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Tiered Energy Storage System for Auxiliary Service of Power Systems with Wind Farms

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Abstract: With high penetration of renewable energy, the cost of frequency control ancillary services (FCAS) has increased substantially and has become one of the main barriers to utilize clean and inexhaustible wind, solar and like power resources in large scale. After investigating a variety of often used energy storage devices (ESDs), the authors present a tiered energy storage system (TESS) for self-provision of regulation services by wind farms. Designed through employing different characteristics of these ESDs with respect to capacity, responding speed and investment/operation costs, the TESS can be applied for FCAS of power grids integrated with wind farms, including frequency regulation and contingency services. Simulations carried out in the research has verified the feasibility of the TESS.

Keywords: *Renewable energy resources; Frequency control auxiliary services; Tiered energy storage systems;*

I. INTRODUCTION

Wind power is a renewable energy resource with untapped potential for massive utilisation as alternative power generation. In recent years, this resource has drawn great attention and increasing support from public utilities and governments in many countries. Wind power, if widely exploited, could significantly reduce the dependence of our modern life and industries on fossil fuels producing detrimental greenhouse gas emissions, which will greatly benefit our societies and ease pressures on the environment [1].

Wind power, however, has some unfavourable characteristics that, when combined with large-scale installation of wind turbines, could impose significant challenges to the operation of wind farms connected to the existing power generation, transmission and distribution grids. It is not uncommon to curtail power generation of wind farms due to the restrictions of the transmission and the energy storage capacity. In addition, wind power is stochastic and intermittent, and can induce "inverse peak regulation", bringing about unexpected risks to the security and stability of power systems [2,3]. Therefore, it is necessary to install energy storage systems (ESS) to smooth power generation of wind turbines and introduce risk-controlling strategies into power systems interconnected with wind farms.

Moreover, the increased penetration of wind power in electricity systems is likely to increase the requirements on self-provision of frequency control and auxiliary services (FCAS) services by wind farms as having been required in some regions and countries such as done by the PJM market in USA and as recommended by Australian Energy Market Operator to South Australia Power [4]. The self FCAS will result in an extra barrier to the installation of further wind generation.

Some types of energy storage devices (ESDs), owing to their fast power input/output capacity, provide a flexible solution to facilitate intermediate storage when operating together with wind farms. Among a few existing technologies, sodium-sulphur (NaS) batteries have particularly attracted attention for their large capacity, high energy density and long cycle life. NaS batteries can be deeply discharged with the instantaneous discharging power reaching five times of their rated value. Consequently, the NaS energy storage system can meet requirements not only for load levelling over a span of hours but also for responding within fractions of a second, evident in the UPS and similar devices. These characteristics of the NaS make it a suitable energy-storage buffer which can provide power frequency regulation in addition to the energy storage function [5]. High annual operating cost of NaS batteries, nevertheless, will greatly increase the overheads of wind power utilization. Therefore, NaS batteries may be unable to provide enough energy storage capacities for power grids with high penetration levels of renewable energy resources due to the high cost of large-scale installation and operation of the batteries. Other supplementary means with larger energy storage capacity should be considered, such as pumped-storage hydroelectricity (PSH), flywheel energy storage (FES) and compressed air energy storage (CAES), to name afew. Among these technologies, the CAES has distinguished merits including storage capacity, low cost, long lifetime, mature technologies and established operation experience, and is deemed as one of the cheapest ESS technologies in terms of capital cost ($/kW-h) and maintenance cost ($/kW-year) [6, 7].

In view of the ever-increasing wind power utilization, a tired ESS (TESS) is presented in the paper to alleviate impacts of wind turbines and provide the FCAS. The paper is organized as follows. Section 2 and 3 explain the significance and the design of the TESS. Simulations is carried out in Section 4 to illustrate operations of the TESS in providing frequency regulation and contingency services. Section 5 concludes the paper.

II. INNOVATION OF TESS

As summarised below, there are quite several barriers in utilizing wind energy with respect to operation security and cost:

- More uncertainties in secure operation of power systems due to integration of renewable energy resources.
- Overdesigning of transmission systems, i.e., a large percent of the transmission capability is not necessary for most time of a year because of intermittent behaviour of wind energy; or insufficient transmission capability due to environment and other constraints.
- Insufficient energy storage capacity or inability of applying renewable energy resources for power system frequency regulation.

- Curtailment of wind power generation due to either transmission limits or inverse peak regulation.
- High prices of batteries installed to alleviate impacts of wind power generation.

