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Executive Summary

The Project Objective is to design innovative energy storage architecture and associated controls for high wind penetration to increase reliability and market acceptance of wind power. The project goals are to facilitate wind energy integration at different levels by design and control of suitable energy storage systems. The three levels of wind power system are: Balancing Control Center level, Wind Power Plant level, and Wind Power Generator level.

Our scopes are to smooth the wind power fluctuation and also ensure adequate battery life. In the new hybrid energy storage system (HESS) design for wind power generation application, the boundary levels of the state of charge of the battery and that of the supercapacitor are used in the control strategy. In the controller, some logic gates are also used to control the operating time durations of the battery. The sizing method is based on the average fluctuation of wind profiles of a specific wind station. The calculated battery size is dependent on the size of the supercapacitor, state of charge of the supercapacitor and battery wear.

To accommodate the wind power fluctuation, a hybrid energy storage system (HESS) consisting of battery energy system (BESS) and super-capacitor is adopted in this project. A probability-based power capacity specification approach for the BESS and super-capacitors is proposed. Through this method the capacities of BESS and super-capacitor are properly designed to combine the characteristics of high energy density of BESS and the characteristics of high power density of super-capacitor. It turns out that the super-capacitor within HESS deals with the high power fluctuations, which contributes to the extension of BESS lifetime, and the super-capacitor can handle the peaks in wind power fluctuations without the severe penalty of round trip losses associated with a BESS. The proposed approach has been verified based on the real wind data from an existing wind power plant in Iowa.

An intelligent controller that increases battery life within hybrid energy storage systems for wind application was developed. Comprehensive studies have been conducted and simulation results are analyzed. A permanent magnet synchronous generator, coupled with a variable speed wind turbine, is connected to a power grid (14-bus system). A rectifier, a DC-DC converter and an inverter are used to provide a complete model of the wind system. An Energy Storage System (ESS) is connected to a DC-link through a DC-DC converter. An intelligent controller is applied to the DC-DC converter to help the Voltage Source Inverter (VSI) to regulate output power and also to control the operation of the battery and supercapacitor. This ensures a longer life time for the batteries. The detailed model is simulated in PSCAD/EMTP.

Additionally, economic analysis has been done for different methods that can reduce the wind power output fluctuation. These methods are, wind power curtailment, dumping loads, battery energy storage system and hybrid energy storage system. From the results, application of single advanced HESS can save more money for wind turbines owners. Generally the income would be the same for most of methods because the wind does not change and maximum power point tracking can be applied to most systems. On the other hand, the cost is the key point. For short term and small wind turbine, the BESS is the cheapest and applicable method while for large scale wind turbines and wind farms the application of advanced HESS would be the best method to reduce the power fluctuation.

The key outcomes of this project include a new intelligent controller that can reduce energy exchanged between the battery and DC-link, reduce charging/discharging cycles, reduce depth of discharge and increase time interval between charge/discharge, and lower battery temperature. This improves the overall lifetime of battery energy storages. Additionally, a new design method based on probability help optimize the power capacity specification for BESS and super-capacitors.

Recommendations include experimental implementation of the controller and energy storage systems in laboratory environment for further testing and verification, which will help commercialization of the proposed system design and controller.

Introduction

Renewable energy sources including wind are highly affected by natural and meteorological situations. While the output power from the wind plant fluctuates, the power grid may experience frequency and voltage deviations [1, 2].

To attenuate the negative impacts of the variability of the renewable power, the use of energy storage system (ESS) has been considered [3-8]. Among the many options, battery and super-capacitor combinations have gained popularity in recent wind energy integration [9-12]. This is because super-capacitors can absorb high frequency fluctuations in the renewable power output. Thus, the addition of super capacitors reduces the high current charging/discharging cycles in the battery systems and contributes to the reduction of round trip losses, better thermal stability, and as a result, the extension of the battery system lifetime and to reduced maintenance requirements.

In this project, a hybrid energy storage system (HESS) consisting of lead acid battery and super-capacitor is adopted and sized to accommodate the fluctuation of wind generation. In references [9-12], the HESS was implemented to smooth out the short-term wind power fluctuations taking consideration of power quality improvement. A new method based on the probability distribution of the HESS power profile is proposed. Both capacities of the BESS and super-capacitor are specified simultaneously to accommodate the wind power fluctuations for daily load tracking or load leveling.

The search for sustainable energy resources becomes ever more urgent as concern on energy security and the environment grows. Amongst the sustainable resources, wind and solar energy has gained rapid development and has made significant in-road into electrical power systems. The trend for this renewable energy is from small area harness to large wind farm which could generate significant amount of energy to loads [1], [2]. Unfortunately, renewable sources including wind and solar generation tend to be unsteady because wind speed and the irradiation are influenced by natural and meteorological situations. As the output power from these solar or wind farm fluctuates, it can result in network frequency and voltage deviations.

To attenuate the negative impacts of the variability of the renewable power, the use of energy storage system (ESS) has been considered [3-11]. From the open literatures the following ESS technologies and their application features have been documented.

