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Battery energy storage system state-of-charge management to ensure availability of frequency regulating services from wind farms

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Abstract

State of charge management in battery energy storage systems will be imperative to ensure that frequency regulating services can be provided when required. Two state of charge controllers are proposed in this paper. One controller was designed to meet the charge/discharge requirements imposed on assets providing enhanced frequency response. The controller makes small corrective changes to the battery's power output to restore nominal charge. Simulation results show that the controller is effective at restoring nominal charge when the deviation from nominal is small. However, when the charge is significantly high or low, operating within the confines of the enhanced frequency response service envelope will lead to long periods where the charge is above or below nominal. This will reduce the availability of frequency regulating services from the system. A second controller is proposed to accelerate the restoration of nominal charge. The controller is intended for use in wind farms that have an integrated battery energy storage system, whereby hybrid dispatch control can be employed. The objective of hybrid control is to create a power exchange between the wind turbine and battery system to accelerate nominal charge restoration, without significantly impacting the system frequency and the wind farm's output.

Keywords

Battery energy storage; wind generation; frequency control; state of charge control; fuzzy logic control.

Acronyms

BESS	Battery energy storage system
DFIG	Doubly fed induction generator
EFR	Enhanced frequency response
FFR	Fast frequency response

44	PAC	Pitch angle control
45	POR	Primary operating reserve
46	R	Percentage droop
47	SoC	State of charge
48	SOR	Secondary operating reserve
49		

50 **Symbols**

51	f_{meas}	Measured frequency
52	f_{nom}	Nominal frequency
53	K_D	Droop constant
54	K_{SoC}	Accelerated state of charge recovery controller gain
55	N_p	Number of cells in parallel
56	N_s	Number of cells in series
57	P_D	Droop controller output
58	P_{FLC}	Fuzzy logic controller output
59	P_{max_BESS}	Active power rating of battery energy storage system
60	P_{max_WT}	Maximum power available from wind turbine
61	P_{order}	BESS power order
62	P_R	Wind turbine active power reserve
63	P_{R_PAC}	Power offset setpoint
64	P_{SoC}	Accelerated state of charge recovery controller output
65	Q_c	Charge capacity
66	S_{max}	Battery energy storage system apparent power rating
67	SoC_{SP}	State of charge setpoint
68	V_{cmax}	Maximum cell voltage
69	V_{cmin}	Minimum cell voltage
70	β	Blade pitch angle
71	β_{max}	Maximum blade pitch angle
72	β_{min}	Minimum blade pitch angle
73	β_{offset}	Blade pitch angle offset
74	Δf	Frequency deviation
75	$\Delta\beta$	Change in blade pitch angle
76	$\Delta\beta_{lim}$	Change in blade pitch angle (limited)
77	$\Delta\beta_{max}$	Maximum rate of change in blade pitch angle
78	$\Delta\beta_{min}$	Minimum rate of change in blade pitch angle
79	$\Delta\omega$	Speed error
80	ω_{max}	Maximum rotor speed
81	ω_{meas}	Measured rotor speed
82		

83 **Units**

84	Ah	Ampere-hour
85	Hz	Hertz

86	MVA	Mega-volt-ampere
87	MW	Mega-watt
88	pu	Per-unit
89	s	Second
90	V	Voltage

92 1 Introduction

93 As the penetration of non-synchronous generation increases on the power system, the negative
94 influence that load-generation imbalances have on the system frequency will be exacerbated
95 [1], [2]. The availability of reliable system (ancillary) services will be imperative to ensure that
96 system stability is always maintained. System services procured from intermittent, renewable
97 generation, such as wind, will be less reliable than those procured from conventional thermal
98 or hydro generation. Battery energy storage systems (BESSs) integrated into wind farms could
99 increase the reliability of ancillary services by reducing intermittency [3]. This could open new
100 income streams for wind farms by enabling them to offer system services to grid operators.

101 Currently, the power system on the island of Ireland (i.e. iSEM) is heavily dependent on
102 interconnection with the power system in England, Scotland and Wales (i.e. referred to as the
103 BETTA) to provide essential system services such as primary operating reserve (POR) and
104 secondary operating reserve (SOR) [4], [5]. If wind generation and BESSs could provide these
105 services, then it would reduce Ireland's dependence on interconnection with the United
106 Kingdom and other European countries. With advances in battery technologies [6], [7], battery
107 energy storage has been considered as being suitable for providing frequency regulating
108 services that operate in the short to medium timescales (1s – 15 minutes) after a frequency event
109 [8]. Such services would include enhanced frequency response (EFR), fast frequency response
110 (FFR) and POR.

111 Recent studies have investigated BESS's ability to provide frequency regulating services [9]-
112 [12]. An investigation into the speed of response of a 10MW BESS in Kilroot Power Station in
113 Northern Ireland, shows that the installed BESS can increase its output from zero to maximum
114 in less than 1.5s [13]. The speed of response of BESSs make them suitable for providing FFR
115 and EFR services [9]. Coordinated BESS and wind turbine control schemes have been
116 investigated in [10], [11]. In [10], a control scheme is proposed that uses coordinated control of
117 a BESS and permanent magnet synchronous generator wind turbine to eliminate a secondary
118 frequency dip during rotor speed recovery, while the use of redox flow batteries in coordination
119 with emulated inertia from a wind turbine is investigated in [11]. S. Dhundhara et al. [11] show
120 that the coordinated responses from the redox flow batteries and wind turbine can reduce stress
121 on the wind turbine during emulated inertial response. The redox flow batteries can also be used
122 to absorb excess power through transmission lines to reduce wind curtailment.

