Energy storage system-based power control for grid-connected wind power farm

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\textbf{A B S T R A C T}

Wind power is characterized as intermittent with stochastic fluctuations, which can result in deviation of grid frequency and voltage when the wind power ratio is high enough. These effects have a definite impact on stability and power quality of grid operation. This paper proposes an energy storage system (ESS) based power control for a grid-connected wind power system to improve power quality and stability of the power system. Vanadium redox flow battery (VRB), as an environmentally-friendly battery provided with many advantages, is employed in the ESS. A dynamic mathematical model of VRB is built by using an equivalent circuit, and its charging and discharging characteristics are analyzed. The VRB’s stable voltage is available in a wide range (around 20–80% state of charge), which is suitable for utilization of a single-stage AC/DC converter in the VRB-based ESS. With a proposed energy storage control method, VRB-based ESS is added at the exit of the grid-connected wind farm to filter fluctuations of wind power, which ensures that smooth power will be injected into the grid and which improves power quality of the power system. Simulations and experiments are carried out to verify the proposed power control method for these grid-connected wind power systems. The grid-connected wind farm with VRB-based ESS, wind speed (characterized as gust and stochastic wind), and wind turbines are modeled in simulations. Simulation results show that the grid-injected active power from the wind farm is effectively smoothed, and reactive power support can be provided for the grid by the designed VRB-based ESS. Experimental verification is achieved with a low power bench, where a RT-LAB real-time simulation platform and a direct torque controlled induction motor simulate a real wind turbine and a wind speed model is built in the RT-LAB real-time simulation platform. The experimental results verify the proposed scheme through demonstrating a stable and smooth power flow injected into the grid though the wind power fluctuated.

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1. Introduction

In recent years, wind power generation technology is developing rapidly and is becoming more mature \cite{1–3}. Wind velocity presents intermittent and stochastic characteristics, which leads to relatively large fluctuations of wind power. Power fluctuations can result in deviation of grid frequency and voltage \cite{4}, and affect stability and power quality of grid operation \cite{5}. If wind power does achieve 20% or more of total system power, peak capacity and safe operation of the grid will face enormous challenges. Nowadays, with a growing number of large-scale grid-connected wind farms and the continuous extension of installed capacity, the wind power ratio is becoming higher. Therefore, the fluctuations of wind power should be overcome urgently to avoid a degradation of the grid’s performance.

All over the world, researchers have proposed several solutions to smooth wind power fluctuations. For example, for a given hour of the day, wind-deficient farms could be compensated by wind-benefiting farms \cite{6}, so a general planning method was proposed in \cite{6} to minimize the variance of aggregated wind farm power output by optimally distributing a predetermined number of wind turbines over a preselected number of potential wind farming sites, in which the objective is to facilitate high wind power penetration through the search for steadier overall power output. Kassem et al. proposed a hybrid power system by combining the continuously available diesel power and locally available, pollution-free wind energy \cite{7–9}, of which the main goal is to reduce fuel consumption and in this way to reduce system operating costs and environmental impact. A wind turbine generator was controlled with a voltage source converter to smooth power fluctuations in \cite{10}, and pitch
control of the turbine blades was employed for the same purpose in [11], but their abilities and control ranges are limited due to reducing wind power acquisition. FACTS were also used to maintain grid voltage stability at the wind power access point by adjusting reactive power [12–14], but it cannot smooth active power fluctuations [15].

Large-scale energy storage technology provides an effective approach for large-scale grid-connected wind farms to improve the wind power quality [16–26], which not only can smooth active power but also can regulate reactive power. As a result, large-scale wind farms with energy storage systems (ESSs) can be easily and reliably connected to the conventional grid. There are many energy storage schemes for this purpose, for example, the compressed air energy storage (CAES) system is a mature and reliable bulk energy storage technique with promising potential to accommodate high wind power penetration in power systems [16,18]. It operates with fast adaptability and low cost, but requires a suitable sealed underground geological cavern for air storage, as a result of that it is located far from user/load. Flywheel based ESS is used in [22] to improve power quality and stability of the wind farms. Superconducting magnetic-based ESS is achieved in [23,24] to smooth the fluctuations of wind power. Super-capacitors are employed in [25,26] to adjust wind farm output power. Practical applications of flywheel, super-conduction, and super-capacitors in the ESS for wind power are restrained due to their high cost or low capacity. At present, lead-acid batteries are widely used because of their mature technology and low price, but cycle life is very limited. Sodium sulfur batteries with their high energy density, high efficiency of charge/discharge and long cycle life, are primarily suitable for large-scale non-mobile applications such as grid energy storage [27–29]. However, it requires a high operation temperature of 280–360 °C and has the highly corrosive nature of sodium polysulfide. Also, hybrid power generation systems use ESS to improve power quality of the grid, for example, diesel generators and renewable energy sources (such as wind power and photovoltaic power units) are deployed at different locations of the system, and electric double layer capacitors as energy storage are utilized to play the main role to control the system’s power quality and system frequency [17]. Operation schedule of thermal generators, wind generators, photovoltaic power generation systems, and batteries are optimized through considering the transmission constraint to reduce operational cost of thermal units [19].