- Compressed air energy storage (CAES) [12-15]
- Hydrogen energy storage systems [16]
- Superconducting magnetic energy storage (SMES) systems [17], [18]
- Flywheels [19-21]
- Advanced batteries: zinc bromine (ZBB) [22] and vanadium redox (VRB) [23], [24]
- Lead acid batteries [17, 18, 21, 25-34, 38]
- Super-capacitor energy storage systems [14, 15, 24, 28-34]

In the above listed the ESS technologies, different technologies have strengths and weaknesses relative to one another in terms of cost, lifetime, and efficiency characteristics. Though CAES has long lifetime, potentially high efficiencies and large capacity, it is relatively expensive from a capital cost perspective and its application is constrained by the geographical conditions where typically an underground salt or limestone cavern is available. Hydrogen energy storage systems have undergone

extensive development in recent years. However, in comparison with other energy storage methods, this technology is at present relatively expensive due to the technological immaturity. SMES systems are highly efficient at storing electricity and can provide both real and reactive power, but are still in the development and testing phase. Flywheels with high energy capacity are still expensive and have not been commercially developed. They will help to ride through momentary power outages. Flow batteries, such as ZBB and VRB address the shortcomings of the traditional lead acid battery in terms of limited durability and high maintenance requirements. These technologies are undergoing further development for commercial application in utility-scale. Conventional lead acid batteries do have the disadvantages of limited durability and high maintenance requirements. However, they are technically mature and inexpensive to gain widely implementation in the utilities. Super-capacitor is another mature technology that has been commercially produced.

To avoid the shortcomings of either energy storage technology, combinations of different ESS have been designed in [14, 15, 17, 18, 21, 24, 30-34], among which battery and super-capacitor combinations have gained popularity in the recent renewable energy integration [30-35]. It is due to that in this hybrid ESS, the super-capacitors absorb the high frequency fluctuations in the renewable power output thanks to their high power features, which reduces the high current charging/recharging cycles in the battery systems and contributes to the extension of the battery system longevity and to reduction of maintenance requirements.

In this report, a hybrid energy storage system (HESS) consisting of lead acid battery and super-capacitor will be designed and sized to accommodate the fluctuation of wind generation. Compared with works that have been conducted in [30-33], where the HESS was implemented to smooth out the short-term wind power fluctuations in terms of power quality improvement [30-32], or the HESS was applied in standalone system in a photovoltaic system for power buffer function, the applications of HESS in the grid connected wind farms need to be investigated due to the penetration of large wind farms are under their way to be connected to the mains grid. In [35], the authors proposed a battery capacity sizing scheme for the battery system in the power buffer systems to accommodate the wind power fluctuation. However, the capacitor size of the HESS has yet been specified. In addition, in [35], the battery system capacity was specified based on the peak value of the possibly occurred battery power over the planned duration, say 1 day in the illustration example of [35]. In practice, one of drawbacks of such specification is to design a huge energy storage system while takes its whole rule just over a few short time durations when the wind power peaks occur. From economy consideration, this approach is not cost effective and needs to be improved. A method to address all the above concerns is proposed in this report based on the probability distribution function of the profile which the HESS is to accommodate. In this method, the battery power capacity in HESS is specified to take over certain confidence, say 95% of the probably occurred HESS peak power value, while the rest 5% up to peak power is assigned to be accommodated by the super-capacitor.

Background

There has been rapid development in the field of wind power; the number of connected wind turbines to the power grid has been increasing dramatically annually. The ratio of renewable energy to the total generated power in the United States is about 9% while it is aimed to be 20% of the total generated power in 2030 [1]. Due to the large percentage of the total capacity that must consist of renewable, the impact of wind energy on the power grid and the quality of dispatched power to the grid become important issues.

While many models for wind turbine generators have been studied [2], the wind industry often employs permanent magnet synchronous generators (PMSG) and full-scale convertors in new wind farms [3]. This configuration allows the system to obtain more energy and then dispatch it to the power grid with high protection. This configuration can also work without a gearbox – the main point of failure in most wind turbines.

Wind speed is not constant. Variable wind speed leads to fluctuating output power which is not acceptable from the standpoint of the Independent System Operator (ISO). For this reason, an ESS is applied to the wind system to accommodate the power difference between the generated and dispatched power. This work is done with the help of power electronics to alleviate the possible problems of not having smooth and regulated output power.

Different kinds of ESS have been studied [2] but recently the combination of different energy storage systems, called hybrid energy storage systems (HESS), has been favored. The most popular HESS is the combination of high power density supercapacitors and high energy density batteries. This HESS is capable of handling large variations in power over the DC-link for a large duration of time. This HESS shares the advantages of both batteries (high energy density) and supercapacitors (high power density).

There are many different configurations in which this particular HESS can be deployed [4]. Energy storage systems, including battery energy storage systems (BESS) and supercapacitor energy storage systems (SESS), have been studied by many researchers [5, 6]. However, calculation of the proper sizes of batteries and supercapacitors in terms of power, energy, cost and life span is an important issue, and has not been studied adequately.

This project primarily address a new control scheme which controls the DC-DC converter based on the state of charge (SOC) of the supercapacitor, as well as other conditions of the wind system (which leads to a considerable increase in battery life time), while ensuring that the output power and voltage are at acceptable levels.

Results and Discussion

A probability-based power capacity specification method is described first. Then an illustrative example to verify the effectiveness of the proposed method is given based on the real wind data from an existing wind farm in Iowa.

There are various topologies of wind turbine-grid connection [2]. With the decrease in cost of permanent magnet material and its lighter weight, permanent magnet synchronous generators (PMSG) are becoming more affordable and attractive, especially as turbine rating increases [2]. PMSG is inter-connected with the grid through back-to-back fully-rated converters so that the variable ac frequency at the generator terminal is converted to steady grid frequency at the output. The power buffer scheme considered in this paper is assumed to be based on such a PMSG-turbine connection, as depicted in Fig. 1.

Fig. 1. PMSG based variable speed wind turbine with inter-connection to the mains grid through power buffer system.

Fig. 1 shows that the wind energy captured by the turbine blades is converted through the PMSG into electrical power, denoted as P_w . From previous references, it is clear that P_w tends to be highly stochastic and an effective way to describe P_w could be through statistical means [13, 14]. Alternatively, as part of wind plant planning, site selection and design process, wind data is often collected at site. As the main focus of this paper is on the design of the ESS, it is now assumed that sufficient wind data is available and the profile of P_w is known over a period of T hours. Fig. 2 shows a typical profile of P_w , derived from the wind speed data taken from a site described in [15]. The profile has been obtained by averaging the wind speed data over 10-minutes interval.

