ROBUST ENERGY MANAGEMENT SYSTEM FOR ISOLATED MICROGRIDS

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OUTLINE

- Research Motivation
- Objectives
- Microgrid centralized control
- Energy Management System (EMS) under uncertainty:
  - » Two-stage recourse actions
  - » Uncertainty representation in the UC
- Robust dispatch problem formulation
  - » RUC Sub-problem
  - » RUC Master-problem
- Microgrid robust EMS architecture
- Results
- Conclusions

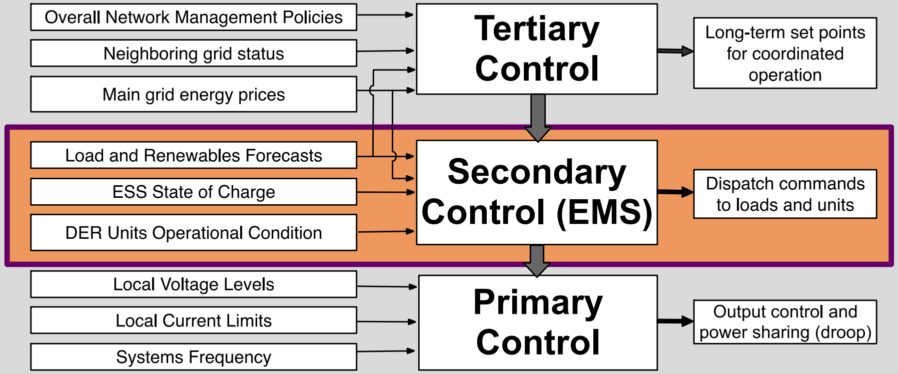
RESEARCH MOTIVATION AND OBJECTIVES

- Microgrids face major challenges to integrate RE sources, which is one of the main motivations to pursue their development:
  - » Isolated microgrids are characterized by low inertia Distributed Energy Resources (DER) and limited availability of generation units.
  - » Reduced physical dispersion causes high correlation of RE sources.
- Consequently variability and uncertainty management become significant issues.

OBJECTIVES

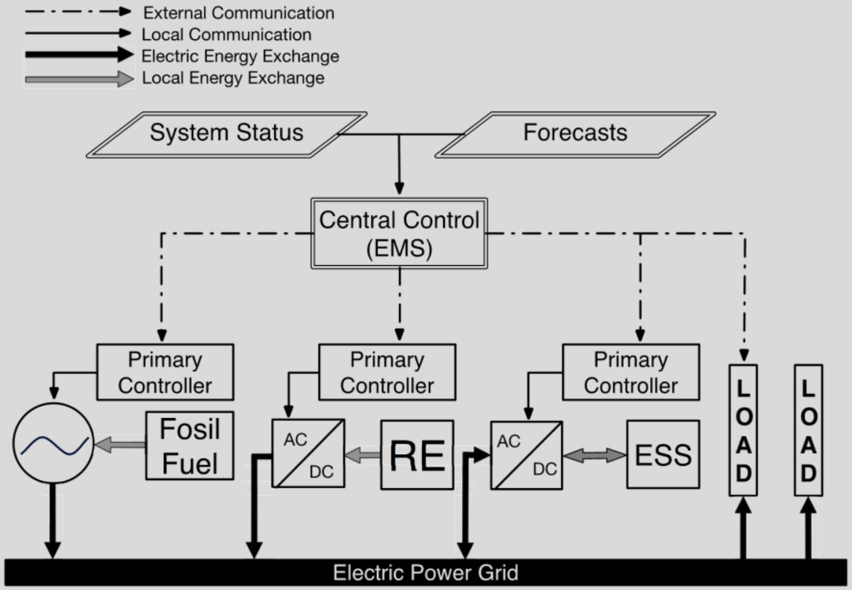
- Given these technical challenges, the main research objectives of this work are:
  - Propose a mathematical model for an uncertainty-aware microgrid EMS using a robust optimization approach, suitable for the operation of isolated microgrids.
  - Provide an appropriate EMS architecture suitable for real-time applications, based on a Receding Horizon Control (RHC) model with a two-stage recourse, and demonstrate its application on a realistic microgrid.

MICROGRID CONTROL HIERARCHY



- Different control actions are assigned to each layer, with appropriate time frames in order to prevent interference between tasks.
- The EMS should be able to account for the uncertainty associated with intermittent energy sources to ensure reliable and economic operation.

