Model and Load Predictive Control for Design and Energy Management of Ship Power Systems

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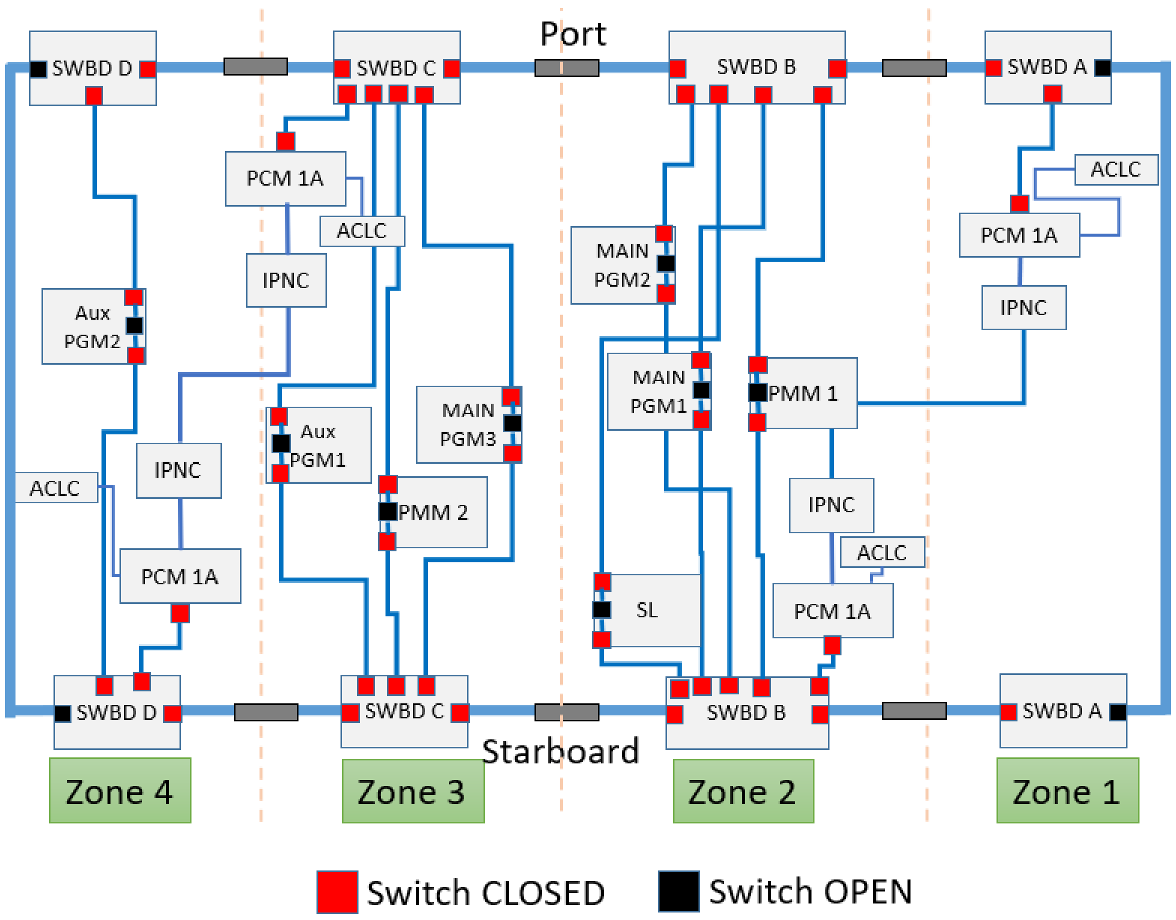
Motivation

