

An intelligent power management controller for grid-connected battery energy storage systems for frequency response service: A battery cycle life approach

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ABSTRACT

BESS are now preferred to provide ancillary services due to their advantages of cost reductions and rapid response times. Based on the criteria in the regulation for the electricity grid, an advanced power management control algorithm with the technical features to provide the grid frequency support specified in the regulation on the use of BESSs in ancillary services has been developed in this study and evaluated in various scenarios. A 2 MW/1 MWh installed power BESS is considered for frequency support control, which is one of the grid ancillary services. The algorithm is tested for providing the appropriate power by optimally using the state of charge of the battery within the limits specified in the regulation. Since the maximum and minimum set limits for the state of charge cannot be exactly defined in the literature, the fuzzy logic method was chosen as the decision-maker for active power output. In the algorithm, the amount of power that must be supplied by the battery energy storage system will change according to the dynamically varied state of charge. The results show that the fuzzy logic control algorithm successfully provides the frequency response in the regulation zone with optimum SOC level and contributes the extending the battery life.

1. Introduction

Considering the developments in the world the rising number of electric vehicles, renewable energy penetration, and improvements in the demand-side response directly affect the electricity transmission and distribution companies. Power grids operating according to traditional synchronous generators have evolved into power system dynamics working with renewable energies that are increasing day by day. In an AC power system, the system frequency should remain the same at every measuring point. For reliable and safe operation of the power system, it is desired that the system frequency remains constant at the nominal system frequency value (50Hz for the ENTSO-E area). Any change in supply and demand causes changes in the frequency level. If the generation level is lower than the consumption, the frequency level is expected to decrease, or if the electricity supply is higher than the demand, the frequency level is expected to increase [1]. For instance, charging/discharging of batteries used by electric vehicles on the electricity grid affects the electricity frequency level.

For the ENTSO-E region, several parameters have been defined by

the European Union commission in the electricity transmission system operation manual for the evaluation of frequency quality and reliability [2]. The unpredictability of energy production with the use of distributed energy which is difficult to forecast since it provides continuously variable output power increases stability problems [3]. The amount of frequency change is specified in each country's electricity grid regulation, and different methods such as load shedding, load reduction, and energy storage systems are applied in the literature in order not to exceed the limit values.

As power generation increases, the role of ancillary service has increased in terms of reliability and cost-effectiveness to avoid operating at critical limits in power systems for optimal use of generation and transmission systems. At this point, the transmission systems operator is responsible for controlling the system frequency at $50\text{Hz} \pm 1\%$, ensuring that there is sufficient generation and demand that is kept ready to manage all conditions that may cause frequency changes. Required reserves are calculated and maintained to assist in setting legal limits for frequency. These reserves are called frequency response services. These services are purchased from various types of technology, from

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conventional power plants to wind farms, and increasingly from ancillary sources (such as batteries). Production changes frequently take less than one second to occur [4]. Many frequency response services are purchased and an automatic response within seconds is essential. Exceeding the legal limits is a very rare occurrence [5].

BESS has become important for grid applications in recent years due to its versatility, fast response time, high energy density, and efficiency. Additionally responding instantly to the needs of power systems, as well as providing services that require long discharge times. In this context, a study that provides ancillary services by considering the voltage dependence of DC-AC converters by using 720 kVA/560kWh BESS in Paolone École Polytechnique Fédérale de Lausanne campus, which is one of the examples in the world [6]. In weak grids, voltage instabilities and technical difficulties are likely to occur due to insufficient system availability. A study on the simultaneous dynamic active and reactive power response of grid-connected BESSs in weak grids has been published by Dozein et al. [7].

Algorithms for providing advanced frequency control with battery energy storage systems have been studied in the literature [8–13]. Bahloul et al. have published a study on the design of a rule-based power management algorithm that controls the hybrid energy battery-supercapacitor storage system (HESS) for Enhanced Frequency Response (EFR) in the UK. To analyze the regulation dynamics and compare the performance for each system, simulation studies were performed for both the BESS only and the HESS [14]. In rule-based algorithms, considering the battery SOC value, the maximum, minimum or reference lines stated in the ancillary service regulation are used directly as the active output power of the battery according to the frequency-active power envelopes specified in the grid code [1,14,15]. Fuzzy logic has the advantage that is less sensitive than rule-based control and does not specify strict limits. However, in the design and application part, the designer must be experienced and have extensive knowledge of the literature in the field to be applied. Fuzzy logic has been applied in primary frequency control and optimum solutions have been produced for different scenarios by Brivio et al.. In a Simulink environment, 1MW/1MWh BESS is simulated to provide primary frequency service and avoid load state saturation (droop control) and charge/discharge (arbitrage) of the battery when economically feasible. By applying 2 operating options via 2 fuzzy logic controllers, determined the operating points for droop control and arbitrage value [16]. The study is reviewed for creating the frequency and battery SOC value membership functions, examining the frequency upper and lower values determination, SOC value effect to the control and fuzzy logic rule creation. Since primary frequency control has a wider range of frequency range, this article has only been methodically examined in the application of fuzzy logic in frequency control.

In the literature, there are studies in which micro grid-level battery energy storage systems and energy management are provided with fuzzy logic, but there are very few studies using fuzzy logic with BESSs from frequency regulation ancillary services to EFR service by connecting directly to the transmission line [17,18]. One of these studies designed a fuzzy-logic controller to enable EFR from the battery, flywheel, and ultra-capacitor storage system [19]. It's aimed to facilitate the integration of other storage technologies into the same system as well as BESSs to provide frequency response service using fuzzy logic (for instance, the difficulty of PID, control requiring a more detailed model for different storage). The main difference here is the frequency deviation membership function and SOC error membership functions. The opposite of setting a constant limit for battery SOC as 50% and calculating with the help of fuzzy logic how the SOC changes after EFR service, in this paper there are maximum and minimum reference SOC levels and the battery can be used at every level. Likewise, the advantage of the fuzzy logic model that will affect battery life has not been stated in any section and fuzzy logic functions have not been designed for battery life consideration.

Another study that provides EFR service with BESS using type-2

fuzzy logic was carried out by Cantillo-Luna et al. [20]. In the fuzzy logic members used in this study, it was aimed to always keep the SOC value at the 50% level, and the charge/discharge mechanism was provided by creating the SOC_{error} value according to the deviation from the 50% value. In terms of battery life, the fact that the SOC value remains at the level of 50% increases the battery life based on the studies in the literature. However, the fact that most of the active power values in the active power-frequency envelope follow the reference line according to the frequency value used in the study, shows that the ramp rate is not taken into account for the change of the frequency, and there is no mention of a function for the ramp rate. Another missing point is that the change intervals of the fuzzy logic membership functions are not clearly shown.

The main purpose of this study is to use all regions between the maximum, minimum and reference lines in the active power-frequency envelope; thus, by getting the maximum benefit from the battery, to increase the life of the battery which is a big issue nowadays. The algorithm manages the battery SOC and focuses on all possible SOC levels the battery can be used, therefore in the case of micro cycles get the advantage of half cycles of the battery and increases the lifetime of the battery. This paper presents the first algorithm in the literature designed by taking into account the battery life extension, except for staying inside the active power-frequency envelope by participating in the frequency ancillary service. Another contribution of this study is that since it is designed specifically for BESSs, the output power can be used directly without the need for another algorithm, not as a reference power. As a result of the simulation studies, the superiority of the power management algorithm designed using the battery life analysis technique (rain flow algorithm), in terms of battery life has been proven by providing ancillary services perfectly.

A detailed literature review shows that the control algorithms developed for the participation of battery energy storage systems in ancillary services, on which the grid criteria are studied, have gained importance in developing countries, whose investments are constantly increasing. At this point, it is expected that the control algorithms developed will be the most economically suitable and long-lasting for the owners of battery assets. In this study, an intelligent power management control system is developed using fuzzy logic. By using the SOC level of the battery in the most optimal way, it is aimed to provide 100% EFR ancillary service performance measure and not to be penalized by the system operators, and to operate the BESS most economically, taking into account the battery life.

The rest of this article is organized as follows: Section 2 discusses the technical criteria for providing EFR service with battery energy storage systems. Section 3 discusses the suggested fuzzy logic controller design for a BESS; introduces the input data as well as membership functions and fuzzy rules. Section 4 explains the simulations and findings produced for the various situations investigated, while Section 5 contains the concluding observations.

2. Technical criteria for frequency response ancillary services: UK and Turkey case

2.1. Delivery envelopes

According to the EFR regulation issued by National Grid (NG) which is an Energy Company operating in the UK, the delivery envelope specifies the area in which the responses of the assets should be in, as shown in Fig. 1. The assets must provide continuous active power as described in one of the two service envelopes.

