Model Predictive Controlled Application of Power Management Algorithm for Battery Energy Storage System Providing Frequency Ancillary Service

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Abstract

The active power that must be provided in accordance with frequency ancillary service regulations when battery energy storage systems participate in the frequency ancillary service is modelled in this study using a Model Predicted Controlled (MPC) 2-Level Voltage Source Converter (2L-VSC). The reference active power for the 2 MW battery energy storage system was determined using the rule-based power management method, and the outcome was then used as the Model Predicted Control's input data. The output power for the MPC 2L-VSC, whose simulation study was conducted in the Simulink, successfully remained within the active power-frequency envelope in the frequency ancillary service regulation, and the demanded power was delivered by using the battery state of charge (SOC) value optimally.

1. Introduction

For providing grid stability and reliability, ancillary services play a role in power transmission systems [1]. Any differences between demand and supply should be rapidly controlled with the goal of ensuring that the frequency variation is within the defined limits [2]. Blackouts and cascading outages could result from a failure to keep the frequency within acceptable limits. Due to its flexibility and rapid responses, a battery energy storage system (BESS) can balance both supply and demand by absorbing or generating power depending on the needs of the electrical grid [3].

BESS with smooth and fast dynamic response during charging and discharging are required for grid frequency response service. The control capability of the voltage source converter (VSC) impacts this performance. For VSC control systems, proportional-integral (PI) control is a common control method. For nonlinear and discontinuous systems, PI control could produce unsatisfactory results [4]. Model predictive control (MPC) is a flexible procedure over a short time-period and determines the next control action based on the optimization [5]. The discrete character of a VSC is appropriate for predictive techniques. Although a power converter has a limited number of switching states, all potential stages are considered when trying to predict the behavior in which the system might operate. The minimum condition value from the cost functions calculated in each time step is applied to the control procedure [6]. For nonlinear systems that achieve the desired goal, MPC provides robust control. MPC has been extensively used in bidirectional AC-DC converters which include batteries, are becoming increasingly popular due to the widespread use of smart grids for the integration of demand-side management and distributed generation systems [7-8].

In this study, to create the Türkiye case, a simulation of the rule-based power management algorithm designed in [9] for battery energy storage systems, which is used in frequency ancillary service, is carried out using a voltage source controller with model predictive control. The developed model is the first study that provides the active power in the active power-frequency envelope in the frequency ancillary service regulation, considering the SOC control for the BESS participating in the frequency ancillary service controlled by the MPC 2L-VSC. By using the July 2023 frequency data obtained from the TEIAS (Türkiye Electricity Transmission Corporation) website [10], the active power of a 2 MW BESS is provided in case of participating the Method-1 from frequency response ancillary services in the electricity grid and this value is provided by considering the battery SOC value. According to the Türkiye electricity grid regulation, it has been observed that the converter output power is within the active power envelope that the BESS should provide.

2. Power Management Algorithm

According to "Technical Criteria for Connecting Electricity Storage Facilities to the Grid and Using Them in Ancillary Services" published by TEIAS, frequency ancillary services from energy storage systems may provide. In Ref [9], Method-1 is used to supply the frequency response service. The graph of Method-1, one of the 4 methods defined in the ancillary service regulation, showing the active power change that must be provided according to the frequency changes occurring in the network, is shown in Fig. 1. Table 1 show the frequency and active power limits in the TEIAS regulation in detail. According to this regulation, for BESS installation, which has at least 10 MW installed power, and this meets the technical criteria specified in the regulation. Therefore, it is expected that applications will be received through the tender method and their integration into the Turkish Electricity Grid in the upcoming days. The frequency range between 50 and ±0.010 Hz is referred as the dead band in the frequency versus active power envelope illustrated in Fig. 1. When the battery energy storage system participates in frequency ancillary services in this range, active power is not obligatory. This range should be considered an advantage regarding offering battery charge level management. Battery energy management algorithms adjust the charge level control most successfully while operating within these limits. Charge management is possible within the specified envelope range along with these constraints. The algorithm created in [9] manages the battery charge level by increasing the battery charge level from 2 to 4 levels in addition to the lowest and highest limitations, particularly in the dead band range and envelope areas outside the dead band. It offers active power output between the restrictions outlined in the grid regulation by taking part in the frequency ancillary service. In this study, the reference power input is taken from Scenario-2 utilizing data from the Türkiye grid.

