HOLMS: Hierarchical Optimal Load Management System for Aircraft Electric Power Distribution


Mehdi Maasoumy, Pierluigi Nuzzo,
Alberto Sangiovanni-Vincentelli and Claire Tomlin
University of California at Berkeley


TerraSwarm

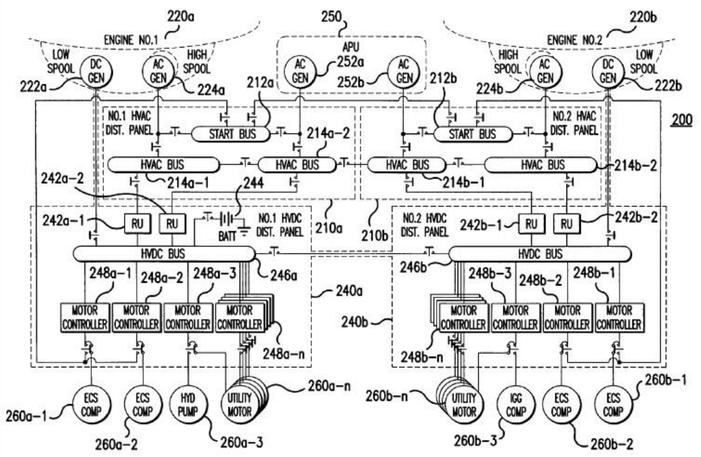
Theme 4, Methodologies and Tools, Task 4.1

We address the problem of correct-by-construction control design for aircraft Electric Power Systems within a Platform-Based Design methodology. We first formalize the system **connectivity**, **safety** and **performance** requirements in terms of mathematical constraints. We then show that the EPS control problem can be formulated as a **Mixed-Integer Linear Program (MILP)** and efficiently solved to yield **load shedding**, **source allocation**, **contactor switching** and **battery charging** policies, while optimizing a number of performance metrics, such as the **number of used generators** and **shed loads**. Our solution comprises a **hierarchical** control scheme that accounts for system faults. The **high-level load management system (HL-LMS)** provides control optimality by solving the MILP within a **receding horizon** approach**.** The **lower-level load management system (LL-LMS)** handles system faults, by directly actuating the EPS contactors and implements the solution from the high-level controller only if it is safe.

Electric Power System (EPS)

An aircraft EPS consists of a combination of **generators**, contactors, buses and loads. Power is distributed via **buses** and connections of generators to loads are routed by a series of electronic switches, denoted as **contactors**.

EPS design is performed today mostly following a sequential derivative design process (V diagram) with limited capability of estimating the effects of earlier design decisions on the final implementation.



Single line diagram. Honeywell, Inc. patent.

Specifications

Safety:

- **NO parallelization of AC sources**
- $15 \leq \tau_{\text{contactor closure}} \leq 25\ ms$
- $10 \leq \tau_{\text{contactor opening}} \leq 20\ ms$
- $\tau_{\text{AC buses unpowered}} \leq 50\ ms$
- $\tau_{\text{DC buses unpowered}} = 0\ ms$
- **Percentage of working motor drives** = 50%

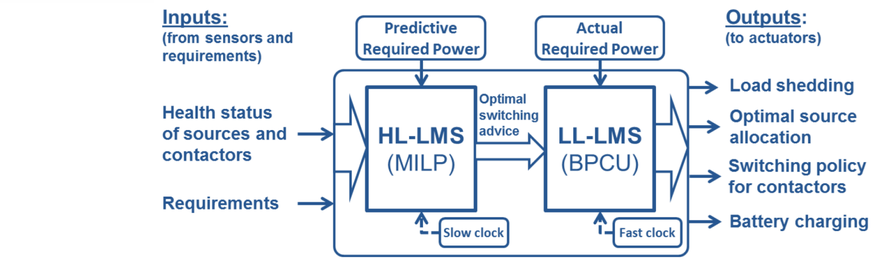
Reliability:

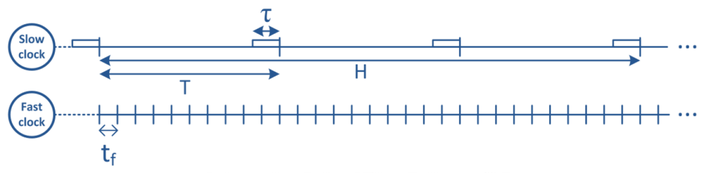
Given **reliability levels** for components the **system** must be designed to be safe to 10^{-9} under all conditions.