Table 1 shows the upper, lower, and reference limits of the response at different frequencies. The dead band is defined as the frequency range between reference points C and D. Within the dead band, the assets' active power need not respond proportionally to the system frequency. This is a significant advantage for ESSs, they do not need to adhere to SOC adjustment periods. According to the regulation, the input or

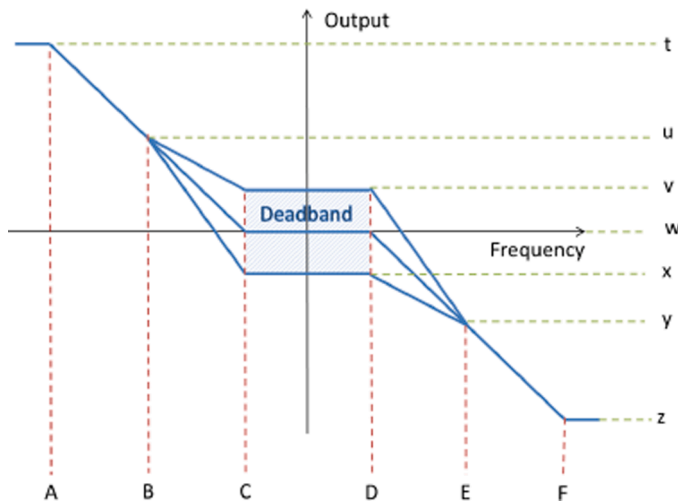


Fig. 1. EFR delivery envelope for UK power grid.

Table 1
Upper, lower, and reference limits of frequency responses for the UK [21].

Reference Point	Service-1 (Hz)	Service-2 (Hz)
A	49.5	49.5
B	49.75	49.75
C	49.95	49.985
D	50.05	50.015
E	50.25	50.25
F	50.5	50.5

output of EFR assets within the dead band should not exceed $\pm 9\%$ of the nominal power [21].

As seen in Table 2, at *u* and *y* points of the delivery envelope, the EFR is divided into two different service types. The main difference between the two services is that the Service-2 type EFR has a much narrower dead band that place a higher technical requirement on EFR assets.

Within the scope of the Technical Criteria Regulation on The Use of Battery Storage Systems in Ancillary Services published by TEIAS (Turkish Electricity Transmission Corporation), there is a narrow service envelope that must provide continuous active power and a dead band where the battery can manage energy. By Turkish regulation, in a certain dead band range (± 10 mHz), the energy storage assets will be able to export or import energy from the grid, not exceeding 10% of its installed power [22].

From Fig. 2, besides the classical frequency droop control method, there are also minimum and maximum power support limits envelope. The output power (P_n) of the system can be calculated by using BESS nominal power in Table 3.

If the frequency decrease under a certain level, BESS facilities have to export energy by providing active power output to the grid for frequency support, and if the frequency is higher than the dead band level then BESS has to import energy to the grid. In addition to that, if batteries are

Table 2
Upper, lower, and reference power limits to provide for frequency responses for UK [21].

Reference Point	Service-1 (kW)	Service-2 (kW)
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%

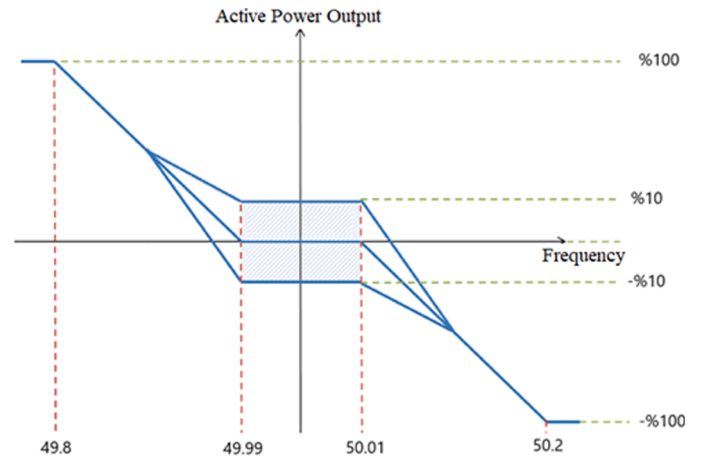


Fig. 2. Frequency response service envelope from Turkish ESS technical regulation method-1 [22].

Table 3
Frequency envelope - frequency and power boundaries for Turkey [22].

Frequency	Power Boundaries ($P_n\%$)
49.8	100
49.99	10
50.1	-10
50.2	-100

chosen as energy storage for this frequency support, SOC is another important issue. While the BESS provides frequency support to the grid, the battery should keep the charge level at the most appropriate levels and protect itself from possible damages for instance an explosion of the battery as a result of exceeding the maximum limit of SOC. As a consequence of SOC level importance, battery management should be the most important consideration.

3. Method

3.1. Input data

According to the designed control algorithm, 2 different scenarios were examined. The first of these is the scenario in the UK, which has comprehensive regulation and on which different control algorithms were designed in the literature, and the second one is the scenario in Turkey, which has just published the technical criteria for the use of batteries in ancillary services and has not a real grid application yet.

In 2 different scenarios, for the algorithm input samples were selected from the real frequency data published by the grid operators on official websites. The histogram distribution of the frequencies was examined, and the control algorithm was tried on the worst (the most deviating from the value where the frequency was 50Hz) scenario. The main aim is here to verify in the worst cases the algorithm which normally gives superior results when being close to the values of 50Hz.

In this section, a comprehensive analysis of one month frequency data of Turkey and the UK has been performed. The idea is to find the frequency deviation from the levels specified in Method-1 in battery regulation and EFR, to build the algorithm using the frequency data with the highest standard deviation with the best performance for the worst conditions.

Frequency data for February 2022 for Turkey and November 2015 are considered a good opportunity to examine considering the weather conditions. Daily and cumulative monthly data standard deviation and histogram are shown in Figs. 3–5. Because on the 2nd of February and the 21st of November 2015 standard deviations are the most higher,

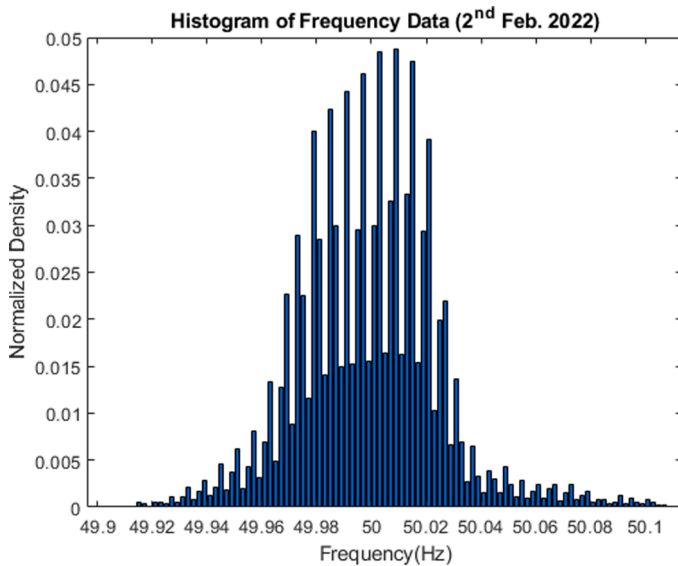


Fig. 3. Histogram of the frequency data for Turkish grid on 2nd of february.

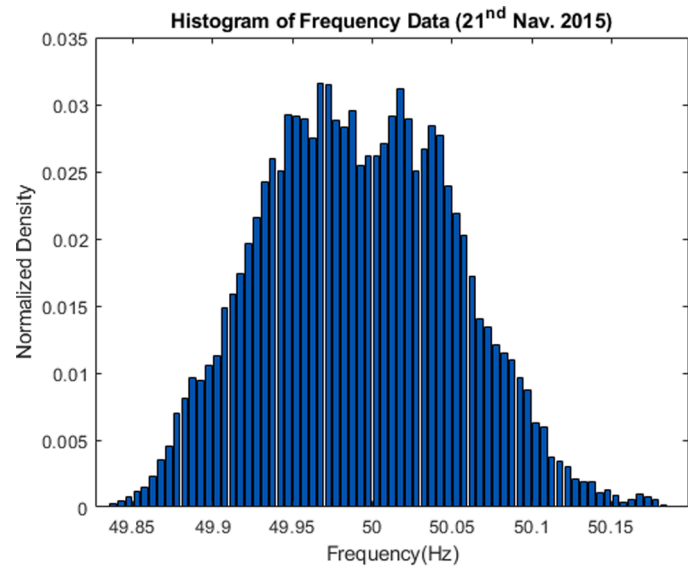


Fig. 5. Histogram of the frequency data for UK Grid on 21st of November 2015.