To cater for grid integration, the back-to-back converters (CON1 and CON2 in Fig. 1) are utilized to connect the generator and grid transformer through a DC-link. One can assume that the power loss in the two converters is negligible. The DC-link capacitor C functions as harmonics filter and in this design, it also takes the role of an energy-storage system. It is further assumed that the dispatched power P_d from CON2 to the mains grid is to be kept constant over the interval T . Although this assumption tends to facilitate analysis, it also has a desirable effect from a practical viewpoint: it prevents the fluctuating P_w from impacting the voltage and frequency on the grid. To realize the constant power feature, the mismatch power between P_w and P_d has to be compensated for by the ESS connected to DC-link. The output power from the ESS is denoted by $P_{HESS}(t)$ which has the component of the super capacitor output $P_c(t)$ and the battery output $P_b(t)$.

Fig. 2. A typical wind power profile based on data taken from [15].

The front-end boost converter (CON1) and the HESS constitute the power buffer system. The power buffer smoothes the fluctuations in P_w in the following way: CON1 is controlled to regulate the output power of the PMSG to achieve maximum power point tracking (MPPT) from the wind turbine. CON2 converts amount of P_d from the DC power into ac form at grid frequency and also controls the reactive power flow. It is noted that in this topology the DC-link voltage is controlled within specified range and its variation depends on the HESS capacity to be specified to maintain the DC-link voltage well within the pre-set limits. In this way the downstream CON2 can be properly operated to maximize energy stored and to protect the power switches, supercapacitors and the BESS from an over voltage.

To ensure the success of the above scheme, the determination of the P_d level and HESS power capacity specification have to be addressed, which is the goal of this paper.

HESS power capacity specification

Wind Generation System Modeling in PSCAD

The wind generation system in PSCAD consists of three parts: wind speed modeling, wind turbine modeling and wind turbine governor modeling.

To study the response of the control system, the wind speed can be internally modeled by gust component, ramp component and the noise component. The wind speed source can also be selected from an external wind speed data file. The latter option can be used when a wind data profile from a real wind farm is available, as will be the case in this study. The wind turbine governor system is modeled based on the transfer-function proposed in [16]. In the wind turbine model, wind power is calculated as

$$P_w = 0.5 \rho A C_p(\lambda, \beta) V_w^3 \quad (1)$$

where P_w is the power captured by the wind turbine, ρ is the air density, A is the blade swept area, C_p is the power coefficient, which is the function of the blade angle β and tip speed ratio $\lambda = \omega R / V_w$, in which R is radius of the turbine and V_w is wind speed. It is noted that the optimized value of C_p is normally around 0.5 [16], in which case the wind turbine is operated under MPPT condition. The generated output torque of the wind turbine is used to drive the synchronous generator, in which the mechanical wind power is converted to electrical power, as shown in Fig. 1.

Analysis on Wind Power Profiles

To study the capacity specification of the HESS in smoothing wind power fluctuation, a time series wind power data is assumed known as shown in Fig. 2. For generalization purpose, the wind power profile is normalized based on the rated power of the wind turbine, 2 MW, and the normalized wind power profile is given in Fig. 3.

Fig. 3. A typical normalized wind power profile based on data taken from [15]: constant P_d is shown.

As shown in Fig. 3, over the planning time duration of T hrs, the dispatched level of the wind farm is proposed to be P_d p.u., or constant amount of power, P_d is expected to be dispatched from the wind farm to the grid. The HESS is designed to accommodate the difference between P_w and P_d . The power profile, $P_{HESS}(t)$ of the ESS can be derived from,

$$P_{HESS}(t) = P_w(t) - P_d \quad (2)$$

From (2), for a given constant P_d , $P_{HESS}(t)$ will vary in the same manner as P_w . Setting P_d to another constant value will only result in the $P_{HESS}(t)$ curve being shifted up or down, but $P_{HESS}(t)$ will remain at the same shape as P_w . For example, for the P_w profile given in Fig. 3, the $P_{HESS}(t)$ profile given in Fig. 4 corresponds to $P_d = 0.9$ p.u.

Fig. 4. ESS power profile for $P_d = 0.9$ p.u.

It is to be noted that in Fig. 4, the positive values indicate that the HESS is charged to store the surplus energy produced from the wind farm while the negative values show that the HESS releases power to keep constant of the dispatched power to the grid. In HESS power capacity sizing, however, the HESS power capacity has to be specified as large as to take or release enough power to satisfy the system design requirements. In this point of view, one can specify the HESS based on its absolute value where only positive values appear in the design. The absolute value of the HESS power profile shown in Fig. 4 is readily obtained and is depicted in Fig. 5.

Fig. 5. Absolute values of ESS power profile for $P_d = 0.9$ p.u.

As mentioned previously, different from the ESS capacity specification method proposed in [12], where the peak HESS power value was used to specify the BESS capacity in the power buffer

system, a new hybrid ESS system, consisting of BESS and super-capacitor, is proposed in this paper based on the probability theory. In this HESS, to avoid the BESS highly overcharged or deep discharged at the peak and valley values, which deteriorates the life length of BESS, one can resort to the super-capacitor system to accommodate the peak values thanks to its high power density. In such an HESS, the super-capacitor system is supposed to take over the peak values in wind power fluctuations and hence its BESS counterpart can handle the low fluctuating parts of the wind power which are not harmful to its utilization longevity. In the meanwhile, the high energy capacity of the existing BESS can make up the drawback of less energy capacity presented by the super-capacitor system alone.