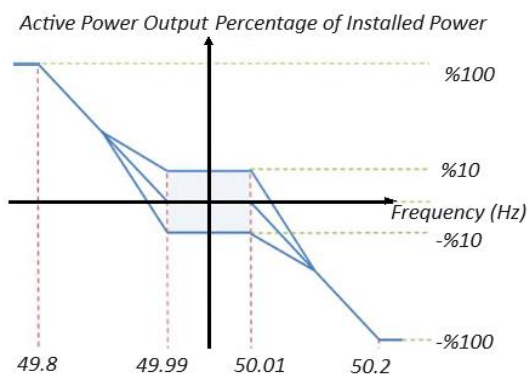

Fig. 1. Active Power Output-Frequency Envelope according to Türkiye Regulation for BESS [11]

Table 1. Frequency Envelope - Frequency and Power Boundaries [11].

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

3.Model Predicted Control Strategy for Power Converter

In this study, BESS active power is controlled with 2-level voltage source converter, which is shown in Fig. 2 [12]. V_s, L and R represent 3-phase grid side voltage, filter inductance and resistance. Sa, Sb and Sc are switch states that are determined by the MPC control algorithm, which used grid voltages and currents with active power set point. Reference power is calculated from a rule-based power management algorithm and converted to reference currents according to power relations in the alfa-beta frame in Eqs. 1 and 2. Power management algorithm determines the optimum charge/discharge power by using real grid frequency from TEIAS and battery charge values as input data.

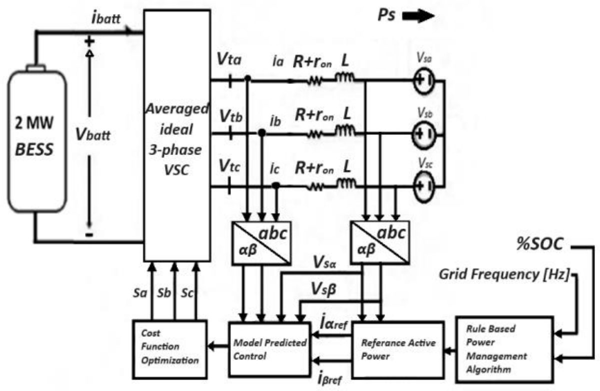

Fig. 2. Grid Connected 3 phase 2L-VSC Model

$$I_{\alpha ref} = 2/3 \times [V_{s\alpha} /(V_{s\alpha}^2+V_{s\beta}^2)] \times P_{sref} + 2/3 \times [V_{s\beta}/ (V_{s\alpha}^2+V_{s\beta}^2)] \times Q_{sref} \quad (1)$$

$$I_{\beta ref} = 2/3 \times [V_{s\beta} /(V_{s\alpha}^2+V_{s\beta}^2)] \times P_{sref} - 2/3 \times [V_{s\alpha}/ (V_{s\alpha}^2+V_{s\beta}^2)] \times Q_{sref} \quad (2)$$