123 It is well documented that BESS can provide frequency regulating services within a very short
124 timeframe. If BESSs are to participate in frequency regulation successfully, then the state of
125 charge (SoC) must be maintained nominally at 0.5pu. Maintaining the SoC at 0.5pu means that
126 the BESS can respond to under-frequency and over-frequency events equally, i.e. the BESS has
127 equal charge and discharge capacity. If the SoC is greater than 0.5pu, then the BESS will have
128 greater capacity to provide under-frequency regulation, but reduced capacity to provide over-
129 frequency regulation. Conversely, if the SoC is less than 0.5pu, then the BESS will have greater
130 capacity to provide over-frequency regulation, but lower capacity to provide under-frequency

regulation. Maintaining the SoC close to 0.5pu may also have the added benefit of increasing the life expectancy of the battery cells [14], [15]. It will be imperative that the BESS SoC is effectively managed to ensure that contracted frequency regulating services can be provided before the next service delivery.

More recent studies have highlighted SoC recovery after a frequency event as being an area of importance. In [16], a battery energy management strategy is proposed that allows the BESS to be charged, within the confines of the charge/discharge limitations imposed on assets providing EFR, for 30 minutes immediately after service delivery. However, no indication is given as to how the power set-point during the restoration period is achieved. The authors highlight the importance of SoC restoration to increase the availability of frequency regulation responses from BESSs and to avoid service performance measure non-conformance penalties [8]. In [12], [17], adaptive SoC feedback controllers are used to re-establish the BESS SoC. This is achieved by varying the adaptive parameter as a function of the measured SoC when the system frequency is within a dead-band.

This paper addresses SoC restoration to increase the availability of system services by presenting two controllers that work to restore nominal SoC after a frequency event. One controller makes small corrective changes to the BESS power flow to restore nominal SoC. These corrective changes are achieved using fuzzy logic control. Unlike the SoC recovery controllers mentioned in the literature above, the proposed controller uses any additional charge/discharge capacity to increase the BESS's response to frequency events. This accelerates the restoration of nominal SoC, while providing additional frequency regulation. The second controller is intended for use in wind farms that have a BESS. The objective of the controller is to reduce the impact that SoC recovery has on the system frequency by creating a power exchange between the wind turbine and BESS to assist SoC recovery. The power exchange reduces the impact on the system frequency and the power flow between the wind farm and the grid. This work is novel in that it not only examines SoC recovery when close to nominal charge but also when close to full discharge/charge, whereas other research focuses on SoC recovery when there is a small deviation from nominal charge. The difference in this work to others is very important for wind farm owners and grid operators in terms of system services in power systems with large penetrations of variable renewable energy (e.g. wind) because it demonstrates that nominal SoC can be re-established quickly after a frequency event without significantly impacting system frequency. Note, for the purposes of this work, a BESS is taken to be a battery device, the associated converters, and controllers.

The remainder of this paper is structured as follows. Section 2 gives an overview of operational requirements for BESS in Ireland, Northern Ireland, and the United Kingdom. Section 3 gives a detailed description of the BESS active power controller, which includes details of the proposed fuzzy logic and accelerated SoC recovery controllers. Section 4 presents the wind turbine model and shows how the pitch controller can be modified to allow the wind turbine to provide delta reserve, frequency-droop control, and charge recovery assistance to the BESS. Section 5 presents the modified IEEE 39-bus power system model that was built in DiGSILENT PowerFactory to produce the results presented in Section 6. The results are analysed in Section 6 and discussed in Section 7. Finally, Section 8 concludes, summarises the key findings and identifies knowledge learned and next steps in the work.

2 Battery Energy Storage System Operational Requirements

Currently, there are no obligatory operational requirements defined by the ENTSO-E relating to SoC management for BESSs or indication as to how the restoration of nominal SoC after

service delivery should be achieved. A European level energy storage specific grid code is currently being designed [18].

The requirements outlined in future European codes will inform National level grid codes for individual countries. In Ireland and Northern Ireland, BESSs must follow the frequency response curve shown in Figure 1.

Figure 1. Frequency response of BESS as defined in [18]

The dead-band limits shall be settable between 49.5-49.985Hz for under-frequency (F₁) and 50.015 – 50.5Hz for over-frequency (F₂). The BESS delivers active power during under-frequency conditions and absorbs active power during over-frequency conditions. There are currently no requirements outlined in grid codes in Ireland [19] and Northern Ireland [20], defining how nominal SoC should be re-established after service delivery. A similar situation exists in the United Kingdom, where BESS specific operational requirements regarding the re-establishment of nominal SoC are yet to be specified. If the deployment of BESSs is to increase to significant levels, then SoC management will be imperative to ensure that the system can provide its contracted post-contingency service when required.

