White Rose Research Online

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk
Universities of Leeds, Sheffield and York

Deposited via The University of Sheffield.

White Rose Research Online URL for this paper:
https://eprints.whiterose.ac.uk/id/eprint/167406/

Version: Accepted Version

Proceedings Paper:

Hutchinson, A.J. and Gladwin, D.T. (2020) Sensitivity analysis of a wind farm with integrated flywheel energy storage. In: 2020 IEEE International Conference on Industrial Technology (ICIT). 2020 IEEE International Conference on Industrial Technology (ICIT), 26-28 Feb 2020, Buenos Aires, Argentina. IEEE. ISBN: 9781728157559. ISSN: 2641-0184. EISSN: 2643-2978.

https://doi.org/10.1109/icit45562.2020.9067176

© 2020 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other users, including reprinting/ republishing this material for advertising or promotional purposes, creating new collective works for resale or redistribution to servers or lists, or reuse of any copyrighted components of this work in other works. Reproduced in accordance with the publisher's self-archiving policy.

Reuse
Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown
If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

UNIVERSITY OF LEEDS
University of Sheffield
UNIVERSITY of York

Sensitivity analyis of a wind farm with integrated flywheel energy storage

Andrew J. Hutchinson
Deparment of Chemical and Biological Engineering
University of Sheffield
Sheffield, United Kingdom
ahutchinson1@sheffield.ac.uk

Daniel T. Gladwin
Department of Electrical and Electronic Engineering
University of Sheffield
Sheffield, United Kingdom
d.gladwin@sheffield.ac.uk

Abstract—**Integration of quick response energy storage with wind-based generation sites has the potential to enhance the performance of these sites. Flywheel Energy Storage Systems (FESSs) are ideally placed to be utilized in this way due to their long lifetime and high cyclability. The effectiveness of this integration is dependent on a set of variables and constraints. A sensitivity analysis has been conducted to investigate the effect of changing system variables on output metrics using a mathematical simulation model.**

Keywords—flywheel, energy storage, wind power, simulation

I. INTRODUCTION

Wind generation sites are often subject to large fluctuations in wind speed and therefore the output of these sites is often highly volatile. This volatility can cause the site to breach agreed export limits with local distribution network operators (DNOs) or conversely not fulfil the full generational potential of the site by setting the pitch to a conservative value in order to prevent these breaches. Previous works have primarily discussed the integration of flywheel energy storage for output smoothing and frequency regulation [1][2].

For frequency regulation services, Flywheel Energy Storage Systems (FESSs) have been found to be a more cost effective solution than competitors lead-acid and lithium-ion batteries [3] when considering whole life cycle costs. This is due to FESSs being able to handle a higher number of cycles than other energy stores, thus reducing the number of replacements required during the system lifetime that would incur additional cost. In [3], a Flywheel energy storage system was found to have an Annualized life-cycle cost (€/kw-yr) of less than half of the equivalent cost for lithium-ion batteries.

For lithium-ion batteries, depth of discharge (DOD) has a large impact on the lifetime of the energy store. Depth of Discharge is defined as the amount of charge that is drained from the batter in a single cycle, for example an energy store discharged from 100% down to 60% SOC represents a 40% DOD. Research has shown that the higher the DOD of a lithium-ion cell, the shorter the life span of the cell [4]. Higher levels of DOD also lead to an acceleration of capacity fade and other forms of degradation. Comparatively, a FESS is unaffected by varying levels of DOD and can be fully discharged and recharged with no degradation effect on the system, leading to a lifespan of >20 years [5].

Flywheels suffer from a high self-discharge rate [6] compared to other energy storage systems, in applications such as renewable integration this becomes less significant. Due to the rapid change of state between charge and discharge, there are rarely occasions when the Flywheel will be 'idle' and hence limited opportunity for it to freely self-discharge.