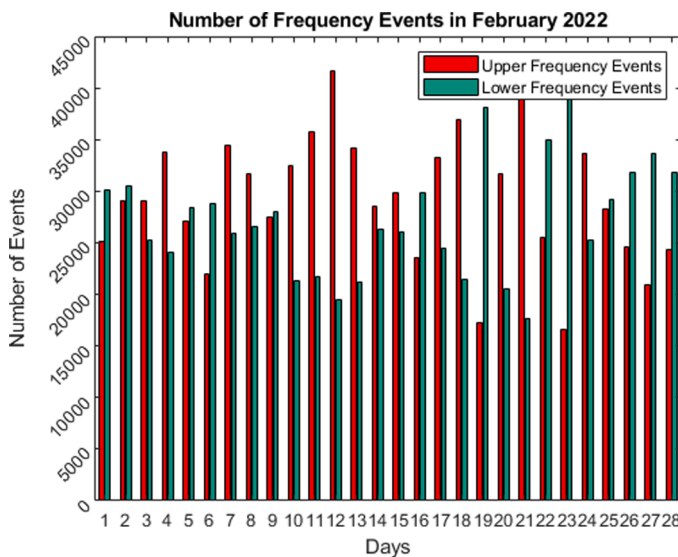


Fig. 4. Histograms and probability distributions of frequency events per day for Turkish regulation, according to the Method-1.

they were chosen as input data for the control algorithm for showing the proposed method's performance in unstable conditions.

3.2. Simulation parameters

Aspects such as the influence of temperature variations on performances, variability of BESS capacity according to operating current, and specific electrical circuitry are not considered in this study.

Frequency droop control is made with a general droop (slope of a curve) formula that uses between two points of a curve. According to the (1), the line known with two points $((A,a)$ and (B,b)) can be written to find the output of the f point. All power outputs are calculated using this formula and another way of getting this equation is the triangle similarity method.

$$Output = \frac{(f - A)}{(B - A)}(b - a) + a$$

The coulomb counting method is one of the most easily applied

techniques for estimating the SOC of the battery by the $SOC(t_0)$ given an initial value and integrating the terminal current concerning time.

Different kinds of methods have been used for SOC estimation in the literature based on such as coulomb counting [1], open-circuit voltage [23], Kalman Filter [24], and machine learning [25,26]. In this study, SOC will be estimated by using the coulomb counting method with (2).

$$SOC_{out}(t) = SOC_{ini}(t_0) + \frac{\int_0^t P_{bat} dt}{3600 \times Q}$$

In this formula, $C_{ini}(t_0)$, P_{bat} and Q represent the battery's initial SOC value, instantaneous battery power, and Watt-hour capacity of the battery .

3.3. Fuzzy-Logic controller model

The fuzzy logic controller design includes three membership functions. These are the instantaneous frequency value for the input data and the SOC value of the battery and the amount of power that must be supplied to the electrical grid as output data.

- **Frequency Membership Function:** 50Hz \pm dead band boundary values have been chosen as the normal frequency membership function (MF) since it is working with countries that use a 50Hz set value as the electricity grid frequency. The highest and lowest values specified for the dead band in the regulations are the limit values for normal high and normal low-frequency membership. The highest and lowest values including the ancillary frequency service envelope are used as high and low frequency membership functions. For all the values in the membership functions, the values belonging to the narrow frequency band are used to avoid the need for an extra design according to the wide-band. Five triangular membership functions capable of detecting frequency values were chosen. The dead band area was chosen for N (normal) triangular MF and deviation from dead band area named with NH (normal high) and NL (normal low) MFs. For higher or lower frequency levels H (high) and L (low) frequency triangular MFs are used.

- **SOC Membership Function:** In the literature, there are no specific limits for SOC of the battery for operating conditions (differences of every battery's chemical ingredient, various C-rate, and diverse application areas of batteries). However, there are optimum operating ranges according to the battery application area. In general for extending battery life 50% SOC is optimal and 20% SOC value is accepted as the battery's end-of-calendar life. The set limits are taken as 70%, 80% and 90% maximum and 30%, 20%, 10% for minimum level. The battery is

normally suggested to operate in a specific range [SOCmin, SOCmax]; however, different SOC ranges have different impacts on the lifetime of a BESS. Abdullah et al. mentioned that the lifetime of the Li-ion battery that spends the majority of its time in a SOC between 30%–50% is longer than those that spend a SOC between 70%–90% or 20%–40% [27]. To try to extend the lifetime of a BESS, another study focuses on 10% and 90% SOC value intervals [28]. After the detailed both energy management control methods and battery life literature research, SOC limits are defined as in the Fig. 7. The authors simulated various models of the SOC and created models that were chosen after many trial and error processes. At the same time, the authors get the advantage of the fuzzy logic variable area and it doesn't have a strict rule for creating a membership function. Since the interval is defined for the optimum SOC value of the battery, 4 trapezoidal MF are defined for the SOC in the fuzzy logic controller design. In addition to the high and low SOC membership functions, the optimum high and optimum low SOC values form the trapezoidal membership functions within the optimum values for the battery.

Figs. 6 and 7 show the ranges and the areas covered by the two input membership functions. In addition, the highest, lowest and linear limit values are specified in the amount of active power that should be supplied to the grid according to the input frequency. Accordingly, since power can be supplied to the grid between the highest and lowest set powers, the SOC value of the battery was used as a decision-maker. Active output power is determined according to the membership function value of which input function has priority, with the help of fuzzy logic, using the intervals determined in the grid regulation.

- Active Power Output Membership Function: The output membership function has been created according to the active power-frequency envelope specified in the electricity grid ancillary services regulation. For this, the upper, lower, and reference power limits table, which must be provided for the frequency responses, is used. A variable slope fuzzy logic set was used based on the installed power. Accordingly, in the scenario created, the membership function of all power limits that a 2MW/1MWh BESS must provide is shown in the Fig. 8. Triangular MF is decided to use which includes for dead band area and the outside of it. P_{db} (dead band area set power) for dead band area, outside of dead band there are upper and lower line boundaries so it was used P_{max_low} and P_{min_low} for charging limits and P_{max_up} and P_{min_up} for discharging limits with defined set power values.

2MW / 1MWh BESS power management controller model was simulated in the MATLAB m-file according to procedures, data, parameters and methods explained in the previous sections. The fuzzy logic rules in the control model are given in Table 5. After the fuzzy logic model membership functions are created according to the reference regulation, grid frequency is measured and battery SOC level is calculated at the first step. Both are used for fuzzy logic control blocks to determine the active set power that the battery should absorb or deliver to the grid according to the EFR service envelope. Another important

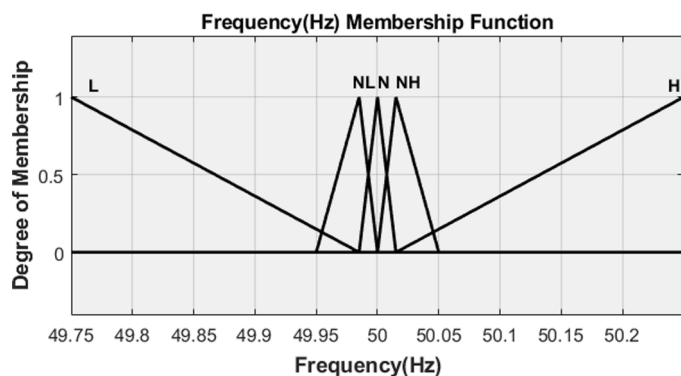


Fig. 6. Frequency membership function.

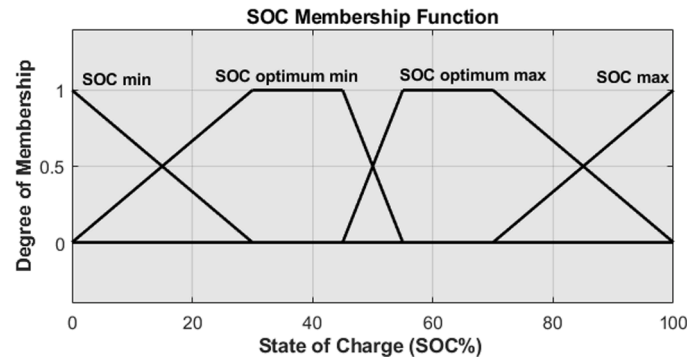


Fig. 7. SOC membership function.

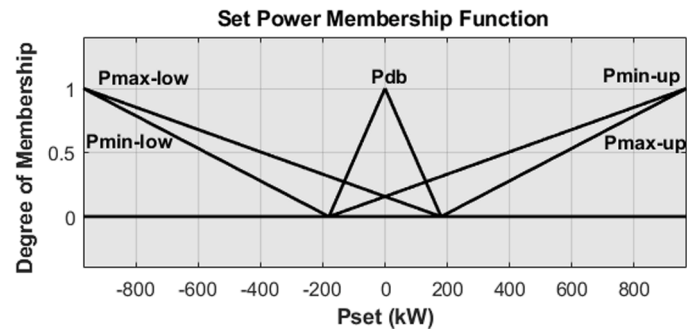


Fig. 8. Fuzzy sets of the output P_{set} membership function.

point in the control algorithm is the changing ratio of active power. In the BESS regulations, there is a set limit for the delivery of active power according to the time. National Grid published ramp rate limits according to the EFR zone [26]. The payment will be penalized if operations are performed in the outside of the ramp rate limits defined in EFR regulation. If the BESS is underperforming which is measured with service performance measurement (SPM), the reduction rate is applied according to the SPM-Availability Factor table in availability fees explained in National Grid EFR regulation for pre-qualified parties [26].