A new system service has been introduced in the United Kingdom called enhanced frequency response (EFR). Enhanced frequency response is intended to serve two purposes. Under normal operation, it is intended to maintain system frequency closer to its nominal value of 50Hz. While post-contingency, EFR provides dynamic frequency support proportional to frequency deviation for a period not less than 15 minutes. Assets providing EFR must deliver continuous active power within one of two service envelopes (see Figure 2). Service 1 has an envelope with a frequency deviation dead-band of ±0.05Hz. Service 2 has an envelope with a frequency deviation dead-band of ±0.015Hz. Service 2 has the most value to the grid operator due to the smaller dead-band.

(a)

Reference Point	Service 1 [Hz]	Service 2 [Hz]
A	49.50	49.500
B	49.75	49.750
C	49.95	49.985
D	50.05	50.015
E	50.25	50.250
F	50.50	50.500

(b)

Reference Point	Service 1 [% Capacity]	Service 2 [% Capacity]
t	100%	100%
u	44.44444%	48.45361%
v	9%	9%
w	0%	0%
x	-9%	-9%
y	-44.44444%	-48.45361%
z	-100%	-100%

Figure 2. Service envelope for assets providing EFR as defined in [8]: (a) Reference points in Hz (b) Reference points as % of active power output

Assets providing EFR can vary their active power output by $\pm 9\%$ of their maximum rating when the system frequency is within the dead-band. For BESSs, which accounted for 68% of total tender submissions [8], this allows the SoC to be managed. As battery projects accounted for a significant amount of the submissions to an EFR invitation to tender, and no other operational specific requirements for BESS have become standardised in Ireland and the United Kingdom, the BESS active power controller proposed in Section 3 was designed to operate within the confines of the EFR service 2 envelope.

3 Battery Energy Storage Active Power Control

Figure 3 shows the BESS active power controller built in DIgSILENT PowerFactory. The active power controller comprises three component controllers, the droop controller, the fuzzy logic controller and the accelerated SoC recovery controller. The active power order, P_{order} , is the summation of the component controllers' outputs and is used to control the BESS's active power output. When P_{order} is negative, the BESS absorbs active power by charging. When positive, it delivers active power by discharging.

Figure 3. BESS active power controller

3.1 Frequency-droop controller

The output of the droop controller, P_D , varies as a linear function of system frequency deviation (Δf) when the frequency deviation dead-band is exceeded. This provides frequency-droop regulation. The BESS will charge when Δf is positive and discharge when Δf is negative [21]. The droop constant, K_D , defines the slope of the frequency-droop characteristic. If Δf exceeds the dead-band, then $P_D = -K_D \Delta f$. If Δf is within the dead-band, then P_D is zero. The fuzzy logic controller and the accelerated SoC recovery controller shown in Figure 3 will be discussed in the following sections.

3.2 Fuzzy logic controller

The output of the fuzzy logic controller, P_{FLC} , is used to make small corrective changes ($\leq 9\%$ of the BESS rating) to the BESS power flow to re-establish nominal charge. The controller was implemented in DIgSILENT PowerFactory using a lookup table. The lookup table was generated in MATLAB using a script that looped through all possible input combinations of a fuzzy inference system. The fuzzy rules used are shown in Table 1.

Table 1. Fuzzy rules. Frequency deviation: BN = big negative, SN = small negative, Z = zero, SP = small positive, BP = big positive. SoC: VL = very low, L = low, M = medium, H = high, VH = very high. Output: BD = big discharge, SD = small discharge, Z = zero, SC = small charge, BC = big charge

		Frequency deviation				
		BN	SN	Z	SP	BP
SoC	VL	Z	SC	BC	BC	BC
	L	Z	SC	BC	SC	BC
	M	Z	Z	Z	Z	Z
	H	BD	BD	BD	SD	Z
	VH	BD	BD	BD	SD	Z

242 The input and output membership functions are shown in Figure 4.

246 **Figure 4. Fuzzy inference system input and output membership functions**

247 The output is produced using the centroid defuzzification method. The surface plots (i.e. surface
248 plot of P_{FLC} against SoC and Δf) are shown in Figure 5.

251 **Figure 5. Fuzzy inference system surface plot: (a) SoC range 0 to 1 pu, Δf range -0.25 to 0.25 (b) SoC**
252 **range 0.45 to 0.55 pu, Δf range -0.015 to 0.015 Hz**

When P_{FLC} is negative, the BESS will charge. When positive, the BESS will discharge. With reference to the surface plots, the BESS will charge when the SoC is below 0.5pu and the system frequency is greater than nominal. The BESS will discharge when the SoC is greater than 0.5pu and the system frequency is below nominal. It can be noted that the controller becomes fully deactivated when the system frequency deviation reaches $\pm 0.25\text{Hz}$ (i.e. P_{FLC} converges to zero at $\Delta f = \pm 0.25\text{Hz}$), and the magnitude of P_{FLC} is limited to 0.09pu, when the frequency deviation is within the $\pm 0.015\text{Hz}$ dead-band (Figure 5 (b)). These two design criteria ensure that the BESS operates within the confines of the EFR service 2 envelope as discussed in Section 2.