Previous works [2][7][8][9] have discussed various implementations of a FESS into renewable energy generation scenarios with all reporting a positive impact provided by the FESS. In [2] the utilisation of a FESS to improve the stability of an isolated power system is discussed, much like the system implemented by ABB in Western Australia to support solar generation on an isolated grid [10]. This research suggests control methods for regulating the frequency of the isolated grid and concludes that the optimum power rating of the FESS should be set as 70% of the wind farm rating. It has also been shown that a FESS can beneficially impact an isolated wind farm by smoothing power variations [11].

A MATLAB/Simulink simulation [7] shows an effective technique of ensuring the power and voltage delivered to a load is constant through flywheel power matching the inverse of the wind power delivered in a 30 second simulation and concludes that for short duration and power quality applications Flywheels can be utilised. Another method for the analysis of FESS effectiveness in wind farm generation used in other works is Fast Fourier Transform (FFT) analysis of the power within the system, in which [9] shows that a FESS can be effectively utilised to reduce the oscillation power of a wind farm during continuous operation.

A key challenge in the specification and integration of flywheel energy storage into a wind generation system is ensuring that the chosen configuration will provide appropriate benefits dependant on the system owners requirements. In this paper, a range of output metrics are considered against the variation of pitch control (target output of the system) and FESS size. The system detailed in this paper consists of a pitch-controlled wind turbine with integrated flywheel energy storage. The output of the site can be controlled by varying the pitch of the wind turbine to target varying levels of output power in the range of 250kW to 300kW. The agreed export limit of the site is 250kW and penalties are enforced for exceeding this value. The sensitivity analysis has been performed using a MATLAB/Simulink mathematical model utilising a 'Bucket model' approach [12] and modelled as a single flywheel.

Real-world data provided by a wind-farm owner contained wind speed and equivalent output power data for a 250kW target output. A process of data transformation was undertaken to producing power curves for 5kW increments of target output power ranging from 255kW to 300kW. The effect of increasing the pitch to target higher output levels has been simulated by transforming the data available using Equation 1, thus creating power curves for a range of different target outputs.

$$255kW\ Target\ Output = \frac{Original\ Data\ Set}{250} \times 255 \qquad (1)$$

II. SENSITIVITY ANALYSIS

A. *Duration of time in breach*

Duration of time in breach of the export limit is the total time period that the output of the site exceeds 250kW as a proportion of the overall simulated time. Table 1 illustrates the results of simulations of varying target output levels for different FESS configurations, along with the baseline results for if no FESS is present in the system.

This metric is key in establishing what impact the integration of a FESS has on the overall system and can show how the variation of target output level has a large impact on the duration of export level breach. The figures contained within Table 1 represent total values of time in breach across all months of the simulation. There is a significant reduction in the duration of time spent in breach of the export limit for all FESS configurations when compared to the baseline example of no FESS.

As the target output is increased, the total breach duration increases at a constant rate for each different configuration, with less time spent in breach of the export limit as the FESS size is increased, illustrated in Fig. 1. The addition of any FESS can have a significant impact on the reduction of time spent in breach, with subsequent increases in FESS size providing a further modest reduction.

Duration in breach of the export limit is an ideal output statistic to constrain in order to maximise the benefits of the system. An example of this would be limiting the duration of time in breach to 5% and modifying the target output on a monthly basis. This will be explored in future works.

Fig. 2 shows the effect of the inclusion of a FESS within the system across individual months of the year. For the summer months (June, July, August) the effect of including a FESS of any size is minimal due to the low baseline wind activity during these months. For months with a higher level of base wind activity there is a significant reduction in duration of time in breach by integrating any size of FESS with progressively less time in breach as FESS size is increased. The number of breaches follows a seasonal pattern of variation that correlates with the average wind speeds across the year for the UK as shown in Fig. 3.

B. *Viable energy increase*

Viable energy is defined within this paper as the amount of energy generated from exports below the agreed export limit of the site i.e. excluding all instances of generation above 250kW. Fig. 4 illustrates how the viable energy varies depending on system configuration.