MICROGRID CENTRALIZED CONTROL

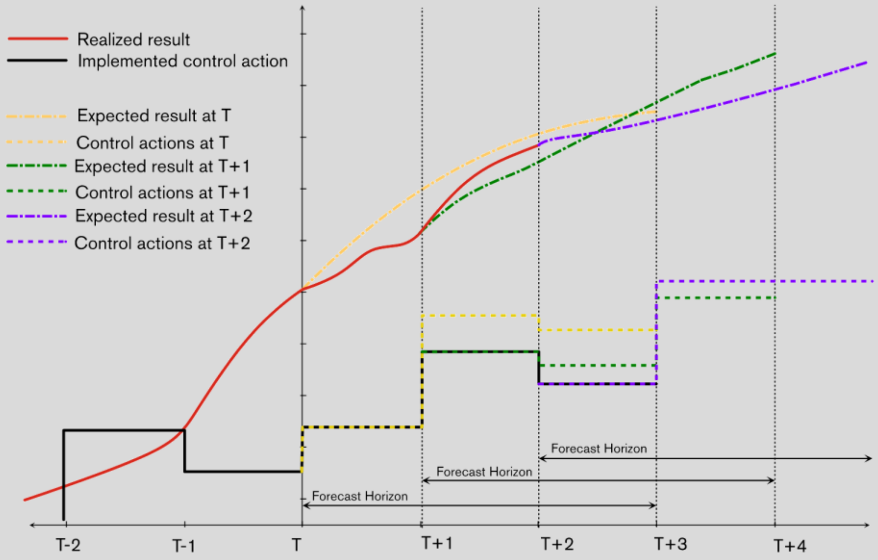


- Centralized, hierarchical structures are the natural choice for operation and control of isolated microgrids.
- A centralized EMS determines the optimal operation point of every DER and uses the results as set-points for each device.

EMS UNDER UNCERTAINTY

- Deterministic models implicitly consider that a forecast will hold for a given time step, but this may not necessarily correspond to the actual value.
- Stochastic Unit Commitment (SUC) and Robust Unit Commitment (RUC) are two formulations able to hedge the system dispatch against uncertain variations in RE sources.
- These formulations are based on a 2-stage recourse model and an RHC approach.

RECEDING HORIZON CONTROL (RHC)



$$\min_{\{z_t,\ldots,z_{t+n}\}} \sum_{t}^{t+n} J(z_t, y_t)$$

$$\text{s.t.} \quad H\left(z_t, y_t, \rho, \mathcal{F}^* | t\right) \leq 0 \qquad \forall t$$

- The technique assumes that control set-points are determined using a finite-horizon mathematical problem.
- The optimization problem is solved for a sequence of control actions over a finite horizon, but only the control action for t=t+1 is implemented.
- The mathematical program accounts for estimates of future system states and forecasted inputs.

TWO-STAGE RHC RECOURSE MODEL

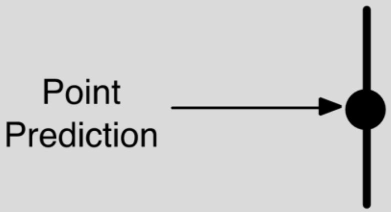
$$\min_{\substack{\{z_{1t},\ldots,z_{1t+n},\\ z_{2t},\ldots,z_{2t+n}\}}} \sum_{t}^{t+n} [J_1(z_{1t}, y_t) + J_2(z_{2t}, y_t)]$$

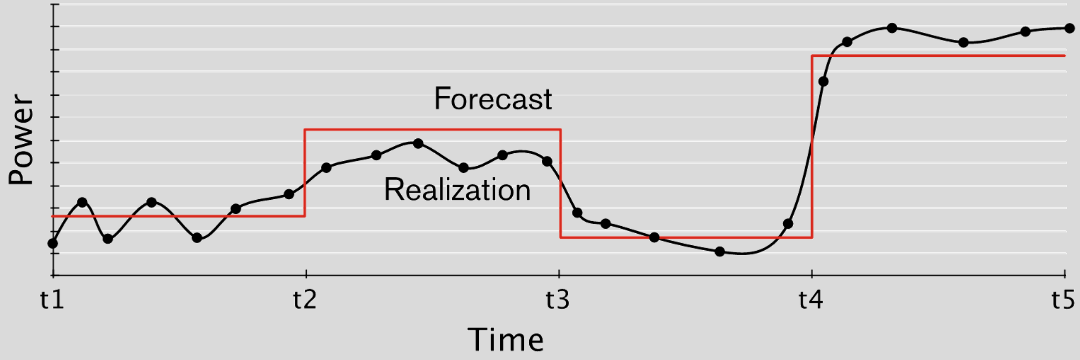
$$\begin{aligned} \text{s.t.} \quad & H_1\left(z_{1t}, y_t, \rho\right) \leq 0 && \forall t \\ & H_2\left(z_{2t}, y_t, \rho, \mathcal{F}^* | t\right) \leq 0 && \forall t \\ & H_3\left(z_{1t}, z_{2t}, y_t, \rho, \mathcal{F}^* | t\right) \leq 0 && \forall t \end{aligned}$$

- The objective is to obtain a solution for the first-stage decision variables such that the second-stage variables can accommodate the uncertain outcomes.
- The dispatch task in the microgrid EMS integrates two decision processes:
  - » First-Stage: Decides on the Unit Commitment (UC) and the target state-of-charge for the ESS.
  - » Second Stage: Decides on the Three-Phase OPF.
- The system is hedged against uncertainty by the first stage or UC solution.

