Optimum Battery State of Charge Control for Frequency Response Service

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***Abstract*—In this paper frequency response, one of the most critical ancillary services, provided by grid-scale battery energy storage systems is studied with manipulating the optimum battery state of charge control area. An algorithm has been developed that primarily provides frequency response service and at the same time optimizes the battery state of charge. The difference between the algorithm developed in this study and the other algorithms is that, apart from the maximum and minimum points of the state of charge level, it has also the optimum highest and optimum lowest state of charge points. Thus, it is aimed that the battery will support the grid at the most extreme points in urgent cases and decides the power output it will provide according to the battery state of charge in the case of non-urgent cases. The algorithm used the one-second resolution 1-day frequency data which has the highest standard deviation in a month obtained from Turkey National Transmission System Operator's database as input data. Assuming a facility in Turkey which has a battery energy storage system that participates in the grid frequency response ancillary service, the output power and the battery state of charge graph are examined.**

Keywords—ancillary services, battery energy storage system, battery lifetime, state of charge, frequency control algorithm, frequency response.

I. INTRODUCTION

All power generators that are connected to the electricity transmission system are operated with a constant frequency value which is 50 Hz in Turkey. Consequently, grid system operators have managed the system frequency between set points defined in grid code for all electrical devices which are sensitive to a little variation of frequency. In energy transmission lines in AC grids, the energy supply and demand which has an impact on the frequency level must always be equal to each other. If supply is lower than demand, the frequency level will drop and vice versa [1].

The use of a battery energy storage system (BESS) has many benefits to the electricity distribution grid. These benefits include improving power quality, load leveling and peak shaving, frequency, and voltage regulation, improvement in backup generation capacity, rapid system recovery, and reduction of greenhouse gas emissions [2]. Power quality and system stability are two main considerations in the transmission and distribution lines of electrical energy. It has long been known that energy storage is a possible way to improve these parameters [3]. The development and high costs of battery technologies and auxiliary power electronics circuits were not enough to meet such expectations. High penetration of renewable energy sources and widespread use of electric vehicles brings some power system stability problems to the electricity grid. To improve the effect of fluctuating energy forms of renewable energy production, the quality and efficiency of energy production can be achieved by using battery energy storage systems [4,5]. It has been observed in the studies that the use of BESS significantly increases the frequency stability in transmission systems.

Ancillary services are essential for grid support. Frequency response ancillary service is one of the most important grid operation for keeping the frequency in the grid code frequency set limits which are defined by Grid Regulation Services. Traditionally, grid system operators set commands to ancillary service market participants for providing ancillary services by conventional generators. Generators are used for load shedding and load reduction when the frequency is low or high.

Nowadays battery energy storage systems (BESS) are one of the most popular alternative resources to take a part of provide grid ancillary service. Batteries are expensive when compared to a solution for grid support but thanks to developing technology prices are decreasing. The main advantages of BESS are its fast response and higher ramp rate in addition to modularity in size. When we look at the BESS projects all around the world, Li-ion batteries are attracted more attention with their faster response and higher energy density [5].

Frequency regulation and voltage support are vital ancillary services for power grids. There have been several studies into the use of BESS to provide frequency response ancillary service. Authors modeled control algorithms for fast, efficient, and reliable frequency support.

Homan et al. by using the Future Energy Scenarios of the UK National Grid found that new ancillary services can be successfully implemented in inertia reduction by adding 50 MW of capacity to dynamic regulation [6].

According to Baig et al., frequency distortions will arise of low inertia levels, which might occur as a result of assumptions that the usage of renewable energy in the UK would increase. For this purpose, it is linked the inertia and frequency response by using the inertial Stochastic Unit Commitment (SUC) model [7].

Moreno has tested the algorithm which uses the battery's health status as input and regulates the frequency by controlling the voltage with the appropriate PWM values at the output in case a battery is used to provide the frequency regulation ancillary service for the Norwegian electricity grid by using the Power Factory dynamic simulation program in the Norwegian 32 busbar transmission system. [8]

Yuan et al. designed and experimentally validated a real-time control algorithm that provides frequency control and voltage support to the power grid with BESS has been applied to 720 kVA / 560 kWh BESS at the Ecole Polytechnique Federale de Lausanne campus and has been observed to work successfully. This control algorithm operates with constraints based on the voltage-dependent capacitance curve of the DC-AC converter and the initial power set point adjusted by the droop control [9].

