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Optimisation of a wind power site through utilisation of flywheel energy storage technology

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Abstract

Due to the intermittent nature of power generation within a wind farm, power generation often either exceeds or does not meet the export limits of the site. Excess power generated above the export limit is considered as a breach and can cause fines from the local grid operator. The excess energy above the export limit can be exploited to supplement periods of low generation, smoothing the output of the wind farm and providing a larger total output of the site. Due to their resilience to high cycle rates, flywheels are ideally suited to act as an energy store in this scenario. This paper utilises real world data to simulate a wind farm operating in tandem with a Flywheel Energy Storage System (FESS) and assesses the effectiveness of different storage capacities.

Peer-review under responsibility of the scientific committee of the 4th Annual CDT Conference in Energy Storage and Its Applications, Professor Andrew Cruden, 2019.

Keywords: Flywheels; Wind power; Energy storage systems; Renewable energy modelling

1. Introduction

As knowledge of the impacts of climate change has deepened there has been a continuous worldwide trend towards reducing fossil fuel consumption, backed up legislatively by legally binding documents such as the Paris agreement [11] and the Climate Change Act 2008 in the UK [1]. In response to these drivers, renewable energy consumption has increased worldwide by over 600% from 1965 to 2016 with wind energy consumption growing from 31.5 TWh to 959.53 TWh in the period 2000 to 2016 [7].

Whilst wind generation is an effective provider of renewable energy, it is not without its drawbacks, key amongst these is the unpredictability of the output levels. This intermittent nature can lead to significant issues being introduced to both local and national grids such as frequency variations and voltage sag [2]. Energy storage can be deployed in order to mitigate the negative effects brought about by increasing amounts of renewable energy being introduced into the generation mix.

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Previous works [8] have explored the issues associated with the fluctuation of power generation from a wind turbine. A significant issue with regards to implementing energy storage is the stochastic nature of wind speed, causing significant fluctuations in wind velocity and direction from second to second. This presents a strain on traditional energy storage mechanisms as it is likely to require rapid transitions from a charge to a discharge state, which causes degradation rates to increase in some energy storage technologies such as batteries [4]. Flywheels, with resilience to high cycle rates with minimal degradation, are ideally suited to this task [3].

This paper utilises real world data to simulate the addition of a FESS into a wind farm system with the aim of reducing breaches in export limits (occasions at which the exported power of the site exceeds the limit agreed with the local DNO). Previous works have discussed control methods for such arrangements including power smoothing applications which illustrates the benefits of utilising a FESS for frequency stabilisation and power smoothing [10]. Other literature such as [6] has discussed detailed statistical analysis and modelling of wind speed and power, however this paper focuses on the concept of wind power connected flywheel energy storage providing a buffer.

2. Background

The scenario analysed within this paper is a small scale wind farm with a nominal power output of 250 kw. The wind turbines are pitch controlled, meaning that there is a closed loop control that manages the pitch of the blades to try to keep the power output below a set maximum power point in high winds. The rate of control and tuning of this controller will determine the under and overshoot of the power output. The wind farm receives financial penalties for breaching the export limits of the site, however, setting a power conservative controller that eliminates all breaches would reduce the energy produced over time and hence constrain potential revenues. Fig. 1 shows a typical output of the wind farm using a controller configured to maximise energy generation, it can be seen that there are many instances where the power output fluctuates significantly above and below 250 kw.

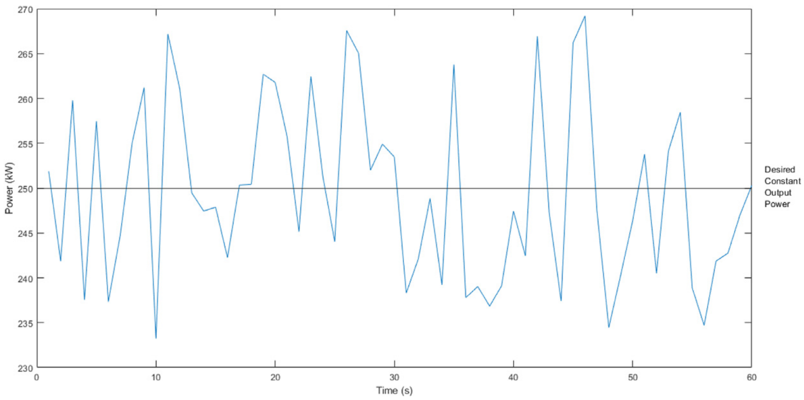

Fig. 1. Typical output power fluctuation of the studied wind farm illustrating desired output.