UNCERTAINTY MODELING IN UC

- Uncertainty in the UC can be addressed in three ways:
  - » Wait-and-see:
    - Close tracking of the problem with small time steps, solving the dispatch problem using the most current information, and including an explicit reserve requirement.
    - Assumes that point forecasts are accurate and the system natural reserve can handle the mismatches, otherwise shed load.

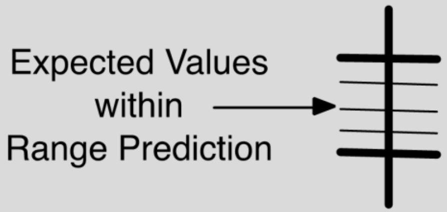


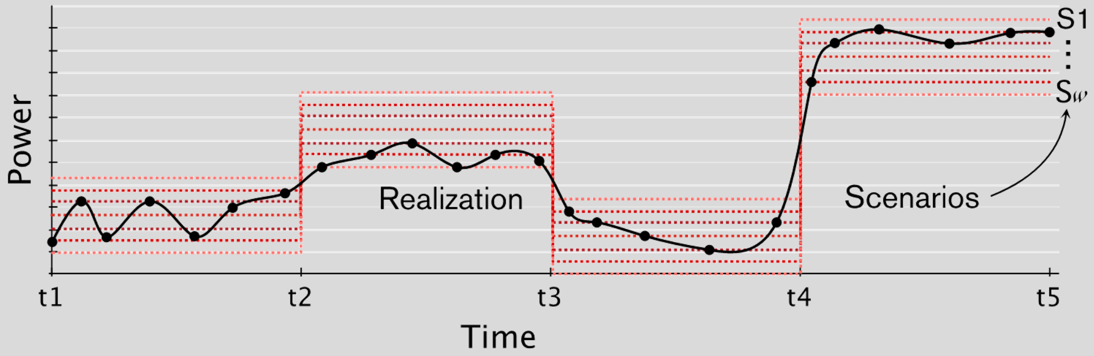


UNCERTAINTY MODELING IN UC

» Stochastic optimization:

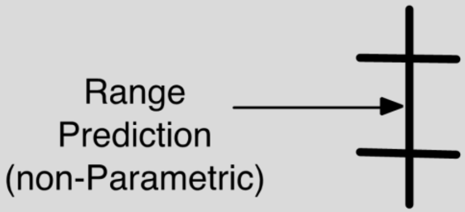
- Minimize the expected cost over a discrete representation of the uncertainty, leading to large-scale problems.
- Accounts directly for the stochastic characteristic of wind power, improving the ability of the system to perform corrective actions without load shedding.
- First stage variables provide probabilistic guarantee on the feasibility of all second stage expected outcomes.