Mahesh et al. developed an algorithm called Dynamic Frequency Regulation (DFR), which uses historical and predicted data, aiming to extend the life of the battery as well as provide ancillary services. The algorithm is simulated with MATLAB and the results obtained are compared with the real-time traditional frequency regulation output of the Li-ion battery integrated into the 22kV power line. It has been observed that the life of the battery is increased by 80% [10].

In this study, a control algorithm has been developed using four different SOC levels for the frequency support by BESS effectively. The aim of the algorithm is not only to provide requested frequency support to the electricity grid but also to protect the battery in case exceeding the limits with the decrease in the cycle of the battery to extend the lifetime. For this purpose frequency and SOC minimum and maximum limits are not restricted according to the battery grid code droop control, optimum values are added for improvement to the control and get a chance to charge or discharge to make a profit in the long period of time prospect.

II. FREQUENCY RESPONSE SERVICES

Grid frequency balancing services are generally categorized into primary frequency response, secondary frequency response, and tertiary frequency response all around the world [11]. Some countries have an improved frequency control which name is ‘fast frequency control’. UK has gone one step more and has one of the most advanced grid frequency control models which is called ‘Enhanced Frequency Response (EFR)’. According to EFR, two different services have different dead band (DB) areas for frequency levels. EFR Service-1 (also called wide service) frequency DB limit is 49.95-50.05 Hz and EFR Service-2 (narrow service) frequency DB limit is 49.985-50.015 Hz.

In Turkey, the Turkish Electricity Transmission Corporation –TEIAS (national transmission system operator) published “Technical Criteria for Connecting Electricity Storage Facilities to the Grid and using them in Ancillary Services” in late 2021 This regulation stated that the energy storage devices can participate in the ancillary services that include primary and secondary frequency response service, reactive power support, and black start (in case they are appointed by TEIAS). According to that regulation,

- The BESS which is connected to the grid from the transmission level must have technical equipment that can be activated within a maximum of 1 second of the Primary Frequency Control (PFC) Reserve Capacity.
- Furthermore, electricity storage facilities must have at least 10 MW installed capacity to participate in PFC ancillary service. While BESSs are providing service within the scope of primary frequency control service, a 10 mHz dead band will be applied.
- Within the scope of the participation of energy storage systems in primary frequency control, in case the stored energy level changes due to the primary frequency control reserve it provides, the energy level of the said electricity storage facility should be brought back to 50%. There are 4 methods specified below to balance the energy storage level [13].

The first method is similar to the UK National Grid Enhanced Frequency Response service envelope, the other 3 methods are not reviewed here. Method-1 is used to provide frequency response ancillary service in this paper. EFR is one of the fast frequency response ancillary service that can provide 100% active power supply within 1 second after the electricity grid system operator’s command. The difference between the other frequency response services and narrow response levels can be seen in Fig. 1. National Grid (NG) announced EFR specifications with tender competition to ESS facilities in 2016 [14].

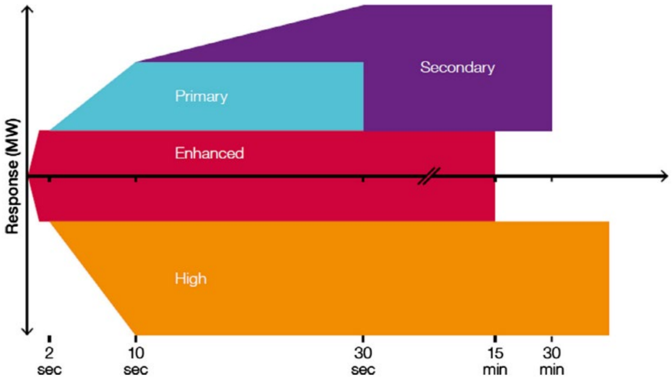

Figure 1. UK National Grid Frequency Response Services [14]

Unlike participating BESS for grid frequency support technical regulations in Turkey, NG has 2 different services as aforementioned before (EFR Service-1 as Wide and EFR Service-2 as Narrow). In accordance with Turkish regulation, in a certain dead band range (±10 mHz), the electricity storage facility will be able to export energy to the grid or import energy from the grid, not exceeding 10% of its installed power.