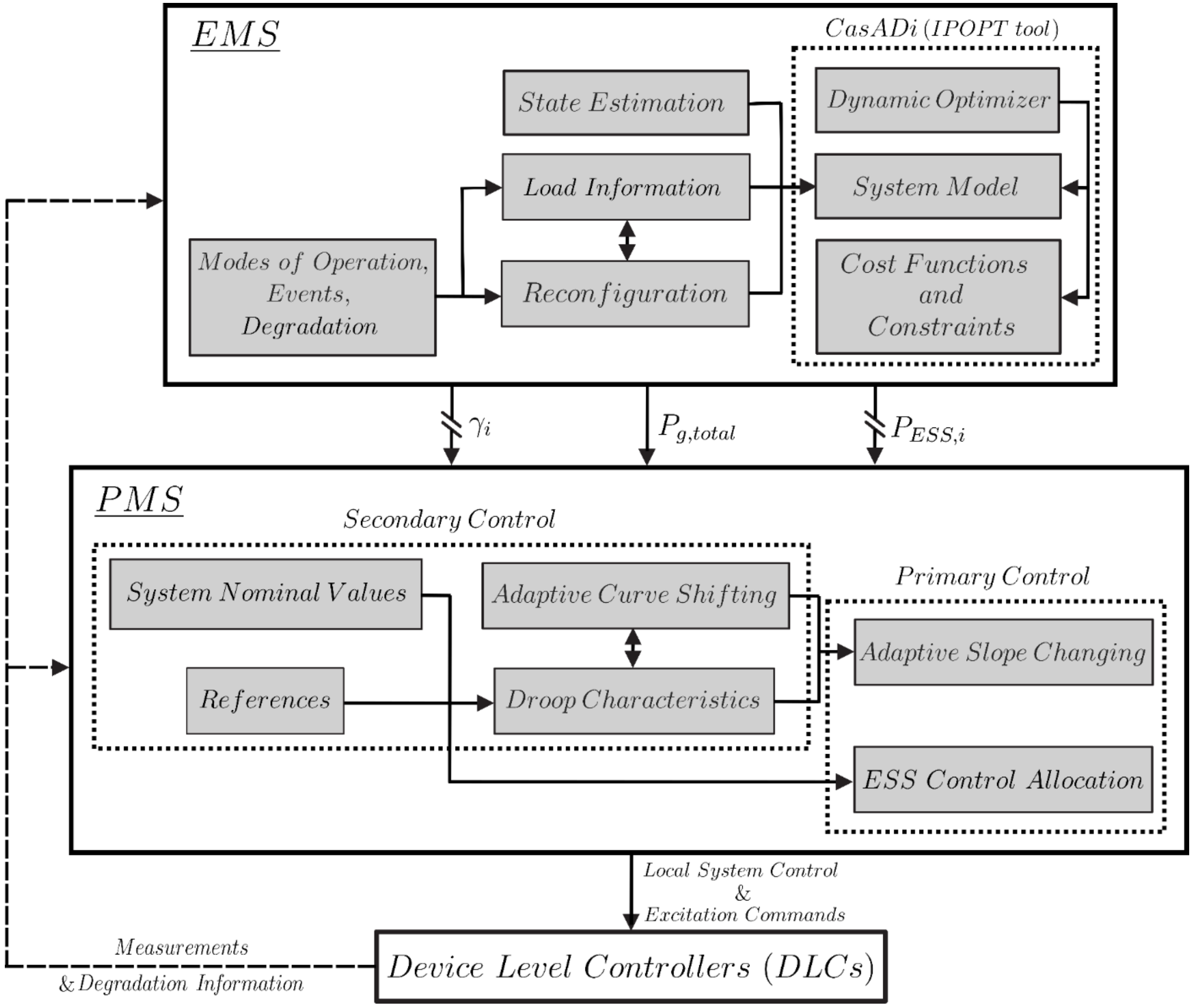
- In current medium voltage DC (MVDC) shipboard power systems (SPS) multiple sources exist to supply power to common DC bus.
- Key power supplying sources:
  - Power Generation Module (PGM)
  - Power Conversion Module (PCM)
  - Auxiliary PGM (APGM)
- Key power demanding modules:
  - Propulsion Motor 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