Performance:

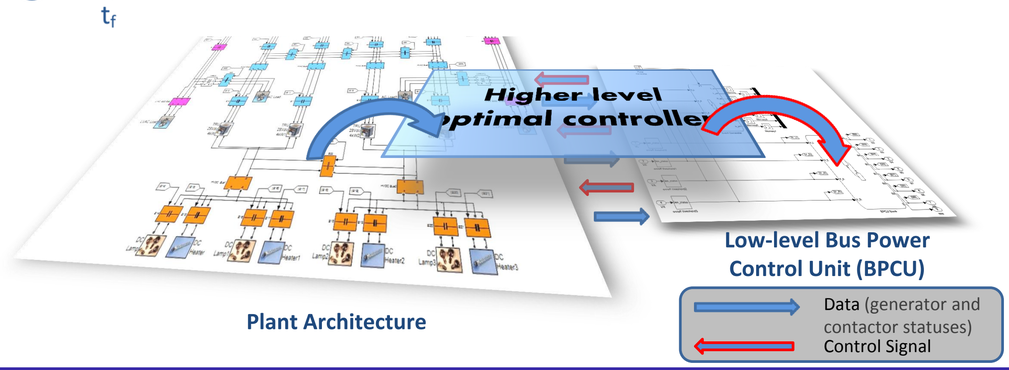
- **Bus Priority**: Each bus has a priority list of which generator will be used to provide power first.
- **No bus has priority over another bus.**
- **Load shedding priority:** Sheddable loads are allowed to be shed if power supplies are insufficient, while non-sheddable loads must remain powered at all times.

Proposed architecture: Hierarchical Optimal Load Management System (HOLMS)



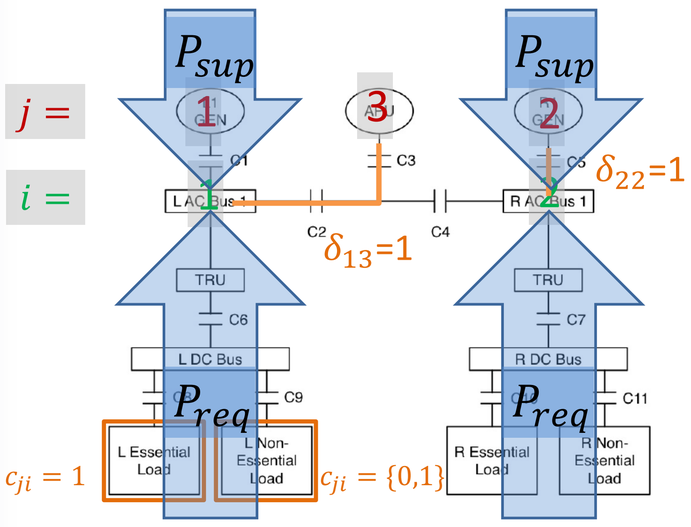


Receding Horizon Scheme
(H is the time horizon, τ is the maximum computation time of the optimal control problem)



Plant Architecture

Problem Formulation: Capturing the specifications and control goals as mathematical constraints to form the optimization problem



Load shedding priority constraints

LOAD PRIORITY TABLE FOR HVAC BUS 1.

Non-sheddable load (W)	sheddable load (W)	Shed priority
1000	1000	1
1000	1000	5
2000	1000	7
2000	1000	10
5000	2000	4
5000	2000	8
500	2000	9
500	2000	3
1000	5000	6
1000	5000	2

$$c_{j1}(t) \leq c_{j2}(t) \leq \ldots \leq c_{jn_j}(t) \quad \forall t \geq 0$$

Where: $c_{ji}(t) = 1 \quad \forall j = 1,2 \quad \forall i \in I_{NS} \quad \forall t \geq 0$
$c_{ji}(t) = \{0,1\} \quad \forall j = 1,2 \quad \forall i \in I_S \quad \forall t \geq 0$

n_j: number of sheddable loads of bus j

Bus priority table

Formulated as a "***penalty***" term in the cost function:

BUS PRIORITY TABLE.

