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An Energy Storage System for Wind Turbine Generators-Battery and Supercapacitor

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ABSTRACT:

Wind is the world's fastest growing energy source today. The wind farm power output have large fluctuations due to sudden wind speed changes. A possible solution for wind power quality and lower need of reserve energy is the storage of wind power in an energy storage equipment. Energy storage is an essential part of wind energy system to overcome the intermittent power generation. The performance of the energy storage system can be improved by combining vanadium-redox flow battery (VRB) and supercapacitor integrated with wind turbine generators. This paper proposed the integration of VRB and supercapacitor with wind turbine generator and the simulation results of VRB and supercapacitor are presented in MATLAB/Simulink.

Keywords: Energy storage system, Vanadium-redox flow battery, Supercapacitor, Wind energy.

I. INTRODUCTION

Wind power is the fastest growing renewable energy source due to its improving technologies and economic competitiveness. Wind power has its unique impacts when connected to a power system due to its power electronic interface and the nature of wind [1]. The time frame of the phenomena of interest varies from microseconds, associated with power electronics switching, to minutes and hours, related to wind fluctuations[2]. The most important features that make them unique can be summarized by: the type of interface with the grid, their relative size, and perhaps most notably, the stochastic nature of the power source[3].

While the first two issues can be tackled relatively easily, the third is a much more imposing technical barrier. Although intermittent generation can depend on central generation to help balance its output, this inevitably will prove to be a limiting factor in terms of the penetration level. Furthermore, the two components of variability, intermittency and uncertainity will both result in additional costs incurred as a result of wind integration[4].

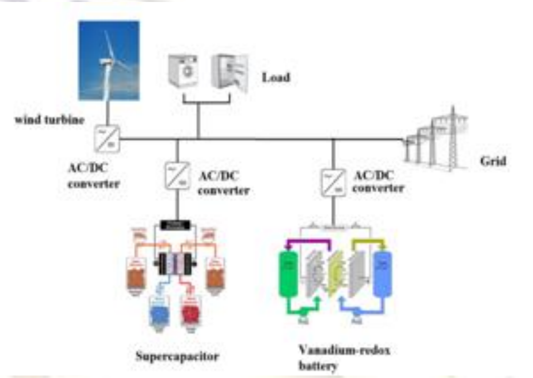


Fig.1. Schematic of wind-energy storage system

Due to this drawback, a high penetration of the WES(Wind Energy System) can create stability, reliability and power quality problems in the main electric grid[5]. Thus, an optimum way of integrating the energy obtained from the WES must be designed. The microgrid is being analysed as a solution to this problem. A microgrid is a system that has at least one distributed energy resource (renewable or not), energy storage systems, power conversion systems, control systems and loads (see Fig.1). Its main characteristic is its ability to work not only connected, but also disconnected from the main electrical grid[6].

An Energy Storage System (ESS) is usually necessary in a microgrid to maintain the power and energy balance as well as to improve the power quality[7]. Nowadays there are many different types of storage technologies, but unfortunately none of them satisfies the requirements of the microgrid application: an ESS must have a high power density in order to face fast power variations, and at the same time it must have a high energy density to give autonomy to the microgrid[8]. For that reason, it is necessary to associate more than one storage technology creating a Hybrid Energy Storage System (HESS)[9]. In this work a HESS based on the association of a Vanadium Redox Battery (VRB), as long-term storage device, and a Supercapacitor (SC), as a short-term storage device, is investigated. The VRB is a flow battery which has independent energy and power densities[10]. It has a long life-cycle, up to

10000 charge/discharge cycles. The VRB has theoretically no depth-of-discharge limitation and a good efficiency, between 75% and 85%[11]. Although the electrochemical response time of the VRB is limited by the flow of the electrolyte, which is controlled by pumps. As the electrochemical reaction occurs, it is necessary to introduce new active species in the stack, and therefore the flow rate must be adapted to each reaction rate.

The use of supercapacitor in parallel with the battery allows reducing the power rating of the VRB and thus also the cost[12]. The supercapacitor stores the energy in electrical form, without converting it into any other kind of energy in order to save it[13]. The most important advantages of a supercapacitor are its very high efficiency (95%), very high power density (up to 10000 W/kg), its tolerance to have deep discharges, and its very long life-cycle (500000 cycles at 100% depth-of-discharge). However, its energy density is very low and it has a high self-discharge current (5% per day). Thus, its use is not oriented for long-term applications[14,15].

