# Degradation Aware Predictive Energy Management Strategy for Ship Power Systems


**Satish Vedula***

**Mehrzad Mohammadi Bijaieh**

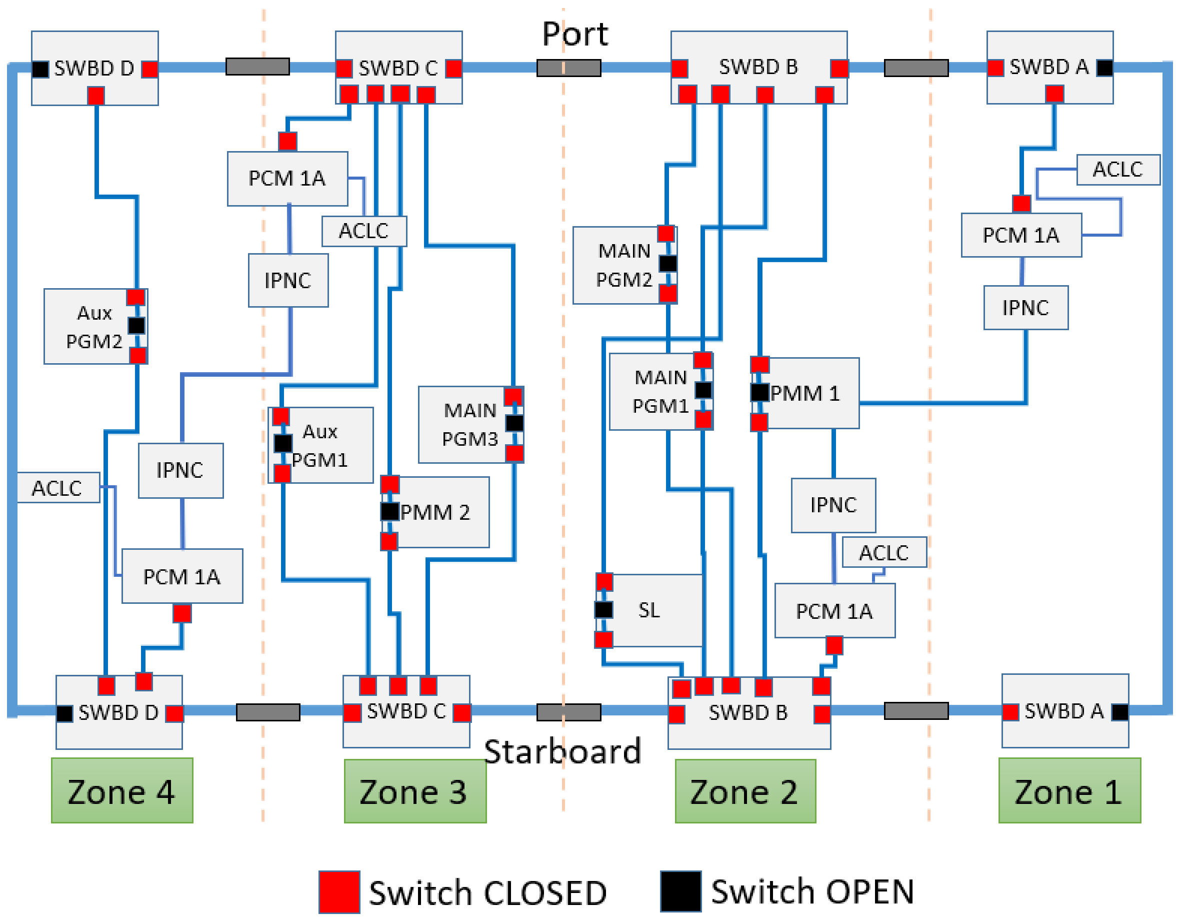
**Ellis Oti Boateng**

**Olugbenga Moses Anubi**

FLORIDA STATE UNIVERSITY
CENTER FOR ADVANCED POWER SYSTEMS

# Motivation

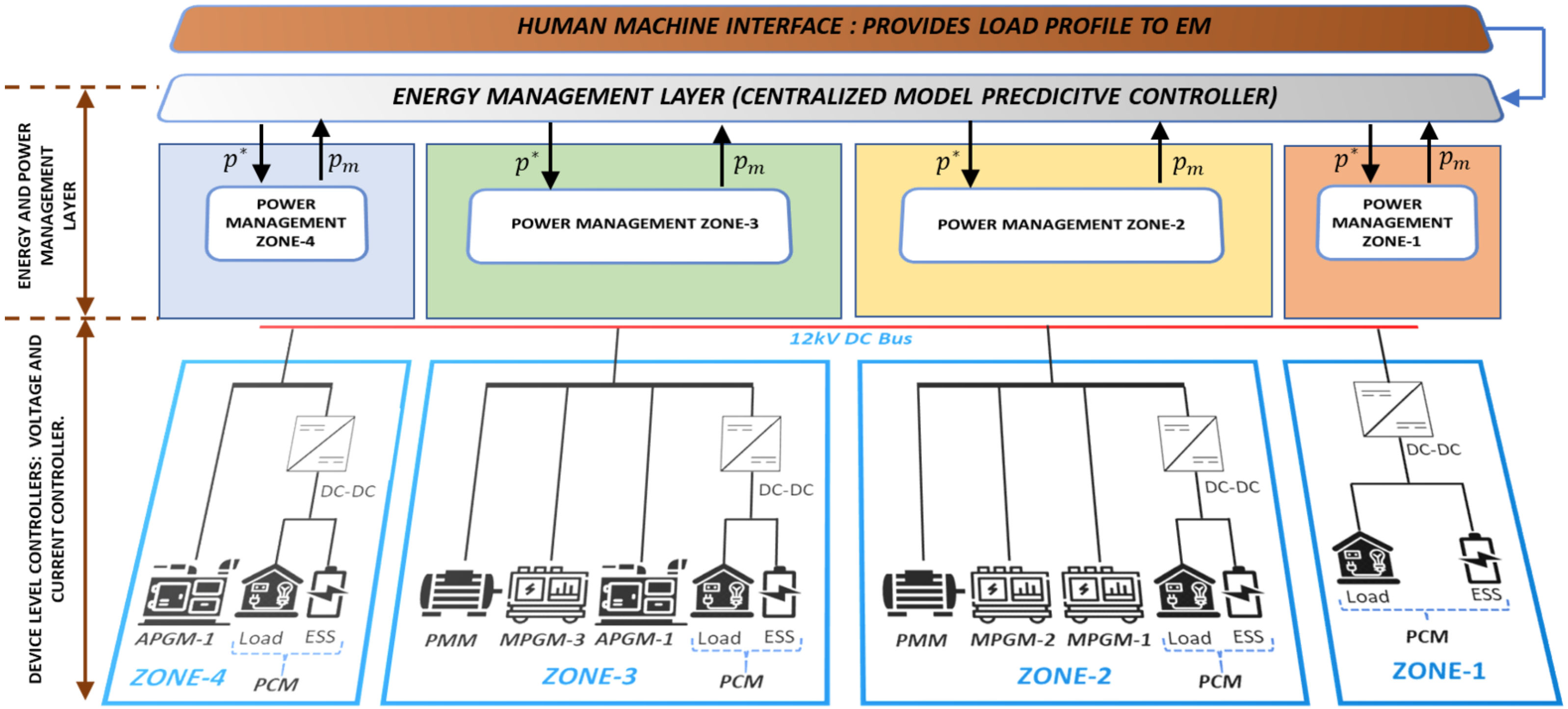
- Integration of modern defense weapons into ship power systems (SPS) poses a challenge in terms of meeting the high ramp rate requirements of those loads.
- Key power supplying sources:
  - Power Generation Module (PGM)
  - Power Conversion Module (PCM)
  - Auxiliary PGM (APGM)
- Key power demanding modules:
  - Propulsion Motor Module (PMM)
  - Pulse Power Loads (PPL)
    - High ramp-rate requirements
- Addressing the PPL ramp-rate requirements by designing an energy management strategy (EMS).