With the installation of the proposed TESS, aside from the wind power generation being smoothed, the transmission lines can then be designed at an appropriate capacity level, and the wind power waste due to the curtailment can be avoided. Furthermore, with the maturity of energy storage technologies, some types of ESDs such as NaS mentioned earlier can be used not only for a normal energy storage device, but also for frequency regulation as spin wheel energy storage. By adding the second tier, the CAES into the TESS, both requirements on fast system regulation and large storage capacity are satisfied. The TESS also makes it possible to design an optimum strategy for the NaS battery charging/discharging in order to greatly extend the batteries' cycle life and thus effectively reduce the operation cost of the power system integrated with renewable energy resources.

In fact, the TESS is to addresses all the challenges summarized above through achieving the following objectives:

- Providing frequency regulation and spinning reserve required to wind farms
- Providing contingence servicesrequired to wind farms
- Extending NaS battery cycle life with optimal charging/discharging strategies
- Avoiding curtailment of wind power generation and overdesign of transmission system expansion with sufficient energy storage capacity

III. IMPLEMENTATION OF TESS

A power grid integrated with wind farm and the TESS (composed of NaS Batteries and CAES) can be illustrated by Fig. 1, where the TESS is installed at the Point of Common Coupling (PCC) of the wind farm to smooth the power injection at the point and provide the required FCAS.

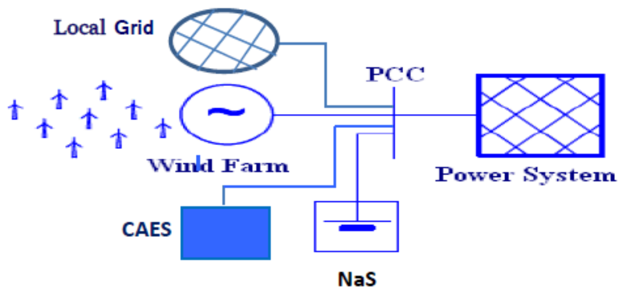

Fig.1Power system integrated with wind farms and TESS

3.1 FCAS

With large-scale utilization of renewable energy resources, the demand on FCAS will be increased significantly, which is due to intermittence and uncertainties associated with operations of wind farms and photovoltaic power stations. For instance, high wind speed cut-outs would need the contingence service for power generation replacement, in addition to the continuous requirement on regulation services for smoothing the fluctuation of wind power generation. As indicated in [4] the increased penetration of wind generation in electricity systems will inevitably bring about the cost increase of the ancillary services. If this cost is solely attributed to wind generators it could be prohibitive to the installation of further wind generation using existing technologies and methods.

Usually, frequency response of a power grid is modelled on a basis of minutes. When the frequency is deviated from the nominal value, Regulation Raise or Regulation Lower service is required. to ensure the frequency within the specified range:

- Regulation Raise: more power generation to correct a minor drop in frequency.
- Regulation Lower: less power generation to correct a minor rise in frequency.

Apart from frequency regulation, contingency service is the other category of FCAS, which is usually caused by a sudden and unexpected trip of a large generator or load. With this service, power generation should be replaced to or removed from the power grid, which can be further divided into the following services [4]:

- Fast Raise: fast power generation replacement in seconds to arrest a major drop in frequency following a contingency.
- Fast Lower: fast power generation removal in seconds to arrest a major rise in frequency following a contingency.
- Slow Raise: Power generation replacement within a minute to stabilise frequency following a major frequency drop.
- Slow Lower: Power generation removal within a minute to stabilise frequency following a major frequency rise.
- Delayed Raise: Power generation replacement in minutes to recover frequency to the normal operating band following a major frequency drop.
- Delayed Lower: Power generation removal in minutes to recover frequency to the normal operating band following a major frequency rise.

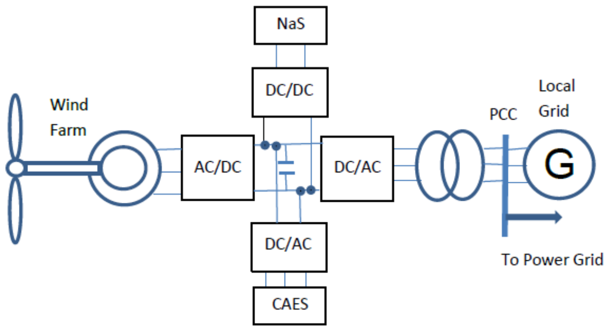

Fig.2 Two tiers of TESS

3.2 TESS

While NaS batteries are very apposite for power system frequency regulation due to their fast response in charging/discharging, their energy storage capacities could be inadequate for power grids with high penetration levels of renewable energy resources. Large scale battery installation would significantly increase power system investment and operation costs which are unnecessary as mechanical methods such as the CAES that can be installed as the second tier of the TESS to increase the overall capacity of the energy storage (Fig.2). To meet the frequency regulation requirements, the batteries can inject (discharging) or absorb (charging) power with a very fast response. For contingence services, the batteries could provide the fast response as required. The CAES will then be switched in to provide the auxiliary power in the following frequency control. By coordinating the two tiers of the TESS with a regulator, both the requirements of enough energy storage capacity and the fast response in system regulation can be satisfied. Furthermore, the TESS will make it possible for the optimal charging/discharging of the batteries to extend their life as addressed in Section 3.3.