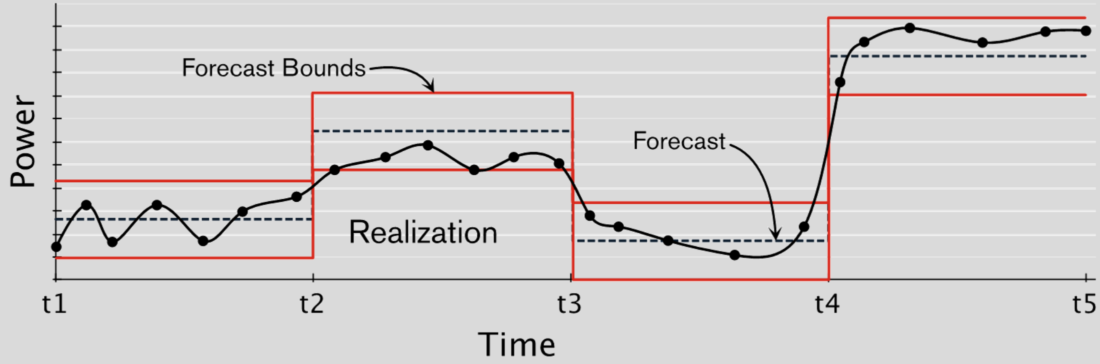




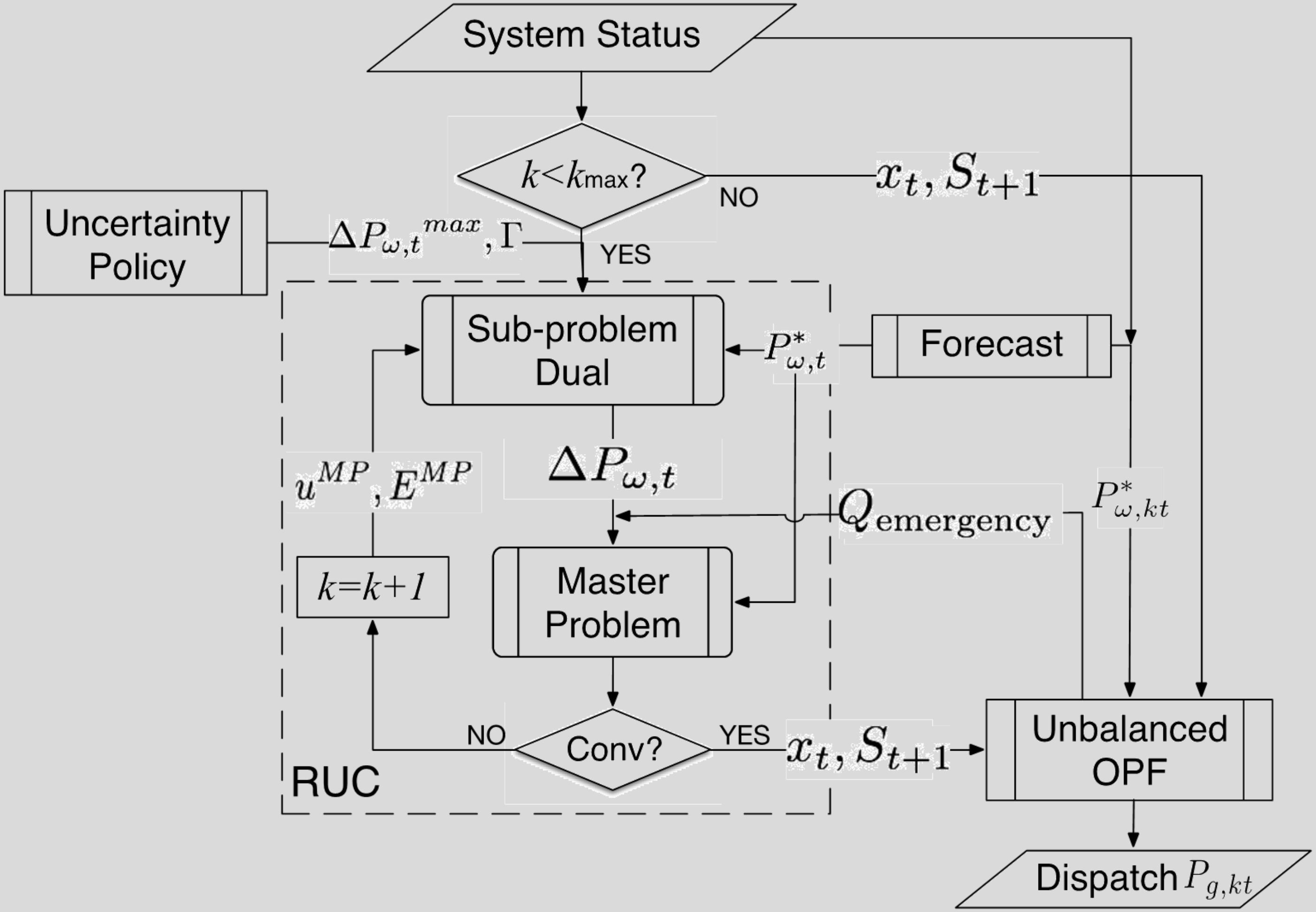
UNCERTAINTY MODELING IN UC

» Robust optimization:
  - Does not require any probabilistic modeling.
  - Determines a suboptimal solution, but guarantees feasibility for any realization within the bounds of the uncertainty set (assuming that ramping-rates are not a significant issue).
  - Bounds can be given or calculated based on the historical forecast errors.
  - Uncertainty sets relate the risk preference of the operator and incorporate probabilistic information if available.