A FESS attempts to achieve the desired output level by storing energy during periods of excess power generation, and then utilising this energy to supplement the output during periods of power generation below the export limit. Fig. 2 shows the basic operation of this mechanism with the green shaded areas showing energy being stored within the FESS, and the red shaded area representing energy being exported from the FESS to supplement the output and increase it to a constant 250 kw. By integrating a FESS into the wind farm the pitch control and target power output can be optimised along with the size of the FESS to maximise energy produced by the wind farm and to minimise breaches.

3. MATLAB/simulink model

In order to perform appropriate simulations to assess differing FESS configurations, a MATLAB/Simulink model has been developed. The flywheel is represented as a ‘bucket model’ [9] whereby energy is stored from one moment to the next within an integrator block. The model includes spinning losses of the flywheel and efficiencies of the

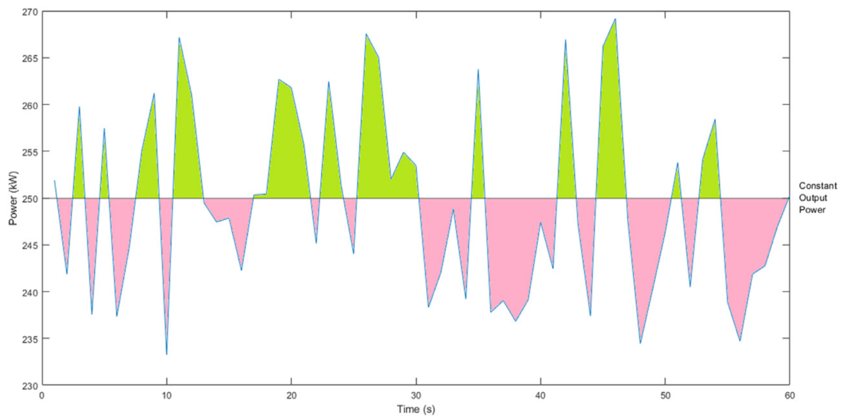

Fig. 2. Representation of the operation of a FESS to provide constant output power.

inverters, drive and electrical machine. The maximum power and energy capacity parameters are variable and the stored energy is treated as an equivalent state of charge (SOC) given by Eq. (1).

$$\frac{\int_0^t P_{flywheel} \cdot dt}{3600 \times Q} \tag{1}$$

The wind farm is represented as a power source with the output dependent on the current wind speed and inertia, more detail about how this was derived is in the next section. A block diagram of the model is given in Fig. 3. Control of the output could be achieved via a range of methods such as utilising the FESS to maintain a specific voltage on the DC bus.

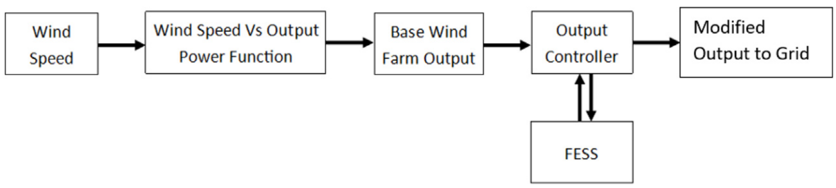

Fig. 3. Block diagram of model used.

4. Case study

Data logged files were provided from a working wind farm containing operational information including 10 s recorded values of wind speed and output power of the site for 12 days of each month in a year. The export limit of this site is 250 kw, with a maximum rated output of 300 kW. The site regularly exceeded the export limit and incurs penalties for breaching their agreed limit. Using this data the wind farm + FESS model is developed to investigate how energy storage can be used to set a higher power set point for the pitch controller to increase energy generation whilst minimising power generation breaches.

4.1. Data cleansing and transformation

The recorded data contained erroneous samples that required cleansing before it could be utilised within the simulation. The first data cleansing process was to correct wind speeds that were recorded with negative values, these were set to zero. The second cleansing process was to correct wind speeds that were recorded in excess of adjacent readings by a factor of 10^3, these were set to the value of the average adjacent recordings. The model is based on a 1 s sample time, in order to resample the wind speeds the 10 s data was interpolated linearly between points. The consequence of this was the requirement to produce a linear relationship between wind speed and output power such that a power output could be generated for the resampled data. A linear relationship was produced through fitting a polynomial equation curve to a scatter graph of wind speed vs power from the supplied data as shown in Fig. 4. As the maximum power of the wind farm is 300 kW, then for the purposes of this study a modest increase in the power set point of the pitch controller of 8 kW to 258 kW represented by scaling the power output using Eq. (2) is deemed appropriate.

$$New\ power\ profile = \frac{Original\ power\ profile}{250} \times 258 \tag{2}$$