The switching state S_x, with $x = 1, \ldots, 6$, can be represented by the switching signals S_a, S_b, and S_c defined as follows:

$$S_a = \begin{cases} 1 \text{ if } S_1 \text{ on and } S_4 \text{ off} \\ 0 \text{ if } S_1 \text{ off and } S_4 \text{ on} \end{cases}$$

$$S_b = \begin{cases} 1 \text{ if } S_2 \text{ on and } S_5 \text{ off} \\ 0 \text{ if } S_2 \text{ off and } S_5 \text{ on} \end{cases}$$

$$S_c = \begin{cases} 1 \text{ if } S_3 \text{ on and } S_6 \text{ off} \\ 0 \text{ if } S_3 \text{ off and } S_6 \text{ on} \end{cases}$$

$$V_{aN}=S_a V_{dc} \quad (3)$$

$$V_{bN}=S_b V_{dc} \quad (4)$$

$$V_{cN}=S_c V_{dc} \quad (5)$$

Table 2. Switching States and Voltage Vectors

S_a	S_b	S_c	V
0	0	0	$V_0=0$
1	0	0	$V_1=2/3V_{dc}$
1	1	0	$V_2=1/3V_{dc} + j\sqrt{3}/3\ V_{dc}$
0	1	0	$V_3=-1/3V_{dc} + j\sqrt{3}/3\ V_{dc}$
0	1	1	$V_4=-2/3V_{dc}$
0	0	1	$V_5=-1/3V_{dc} - j\sqrt{3}/3\ V_{dc}$
1	0	1	$V_6=1/3V_{dc} - j\sqrt{3}/3\ V_{dc}$
1	1	1	$V_7=0$

Equations presenting the dynamics of load current in each phase can be expressed as

$$V_{aN}=L\ (di_a)/dt+Ri_a+e_a+V_{nN} \quad (6)$$

$$V_{bN}=L\ (di_b)/dt+Ri_b+e_b+V_{nN} \quad (7)$$

$$V_{cN}=L\ (di_c)/dt+Ri_c+e_c+V_{nN} \quad (8)$$

The load current derivative is approximated by a forward Euler as follows:

$$di/dt \approx (i(k+1)-i(k))/T_s \quad (9)$$

The prediction of the future load current at time $k + 1$, for each one of the values of the voltage vector is calculated. Ts represent the sampling time for discrete current calculation.

$$i^p\,(k+1)=(1-(RT_s)/L)i(k)+T_s/L\,(V(k)-e(k)) \quad (10)$$

In Eq. 10 i^p is the predicted current from MPC and e represents the back emf that calculated as follows:

$$e(k-1)=V(k-1)-L/T_s\,i(k)-(R-L/T_s\,)i(k-1) \quad (11)$$

Finally, the cost function is optimized with Eq. 12 and determines one of the switching states for VSC.

$$g=|i_{\alpha ref}\,(k+1)-i_\alpha{}^p\,(k+1)|+|i_{\beta ref}\,(k+1)-i_\beta{}^p\,(k+1)| \quad (12)$$

4. Control Performance of MPC Controlled VCS Providing BESS Power

As shown in Fig. 3, simulation studies were carried out in a Matlab/Simulink environment using version 2023a to confirm the control performance of the MPC for the 2L-VSC. The 2L-VSC with output LC filter was designed using the SimPowerSystems toolbox. 2 MW BESS connected to 3 phase AC grid via 2L-VSC. Real grid frequency data used for reference power output (P_{set}) for Türkiye ancillary service regulation for energy storage systems. P_{set} value used as desired active power for MPC algorithm and 6 IGBTs switch states applied after cost function optimization.

Table 3. MPC Controlled VSC Simulation Parameters for BESS

Parameter	Symbol	Value
BESS Rated Power	P_{BESS}	2 MW
Initial State of Charge	SOC_{init}	%50
Minimum State of Charge	SOC_{min}	%30
Maximum State of Charge	SOC_{max}	%70
Optimum Minimum State of Charge	SOC_{opt_min}	%45
Optimum Maximum State of Charge	SOC_{opt_max}	%55
DC Voltage Level	V_{dc}	600 V
Series Filter Resistance	R_{f1}	0.75 mΩ
Parallel Filter Resistance	R_{f2}	0.1 Ω
Filter Capacitance	C_f	330 µF
Filter Inductance	L_f	100 µH
Grid Frequency	f	50 Hz
Grid Voltage	V_s	220 V
Sampling Time	T_s	1 µs