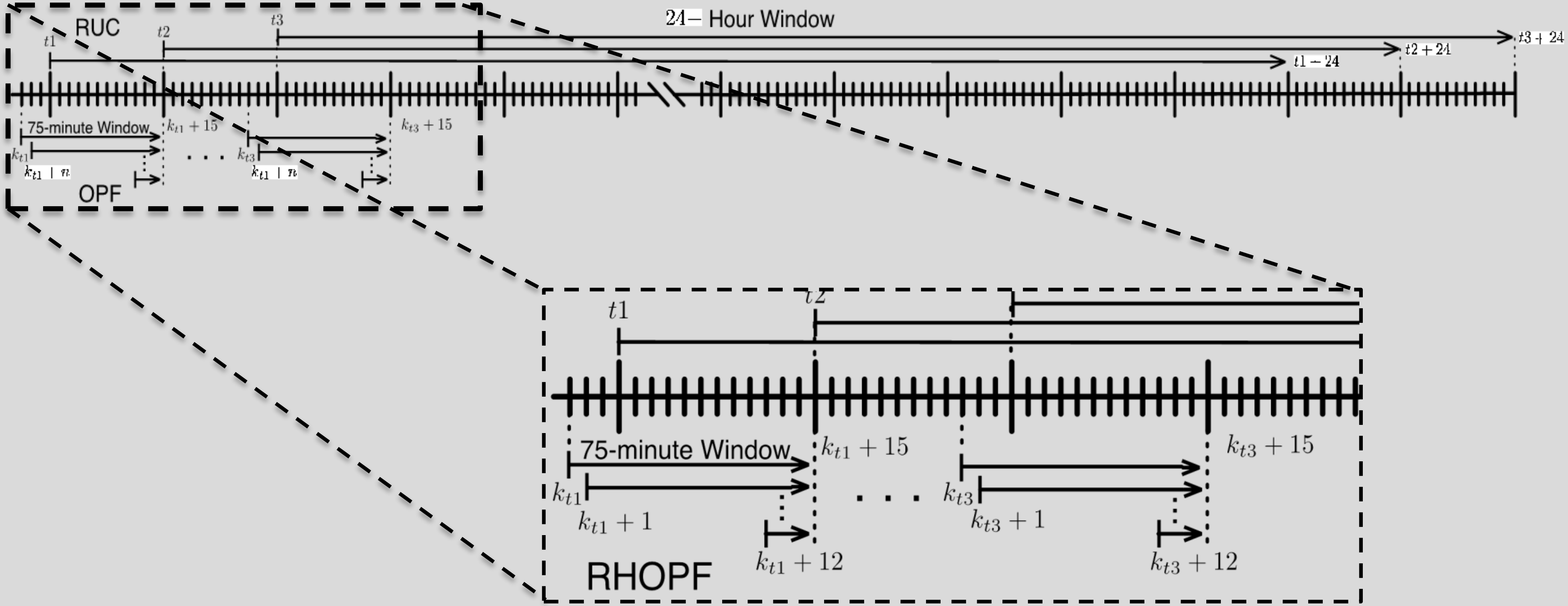


MICROGRID EMS ARCHITECTURE



MICROGRID EMS ARCHITECTURE

- The look-ahead windows used are:



RUC PROBLEM FORMULATION

- The classical UC problem is modified to include storage, and consider the SOC of batteries at t=t+1 as first stage variables, thus using the ESS as hedging mechanism.
- The objective is to obtain the least-cost uncertainty-aware solution for the first-stage variables, given a bounded uncertainty set:

$$\min_{\substack{u_{g,t},v_{g,t}\\ w_{g,t},P_{g,t}}} \max_{\Delta P_{w,t}} \sum_{t}\sum_{g}\left[C_g^u u_{g,t} + C_g^v v_{g,t} + C_g^w w_{g,t} + \underbrace{C_g^P P_{g,t} + C_{sh} P_{sh,t} + C_c P_{c,t}}_{\text{Recourse}} \right]$$

$$\begin{aligned}
\text{s.t.}\quad & H_1(\rho, u_{g,t}, v_{g,t}, w_{g,t}, SOC_{s,t+1}) \leq 0 \\
& H_2(\rho, P^*_{\omega,t}, SOC_{s,t}, P_{g,t}, P_{sh,t}, P_{c,t}, \Delta P_{w,t}) \leq 0 \\
& H_3(\rho, P^*_{\omega,t}, u_{g,t}, v_{g,t}, w_{g,t}, SOC_{s,t}, P_{g,t}, P_{sh,t}, P_{c,t}, \Delta P_{w,t}) \leq 0 \\
& \Delta P_{w,t} \in \mathcal{U}
\end{aligned}$$

RUC PROBLEM FORMULATION

- The RUC is solved using the primal cutting planes algorithm:
    - This method is regarded as a constraint-and-column generation strategy.
    - The method exploits the problem structure, and the location of the worst realization at a vertex of the uncertainty set.
    - Similar to other decomposition techniques, the primal cut is solved using a master- sub-problem framework.
- The master- and sub-problem are kept as MILP problems and solved using CPLEX.

RUC SUB-PROBLEM

$$\max_{\Delta P_{\omega,t}{}^{k+1}} \min_{P^{k+1}_{g,t}} \sum_{t} \Big[C_{sh} P^{k+1}_{sh,t} + C_c P^{k+1}_{c,t} + \sum_{g} C^P_g P^{k+1}_{g,t} \Big]$$

$$\text{s.t.} H_2(\rho, P^*_{\omega,t}, SOC^{k+1}_{s,t}, P^{k+1}_{g,t}, P^{k+1}_{sh,t}, P^{k+1}_{c,t}, \Delta P^{k+1}_{w,t}) \leq 0$$

$$H_3(\rho, P^*_{\omega,t}, u^k_{g,t}, v^k_{g,t}, w^k_{g,t}, SOC^{k+1}_{s,t}, P^{k+1}_{g,t}, P^{k+1}_{sh,t}, P^{k+1}_{c,t}, \Delta P^{k+1}_{w,t}) \leq 0$$

$$\Delta P^{k+1}_{\omega,t} \in \mathcal{U}$$

- Calculates the worst-case forecast mismatch, given the solution of first-stage variables.
- Used to calculate the recourse, and corresponds to a linear approximation of the microgrid OPF problem.
- This results in the optimal solution of the control variables for the worst realization of the uncertainty, interpreted as a mismatch from the forecast.