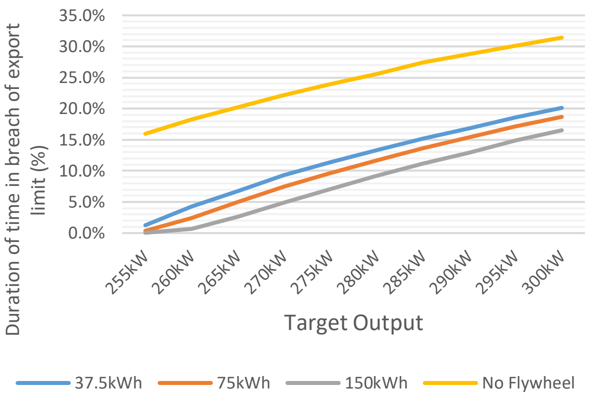

Fig. 1. % time in breach of export limit for varying FESS sizes and target output levels

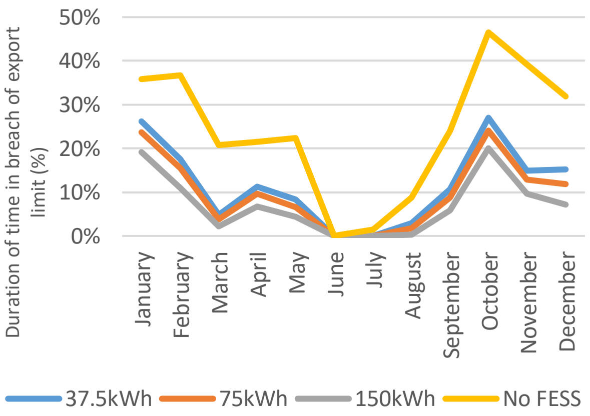

Fig. 2. % time in breach of export limit for varying FESS sizes at a target output level of 275kW

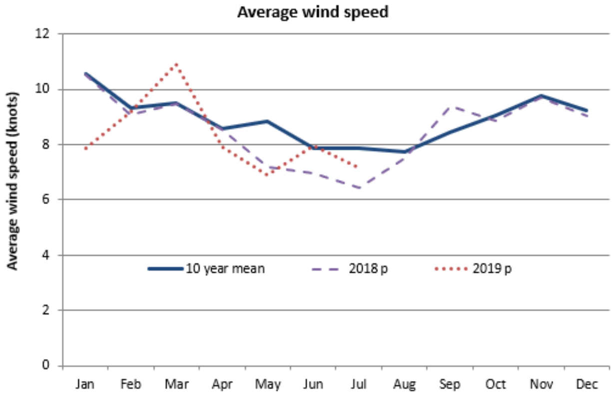

Fig. 3. Latest average wind speed statistics for the UK [13]

TABLE I. TOTAL PERCENTAGE OF TIME IN BREACH OF EXPORT LIMIT FOR DIFFERING FESS SIZES AND TARGET OUTPUT LEVELS

Target Output	**255kW**	**260kW**	**265kW**	**270kW**	**275kW**	**280kW**	**285kW**	**290kW**	**295kW**	**300kW**
No FESS	16.0%	18.3%	20.2%	22.2%	23.9%	25.6%	27.4%	28.8%	30.1%	31.4%
37.5kWh	1.3%	4.2%	6.7%	9.3%	11.4%	13.4%	15.2%	16.9%	18.6%	20.1%
75kWh	0.4%	2.5%	5.0%	7.4%	9.7%	11.7%	13.6%	15.3%	17.2%	18.7%
150kWh	0.0%	0.7%	2.6%	4.9%	7.0%	9.2%	11.1%	13.0%	14.9%	16.5%

