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Enabling wind farm to be black-start source by energy storage

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Abstract: An energy storage system (ESS) sizing method is proposed to enable wind farm (WF) to be a black-start (BS) source. This method handles three challenges: firstly, ESS has enough power to help WF start up. Secondly, the WF together with ESS is modelled as a virtual synchronous generator (VSG), and its frequency regulation capability is considered when sizing ESS. Thirdly, the power and capacity of ESS are determined so that VSG can deliver the required power during black-start. Instead of using wind speed probability distribution, kernel density estimation is used in this paper to directly estimate the probability distribution characteristics of ESS sizing. Simulation results show that with minimum investment cost on ESS, WF is able to be BS source.

1 Introduction

Due to the intermittent nature of wind power, wind power integration increases the risk of the massive blackout in power system [1]. Therefore, power system restoration has become a more and more important issue. In local power grids with high wind power penetration, wind power should be used in restoration to achieve fast restoration and decrease outage time. However, wind farm (WF) cannot directly operate as black-start (BS) source [2]. Using a wind farm to start up a thermal power plant, the challenges are twofold. Firstly, the wind farm has to ride through the frequency and voltage impact caused by the dynamic processes, including energising no-load transmission line and transformer, and starting up the auxiliary machine in a thermal power plant. Secondly, the active power and reactive power reserve of wind farm vary with wind speed. For a successful BS, firstly energy storage system (ESS) configuration is necessary to enable wind farm to be BS source. Secondly, WF and ESS need coordinated control to maintain frequency and voltage stability when facing active and reactive power impact. This paper focuses on the ESS configuration with minimum cost to deal with active power fluctuation of WF during BS progress.

ESS has been widely used to deal with the wind power uncertainty in power system. As far as the authors' knowledge, there is no study on the ESS configuration for enabling WF to be BS source, which mainly has two challenges. One is to maintain frequency stability and achieve fast frequency recovery. In [3] and [4], it turns out that ESS can be an economical option to help WF meet system frequency regulation requirements. In [5] and [6], the optimal sizing of an ESS based on secondary batteries is addressed for voltage and frequency control purposes in an isolated grid with wind power generation. The other challenge is to deliver the required power during certain time periods. This is actually a wind power smoothing problem. The ESS sizing is determined based on the worst day scenario in [7], which is clearly not economical. The key point of ESS sizing is how to describe the uncertainty of wind speed. The commonly used method is to model wind speed as probability distribution such as Weibull distribution [8]. However, whether the chosen probability distribution matches the wind speed fluctuation characteristics or not cannot be guaranteed. In this paper, an ESS configuration scheme for enabling WF to be a BS source is proposed. The kernel density estimation is used to directly obtain the distribution characteristics of ESS sizing.

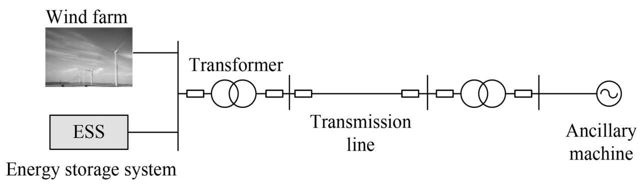

Fig. 1 *System using WF as BS source*

The reminder of this paper is organised as follows. Section 2 gives the framework of ESS configuration scheme. Detailed ESS power and capacity determination are presented in Section 3. Simulation results are shown and discussed in Section 4, followed by conclusions.

2 ESS configuration scheme

System using WF as a BS source is shown in Fig. 1. The proposed ESS configuration scheme has 3 steps. First of all, due to the lack of self-starting capability [2], ESS should have enough power to support WF in starting up. Energising no-load transformer and transmission line will cause overvoltage. WF can ride through overvoltage under 30%. Secondly, when starting up the ancillary machine in a thermal power plant, the system will undergo active power impact. For simplicity, WF is modelled as one wind turbine. The WF together with ESS is modelled as a virtual synchronous generator (VSG) to provide frequency response. Considering the uncertainty of wind power, ESS should make up for the insufficient frequency regulation power to maintain frequency stability and achieve fast frequency recovery. Thirdly, after all, ancillary machines are started up, the thermal power plant still needs up to 1∼2 h to be integrated into the system. The control objective of VSG is to deliver the required power during this time.