RUC SUB-PROBLEM

- The resulting sub-problem has a min-max structure, which can be transformed into a max-max formulation by using the dual of the dispatch problem.
- The dualization introduces bi-linear terms, which complicate the problem.
- These terms can be eliminated transforming the problem into an MILP problem using the KKT conditions and disjunctive constraints.

RUC MASTER-PROBLEM

$$\min_{\substack{u_{g,t}^{k+1}, v_{g,t}^{k+1}, w_{g,t}^{k+1} \\ P_{g,t}^{k+1}}} \sum_t \sum_g \left[C_g^u u_{g,t}^{k+1} + C_g^v v_{g,t}^{k+1} + C_g^w w_{g,t}^{k+1}\right] + \theta^{k+1}$$

$$\text{s.t.} \sum_t \left[C_{sh} P_{sh,t}^{k+1} + C_c P_{c,t}^{k+1} + \sum_g C_g P_{g,t}^{k+1}\right] \leq \theta^{k+1} \qquad \forall k$$

$$SOC_{s,t+1}^{k+1} = SOC_s^{fix} \qquad \forall k$$

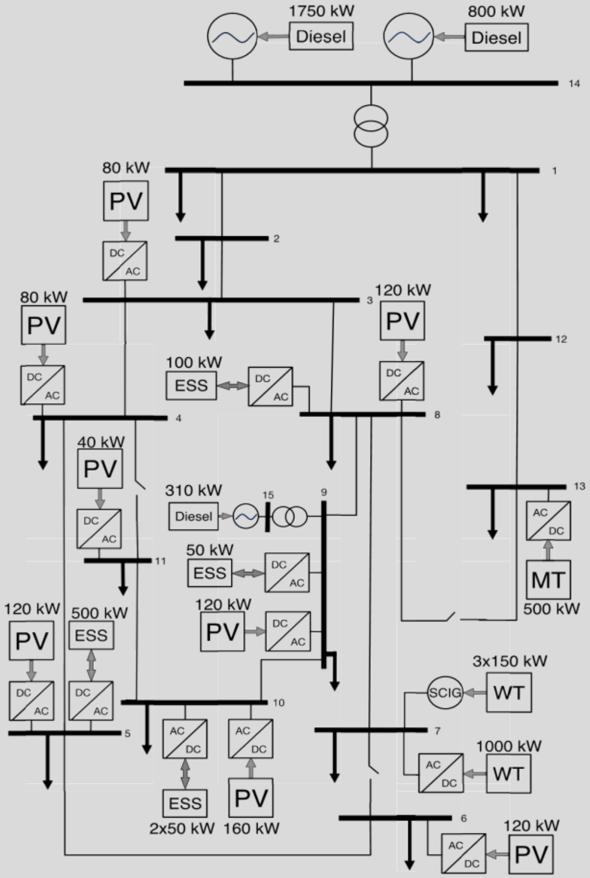
$$H_1(\rho, P_{\omega,t}^*, u_{g,t}^{k+1}, v_{g,t}^{k+1}, w_{g,t}^{k+1}, SOC_{s,t+1}^{k+1}) \leq 0$$

$$H_2(\rho, P_{\omega,t}^*, SOC_{s,t}^{k+1}, P_{g,t}^{k+1}, P_{sh,t}^{k+1}, P_{c,t}^{k+1}, \Delta P_{w,t}^{k+1}) \leq 0 \qquad \forall k$$

$$H_3(\rho, P_{\omega,t}^*, u_{g,t}^{k+1}, v_{g,t}^{k+1}, w_{g,t}^{k+1}, SOC_{s,t}^{k+1}, P_{g,t}^{k+1}, P_{sh,t}^{k+1}, P_{c,t}^{k+1}, \Delta P_{w,t}^{k+1}) \leq 0 \quad \forall k$$