One concern is how to assign the power ratings of BESS and super-capacitor in the HESS. To this end, the ESS profile in Fig. 5 is interpreted in another histogram perspective, as shown in Fig. 6, from which it can be easily seen that frequency of the peak values in the ESS power profile is very low, i.e. the peak values happen much rarely compared to the medium values, say from 0.1 to 0.25 p.u.

To get clear visibility of the distribution of the power profile shown in Fig. 6, different probability density functions (PDFs) can be selected to fit the histogram in Fig. 6. Compared with the parametric methods, as usually adopted in description of wind speed, for example Weibull or Rayleigh distributions, the non-parametric PDFs possess advantage that they can reflect the practical data in more visibility [17]. A non-parametric PDF estimation method, Kernel smoothing density estimation, is adopted in this paper and is introduced in next section.

Fig. 6. Histogram of the absolute values of ESS power profile for $P_d = 0.9$ p.u.

Kernel smoothing density estimation and its application in ESS capacity specification

Kernel smoothing density estimation (KSDE) computes a probability density estimate of the sample in the investigated vector, x . The function,

$$[\Phi, |P_{ESS,i}|] = \text{KSDE}(|P_{ESS}|) \quad (3)$$

returns the vector of density values, Φ , evaluated at the points in $|P_{ESS,i}|$. By default, the estimate is based on a normal kernel function, using a window parameter that is a function of the number of points in $|P_{ESS}|$. And the density is by default evaluated at 100 equally spaced points that cover the range of the data in $|P_{ESS}|$, for further readings, the readers are advised to obtain detailed information from [18].

By applying KSDE to the histogram shown in Fig. 6, the PDF of the absolute values of ESS power, $\Phi(|P_{ESS}|)$ is obtained as shown in Fig. 7.

In Fig. 7, one can find that the default width of the kernel-smoothing window, plotted in blue, does a good job. It looks reasonably smooth, but not so smooth as to obscure features of the data. This bandwidth is the one that is theoretically optimal for estimating densities for the normal distribution. For comparison purpose, two different bandwidths, one-third and 3 times of the default bandwidth are also adopted in the estimations. The results are shown in Fig. 7, in red and in green respectively. From these three estimations, one can find that the green curve shows a density with the width of kernel-smoothing window set too high. This curve smoothes out the data so much that the end result looks just like the kernel function. The red curve has a smaller width of kernel-smoothing window and is rougher looking than the blue curve. It may be too rough, but it does provide an indication that there might be two major peaks rather than the single peak of the blue curve. A reasonable choice of width might lead to a curve that is intermediate between the red and green curves.

Fig. 7. PDF of the absolute values of the ESS power profile for $P_d = 0.9$ p.u.

Power Capacities Determination for BESS and Super-Capacitor

Based on the PDF given in Fig. 7, the cumulative density function (CDF) of the absolute values of ESS power profile $F(x)$, is readily obtained as,

$$F(x) = \int_0^x \Phi(|P_{ESS}|) d|P_{ESS}| \quad (4)$$

The CDF obtained from (4) is shown in Fig. 8, from which and the analysis in Section III.B, one can specify the BESS capacity to accommodate a given confidence level, say 95 percent of the required ESS power in Fig. 5, which corresponds to the point shown in Fig. 8 at $P_{b,P_d=0.9} = 0.37$ p.u. for CDF = 0.95, or,

$$P_{b,P_d=0.9} = F^{-1}(0.95) \quad (5)$$

The rest 5% of mismatch power in Fig. 5 is supplied by the super-capacitor within HESS. Therefore, the power capacity of the super-capacitor, $P_{c,P_d=0.9}$ can be specified by,

$$P_{c,P_d=0.9} = \max(|P_{ESS}|) - P_{b,P_d=0.9} \quad (6)$$

Battery and HESS Models

Battery Model

Several equivalent battery circuit models have been reported in the literature. The models are applicable to study the battery behavior over short or long-term intervals during its charge/discharge process [19, 20]. Some physics-based models have been developed to study the internal chemical dynamics of lead-acid batteries. However, these models are generally not suitable for electrical system design exercises. Though the capacitor/resistor branches based models, like the fourth order model [21] can describe the nonlinear phenomena within the battery, they become dramatically complex in the modeling process. In this study, the voltage source-resistor model, as shown in Fig. 9 is selected to avoid detailed calculations of internal electrochemical processes. However, the internal resistors are differently specified based on the charge and discharge cases, as described in the next contents.

Fig. 8. CDF of the absolute values of the ESS power profile for $P_d = 0.9$ p.u.

Fig. 9. Equivalent circuit of lead acid battery.

Fig. 9 shows the investigated battery model. In this model, E_m denotes the battery internal EMF, which is the open circuit voltage at no load condition. The internal resistance, R_2 has two components, $R_{2,c}$ and $R_{2,d}$, which contribute to the power loss inside the battery units under charge and discharge conditions respectively. The charge/discharge current is depicted by i_b and the terminal voltage v . As shown in Fig. 9, positive values of i_b denote discharge and negative values for charge currents.

In this model, the EMF, E_m and the electrical parameters, $R_{2,c}$ and $R_{2,d}$ are all functions of the State

of Charge (SOC) of the battery and its operation temperature, T . Therefore, E_m , $R_{2,c}$, and $R_{2,d}$ are indexed by SOC and T in the developed model.