At the third step, both power and capacity sizing of ESS are considered, while in the first two steps, only the power sizing of ESS is considered because their time scale is much smaller compared to the last step. Power and capacity of ESS are finally determined considering results of all 3 steps.

3 ESS power and capacity sizing

This section presents how the ESS power and capacity sizing is determined at each step and how ESS configuration is optimally chose according to the results of these 3 steps.

3.1 Start up WF

When a wind turbine starts, its yaw and pitch equipment needs an external power supply to control. This can be considered as

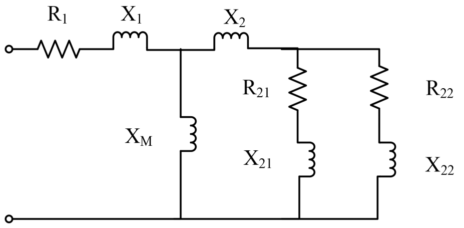

Fig. 2 *simplified equivalent circuit of the induction machine*

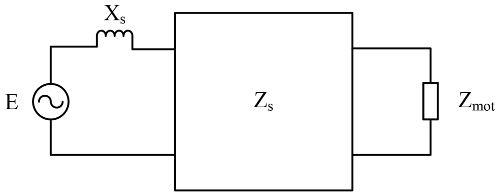

Fig. 3 *Thevenin's equivalent circuit*

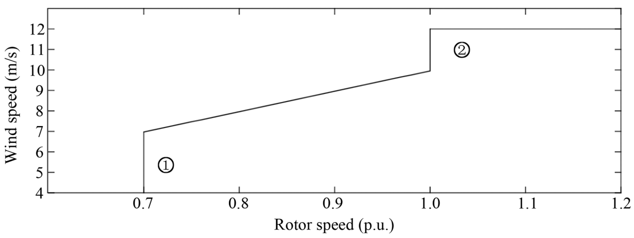

Fig. 4 *Rotor speed of the wind turbine*

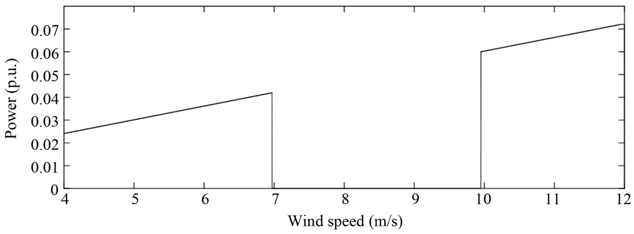

Fig. 5 *Required ESS power for virtual inertia response*

constant active and reactive power load [9]. The apparent power ESS needed is

$$S_{ESS}^{(1)} \geq \sum_{i=1}^{M} S_{wi} \tag{1}$$

where $S_{ESS}^{(1)}$ is the ESS apparent power, S_{wi} is the apparent power a wind turbine needed to start, and M is the number of wind turbines in a WF.

3.2 Start up the ancillary machine

Usually, the ancillary machines in a thermal power plant are double-squirrel induction machine. The simplified equivalent circuit is shown in Fig. 2. The parameter calculation is discussed in [10].

The Thevenin's equivalent circuit of VSG starting up ancillary machine is shown in Fig. 3. WF together with ESS is modelled as a VSG.

where E is the equivalent electromotive force of VSG, X_s is the equivalent inductance of VSG, respectively; Z_s represents a transmission line model, and Z_{mot} is the impedance of double-squirrel induction machine. According to this figure, VSG output is a function w. r. t the slip ratio

$$P_e(s) = \text{real}\left(\frac{\sqrt{3}E^2}{Z_{mot} + Z_s + jX_s}\right) \tag{2}$$

where s is the slip ratio of induction. The average impact power during induction machine starting up is given by

$$P_{e\_av} = \frac{1}{1 - s_0}\int_1^{s_0} P_e(s)\mathrm{d}s \tag{3}$$

where s_0 is the slip ratio under a no-load condition. The VSG operates under no-load condition before starting up an induction machine, which means the average impact power is the required frequency regulation power.