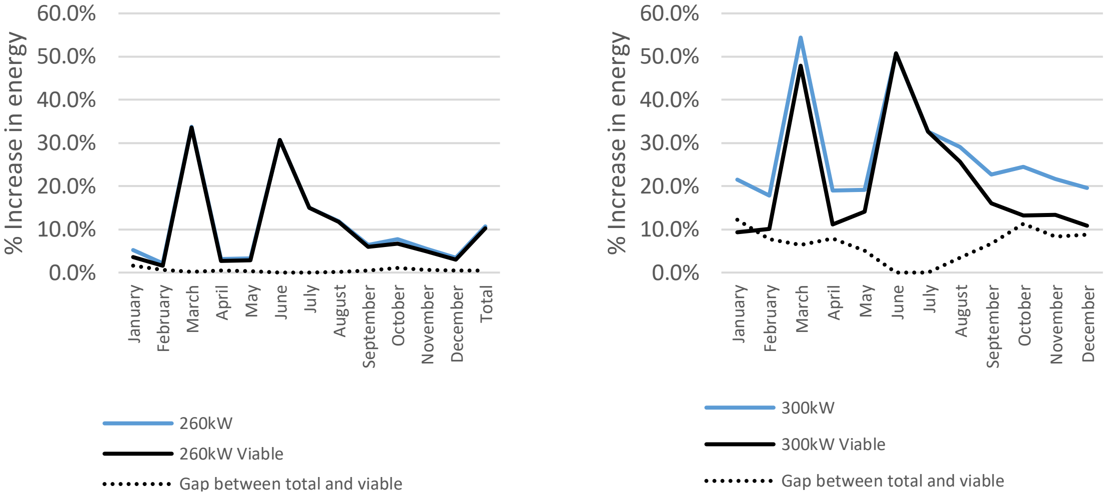

Fig. 4. Total % increase in energy generated vs viable increase in energy generated for a 37.5kWh FESS using a) a 260kW target output b) a 300kW target output

Comparing percentage increase in total energy generated against the viable energy increase shows that for a modest increase in target output (260kW in Fig. 4a) the two values remain closely aligned throughout the year. However, when the target output is increased significantly (300kW in Fig. 4b) a disparity forms between the two values representing a higher proportion of energy now being produced from power that exceeds 250kW. For the low wind activity months (June and July) the viable proportion makes up 100% of the total additional energy generated.

For a 150kWh FESS in the month of December, an increase from 255kW target to 275kW generates an additional 2638kWh of energy over the 12 days simulated, with an increase to 300kW generating a further 2045kWh of energy. Table 2 compares a low generation month (June) and a high generation month (December) in terms of total viable energy generated.

For a lower generation month, the effect of increasing the FESS size is minimal, as all of the energy being generated falls below the 250kW threshold and hence there is minimal excess for the FESS to capture. For the lower target output, a similar outcome is seen for a high generation month due to there being only a small increase in the amount of extra power above 250kW produced due to the target increase. For the larger target output increases however, the benefit of both the addition of any FESS, and an increasing FESS size can clearly be seen.

C. *Non-viable energy increase*

Non-viable energy can be quantified as the proportion of the total increase in energy generated from exported power that exceeds 250kW, for instance if overall generation increases by 50% of which only 40% is viable (<250kW) then the remaining 10% is considered a ‘non-viable’ energy increase.

As the target output is increased, the non-viable energy generated converges towards the baseline amount for all FESS sizes to varying degrees (Fig. 5). This represents the FESS reaching the limit of operation due to increasing amounts of excess energy, reaching 100% SOC quicker and for longer periods leaving greater amounts of energy to be non-viable.

Fig. 5a. shows that the non-viable energy can be kept to a minimum by specifying a low target output level. However, as seen previously in Fig 4 this reduces the additional benefits of enhanced generation capabilities. Conversely increasing the target output to its maximum can significantly increase the additional viable generation but carries the drawback of increased non-viable generation and a greater duration of time in breach.

Increasing FESS size decreases the proportion of energy that is classified as non-viable and is more effective in some months than others. Seasonal variation has a large impact on the amount of non-viable energy generated. As with other metrics, there is a significant difference in the quantity of non-viable energy when comparing summer months to winter. The data for both viable and non-viable energy generated suggests that a balance between the two needs to be maintained in order to provide the most efficient system solution.

D. *Number of cycles*

Quantity of cycles that an energy store undergoes is a key factor in determining which type of energy storage is most appropriate. If the number of cycles per month/year is high then an energy storage such as Flywheels is a more appropriate choice, however a low cyclability of the system would indicate other energy storage systems may be considered. The approximate number of cycles per year has been modelled and the results of this can be seen in Fig 6.