Priority	HVAC 1	HVAC 2
1	Eng 1 HV-VFG	Eng 2 HV-VFG
2	Eng 2 HV-VFG	Eng 1 HV-VFG
3	APU-VFG	APU-VFG

$$\sum_{j=1}^{N^b} \sum_{t=t^*}^{t^*+H\cdot T_s} \Lambda_j^T \Delta_j(t)$$

Where: $\Lambda_j = [\lambda_{j1} \quad \lambda_{j2} \quad \lambda_{j3}]^T$ Weighting matrix

$\Delta_j(t) = [\delta_{j1}(t) \quad \delta_{j2}(t) \quad \delta_{j3}(t)]^T$ Decision variables

e.g. : $\lambda_{13} \gg \lambda_{12}$, $\lambda_{11} = 0$

Shedding the smallest number of loads

$$\sum_{j=1}^{N^b} \sum_{t=t^*}^{t^*+H\cdot T_s} \Gamma_j^T [1 - C_j(t)] + \mu \sum_{j=1}^{N^s} \sum_{t=t^*}^{t^*+H\cdot T_s} \alpha_j(t)$$

(Penalty term in the cost function)

Minimize the number of generators utilized at all times

Formalization of the specifications

$$P_{req_j}(t) = \sum_{i=1}^{n_j} c_{ji}(t) L_{ji}^s(t) + \sum_{i=n_j+1}^{N_j} c_{ji}(t) L_{ji}^{ns}(t)$$

The required power at time t equals the summation of contributions from different power sinks (loads).

$$\sum_{k=1}^{N^s} \delta_{ik}(t) P_{ktoi}(t) = P_{sup_i}(t)$$

The power supplied to bus i originates from one of the power sources, i.e. the engines or the APU.

$$\sum_{k=1}^{N^s} \delta_{ik}(t) = 1$$

No AC sources can be connected in parallel

$$\sum_{k=1}^{N^b} \delta_{kj}(t) P_{jtok}(t) = \alpha_j(t) P_j^{max}(t)$$

The power available at each generator equals the power flow from the generator to the supported buses.

$$SoC_i(t+1) = SoC_i(t) + T_s \cdot K \cdot \beta_i(t)$$
$$\underline{SoC} \leq SoC_i(t) \leq \overline{SoC}$$

Battery state-of-charge within desired bounds

$$P_{req_i}(t) = P_{sup_i}(t) - \beta_i(t)$$

Power balance equation for each bus i.

$$NoS_{ij}(t^*) = \sum_{t=t^*}^{t^*+H\cdot T_s} |\delta_{ij}(t) - \delta_{ij}(t+1)| \leq N^{as}$$

Contactor wear

Results

Optimization problem for HL-LMS

$$\min_{S} \sum_{t=t^*}^{t^*+H\cdot T_s} \left\{ \sum_{j=1}^{N^b} [\Gamma_j^T (1 - C_j(t)) + \Lambda_j^T \Delta_j(t)] + \mu \sum_{j=1}^{N^s} \alpha_j(t) \right\}$$

subject to:

$$\sum_{k=1}^{n_i} c_{ik}(t) L_{ik}^s(t) + \sum_{k=n_i+1}^{N_i} c_{ik}(t) L_{ik}^{ns}(t) = P_{\text{sup}_i}(t) - \beta_i(t) \quad \forall i = 1,\ldots,N^b \quad (15a)$$

$$\sum_{k=1}^{N^s} \delta_{ki}(t) P_{\text{ktoi}}(t) = P_{\text{sup}_i}(t) \quad \forall i = 1,\ldots,N^b \quad (15b)$$

$$\sum_{k=1}^{N^b} \delta_{jk}(t) P_{\text{jtok}}(t) = \alpha_j(t) P_j^{\max}(t) \quad \forall j = 1,\ldots,N^s \quad (15c)$$

$$\sum_{k=1}^{N^s} \delta_{ki}(t) = 1 \quad \forall i = 1,\ldots,N^b \quad (15d)$$

$$SoC_i(t+1) = SoC_i(t) + \beta_i(t) \quad \forall i = 1,\ldots,N^b \quad (15e)$$

$$\underline{SoC} \leq SoC_i(t) \leq \overline{SoC}, \forall t \geq t_{\text{chrg}}, \forall i = 1,\ldots,N^b \quad (15f)$$

$$\sum_{t=t^*}^{t^*+H\cdot T_s} |\delta_{ij}(t) - \delta_{ij}(t+1)| \leq N^{as} \quad \forall i = 1,\ldots,N^b$$

$$\forall j = 1,\ldots,N^s \quad (15g)$$

$$\delta_{ij}(t) = \{0,1\} \quad \forall j = 1,\ldots,N^b \quad \forall i = 1,\ldots,N^s \quad (15h)$$