The SOC is obtained by the following equation,

$$SOC = 1 - \frac{Used \text{ Ah Capacity}}{Max \text{ Ah Capacity}} \quad (7)$$

where the used Ah capacity is calculated by,

$$Used \text{ Ah Capacity} = \begin{cases} \int_0^t i_b(t) dt & \text{for } i_b(t) \geq 0 \text{ discharge} \\ \int_0^t \eta_{coulomb} i_b(t) dt & \text{for } i_b(t) < 0 \text{ charge} \end{cases} \quad (8)$$

where $i_b(t)$ is the charge/discharge current for the battery and $\eta_{coulomb}$ is the coulombic efficiency.

Based on the current direction, the internal resistance R_2 can be selected by,

$$R_2 = \begin{cases} R_{2,d}(SOC, T) & \text{for } i_b \geq 0 \\ R_{2,c}(SOC, T) & \text{for } i_b < 0 \end{cases} \quad (9)$$

The battery terminal voltage is derived by,

$$v(SOC, T) = E_m(SOC, T) - i_b R_2(SOC, T) \quad (10)$$

In this paper, the internal E_m and R_2 are indexed by the SOC and temperature, T from two two-dimension lookup tables respectively, which are obtained from the experimental test of Hawker Genesis 12V26Ah10EP sealed valve-regulated lead-acid (VRLA) battery. The open circuit voltage of each unit is set from 11.7 to 12.89 V corresponding to SOC from 0 to 1 respectively.

Hybrid ESS Model

Based on the battery model described in last sub-section, an electrical model for a hybrid energy storage system (HESS) consisting of battery and super-capacitor systems will be developed in this part. The equivalent circuit of the HESS is shown in Fig. 10.

Fig. 10 Equivalent circuit model for HESS consisting of lead acid battery and super-capacitor.

In Fig. 10, the lead acid battery is modeled by the internal EMF, E_m and the internal resistor R_2 , as described in last sub-section.

Though the charge/discharge characteristic of the super-capacitor can be described in very complex forms as given in [22], where the models contain multiple time constants or have distributed capacitance and resistance, the super-capacitor model used in this paper is represented by a single lumped capacitance, C_c and a single lumped resistance, R_c , as shown in Fig. 10 [23]. In this model, C_c is the capacitance between the double layers of the super-capacitor and R_c is to describe the internal loss inside the super-capacitor.

For given discharge current i_0 , one can assume that it is distributed between the battery- and super-capacitor-branches based on the impedances of the two branches, as denoted by i_b and i_c respectively in Fig. 10. The calculation of i_b and i_c for given i_0 will be detailed as following.

The Thevenin equivalent circuit of the HESS as shown in Fig. 10 can be depicted in Fig. 11, where the Thevenin equivalent voltage and impedance of the HESS circuit are denoted by $E_{th}(s)$ and $Z_{th}(s)$ respectively. It is noted that Fig. 11 is derived in frequency domain and the $E_{th}(s)$ and $Z_{th}(s)$ are obtained by,

$$E_{th}(s) = \frac{R_c}{R_2 + R_c} E_m \frac{s + \alpha}{s(s + \beta)} + \frac{R_2}{R_2 + R_c} V_{c0} \frac{1}{s + \beta} \quad (11)$$

$$Z_{th}(s) = \frac{R_2 R_c}{R_2 + R_c} \frac{s + \alpha}{s + \beta} \quad (12)$$

where s is the complex frequency, V_{c0} is the initial voltage across the super-capacitor and,

$$\alpha = \frac{1}{R_c C_c}$$

(13)

Fig. 11 Thevenin equivalent circuit of the HESS.

$$\beta = \frac{1}{(R_2 + R_c)C_c} \quad (14)$$

By assuming the charge/discharge current is a pulsed signal with period T_1 and duty ratio D , the current for the first N pulses can be expressed as,

$$i_0(t) = I_0 \sum_{k=0}^{N-1} [\Phi(t - kT_1) - \Phi(t - (k + D)T_1)] \quad (15)$$

where I_0 is the magnitude of the current pulse and $\Phi(t)$ is a unit step change function at $t = 0$. By applying Laplace transform operation to (15), one can readily obtain the current in frequency domain as,

$$I_0(s) = I_0 \sum_{k=0}^{N-1} \left[\frac{e^{-kT_1 \cdot s}}{s} - \frac{e^{-(k+D)T_1 \cdot s}}{s} \right] \quad (16)$$

Based on (12) and (16), the internal voltage drop inside the HESS, $V_i(s)$ is,

$$V_i(s) = I_0(s) \cdot Z_{th}(s) = \frac{R_2 R_c}{R_2 + R_c} I_0 \left[\left(\frac{\alpha}{\beta} \frac{1}{s} + \frac{\beta - \alpha}{\beta} \frac{1}{s + \beta} \right) \times \left(e^{-kT_1 \cdot s} - e^{-(k+D)T_1 \cdot s} \right) \right] \quad (17)$$

From the circuit shown in Fig. 11, the terminal voltage of the HESS, $V_{th}(s)$ can be calculated by,

$$V_{th}(s) = E_{th}(s) - V_i(s) \quad (18)$$

Substituting (11) and (17) into (18) and performing inverse Laplace transform yield,

$$v(t) = E(t) - v_i(t) = E_m + \frac{R_2}{R_2 + R_c} (V_{c0} - E_m) e^{-\beta t} - R_b I_0 \sum_{k=0}^{N-1} \left[\left(1 - \frac{R_2}{R_2 + R_c} e^{-\beta(t-kT_1)} \right) \Phi(t-kT_1) - \left(1 - \frac{R_2}{R_2 + R_c} e^{-\beta[t-(k+D)T_1]} \right) \Phi[t-(k+D)T_1] \right] \quad (19)$$

It is noted that the second term in (19) is caused by the energy re-distribution between the battery and super-capacitor at the beginning of the discharge. This item decays with time lasts. The Thevenin voltage of the HESS is finally approaching to E_m .