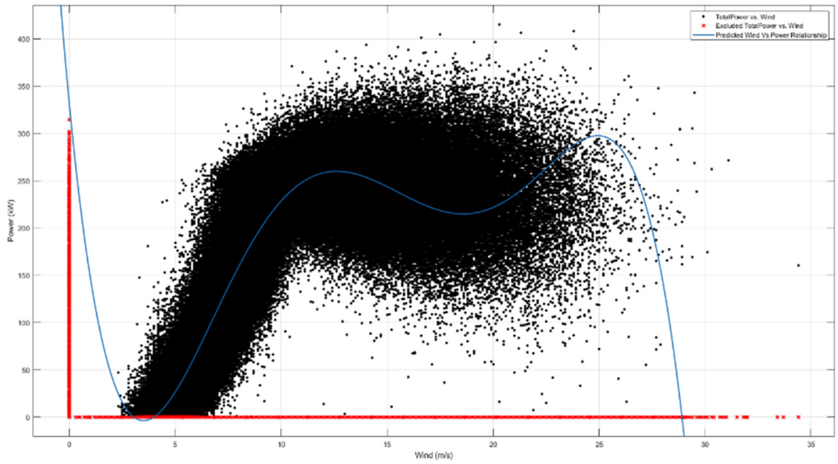

Fig. 4. Polynomial curve fit to the scatter graph of Wind Speed Vs Recorded Power.

The polynomial curve fit was then modified to produce a plot as seen in Fig. 5, which closely aligns to typical wind power curves as presented in Lange [5]. This represents a turbine power graph with the following characteristics; for a wind speed greater than 13 m/s output is 258 kW, wind speeds greater than 28 m/s output is 0 kW and for wind speeds less than 4 m/s output is 0 kW. These characteristics represent rated output speed, cut-out speed and cut-in speed respectively.

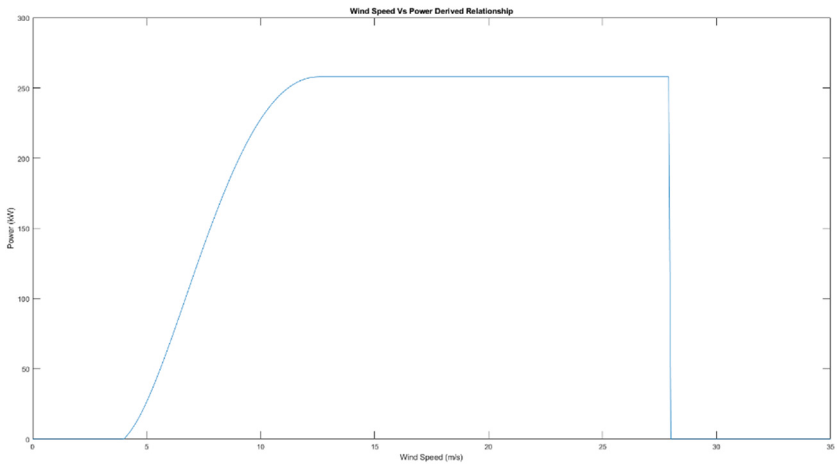

Fig. 5. Wind Speed Vs Power relationship derived from data analysis.

With an appropriate relationship between wind speed and output power for this site derived, this information was used to create a function to give an output power for any input wind speed. Simulated inertia was added by limiting the ramp rate of the output of this function to prevent rapid changes in output power that are present in the real world due to the mechanical inertia of the turbine machine and blades. The processed 1 s wind speed data can then be utilised in the model to simulate the power generation of the wind farm and the operation of a FESS connected as shown in Fig. 3.

4.2. Simulation operation

An excerpt from the simulation results with a FESS of size 600 kW/75 kWh can be seen in Fig. 6, where the effect of the FESS on the power output of the wind farm site is shown. At the start of the time period, the base wind farm output without the flywheel is steady around 260 kW and hence the FESS is attempting to charge during this period. However, it can be seen in Fig. 6c that in the first half of the simulation the power output to the grid exceeds 250 kw on multiple occasions, illustrating moments when the FESS has reached 100% state of charge; it cannot accept any further energy and hence breaches occur at this time. Later on in the simulation at around 7.72×10^5 s the wind speed starts to decrease and at this point the FESS is exporting the required power to maintain a 250 kw power output to the grid