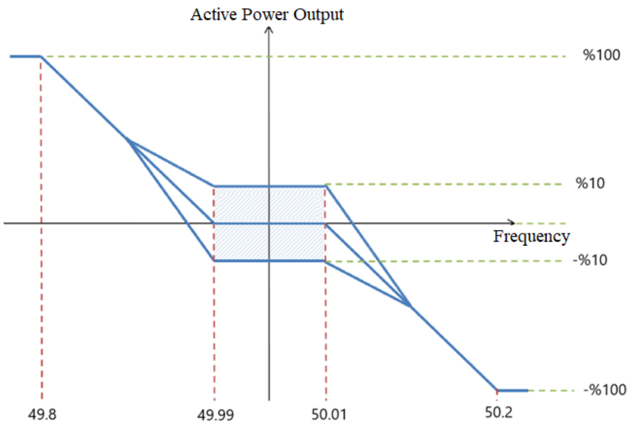

Figure 2. Frequency Response Ancillary Service Envelope from Turkish ESS Technical Regulation Method-1 [13].

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

Table I. Frequency Envelope - Frequency and Power Boundaries [13].

Frequency	**Power Boundaries (*%Pn*)**
49.8	100
49.99	10
50.1	-10
50.2	-100

If the frequency is lower than 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 dead band level BESS has to import energy to the grid. Apart from that, if batteries are chosen as energy storage for frequency support, state of charge (SOC) is another important issue. While the battery provides frequency support to the grid, it should keep its charge level at the most appropriate points and protect itself from possible damages. As an example of this damage explosion of the battery as a result of a very high SOC level could be given so battery management should be the most important consideration.

III. HISTORICAL FREQUENCY DATA ANALYSIS

The system operator TEIAS places one-second resolution daily frequency data on its website [14]. Based on these data frequency support facilities assess the technical viability of their energy systems outputs. In this section comprehensive analysis of one month (February) data has been performed. The aim here is to find the amount of deviation of the frequency from the levels specified in Method-1 and 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 is considered a good opportunity to examine considering the weather conditions. Daily and cumulative monthly data standard deviation and histogram are shown in Figure 3 and Figure 4. Because of 2nd of February standard deviation is the most higher, it was chosen as input data for the control algorithm.

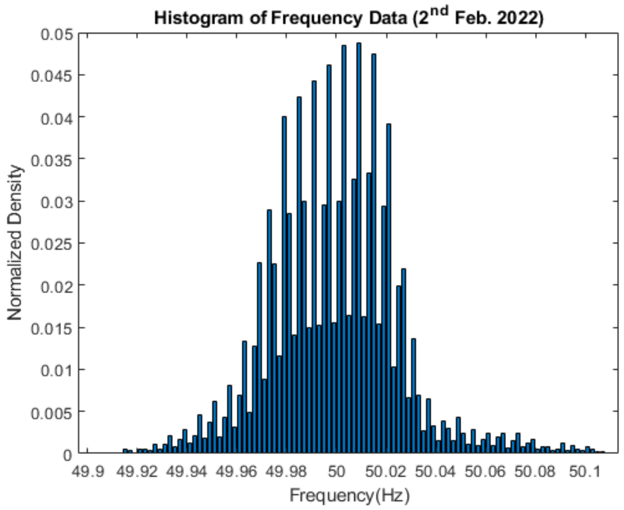

Figure 3. Histogram of the frequency data for February 2022

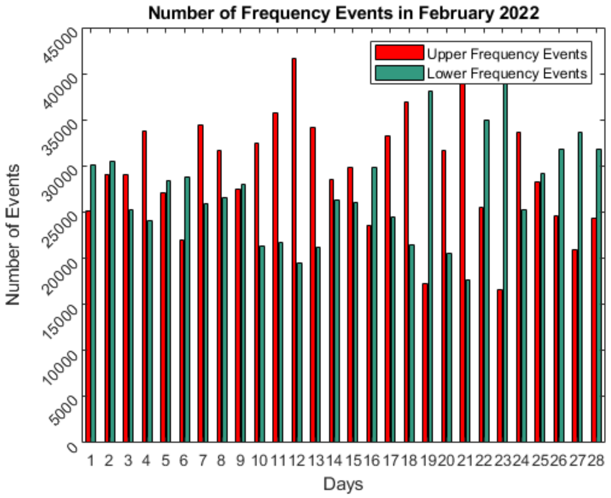

Figure 4. Pprobability distributions of frequency events per day for Method-1.