TABLE II. INCREASE IN VIABLE ENERGY GENERATED IN KWH

	June				December			
	255kW	***275kW***	***300kW***	***Increase***	***255kW***	***275kW***	***300kW***	***Increase (kWh)***
37.5kWh	1434.9	1945.0	2583.6	1148.7	584.9	2779.6	4585.3	4000.4
150kWh	1483.4	1993.5	2635.2	1151.8	651.4	3289.1	5334.6	4683.2
Increase (kWh)	48.5	48.5	51.6	N/A	66.5	509.5	749.3	N/A

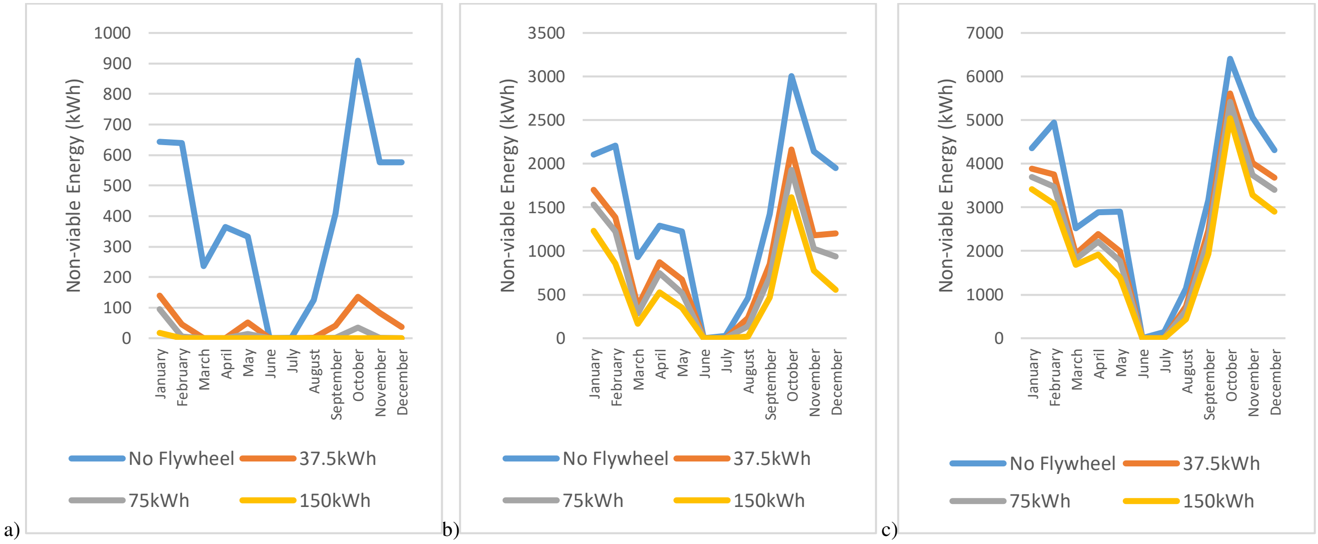

Fig. 5. Amount of energy generated >260kW for various FESS configurations with a) a 255kW target output b) a 275kW target output c) a 300kW target output

As the target output is increased, the amount of cycles per year also increases due to the additional energy being generated by the site and hence passing through the FESS. The effect of increasing FESS sizes is also clear, showing that for larger FESS configurations there is a greatly reduced cycle rate compared to smaller configurations.

Table 3 illustrates how these cycle rates would extrapolate to a 25-year operational period for selected target outputs. The data in Table 3 suggests that a FESS is more suited to this manner of application than a battery energy storage system when taking into account cycle rates, depth of discharge and calendar ageing of a battery system.

More broadly it suggests that if the number of cycles is a limiting factor then a larger energy store can mitigate against this issue. Cycle life will be affected by modifying the target output throughout the year to maximise benefits of the energy store. Alternatively, a system could be designed around cycle life in order to minimise the number of cycles that the energy store is exposed to.