After obtaining the HESS terminal voltage by (19), the charge/discharge currents flowing through the BESS and the super-capacitor can be calculated by the following two equations respectively,

$$i_b(t) = \frac{1}{R_2} [E_m(t) - v(t)] \quad (20)$$

$$i_c(t) = i_0(t) - i_b(t) \quad (21)$$

Illustration

The wind data obtained from an existing wind farm is used to illustrate the HESS design procedure proposed in Section IV. In the study, wind speed profile of a winter day (January 24, 2010) was obtained from the wind farm at Audubon, USA [15]. The wind speed was then averaged over 10-minute intervals, to form the input to the wind turbine and synchronous generator modeled in PSCAD/EMTDC software package to produce the wind power P_w shown in Fig. 2. In this instance, maximum P_w is 2.82 MW and minimum P_w 0.7 MW. By selecting the wind turbine rating, 2 MW as the base power for normalization in the study, one readily observes that P_w varies within the range 0.35 to 1.41 p.u. as shown in Fig. 3.

By assuming the dispatch level at 0.9 p.u., i.e., over the investigated day, constant amount power of 0.9 p.u. is dispatched from the wind plant to the grid. The corresponded HESS power and its absolute values can be readily obtained as shown in Figs. 4 and 5 respectively.

The histogram of $|P_{ESS}|$ is obtained from Fig. 5 as shown in Fig. 6, from which one can apply the KSDE method to get the PDF of $|P_{ESS}|$, as given in Fig. 7. Again it is noted that the blue curve in Fig. 7 best matches the histogram in Fig. 6, compared with other band width values and so the default band width value is selected in the non-parametric density estimation.

By following the HESS power capacity specification as described in Section III.D, and assigning a confidence value to be 0.95 in this study, one can readily find the BESS power capacity to be 0.37

p.u., or 740 kW. Hence the power capacity of the super-capacitor should be 0.18 p.u., or 360 kW.

To illustrate the effectiveness of HESS on improving lifetime of battery energy storage system alone, the models described in Section IV are built in Matlab and implemented for wind power fluctuation smoothing.

The simulation results for the battery model are shown in Fig. 12. In this simulation, only the battery system is used to accommodate the ESS power profile, as given in Fig. 12(a). Under normal condition, the dc-link voltage of the back-to-back converter is assumed to be 1408 V [12], while the terminal voltage of the Hawker Genesis 12V26Ah10EP sealed valve-regulated lead-acid (VRLA) is 12.96 V at $SOC = 1$. Therefore, to build up the required dc-link voltage, one can connect the battery units in series. The series connected battery units can be calculated to be $1408/12.96$ or 112. The C_5 capacity of one battery unit is 26 Ah, and hence the power capacity for each series connected branch is $26/5 \times 1408 = 7.32$ kW. To cater for the peak value of the ESS variations, the parallel connected branch number of the battery system can be specified to be $0.55 \times 2 \text{ MW} / 7.32 \text{ kW} = 150$. The terminal voltage profile over the investigated day is given in Fig. 12(b). Fig. 12(c) shows the battery current profile, which is derived as following. By knowing the ESS power profile and the battery terminal voltage profile, one can derive the battery current as the discharge current input that feeds to the battery model as shown in Fig. 9. The variation of the battery SOC over the studied day was depicted in Fig. 12(d). In this figure, one can find that the SOC increases from its original status 0.5 to 0.65 at the end of the day, which reflects that the battery system is charged more than discharged over the entire day.

To verify the effectiveness of the HESS in smoothing wind power fluctuations, the HESS model shown in Fig. 10 is implemented to accommodate the ESS power profile. In this HESS design, the Hawker Genesis 12V26Ah10EP batteries and Nesscap 2.7V/600F super-capacitors within the HESS are specified as follows. From above probability-based analysis, the battery system capacity is 740 kW and the super-capacitor capacity is 360 kW. From the battery system, the similar specification method in the last simulation is deployed and it is specified to be 112 units connected in series and 100 branches connected in parallel.

(a)

(b)

(c)

(d)

Fig. 12. Simulation results of the battery model for the wind power fluctuation smoothing, profiles of (a) the battery power, (b) battery terminal voltage, (c) battery current, and (d) SOC of the battery.

For the super-capacitor system, the rated voltage of the super-capacitor is 2.7 V and it needs to connect 539 units in series to build up the normal dc-link voltage of 1408 V. From the datasheet of Nesscap 2.7V/600F, one can find that the rated current of the super-capacitor unit is 145 A. One can readily derive that the rated power of each super-capacitor string is 211 kW. Therefore, it needs to connect 360/211 or about 2 strings in parallel. The HESS as specified above is used to cater for the ESS power profile shown in Fig. 12(a). The power profile is fed to the HESS input and then divided by the terminal voltage to obtain the HESS input current. The procedure described in Section IV.B is adopted to calculate the battery current based on the current pulses. It is to be noted that in this calculation, the continuous current series over one day is discretized in terms of 20 mins., while the duty ratio of each pulse, $D = 1$. Eqs. (11)-(21) are employed for this discretized pulses to calculate the battery current. The simulation results are shown in Fig. 13.

(a)

Fig. 13 Simulation results of the HESS model for the wind power fluctuation smoothing, profiles of (a) the total charge/discharge current, (b) super-capacitor current, (c) battery current, (d) HESS terminal voltage, (e) SOC of the battery, and (f) SOC of the super-capacitor.