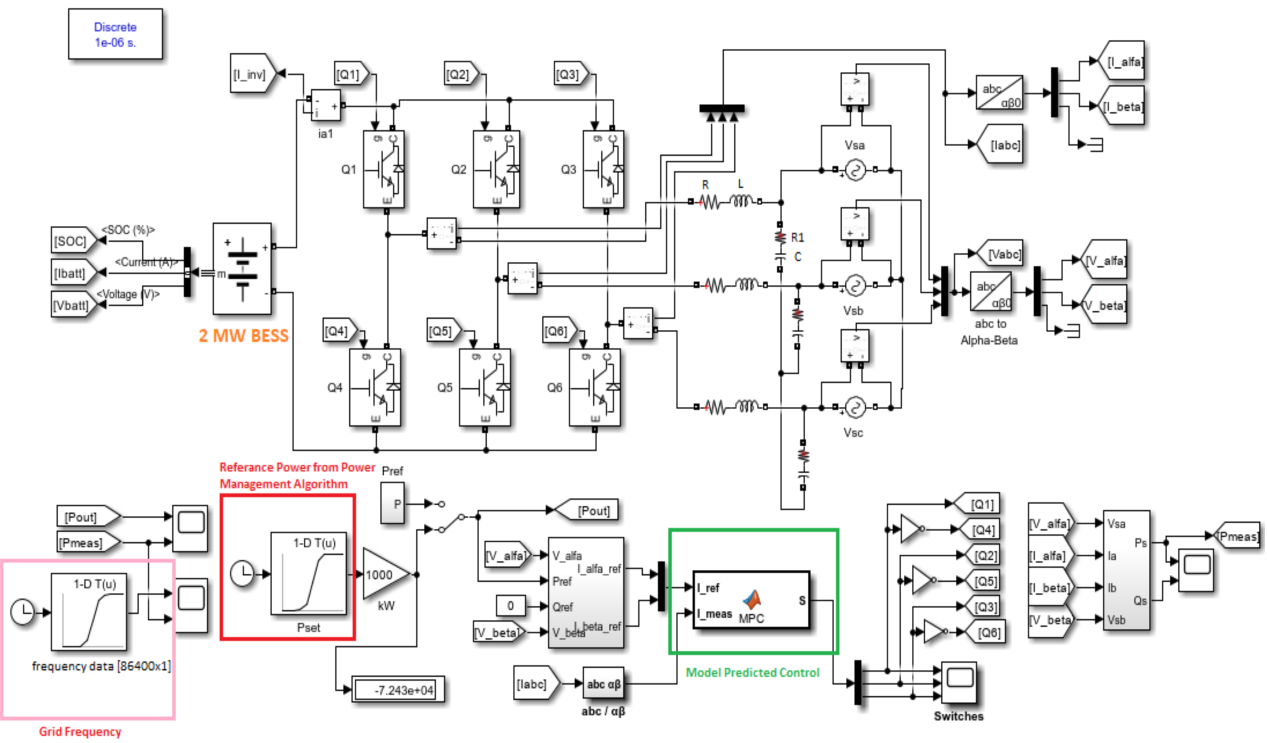

Fig. 3. Matlab/Simulink model of Bidirectional VSC MPC controlled BESS Energy Management for Frequency Ancillary Service

The simulation environment parameters used in the 2L-VSC control where the power management algorithm is integrated are given in Table 3. As can be seen here, a 4-level SOC control has been performed for a 2MW BESS.

When the SOC graph of the modelled battery energy storage system in the MATLAB environment is analyzed, it operates within the parameters set by the power management algorithm. According to the 24-hour frequency data, the change in BESS SOC at 2 MW power is given in Fig. 4. Accordingly, due to the rule-based power management algorithm of the battery, it does not deviate much from 50% SOC due to the fact that the electrical grid frequency does not fluctuate much. To maximize battery life, it is not recommended for the SOC to change significantly either charge or discharge within a short period of time [13]. The control of the SOC value, which is used as the control input in the rule-based power management algorithm, has also been successfully provided by the 2L-VSC.