E. Spinning losses

Spinning losses are the main drawback of a FESS as these occur constantly whenever any energy is stored within the FESS. These are parasitic losses that mostly consist of the friction the bearings are exposed to with mechanical bearings subject to greater losses than magnetic bearings [14].

Fig 7 shows that as the FESS size is increased the losses experienced by the energy store due to idle spinning also increase whilst they remain mostly constant as the target output is increased. The exception to this is a slight rise for all FESS sizes between 260kW and 285kW target outputs, due to this being the point at which most of the available energy can be stored within the FESS and hence subject to losses.

TABLE III. ESTIMATED TOTAL NUMBER OF CYCLES FOR A 25-YEAR OPERATIONAL PERIOD

	Target Output					
	255kW	***265kW***	***275kW***	***285kW***	***295kW***	***300kW***
37.5kWh	16670	20478	22308	23247	24186	25021
75kWh	10764	14056	15597	16277	17075	17648
150kWh	7075	10304	11806	12467	13157	13550

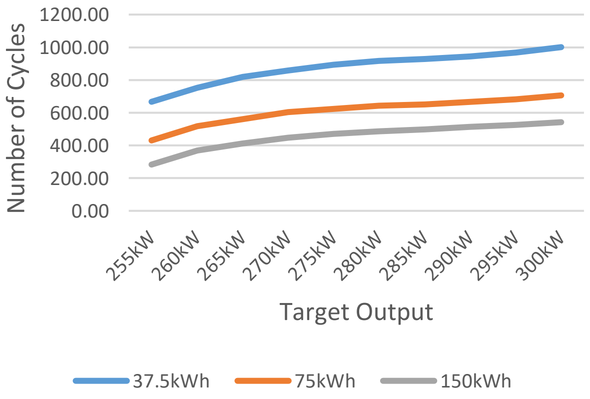

Fig. 6. Number of cycles per year with increasing target output for varying FESS sizes

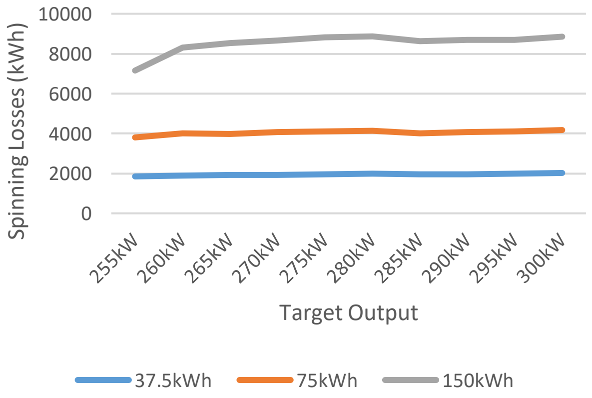

Fig. 7. Spinning losses for varying target outputs and FESS sizes

Once the target output exceeds 285kW, a smaller proportion of the overall energy available passes through the FESS due to it reaching and staying at 100% SOC at an earlier point in the simulation. This gives rise to a lower overall level of spinning loss as more energy is exported above 250kW as 'non-viable energy'.

III. CONCLUSIONS AND FUTURE WORK

In this paper, a sensitivity analysis has been carried out on a wind generation site with integrated FESS for a range of output performance metrics. The various performance metrics have been analysed to identify areas where system enhancement could be conducted through varying certain system settings throughout the year. It has been shown that varying the target output and FESS size allows the system outputs to be tailored towards system owner priorities. Target output and FESS size have significant effects on the performance of a wind generation site, and this can be exploited through appropriate system selection.

A larger energy store can provide many benefits such as reduced breach duration, additional viable generation and lower cycle rates. However, it can also lead to greater degrees of spinning loss and non-viable generation. Seasonal variation has been shown to have a significant impact on system performance and this could be utilised to reduce the FESS size whilst maintaining performance enhancements.