Consequently, in the algorithm after the zone assignment code process, set power limits are calculated. After all, if the ramp rate is obeyed the power set limit is calculated active power is directly applied. On the other hand, if the zone assignment code determines the active power output derivative outside the RoCoF limits, the ramp rate control code change the calculated output power from fuzzy inference and increases or decreases the active power with the help of grid regulation. The ramp rate control algorithm is the next step for adding or subtracting another active power from the set power limit. The output power was used for input data near the initial SOC level and battery Q (Watt-hour capacity) level for SOC estimation proposed in Section 3.2. The flowchart of the algorithm and the block diagram of the fuzzy controller block can be seen in Figs. 9 and 10.

4. Simulation results

Simulation results were analyzed separately for two different scenarios using the same power management control code with the same parameters, and the results were presented. It is shown that the fuzzy logic control algorithm designed in scenarios created for different countries using their frequency data ensures that the most suitable active power values are given to the electricity grid from all points between the highest and lowest slope options according to three different slopes as upper, reference and lower line.

For the first scenario, real grid frequency data with one-second resolution downloaded from the National Grid database was used as input

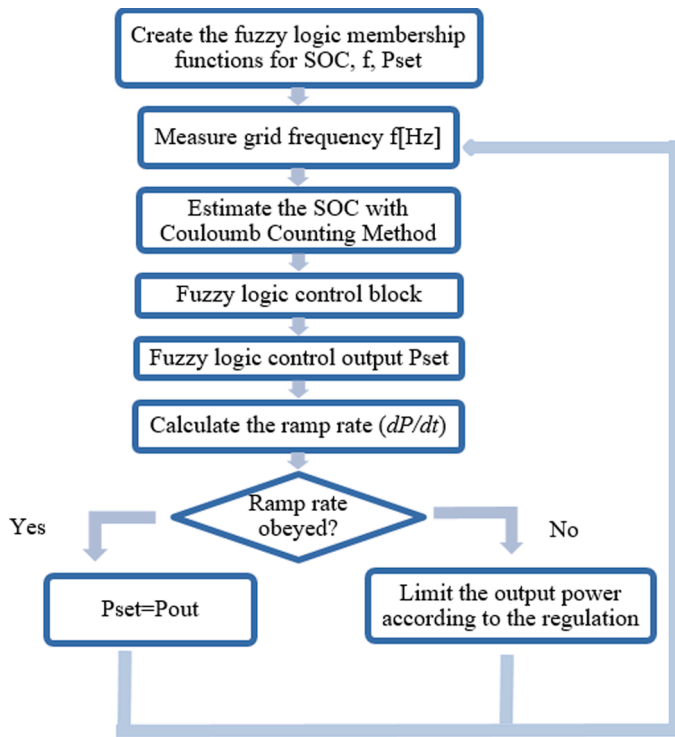


Fig. 9. Flowchart of power management control for frequency response ancillary service.

data. A daily frequency data set that deviates more than 50Hz of the frequency is selected for the power management algorithm. The graph of the change over time of the frequency data set used as input data is shown in Fig. 11.

Frequency and initial SOC level are used at first for frequency support service. The fuzzy logic controller decides to active power set point based on the difference in SOC level and frequency deviation from the dead band level. Due to the fact that there is a limit for power set point in which increasing or decreasing, the ramp-rate controller algorithm runs at the same time. As described before in Table 4, the nominal power for BESS is chosen to be 2 MW. In the dead band area, according to the EFR regulation, the maximum power limit is $\pm 9\%$ of the nominal power which is $\pm 180\text{kW}$ for 2 MW. It can be seen in Fig. 11 that when the frequency is lower than 50Hz, BESS power output is positive which means that it supports the grid for balancing the frequency. Also as a result of BESS discharge, the SOC level of the battery is decreasing. Fig. 12 shows the SOC level change graph in the 24-hour period. The fuzzy logic controller decided on critical points for the SOC level. The active power output change of the controller according to the frequency level is shown in the Fig. 13. After the fuzzification step, it decides to

power the output value in the EFR envelope at the appropriate point, not just on the upper, reference or lower power output line. And resultant graph for the EFR envelope is shown in Fig. 14.

In the second scenario, the time variation of the frequency value received from the TEIAS (national transmission system operator in Turkey) database is used as input data in the control algorithm, in which regions it exceeds the dead band limits set in the frequency response regulation is shown in Fig. 15.

According to the second scenario where a battery energy storage system with 2 MW installed power supports the grid frequency with ancillary services, the amount of active power (kW) that needs to be charged or discharged at the time of frequency fluctuation is calculated by the algorithm and in Fig. 16 its graph over time is shown. It can be seen that when the frequency is higher than the upper limit, power out is the opposite value of the frequency value and BESS charging itself. When BESS charges/discharges itself the algorithm also controls the battery SOC level to protect the battery and optimize the cycle of the battery with optimum SOC levels. In Fig. 17, SOC against time is showing that the BESS operates between 49.3784% and 80.9006%. The

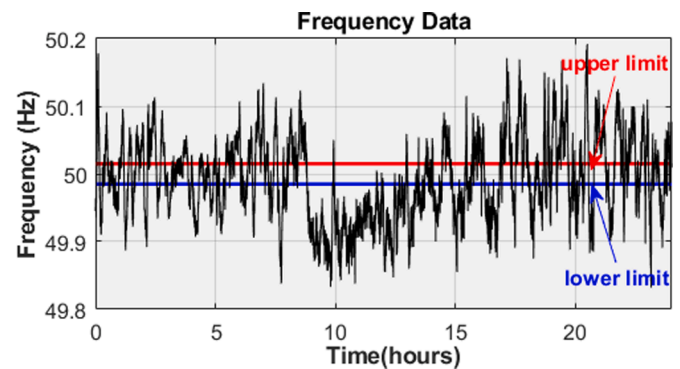


Fig. 11. Frequency trend adopted in the simulations - Frequency data for (21st November 2015).

Table 4
BESS parameters used for simulation.

Description	Parameter Name	Value
Nominal Power	P_n	2 MW
Battery Capacity	E_{batt}	1 MWh
Initial SOC Value	SOC_{init}	50%
Theoretical Maximum SOC	SOC_{max}	70%
Theoretical Minimum SOC	SOC_{min}	30%
Optimum SOC_{max}	SOC_{opt_max}	55%
Optimum SOC_{min}	SOC_{opt_min}	45%
Dead Band Range	DB	EFR_{narrow}
Max Droop Frequency Value	-	49.75 Hz
Min Droop Frequency Value	-	50.25 Hz

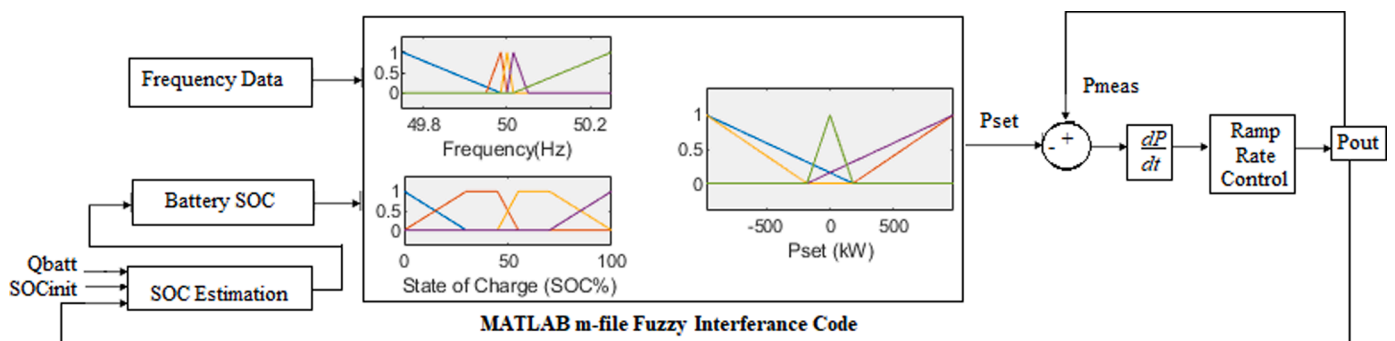


Fig. 10. Fuzzy controller block diagram.

Table 5
Fuzzy inference rules for EFR ancillary service.

