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A Hybrid Control Framework for Large-Scale Battery Integration to the Power System for Stability Analysis

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***Abstract*—The increasing penetration of renewable energy sources in the grid can raise the likelihood of instability in the power grid, e.g., small signal and voltage instability incidents. To study the effect of BESS integration on the grid and power system behavior, accurate battery modeling plays a key role. As the majority of power system studies including small signal stability analysis is carried out in the *d-q* axes, a precise model of the battery in the *d-q* axes is necessary. The lack of parametric based models of the battery in *d-q* axes makes stability analysis more challenging especially as the contributions of batteries in power systems are growing rapidly. In this paper, we develop an analytical model for the battery and its inverter in *d-q* axes. To validate the fidelity of the model, we simulate both the original and the obtained *d-q* models and compare the simulation results. Also, a hybrid control framework based on the presented battery model is proposed for stabilization of the power grid.**

***Index Terms*-- Battery energy storage system, disturbance rejection, hybrid control, load frequency control, small signal stability.**

I. Introduction

The growing interest of battery energy storage systems (BESSs) in power systems highlights their significant role in future power grids. At the transmission level of power grids, large-scale batteries can provide load frequency control [1]- [2] and backup for large wind farms [3]-[4], among other services, due to their fast response. Battery integration in the power grid can effectively reduce oscillations in frequency and tie-line power profiles caused by small load disturbances [5]. In general, small time constants, fast response, and their high energy density creates a large spectrum of potential applications for BESSs in power systems. Large-scale battery integration in the power system can also improve the transient stability of the power system. In [6], battery integration in the power system enhances the transient stability during the active power transferring process through transmission lines. In [6], it is also shown that the transient stability performance of the system is enhanced by suitable placement of a BESS in the system. To analyze the effects of BESSs in power grids for all the aforementioned applications, a precise model is required.

The dynamic model for large-scale batteries and their integration in power grids was first proposed in [7]. In this model, the battery was represented by a constant voltage source parallel to a resistance and capacitor (RC) circuit. The model was later improved and implemented in power system studies [8]-[9]. The proposed model in [9] has been used in research studies for load frequency control and power system stability analysis [7], [10], [11]. However, nonlinearities in some of these models are a disadvantage as it complicates the stability analysis. Moreover, in these studies BESSs are considered as active power sources, while a major advantage of BESSs is that both its active power and power factor are adjustable and controllable by the firing angle of the thyristors in the inverter. Therefore, by controlling the inverter, it is possible to have reactive power injection into the power system. As reactive power directly affects voltage deviation in power systems, reactive power injection has the potential to mitigate voltage instability in the grid.

In recent years, the Western Electricity Coordinating Council (WECC) has developed a new set of simple generic models for the simulation of grid integrated renewable energy systems and BESSs in positive sequence power simulation tools [12], [13]. In the proposed model [13], the user will be able to emulate, for the purposes of stability studies, the dynamic behavior of BESSs. Moreover, both active and reactive power have been considered, However, in these models the details of the DC side dynamics in BESSs are neglected [13], [14], [15]. The ideal dynamic model for large-scale battery integration for the power grid should be able to represent both the battery's DC dynamics and active/reactive power models.

The possibility of switching the battery's operating points between charging and discharging scenarios to increase the stability of the power system, highlights the hybrid control application. Hybrid control in frequency and voltage regulation for load adjustment is well investigated [16]- [18]. A hybrid control model using the concept of the Cooperative Home Energy Management (CoHEM) strategy is proposed in [19], for frequency regulation. They considered refrigerators as controllable loads to validate the proposed control model against system with no controller as well as the centralized controller strategy. In another study, a hybrid control algorithm is derived to regulate the output voltage in a boost converter; which is quite a suitable approach for real-time implementation. The applicability of the hybrid control to both the continuous current mode (CCM) and discontinuous current mode (DCM) operations is a useful feature, considering that the operating mode of a power converter may change from CCM to DCM and vice versa depending on the load conditions [18].

Considering the fact that the batteries in power systems are accompanied by the inverters, switching and as a result

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hybrid control strategy application is inevitable. This paper describes a new modeling approach using *d-q* analysis for batteries integrated with the power grid. A state space representation of the battery energy storage model accompanied by an inverter in the *d-q* axes is presented. Since the inverter firing angle in this paper is considered as an input, enabling the control of the battery's power factor, a hybrid control is proposed to minimize the unnecessary switching in the inverter.