The vanadium redox flow battery (VRB) is well suited for applications of large-scale power energy storage when compared to other energy storage batteries, because of its large capacity, long life, low materials cost, low maintenance requirements, and fast response, etc. [30,31]. VRB-based ESS has been applied to wind power projects in Hokkaido of Japan, in Australia, etc. Currently, VRB has already started to achieve its commercial operation and is expected to play an important role in wind power system and other renewable energy source areas.

In this paper, VRB-based ESS is directly added at the exit of a wind farm to regulate grid-injected power, which will absorb wind power fluctuations, provide an amount of reactive power support, and effectively improve power quality and stability of the power system. The experimental results and simulation results verify the proposed scheme.

2. VRB model

2.1. Operating principle of VRB

As shown in Fig. 1 [31,32], VRB is an electrochemical cell divided into two compartments by an ionic membrane where battery reaction takes place. Positive and negative vanadium electrolytes are stored in two tanks. A pump per compartment will achieve the electrolyte circulation between the tank and the cell, which will improve battery performance and efficiency.

Total power available is related to electrode area of the cell and total energy stored in VRB, which depends on both state of charge (SOC) and amount of active chemical substances. Simplified electrode reaction processes are as follows:

\[ \text{For positive electrode, it is} \]
\[ V^{4+} + e^{-} \xrightarrow{\text{Charge}} V^{5+} \]

\[ \text{For negative electrode, it is} \]
\[ V^{3+} + e^{-} \xrightarrow{\text{Discharge}} V^{2+} \]

2.2. VRB modeling

VRB model based on an equivalent circuit [31,32] takes into account physical and mathematical characteristics, as shown in Fig. 2. The proposed model has the following characteristics: (1) the SOC is modeled as a dynamically updated variable; (2) the stack voltage is modeled as a controlled voltage source, and the power flowing through this source will impact the SOC; (3) the variable pump loss model, as a controlled current source, is controlled by the pump loss current \( I_{\text{pump}} \) that is related to the SOC and the current \( I_{\text{stack}} \) flowing through the battery stack. VRB power loss
includes two parts: (1) one is from the equivalent internal resistances $R_{\text{reactor}}$ and $R_{\text{resistive}}$ and (2) one is parasitic loss due to the parasitic resistance $R_{\text{fixed}}$ 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. Therefore, the VRB will provide a rated power $P_N$ with 21% loss [32]. If the cell stack’s output power is

$$P_{\text{stack}} = \frac{P_N}{1 - 21\%} \quad (1)$$

A single cell stack voltage $V_{\text{cell}}$ is directly related to the SOC, as follows:

$$V_{\text{cell}} = V_{\text{equilibrium}} + 2k \cdot \lg \left( \frac{\text{SOC}}{1 - \text{SOC}} \right) \quad (2)$$

where $k$ is a constant related to temperature impact on the battery operation, $k = 0.059$; $V_{\text{equilibrium}}$ is a standard electromotive force difference of each cell, $V_{\text{equilibrium}} = 1.25$ V.

The parasitic loss, which is related to the pump operation, is separated into fixed and variable losses as follows

$$P_{\text{parasitic}} = P_{\text{fixed}} + P_{\text{pump}} = P_{\text{fixed}} + k \left( I_{\text{stack}} \cdot \frac{V_b}{\text{SOC}} \right) \quad (3)$$

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

$$R_{\text{fixed}} = \frac{V_b^2}{P_{\text{fixed}}} \quad (4)$$

$$I_{\text{pump}} = k \left( I_{\text{stack}} \cdot \frac{V_b}{\text{SOC}} \right) \quad (5)$$

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 $R_{\text{reactor}}$ and the loss of 6% from $R_{\text{resistive}}$. Each cell has 6 F capacitance, i.e., $C_{\text{electrodes}} = 6$ F. The single cell voltage is very low, so a high voltage VRB needs a number of cells connected in series.