The association of a SC and a VRB permits to take advantage of the characteristics of both ESSs obtaining a high energy density, high power density, high life-cycle and high efficiency HESS. This article describes the VRB-Supercapacitor energy storage system for wind turbine generator and the simulated results of energy storage system for the operation of energy storage system intended for wind energy applications.

II. MODELLING

The modeling of supercapacitor and VRB is given as follows.

1. Supercapacitor

The dynamic model that has been used to represent the SC is shown in Fig. 2.The first-order supercapacitor model is a series *RLC* circuit, which is frequency, temperature, and voltage dependent in very accurate models[2]. In wind applications, the supercapacitor operates in a frequency range well below its self-resonant frequency. Therefore, the inductance is ignored[3]. A constant capacitance and equivalent series resistance (ESR) model gives enough accuracy and is adopted in this study. The model is based on a 0.58-F 400-V supercapacitor module. The ESR is 0.6 Ω, as specified by the manufacturer and verified . The supercapacitor works in the 10% to 100% SOC range, i.e., 0.3 to 1 per unit (p.u.) voltage. The effective energy capacity of each supercapacitor module is 42.2 kJ (0.5 $*$ 0.58 F $*$ 400 V2 $*$ 0.9) or 0.0117 kWh[4].*3*

Fig. 2. Dynamic model of supercapacitor.

2. Vanadium redox battery

The electrical equivalent circuit model of the VRB that has been used is shown in Fig. 3. This model to simulate the effect of a VRB for wind power smoothing application[3]. The parameters of the model are determined assuming that at the operation point where the stack current is maximum and the state-of-charge (SOC) 20% the power losses of the VRB are of 21%. Therefore, at this operation point the overall efficiency is supposed to be 79%[4]. The transient behavior of the VRB is related to the electrode capacitance as well as to the VRB is related to the electrode capacitance as well as to the concentration depletion close to the electrodes[5]. The proposed model has the following characteristics: (i) the SOC is modeled as a dynamically updated variable;(ii) the stack voltage is modeled as a controlled voltage source, and the power flowing through this source will impact the SOC;(iii) the variable pump loss model, as a controlled current source, is controlled by the pump loss current *Ipump* that is related to the SOC and the current *Istack* flowing through the battery stack[4,5]. VRB power loss includes two parts: (1) one is from the equivalent internal resistances $R_{reactor}$ and $R_{resistive}$ and (2) one is parasitic loss due to the parasitic resistance, *Rfixed* and the pump loss. VRB equivalent circuit parameters are calculated on the basis of the estimated losses for the worst case. When the SOC of 20% is assumed as the worst case, we estimate 15% internal loss and 6% parasitic loss, and resultant total 21% loss[7,8].

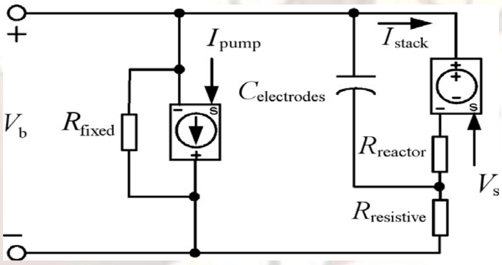


Fig. 3. Equivalent circuit of the VRB

Therefore, the VRB will provide a rated power *PN* with 21% loss. If the cell stack's output power

$$P_{stack} = P_N \; / (1 - 21\%) \qquad (1)$$

A single cell stack voltage *Vcell* is directly related to the SOC, as follows:

$$V_{cell} = V_{equilibrium} + 2k \,.\, lg\left(\frac{SOC}{1 - SOC}\right) \qquad (2)$$

where k is a constant related to temperature impact on the battery operation, k = 0.059; $V_{equilibrium}$ is a standard electromotive force difference of each cell[5] , $V_{equilibrium}$ = 1.25 V. The parasitic loss, which is related to the pump operation, is separated into fixed and variable losses as follows

$$P_{parasitic} = P_{fixed} + P_{pump}$$
$$= P_{fixed} + K(I_{stack}/SOC) \qquad (3)$$