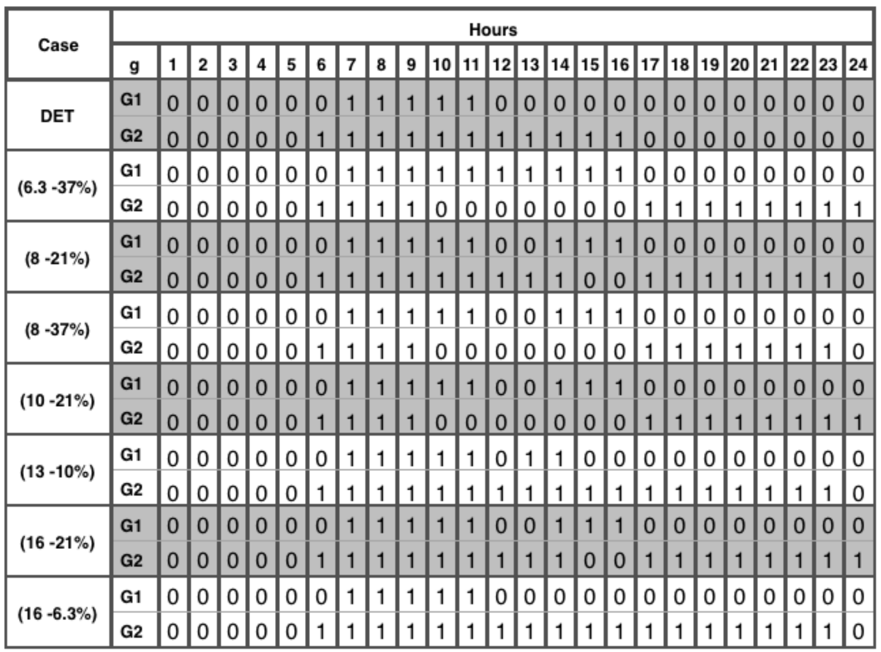
- Once the sub-problem yields a solution for the uncertainty vector, the result is employed in updating the solution of the first-stage variables.
- New cuts are introduced at each iteration by duplicating H2 and H3.

TEST SYSTEM



- The microgrid test system features 3 diesel units with capacities of 1750 kW, 310 kW and 800 kW.
- The two larger diesel units replace the connection to the main grid.
- The system's total capacity is 6,400 kW.
- The RUC load is modeled as constant power and balanced.
- In the three-phase OPF the load is unbalanced with a combination of constant impedance and constant power.

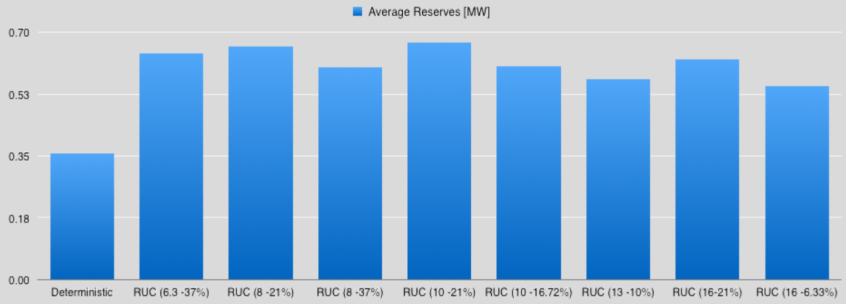
RESULTS



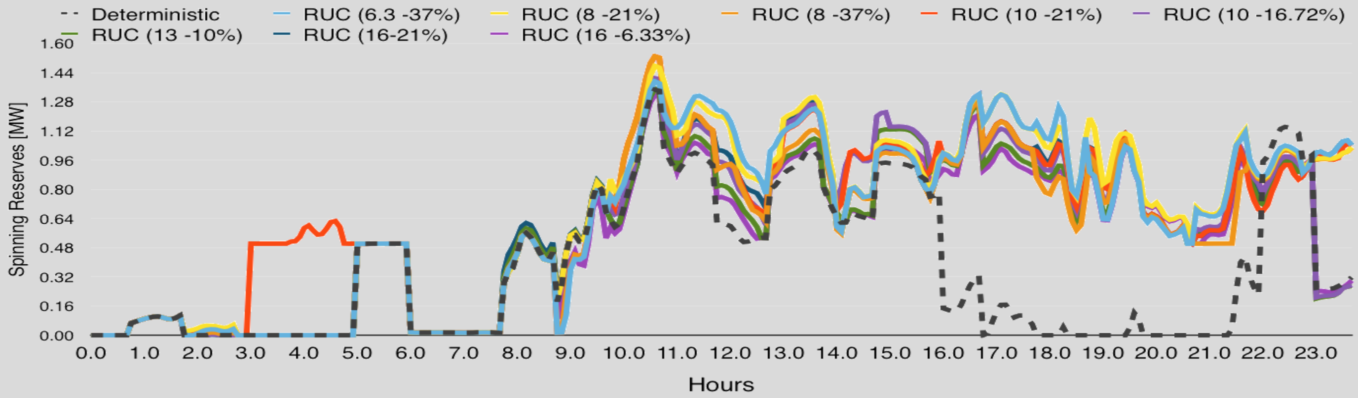
Case	Hours																								
	g	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
DET	G1	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	G2	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
(6.3 -37%)	G1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
	G2	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
(8 -21%)	G1	0	0	0	0	0	0	1	1	1	1	1	0	0	1	1	1	0	0	0	0	0	0	0	0
	G2	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	0
(8 -37%)	G1	0	0	0	0	0	0	1	1	1	1	1	0	0	1	1	1	0	0	0	0	0	0	0	0
	G2	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0
(10 -21%)	G1	0	0	0	0	0	0	1	1	1	1	1	0	0	1	1	1	0	0	0	0	0	0	0	0
	G2	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
(13 -10%)	G1	0	0	0	0	0	0	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0
	G2	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
(16 -21%)	G1	0	0	0	0	0	0	1	1	1	1	1	0	0	1	1	1	0	0	0	0	0	0	0	0
	G2	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1
(16 -6.3%)	G1	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	G2	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0

