SAND2020-6467C

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

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July 2020

ACC2020 DENVER

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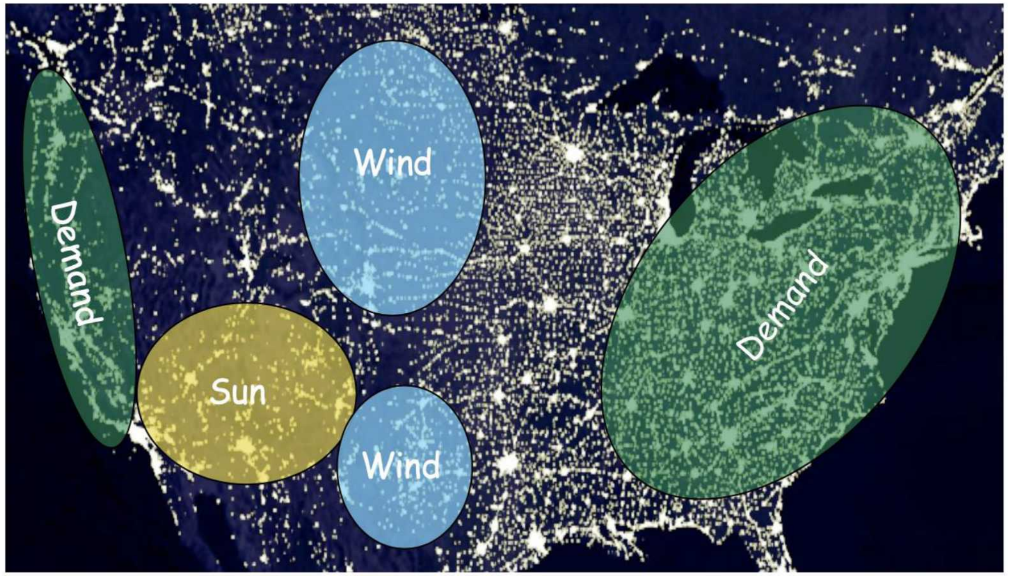
Presentation Outline

- Introduction
- Power system structure
- Existing battery models
- Proposed model
- Proposed control model
- Future Work

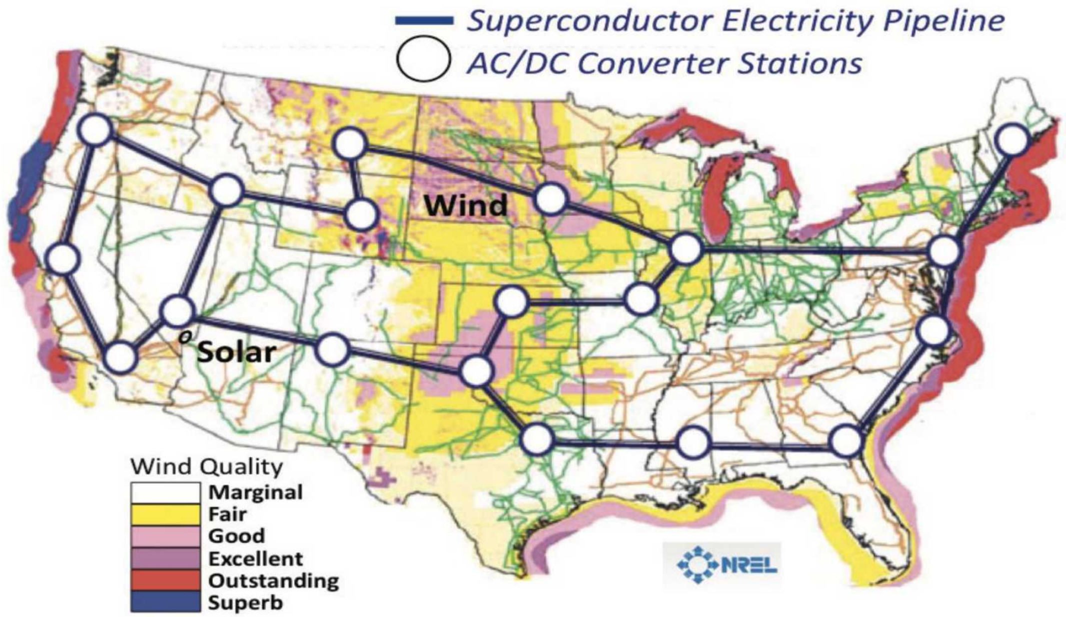
Future Power Grid Challenges



Separation between the renewable sources and demand [1]

Challenges:
- Unpredictable and unreliable
- Distance between demand and renewable sources

Solutions:
- Superconductors and AC/DC converters
- Battery energy storage system



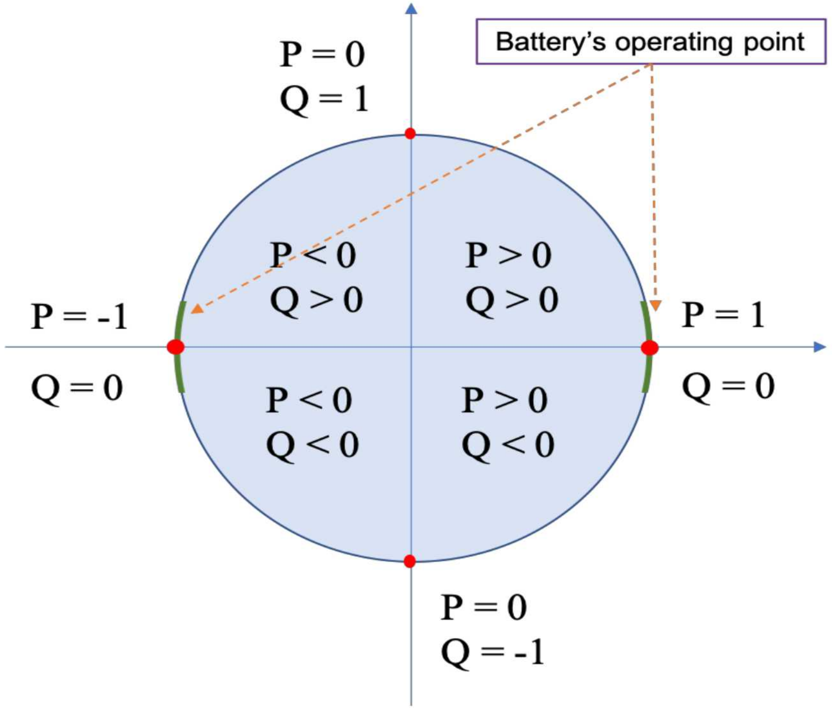
The proposed DC superconductor electricity pipeline for carrying large amounts of renewable energy [1]