If the Ah rating of the BESS is such that full discharge occurs, from nominal SoC, after full power delivery for 15 minutes, then the BESS would take a minimum of 2 hours and 47 minutes to restore its nominal charge after a service delivery using recovery control schemes that adhere to the charge/discharge restrictions imposed on assets providing EFR. This minimum re-charge duration has been determined by assuming that the BESS is charging at 9% of its power rating and that the frequency is within the dead-band for the entirety of the charging period (i.e. 15/0.09 minutes). The calculation of the minimum re-charge duration assumes that only the nominal charge restoration control scheme is used to restore nominal charge. Obviously, any over-frequency regulating response from the BESS would reduce the re-charge time.

If the SoC is very low and a significant under-frequency event occurs, the BESS may not have enough charge to provide its contracted frequency response, which could result in service performance measure non-conformance penalties, unless the BESS Ah rating is significantly overrated. Similarly, if the SoC is very high and a significant over-frequency event occurs, the BESS will have limited charging capacity because the SoC is already very high.

If service performance measure non-conformance penalties are to be avoided, then a BESS should not sustain a SoC outside the nominal range for significant periods. This highlights the need for accelerated SoC recovery. The accelerated SoC recovery controller proposed in the following section (Section 3.3) is intended to be used to quickly re-establish nominal charge in cases where the control scheme presented in this section would lead to very long recovery times, (i.e. when the SoC is very high or very low).

3.3 Accelerated State of Charge Recovery Controller

The accelerated SoC recovery control scheme will be discussed in the following sub-sections. The control scheme can operate autonomously, however, hybrid dispatch control of a wind farm and BESS is investigated to show that the accelerated recovery scheme can be implemented without significantly impacting on system frequency. Though the control scheme presented applies to wind farms with integrated battery energy storage, the same principle could be applied to other generation sources such as thermal, hydro, or solar photovoltaic generation.

3.3.1 Implementation

Accelerated SoC recovery is achieved by controlling the SoC setpoint, SoC_{SP} , in the BESS active power controller (see Figure 3 and Figure 6). During normal operation, SoC_{SP} is set to the measured SoC. This means that SoC_{SP} follows the SoC, essentially making the accelerated recovery controller inactive, allowing the BESS to charge or discharge as required by the frequency-droop and fuzzy logic controllers. When the SoC is significantly high or low, a dispatch signal is used to change SoC_{SP} to the nominal value of 0.5pu. Dispatching can be manual or automatic (e.g. when the SoC reaches a certain threshold). The rate of change of SoC_{SP} is limited using a ramp function to prevent a sudden frequency excursion. A proportional-integral (PI) controller is used to generate the controller output P_{SoC} .

Figure 6. Accelerated SoC recovery controller

3.3.2 Hybrid Control

Hybrid dispatch control is intended to reduce the impact that accelerated SoC recovery has on the system frequency. Hybrid operation of the BESS and wind turbine is achieved by sending P_{SoC} (output of the controller in Figure 6) to the wind turbine blade pitch controller to change the blade pitch angle (blade pitch controller is discussed in Section 4). If the SoC is below nominal, P_{SoC} will be negative, which will cause the BESS to charge. The same signal is scaled and added to the wind turbine blade pitch angle setpoint to decrease the wind turbine's blade pitch angle, which increases the wind turbine's active power output. It should be noted that this control scheme is proposed for use with wind turbines that are operating with an active power reserve that is achieved using pitch angle control. Therefore, the blade pitch angle will be greater than zero under normal operation. Scaling the control signal P_{SoC} so that the charging power is equal to the wind turbine's increase in power reduces the impact that accelerated SoC recovery has on the system frequency. If the BESS SoC is very high, the BESS must be discharged. When the SoC is greater than nominal, P_{SoC} will be positive, which will cause the BESS to discharge. Simultaneously, the positive P_{SoC} value will be scaled, and added to the wind turbine's blade pitch angle setpoint to decrease the wind turbine's active power output.

4 Wind Turbine Model

The wind turbine was modelled as a type 3, doubly fed induction generator (DFIG) [22]. The active power output and speed of DFIG wind turbines are usually limited using blade pitch angle control. Pitch angle control can also be used to de-load wind turbines, thereby creating reserve that can be used to provide frequency regulation [23]-[26]. Reserve in wind turbines can be categorised as either balance or delta [27], [28]. With balance control, the wind turbine's active power reference is set to a constant value below the maximum available power. The amount of reserve is not constant and varies as the maximum available power varies. With delta control, a constant power or percentage reserve is maintained.

Figure 7 shows the control diagram of a variable speed wind turbine blade pitch angle controller. The error between the wind turbine's maximum speed, ω_{max} , and the measured speed, ω_{meas} , is used as the input to a proportional-integral controller to give the pitch angle setpoint, β_{set} . The set-point is limited to the range β_{min} to β_{max} . When the rotor speed is less than rated speed, the blade pitch angle is β_{min} (β_{min} is set to 0°). If the speed increases beyond ω_{max} , then β_{set} will increase to reduce the wind turbine's active power output and speed. The supplementary control loops (shaded area in Figure 7) added to the blade pitch controller provide active power operating reserve (percentage delta reserve), frequency-droop regulation, and assisted SoC recovery.