The SOC is defined as

$$\text{SOC} = \frac{\text{Energy in VRB}}{\text{Total Energy Capacity}} \quad (6)$$

One way to track the SOC is by

$$\text{SOC}_t = \text{SOC}_{t-1} + \Delta \text{SOC} \quad (7)$$

$$\Delta \text{SOC} = \frac{AE}{E_N} = \frac{P_{\text{stack}} \cdot \Delta t}{E_N} = \frac{I_{\text{stack}} \cdot V_b \cdot \Delta t}{P_N \cdot T_N} \quad (8)$$

where $\text{SOC}_t$ and $\text{SOC}_{t-1}$ are the SOC at the instants of $t$ and $t - 1$, respectively; $\Delta \text{SOC}$ is the SOC variation in a time step $\Delta t$; $T_N$ is the time when total energy $E_N$ is charged into the battery at a power $P_N$.

2.3. Charge–discharge characteristics of VRB

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

Fig. 3 shows the SOC variation in a charge–discharge cycle, where the VRB is charged at a constant current of 320 A for the first 1.5 h, and discharged at the same current for another 1.5 h later.

3. Wind farm with VRB-based ESS

3.1. System structure

As shown in Fig. 5, VRB-based ESS is directly added at the exit of grid-connected wind farm to regulate the grid-injected power,
which does not need to change the existing status of the grid-connected wind farm. Since a wind farm consists of many generation units, each generation unit may contribute random complementary power to the total power, which mitigates the fluctuation of total grid-injected power. As a result, the proposed scheme requires a smaller total VRB capacity when compared to the distributed installation of VRB-based ESS at the exit or dc-link bus of every wind generation unit. The resultant benefits include lower maintenance, improved system reliability, and low cost, etc.

The configuration of Fig. 5 includes 10 generator units, with a total installed capacity of 25 MW. Each unit is a direct-drive permanent magnet synchronous wind turbine, with the rated capacity of 2.5 MW. The VRB-based ESS consists of 30 VRB energy storage units, with a total rated power of 8.1 MW, and the rated power of 270 kW per unit. To simplify the illustration of the proposed system, the paper supposes that every generation unit is the same in the wind farm, and every VRB-based ESS is also the same.

Every direct-drive wind turbine mainly includes the wind turbine, permanent magnet synchronous generator (PMSG), dual-PWM converters, and inductors, through a 690 V/10 kV step-up transformer connected to the point of common coupling (PCC). As the aforementioned reason, this paper uses a single-stage AC/DC converter as power converter to control VRB charging and discharging, and the AC/DC converter’s AC side is connected to the exit of the wind farm through a 380 V/10 kV step-up transformer. There are local loads at the grid side of PCC.

3.2. Direct-drive wind turbine control system

Fig. 6 shows the control strategy of a dual-PWM converter for each direct-drive wind turbine [33]. The decoupling control of torque and reactive power can be achieved by controlling the d-axis and q-axis current components of the generator-side converter, respectively. The active power $P$ and reactive power $Q$ flowing into the grid can be controlled by the d-axis and q-axis current components of the grid-side converter, respectively. It is very convenient to adjust the power factor and make the system provide reactive power support for the grid; also the maximum power point tracking (MPPT) with hill-climbing method will ensure the capture of maximum wind energy [34–36].

3.3. VRB control system

The control principle of the VRB-based ESS is shown in Fig. 7. Active power and reactive power of the VRB-based ESS are controlled by a bi-directional AC/DC converter, through two given references denoted as $P'_{\text{ref}}$ and $Q'_{\text{ref}}$, respectively.

Every direct-drive wind turbine could operate at unity power factor by controlling the grid-side converter during normal operation of the grid. If the grid needs reactive power support, the VRB-based ESS provides the required reactive power to the grid by controlling the AC/DC converter, and for this case a given reactive power $Q'_{\text{ref}}$ will be set rather than a zero reactive power reference.