- The commitment results for different uncertainty policies show the changes in the level of conservatism.
- The RUC formulation commits more capacity than the deterministic case between hours 12 to 24.
- The effect of the extra commitment are reflected in the reserve levels.

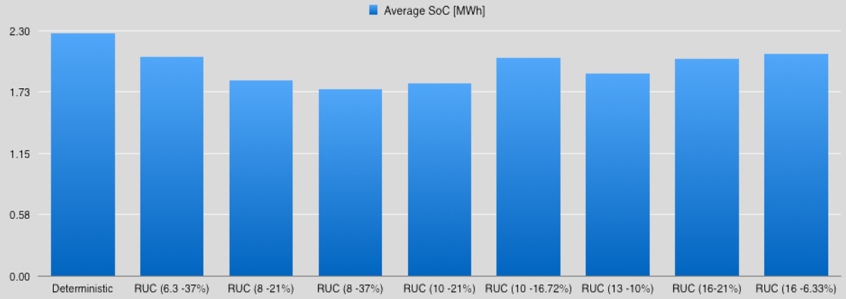
RUC RESULTS



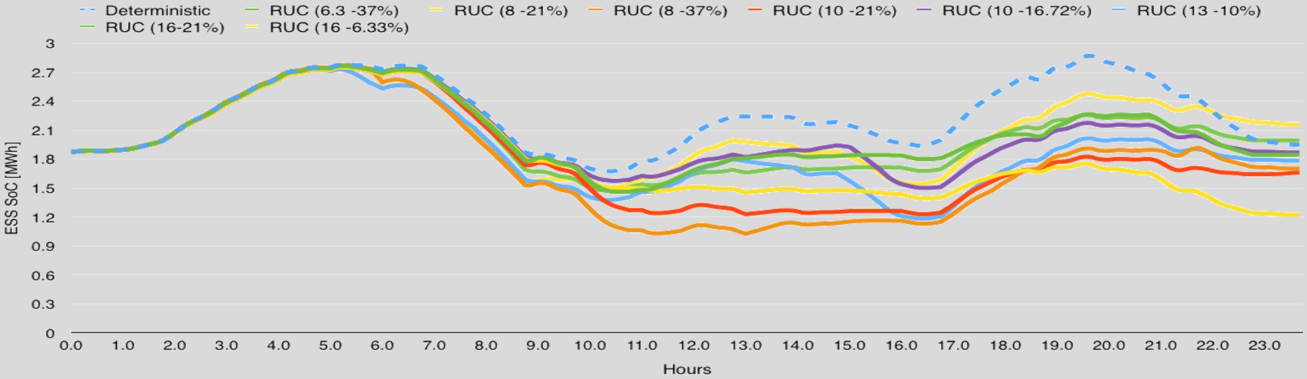
- The hedged approach is able to commit enough reserves to compensate for variations on the instantaneous wind power with respect to the forecast.
- More conservative policies yield increased levels of reserves.



RUC RESULTS



- The deterministic case maintains an average SoC higher than the hedged UC.
- The robust formulation leads to a higher utilization of the ESS and a flatter profile of SoC levels, consistent with a more conservative management of the storage



CONCLUSIONS

- Various concepts and mathematical tools were used in order to hedge the microgrid dispatch against uncertainty using Robust Optimization.
- A centralized EMS for isolated microgrids using a two-stage process, comprised of RUC and a unbalanced OPF, was developed and presented.
- The two-stage decision process was able to handle the complex mathematical formulations making them suitable for real-time applications.
- The proposed algorithm was tested on a modified CIGRE test system under different configurations, using different energy storage capacities, look-ahead windows, and scenario generation techniques.

FUTURE WORK

- Implement the proposed microgrid EMS architecture in test bed to determine its practical feasibility, and the hardware and software requirements.
- Extend the formulation and tests, combining different sources of uncertainty such as solar powered DER and loads.
- Enhance the proposed EMS to include more resources in the recourse model, such as demand response mechanisms.

ACKNOWLEDGEMENTS

- The authors acknowledge the financial assistance of Natural Resources Canada (NRCan) and Hatch Ltd.
- The contents of this presentation do not necessarily represent the views of NRCan or Hatch.

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