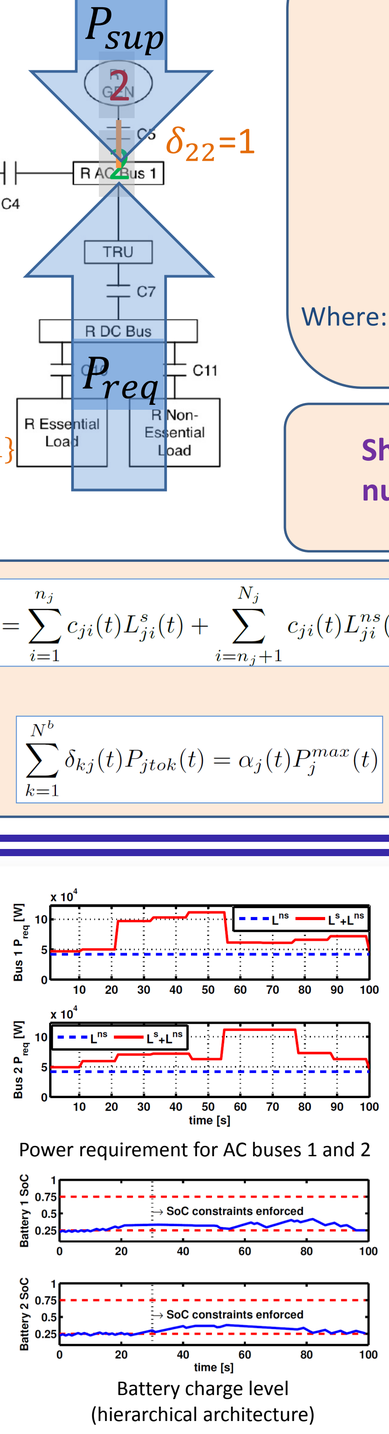
$$c_{j1}(t) \leq c_{j2}(t) \leq \ldots \leq c_{jN_j}(t) \quad \forall j = 1,\ldots,N^b \quad (15i)$$

$$c_{ji}(t) = 1 \quad \forall j = 1,\ldots,N^b \quad \forall i \in I_j^{ns} \quad (15j)$$

$$c_{ji}(t) = \{0,1\} \quad \forall j = 1,\ldots,N^b \quad \forall i \in I_j^{s} \quad (15k)$$

$$\alpha_i(t) = \{0,1\} \quad \forall i = 1,\ldots,N^s \quad (15l)$$

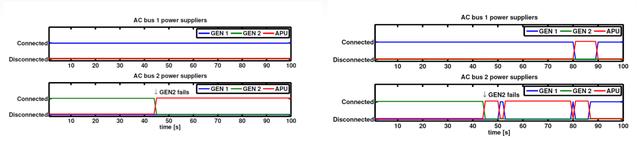
Optimization problem



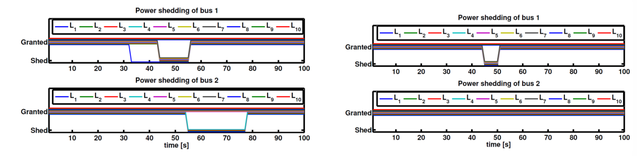
Power requirement for AC buses 1 and 2

Battery charge level (hierarchical architecture)

LL-LMS Only | **Hierarchical Architecture**



Power allocation to AC buses



Load shedding for AC buses

Scalability

NUMBER OF OPTIMIZATION VARIABLES AND SOLVER TIME FOR A 2-BUS 3-GENERATOR EPS, WHEN THE TIME HORIZON INCREASES

Prediction horizon (H)	10	20	50	100
Number of opt. var.	430	860	2150	4300
Solver time (s)	0.3	0.19	1.25	25

NUMBER OF OPTIMIZATION VARIABLES AND SOLVER TIME FOR H=30 (B AND G STAND FOR BUS AND GENERATOR, RESPECTIVELY)

Number of nodes	Number of opt. var.	Solver time (s)
B=4, G=3	binary: 960, real: 660	ave: 0.20, max: 0.29
B=10, G=5	binary: 2300, real:1650	ave: 2.10, max: 2.22
B=20, G=10	binary: 6100, real: 6300	ave: 6.87, max: 7.0

Conclusions

- Developed a **hierarchical optimal load management system** for aircraft electrical power distribution
  - a **high-level load management system** coordinates load shedding, source allocation and battery utilization by solving an efficient mixed integer-linear program
  - the result of is offered as advice to a **low-level load management system** that directly actuates the contactors
- Achieved substantial **performance improvements** with respect to conventional architectures in terms of **percentage of shed loads** (5x) and **number of utilized sources** (31% reduction)
  - system safety is guaranteed
  - the optimal control problem scales reasonably in the context of the selected application

To be presented at the IEEE Conference on Decision and Control (CDC), December 2013

Sponsored by the TerraSwarm Research Center, one of six centers administered by the STARnet phase of the Focus Center Research Program (FCRP) a Semiconductor Research Corporation program sponsored by MARCO and DARPA.