Figure 7. Wind turbine blade pitch angle controller

4.1 Operating Reserve

Operating reserve is achieved by adding an offset, β_{offset} , to β_{set} . The offset increases the blade pitch angle, thereby decreasing the wind turbine's power extraction from the incident wind. A lookup table that relates power reserve, P_{R_PAC} , to the blade pitch angle was created in MATLAB using a while-loop. The flowchart representation of the MATLAB script is shown in Figure 8. The script calculates the per-unit power reserve P_{R_PAC} that results from incremental changes in blade pitch angle, β , and stores the result in a matrix. The elements of this matrix were used to populate the $(P_{R_PAC} - \beta)$ lookup table shown in Figure 7.

Figure 8. Flowchart representation of MATLAB script used to create $(P_{R_PAC} - \beta)$ lookup table

The power coefficient to tip speed ratio ($C_p - \lambda$) lookup table shown in Figure 8 was created in MATLAB using a script that calculates $C_p(\lambda, \beta)$ using varying values of λ and β according to [29],

$$C_p(\lambda, \beta) = 0.5176(116/\lambda_i - 0.4\beta - 5)e^{-21/\lambda_i} + 0.0068\lambda \quad (1)$$

where,

$$\lambda_i = \left(\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \right)^{-1} \quad (2)$$

The script stores the resultant C_p values in a lookup table. The flowchart representation of the script is shown in Figure 9.

Figure 9. Flowchart representation of MATLAB script that creates $C_p(\lambda, \beta)$ lookup table

4.2 Frequency–Droop Regulation

Frequency-droop control is implemented by adding P_D to the per-unit active power reserve setpoint, P_R . A dead-band is used to prevent activation of the frequency-droop controller when the system frequency is within normal limits. If the magnitude of the frequency deviation exceeds the dead-band, then P_D will vary proportionally to frequency deviation, according to (3). If the magnitude of the frequency deviation is within the dead-band, then P_D will be equal to zero.

$$P_D = \begin{cases} \Delta f K_D, & |\Delta f| > \text{deadband} \\ 0, & |\Delta f| \leq \text{deadband} \end{cases} \quad (3)$$

Negative Δf , outside of the dead-band, will decrease β_{offset} , reducing the blade pitch angle. This will increase the wind turbine's active power output, utilising some or all the reserve depending on the magnitude of the frequency deviation. Positive Δf , outside of the dead-band, will increase the blade pitch angle, thus increasing the spillage of wind, and decreasing the active power output of the wind turbine. The droop constant K_D shown in Figure 7 sets the slope of the frequency-droop characteristic. The droop constant can be calculated as,

$$K_D = \frac{1}{\left(\frac{R}{100}\right) \times f_{nom}} \quad (4)$$

where, R is percentage droop, and f_{nom} is the nominal frequency. The Irish Grid Code [19] stipulates that wind turbines must operate according to a frequency-droop characteristic settable between 2-10% and defaulting at 4% when the system frequency deviation is outside the $\pm 0.015\text{Hz}$ dead-band. The grid code in Northern Ireland [20] also stipulates a $\pm 0.015\text{Hz}$ dead-band and default frequency droop setting of 4% for generators. In the simulations performed, K_D was set to 0.5 to provide 4% frequency-droop regulation, and the dead-band was set to $\pm 0.015\text{Hz}$.

4.3 Assisted State of Charge Recovery

Assisted SoC recovery is achieved using hybrid dispatch control of the wind turbine and BESS. The signal P_{SoC} from the BESS active power controller is scaled and added to P_R . The scaling factor, K_{SoC} , is set so that the change in the wind turbine's active power output is equal, and opposite, to the change in active power output from the BESS. The scaling factor, K_{SoC} , is determined by the ratio of the BESS active power rating, $P_{\max_BESS}$, to the wind turbine's maximum power output,

$$K_{SoC} = \frac{P_{\max_BESS}}{P_{\max_WT}} \quad (5)$$

$P_{\max_WT}$ is the maximum power available from the wind turbine when the blade pitch angle is 0° . Setting K_{SoC} according to (5) means that the change in the wind turbine's active power output is equal to the change in active power output from the BESS resulting from accelerated SoC recovery.

5 Power System Model

The performance of the accelerated SoC recovery scheme was assessed in DIgSILENT PowerFactory using the IEEE 39-bus model. The model represents the New England power system [30], [31] and consists of 10 synchronous generators, G01-G10, with G01 representing interconnection with a much larger power system. The model was modified to include wind generation and BESS by replacing the synchronous generator G07 with a wind farm and BESS as shown in Figure 10.

Figure 10. IEEE 39-bus power system model modified to include wind generation and BESS

The generator to be replaced with the wind farm was selected arbitrarily. The wind farm was modelled as 250 x 6MW DFIG wind turbines operating in parallel according to the same control scheme. Using this modelling technique, the wind farm is modelled as a single large DFIG, which is partially de-coupled from the grid frequency via a power electronic convertor. The active power setpoint of the wind turbine was set to 560MW, which was the active power output of G07 in the load flow of the original model. This represents only 37.33% of the wind turbine's rated power output, which lies within the cubic region of its power tracking curve during simulations (i.e. the wind turbine operated below rated power and rated speed during simulations). The wind turbine model was initialised with a wind speed that enabled the wind turbine to provide 560MW output while providing 5% delta reserve.

The generator governors were modelled using the IEEE G1 governor model. The model was parameterized using the gain and time constant values outlined in Table 2. Brogan et al. [13], suggest that these parameters simulate the dynamics of the Irish power system.