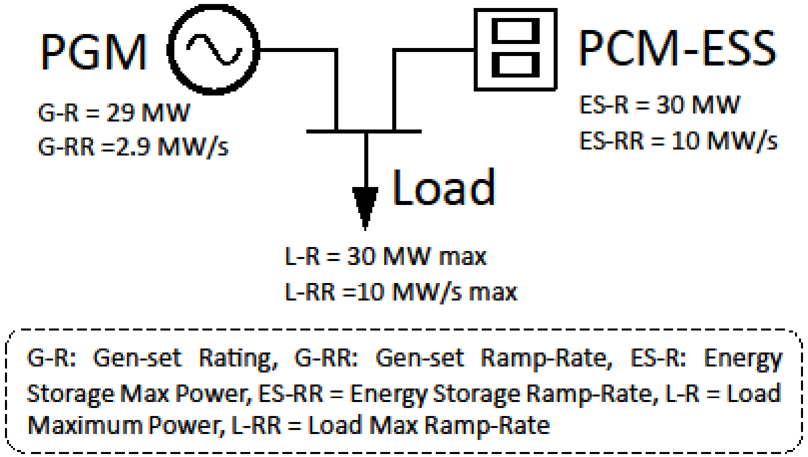
- Hierarchical Control Structure in SPS
  - Energy Management Layer (EMS)
    - Optimizer
  - Power Management Layer (PMS)
    - Droop Control
  - Device Level Controllers (DLCs)
    - PI Control
- Power flow model in SPS
  - $f(P_g, P_L, P_B) = 0$
  - P_g, P_L, P_B represent the gen-set, load and batteries powers.
- PGM feedforward and feedback control.



Problem Statement

Component Models

- PGM Component Model:
  - The low band width model consisting of first order filter fed into control dependent voltage source, an RL line, a shunt capacitor and a parallel damping resistor.
- PCM Component Model:
  - Consists of ideal Energy storage system (ESS) which may include single or hybrid storage systems such as battery energy storage systems (BESS).
- PMM Component Model:
  - Controlled current source and a parallel RC pair.
- Detailed mathematical description and modelling is available in the paper.



Problem Statement

MPC Problem Formulation

- Decision Variables
  - P_{g_k} : Generator Power
  - P_{b_k} : Battery Power
- Load Forecast : $P_{L_k}^f$
- Ramp Rate Limitations
  - r_g : Generator Ramp Limitation
  - r_b : Battery Ramp Limitation
- Upper and Lower power limitations for generator and battery.
- Other Descriptions:
  - Q_T : Battery Capacity
  - x_0 : Initial State of Charge (SOC)
  - x_h : Final or Parking SOC
    - Desired SOC at the end of Horizon
  - v_b^* : Controlled Bus Voltage

Objective

$$\min \underbrace{\sum_{k=1}^{h} \left(\left\| P_{g,k} + P_{b,k} - P_{L,k}^{f} \right\|^2 + \lambda C(P_{g,k}) \right)}$$