The parasitic resistance R_{fixed} and the pump loss current are calculated as

$$R_{fixed} = (V_b^2)/(SOC) \qquad (4)$$

$$I_{pump} = K\left(\frac{Istack}{SOC}\right)/V_b \qquad (5)$$

where V_b is the output terminal voltage of VRB; K is a constant related to pump loss.The internal resistance loss of 15% can be approximately divided into two parts, i.e., the loss of 9% from $R_{reactor}$ and the loss of 6% from $R_{resistive}$. Each cell has 6 F capacitance, i.e., $C_{electrodes}$ = 6F. The single cell voltage is very low, so a high voltage VRB needs a number of cells connected in series[5,6]. The SOC is defined as

$$SOC = \left(\frac{Energy\ \ in\ VRB}{Total\ \ energy\ \ capacity}\right) \qquad (6)$$

$$SOC_t = SOC_{t-1} + \Delta SOC \qquad (7)$$

$$\Delta SOC = \Delta E/E_N$$
$$= (I_{stack}.V_b.\Delta t)/(P_N.T_N) \qquad (8)$$

Where SOC_t and SOC_{t-1} are the SOC at the instants of t and t-1,respectively; ΔSOC is the SOC variation in a time step Δt; T_N is the time when total energy E_N is charged into the battery at a power P_N.

The equivalent circuit model based simulations are employed to study the charge–discharge characteristics of VRB[4]. The parameters are listed as: rated power P_N = 270 kW, rated capacity E_N = 405 kW h, initial voltage value V_N = 810 V, the cell number n = 648, $R_{reactor}$ = 0.174 Ω, $R_{resistive}$ = 0.116 Ω, R_{fixed} = 60.5 Ω.

III. INTEGRATED WTG AND ESS SYSTEM

A permanent-magnet synchronous machine (PMSM) WTG integrated with a VRB supercapacitor hybrid ESS is modeled as shown in Fig. 4[4]. The PMSM WTG power rating is 1.5 MW, the dc bus voltage is 1400 V, and the grid-side ac voltage is 690 V. The rectifier and inverter are three-level converters. The VRB and the supercapacitor are connected to the dc bus through two bidirectional dc/dc choppers. The energy management-algorithm manages the storage and discharge of energy from VRB and supercapacitor.

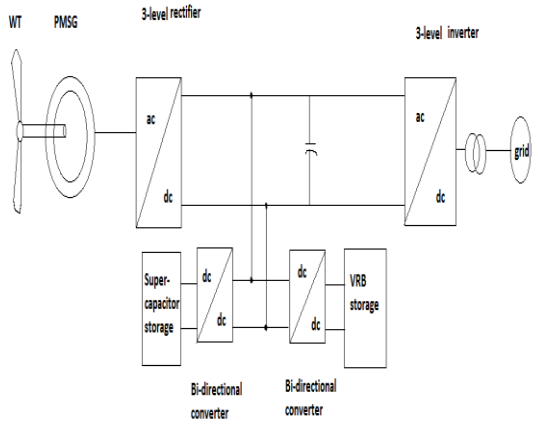


Fig.4.Wind turbine generator-VRB and supercapacitor

The Fig.5 is the main system diagram of wind in combination with battery and supercapacitor. The wind turbine generator used here is 1.5 MW PMSG (permanent magnet synchronous generator),810 V battery and 58 F supercapacitor. The three gratez bridge is used here so that the pulses are given through pulse width modulation(PWM) generator. The pulses are given from the PWM generator to trigger the MOSFET during phase angle and amplitude changes. If there is excess power from the wind, and if main source supplies power to the load the excess power from the wind turbine generator is stored in battery and supercapacitor. When the wind power output is low, the power demand is maintained by the discharge of energy from battery and supercapacitor.