Frequency(Hz)	SOC(%)			
	Low(L)	Optimum Low (L _{opt})	Optimum High (H _{opt})	High (H)
Low (L)	P _{min_up}	P _{min_up}	P _{min_up}	P _{max_up}
Normal Low (NL)	P _{db}	P _{db}	P _{db}	P _{db}
Normal (N)	P _{db}	P _{db}	P _{db}	P _{db}
Normal High (NH)	P _{db}	P _{db}	P _{db}	P _{db}
High (H)	P _{min_low}	P _{min_low}	P _{min_low}	P _{max_low}

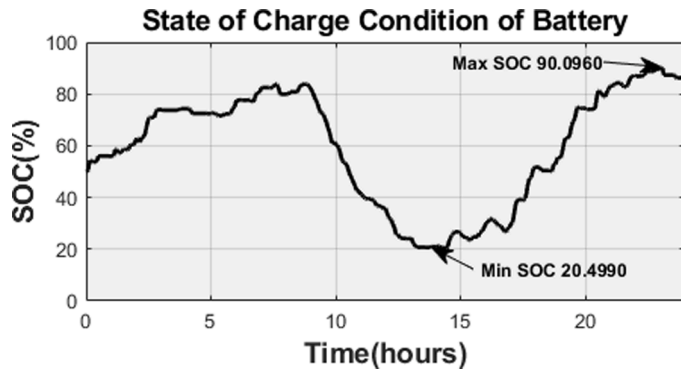


Fig. 12. SOC level changing according to charge/discharge.

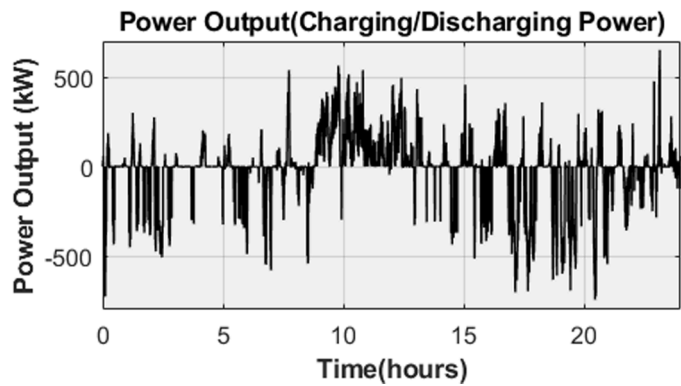


Fig. 13. Power output (kW) of the 2MW/1 MWh BESS.

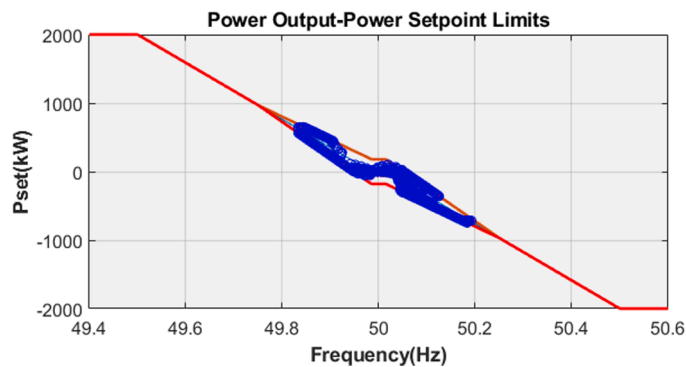


Fig. 14. Frequency dead band and power set limits in the Regulation, Method-1 with power outputs.

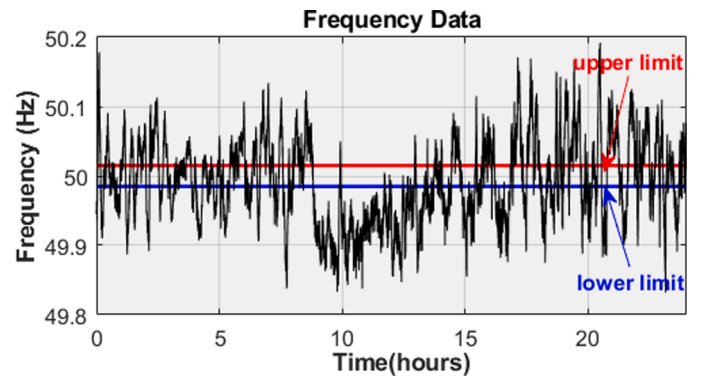


Fig. 15. Frequency data distribution (2nd of February 2022).

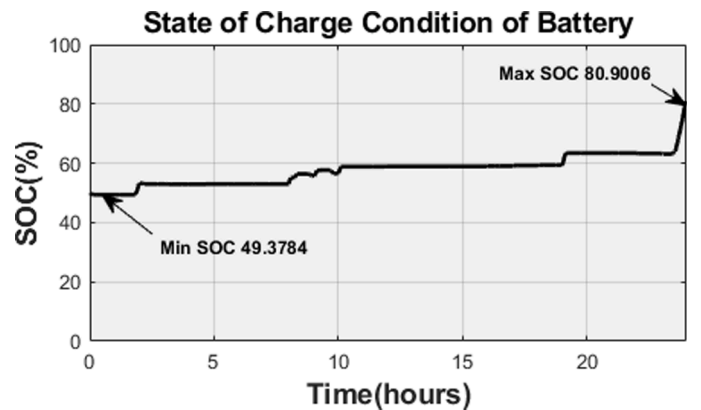


Fig. 16. SOC level changing according to charge/discharge.

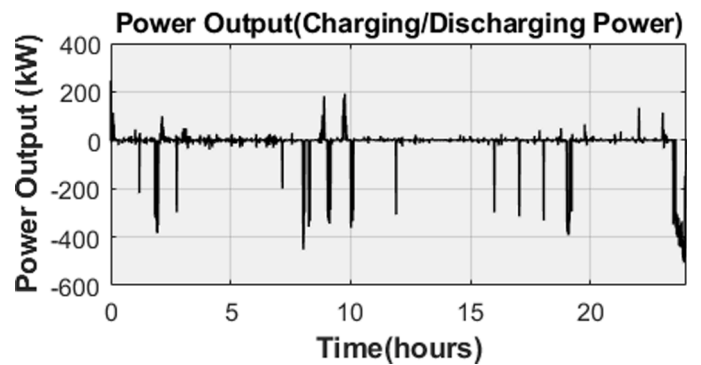


Fig. 17. Power output (kW) of the 2MW/1 MWh BESS.

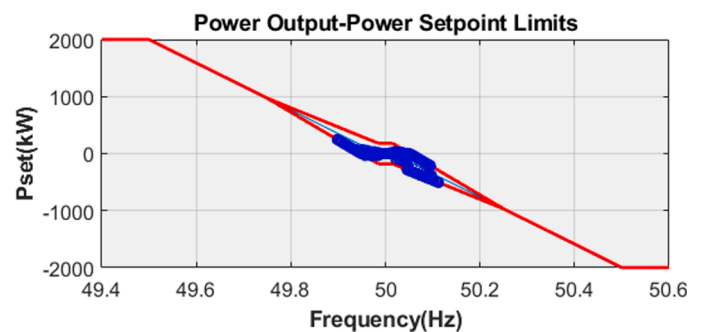


Fig. 18. Frequency dead band and power set limits in the UK NG EFR Regulation with power outputs.

fuzzy controller successfully provides frequency support between the Method-2 Pset-frequency envelope areas as can be seen in Fig. 18.

5. Comparison results with rule-based algorithm

For proving the fuzzy logic-base algorithm’s efficiency, the rule-based algorithm applied the same frequency data and initial SOC level for Turkey and UK. This comparison is achieved by the cycle life counted and cycle range difference in the SOC profile of the battery. Ref. [1] is applied as the reference study for the rule based algorithm. Rain flow counting is a technique for calculating the number of fatigue cycles in a load-time history. This method is chosen and used for the comparison of fuzzy logic and rule-based algorithms in this section.

In the Figs. 19 and 20, SOC profiles and battery performances show that the number of cycles are higher in the rule based controlled algorithm results than the fuzzy logic controlled EFR algorithm.

In Fig. 21, after the fuzzy logic controller applied the frequency control it can be seen that the UK SOC profile with cycle average change between 20% and 90%, and at the same time number of cycles in that SOC range is shown. Approximately 100 cycles counted for 25% and 70%, 80 cycle counted for 50% SOC level. In the literature around 50% SOC level is recommended for improving the state of health and cycle life of the battery. It is achieved that the average cycle counted between 45% and 55%, in addition in emergency cases every possible level of SOC is used. The most important point here is the decreasing cycle range as possible which is also shown that the cycle range is around less than 4 for the majority of cycles.

In Fig. 22, the rain flow-counting algorithm was applied to the SOC level-time graph and the resultant matrix histogram was shown. Every axis gives information about the counted cycle in the SOC graph. Turkish real frequency data histogram is more close to the normal distribution, so the rain flow matrix histogram is more ideal than the UK’s. Cycle averages are between 50% mostly, it is another ideal situation. Additionally, the number of cycles and cycle range scale are less than UK rain flow matrix histogram values.

In battery deterioration study, cycle range is a critical metric. As a result, the "from-to" representation is studied and characterized. In the

"from-to" representation, the x-axis and y-axis of Fig. 23 display the SOC level that the cycle starts and the SOC level that the cycle finishes at in a time step. For the battery’s lifetime, it is always preferable to keep this range limited. A linear line should be used for zero range value so for the enhanced lifetime of a battery SOC profile should be close to this line. As one can observe fuzzy logic controller for frequency response with BESS SOC level cycle range is closer than the rule-based ERF controller.