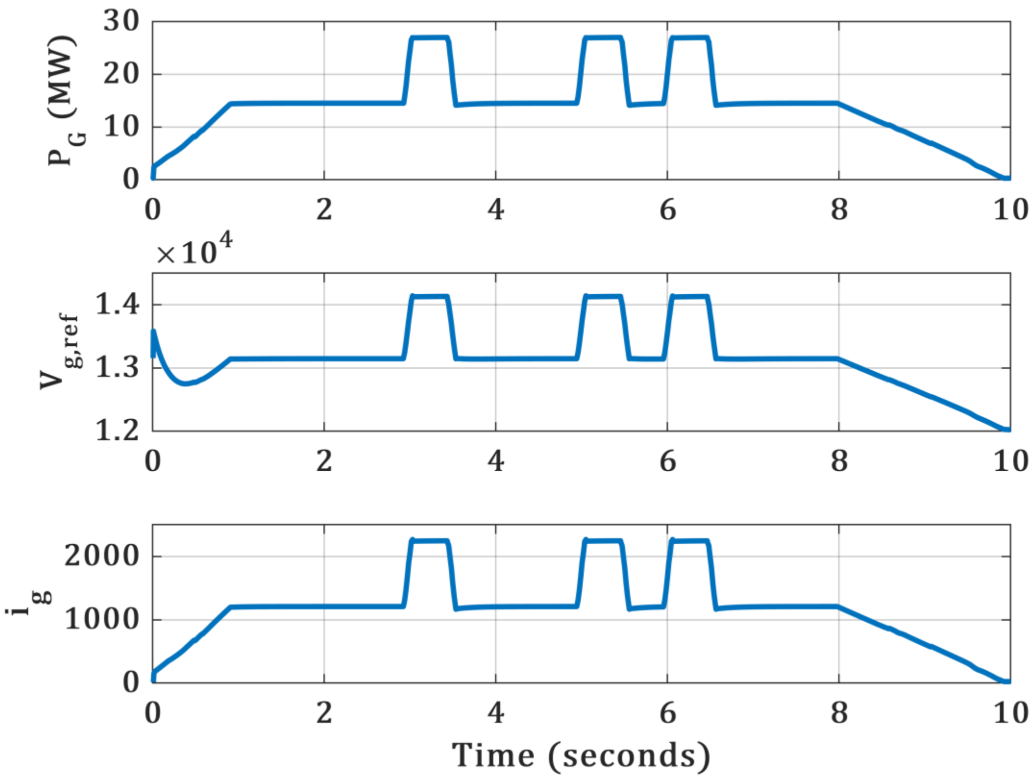
Constraints

$$\left.\begin{aligned}
&\sum_{k=1}^{h} P_{b,k} = Q_b \\
&\underline{P_g} \leqslant P_{g,k} \leqslant \overline{P_g} \\
&|P_{g,k} - P_{g,k-1}| \leqslant r_g \\
&\underline{P_b} \leqslant P_{b,k} \leqslant \overline{P_b} \\
&|P_{b,k} - P_{b,k-1}| \leqslant r_b, \\
&Q_b = \frac{3600 * Q_T * v_b^*}{T_s}(x_0 - x_h).
\end{aligned}\right\}$$

Results

Case 1: Initial SOC as Final SOC

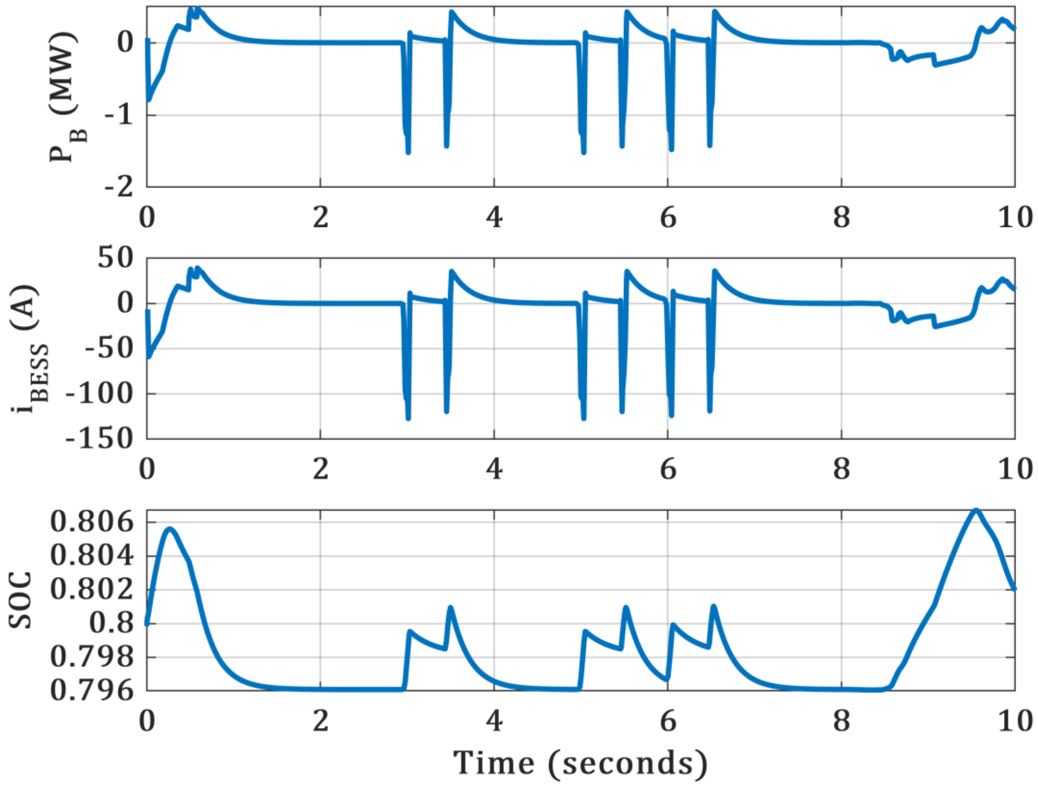
- Initial SOC : 0.8
- Power Forecast is generated to replicate the usage of PPLs (Shown in Next Slide).
- Simulation Setup
  - Software in Loop (SIL) on SN5726 SPEEDGOAT performance target
  - Horizon Length (h) = 5
  - Simulation Timestep = 100μs
  - EMS and System Timescale separation = 1ms
- Figure
  - Power injected by PGM in (MW)
  - Reference voltage with respect to power injection in (V)
  - Generator current in (A)