# Problem Statement

## Control Structure

- Hierarchical Control Structure in SPS
  - Energy Management Layer (EMS)
    - Optimizer
  - Power Management Layer (PMS)
    - Droop Control
  - Device Level Controllers (DLCs)
    - PI Control
- Power flow model in SPS
  - $g(\boldsymbol{p}_g, \boldsymbol{p}_b, \boldsymbol{p}_l) = 0$
  - $\boldsymbol{p}_g \in R^{n_g}$ represents the power injected by $n_g$ number of generators
  - $\boldsymbol{p}_b \in R^{n_b}$ represents power injected by $n_b$ number of ESS
  - $\boldsymbol{p}_l \in R^{n_l}$ represents number of loads in the system ($n_l$)




**APGM:** Auxiliary Power Generation Module, **PMM:** Propulsion Motor Module, **MPGM:** Main Power Generation Module, **PCM:** Power Conversion Module
**ESS:** Energy Storage System, **DC-DC:** DC to DC Convertor, **EM:** Energy Management, $\boldsymbol{p}_m$: Measured Power from Modules, $\boldsymbol{p}^*$: Optimal Power from EM

# Problem Statement

## MPC Formulation

- Decision Variables
  - $p_{g_k}$ : Generator Power
  - $p_{b_k}$ : Battery Power
- Load Forecast : $p_l^f$
- Decision Variable Initialization
  - $p_{g_m}$ : Measured Generator Power
  - $p_{b_m}$ : Measured Battery Power
- Upper and Lower Power Limitations
- Ramp Rate Limitations
  - $r_g$ : Generator Ramp Limitations
  - $r_b$ : Battery Ramp Limitations
- State of Charge (SoC)
  - $q_0$ : Initial SoC
  - $q_h$ : Final SoC (End of Horizon SoC)

Objective

$$\text{Minimize:} \quad \sum_{k=1}^{h} \left\| p_{g_k} + p_{b_k} - p_l^f \right\|^2 + \gamma C(p_k)$$

$$\text{s.t.} \quad \sum_{k=1}^{h} p_{b_k} = \frac{3600 Q_T v_b^*}{T_s}(q_0 - q_h)$$

$$p_{g_0} = p_{g_m}$$

$$p_{b_0} = p_{b_m}$$

$$\underline{p}_g \preceq p_{g_k} \preceq \overline{p}_g$$

$$\underline{p}_b \preceq p_{b_k} \preceq \overline{p}_b$$

$$|p_{g_k} - p_{g_{k-1}}| \preceq r_g, \quad k = 1, 2, ...., h$$

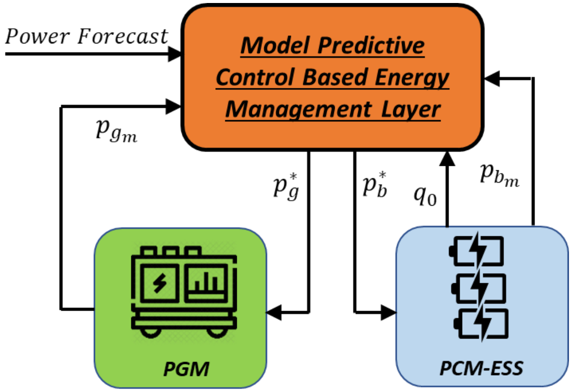
$$|p_{b_k} - p_{b_{k-1}}| \preceq r_b, \quad k = 1, 2, ...., h$$

Constraints

# Problem Statement

- Other Descriptions
  - $Q_T$ : Battery Capacity in AHr
  - $v_b^*$ : Bus Voltage
  - h : Horizon
- Battery Monitored Quantities
  - State of Health (SOH)
    - $Q_{loss}$ : Battery Capacity Loss
    - Ah : Ah-throughput
      - Calculated as Integral of current throughput till end of life.
  - State of Charge (SOC)
- Generator Monitored Quantities
  - State of Power (SOP in %)
    - Measured by dividing current power by rated power and multiplied by 100.
  - State of Health (SOH)
    - Based on Stress Equation and degradation determined through integral of power supplied through end of life.
- Simulation tested on Single generator, battery and load model shown to the left

$$Q_{loss} = Be^{\frac{-A \times C_{rate}}{RT}} (Ah)^{0.5}$$



# Results

## Load Forecast

- Power Forecast is generated to replicate the usage of PPLs.
- Noise varying from 1% to 10% threshold is introduced to the load forecast as seen in the figure to the left.
- The table showing the component ratings for PCM, PGM and PMM used for the simulation.