Duration of time in breach of the export limit can be reduced by a significant amount through the addition of a FESS and system configuration has a large impact on the scale of the reduction. Increasing sizes of FESS lead to a consistent reduction of duration of time in breach and this can be exploited to enhance overall system performance. FESS and target output configuration is highly dependent on system owner requirements and can be manipulated to reduce time in breach, enhance generation or a combination of these factors.

When the system is subjected to a consistently high target output there is a significant increase in total number of cycles with an increase from 255kW to 300kW target output leading to an additional 8351 cycles over a 25-year period of operation. However, cycle numbers can be reduced through increases to the size of the FESS with the transition from a 37.5kWh to a 150kWh FESS leading to a reduction from 25021 cycles to 13550 cycles over a 25-year period at 300kW target output.

Future work should progress this research by showing how the system performance can be enhanced by seasonal pitch variation. Certain constraints can be applied to the system with system owner defined targets such as restricting duration of time in breach to below a set value or minimising total number of cycles. Different constraints can bring different benefits and drawbacks and hence this should be performed considering all available output metrics. It should also consider the whole life costs of various FESS sizes selected through the enhancement process to illustrate a method for appropriately sizing the integrated FESS to reflect the best cost/benefit balance.

REFERENCES

[1] F. Díaz-González, A. Sumper, O. Gomis-Bellmunt, and F. D. Bianchi, "Energy management of flywheel-based energy storage device for wind power smoothing," Appl. Energy, vol. 110, pp. 207–219, 2013.

[2] R. Takahashi and J. Tamura, "Frequency control of isolated power system with wind farm by using flywheel energy storage system," Proc. 2008 Int. Conf. Electr. Mach. ICEM'08, pp. 8–13, 2008.

[3] B. Zakeri and S. Syri, "Electrical energy storage systems: A comparative life cycle cost analysis," Renew. Sustain. Energy Rev., vol. 42, pp. 569–596, 2015.

[4] J. D. Dogger, B. Roossien, and F. D. J. Nieuwenhout, "Characterization of li-ion batteries for intelligent management of distributed grid-connected storage," IEEE Trans. Energy Convers., vol. 26, no. 1, pp. 256–263, 2011.

[5] R. Peña-Alzola, R. Sebastián, J. Quesada, and A. Colmenar, "Review of flywheel based energy storage systems," Int. Conf. Power Eng. Energy Electr. Drives, no. May, 2011.

[6] I. Hadjipaschalis, A. Poullikkas, and V. Efthimiou, "Overview of current and future energy storage technologies for electric power applications," Renew. Sustain. Energy Rev., vol. 13, no. 6–7, pp. 1513–1522, 2009.

[7] S. Ould Amrouche, D. Rekioua, T. Rekioua, and S. Bacha, "Overview of energy storage in renewable energy systems," Int. J. Hydrogen Energy, vol. 41, no. 45, pp. 20914–20927, 2016.

[8] L. Wang, J. Y. Yu, and Y. T. Chen, "Dynamic stability improvement of an integrated offshore wind and marine-current farm using a flywheel energy-storage system," IET Renew. Power Gener., vol. 5, no. 5, pp. 387–396, 2011.

[9] J. Tan, X. Wang, T. Wang, and Y. Zhang, "Alleviation of oscillations power of wind farm using flywheel energy storage," IEEE Power Energy Soc. Gen. Meet., vol. 2014-Octob, no. October, pp. 1–5, 2014.

[10] ABB, "PowerStore Renewable microgrid stabilization," 2017.

[11] R. Sebastián and R. Peña Alzola, "Flywheel energy storage systems: Review and simulation for an isolated wind power system," Renew. Sustain. Energy Rev., vol. 16, no. 9, pp. 6803–6813, 2012.

[12] T. Simpkins and C. O. Donnell, "Optimizing Battery Sizing and Dispatching To Maximize Economic Return," Battcon Station. Batter. Conf., no. May, pp. 1–14, 2017.

[13] UK Government, "Average wind speed and deviations from the long term mean." 2019.

[14] M. E. Amiryar and K. R. Pullen, "A review of flywheel energy storage system technologies and their applications," Appl. Sci., vol. 7, no. 3, 2017.