In output active power of wind farm, power components over 0.01 Hz will badly degrade the power quality of the power system [37]. Therefore, VRB-based ESS is designed to filter this part of power fluctuations through a first-order Butterworth High Pass Filter (HPF) in this paper. The designed HPF transfer function $G_H(s)$ is expressed by

$$G_H(s) = \frac{16s}{1 + 16s}$$

As shown in Fig. 7, $P_W$ represents output active power of the wind farm, which is filtered by the HPF $G_H(s)$, as a result of the given active power reference $P'_{\text{ref}}$ for the VRB-based ESS. The system operation should avoid the VRB have any over-charge or over-discharge, since it will degrade the VRB performance. Therefore, an energy management unit is necessary to ensure the VRB’s safe operation, which will control the VRB’s SOC within an allowlable range. The VRB-based ESS will stop work if the VRB terminal voltage is greater than the predefined upper limit or less than the predefined lower limit, that is, if $V_{\text{VRB}} > V_{\text{VRBmax}}$ or $V_{\text{VRB}} < V_{\text{VRBmin}}$, there will be $P'_{\text{ref}} = 0$ and $Q'_{\text{ref}} = 0$. The VRB-based ESS is limited to the rated power if the reference power $P'_{\text{ref}}$ is greater than the rated power $P_B$. Active power and reactive power of the VRB-based ESS can be controlled by its d-axis and q-axis current components, respectively.

4. Simulated results

The wind farm with VRB-based ESS is simulated to verify the proposed energy stored grid-connected wind power generation system. The parameters of every VRB are listed in Section 2.3, and the parameters of direct-drive wind turbine are as follows: air density $\rho = 1.225$ kg/m$^3$, wind turbine radius $r = 38.5$ m, pitch angle $\beta = 0^\circ$; The PMSG rated capacity $P_{\text{SN}} = 2.5$ MW, pole pairs $n_p = 40$, rated frequency $f_N = 15.885$ Hz, stator resistance $R_s = 0.001$ $\Omega$, d-axis and q-axis inductance $L_d = L_q = 1.5$ mH; The
grid-side inductance $L = 0.5$ mH; dc-link capacitor $C = 12$ mF, and given dc-link voltage $U_{dref} = U_{dc} = 1.2$ kV.

A wind speed model characterized as gust and stochastic wind and a wind turbine model are built to simulate wind power fluctuations. As shown in Fig. 8, the wind speed variation of the wind farm presents a gust during the time interval of 20–60 s, and a stochastic wind occurs during 60–100 s. The given reactive power of VRB-based ESS is 0 MVar during 20–60 s, and 1 MVar during 60–100 s. The PMSG speed $\omega_{pm}$, the output active power $P$ and the reactive power $Q$ of every wind turbine, the DC–link capacitor voltage $U_{dc}$, the grid-injected active power, and the grid-injected reactive power are shown in Figs. 9–13, respectively.
From Fig. 9, we can see that the rotor speed of each PMSG is adjusted to capture the maximum wind energy through the MPPT control when the wind speed is changing.

From Fig. 10, we can find that the active power fluctuations of each wind turbine are huge, with a maximum variation of 0.8 MW, due to the variation of wind speed and the utilization of maximum wind energy. The output reactive power of each wind turbine is kept on 0 Var by controlling the grid-side converter. Fig. 11 shows that the dc-link capacitor voltage can be well maintained at 1.2 kV through the voltage closed-loop control of the grid-side converter.

Fig. 12 shows that the instantaneous active power fluctuations of wind farm reach 8 MW. When there is the VRB-based ESS, the power fluctuations of wind farm can be rapidly smoothed, and the power fluctuations are filtered by the VRB-based ESS, as a result of a smooth grid-injected power with a maximum fluctuation of 2 MW. As shown in Fig. 12, when \( P_b < 0 \), the VRB-based ESS absorbs the superfluous active power from the wind farm; when \( P_b > 0 \), the VRB-based ESS provides the extra active power to the grid for the purpose of smoothing the grid-injected power.

Fig. 13 shows that the output reactive power of the VRB-based ESS is 0 Var during 20–60 s, and \(-1\) MVar during 60–100 s. Reactive power of wind farm is kept at 0 Var during the whole operation. Because of \( Q_b < 0 \), the VRB-based ESS provides the reactive power to the grid. Therefore, the VRB-based ESS would achieve the purpose to provide the reactive power compensation for the grid.