[1] "Integrating Renewable Electricity on the Grid", A Report by the American Physical Society (APS) Panel on Public Affairs

Large-Scale Battery in Power System

By implementing a proper control strategy, Battery can provide various functionality in the power grid based on power system requirements:

- ❑ Load frequency support;
- ❑ Voltage control and regulation at the local terminals of the BESS; and
- ❑ Power oscillation damping and transient stability of the power system.



BESS Four quadrant control and operation diagram (adapted from [2])

[2] P. Pourbeik, S. E. Williams, J. Weber, J. Sanchez-Gasca, J. Senthill, S. Huang, and K. Bolton, "Modeling and Dynamic Behavior of Battery Energy Storage," *IEEE Electrification Magazine*, pp. 47-51, Sept. 2015

Oscillations (modes) in Power Systems

Local modes

- Generally observed at frequencies > 2 Hz
- Oscillations associated with local “electrically close” groups of generators.
- Sometimes caused by inadequate tuning of control systems (exciters, HVDC converters, SVCs, and PSS)

Inter-area modes

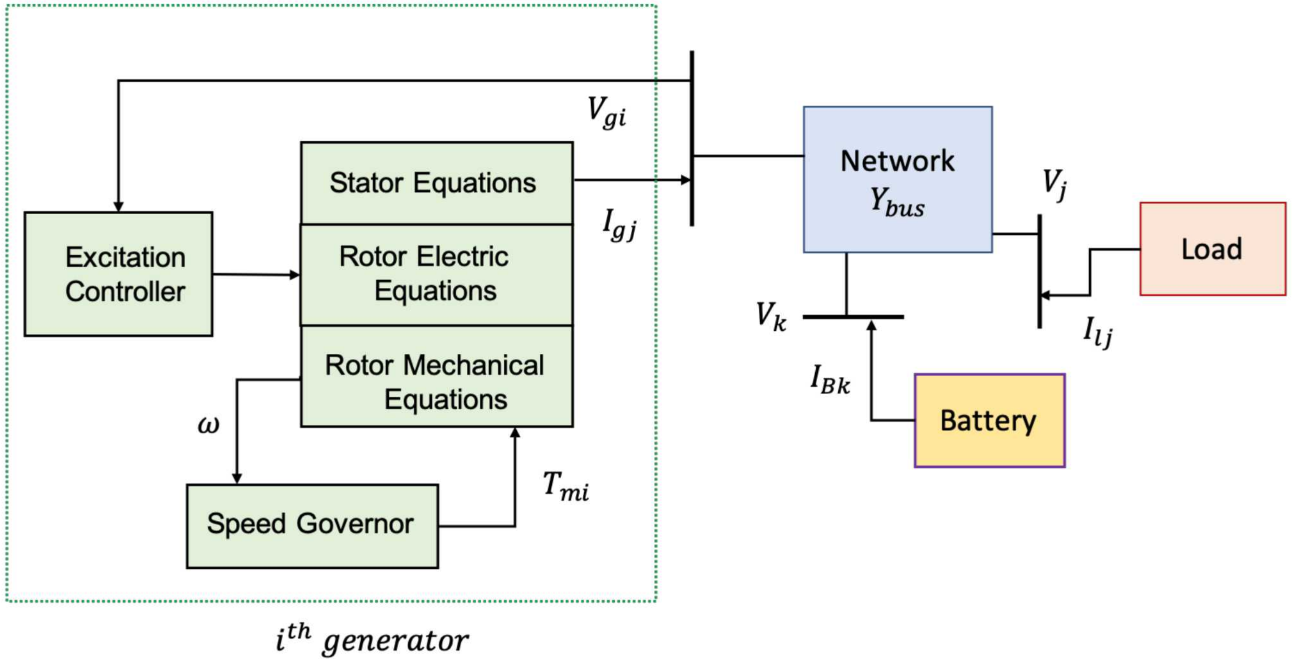
- Generally observed at frequencies between 0.1-2 Hz
- ***Oscillations associated with the flow of power;*** they involve “electrically far” areas
- Groups of generators in one area swinging against another group of generators in another area
- Occur across weak or heavily loaded transmission paths over long corridors

Local and inter-area modes are small-signal stability issues

Power System Network Model

Power system model is represented as

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



Power system Structure

We need dynamic mode for stability analysis $\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases}$