The advantages of the proposed model with respect to the other battery models [7] – [10] and [13] – [15] are: *i)* the reactive power has been considered such that grid voltage deviations can be taken into account; *ii)* the state space model of the battery has been represented in *d-q* structure, which is well suited for stability analysis in power systems; and *iii)* a hybrid control algorithm to control frequent switching between charging and discharging modes of the battery.

The rest of the paper is organized as follows. Section II describes the problem statement. In Section III, the battery equations and linearized model in the *d-q* axes are presented. Battery integration and proposed control strategy is explained in Section IV. Finally, Section V presents conclusions and future study.

II. PROBLEM STATEMENT

Small signal stability in a power system is defined as the ability of the power system to maintain synchronism in the presence of small disturbances such as load deviations. In this context, since the power system is inherently a nonlinear system, the power system model is linearized in the vicinity of its operating point for the small signal analysis. This enables us to apply linear system theory to the power system even though the system is inherently nonlinear. In this regard, all power system components can be modeled in the state space representation as

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases} \tag{1}$$

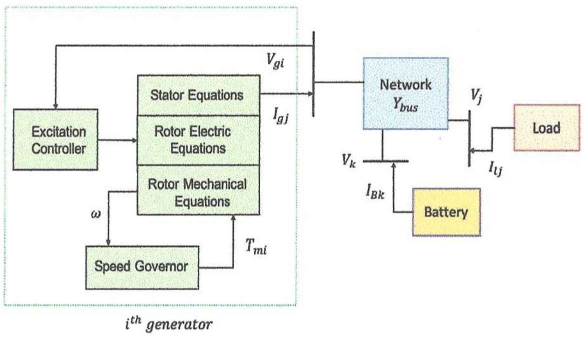

Fig. 1. Power system Structure

A general power system structure is shown in Fig. 1. Based on the given model, we can define the general equation of the system as:

$$[Y_{bus}]\Delta v_t = \Delta I_G - \Delta I_L - \Delta I_S + \Delta I_B \tag{2}$$

where, Y_{bus} is the power system admittance matrix, Δv_t is the voltage deviation in the buses and $\Delta I_G, \Delta I_L$, ΔI_S, and ΔI_B are the changes in generator, load, static var compensator (SVC) and battery current injections to the power system, respectively.

A. Generator Model

The generator model in state space representation varies based on the modeling approaches chosen [19]– [20]. The generator differential equations after linearization are represented as:

$$\begin{cases} \Delta\dot{x}_g = [A_g]\Delta x_g + [B_g]\Delta V_g + [E_g]\Delta u_{cg} \\ \Delta I_g = [C_g]\Delta x_g + [D_g]\Delta V_g \end{cases} \tag{3}$$

where ΔV_g represents the voltage deviation in the generator bus, ΔI_g is the generator current deviation and Δu_{cg} is a small perturbation in the generator reference input variables for the generator controllers. Note that, ΔI_g, and ΔV_g are represented in *d-q* axes as

$$\Delta I_g = \begin{bmatrix} \Delta I_{dg} \\ \Delta I_{qg} \end{bmatrix} \text{ and } \Delta V_g = \begin{bmatrix} \Delta V_{qg} \\ \Delta V_{dg} \end{bmatrix}$$

To be able to study the power system, all other equipment such as loads, SVCs and batteries should be written in $d-q$ format. These devices are modeled in state space representation in the following subsections.

B. Load model

Power system loads including induction motors and nonlinear loads are modeled as

$$\begin{cases} \Delta\dot{x}_l = [A_l]\Delta x_l + [B_l]\Delta V_l + [E_l]\Delta u_{cl} \\ \Delta I_l = [C_l]\Delta x_l + [D_l]\Delta V_l \end{cases} \tag{4}$$

where, Δx_l are the dynamic loads such as induction motor states and Δu_{cl} are the load control inputs. ΔV_l is the load bus voltage deviation and ΔI_l is the load (demand) current deviation. For the static loads the equation will be simplified to

$$\Delta I_l = [D_l]\Delta V_l = [Y_l]\Delta V_l \tag{5}$$

C. Static Var Compensator (SVC) model

Similar to the load equations, static *var* compensator in state space representation is modeled as

$$\begin{cases} \Delta\dot{x}_s = [A_s]\Delta x_s + [B_s]\Delta V_s + [E_s]\Delta u_{cs} \\ \Delta I_s = [C_s]\Delta x_s + [D_s]\Delta V_s \end{cases} \tag{6}$$

where, Δx_s are the SVC states and Δu_{cs} are the SVC control inputs. ΔV_s and ΔI_s are the SVC bus voltage and current deviations, respectively.