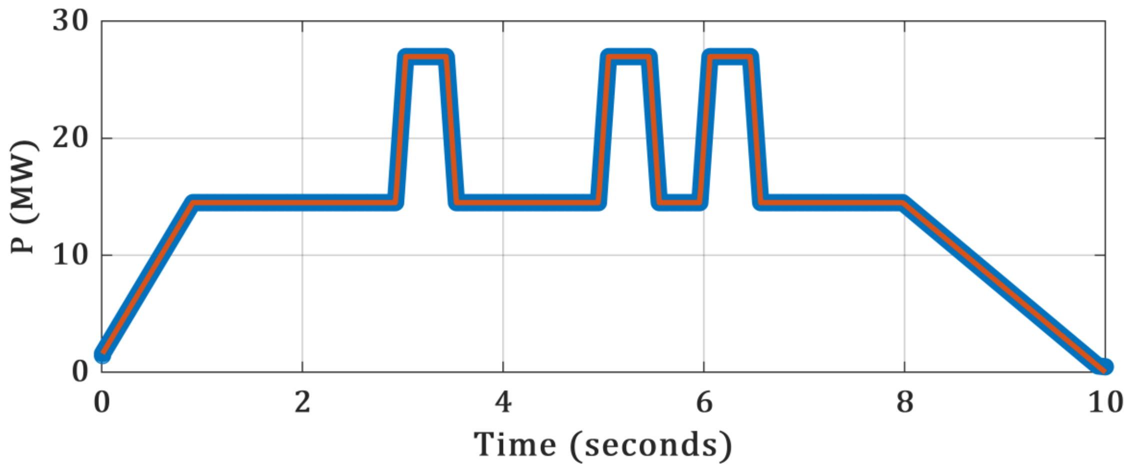


Results

Case 1: Initial SOC as Final SOC

- Initial SOC : 0.8
- Figure Right
  - Battery Power Injection in (MW)
  - Battery Current response to injection in (A)
  - Battery SOC
- Figure Left Bottom
  - Blue Line : Combined Power Injected by Battery and Generator
  - Red Line : Power Forecast