6. Conclusion

Grid-connected BESSs draw attention to the advantage of fast response time in ancillary services for adjusting the frequency value, which becomes difficult to balance with the increased use of distributed energies. Quickly balancing the frequency value helps to increase grid security, flexibility and reliability. In this study, it is ensured that the ancillary service-based frequency response for BESSs is realized faster within the limits of the electricity grid regulations by manipulating the SOC value of the battery with a fuzzy logic control algorithm. The aim here is to use the SOC ranges at the optimum and optimum minimum and optimum maximum values of the battery, by making use of all points between the maximum and minimum values from the amount of power that the battery can provide to itself or the grid at a frequency value, and thus extend the battery life by reducing the number of the cycle since the amount of power required to be provided at a frequency value is proportional to the SOC value of the battery, the SOC value has been controlled using fuzzy logic. The reason that fuzzy logic is preferred is that it is easy to implement and also allows the use of values between limit values by fuzzifying the data. Another reason is to increase the effect on battery life by including all areas between the maximum, minimum and reference lines in the frequency-active power envelope, unlike rule-based algorithms. In this study, the active power to be supplied to the grid and the SOC value of the battery provided the most appropriate way to use values between the maximum and minimum limits.

After the literature review, the frequency data received from the real grid was examined and input data was selected to include the worst-case scenario. Since there isn’t any algorithm that takes into account the

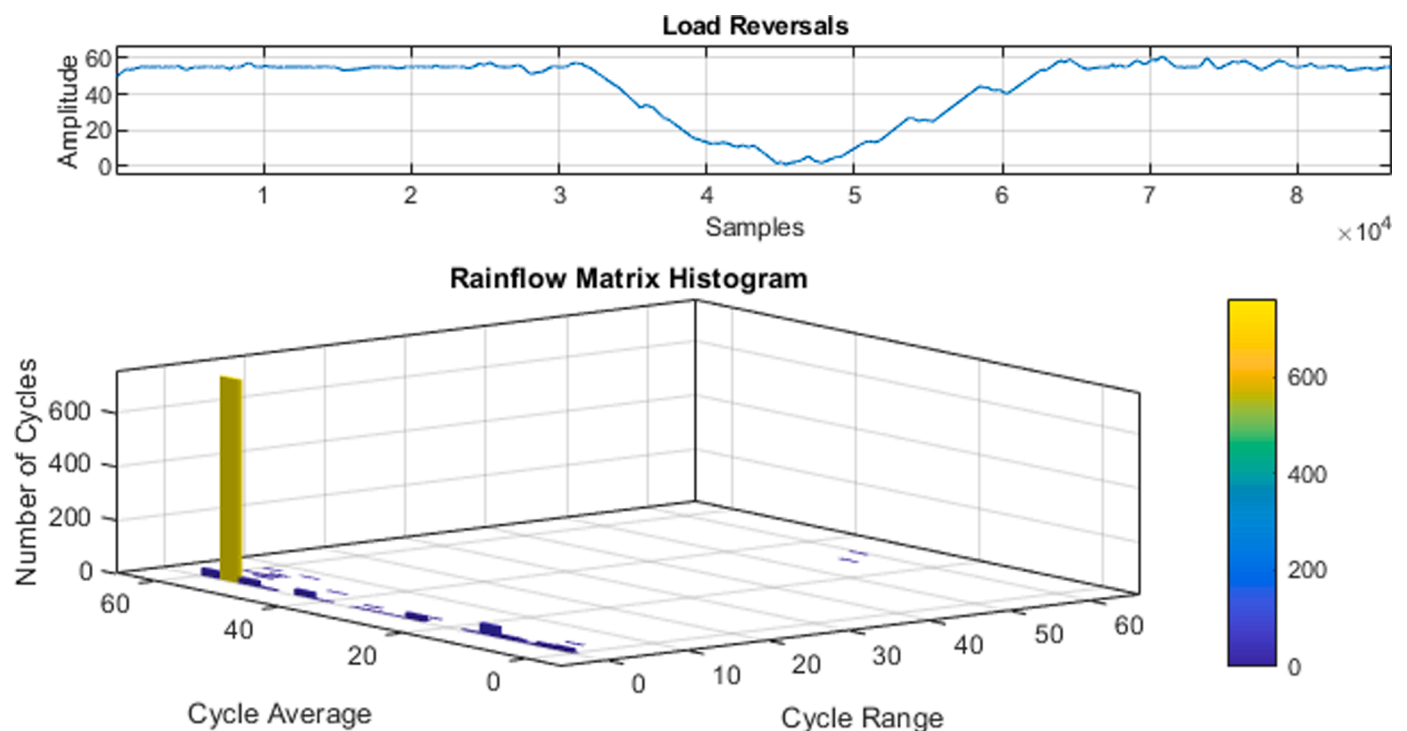


Fig. 19. Rain flow-counting algorithm results for EFR-Rule-Based control applied UK frequency data.

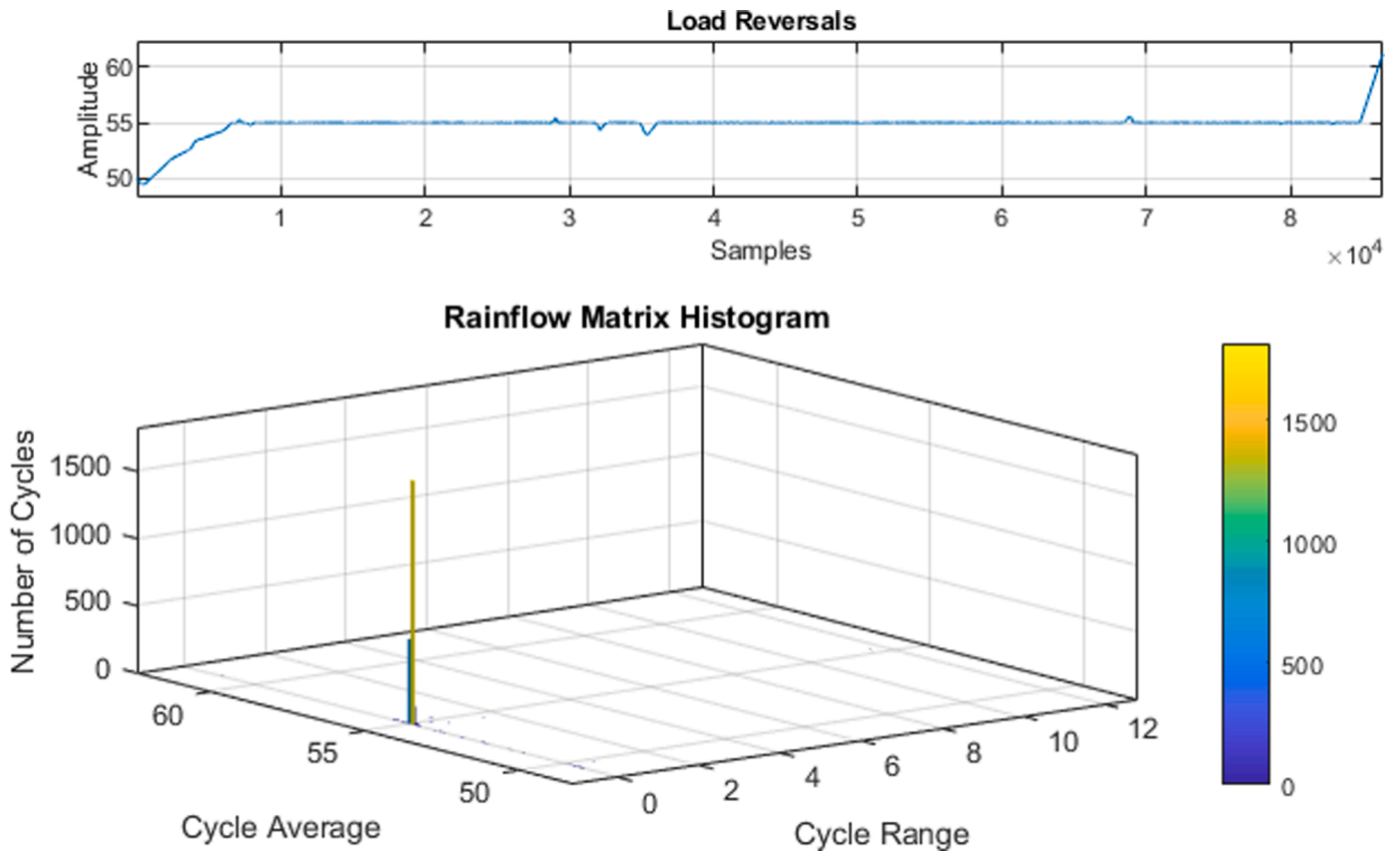


Fig. 20. Rain flow-counting algorithm results for EFR-Rule-Based control applied Turkish frequency data.