D. Battery model

To add the battery dynamics to the power system model, the battery also should be represented as

$$\begin{cases} \Delta\dot{x}_b = [A_b]\Delta x_b + [B_b]\Delta V_b + [E_b]\Delta u_{cb} \\ \Delta I_b = [C_b]\Delta x_b + [D_b]\Delta V_b \end{cases} \tag{7}$$

Remark1: Note that all equations are in *d-q* axes, hence:

$\Delta I_{(.)} = \begin{bmatrix}\Delta I_d \\ \Delta I_q\end{bmatrix}$ and $\Delta V_{(.)} = \begin{bmatrix}\Delta v_q \\ \Delta v_d\end{bmatrix}$

where $\Delta V_{(.)}$ represents voltages deviations in load, SVC or the battery buses, $\Delta I_{(.)}$ is the current deviations and $\Delta u_{c(.)}$ is the small perturbation in their reference input variables.

E. Network Equations

As shown in Fig. 1, generators, SVCs, batteries and loads in the power system network are interfaced to the network as current injections which leads us to the following equation

$$[Y_{bus\_DQ}]\Delta V_{QD} = [P_G]\Delta I_G - [P_L]\Delta I_L - [P_L]\Delta I_S + [P_B]\Delta I_B \quad (8)$$

Y_{bus_DQ} is the network admittance matrix in *d-q* axes and $P_g(i,j) = \begin{bmatrix}1 & 0 \\ 0 & 1\end{bmatrix}$ if the i^{th} generator is connected to the j^{th} bus, otherwise $P_g(i,j) = \begin{bmatrix}0 & 0 \\ 0 & 0\end{bmatrix}$. Same interfacing matrices are defined for P_l, P_{svc}, and P_b [19]-[20].

After substituting the equations (3), (4), (5), and (7) in (8) and simplifying, the overall system representation becomes

$$\dot{X} = [A_t]X + [E]U_c \quad (9)$$

where

$$A_t = [A] + [B][P]^t[Y'_{bus_{DQ}}]^{-1}[P][C] \quad (10)$$

$$[P] = [P_G \; P_L \; P_S \; P_B] \quad (11)$$

And

$$\left[Y'_{bus_{DQ}}\right]\Delta V_{QD} = [P_G][C_G][X_G] + [P_L][C_L][X_L] + [P_S][C_S][X_S] + [P_B][C_B][X_B] \quad (12)$$

A_t represents the state matrix of the entire power grid, and the stability of the system is studied based on this matrix.
To be able to study the effect of the battery integration on the power system stability, we need to model the battery in the state space model structure given in (7). Then we will be able to add the battery model to the power system model in (8). For this purpose, the BESS current equations in *d-q* axes is derived and linearized in the vicinity of the operating point.

III. BATTERY MODEL

Batteries are accompanied by inverters in power grids [9]. Figure 2 shows the equivalent circuit model of a battery and its inverter.

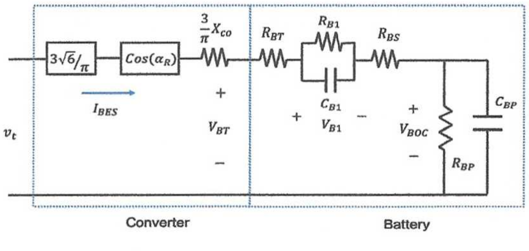

Fig. 2. Battery and inverter circuit model

Inverter connection in the battery provide a unique opportunity for power system control. Considering the dynamic model of the battery in charging and discharging modes along with the inverter, allow us to have full control on four quadrants of active and reactive power by controlling the inverter's operating point as shown in Fig. 3.