Results

Case 2: Arbitrary Parking SOC

- Initial SOC : 0.8
- Parking SOC : 0.77
- Simulation Setup
  - Software in Loop (SIL) on SN5726 SPEEDGOAT performance target
  - Horizon Length (h) = 5
  - Simulation Timestep = 100μs
  - EMS and System Timescale separation = 1ms
- Figure
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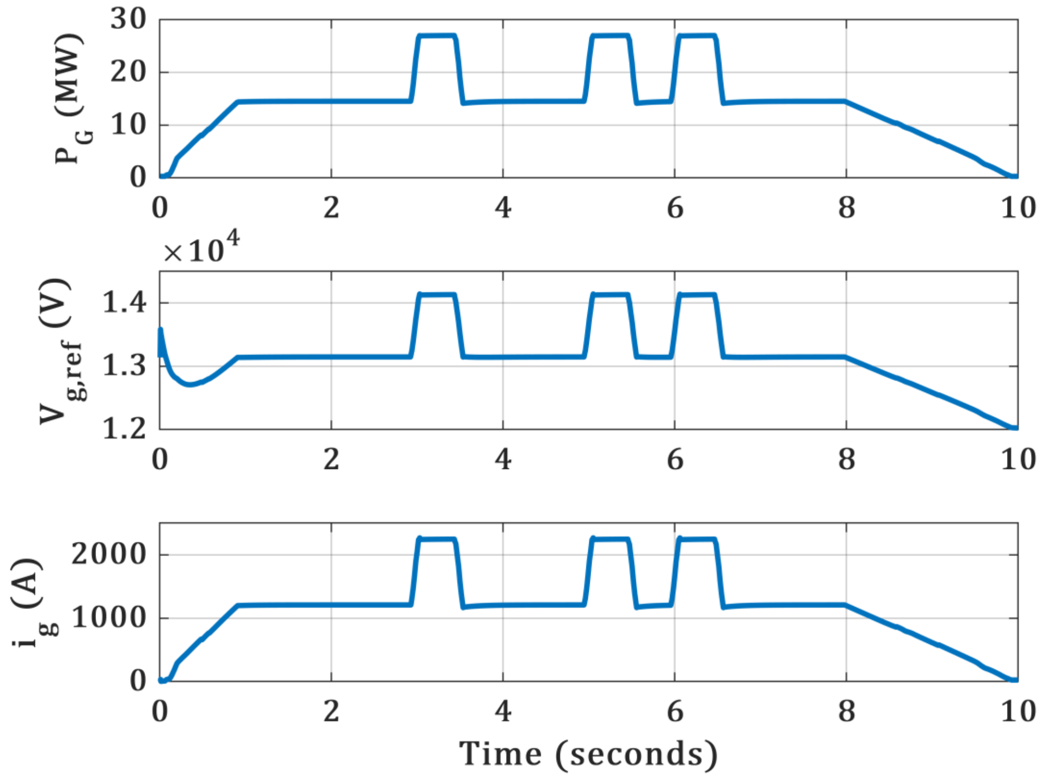

