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Enhancing Frequency Response of Wind Farms using Hybrid Energy Storage Systems

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Abstract—The decarbonisation of electricity networks has led to increasing numbers of renewables in the energy mix. Besides energy generation, large-scale wind generators are now called to provide mandatory frequency response according to several grid regulations. This, however, could impose significant constraints on their operation, reducing the capabilities in power and energy delivery and resulting in loss of profits. Energy storage systems (ESSs) can act as a means to limit these losses and ensure that services are delivered according to network regulations. However, there are many occasions where a single energy storage (ES) technology would fail to be economically viable for this purpose. This paper builds on established techniques for sizing ES to complement wind generators in providing frequency support and introduces considerations for hybrid ES systems (HESSs) comprised of more than one technology. The methodology was applied for a 60 MW wind farm complemented by a Vanadium Redox flow battery (VRFB) and supercapacitors for the provision of Primary, Secondary and High frequency response as defined in United Kingdom (UK) Grid Code, however it is technology-independent and could be used to support various cases. Linear Programming is used for sizing the system and maximizing revenues and three cases are compared i.e. using no storage, using a single ESS and using a HESS respectively. The results confirm that, under certain conditions, the use of a HESS can provide increased revenues for this type of applications.

Keywords— *Wind Farm Frequency Support, Hybrid Energy Storage System; Energy Storage Sizing;*

I. INTRODUCTION

Governments nowadays are recognizing the importance of decarbonizing the electricity generation and setting ambitious targets which requires step changes to be made regarding the proliferation of renewables. In the UK these targets dictate a 15% of the total electricity generation to be originating from renewable energy by 2020 and a reduction of at least 80% of Greenhouse Gas (GHG) emissions by 2050 relative to 1990 levels [1]. Renewable sources, such as wind and solar are however variable and stochastic. Therefore when high levels of penetration are introduced, intermittency of these renewables can lead to important techno-economic challenges for network operators, decision makers and solution providers relating to both integration costs and power flow management [2].

In particular, fluctuations of wind generation can seriously affect power quality [3][4]. The UK National Grid has therefore established mandatory requirements around the operation of wind generators which include mechanisms to ensure balance is maintained between generation and demand

such as the Mandatory Frequency Response service [5][6]. This regulation applies to all generators under the National Grid Code including wind generators or wind parks with a registered capacity of 50MW or more and it is a compulsory condition of connection with the Great Britain (GB) Transmission System [7]. The main target is to automatically modify active power for maintaining frequency within statutory limits (i.e. 49.5Hz to 50.5Hz) and operational limits (49.8Hz to 50.2Hz) [7]. This includes: 1) Primary Response i.e. minimum provision of active power for low frequency events within the first 10 seconds and sustained for an additional of 20 seconds, 2) Secondary Response i.e. minimum provision of active power for low frequency cases between 30 seconds and 30 minutes from the beginning of the event, and 3) High Response i.e. decrease of active power for high frequency scenarios within 10 seconds after the event and sustained thereafter [5] as shown in Fig.1.

Fig. 1 Power behaviour for primary and secondary frequency responses [5]

One of the methods for accomplishing this task consists of modifying the generators' output so that they do not operate at maximum aerodynamic efficiency [6]. This involves de-rating of the power capability of the wind turbine in order to obtain reserve power for frequency response i.e. wind generators not operating at their maximum available power and the reserve utilized to respond to frequency deviations [6].

The aforementioned method forces the wind generator to reduce its output and operate at reduced efficiency. This represents a loss of revenue. ESSs can act as a means to limit losses and ensure that frequency services are delivered. At present, ES is still less cost-effective than other conventional solutions. Therefore, optimal sizing is essential. In [9], the optimal sizing of an ESS for this type of application is determined by delivering the wind energy that would be shed. An optimal sizing of battery ESS is addressed in [10] based on the short term overloading capacity of the storage device for primary frequency support in islanded microgrids. For isolated grids fully supplied by wind power, reliability requirements and a bi-level control strategy is considered in [11] for the optimal

sizing of the ESS. The sizing method applies genetic algorithms and sequential simulation. In [6], an economic optimization for sizing the ESS is addressed for primary frequency support in wind power plants considering the regular energy market and the frequency response market under UK regulations. Although the ESS can provide power reserves for frequency response under certain assumptions and relieve the wind generators from having large energy reserves, a combination of storage technologies is suggested in the conclusions as a means to improve the techno-economic feasibility of such solutions [6].