3.3 Optimal charging/discharging of NaS batteries

It is known that the life span of a battery is determined by the number of charging/discharging cycles and the discharging depth of each cycle (Figure 3). Based on the investigation, optimal control strategies are to be adopted in the TESS to help extend batteries' cycle life for minimising the operation cost [5].

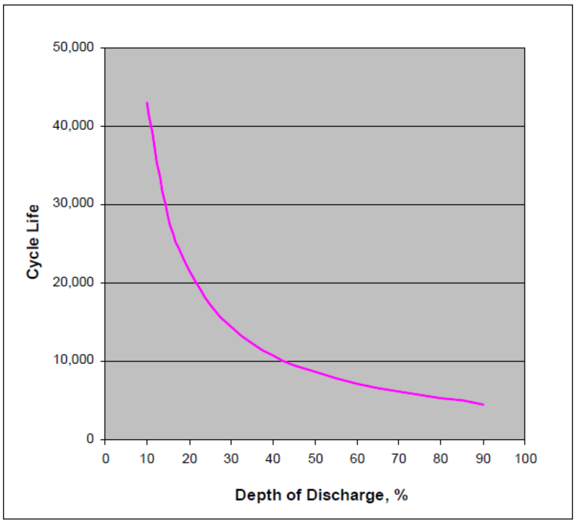

Fig.3 Cycle life of NaS battery versus its discharge depth

In providing frequency and contingence, consequently, NaS batteries' state of charge (SoC) is monitored. The SoC of batteries is controlled within a certain percentage range during performing the FCAS.

3.4 Methodologies

Coordinated charging/discharging of batteries and the operation of the CAES for maximum cycle life of the batteries and the optimal ancillary services. The TESS thereby designed is to meet the demands on capacity and response speed for regulating frequency, auxiliary power reserve, and alleviating the impact of wind power fluctuations.

The rule of thumb and assumptions in coordinating NaS Batteries and CAES for FCAS are as follows:

- NaS is for frequency regulation (raise and lower).
- CAES is for slow and delayed contingence services (Raise and Lower).
- NaS switches in for fast contingence service (Raise and Lower) until being replaced by CAES.
- SoC of NaS is monitored to avoid over charged/discharged
- The output of CAES may be adjusted to control the SoC of NaS within the specified percentage range.
- The energy storage level of CAES is monitored and conventional FCAS may be required when the TESS reaches its limit.

In performing the FCAS, both the NaS batteries and the CAES can inject/absorb power into/from the electricity grid as shown in Fig. 2. The two-way power transmission is controlled via the DC/DC and DC/AC converters that connected the NaS and the CAES to the grid.

IV. SIMULATIONS AND DISCUSSIONS

As typical power demands can be modelled by multiple Gaussian distribution [8], the discrepancy between the power generation and demand, i.e., the frequency regulation is modelled with a normal distribution. The contingence service requests are generated randomly in terms of time points, response speeds (fast, slow or delayed) and amount of power injection or absorption. The total power required by the FCAS in the case study is illustrated in Fig. 4.