Four quadrant control means the real current flow directions can indicate either charging or discharging modes, while the reactive current flows can represent either supplying or absorbing reactive power simultaneously and independently. By implementing a proper control strategy, the BESS can provide the following functionalities in the power grid based on system requirements [13]:

i) voltage control and regulation at the local terminals of the BESS, at the point of interconnection (POI) or plant level (when BESS is incorporated in a power plant);
ii) frequency support by quickly providing or absorbing real power or being part of automatic generation control (AGC); and
iii) power oscillation damping and transient stability of the power system.

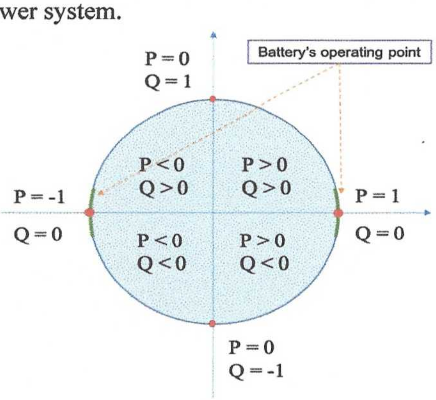

Fig. 3. BESS Four quadrant control and operation diagram

(adapted from [14])

To extract the state space model of the battery, we need to consider two cases for the charging and discharging modes. The dynamics of the battery in the charging mode are slightly different from the discharging mode. In the first case, we obtain the state space model of the battery for the charging scenario. In the second case, with slight modifications, we derive the discharging model from the first case.

A. Case I: Charging Mode

In the charging mode, using Kirchhoff's voltage law, the output voltage of the battery, V_{BT}, is

$$V_{BT} = \frac{3\sqrt{6}}{\pi} v_t \cos(\alpha_R) - \frac{3}{\pi} x_{co} I_{BES} \quad (13)$$

$$V_{BT} = V_{BOC} + V_{B1} + (R_{BT} + V_{BS})I_{BES} \quad (14)$$

where, I_{BES} is the battery's terminal current. The dynamic model of the battery for the charging mode is shown in Fig. 4, where, α_R is the inverter's firing angle and v_t is the bus voltage to which the battery is connected.

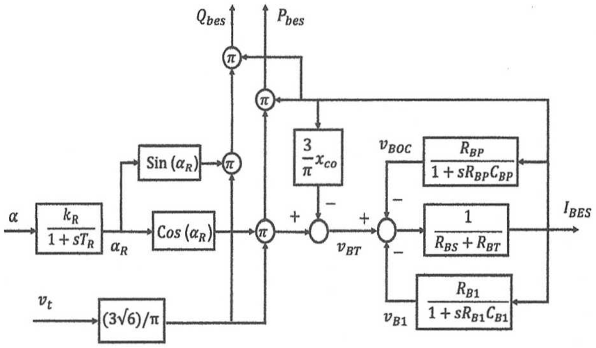

Fig. 4. Battery and inverter dynamic model in the charging mode

Assuming $\lambda = 1 + \frac{3}{\pi R}x_{co}$, and $R = R_{BS} + R_{BT}$ the battery current will be

$$I_{BES} = \frac{3\sqrt{6}}{\pi\lambda R} v_t \cos(\alpha_R) - \frac{1}{\lambda R} V_{BOC} - \frac{1}{\lambda R} V_{B1} \tag{15}$$

where V_{B1} is the overvoltage, and V_{BOC} is the open circuit voltage of the battery. In the nonlinear model of the battery, represented in Fig. 3, we consider $x_{b\_c} = [V_{BOC}, V_{B1}, \alpha_R]^T$ as the state vector of the battery in charging mode.

By linearizing (15) in the vicinity of the operating point of the battery in the power grid, $\alpha_R = \alpha_{r0}$, $v_t = v_{t0}$, $V_{BOC} = V_{boc0}$, $V_{B1} = V_{b10}$, and $I_{BES} = I_{b0}$, the current deviation is

$$\Delta I_{BES} = \frac{3\sqrt{6}}{\pi\lambda R} \cos(\alpha_{r0})\, \Delta v_t - \frac{3\sqrt{6}}{\pi\lambda R} v_{t0} \sin(\alpha_{r0})\, \Delta\alpha_R - \frac{1}{\lambda R}\Delta V_{BOC} - \frac{1}{\lambda R}\Delta V_{B1} \tag{16}$$