HESS refers to the combination of two or more electrical energy storage technologies and it benefits by merging the individual advantages of different storage devices without presenting any of their drawbacks [12]. In wind generator applications with high wind speed fluctuations, the output power requires an ESS with large energy capacity and high power response characteristics for frequency response provision and power reserves [6][13]; ES hybridisation can thus prove to be an attractive choice as there is currently no single solution able to provide both energy and power at a comparatively low cost. In [6], a VRFB was used in a wind park for the provision of frequency response in the UK market. Although this technology could be considered as a good candidate for renewable energy applications due to its long lifetime it is still expensive compared to other technologies for power demanding applications [12]. Therefore, it can be further improved by hybridizing it with a power-dense technology like supercapacitors. Supercapacitors can deliver higher power with lower cost than VRFBs and they have high efficiency and cycle lifetime, however their energy capacity is relatively low [14][15].

In this paper we present a techno-economic sizing methodology for HESSs with appropriate power and energy reserve capacity for enhancing the efficiency of wind turbines in frequency response building on established tools [6]. A high power density ESS (i.e. supercapacitor bank) is used to provide the required frequency response whilst the energy dense device (i.e. a VRFB) is used to manage longer-term energy reserve levels. This will allow the wind generator to increase its operating efficiency and work closer to its maximum available energy level. The HESS sizing results are then applied in an investment tool developed for calculating and verifying the total annualized capital costs and the contribution of each technology based on real market prices. The paper is organized as follows: Section II presents the methodology for sizing HESS based on the net incomes for the wind generator and the system constraints. Section III presents and discusses results for a case study in the UK. Conclusions are summarized in Section IV.

II. SIZING METHODOLOGY

Our methodology is based in the one presented in [6], where the economic improvement of using storage devices and wind power reserves is measured according to the total revenue that the User obtains for providing frequency response. In this paper we define the User as the wind generator and its aim is to find the highest income for selling energy in the wholesale regular market and the frequency response market under the UK regulations. Therefore, an optimization model for sizing one or multiple energy storage devices is applied in order to achieve the best combination of the HESS and the wind generator power

reserve in terms of sizing and maximum revenues. This model uses the equations developed in [6] but considers multiple ES technologies and related constraints in the optimization objective. The corresponding flowchart is shown in Fig. 2.

Fig. 2. HESS Sizing Methodology

A. Optimization Objective

The optimization objective (F) is composed of four particular parts: the capital cost of HESS (TC_{HESS}), the cost of degradation of HESS ($TC_{DEG(t)}$), and the revenues from the wholesale electricity market ($I_{RM(t)}$) and the frequency response market ($I_{FREQ(t)}$). This function is analysed for a period of time D in days, with a sample time T in minutes, and during the life time of the HESS in years (LT).

$$F = \left(\frac{365 \cdot LT}{D} \sum_{t=t_0}^N I_{RM(t)} + I_{FREQ(t)} - TC_{DEG(t)} \right) - TC_{HESS} \quad (1)$$

B. Main Constraints

In order to obtain the maximum income for the wind generator operator, the optimization process must include a number of constraints which represent a realistic scenario. These constraints considered are:

1) *HESS Capital Cost*: The initial investment for acquiring storage technologies is considered as the major factor for sizing these devices [11]. Their capital cost is a function of the storage

$$TC_{HESS} = (C_{ESS1}^{pwr} \cdot P_{ESS1}) + (C_{ESS1}^{en} \cdot E_{ESS1}) + (C_{ESS2}^{pwr} \cdot P_{ESS2}) + (C_{ESS2}^{en} \cdot E_{ESS2}) \quad (2)$$

where C_{ESS1}^{pwr} and C_{ESS2}^{pwr} are the costs of power for the energy storage device 1 (ESS1) and energy storage device 2 (ESS2) respectively in £/MW, C_{ESS1}^{en} and C_{ESS2}^{en} are the costs of energy for ESS1 and ESS2 in £/MWh, P_{ESS1} and P_{ESS2} are the power rating of ESS1 and ESS2 in MW, and E_{ESS1} and E_{ESS2} are the energy capacity of ESS1 and ESS2 in MWh.