The required frequency response is provided by WF and ESS together

$$\Delta P_e = \Delta P_{WF} + \Delta P_{ESS} \tag{4}$$

where ΔP_e is the required frequency regulation power, ΔP_{WF} and ΔP_{ESS} is the frequency response provided by WF and ESS, respectively. The virtual inertia response $\Delta P_{\omega\_inertia}$ is provided by over-speed control, and pitch control provides steady-state frequency regulation power ΔP_β.

$$\Delta P_{WF} = \Delta P_{\omega\_inertia} + \Delta P_\beta \tag{5}$$

The frequency regulation power WF can possibly output varies with wind speed. ESS power is determined by the insufficient power of WF

$$\begin{aligned}\Delta P_{ESS} &= \Delta P_e - \Delta P_{WF} \\ &= (\Delta P_{e\_inertia} - \Delta P_{\omega\_inertia}) + (\Delta P_{e\_ss} - \Delta P_\beta)\end{aligned} \tag{6}$$

where $\Delta P_{e\_inertia}$ and $\Delta P_{e_ss}$are the required inertia response and the required steady-state frequency regulation response, respectively. And there is $\Delta P_{e\_ss} = P_{e\_av}$. The required virtual inertia response power of WF is

$$\Delta P_{\omega\_\text{inertia}} = 2H_{\text{eq}}\omega^* \frac{\mathrm{d}f^*}{\mathrm{d}t} \tag{7}$$

where H_{eq} is the equivalent inertia time constant, ω^* is the rotor speed of wind turbine and df^*/dt is the rate of change of frequency (RoCoF). However, as Fig. 4 shows, when wind speed is near the cut-in speed (segment ①) and rated wind speed (segment ②), the wind turbine cannot provide virtual inertia response due to fixed rotor speed. Under these situations, ESS should provide the required power for virtual inertia response as shown in Fig. 5.

Equation6) shows that ESS power needed has probability distribution characteristics, similar to wind speed. In this paper, the kernel density estimation (KDE) is used to obtain the probability distribution of ESS power and capacity. KDE is a non-parameter way to estimate the probability density function of a random variable. Let $x = \{x_1, x_2, \ldots, x_n\}$ be a univariate independent and identically distributed sample drawn from some distribution with an unknown probability density function (PDF) f_{est}. Its kernel density estimation is

$$f_{est}(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x - x_i}{h}\right) \tag{8}$$

where n is the total number of samples, h is a positive smoothing parameter called bandwidth, and $K(\cdot)$ is the kernel function, which is often chose as the Gaussian Function. The bandwidth h is a key parameter to estimation accuracy, for which the optimal choice is given by

$$h = \left(\frac{4}{3n}\right)^{\frac{1}{5}}\sigma \approx 1.06\sigma n^{-\frac{1}{5}} \tag{9}$$

where σ is the standard deviation of the samples. The cumulative distribution function (CDF) is the integral of PDF