Moreover, using the dynamic block diagram shown in Fig. 3, we have the following state dynamics

$$\Delta\dot{V}_{BOC} = \frac{1}{C_{BP}}\, \Delta I_{BES} - \frac{1}{C_{BP}R_{BP}}\, \Delta V_{BOC} \tag{17}$$

$$\Delta\dot{V}_{B1} = \frac{1}{C_{B1}}\, \Delta I_{BES} - \frac{1}{C_{B1}R_{B1}}\, \Delta V_{B1} \tag{18}$$

$$\Delta\dot{\alpha}_R = \frac{k_R}{T_R}\, \Delta\alpha - \frac{1}{T_R}\, \Delta\alpha_R \tag{19}$$

The final state space representation of the battery dynamics and its inverter for charging case can be summarized as (20) and (21) in the vicinity of its operating point. More details on deriving the state space representation of the battery are provided in [21].

$$\begin{bmatrix} \Delta\dot{V}_{BOC} \\ \Delta\dot{V}_{B1} \\ \Delta\dot{\alpha}_R \end{bmatrix} = A_{b\_c} \begin{bmatrix} \Delta V_{BOC} \\ \Delta V_{B1} \\ \Delta\alpha_R \end{bmatrix} + B_{b\_c}\, \Delta v + E_{b\_c} \Delta u_{cb\_c} \tag{20}$$

$$\begin{bmatrix} \Delta I_{bd\_c} \\ \Delta I_{bq\_c} \end{bmatrix} = C_{b\_c} \begin{bmatrix} \Delta V_{BOC} \\ \Delta V_{B1} \\ \Delta\alpha_R \end{bmatrix} + D_{b\_c}\, \Delta v \tag{21}$$

In this state space model, the states are the deviation values of nonlinear states as

$$\Delta x_{b\_c} = [\Delta V_{BOC}, \Delta V_{Bq}, \Delta\alpha_R]^T$$

The input reference control for the battery is defined as $\Delta u_{cb\_c} = \Delta\alpha$, which controls the active and reactive output power of the battery. The output signals are active (ΔI_{bd_c}) and reactive (ΔI_{bq_c}) current deviations of the battery in charging mode. Note that the voltage input signal is in *d-q* axes as $\Delta v = [\Delta v_q, \Delta v_d]^T$. Δv is the deviation of the battery's terminal voltage as a result of the battery connection to the power grid.

To validate the credibility of the obtained linearized model in *d-q* axes, we use simulations results to compare the behavior of the new model with the original one. For brevity, only the results for the charging mode are presented. The discharging mode has the same quality of results. In the simulation study, the following system operating conditions were considered: $v_{tq0} = 100\,V$,

$v_{td0} = 692.82\,V$, $v_{t0} = 700\,V$, and $\alpha_0 = 15°$.

At this operating point, a small perturbation on the firing angle of the inverter with the value of $\Delta\alpha = -1.97°$ was considered. Figure 5 compares the results of the state vector $x_{b\_c} = [V_{BOC}, V_{B1}, \alpha_R]^T$ in both models. The states in the original model are shown in blue and states of the linearized *d-q* axis model are depicted with red.

All states start with the same initial conditions as both models were in the same operating points. The slopes of deviations are very close to each other and there are slight differences in the final values.

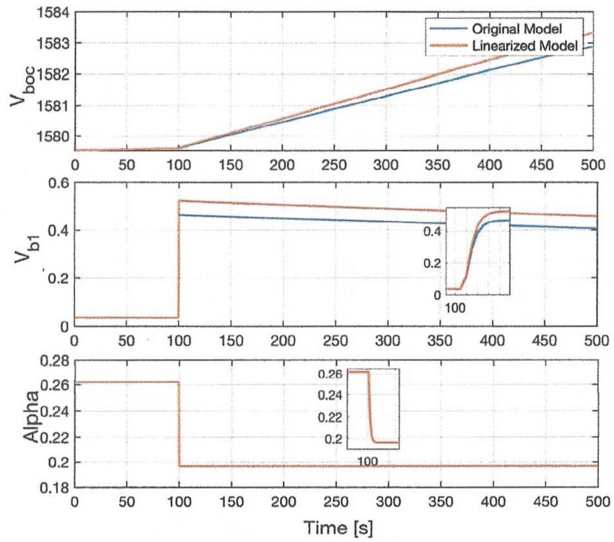

Figure 5. States of the battery for original and linearized model

The bias errors are mainly noticeable in the steady state because of the linearization approximation whereas the application of this model is for transient behavior analysis for no more than a few seconds time duration.