2) *Degradation Cost*: The total degradation cost ($TC_{DEG(t)}$) in £ is calculated based on the unitary cost of degradation for ESS1 (C_{DEG1}) and ESS2 (C_{DEG2}) in £/MWh, the loss compensation for ESS1 and ESS2 in MWh ($E_{CL1(t)}$, $E_{CL2(t)}$), the energy discharge or charged by ESS1 and ESS2 for low frequency or high frequency responses respectively in MWh ($E_{FREQ1(t)}^{dis}$, $E_{FREQ1(t)}^{ch}$, $E_{FREQ2(t)}^{dis}$, $E_{FREQ2(t)}^{ch}$), and the energy lost in ESS1 and ESS2 caused by the leakage of charge in MWh ($E_{LEAK1(t)}$, $E_{LEAK2(t)}$).

$$TC_{DEG(t)} = (E_{CL1(t)} + E_{FREQ1(t)}^{dis} + E_{FREQ1(t)}^{ch} + E_{LEAK1(t)}) \cdot C_{DEG1} + (E_{CL2(t)} + E_{FREQ2(t)}^{dis} + E_{FREQ2(t)}^{ch} + E_{LEAK2(t)}) \cdot C_{DEG2} \quad (3)$$

3) *Wholesale Regular Market Revenue*: The revenue obtained through the UK wholesale market ($I_{RM(t)}$) is defined as follows:

$$I_{RM(t)} = C_{RM(t)} \cdot E_{RM(t)} \quad (4)$$

where $C_{RM(t)}$ is the market price in £/MWh and $E_{RM(t)}$ is the energy delivered under this scheme.

4) *Frequency Response Market Revenue*: The revenue achieved for supporting frequency under the UK frequency regulations ($I_{FREQ(t)}$) is calculated based on the energy used for primary response, secondary response or high frequency response ($E_{FREQ(t)}$) and the market costs for these services ($C_{FREQ(t)}$).

$$I_{FREQ(t)} = C_{FREQ(t)} \cdot E_{FREQ(t)} \quad (5)$$

C. Additional Constraints

The following additional constraints are designed to comply with the balance wind generator – grid, within the wind generator, guarantee frequency support, maintain mandatory reserved levels, consider the ESS state of charge limitations and operational charge. The corresponding nomenclature for Eq. 6 – Eq. 22 is shown in Table I.

- Energy Balance: Wind Generator – Grid:

$$E_{RM(t)} = E_{w(t)} - \frac{E_{CL1(t)}}{\eta_{ESS1}^{ch}} - \frac{E_{CL2(t)}}{\eta_{ESS2}^{ch}} \quad (6)$$

- Energy Balance: Wind Generator

$$E_{w(t)} = E_{w(t)}^{max} - E_{WRES(t)} - E_{WFREQ(t)}^{dis} \quad (7)$$

- Energy Balance: Frequency Support

$$E_{FREQ(t)} = \left(E_{WFREQ(t)}^{dis} + \frac{E_{FREQ1(t)}^{dis}}{\eta_{ESS1}^{dis}} + \frac{E_{FREQ2(t)}^{dis}}{\eta_{ESS2}^{dis}} \right) - \left(E_{WFREQ(t)}^{red} + \frac{E_{FREQ1(t)}^{ch}}{\eta_{ESS1}^{ch}} + \frac{E_{FREQ2(t)}^{ch}}{\eta_{ESS2}^{ch}} \right) \quad (8)$$

$$E_{FREQ(t)} - E_{FREQ(t)}^{REQ} = 0 \quad (9)$$

- Energy Balance: Energy Storage Devices

$$E_{C1(t)} - E_{C1(t-1)} = E_{CL1(t)} + E_{FREQ1(t)} - E_{LEAK1(t)} \quad (10)$$

$$E_{C2(t)} - E_{C2(t-1)} = E_{CL2(t)} + E_{FREQ2(t)} - E_{LEAK2(t)} \quad (11)$$

$$E_{FREQ1(t)} = E_{FREQ1(t)}^{ch} - E_{FREQ1(t)}^{dis} \quad (12)$$

$$E_{FREQ2(t)} = E_{FREQ2(t)}^{ch} - E_{FREQ2(t)}^{dis} \quad (13)$$

- Reserve Levels:

$$E_{FREQ(t)}^{max} \leq E_{UC1(t)} + E_{UC2(t)} + E_{WRES(t)} + E_{WFREQ(t)}^{dis} - E_{WFREQ(t)}^{red} \quad (14)$$