Power System Component Model

Generator Model

$$\Delta\dot{x}_g = [A_g]\Delta x_g + [B_g]\Delta V_g + [E_g]\Delta u_{cg}$$

$$\Delta I_g = [C_g]\Delta x_g + [D_g]\Delta V_g$$

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

Network Model

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

Load Model

$$\Delta\dot{x}_l = [A_l]\Delta x_l + [B_l]\Delta V_l + [E_l]\Delta u_{cl}$$

$$\Delta I_l = [C_l]\Delta x_l + [D_l]\Delta V_l$$

$$\Delta I_l = [D_l]\Delta V_l = [Y_l]\Delta V_l$$

Battery Model

$$\Delta\dot{x}_b = [A_b]\Delta x_b + [B_b]\Delta V_b + [E_b]\Delta u_{cb}$$

$$\Delta I_b = [C_b]\Delta x_b + [D_b]\Delta V_b$$

$$\dot{X} = [A_t]X + [E]U_c$$

$$A_t = [A] + [B][P]^t\left[Y'_{bus_{DQ}}\right]^{-1}[P][C]$$

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

Existing Battery Models

- Active power model of the battery
- WECC battery storage dynamic model

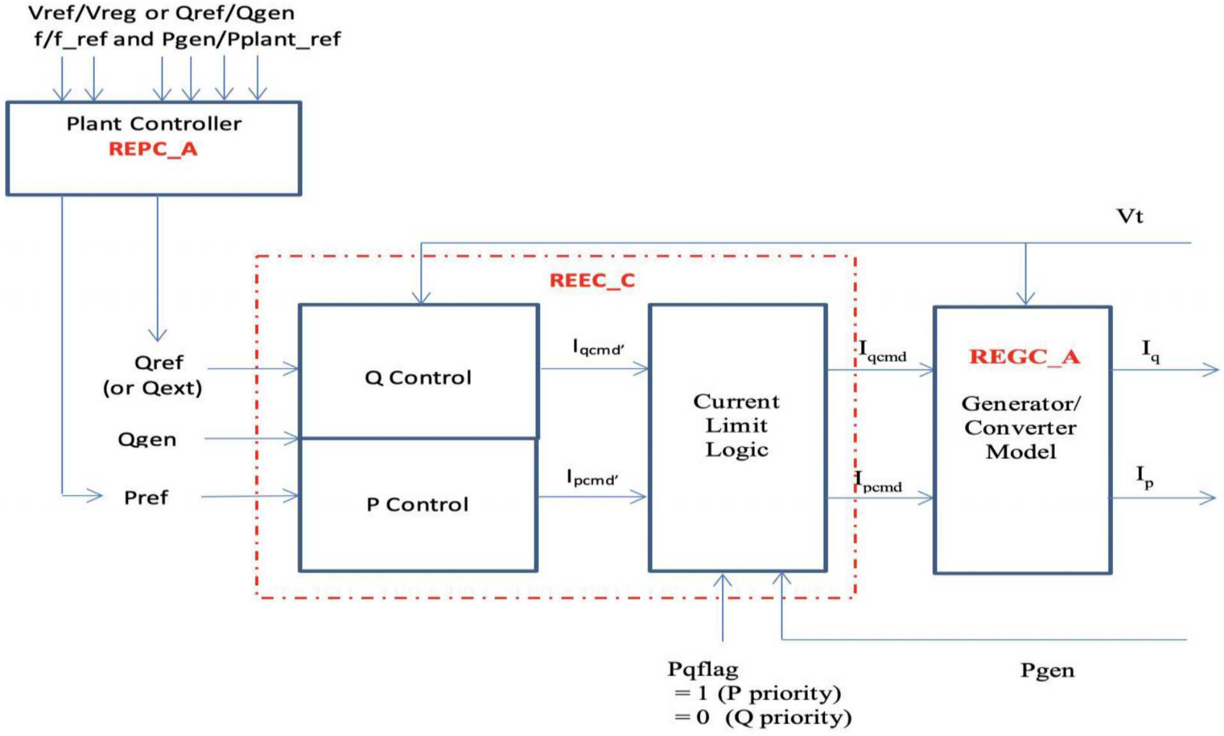
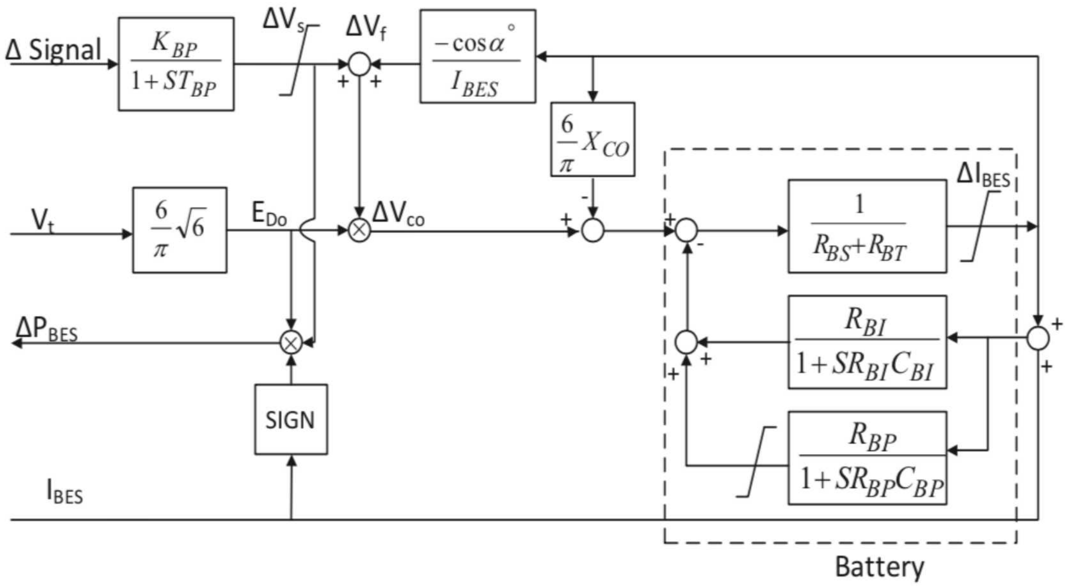