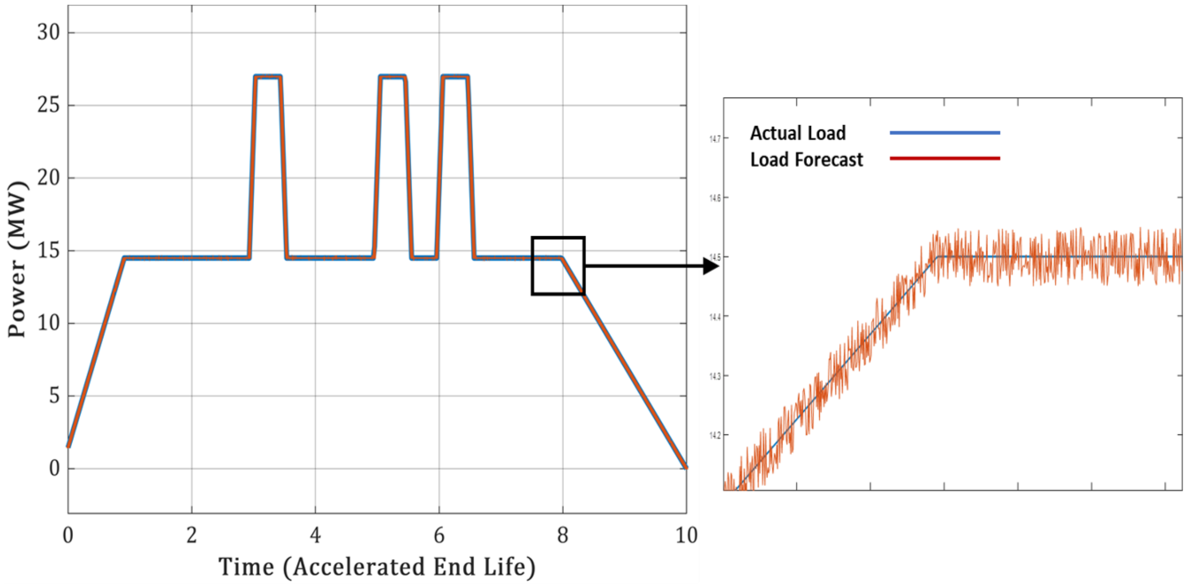
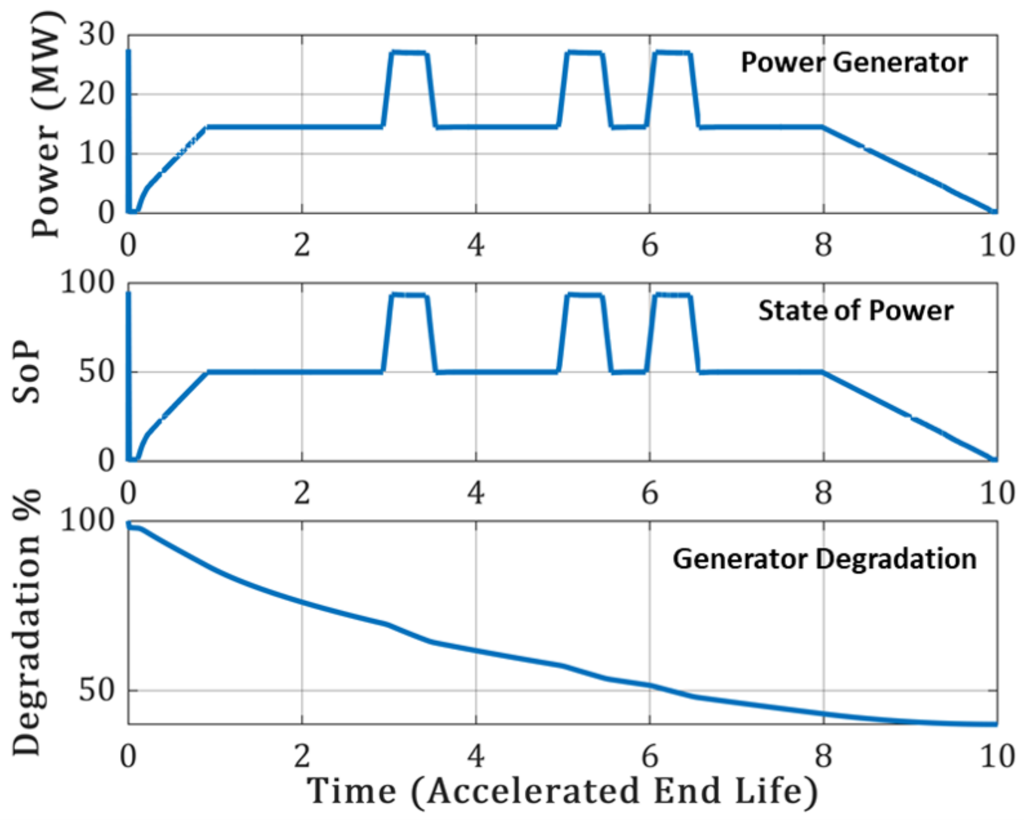



