electrolytic tanks where the energy is stored. The electrolyte flow to the stack is controlled by the two identical pumps.

A proton exchange membrane (PEM) placed between the two half cells allows proton (H^+) crossing from anode side of the stack to the cathode and vice versa during charging and discharging. The scalability of energy capacity of VRFB can be made feasible by adding more electrolytes to the tanks. Hence unlike other conventional battery storage systems, complete renovation of the whole battery storage system is not required in case of VRFB.

The relation between battery stack voltage and State of Charge (SOC) is governed by Nernst equation [6] and it is represented by,

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

For stack voltage, $V_{stack} = n \times V_{cell}$ (2)

And battery terminal voltage is expressed as,

$$V_b = V_{stack} - I_{stack}(R_{Reactance} + R_{Resistive}) \quad (3)$$

For VRFB SOC estimation,

$$SOC = \frac{P_{stack} \times T_{step}}{E_{capacity}} \quad (4)$$

The physical model of VRFB is shown in Fig. 4,

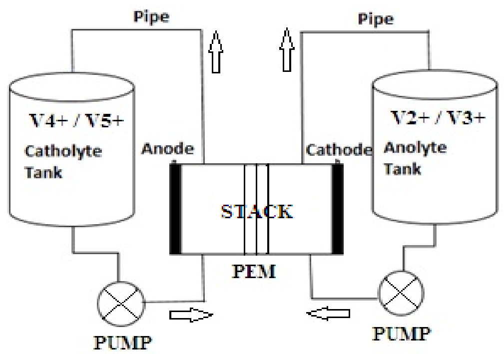

Fig. 4 Physical model of a VRFB system

Based on the above electrical equivalent equations, a practical 200cell 10kW 5hr VRFB system has been modeled for the proposed grid connected solar PV power system in MATLAB/Simulink environment shown in figure 5.

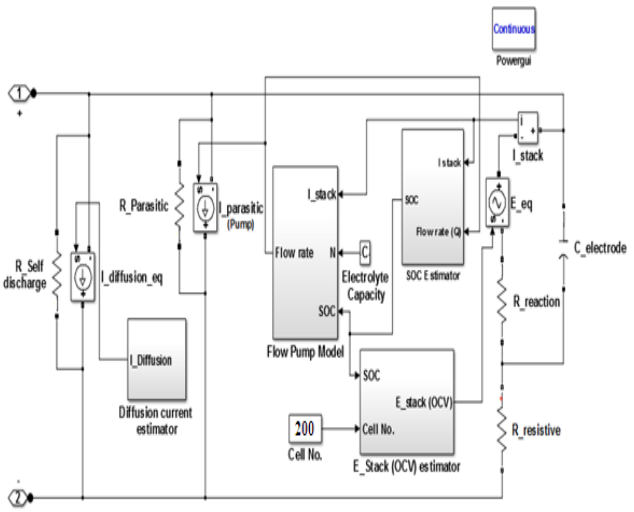

Fig. 5 MATLAB/Simulink model of the proposed VRFB system

In this model, the pump and the associated controller circuit losses (parasitic losses) are represented as a combination of controlled current source (I_parasitic) and a shunt resistor (R_parasitic) in the VRFB electrical equivalent model. Similarly, the self-discharge loss of VRFB is also represented in the model.

4. Bi-directional inverter modeling:

To ensure power flow to the grid and from the grid in required condition, a suitable bi-directional inverter has been designed in MATLAB/Simulink as shown in figure 6. The inverter dc-link input side is connected to the PCC (point of common coupling) of the proposed grid connected solar PV system. The sinusoidal PWM is applied to control the inverter operation as shown in figure 6.

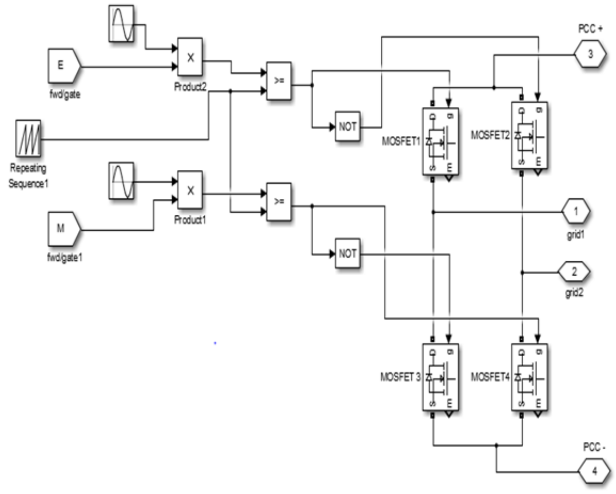

Fig. 6 MATLAB/Simulink model of bi-directional inverter with PWM controller

5. Proposed power management algorithm:

The algorithm for demand side power management proposed in this work is described below.