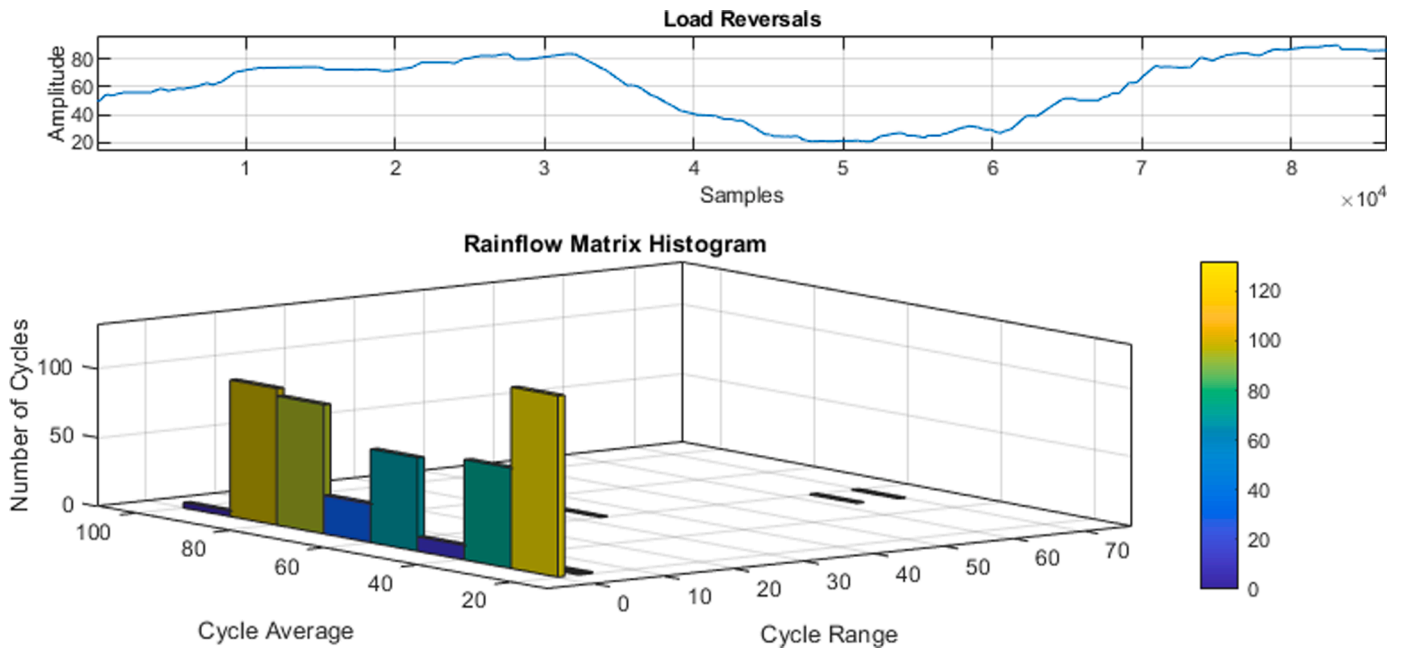


Fig. 21. Rainflow-counting algorithm results for EFR-Fuzzy control applied UK frequency data.

battery life of power management control algorithms in the participation of BESSs connected at the transmission system level, which is made with fuzzy logic in the literature, to the frequency ancillary services, the study will also benefit market participants. Two different scenarios have been tested using the same parameters for the controller, for UK, where the enhanced frequency response has been actively used for a while, and

for Turkey, where the regulation of the application has just been published and is expected to be implemented shortly. The battery SOC value ranges between 0% and 60% when the EFR ancillary service is provided for the UK frequency data, according to an analysis of the rule-based algorithm's results for the two countries individually. Approximately 800 cycles were counted for the SOC value, mostly following 50%. It has

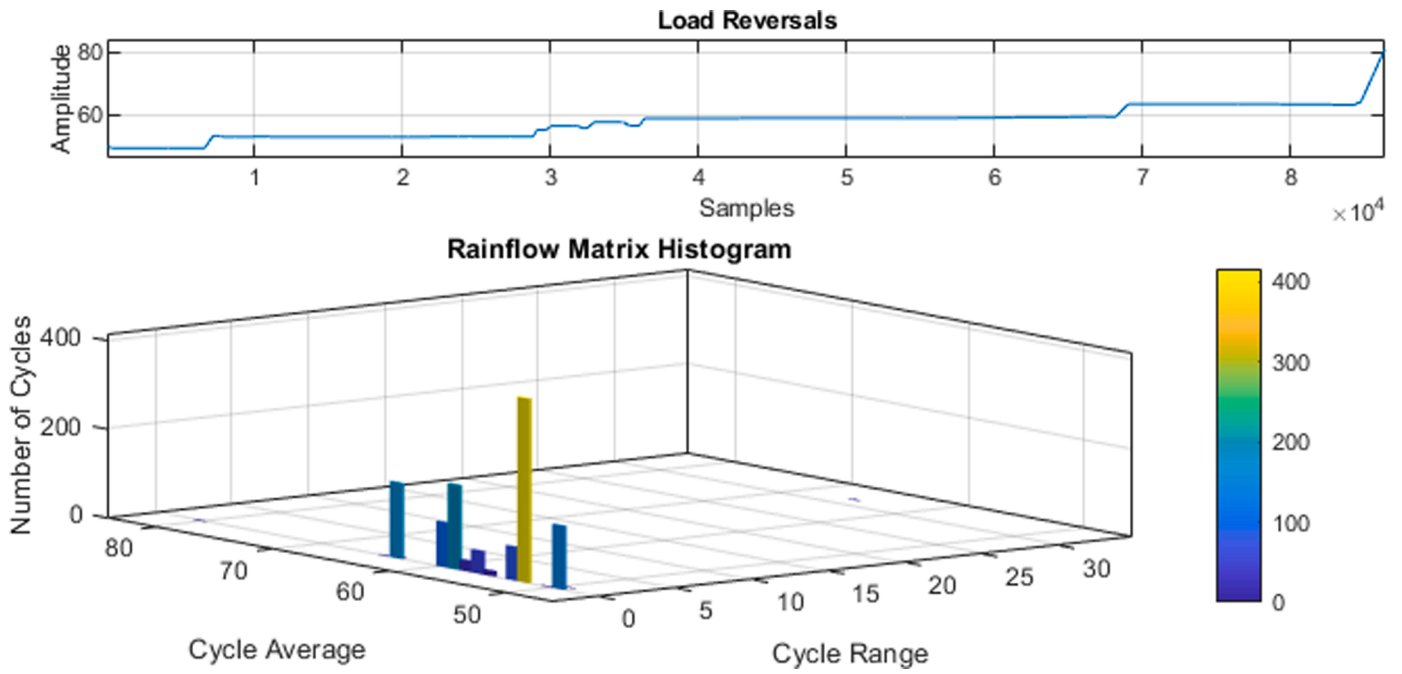


Fig. 22. Rainflow-counting algorithm results for EFR-Fuzzy control applied Turkish frequency data.