Having the state space model for the battery in the charging mode, we will derive a similar model for the discharging case with slight modifications in the battery equations.

B. Second Case: Discharging Mode

To modify the charging model in Fig. 3 for the discharging mode two slight changes are required: *i)* changing the firing angle to $\beta = \pi - \alpha$; and *ii)* changing the current flow direction. Therefore, the obtained battery voltage is

$$V_{BT} = V_{BOC} - V_{B1} - (R_{BT} + V_{BS})I_{BES} \tag{22}$$

Considering the inverse flow of the current, I_{BES} has negative value in the equation (13). So, (22) is modified to

$$V_{BT} = V_{BOC} - V_{B1} + (R_{BT} + V_{BS})I_{BES} \tag{23}$$

The states of the battery for discharging mode with the discharge current are defined as

$$\Delta x_{b\_d} = [\Delta V_{BOC}, \Delta V_{B1\_d}, \Delta\beta_R]^T$$

Where

$V_{B1\_d} = -V_{B1}$ and $\beta_R = \pi - \alpha_R$

Finally, the state space model matrices of the battery for discharge case will be similar to the charging case as

$$\begin{bmatrix} \Delta\dot{V}_{BOC} \\ \Delta\dot{V}_{B1\_d} \\ \Delta\dot{\beta}_R \end{bmatrix} = A_{b\_d} \begin{bmatrix} \Delta V_{BOC} \\ \Delta V_{B1\_d} \\ \Delta\beta_R \end{bmatrix} + B_{b\_d}\,\Delta v + E_{b\_d}\Delta u_{cb\_d} \tag{24}$$

$$\begin{bmatrix} \Delta I_{bd\_d} \\ \Delta I_{bq\_d} \end{bmatrix} = C_{b\_d} \begin{bmatrix} \Delta V_{BOC} \\ \Delta V_{B1\_d} \\ \Delta\beta_R \end{bmatrix} + D_{b\_d}\,\Delta v \tag{25}$$

Where

$$\begin{bmatrix} \Delta V_{BOC} \\ \Delta V_{B1} \\ \Delta\alpha_R \end{bmatrix} = T. \begin{bmatrix} \Delta V_{BOC} \\ \Delta V_{B1\_d} \\ \Delta\beta_R \end{bmatrix} \tag{26}$$

And

$$T = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix}$$

Substituting the state space models of the charging and discharging cases of the battery in the power system equations given in (10) and (12), the state space model of the power system in the presence of the battery will be as follows

$$\begin{cases} \dot{x}_c = A_c x_c + B_c u_{c\_c} \\ y_c = C_c x_c \end{cases} \tag{27}$$

$$\begin{cases} \dot{x}_d = A_d x_d + B_d u_{c\_d} \\ y_d = C_d x_d \end{cases} \tag{28}$$

where x_c, and x_d are the augmented states of the power system for charging and discharging scenarios; A_c, and A_d represent the state matrices of the entire the power grid for charge and discharge cases and the augmented input signals of the system are

$$u_{c\_c} = [\Delta u_{cg}\ \Delta u_{cl}\ \Delta u_{cs}\ \Delta u_{cb\_c}]^T \tag{29}$$

$$u_{c\_d} = [\Delta u_{cg}\ \Delta u_{cl}\ \Delta u_{cs}\ \Delta u_{cb\_d}]^T \tag{30}$$

IV. Battery Integration and Control Strategy

To simulate the effect of the battery integration on the power grid, a two-area case study model adapted from [19] is considered. Considering the battery integration to the bus 6 in two area case study model, the effect of the linearized battery model integration, for charging case, is presented in Fig. 6. Eigenvalue plot of the two-area case study model with the battery is represented in Fig. 7. It is shown that the battery connection has improved the small signal stability of the entire system.