Table 2. IEEE G1 governor parameters used to model the dynamics of the Irish power system [13]

G2-G9				G10			
Time Constants (s)		Gain		Time Constants (s)		Gain	
T1	0.15	K	15	T1	0.2	K	5
T2	1	K1	0.35	T2	1	K1	0.3
T3	0.6	K2	0	T3	0.6	K2	0
T4	12	K3	0.2	T4	0.6	K3	0.25
T5	0.8	K4	0	T5	0.5	K4	0
T6	0.6	K5	0.3	T6	0.8	K5	0.3
T7	1	K6	0	T7	1	K6	0
		K7	0.15			K7	0.15
		K8	0			K8	0

The BESS rating was set to 30MVA. The Ah rating of the BESS was set according to the minimum response capacity of assets providing EFR, i.e. the BESS must be capable of supplying its rated power for a minimum of 15 minutes. The minimum number of cells in parallel to meet this requirement was calculated as,

$$N_p = \frac{S_{max}}{(V_{cmax} + V_{cmin}) \times N_s \times Q_c} \quad (6)$$

where, S_{max} is the apparent power rating of the BESS, V_{cmax} is the maximum cell voltage, V_{cmin} is the minimum cell voltage, N_s is the number of cells in series, and Q_c is the Ah rating of each cell. The following parameters were used for the BESS model, $S_{max} = 30\text{MVA}$, $V_{cmax} = 13.85\text{V}$, $V_{cmin} = 12\text{V}$, $N_s = 65$, $N_p = 223$, and $Q_c = 80\text{Ah}$.

6 Results and Analysis

The results and analysis section is divided into two parts. Section 6.1 presents the results and analysis for the fuzzy logic simulations, which were performed using a time series frequency sample recorded by National Grid Electrical System Operator [32]. Section 6.2 presents the results of the accelerated SoC recovery simulations performed under constant wind speed conditions.

6.1 Fuzzy Logic Control

The fuzzy logic controller was tested under variable frequency conditions in DIgSILENT PowerFactory using a frequency sample recorded by National Grid Electricity System Operator [32]. The frequency sample was used as the frequency input to the BESS active power controller (Figure 3), and the response of the controller assessed. The following two cases are presented.

Case 1: 1% frequency-droop control, without fuzzy logic control.

When operated without the fuzzy logic controller, the BESS does not make corrective changes to its power flow to restore nominal SoC. It responds only to deviations in system frequency outside the $\pm 0.015\text{Hz}$ dead-band. It does this according to a 1% frequency-droop characteristic.

Case 2: 1% frequency-droop control, with fuzzy logic control.

In addition to responding to frequency deviations according to a 1% frequency-droop characteristic, the BESS makes corrective changes to its power flow to restore the SoC to nominal based on SoC and system frequency deviation measurements. Both Case 1 and Case 2 meet the requirements of EFR as outlined in Section 2.

6.1.1 SoC initialised at 0.5 p.u.

Figure 11 shows the results of a 2-hour simulation performed in DigSILENT PowerFactory when the SoC was initialised at 0.5pu. The traces in dashed red are the results of Case 1, while the traces in solid blue are those for Case 2.

Figure 11. Variable frequency results: SoC initialised at 0.5pu

Figure 12 shows 10-minute results samples, which more clearly shows the response of the fuzzy logic controller to the variable frequency sample when the SoC is below nominal (Figure 12(a)) and when the SoC is above nominal (Figure 12(b)).

Figure 12. Fuzzy logic controller results: (a) SoC below nominal (b) SoC above nominal

6.1.1.1 Fuzzy logic control: SoC above nominal

When the system frequency deviation is within the dead-band, the BESS discharges proportionally to the deviation from nominal SoC only (i.e. the BESS does not respond to changes in frequency). The fuzzy logic controller provides corrective changes to the BESS power flow to restore nominal SoC. When the system frequency deviation falls below the lower limit of the dead-band, the fuzzy logic controller causes the BESS to discharge in response to both SoC deviation and frequency deviation. This is evident between 30 and 40 minutes in Figure 11. Under-frequency events occur when system generation is lower than load demand. In such situations, a BESS should discharge to reduce the imbalance. It can be noted that the fuzzy logic controller remains active when the frequency deviation is outside the dead-band, which allows the BESS to utilise its additional discharge capacity to accelerate the restoration of the nominal SoC, while providing additional under-frequency regulation. When the frequency deviation reaches the upper limit of the dead-band, the output of the fuzzy logic controller, P_{FLC} , converges to zero. This is important because the BESS transitions from discharging to charging at the upper limit of the frequency deviation dead-band. If P_{FLC} did not converge to zero, then the fuzzy logic controller would attenuate the frequency-droop response of the BESS. When the frequency deviation exceeds the upper limit of the dead-band, the BESS charges in response to frequency deviation only. The fuzzy logic controller has no effect on the BESS's power flow when the SoC is high and the frequency deviation is above the upper limit of the dead-band.