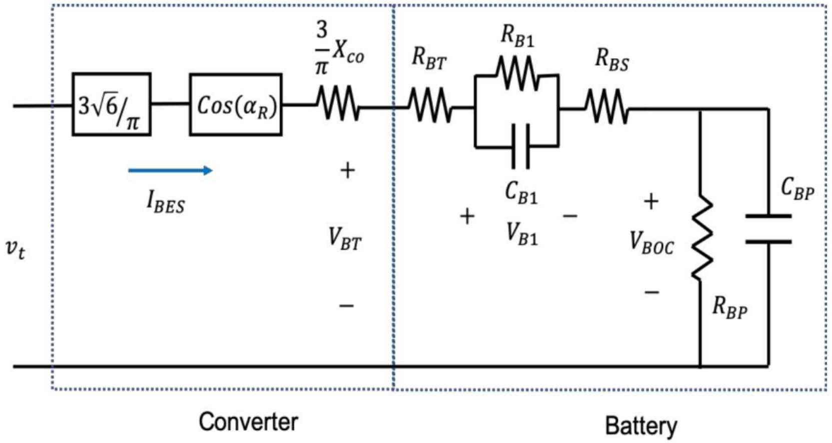
Diagram Representation of the BESS Model with the Plant Controller [3]



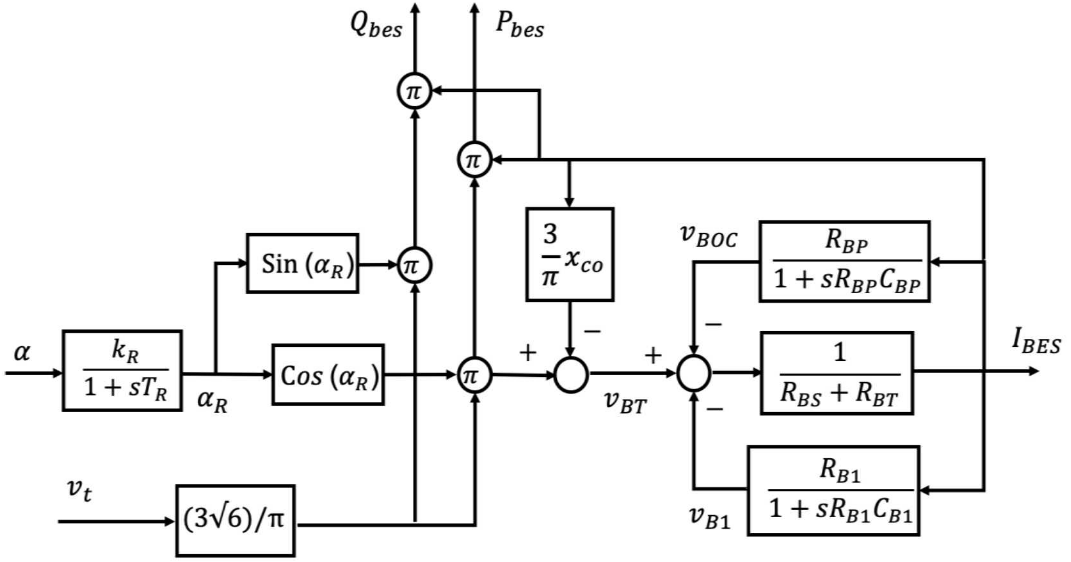
Active power model of the battery

[3]https://www.wecc.org/Reliability/WECC%20Approved%20Energy%20Storage%20System%20Model%20-%20Phase%20II.pdf

Battery Model (Charging Scenario)



Battery and inverter circuit model



Battery and inverter dynamic model in the charging mode

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

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

$\lambda = 1 + \frac{3}{\pi R} x_{co}$, and $R = R_{BS} + R_{BT}$

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

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

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

The discharge scenario is very similar to the charging scenario (see the paper for details)

State Space Model (Charging Scenario)

$$\begin{bmatrix}\Delta\dot{V}_{BOC}\\ \Delta\dot{V}_{B1}\\ \Delta\dot{\alpha}_R\end{bmatrix} = A_b\begin{bmatrix}\Delta V_{BOC}\\ \Delta V_{B1}\\ \Delta\alpha_R\end{bmatrix} + B_b\,\Delta v + E_b\Delta u_{cb}$$

$$\begin{bmatrix}\Delta I_{bd}\\ \Delta I_{bq}\end{bmatrix} = C_b\begin{bmatrix}\Delta V_{BOC}\\ \Delta V_{B1}\\ \Delta\alpha_R\end{bmatrix} + D_b\,\Delta v$$