TABLE I: System Components Power Ratings

| PGM, PCM and Load Ratings | | | | |
|---|---|---|---|---|
| | Power (MW) | RR (MW/sec) | LL (MW) | UL (MW) |
| PGM | 29 | 2.9 | 0.29 | 27.5 |
| PCM | 30 | 10 | -10.64 | 10.64 |
| Load | 30 | 10 | - | - |

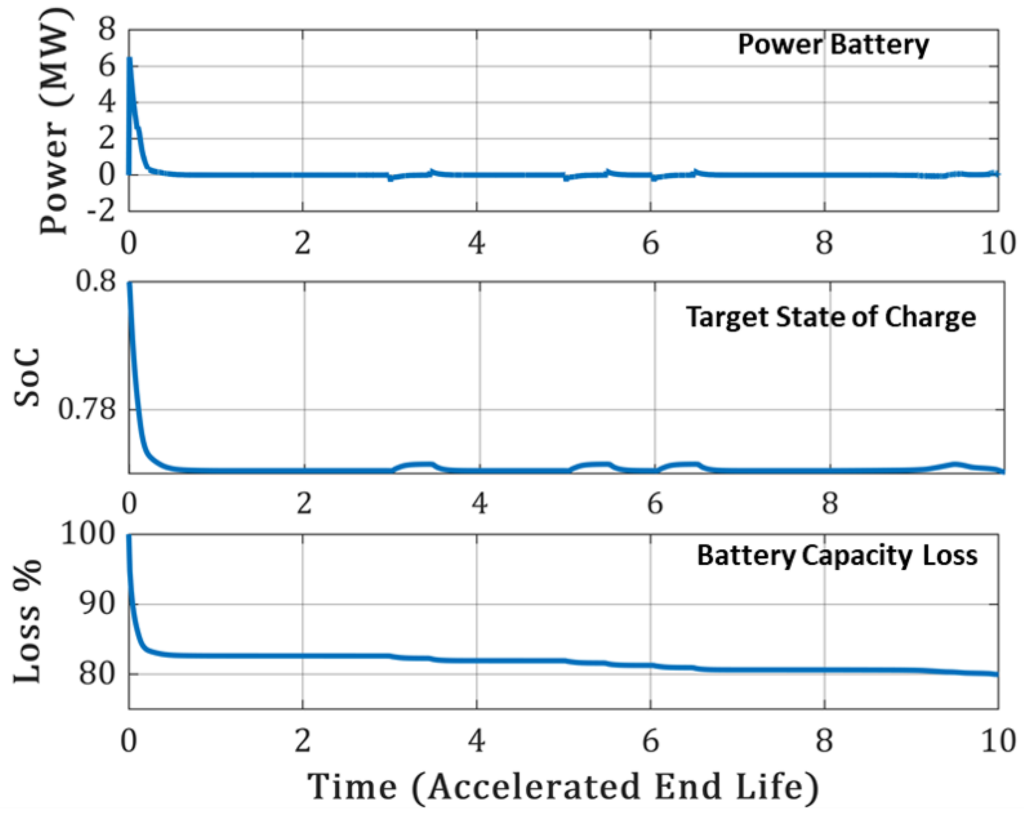
# Results

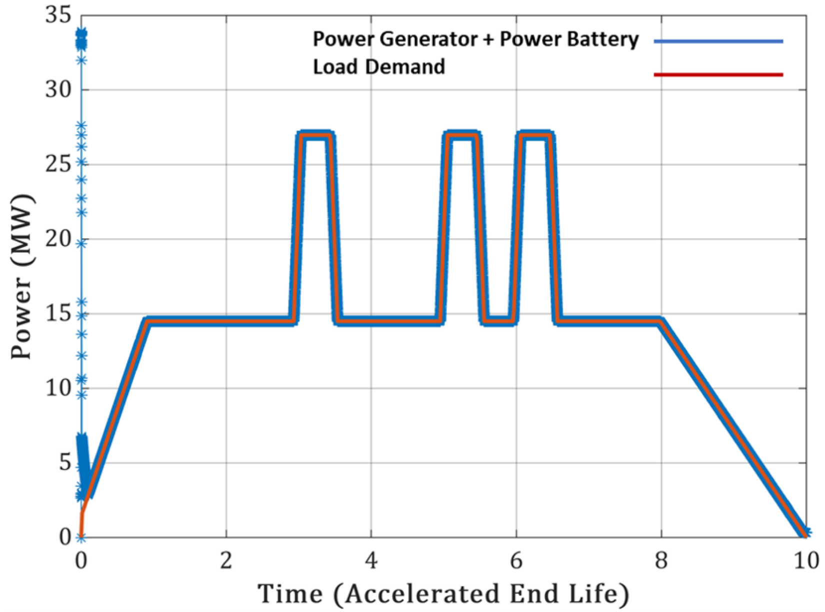
- **Simulation Setup**
  - Initial SOC : 0.8
  - Final SOC : 0.77
  - Simulation Timestep : 100$\mu s$
  - EMS and System Timescale separation = 1$ms$
- PGM
  - Power Injected by the PGM in (MW)
  - SOP of the PGM throughout the simulation
  - SOH of the PGM are shown in the figure to the right.