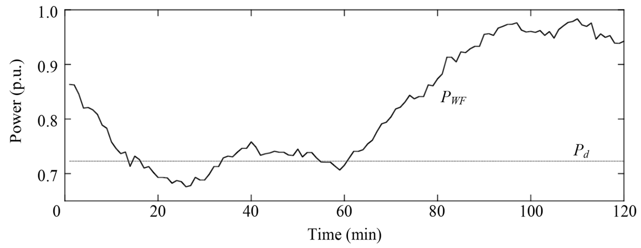

Fig. 6 *Wind power and objective output*

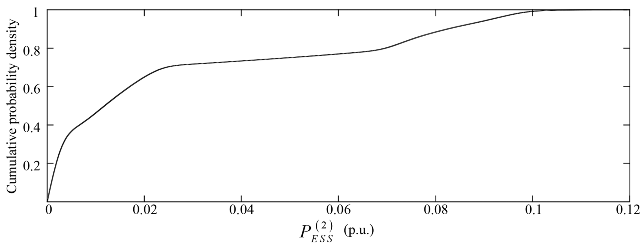

Fig. 7 *CDF of $P^{(2)}_{ESS}$*

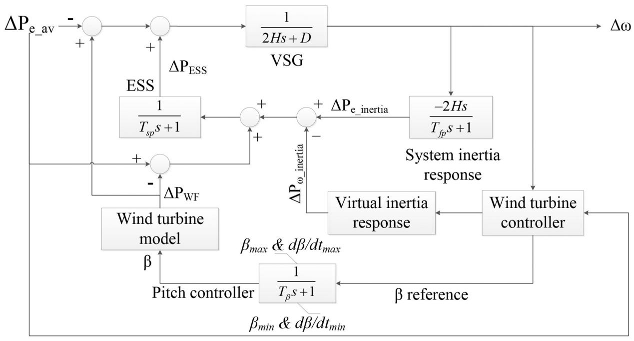

Fig. 8 *System frequency response model*

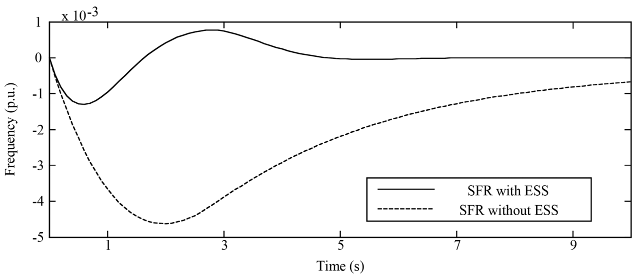

Fig. 9 *SFR with and without ESS*

$$F(x) = \int_0^x f_{est}(\Delta P_{ESS}) d\Delta P_{ESS} \tag{10}$$

Given different confidence level α, the ESS power can be sized

$$P^{(2)}_{ESS} = F^{-1}(\alpha) \tag{11}$$

3.3 Constant power output

A coal fuelled thermal power plant needs quite a long time from all ancillary machines started to generator unit integration. Even for thermal power plant below 100MW, it will take 1∼2 h. Thus during this time, it is required that VSG supply abundant power for ancillary machines. This is actually a problem with ESS sizing for wind power smoothing during a certain period of time.

The wind power during this time is a stochastic process described by scenarios. For example, under the scenario in Fig. 6, P_{WF} is the output power of WF, and $P_d$is the objective output of VSG.

The output power of ESS is

$$P_{ESS}(t) = P_{WF} - P_d \tag{12}$$

$P_{ESS}(t) > 0$ means ESS is charging and $P_{ESS}(t) < 0$ means ESS is discharging. The discharging power is more concerned since when discharging, ESS makes up for insufficient power of WF. Assume there are N scenarios in total, so the ESS power sizing for the ith scenario is the maximum discharging power

$$P_{ESS\_i} = \max \{P_{ESS}(t) | P_{ESS}(t) < 0\} \tag{13}$$

Correspondingly, the capacity sizing of ESS under this scenario is the one-time maximum discharge capacity

$$E_j = \int_{t_{j1}}^{t_{j2}} |P_{ESS}(t)| \mathrm{d}t \qquad E_{ESS\_i} = \max \{E_j\} \tag{14}$$

where E_j is the jth discharging energy of ESS under this scenario, t_{j1} and $t_{j2}$are the start and end time of the discharging, respectively. Under every scenario, the ESS power $P_{ESS_i}$and capacity E_{ESS_i} can be determined by (13) and (14). For the N-dimensional scenario set, statistical data of ESS power and capacity sizing can be obtained repeatedly apply (13) and (14) to every scenario.