The obtained HESS current profile is given in Fig. 13(a), which is similar with that shown in Fig. 12(c). The current flowing through the super-capacitors within the HESS is given in Fig. 13(b). It can be observed from this figure that the high frequency fluctuations appearing in Fig. 13(a) are accommodated mostly by the super-capacitors. The rest of the current with low fluctuations is taken by the battery units within the HESS, as shown in Fig. 13(c). This lower fluctuation will benefit the operation time of the battery pack. The terminal voltage of the HESS is shown in Fig. 13(d), comparing which with that given in Fig. 12(b), one can find that the voltage profile for the HESS has

less fluctuation than that in case when only batteries take care of the fluctuations. The variation of battery SOC can be observed in Fig. 13(e). It can be readily observe that the SOC in this case changes within a smaller range over the studied day compared with that in the battery case, as shown in Fig. 12(d). The SOC of the super-capacitor is depicted in Fig. 13(f).

Optimal determination of P_d

The power capacities specification method of BESS and super-capacitor within the HESS has been proposed for given dispatched power level to the grid based on a pre-assumed wind power profile from probability point of view.

However, from above derivations, one can observe that the power capacities of BESS, P_{b,P_d} and super-capacitor, P_{c,P_d} are dependent on the absolute values of ESS power profile, $|P_{ESS}|$, which is indirectly determined by the desired constant power dispatched level P_d . With variation of P_d , the corresponding BESS and super-capacitor power capacities will change accordingly. To find a proper pair of BESS and super-capacitor power capacities to accommodate the wind power fluctuations is critically dependent on choosing an optimized dispatched level, which is the objective of this sub-section.

In this project, a benefit-cost function is formed in terms of the revenue achieved from selling P_d amount of electricity to the grid, considering the costs to install the corresponding HESS to smooth out the wind power fluctuations over a planning duration, T . The benefit function can be written as,

$$B = \alpha P_d - \beta P_{b,P_d} - \gamma P_{c,P_d} \quad (22)$$

where, α , β and γ are the coefficients for P_d , P_{b,P_d} and P_{c,P_d} respectively. In practice, these three parameters can be selected based on the retail price for electricity, amortized price for BESS and super-capacitor systems respectively.

It is noted that the costs for the converters in the wind power generation system as well as the cost for maintenance are assumed constant, and hence are not included in (22). To achieve the maximum economy benefit, one should maximize the profit for exporting P_d amount of power from the wind farm to the grid. Or, one should optimize the benefit function given in (22) in terms of variation of P_d .

However, the benefit B in (22) is a non-linear function of the dispatched level, P_d . To solve this non-linear optimization problem, an iterative method is adopted in this paper to obtain the maximum value of B , B_{max} , by adjusting P_d step-by-step over its available range, $[P_{w,min}, P_{w,max}]$.

New Controller for Hybrid Energy Storage System to Extend Battery Life

Batteries have limited life cycle and after a limited number of charge and discharge cycles the battery cannot perform like a new battery. The average number of life cycles a typical Li-ion battery employed in industry is 200 to 1000 cycle. Different types of batteries exhibit different average life cycles.

When the battery works at a low depth of discharge (DOD), it can last longer (e.g. 90,000 life cycles) and when the battery works at high DOD, the life time of the battery gets shortened (e.g. 600 life cycles). DOD is one of the most important factors in increasing the number of battery life cycles, so operating the battery at a high DOD should be avoided, as shown in Fig. 14.

Fig.14- life cycle of battery versus depth of discharge (DOD), [67]

According to Fig. 14, if the battery operates at a DOD equal to 40% or less, the battery exchanges more energy and lasts longer. The other factor is the life cycle which is directly proportional to the exchanged energy between the battery and the DC-link. In other words, if the battery does not work for some period of time, it exchanges less energy and the battery life increases.

A typical controller of a DC-DC power converter compares the generated power to the reference power and provides a pulse width modulation (PWM) control signal. This signal is typically sent directly to the converter's IGBT's. However in our design, we would like to account for the SOC of the supercapacitor. Therefore we instead send the PWM signal to a set of AND gates. One AND gate is responsible for charging the DC-link from the battery depending upon the SOC of the supercapacitor, while the other AND gate is responsible for discharging the DC-link to the battery depending on the SOC of the supercapacitor, as shown in Fig. 15.

Fig. 15- Logic Gates work as on-off switches in HESS

Based on simulation results, battery operating time drops substantially (up to 28% of total time from case study) which results in an increase in the battery life time. This reduction in the operating time of the battery is directly proportional to the overall increased battery life time.

Another important item for consideration is battery wear (the amount of exchanged energy). Note that the battery wear shows the battery life without taking into account of DOD. Recognizing that the exchanged energy is equivalent to the battery wear, we can use this to estimate the remaining life of the battery. This method does not take DOD into account and will therefore be inexact. Using this estimation we find that the battery can last nearly 1.75 times longer than when using the regular control scheme.

The third parameter is the battery loss. When the battery operates, the battery gets warm and the

internal resistance of the battery increases. Consequently we have more losses (the battery has to compensate the loss by charging/discharging more) due to the internal resistance. If the battery does not work continuously, it has some time to cool down, thus decreasing the internal resistance of battery.

A large portion of maintenance costs of wind turbines with energy storage systems is battery replacement. These costs increase significantly if the life of the battery is short. The new control design increases the life time of the battery, which consequently reduces the number of battery replacements.

The proposed control design has the greatest benefit for wind turbines operating in highly fluctuating wind profiles. From case study, the proposed system can greatly increase the battery life over the regular control system under highly fluctuating wind profiles. This is thanks to the heavy utilization of the supercapacitor in regulating the output power. The intelligent control scheme regulates the output wind power and also substantially increases the battery life time in hybrid energy storage of the variable speed wind turbines.