IV. CONTROL STRATEGY

A. Frequency Droop

Droop mean is the slope of a curve. Frequency droop control is made with general droop formula that uses between two points of a curve.

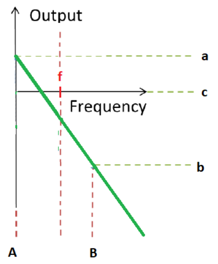

Figure 5. Droop Formula Example

According to Fig. 5, the equation of the line known with two points can be written to find the output of the f point.

$$Output = \left(\frac{f-A}{B-A}\right)(b-a)+b \qquad (1)$$

In this study, all power outputs are calculated using Formula (1). Another way of getting this equation is the triangle similarity method.

B. *SOC Calculation*

Different kinds of methods have been used for SOC estimation in the literature based on such as coulomb counting, open-circuit voltage, Kalman Filter, and machine learning. In this study, SOC will be estimated using the formula below.

$$SOC_{out}(t) = SOC_{init}(t_0) + \frac{\int_0^t P_{batt}dt}{3600\ x\ Q} \qquad (2)$$

In this formula, $SOC_{init}(t_0)$, $P_{batt,}$ and Q represent the battery's initial SOC value, instantaneous battery power, and Watt-hour capacity of the battery [15].

C. *SOC Limits*

The operational limits for battery SOC can be changed according to the urgency requested by the system operator and extreme points of frequency levels determined in the regulation for frequency response services. For example, Oudalov et al. used a fixed SOC level in their primary frequency response control algorithm [16]. They protect the battery from overcharge and discharge conditions; also allow a small amount of energy to the electricity market for changing the charge level between SOC limits.

In this study, there are four SOC levels shown in Table II and Fig. 6 to improve the battery life.

Table II. Battery SOC operation limits for frequency support

SOC Minimum (%)	**SOC Optimum Minimum (%)**	**SOC Optimum Maximum (%)**	**SOC Maximum (%)**
30	45	55	70

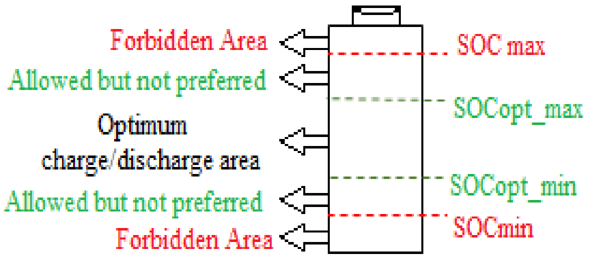

Figure 6. Purposed Battery SOC limits in the algorithm

In many studies, battery SOC level has only 2 levels as a minimum and maximum operating point. In this control algorithm, according to frequency response urgency, SOC operation levels change between 4 levels. These extra levels are called optimum minimum and optimum maximum in the code. The aim here is to decrease the cycle counting of the battery in case of narrow levels between determined maximum and minimum. Outside of the dead band if the frequency is normally high or normally low level then the optimum SOC levels are enough to provide active power support. On the other hand, frequency is very high or low according to Method-1, maximum and minimum SOC levels can be applied.

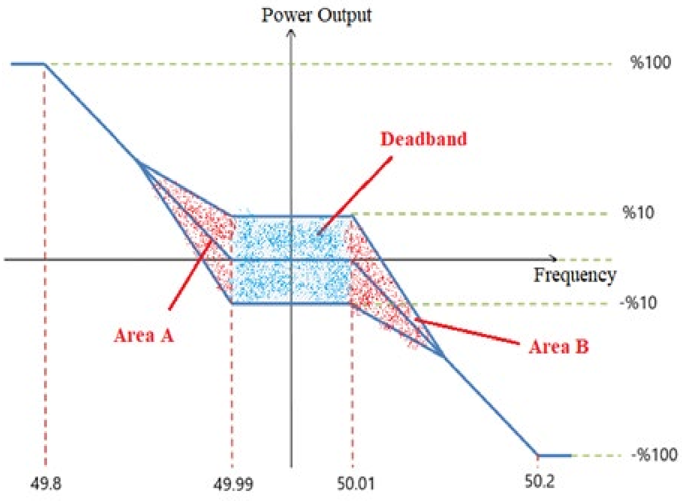

Figure7. Frequency levels areas

There are three power output states which are the dead band and area A and area B which are shown in Fig. 7.