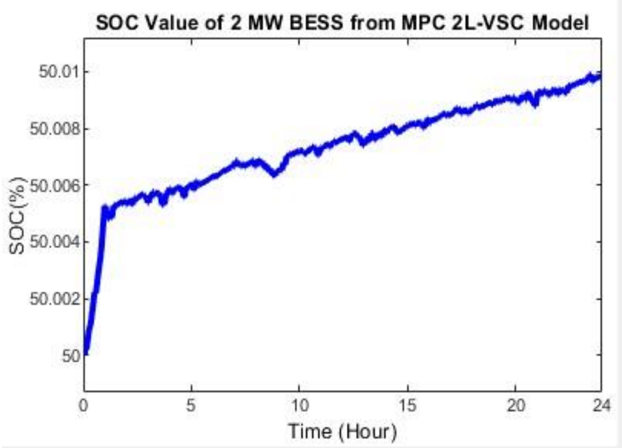

Fig. 4. State of Charge Value of 2 MW BESS from MPC Controlled 2L-VSC Model

Figs. 5 and 6 show frequency - active power outputs for the power management algorithm, and model predicted controlled voltage source converter. The creation of the reference, upper and lower lines in these figures is described in in [9]. The reference power value remains between frequency - active power envelope specified in the Türkiye frequency ancillary service regulation, it is clear that the 2L-VSC's active power output also remains within that range.

In Fig. 7, the reference power output change of the power management algorithm, which is optimally adjusted to the SOC value depending on the criteria in the frequency ancillary services regulation, and the active power change provided by the MPC 2L -VSC are shown. It may be concluded from comparing the 24-hour active power variation graphs that MPC 2L-VSC offers high-precision active power output. Furthermore, it can be said that the active power changes are nearly the same between the two graphics when they are evaluated closely between the 12^{th} and 12.05^{th} seconds from the randomly selected time interval.

The power variation provided for the 2 MW BESS system varies between approximately ±200 kW. This ratio also represents ±%10 of the specified installed power in the frequency-active power envelope dead band area.

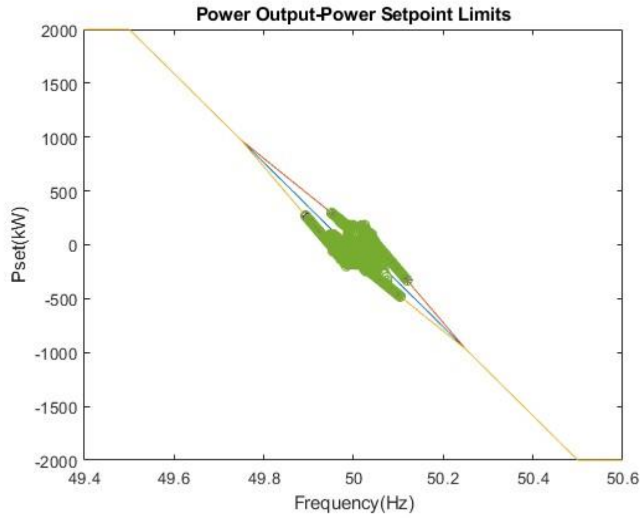

Fig. 5. Rule-Based Algorithm Active Power Output-Frequency Envelope According to Türkiye Frequency Ancillary Service - Method-1