Similar to subsection 3.2, the PDF of $p = \{P_{ESS\_i} | i = 1, 2, \ldots, N\}$ and $e = \{E_{ESS\_i} | i = 1, 2, \ldots, N\}$ are estimated by KDE

$$F_p = \int_0^x f^p_{est}(p) d\, p \qquad F_e(x) = \int_0^x f^e_{est}(e) de \tag{15}$$

$$P^{(3)}_{ESS} = F_p^{-1}(\beta) \qquad E_{ESS} = F_e^{-1}(\beta) \tag{16}$$

where β is the confidence level. The capacity of ESS is sized as $E_{ESS,}$ and the power of ESS is sized as the maximum of the results from Sections 3.1, 3.2 and 3.3

$$P_{ESS} = \max \left\{S^{(1)}_{ESS}, P^{(2)}_{ESS}, P^{(3)}_{ESS}\right\} \tag{17}$$

4 Simulation results

Wind power data used in this paper is measured from Taoshanhu WF of the State Grid Jibei Electric Power Company Limited of China. This WF has 133 1.5MW wind turbines with a total capacity of 199.5MW. The data resolution is 1 min, and total data number is 525600. All wind power output scenario is directly from annual measured data.

The apparent power needed to start up a wind turbine is ∼18kVA [9]. Thus from (1), $S^{(1)}_{ESS} = 2.394MVA$.

The CDF of $P^{(2)}_{ESS}$ in subsection 3.2 is shown in Fig. 7. Set confidence level $\alpha = 0.9$, there is $P^{(2)}_{ESS} = 0.0823(\mathrm{p.u})$.

The system frequency response model is shown in Fig. 8. The system frequency response (SFR) with wind speed at 5 m/s is shown in Fig. 9. Compared to the SFR without ESS, the SFR with ESS can achieve fast frequency recovery due to the virtual inertia response supplied by ESS. WF cannot provide virtual inertia response because of the low wind speed. In this case, ESS also provides insufficient frequency regulation power of WF to maintain frequency stability.

Assume $P_d = 0.2$ (p.u.), The CDF of $P^{(3)}_{ESS}$ and E_{ESS} in 3.3 are shown in Fig. 10 and 11. Set confidence level $\beta = 0.9$, there is $P^{(3)}_{ESS} = 0.2026(\mathrm{p.u})$ and $E_{ESS} = 0.0163$ (p.u.). According to (17), $P_{ESS} = 0.2026$.

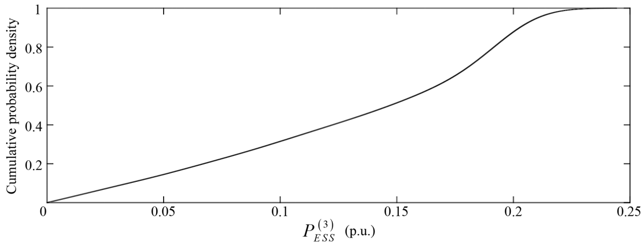

Fig. 10 *CDF of* $P_{ESS}^{(3)}$

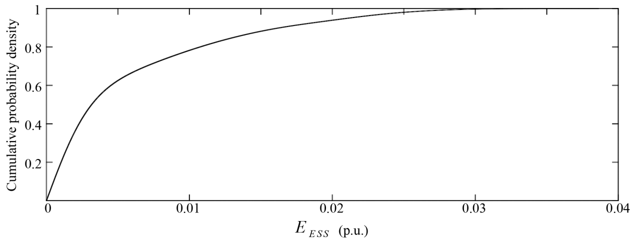

Fig. 11 *CDF of* E_{ESS}

5 Conclusion

An ESS configuration scheme for enabling WF to be a BS source is proposed in this paper. The scheme aims to deal with three challenges WF will confront during the BS process: support WF in starting up, improve frequency response characteristics when starting up auxiliary machines and deliver required power during certain time periods. Utilising KDE to estimate the probability distribution characteristics of ESS power and capacity is more accurate. Simulation results show that with the minimum ESS sizing, WF can handle these challenges and be able to operate as BS source.

6 Acknowledgments

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