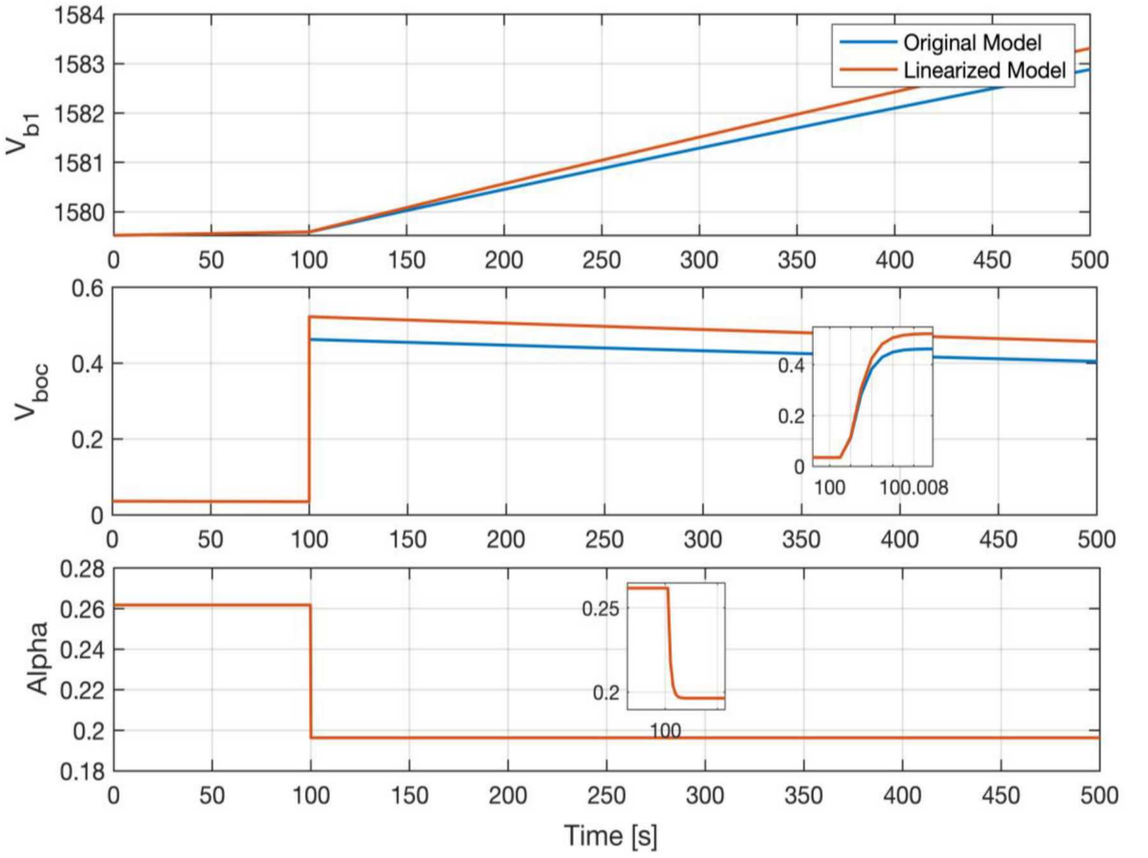
$$A_b = \begin{bmatrix}\left(\frac{-1}{R_{BP}C_{BP}} - \frac{1}{R\lambda C_{BP}}\right) & \frac{-1}{R\lambda C_{BP}} & \left(\frac{-3\sqrt{6}\,.\,v_{t0}}{\pi R\lambda C_{BP}} sin(\alpha_{r0}\right)\\ \frac{-1}{R\lambda C_{B1}} & \left(\frac{-1}{R_{B1}C_{B1}} - \frac{1}{R\lambda C_{B1}}\right) & \left(\frac{-3\sqrt{6}\,.\,v_{t0}}{\pi R\lambda C_{B1}} sin(\alpha_{r0}\right)\\ 0 & 0 & \frac{-1}{T_R}\end{bmatrix}$$

$$B_b = \begin{bmatrix}\left(\frac{3\sqrt{6}\;v_{q0}}{\pi\lambda C_{BP}v_{t0}} cos(\alpha_{r0}\right) & \left(\frac{3\sqrt{6}\;v_{d0}}{\pi\lambda C_{BP}v_{t0}} cos(\alpha_{r0}\right)\\ \left(\frac{3\sqrt{6}\,v_{q0}}{\pi R\lambda C_{B1}v_{t0}} cos(\alpha_{r0}\right) & \left(\frac{3\sqrt{6}\,.\,v_{d0}}{\pi R\lambda C_{B1}v_{t0}} cos(\alpha_{r0}\right)\\ 0 & 0\end{bmatrix}$$

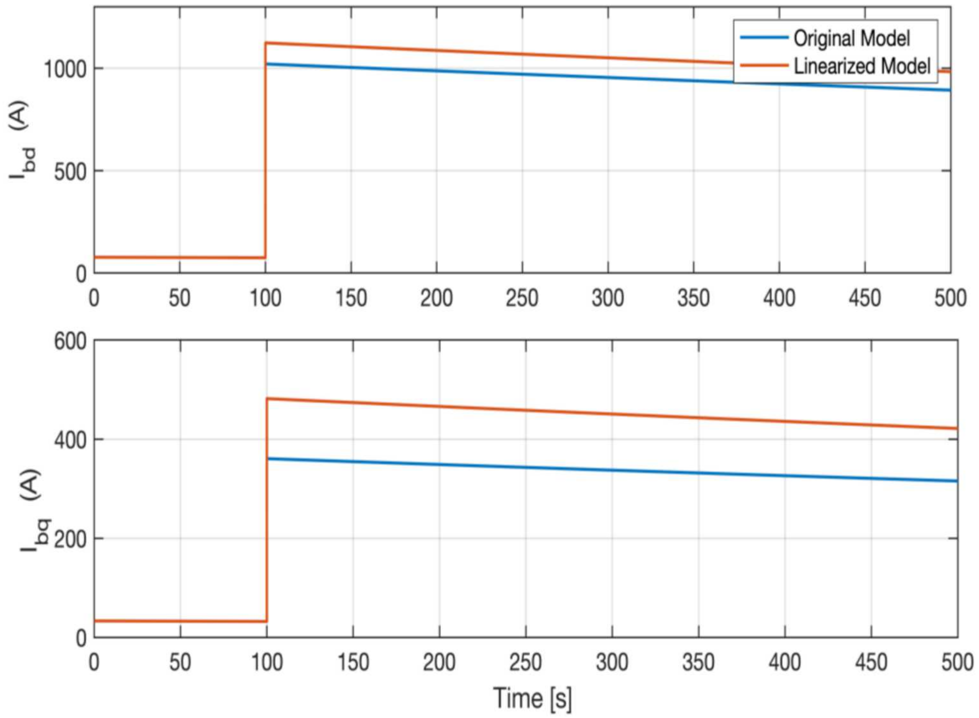
$$E_b = \begin{bmatrix}0\\ 0\\ \frac{k_R}{T_R}\end{bmatrix}$$

For more details on battery state space model see the paper

Linearization Results (Charging Scenario)