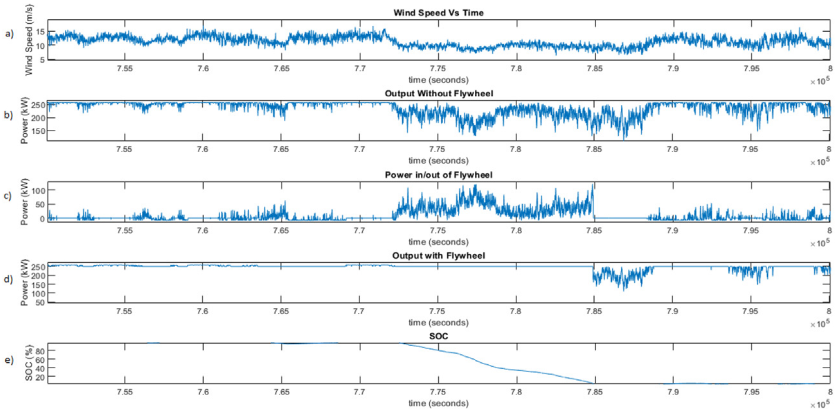

Fig. 6. Operation of simulation during period of breaching export limit (a) Wind Speed (b) Output to grid without FESS (c) Power in/out of FESS (d) Output to grid with FES (e) State of charge of FESS.

Towards the end of the time period at around 7.85×10^5 s the FESS can no longer output power as it has reached the cut-off point for low state of charge (in this case set to 1% state of charge), and hence the power output to the grid is determined by the wind speed until excess power is once again generated to charge the FESS. The simulation shows that the utilisation of a FESS connected to the wind farm can help deliver a constant power output to the grid whilst there is capacity charge/discharge the FESS. If the FESS reaches its limits then the output power to grid will fluctuate according to the power output of the wind farm. It is therefore apparent that the sizing of the energy capacity of the FESS is critical to its effectiveness.

4.3. Simulation results

Three different sizes of FESS for the 250 kw wind farm case study were simulated consisting of arrays of individual flywheels of 7.5kWh each, configurations of 37.5 kWh (5 flywheels), 75 kWh (10 flywheels) and 150 kWh (20 flywheels). Three months of wind speed data, June, September and October, were used representing the lowest amount of breaches in a month, the most amount of breaches, and an 'average' month respectively. The effects of the FESS in reducing the number of breaches are summarised in Table 1. Within all simulations the starting state of charge has been set to 50%, and it should be noted from preliminary work that this can cause significant difference in results, March is significantly affected as the majority of the excess energy is generated in the first 6 days, hence the capacity is reached quickly and not depleted until further into the simulation.

The results show that there is a significant reduction in breach occurrences throughout the year for all simulated configurations of FESS. The months of March and October both present scenarios where the FESS struggles to provide a good service and this is mainly down to consistent periods of time where breaches are occurring regularly but with minimal instances of power output to the grid below 250 kw; therefore providing too much additional power

Table 1. Reduction of Breaches for varying months and FESS configurations.

Month	Original breaches	37.5 kWh (% reduction)	75 kWh (% reduction)	150 kWh (% reduction)
January	231878	86.75%	94.52%	100%
February	268326	78.94%	94.07%	100%
March	225715	18.33%	22.21%	29.95%
April	146495	85.2%	100%	100%
May	137221	76.7%	95.71%	100%
June	0	100%	100%	100%
July	1482	100%	100%	100%
August	46986	100%	100%	100%
September	149272	95.85%	100%	100%
October	243724	42.9%	51.61%	66.7%
November	285581	60.03%	78.25%	93.67%
December	274454	61.04%	72.94%	85.53%
Average	–	75.48%	84.11%	86.99%

for the FESS and not enough opportunities for it to discharge. This indicates that the targeted power output in the pitch controller plays a significant role. The results presented represent a targeted export limit of 258 kW utilising pitch control as discussed in Section 4.1, however the data can be modified to represent a target of anywhere up to 300 kW. Increasing the export limit target will provide additional energy to utilise for supplementing periods of low generation, however it will also result in increasing Flywheel sizes and therefore sensitivity analysis will be performed in future works to study the effect of varying the target power can have on FESS sizing.

From the results in Table 1 it can be seen that the advantage gained from increasing the FESS size from 75 kWh to 150 kWh appears to be minimal when considering breach reduction. As the cost of the FESS increases with size then 75 kWh therefore appears to be the most viable option for FESS size at this particular site. It should be noted that whilst this simulation shows that a FESS can have a significant impact on reducing number of breaches at a wind farm, further financial studies should be undertaken to assess its viability with respect to return on investment.

5. Conclusions

Detailed data has been generated from real-world data sets, and a mathematical simulation model for a wind farm connected FESS has been developed. An assessment as to whether there are any benefits to introducing a FESS into a wind farm system has been made, showing that there is grounds for further investigation into the financial merits of FESS installation based on an efficient sizing of the FESS. More detailed analysis on the effects of changing the target power of the wind farm and how this impacts upon FESS size should be undertaken to reach an efficient compromise between FESS size, target power and breach reduction.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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