The flowchart of the algorithm can be seen in Figure 9. The algorithm starts with measuring gird frequency and estimating battery SOC level using Equation (2). According to the grid frequency response regulation, power set limits are calculated based on the frequency area which can be in the dead band, Area A, Area B, or outside of these. If the frequency is in the dead band there are 2 more options for 50 Hz. Because the power set limits are the same in the dead band (Pmax and Pmin are symmetrical) for charging or discharging differentiation can be achieved according to the right or left the place of 50 Hz. For Area A and Area B, there are 3 states; minimum, maximum, and linear line power output calculation. In the stage of decision for power output, SOC limits and SOC changes according to the time step help the algorithm. On the outside of all these areas, there is only one option for power output which can be calculated with Equation (1). In this step of the algorithm, if the *SOC (t)* is higher or lower than the maximum and minimum SOC levels, the battery must not charge or discharge to protect itself.

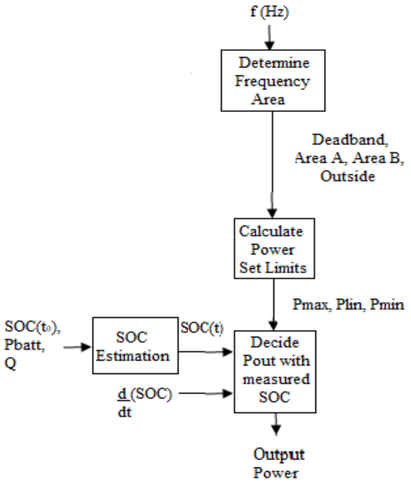

Figure 8. Control Algorithm Block Structure

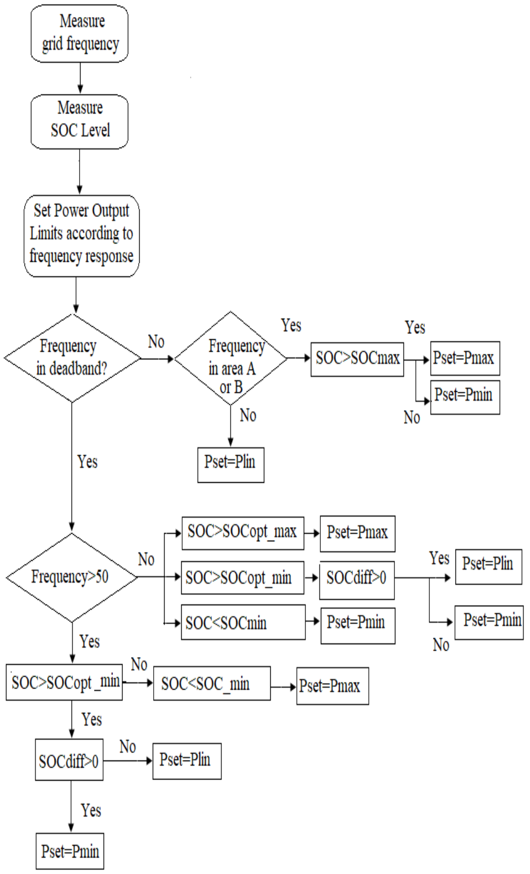

Figure 9. The control algorithm used for the frequency support with manipulating SOC level

V. SIMULATION RESULTS

The time variation of the frequency value received from the TEIAS website 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 Figure 10. In the scenario where a battery energy storage system with 2 MW installed power supports the grid frequency with ancillary services, the amount of power (kW) that needs to be charged or discharged at the time of frequency fluctuation is calculated by the algorithm and in Figure 11 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 charge/discharge itself the algorithm also control the battery SOC level for protect the battery and optimize the cycle of the battery with optimum SOC levels. In Figure 12, SOC against time is showing that the BESS operates between 50% and 70% and remains close to 70% which is the maximum SOC level of BESS throughout its operation; this level could be changed.