Battery's states



Battery *d-q* axis output current

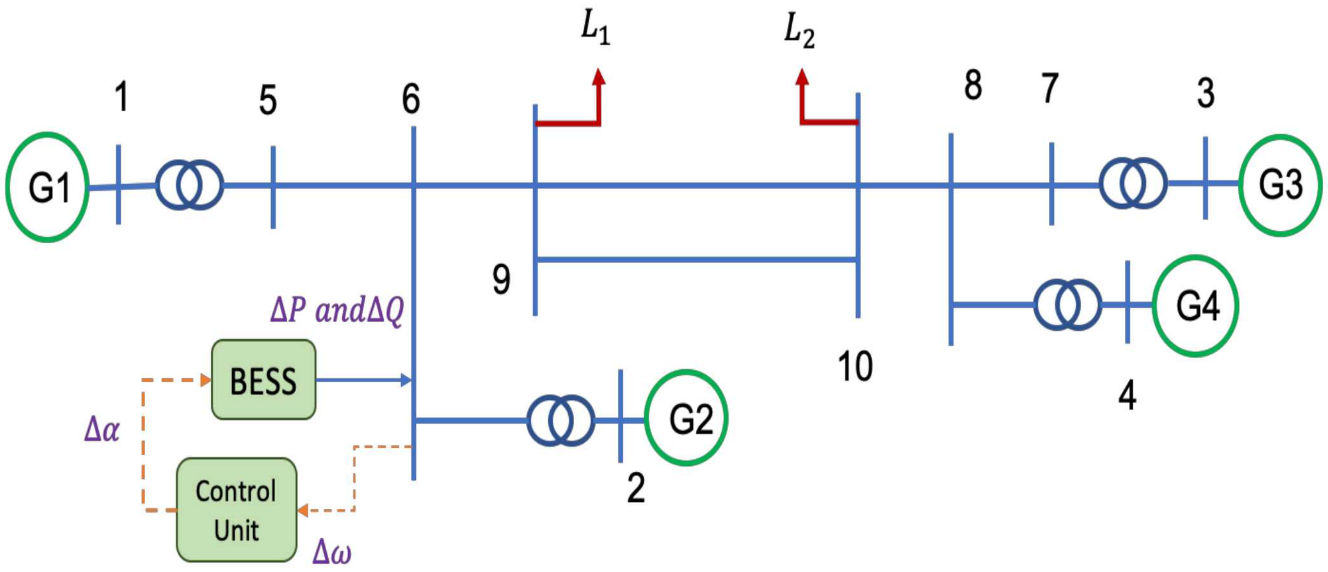
- We have accurate model for stability analysis especially for transient analysis.
- Since we have battery's states, we will be able to evaluate battery integration to the power system.

Two-Area Case Study Model

- A large-scale battery in connected to the two-area case study model
- we assume that we have access to all states' measurements
- The only control input is the battery's firing angle