# Results

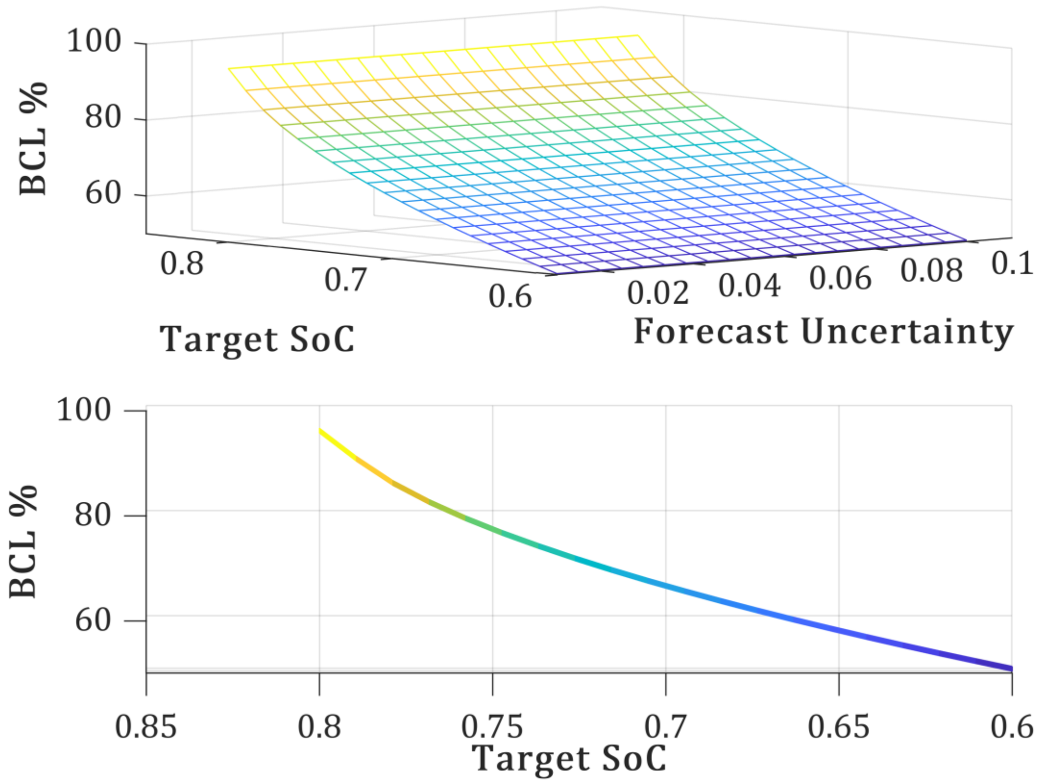
- PCM
  - Power Injected by the battery in (MW)
  - SOC of the battery throughout the simulation
  - SOH of the battery are shown in the figure to the right. The simulation run is adjusted to meet the accelerated end of life for components
- Combined Power injections by generator and battery compared to power forecast shown in figure below.



# Results

- Battery Degradation Data
  - Varying noise power from 1% to 10% is injected into load forecast and the resulting effect on the robustness of the controller, the battery target SoC and battery accelerated capacity loss is studied.
  - The target SOC is swept from 0.8 to 0.6
  - Using parallel simulation (*parsim)* environment in Simulink the simulation is run 400 times based on situations mentioned above.
- The collected data from the simulations is plotted as "degradation curve" shown in the figure to the right.



# Conclusions and Future Work

- Conclusion
  - An EMS for SPS considering the ramp-rate limitations of Generator and Batteries is presented.
  - Power forecast is designed to address the usage of PPLs.
  - The formulated MPC is validated is run in *parsim* and the degradation data is collected and plotted.