- ESS: Operational Charge

$$E_{UC1(t)} \leq P_{ESS1} \cdot \frac{T}{60} \quad (15)$$

$$E_{UC2(t)} \leq P_{ESS2} \cdot \frac{T}{60} \quad (16)$$

$$E_{UC1(t)} \cdot \frac{T_{reg}}{T} \leq E_{C1(t)} \quad (17)$$

$$E_{UC1(t)} \cdot \frac{T_{reg}}{T} \leq E_{C1(t)} \quad (18)$$

- ESS: State of Charge Limitation

$$E_{C1(t)} \leq SOC_{ESS1}^{max} \cdot E_{ESS1} \quad (19)$$

$$E_{C2(t)} \leq SOC_{ESS2}^{max} \cdot E_{ESS2} \quad (20)$$

$$E_{C1(t)} \geq SOC_{ESS1}^{min} \cdot E_{ESS1} \quad (21)$$

$$E_{C2(t)} \geq SOC_{ESS2}^{min} \cdot E_{ESS2} \quad (22)$$

Constraints regarding power limits and storage losses are also considered. Linear programming is applied to the objective function and constraints for obtaining the maximum revenue and related storage sizing values. Other important values can also be acquired such as storage energy delivered/absorbed for frequency response and the wind power profile throughout the sample time.

After this stage, the results are entered into the Investment Tool developed to calculate the annualized capital costs of HESS under real-market prices for storage technologies. This tool applies HESS Capital Costs equation (Eq. 2) considering actual market prices from different providers and annualize the result through the capital recovery factor (CRF) and annual interest rate (i) which is calculated as follows:

$$CRF = \frac{(1+i)^{LT} \cdot i}{(1+i)^{LT} - 1}$$

III. RESULTS AND DISCUSSION

The economic benefits of using HESSs in wind generators for the provision of frequency response service were assessed in a study case based on a 60MW wind farm with a hybrid energy system composed of a VRFB and supercapacitors and operating under UK market and regulations. The methodology

described in Section II was developed and solved in MATLAB® and it requires a number of inputs as defined in Eq.1 – Eq.22. The Market Index Price (MIP) in £/MWh was obtained from [16] and the Frequency Response Price was calculated according to the UK Response Energy Payment scheme described on “The Connection and Use of System Code” [17]. The maximum generation of the wind generator was adjusted from NREL Western Wind Dataset [18]. For calculating the requested frequency support ($E_{FREQ(t)}^{REQ}$) and maximum frequency support ($E_{FREQ(t)}^{max}$), the UK regulations were followed as explained in [5]. The rest of parameters for this study case are summarized in Table II.

Table I. Nomenclature for Eq. 6 – Eq. 22

ABBREVIATION	
$E_w(t)$	Energy produced by wind generator (MWh)
$E_w^{max}(t)$	Max. energy that wind generator could produce (MWh)
$E_{WRES}(t)$	Wind generator reserves (MWh)
$E_{WFREQ(t)}^{dis}$	Wind energy for low frequency response (MWh)
$E_{WFREQ(t)}^{red}$	Wind energy for high frequency response (MWh)
η_{ESS1}^{dis}	Discharging efficiency of Storage device 1
η_{ESS2}^{dis}	Discharging efficiency of Storage device 2
η_{ESS1}^{ch}	Charging efficiency of Storage device 1
η_{ESS2}^{ch}	Charging efficiency of Storage device 2
$E_{FREQ(t)}^{REQ}$	Requested energy for frequency response (MWh)
$E_{C1(t)}$	Charge of Storage device 1 (MWh)
$E_{C2(t)}$	Charge of Storage device 2 (MWh)
$E_{FREQ1(t)}$	Frequency response of Storage device 1 (MWh)
$E_{FREQ2(t)}$	Frequency response of Storage device 2 (MWh)
$E_{UC1(t)}$	Usable charge of Storage device 1 (MWh)
$E_{UC2(t)}$	Usable charge of Storage device 2 (MWh)
T_{reg}	Regulatory time to sustain frequency response (minutes)
T	Sample time (minutes)
SOC_{ESS1}^{max}	Maximum state of charge of Storage device 1
SOC_{ESS2}^{max}	Maximum state of charge of Storage device 2
SOC_{ESS1}^{min}	Minimum state of charge of Storage device 1
SOC_{ESS2}^{min}	Minimum state of charge of Storage device 2