5. Experimental verification

An experimental bench of small-scale power, due to limited conditions, for the purpose of verifying the proposed scheme, consists of a 1.5-kW induction motor drive, a 1.5-kW PMSG with the converter and controller, a grid-side inverter with the controller, a 48-V battery based ESS with an AC/DC converter and its controller, and two step-up transformers with a voltage ratio of 15. The direct torque control is implemented in the induction motor drive, and the torque closed-loop control will ensure that the induction motor torque will simulate the torque of a wind turbine. The models of wind speed (characterized as gust and stochastic wind) and the wind turbine are built in a RT-LAB real-time simulation platform, which will send a torque reference to the induction motor drive that will output a simulated wind power. The grid-side inverter is connected to the grid through a step-up transformer and also there is a step-up transformer between the grid and AC/DC converter of the ESS. The grid of 220-V phase-neutral voltage and 50 Hz frequency is employed in the experiments.

Fig. 14 shows the experimental results of the battery based ESS during charging and discharging, where Fig. 14a is related to change from charging to discharging, and Fig. 14b related to change from discharging to charging. At the beginning, the ESS works on the charging state, and stores the energy coming from

\[\text{Fig. 14. Experimental results of the battery based ESS during charging and discharging. (a) Change from charging to discharging. (b) Change from discharging to charging.}\]

Fig. 15 shows the experimental results to smooth the grid-injected active power. (a) Active power. (b) Voltage and current of the battery. (c) Battery voltage and three ac currents.

\[\text{Fig. 15. Experimental results to smooth the grid-injected active power. (a) Active power. (b) Voltage and current of the battery. (c) Battery voltage and three ac currents.}\]
the induction motor drive; then the ESS works on the discharging state, and sends out the energy to the grid, as shown in Fig. 14a. The reactive power is kept on 0 Var because of \(i_q = 0\) during the whole process; but the active power changes its direction of flow because the current \(i_a\) varies from a positive value to a negative value. Accordingly, the phase current \(i_p\) presents an identical phase with the voltage \(u_a\) when the ESS is charging, and 180° phase difference when discharging. There is a reverse process in Fig. 14b when compared with Fig. 14a, where the ESS discharges at the beginning, then switching to charging. The results show that the ESS has fast dynamic response and good performances with unity power factor to charge and discharge, although there is a small charging or discharging power of 30 W in the experiments.

Fig. 15 shows the smooth grid-injected active power due to using the ESS. In the experiments, a stochastic wind is fulfilled in the aforementioned wind speed model through the RT-LAB real-time simulation platform. The stochastic wind causes the wind turbine model to output a variable torque reference to the induction motor drive, as a result of the induction motor drive’s power fluctuations. With the MPPT control, the PMSG generates a fluctuated active power \(P_a\) fed to the PCC, as shown in Fig. 15a. The ESS connected to the PCC absorbs the superfluous active power from the induction motor drive and compensates the insufficient power to the PCC. Therefore, the grid is injected with a smooth power \(P_g\) from the PCC. In Fig. 15a, \(P_a\) represents the active power of the ESS, where the positive value denotes the VRB charging to absorb the superfluous power and the negative value corresponds to discharging VRB for compensating the insufficient power to the grid. Fig. 15b shows the voltage and current. It can be seen that, the battery voltage is constant even though the battery current changes a lot, where the positive value of the battery current accords to charging and the negative value to discharging. The grid-injected current \(i_{ka}\), the output current \(i_{ba}\) of the ESS, and the output current \(i_{wa}\) of the grid-connected inverter of the generator unit are shown in a small time interval, as shown in Fig. 15c, to clarify the details of three currents flowing into the PCC. It can be seen that \(i_{ka} = i_{ba} + i_{wa}\). During this interval, the produced active power of the generator unit is divided into two parts, i.e., one flowing into the grid and another one flowing into the ESS. In this way, finally the grid-injected power is effectively smoothed, and the fluctuated part of the active power \(P_a\) is filtered out by the ESS.

6. Conclusion

VRB presents many advantages in applications to large-scale power energy storage. Its terminal voltage remains stable when the SOC is within 20–80%, which encouraged this paper 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. The grid-connected wind farm with VRB-based ESS, wind speed characterized as gust and stochastic wind, and a wind turbine were modeled in simulations. Simulation results showed that the grid-injected active power from the wind farm was effectively smoothed even if the wind speed varied drastically, also, reactive power support could be provided for the grid by the designed VRB-based ESS with a rapid dynamic response. Experimental verifications were achieved in a low power bench, where a RT-LAB real-time simulation platform and a direct torque controlled induction motor were employed to simulate a real wind turbine. The experimental results verified the proposed scheme through demonstrating a stable and smooth power flow injected into the grid even though wind power fluctuated.

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