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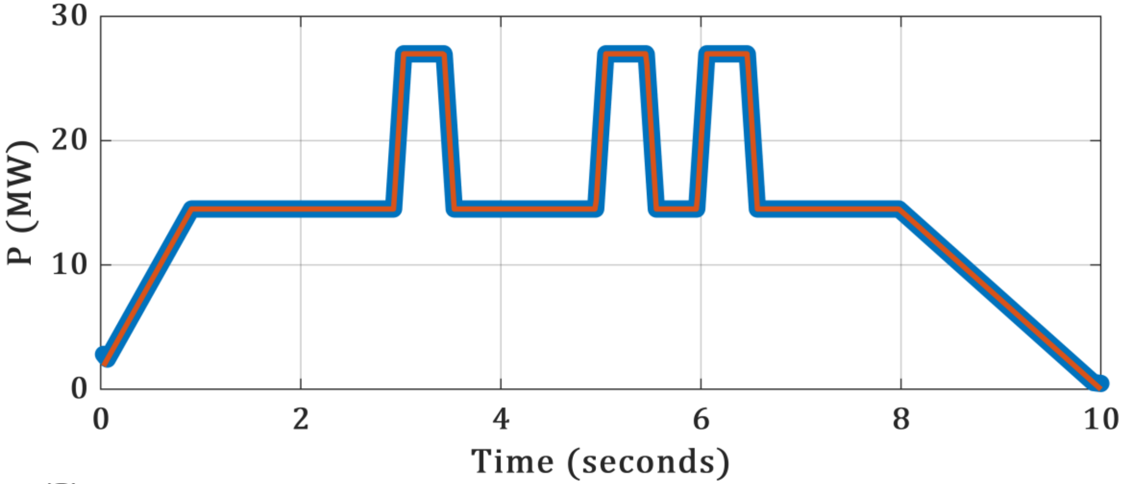
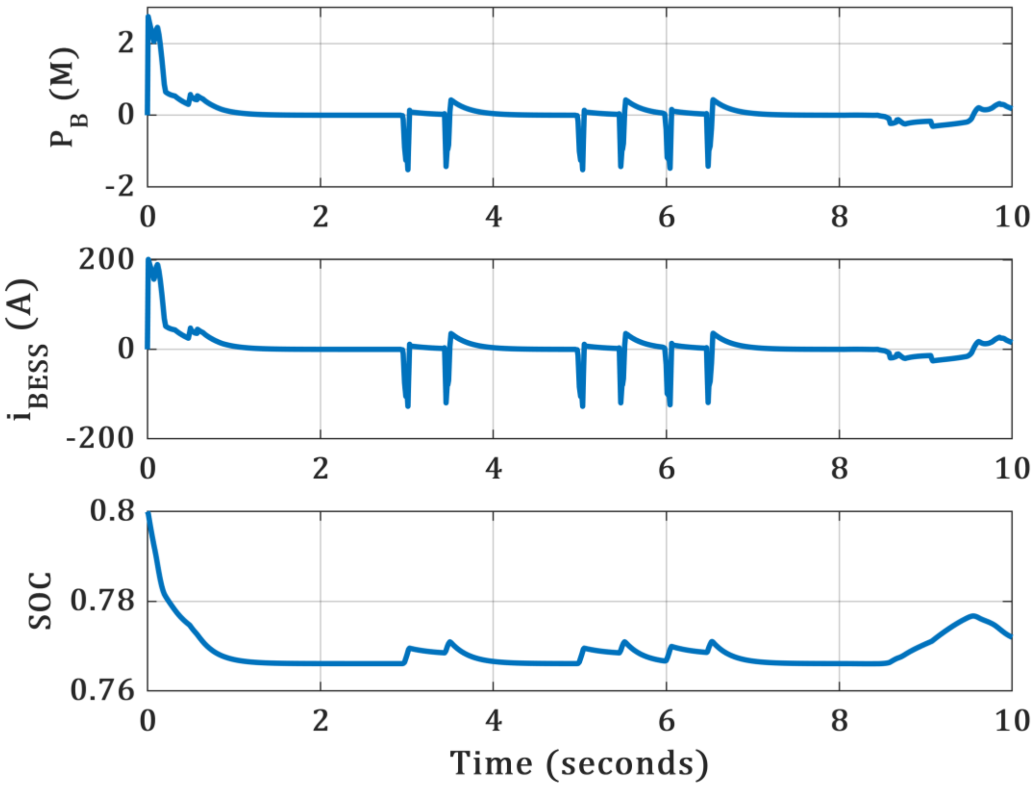
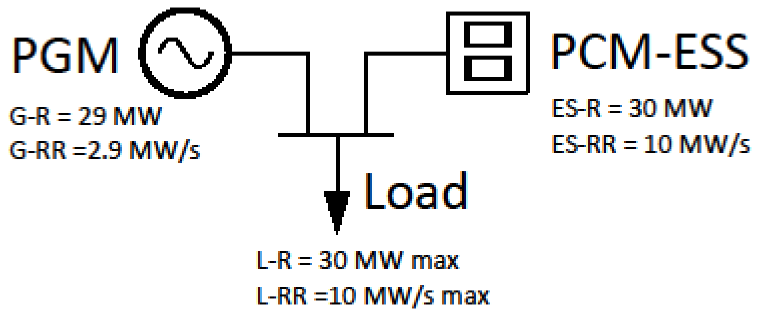




Conclusions and Future Work

- 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 in a SIL environment, and the results are presented.
- 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.
  - The battery and generator component degradation is not considered in this work. The future iterations will include battery degradation model and a degradation based reformulated MPC problem.



G-R: Gen-set Rating, G-RR: Gen-set Ramp-Rate, ES-R: Energy Storage Max Power, ES-RR = Energy Storage Ramp-Rate, L-R = Load Maximum Power, L-RR = Load Max Ramp-Rate

THANK YOU

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