Table II. Study Case Parameters

INPUTS	VRFB	SUPERCAPACITOR
Period	24 hours	24 hours
Sample Time	15 s	15 s
ESS Lifetime	15 years	15 years
ESS Maximum SOC	90%	90%
ESS Minimum SOC	40%	10%
ESS charging efficiency	0.8	0.83
ESS discharg. efficiency	0.8	0.83
ESS Cost of Energy	470 £/kWh	7875 £/kWh
ESS Cost of Power	313 £/kW	175 £/kW
ESS Degradation Cost	0.047 £/kWh	0.0079 £/kWh

The optimization process was executed for three different cases for comparative purposes. These cases are based on the same frequency response scenario but they consider the wind generator together with a HESS for Case 1, a single storage technology for Case 2, and non-storage technologies for Case 3. From these situations, only Case 1 and Case 2 allow to size the ESS. The optimal sizing results are shown in Table III.

Table III. Results from Optimal Sizing Methodology

	Case1–HESS VRFB	Case 2–ESS Supercap	Case 3– Non-ESS
Revenue (Millions £)	252.26	147	129
Power Rating (MW)	0.22	9.55	5.13
Energy Capability (MWh)	2.44	1.05	11.52
			-

From Table III, it can be seen that using ES results in a higher income from Frequency Response Market and Wholesale Regular Market against using only the wind generator, in both cases despite the required initial investment. Nevertheless, the best case in terms of income is a HESS with a total revenue of $£252.26 \times 10^6$ for the examined scenario. This represents 71.35% higher revenue in comparison with a single VRFB technology, 95.38% higher in comparison with a single Supercapacitor technology and 74.72% higher income than only using wind generation in 15 years' period. The

Fig. 3. Wind Generator Power Profile over a day

improvement of using multiple storage technologies for frequency response relies on the power absorbed and discharged by these devices which allows the wind generator to operate at higher efficiency closer to the maximum available level. This can be seen in Fig 3 showing wind generator power profile over a day, where wind power for providing frequency response, maximum wind power available and wind power generation are displayed. Fig. 4 shows Energy delivered by the VRFB and supercapacitors for High and Low Frequency Response. Fig 5 shows SOC variation for the VRFB and supercapacitors.

Fig. 4. Energy delivered by the VRFB and supercapacitors for High and Low Frequency Response

Fig. 5. SOC variation for the VRFB and supercapacitors

The optimal sizing results from Table III were annualized and applied to real-market prices for storage technologies by using an investment tool. The annual interest considered in the calculations was 3% per year for a lifetime of 15 years. The results of this analysis can be seen in Figure 6.

Fig. 6. Annualised capital costs for VRFB and Supercapacitors

IV. CONCLUSIONS

This paper has presented a techno-economic methodology for sizing HESSs operating in conjunction with a wind generator to improve its efficiency in delivering frequency response. This resulted in significant increases in revenues i.e. 74.72%, 95.38% and 71.35% higher income than considering no storage, a single VRFB storage system, and a single

Supercapacitor storage system respectively in a period of 15 years. The analysis was performed in the UK wholesale regular market and frequency response market for a wind turbine of 60MW considering actual prices for the services provided and the specific ES assets deployed. The objective function and constraints can, however, be applied to other storage technologies and markets.

The results show that, under certain conditions, the use of HESS together with wind generators provides higher revenues for providing Primary, Secondary and High frequency response while meeting the grid regulations.

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