If $P_{PV} > P_{LOAD}$ and 90% ≥ $VRFB_{SOC}$ ≥ 10%,
Then Solar PV supplies the load demand (P_{LOAD}) and VRFB is in charging mode.
Else if, $P_{PV} > P_{LOAD}$ and $VRFB_{SOC}$ ≥ 90%,
Then PV will deliver excess power to the Grid after satisfying P_{LOAD}.
If $P_{PV} < P_{LOAD}$ and 90% ≥ $VRFB_{SOC}$ ≥ 10%,
Then $P_{PV} + P_{VRFB} \longrightarrow P_{LOAD}$
Else if, $P_{PV} < P_{LOAD}$ and $VRFB_{SOC}$ ≤ 10%,
Then $P_{PV} + P_{GRID} \longrightarrow P_{LOAD}$
If $P_{PV} \ll P_{LOAD}$ and $VRFB_{SOC}$ ≥ 50%, (At night or cloudy weather)
Then $P_{GRID} + P_{VRFB} \longrightarrow P_{LOAD}$
Else if $P_{PV} \ll P_{LOAD}$ and $VRFB_{SOC}$ ≤ 10%,
Then $P_{GRID} \longrightarrow P_{LOAD}$

The SOC upper and lower limits of VRFB has intentionally been kept within 10% to 90% in order to avoid deep discharge and safe operation when connected to the PCC of the grid connected Solar PV system.

III. SIMULATION RESULTS AND DISCUSSION

Based on the proposed power management algorithm, the whole system is simulated under practical irradiance and temperature data as input to the model. The optimized power sharing for demand side management over a span of 8:00 hours to 20:00 hours is shown in figure 7. It has been observed from figure 7 that the peak load demand occurs around 10:00 hours to 12:00 hours and 18:00 hours to 20:00 hours respectively. The VRFB storage is charged or discharged depending on the availability of solar PV source, VRFB state of charge (SOC) and the instantaneous load demand. At night time the load demand is managed by Grid and VRFB storage together as shown in the results.

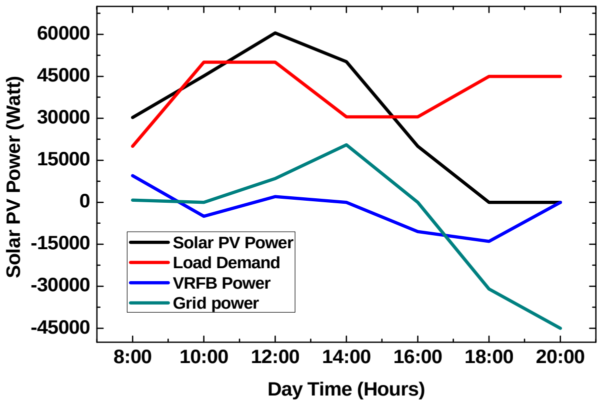

Fig. 7 Power sharing in a grid connected solar PV system integrated with VRFB storage for demand side management

IV. CONCLUSION

The proposed work has demonstrated the performance of VRFB storage for peak load shaving in a grid connected solar PV power system. An efficient power management algorithm is introduced in this work for optimized power sharing among the solar PV, VRFB storage, load and the distribution grid. The VRFB storage state of charge (SOC) is kept within an operating limit of 10% to 90% to avoid deep discharge and thus lengthening the battery lifetime.

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BIOGRAPHICAL INFORMATION

Ankur Bhattacharjee was born on 16th December, 1988. He pursued his B.Tech and M.Tech in Electrical Engineering in 2010 and 2012 respectively. At present he is pursuing PhD research at Indian Institute of Engineering Science and Technology, Shibpur. He is a member of the Instituion of Engineer India. His research areas are; solar PV system design, Microgrid, energy storage and power management.

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Hiranmay Saha was born on 4th January, 1946. He received his PhD in Solar Cells in Jadavpur University He is a chair professor and Coordinator of the Centre of Excellence for Green Energy & Sensor systems, IIEST, Shibpur, India. He has teaching, research and industry experience of over 50 years. He is Fellow of IEE (UK), IETE and Member of IEEE, NCS (WB), Dept. of Science & Technology (WB), WBREDA. His present areas of research are, Solar cell fabrication, solar PV systems, smart microgrid, energy storage.