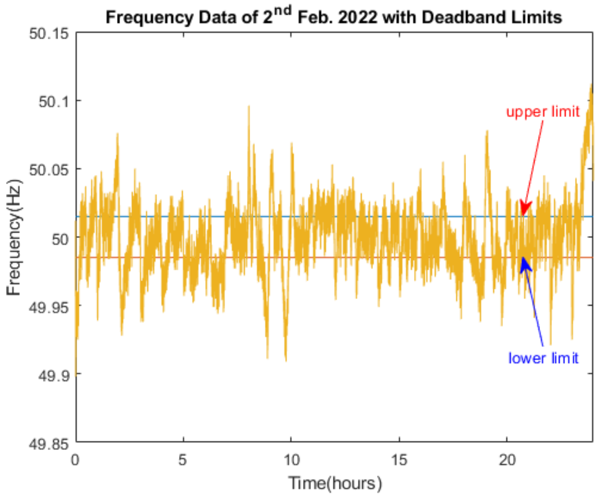

Figure 10. Frequency Data distribution (2^{nd} of February 2022)

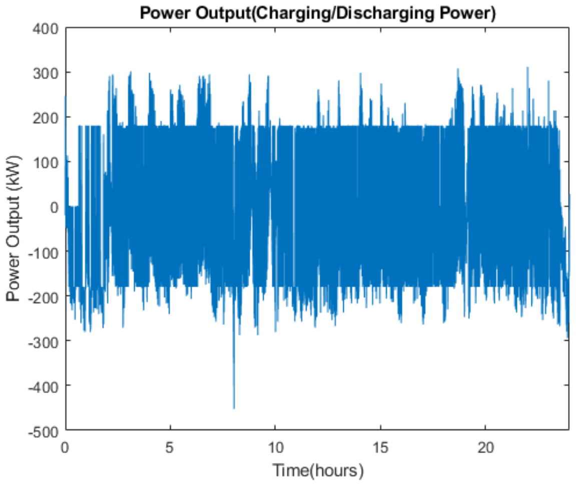

Figure 11. Power output (kW) of the BESS

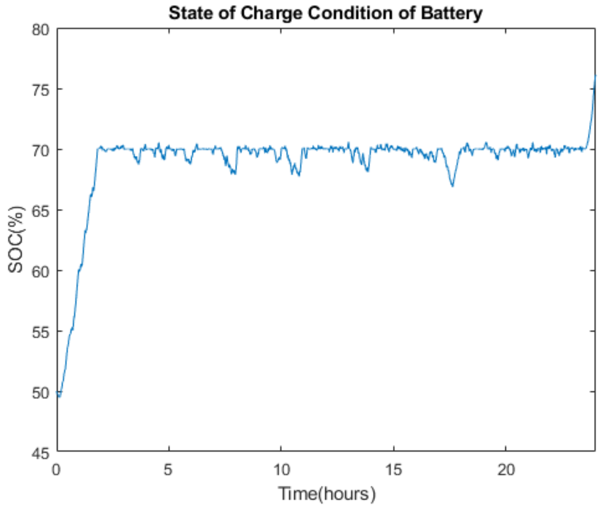

Figure 12. Battery SOC level changing according to charge/discharge

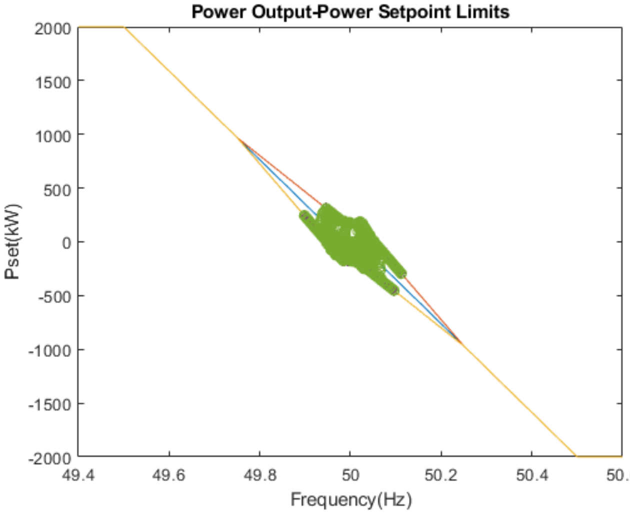

Figure 13. Frequency dead band and power set limits in the Regulation, Method-1 with power outputs.

VI. CONCLUSION

In this study, an algorithm is designed to provide optimum use of SOC value in case of fast frequency response from ancillary services by battery. Moreover, this designed algorithm meets the criteria determined according to the grid code.

According to the scenario in which a battery to be connected to the Turkish Electricity Grid is considered, the results obtained are analyzed with graphical representations. Statistical analysis of real frequency data was obtained and used as input data in the algorithm. In addition, a control was created by using variable values for the maximum and minimum SOC values of the battery. As a result, it has been shown that fast frequency support is provided according to the grid code criteria and at the same time, the battery works optimally.

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