- Future Work
  - Current simulation results have been implemented on a single generator, battery and load model as shown to the left.
  - Future goal is to expand this work to multi zone SPS, staring with 2-zone model and then the 4-zone model.
  - Introducing the collected battery degradation data as the cost function in the objective shown to the right.

Objective

$$\text{Minimize:} \quad \sum_{k=1}^{h} \left\| \mathbf{p}_{g_k} + \mathbf{p}_{b_k} - \mathbf{p}_l^f \right\|^2 + \gamma C(\mathbf{p}_k)$$

*Introduce Degradation*

$$\text{s.t.} \quad \sum_{k=1}^{h} \mathbf{p}_{b_k} = \frac{3600 Q_T v_b^*}{T_s}(q_0 - q_h)$$

$$\mathbf{p}_{g_0} = \mathbf{p}_{g_m}$$

$$\mathbf{p}_{b_0} = \mathbf{p}_{b_m}$$

$$\underline{\mathbf{p}}_g \preceq \mathbf{p}_{g_k} \preceq \overline{\mathbf{p}}_g$$

$$\underline{\mathbf{p}}_b \preceq \mathbf{p}_{b_k} \preceq \overline{\mathbf{p}}_b$$

$$|\mathbf{p}_{g_k} - \mathbf{p}_{g_{k-1}}| \preceq r_g, \quad k = 1, 2, ...., h$$

$$|\mathbf{p}_{b_k} - \mathbf{p}_{b_{k-1}}| \preceq r_b, \quad k = 1, 2, ...., h$$

Constraints

# THANK YOU

**Satish Vedula: svedula@fsu.edu**

FLORIDA STATE UNIVERSITY
CENTER FOR ADVANCED POWER SYSTEMS