Accomplishments

The following is the list of publications as a result of this project:

- [1] Hamed Babazadehrokni and Wenzhong Gao, “An Intelligent Controller Design to Increase the Battery Life Time in Hybrid Energy Storage System of Wind Turbine Generators,” to be submitted to a journal.
- [2] Hamed Babazadehrokni and Wenzhong Gao, “Analysis of Power Fluctuation Reduction in Wind Turbine Generator Systems,” to be submitted to a journal.
- [3] Hamed Babazadehrokni, David Gao, Kurt Duncan, “A New Control Scheme in a Battery Energy Storage System for Wind Turbine Generators” IEEE Power and Energy Society General Meeting 2012, San Diego, California, July 2012.
- [4] Hamed Babazadehrokni and Wenzhong Gao, Jin Lin, Lin Cheng, “Sizing of Battery and Supercapacitor in a Hybrid Energy Storage System for Wind Turbines,” 2012 IEEE PES Transmission & Distribution Conference & Exposition, Florida, 2012.
- [5] Wenzhong Gao, Xiaoyu Wang and Eduard Muljadi, “Power Capacity Specification for Energy Storage in Wind Application Using Probability-Based Method,” 2011 IEEE Energy Conversion Congress and Exposition, Phoenix, Arizona, September, 2011.
- [6] Hamed Babazadehrokni, Wenzhong Gao, Xiaoyu Wang, “Controller Design for a Hybrid Energy Storage System Enabling Longer Battery Life in Wind Turbine Generators,” 43rd North American Power Symposium (NAPS), Boston, Massachusetts, August, 2011.

The following is the list of SOPO of the project and the status:

- Task 1 Level 1 Energy Storage System (ESS) design, task accomplished
- Task 2 Level 2 ESS design, task accomplished
- Task 3 Level 3 ESS design, task accomplished
- Task 4 Level 1 ESS controller design, task accomplished
- Task 5 Level 2 ESS controller design, task accomplished
- Task 6 Level 3 ESS controller design, task accomplished
- Task 7 Benchmark wind power system modeling and simulation with ESS at three levels (steady-state), task accomplished
- Task 8 Benchmark wind power system modeling and simulation with ESS at three levels (dynamic state), task accomplished
- Task 9 Benchmark wind power system modeling and simulation with ESS at three levels, comprehensive studies, task accomplished
- Task 10 Analysis of benchmark simulation study results, task accomplished
- Task 11 Project Management and Reporting, task accomplished

Conclusions

To accommodate the wind power fluctuation due to the intermittent nature from the wind speed, a hybrid energy storage system (HESS) consisting of traditional battery energy storage system (BESS) and super-capacitor is adopted in this study. With the help from this HESS, the dispatched level from the wind farm is expected to be constant over the planned time duration. The mismatch power between the wind power output and the dispatched level is absorbed/released by the HESS. A probability based power capacity specification method for the BESS and super-capacitor within the HESS is proposed in this paper. The BESS capacity is specified to take over the wind power fluctuation with magnitude less than a certain value corresponding to a preset confidence value on the cumulative density function (CDF) of $|P_{ESS}|$. The rest part of the HESS power capacity with high magnitude is assigned to the super-capacitor. In this way, the super-capacitor can take over the peaks/valleys of the wind power due to its high power density property, which is beneficial for BESS life. Illustration of this approach has been shown in this paper and the simulation results verified the effectiveness of this method in HESS power capacity specification.

A HESS model, consisting of battery and super-capacitor is adopted in this project. With the probability-based specified battery and super-capacitor capacities, the HESS model is implemented to accommodate the wind power fluctuations. By comparing the results with that obtained from the battery system alone, it is found that the super-capacitor within the HESS can deal with the high frequency current fluctuations occurring in the ESS terminals, which contributes to the lifetime extension of the battery system.

In this project, the power capacity specification method of BESS and super-capacitor within the HESS has been proposed for a given dispatched power level. With variation of P_d , the corresponding BESS and super-capacitor power capacities will change accordingly. To find a proper pair of BESS and super-capacitor power capacities to accommodate the wind power fluctuations is critically dependent on choosing an optimized dispatched power level P_d .

The hybrid energy storage system in this project takes advantages of high power density supercapacitor and high energy density battery. An intelligent controller is applied to the DC-DC converter to help the Voltage Source Inverter to regulate output power and also to control the operation of the battery and supercapacitor. This ensures a longer life time for the batteries. The detailed model is simulated in PSCAD/EMTP. The permanent magnet synchronous generator, coupled with a variable speed wind turbine, is connected to the power grid (14-bus system). A rectifier, a DC-DC converter and an inverter are used to provide a complete model of the wind system. The Hybrid Energy Storage System is connected to a DC-link through a DC-DC converter.

Although the developed design and control method for HESS is modeled and simulated for Type 4 permanent magnet synchronous generator based wind turbine system, the results can be adapted to Type 3 doubly-fed induction generator based wind turbine system. The HESS with the controller can be made as a Plug-in module to be applied to existing wind turbine generator system or wind power plant. There is no need to modify the existing wind control system equipped by the wind turbine manufacturers. Thus, the technology can be commercialized with further development. The major obstacle for large-scale commercialization is the cost of battery and supercapacitor.

Recommendations

Recommendations include experimental implementation of the controller and energy storage systems in laboratory environment for further testing and verification, which will help commercialization of the proposed system design and controller.

Specifically, the following follow-up R&D work is recommended:

1. Construct HESS module with controller in laboratory consisting of battery (lead acid or li-ion), supercapacitor, and micro-controller
2. Perform hardware-in-the-loop experiment in the lab for performance testing of the HESS in terms of smoothing wind power
3. Perform experiment to test effectiveness of extending battery life under fluctuating power with the control strategy
4. Test the HESS module with controller at actual wind turbine generator
5. Test the HESS module with controller at actual wind power plant

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