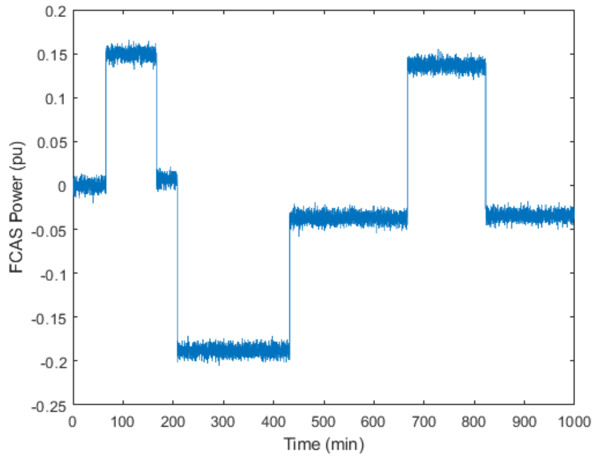

Fig.4Power Demand for FCAS

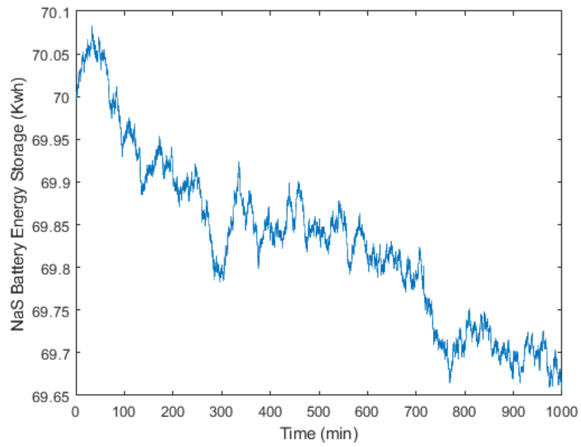

Fig.5NaS Battery Energy Storage

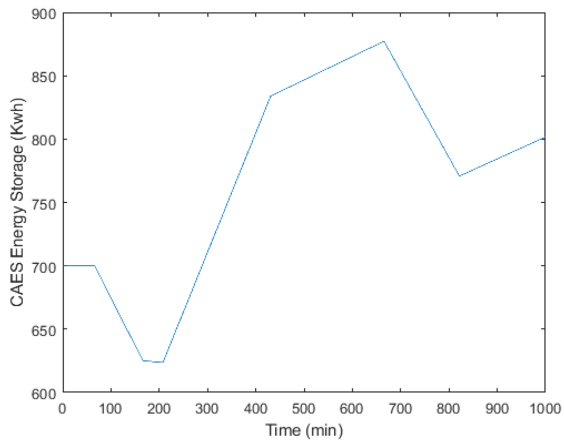

Fig.6CAES Energy Storage

Initially, the SoC of NaS is 70% (70 Kwh) and the energy storage level of the CAES is 70% (700 Kwh). It is assumed that the charge levels of both NaS and CAES are controlled in between 30% ~ 90%.

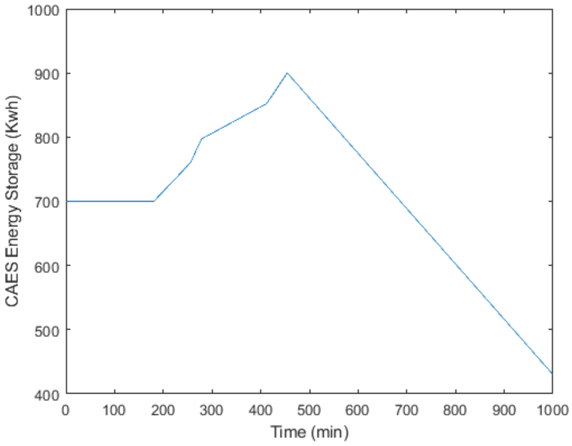

Fig.7CAES Energy Storage Reaching Limit

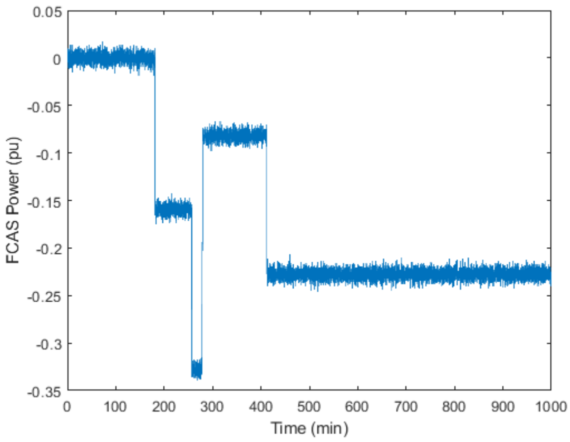

Fig.8FCAS with Long Duration Lower

Fig. 5 & 6 show that both NaS and CAES are working in the specified limit range to provide the FCAS (Fig. 4) and there are no requests on conventional FCAS from the local grid.

It has been observed that, however, long duration contingence services in one direction (either raise or lower) may drive the TESS towards its limit and convention FCAS may be required. As shown by Fig. 7 the energy storage of the CAES had once reached to 90% corresponding to long durations of contingence lower services (Fig. 8). In both cases, the SoC of the NaS battery is controlled in the specified range.

CONCLUSIONS

Surveys show that the main barriers of utilization of wind power are the higher electricity price compared with that of conventional thermal power plants and security issues due to intermittent characteristics of wind power, which has become a major concern for sustainable economic development, particularly in planning the future power utility infrastructure. The project is to deepen the research in this filed. Through circumventing overdesign of extended transmission lines, reducing installation capacity of NaS batteries and extending their cycle life, and avoiding curtailment of power generation, a competitive electricity price of renewable power is achievable. Besides, the security problems of power systems with wind farms can be greatly improved by installed the proposed TESS for self-provision of auxiliary frequency regulation. The simulations show that the TESS is a feasible solution to provide the FCAS by wind farms. Our future work is to complete the designing of the TESS based on the proposal outlined in the paper.

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