$$\dot{X} = [A_t]X + [E]U_{c\_B}$$

$$A_t = [A] + [B][P]^t \left[Y'_{bus_{DQ}}\right]^{-1} [P][C]$$

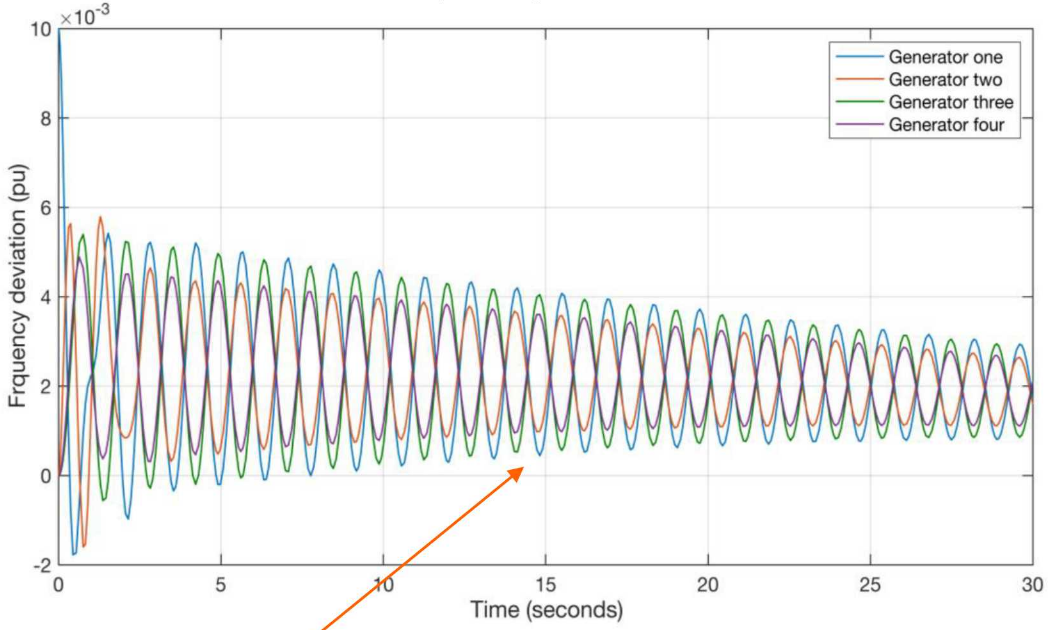


Battery integration to the two-area case study model

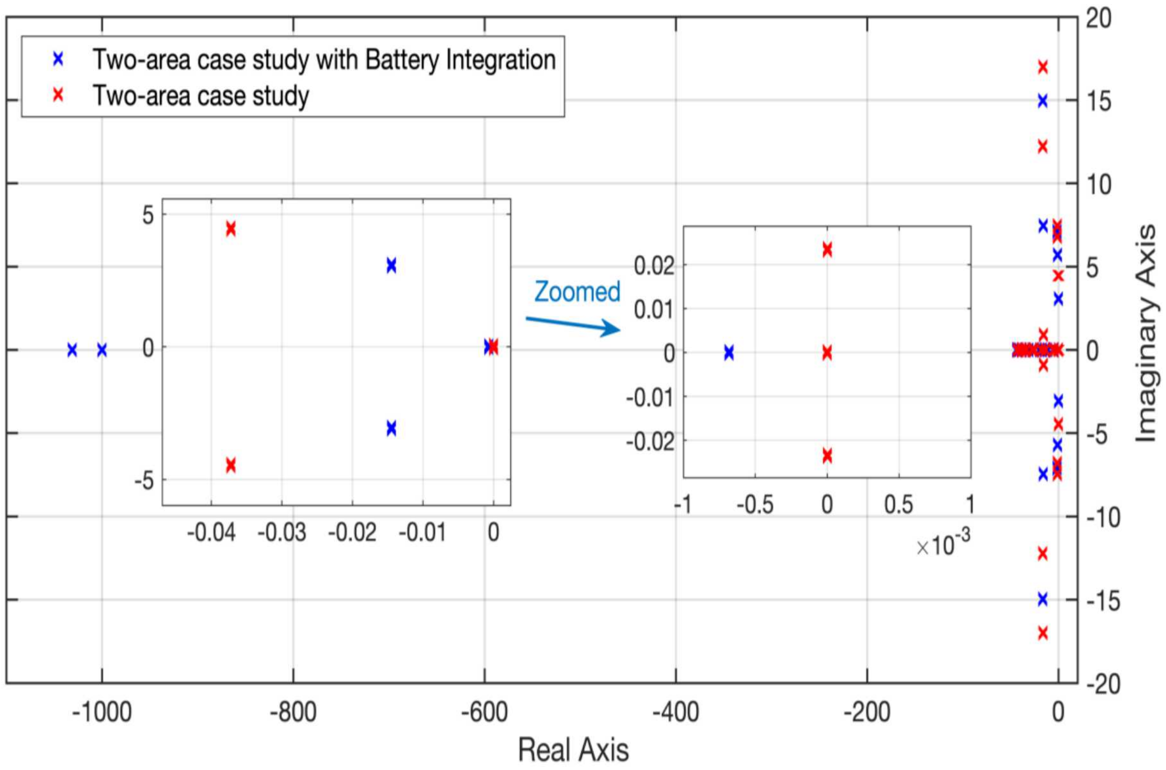
$$\left[Y'_{bus_{DQ}}\right] \Delta V_{QD} = [P_G][C_G][X_G] + [P_L][C_L][X_L] + [P_S][C_S][X_S] + [P_B][C_B][X_B]$$

Battery Integration Result

Generators' frequency deviation



Battery integration to two-area model eigenvalues



First and second generators in the first area are oscillating against the third and forth generators in the second area with the frequency of 2.37 hz.

Battery integration increase the stability of the system

Battery Control Design Approaches

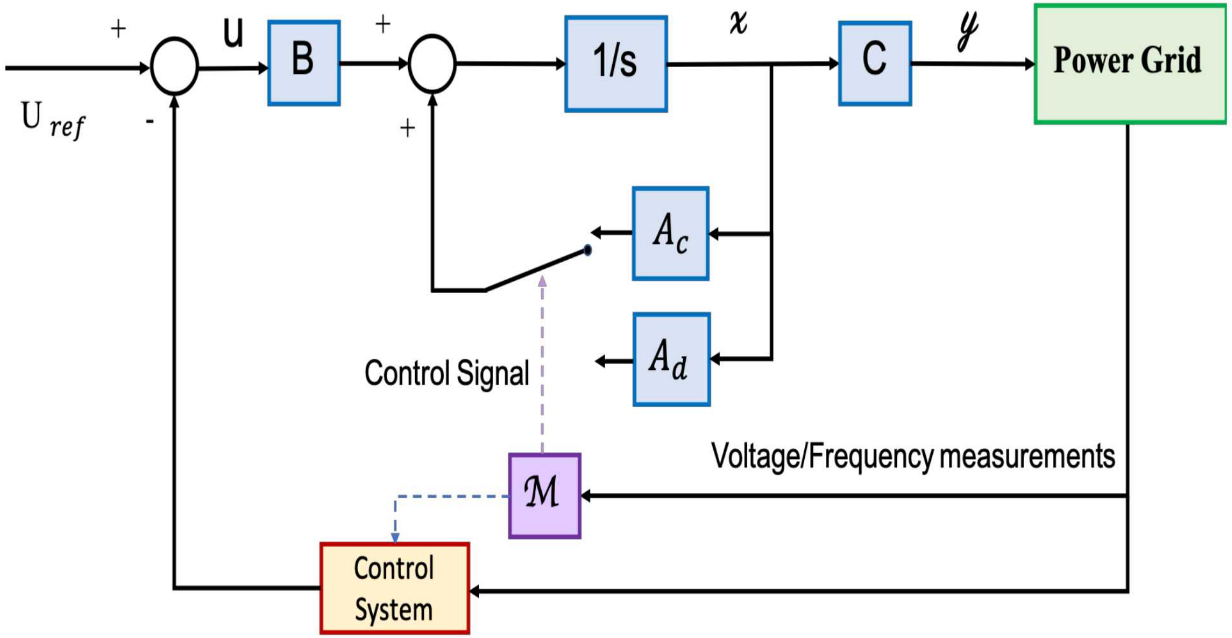
System state space model

Charging mode	$\begin{cases} \dot{x} = A_c x + B u_{cb\_c} \\ y_c = Cx \end{cases}$
Discharging mode	$\begin{cases} \dot{x} = A_d x + B u_{cb\_d} \\ y_d = Cx \end{cases}$