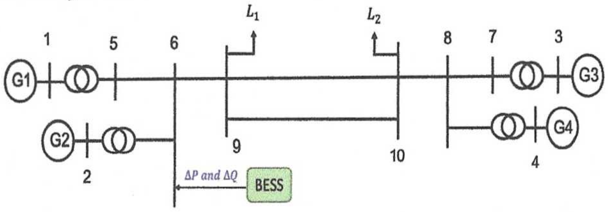

Fig. 6. Battery integration to the two-area case study model

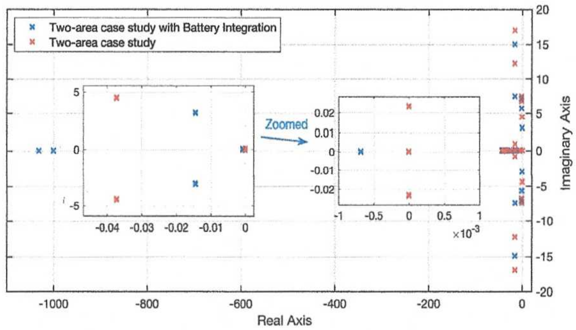

Fig. 7. Eigenvalue analysis of two-area model with battery

Considering the state space model of the power system in presence of the battery and the battery's input as the control input, (27) and (28) will be rewritten as

$$\begin{cases} \dot{x}_c = A_c x_c + B_c u_{cb\_c} \\ y_c = C_c x_c \end{cases} \tag{31}$$

$$\begin{cases} \dot{x}_d = A_d x_d + B_d u_{cb\_d} \\ y_d = C_d x_d \end{cases} \tag{32}$$

Since the power system is represented with two state space models, control design strategy should be able to frequently switch between charging and discharging operating conditions (as shown in Fig. 8).

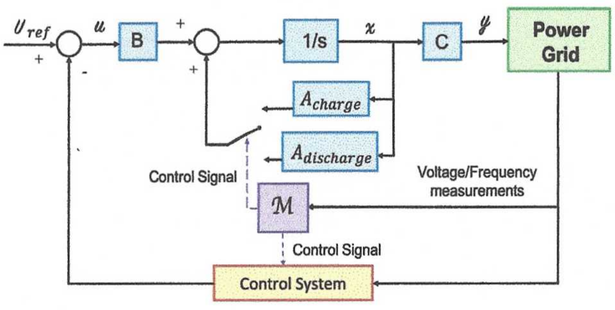

Fig. 8. Control design approach based on charge and discharge of the battery

To prevent frequent unnecessary switching and design a proper control for the battery, a cost function for each scenario is defined as (33) and (34).

$$J_c = \int_{t_{k-1}}^{t_k} (x_c^T\, Q_c\, x_c + u_{cb\_c}^T\, R_c\, u_{cb\_c})\; d\tau \quad (33)$$

$$J_d = \int_{t_{k-1}}^{t_k} (x_d^T\, Q_d\, x_d + u_{cb\_d}^T\, R_d\, u_{cb\_d})\; d\tau \quad (34)$$

A switching policy will be considered to shift between charging and discharging condition and moving in operating spectrum (the green arcs in Fig. 3) to minimize the cost function in each time interval of (t_{k-1}, t_k) and consequently the total cost function of the battery operation in the power system.

V. Conclusion

In this paper an analytical linearized dynamic model of a large-scale BESS in the *d-q* axes is presented. The model is expressed in the state space representation which can be easily applied in stability studies and dynamic simulations of power systems. A parametric based model of BESS in *d-q* axes makes stability analysis of power grids with BESS integration more tractable especially as the contributions of batteries to power system performance are rapidly growing.

To examine the dynamic behavior of this model, the active and reactive power of the linearized model are compared to those of the original model with excellent agreement. Battery integration to a two-area case study model show improved stability of the power system. Preserving two state space model for charge and discharge of the battery demands a new control approach to manage the switching between two operating points of charge/discharge. In the future study, the proposed control will be applied to the case study model to increase the small signal stability of the system in presence of the disturbances.

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Appendix

System parameters are:

$X_{co} = 0.0274\,\Omega$, $C_{BP} = 52600\,F$, $C_{B1} = 1\,F$, $R_{BT} = 0.0167\,\Omega, R_{BS} = 0.013\,\Omega, R_{B1} = 0.001\,\Omega, R_{BP} = 10000\,\Omega, K_R = 1, T_R = 0.001\,s, v_{t0} = 790\,V, v_{q0} = 100\,V, \alpha = 15°$.

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