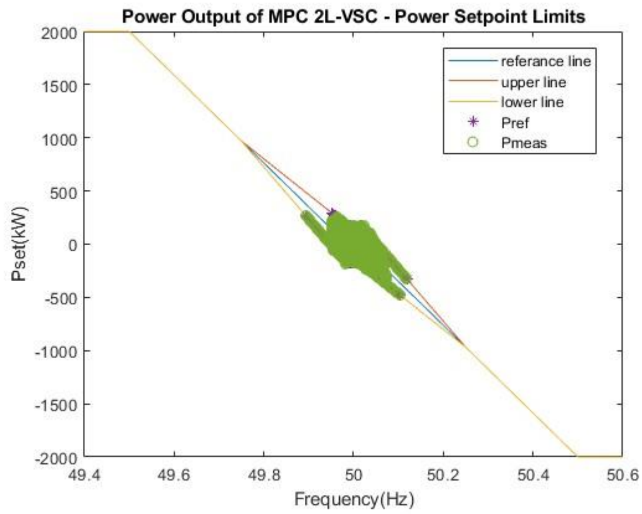

Fig. 6. MPC Controlled 2L-VSC Active Power Output-Frequency Envelope According to Türkiye Frequency Ancillary Service -Method-1

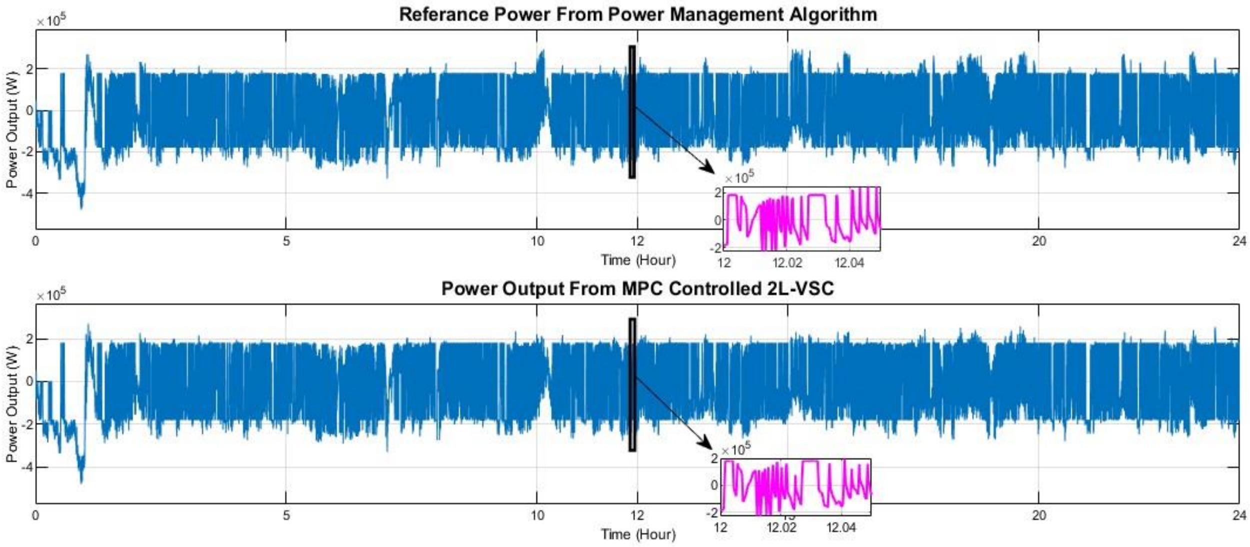

Fig. 7. Referance Power Output and MPC Controlled 2L-VSC Model Real Power Output Simulation Results

5. Conclusions

In this paper, the charge and discharge active power levels of the battery energy storage systems participating in the frequency ancillary service are determined by the rule-based algorithm according to the electricity grid frequency ancillary services regulation taken as the reference active power by the voltage source converter and provided by the Model Predicted Control method. The simulation study was carried out for 2L-VSC with 6 IGBTs in a Simulink environment, and the active power produced by power control with MPC was compared with the reference power value. In addition, it has been graphically shown that the active power produced remains within the active power-frequency envelope in the frequency ancillary services regulation and that it successfully provides the active power that needs to be provided. It has been shown that the battery SOC value variation is provided by the MPC 2L-VSC as regulated in the power management algorithm. In future studies, it may be recommended to optimize the VSC switching and provide a faster control method.

6. References

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