Switching policy

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

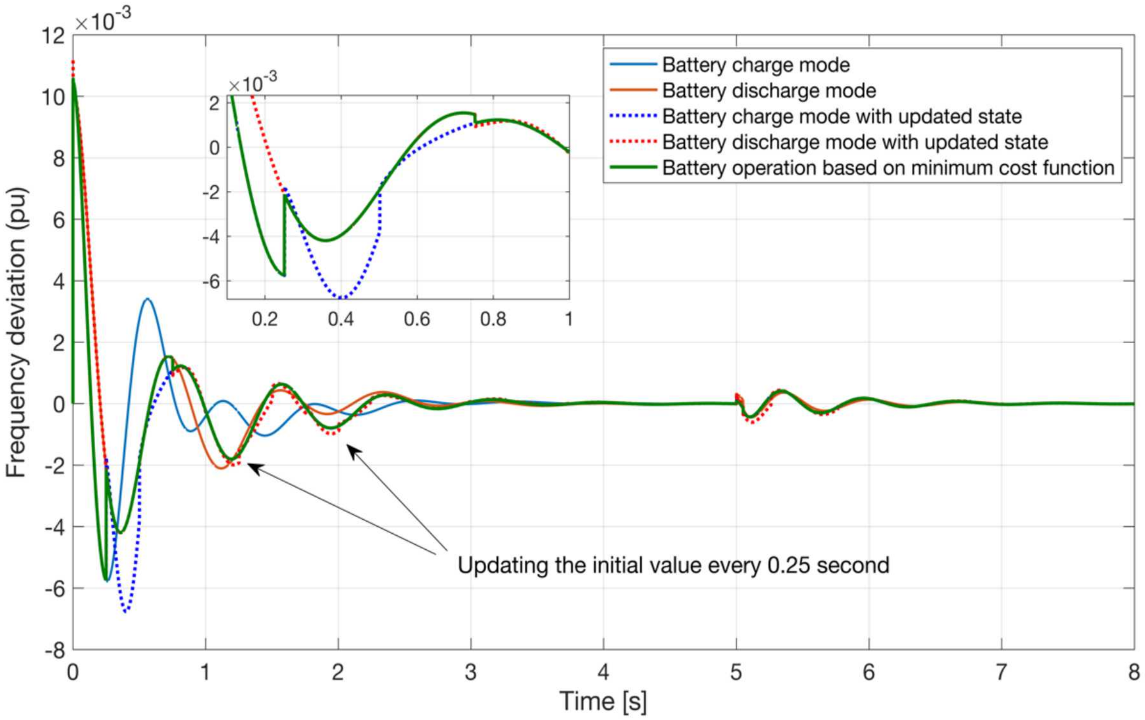
$$J_d = \int_{t_{k-1}}^{t_k} (x^T\, Q_d\, x + u_{cb\_d}^T\, R_d\, u_{cb\_d})\ d\tau$$



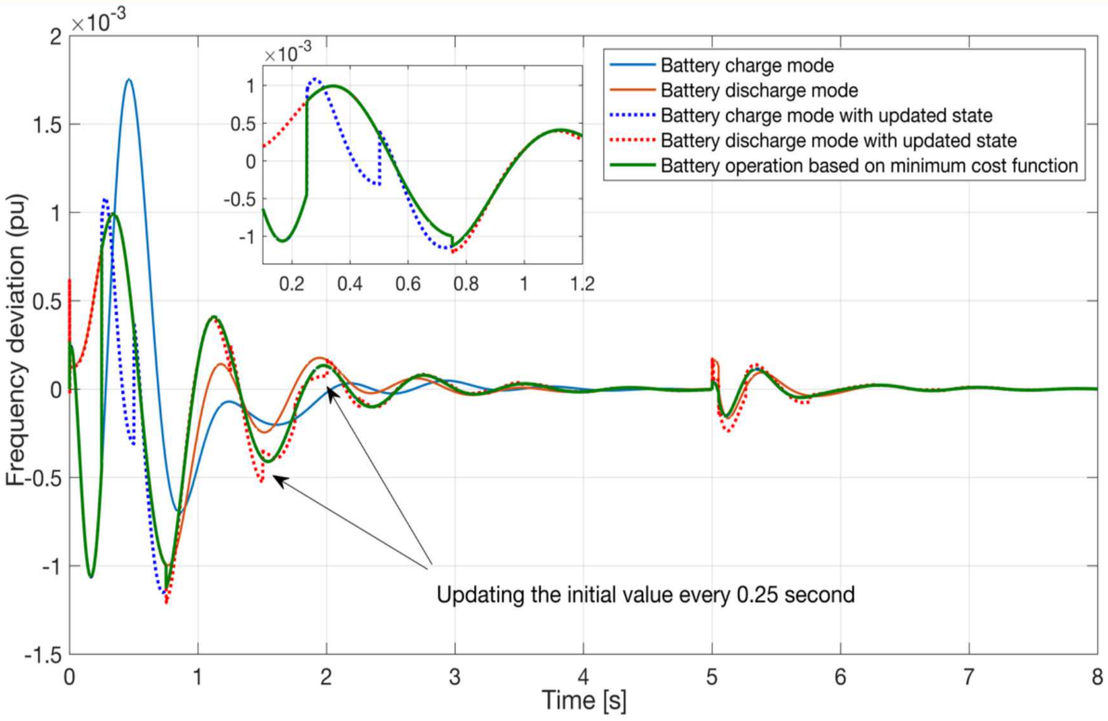
Control design approach based on charge and discharge of the battery

A switching policy will be considered to shift between charging and discharging conditions to minimize the cost function in each time interval of (t_{k-1}, t_k).

LQR State Feedback



Generator one in the first area



Generator three in the second area

- Using the LQR state feedback for charging and discharging scenarios, and switching between them, the frequency oscillations are damped in less than 5 seconds.
- Switching between charging and discharging occurs based on cost functions.

Conclusion and Future Work

Conclusion

- State space model of the battery has been represented in d-q structure, which is well suited for stability analysis in power systems
- Inverter firing angle is considered as an input enabling control of the battery’s power factor
- Hybrid control algorithm is designed to minimize frequent switching between charging and discharging modes of the battery

Future Work

- Suboptimal pole placement to move some critical poles to reduce the frequency deviation
- Decentralized output control design using distributed battery sites considering considering the limited availability of information

The authors gratefully acknowledge financial support from the U.S. Department of Energy’s Energy Storage Program, managed by Dr. Imre Gyuk.