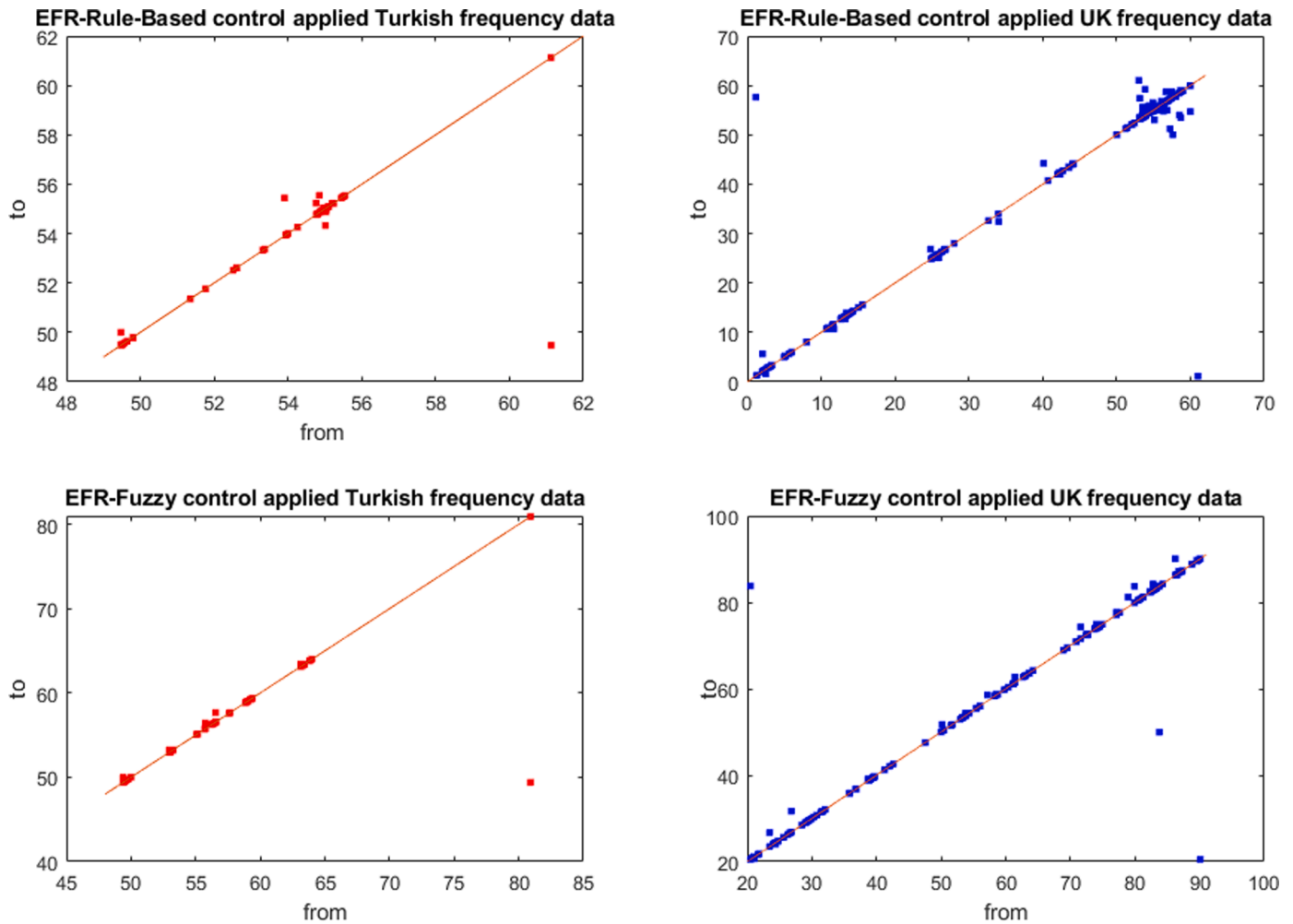


Fig. 23. Rain flow-counting algorithm performance for comparison rule-based and fuzzy logic control algorithm.

been observed that the rule-based algorithm applied using Turkey frequency data is in the range of 50%–65% and mostly at 55% SOC value, approximately 1700 cycles have been counted. As a result of providing the EFR ancillary service developed in this study for UK frequency data with fuzzy logic control, the battery SOC value changed between 20%–50%. 100 cycles at 20% SOC, 40 cycles at 40%, 80 cycles at 60% and 90 cycles at 80% SOC were counted. In the scenario designed using the frequency data of Turkey, using fuzzy logic controlled algorithm, the battery SOC value varies between 50%–80%, 400 cycles at 50% SOC and approximately 100 cycles at 60% SOC are counted. The results show that the designed fuzzy logic controller provides appropriate frequency support by protecting itself with the SOC value of the battery. Furthermore, by analyzing the lifetime of the BESS, it is shown that the fuzzy logic controller has a better impact on the battery’s lifetime when providing the frequency response service.

In future studies, with smarter versions of this controller, long and short-term active power consumption and frequency change estimation can be realized by using methods such as machine learning and artificial intelligence, and the battery system can be charged and discharged most efficiently. In addition, lifetime analysis can be made and economic profit status can be examined by using this controller for the battery energy storage system. As another study, a controller model that does not include ramp rate control can be designed and the effect of including ramp rate control on the performance of the algorithm can be studied.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.epr.2022.109040](https://doi.org/10.1016/j.epr.2022.109040).

Appendix A. Mathematical expressions for fuzzy logic controller

The membership function representing fuzzy subset **frequency** in Fig. 6 is defined as;

$$\mu_{Low(L)} = \begin{cases} \frac{|49.985| - |f|}{|49.985| - |49.75|}, & \text{for } 49.75 \leq f \leq 49.985 \\ 0, & \text{otherwise} \end{cases}$$

$$\mu_{Normal-Low(NL)} = \begin{cases} \frac{|f| - |49.985|}{|49.95| - |49.985|}, & \text{for } 49.985 \leq f \leq 49.95 \\ \frac{|50| - |f|}{|50| - |49.95|}, & \text{for } 49.95 \leq f \leq 50 \\ 0, & \text{otherwise} \end{cases}$$

$$\mu_{Normal(N)} = \begin{cases} \frac{|f| - |49.985|}{|50| - |49.985|}, & \text{for } 49.985 \leq f \leq 50 \\ \frac{|50.015| - |f|}{|50.015| - |50|}, & \text{for } 50 \leq f \leq 50.015 \\ 0, & \text{otherwise} \end{cases}$$

$$\mu_{Normal-High(NH)} = \begin{cases} \frac{|f| - |50|}{|50.015| - |50|}, & \text{for } 50 \leq f \leq 50.015 \\ \frac{|50.05| - |f|}{|50.05| - |50.015|}, & \text{for } 50.015 \leq f \leq 50.05 \\ 0, & \text{otherwise} \end{cases}$$

$$\mu_{High(H)} = \begin{cases} \frac{|f| - |50.015|}{|50.25| - |50.015|}, & \text{for } 50.015 \leq f \leq 50.25 \\ 0, & \text{otherwise} \end{cases}$$

Other membership functions are created in a similar way, the exact limit values and mathematical representations can be seen below. The membership function representing fuzzy subset **SOC** in Fig. 7 is defined as;

CRedit authorship contribution statement

Kubra Nur Akpınar: Methodology, Software, Investigation, Writing – original draft. **Burcu Gundogdu:** Methodology, Validation, Supervision, Writing – review & editing. **Okan Ozgonenel:** Supervision, Writing – review & editing. **Genk Gezeğin:** Supervision, Writing – review & editing.

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.

Data availability

The authors do not have permission to share data.

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$$\mu_{Low(L)} = \begin{cases} \frac{|30| - |SOC|}{|30| - |0|}, & \text{for } 0 \leq SOC \leq 30 \\ 0, & \text{otherwise} \end{cases}$$

$$\mu_{Normal-Low(NL)} = \begin{cases} \frac{|SOC| - |0|}{|30| - |0|}, & \text{for } 0 \leq SOC \leq 30 \\ 1, & \text{for } 30 \leq SOC \leq 45 \\ \frac{|55| - |SOC|}{|55| - |45|}, & \text{for } 45 \leq SOC \leq 55 \\ 0, & \text{otherwise} \end{cases}$$

$$\mu_{Normal-High(NH)} = \begin{cases} \frac{|SOC| - |45|}{|55| - |45|}, & \text{for } 45 \leq SOC \leq 55 \\ 1, & \text{for } 55 \leq SOC \leq 70 \\ \frac{|100| - |SOC|}{|100| - |70|}, & \text{for } 70 \leq SOC \leq 100 \\ 0, & \text{otherwise} \end{cases}$$

$$\mu_{High(H)} = \begin{cases} \frac{|SOC| - |70|}{|100| - |70|}, & \text{for } 70 \leq SOC \leq 100 \\ 0, & \text{otherwise} \end{cases}$$

The membership function representing fuzzy subset **Active Power Output (P_{out})** in Fig. 8 is defined as;

$$\mu_{min_low} = \begin{cases} \frac{|x| - |P|}{|x| - |y|}, & \text{for } y \leq P \leq x \\ 0, & \text{otherwise} \end{cases}$$

$$\mu_{max_low} = \begin{cases} \frac{|v| - |P|}{|v| - |y|}, & \text{for } y \leq P \leq v \\ 0, & \text{otherwise} \end{cases}$$

$$\mu_{db} = \begin{cases} \frac{|P| - |x|}{|w| - |x|}, & \text{for } x \leq P \leq w \\ \frac{|v| - |P|}{|v| - |w|}, & \text{for } w \leq P \leq v \\ 0, & \text{otherwise} \end{cases}$$

$$\mu_{max_up} = \begin{cases} \frac{|P| - |v|}{|u| - |v|}, & \text{for } v \leq P \leq u \\ 0, & \text{otherwise} \end{cases}$$

$$\mu_{min_up} = \begin{cases} \frac{|P| - |x|}{|u| - |x|}, & \text{for } x \leq P \leq u \\ 0, & \text{otherwise} \end{cases}$$

u,v,w,x and y represent the active power-frequency envelope limits which depends on the installed power of the BESS and ancillary service regulation of the each country.

Second step for fuzzy controller block is fuzzification and the third one is defuzzification.

Fuzzification step: $\mu_{fhigh}(x) \cup \mu_{SOCmin}(x)$ is an example of the high grid frequency and minimum SOC value of BESS.

Defuzzification step: $\mu_{Pdb}(x) = \min(\mu_{fhigh}(x) \cup \mu_{SOCmin}(x))$ (minimum value of union set is equal to power output membership function value according to the design algorithm)

$$\text{Output Value} = \max \begin{bmatrix} \mu_{Pdb}(x) & \cdots & \mu_{Pdb}(x) \\ \vdots & \ddots & \vdots \\ \mu_{Pmax_low}(x) & \cdots & \mu_{Pmin_low}(x) \end{bmatrix} \text{ (After the apply all the rules and max value is taken as the output active power value from the rules matrix.)}$$

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