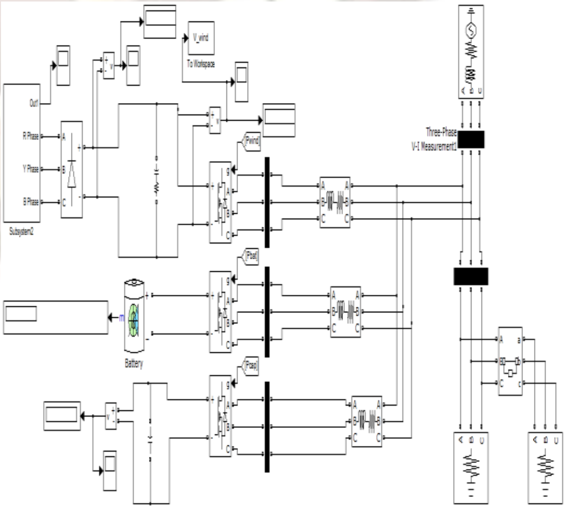


Fig.5. Simulink of wind-battery and supercapacitor

IV. SIMULATED RESULTS

The simulated performance analysis of voltage and current characteristics of Vanadium redox battery and supercapacitor are determined in Fig.6(a,b) and Fig.7(a,b). The vanadium redox battery and supercapacitor is charged at the rate of 50%. When the phase angle of the Battery and supercapacitor reduces, a part of wind power is used for charging. When there is reduction in wind power the stored energy from battery and supercapacitor is discharged to the load which is controlled by algorithm. The simulated results shows the state of charging and discharging of current and the voltage in p.u. The real power and the reactive power are inferred from the battery, supercapacitor, wind turbine and the loads.

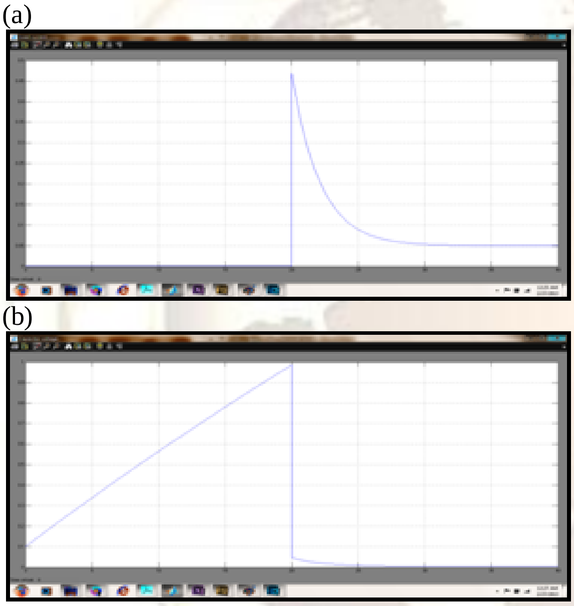
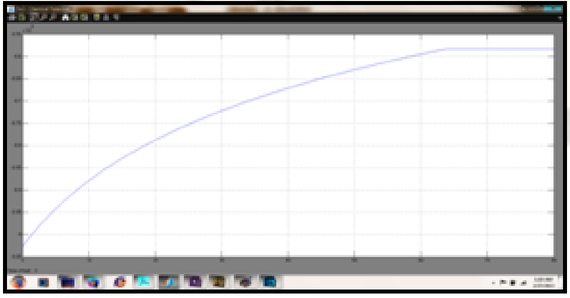


Fig. 6. (a) Current of supercapacitor vs time,(b) Voltage of supercapacitor vs time

(a)



(b)

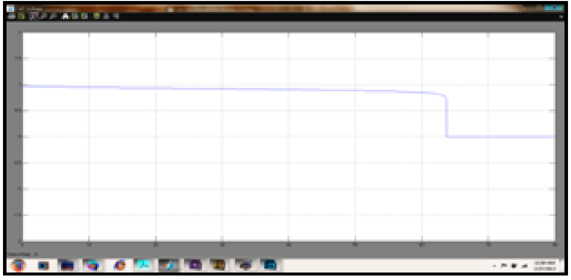


Fig. 7. (a)Voltage of VRB vs time , (b) Current of VRB vs time.

V. CONCLUSION

Although the storage management scheme is able to adjust to accommodate errors in wind power prediction, long term storage would be required in order to continue to provide a preset power output. During transients, the storage device provides an effective means to ride through disturbances and exhibits superior characteristics during and following extreme voltage events. The supercapacitor meets the real power need, by absorbing or delivering power as required by the system, thus improving the damping profile. VRB presents many advantages in applications to large-scale power energy storage. Its terminal voltage remains stable when the SOC is within 20–80%, to employ only a single-stage AC/DC converter in the VRB-based ESS to achieve charging and discharging controls, as a result of the simple system structure with high efficiency. VRB-based ESS was added at the exit of a grid-connected wind farm to improve power quality of the power system through filtering the fluctuations of wind power. Simulation results demonstrate the proposed hybrid ESS has advantages of lower battery cost due to its reduced power rating, prolonged battery life due to lower depth of discharge, and higher overall system efficiency. The simulated results determines the voltage and current characteristics of VRB and supercapacitor.The excess energy from the wind turbine power output is utilized for battery and supercapacitor charging. By utilizing the discharged energy from the energy storage system the power quality is maintained.

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