6.1.1.2 Fuzzy logic control: SoC below nominal

When the frequency deviation is within the dead-band, the BESS charges proportionally to SoC deviation to restore nominal SoC. When the frequency deviation exceeds the upper limit of the

dead-band, the BESS charges in response to both SoC deviation and frequency deviation. This utilises the additional charge capacity of the BESS to accelerate nominal SoC restoration, while enhancing the BESS's contribution to over-frequency regulation. This is evident between 95 and 108 minutes in Figure 11. When the SoC is below nominal, the BESS transitions from charging to discharging when the frequency deviation falls below the lower limit of the dead-band (P_{FLC} converges to zero when the system frequency deviation reaches the lower limit of the dead-band). The BESS discharges in response to frequency deviation only when the frequency deviation is below the lower limit of the dead-band. Therefore, the fuzzy logic controller has no effect on the BESS's frequency regulating response to under-frequency events when the SoC is below nominal.

6.1.2 Low SoC: SoC initialised at 0.4pu

Figure 13 shows the results when the BESS SoC was initialised at 0.4pu. It can be noted that the SoC increases more rapidly when the fuzzy logic controller is used. With the fuzzy logic controller employed, the BESS utilises its additional charge capacity during over-frequency events to restore the SoC towards nominal, whilst providing additional over-frequency regulation. It can be noted that the SoC stays closer to nominal when the fuzzy logic controller is employed, which increases the availability to respond to frequency contingencies.

Figure 13. Variable frequency results: SoC initialised at 0.4pu

6.1.3 High SoC: SoC initialised at 0.6pu

Figure 14 shows the results produced when the SoC is initialised at 0.6pu. It can be noted that the BESS uses its additional discharge capacity to increase its active power response to under-

frequency conditions by remaining active when the frequency deviation falls below the lower limit of the dead-band.

Figure 14. Variable frequency results: SoC initialised at 0.6pu

Figure 15 shows that the BESS operates within the confines of the EFR service 2 envelope. When the fuzzy logic controller is employed, the BESS utilises any additional charge/discharge capacity, by operating at the extremes of the service envelope (i.e. the outer confines of the service envelope) to accelerate the restoration of nominal charge, while enhancing its frequency regulating response.

Figure 15. BESS active power vs system frequency response and EFR service 2 envelope. The blue circles represent the BESS active power output in response to the system frequency

6.2 Accelerated State of Charge Recovery

The accelerated SoC recovery control scheme was simulated in DIgSILENT PowerFactory under constant wind speed conditions. A dispatch signal was used to activate the scheme at $t = 1$ minute. Firstly, the simulations were performed where the BESS and wind turbine were controlled autonomously. Then, the same simulation parameters were used with hybrid dispatch control enabled. The results of the simulations are presented in the following sub-sections.

6.2.1 Constant Wind Speed: Low SoC (SoC initialised at 0.2pu)

Figure 16 compares the results produced when the SoC was initialised at 0.2pu. The results show that there is no difference in the BESS active power and SoC trajectories for the two cases. Autonomous control, however, had significant impact on the system frequency. The frequency fell below the lower limit of the dead-band, which resulted in the activation of the wind turbine and BESS frequency-droop controllers.

As expected, autonomous control had almost no impact on the wind turbine's active power output. The slight increase exhibited is due to the significant drop in system frequency activating the wind turbine's frequency-droop response as opposed to a change to wind turbine dispatching. With hybrid dispatch control, the wind turbine increases its active power output to match the BESS charging power, which reduces the impact on system frequency. The system frequency stayed within the dead-band during accelerated SoC recovery when hybrid dispatch control was used, which meant that activation of primary response schemes was avoided.

It can be noted that the SoC increases from 0.2pu to 0.5pu in approximately 20 minutes. The charging period can be controlled by changing the slope of the ramp function in the setpoint controller (see Figure 6) and the gains of the proportional-integral controller. If the charging power was limited to 9% of the maximum power as is the requirement for EFR, then it would take a minimum of 100 minutes to restore the SoC from 0.2pu to 0.5pu.

Figure 16. Accelerated SoC recovery results: SoC initialised at 0.2pu

6.2.2 Constant Wind Speed: High SoC (SoC initialised at 0.8pu)

Figure 17 compares the results produced when the SoC was initialised at 0.8pu. Like the results for the low SoC simulations, the trajectories of the BESS active power output and SoC are identical for the two cases. The results show that the system frequency does not exceed the dead-band when hybrid dispatch control is used, meaning that the activation of primary response schemes was avoided. With hybrid dispatch control, the wind turbine's active power output is decreased by an amount equivalent to the BESS discharging power, which reduces the impact on the system frequency.

Figure 17. Accelerated SoC recovery results: SoC initialised at 0.8pu

6.2.3 Response to contingency when charging

A frequency event was simulated during accelerated SoC recovery to investigate the impact on the wind farm's frequency response performance (the wind farm consists of the wind turbine and BESS). Accelerated SoC recovery was initiated at $t = 1$ minute. An under-frequency event was created by suddenly connecting a 100MW load to busbar 16 at $t = 3$ minutes. The results are compared to those produced without the initiation of accelerated SoC recovery in Figure 18. The results show that accelerated SoC recovery has almost no impact on the system frequency response. The charging power of the BESS during accelerated SoC recovery is compensated for by the increase in the wind turbine's power output. It can be noted that the wind farm's active power output is almost identical for both cases, there only being a slight dip in the wind farm's output when accelerated SoC recovery is first initiated.

Figure 18. Response to frequency contingency. Accelerated SoC recovery initiated at $t = 1$ minute. Under-frequency event initiated at $t = 3$ minutes

7 Discussion

The results show that the proposed fuzzy logic controller effectively operated within the confines of the EFR service 2 envelope when tested under variable frequency simulations. The improvement of this control scheme over others in published research literature is that the controller remains operational outside of the $\pm 0.015\text{Hz}$ dead-band, to utilise any additional charge/discharge capacity. This accelerates nominal SoC recovery, while also providing additional frequency support. It should be noted that though the additional charge/discharge responses would have a positive effect on the frequency dynamics, this is not reflected in the simulation results presented in figures 10-13. This is because a time series frequency sample was used to assess the performance of the fuzzy logic controller, hence the simulation results presented do not assess the dynamic frequency support offered by the BESS. The aim of the research is to prove that the controller is effective at re-establishing nominal charge. Future work will involve performing dynamic frequency simulations to assess the enhanced frequency support performance of the BESS when operated according to the proposed control scheme.

When the SoC is below nominal, the BESS has impaired capacity to respond to under-frequency events, while having increased capacity to respond to over-frequency events. Though the fuzzy logic controller makes use of this increased charge capacity to restore nominal SoC when the system frequency exceeds the nominal frequency, the impaired charging capacity of the BESS is a concern. It is imperative that the nominal SoC is restored as quickly as possible to ensure availability and reliability of frequency regulating services. A similar situation exists when the SoC is greater than nominal, with the BESS having impaired charging capacity to over-

frequency events. Though this condition may not be as serious as the former because committed generating units can down-dispatch to restore nominal frequency in the case of a significant over-frequency event.

The research highlights the requirement for accelerated SoC restoration. This is something that has been neglected in published research literature in this field. State of charge recovery schemes that operate within the confines of the EFR service envelope will incur long periods where the BESS has reduced capacity after service delivery (i.e. long periods where the SoC is above or below nominal). If BESSs are to avoid system performance measurement non-performance penalties, then their SoC must be kept close to nominal. Long restoration times after significant charging or discharging will result in reduced availability. If the availability is to be improved, then there must be a way to reduce the time it takes to restore nominal charge, without significantly impacting the system frequency.

The results presented in Section 6.2 show that the proposed accelerated SoC recovery controller is effective at accelerating the re-establishment of nominal SoC. Hybrid dispatch control can be used to reduce the impact that accelerated SoC recovery has on the system frequency. The simulation results show that the accelerated SoC recovery scheme is effective at restoring nominal charge within 20 minutes, which is at least 5 times faster than that which could be achieved with control schemes that operate within the confines of the EFR service envelope. Contingency simulations show that the scheme has very little impact on the wind farm's frequency response (the wind farm's response is taken to be the aggregate of the wind turbine and BESS power output).

8 Conclusion

This research presents an analysis of SoC management schemes for BESSs to restore nominal SoC. The fuzzy logic controller presented was designed in MATLAB and implemented in DIgSILENT PowerFactory using a look-up table. Frequency simulations were performed using a time series frequency sample provided by the National Grid Electricity System Operator, to assess the performance of the proposed fuzzy logic controller. The simulation results presented show that the controller works to restore the SoC to nominal when the system frequency deviation is within the $\pm 0.015\text{Hz}$ dead-band. The controller differs from other controllers in published research literature in that the BESS utilises any additional charge/discharge capacity to accelerate SoC restoration, even when the frequency deviation is outside the $\pm 0.015\text{Hz}$ dead-band (up to a limit of $\pm 0.25\text{Hz}$). It does this by operating at the outer extremes of the EFR service envelope. The limitations of SoC management systems that operate within the confines of the EFR service envelope are highlighted, which led to the development of the accelerated SoC recovery control scheme proposed. An IEEE 39-bus test bed with type 3 DFIG wind turbine and BESS was built in DIgSILENT PowerFactory to assess the performance of the proposed accelerated SoC recovery control scheme. The analysis shows that nominal SoC was achieved 5 times faster than that which could be achieved using recovery controllers that operate within the confines of the EFR service envelope. Hybrid dispatch control of the wind turbine and BESS reduced the impact that accelerated SoC restoration had on the system frequency (the frequency did not deviate outside the $\pm 0.015\text{Hz}$ dead-band). The ability to quickly restore nominal SoC to increase availability of system services, without significantly affecting system frequency, is a novel contribution to the published research literature in the field.

Overall, this research has demonstrated the ability of BESS to quickly restore nominal charge to increase availability of frequency regulating system services, which will be important if the

penetration of intermittent renewable generation is to continue to increase to significant levels. For this to be successful, BESSs must have a robust operational strategy, which ensures that the SoC remains at nominal most of the time. This is particularly important in countries such as Ireland, the United Kingdom, Italy, and Spain who have large wind power penetration and limited interconnection and or grid constraint/congestion problems. The research presented is limited by the availability of wind farm and BESS data, which is commercially sensitive. However, this limitation does not affect the key findings of the analysis presented. Future work will further investigate accelerated SoC recovery, to optimise performance based on SoC status decision making during frequency events. Another further piece of work, which could follow on to inform countries with large solar photovoltaic generation, would be to examine solar photovoltaic with BESS, and different controller configurations, as an option to diversify the renewable generation mix.

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