Methods and methodologies for implementing a fossil-free society on the Faroe Islands

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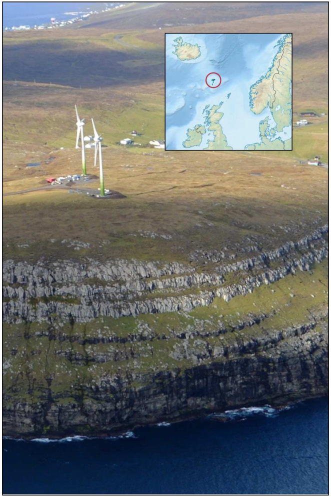
The Faroe Islands



- Approximately 1/100 the size of Denmark with regard to total population, number of cars, and energy consumption
- No interconnectors to other countries (isolated power system)
- Some of the worlds best conditions for wind power due to their geographic position
- Historically, the Faroe Islands have around 30 power outages each year

DONG Energy is testing new smart grid technologies in the Faroe Islands (GRANI project).

Production Planning

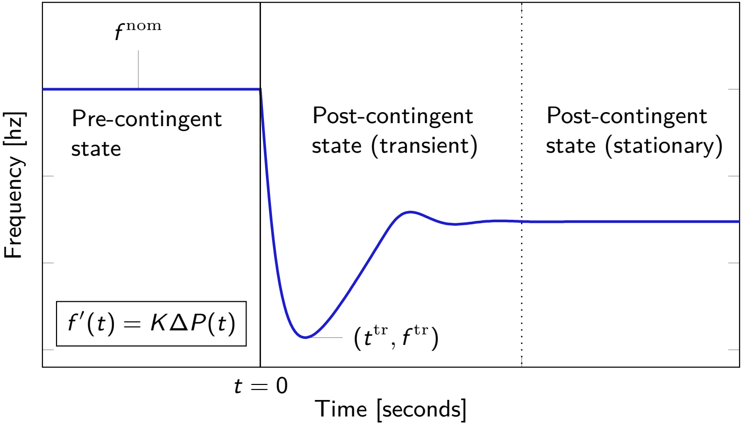
Conventional production planning can be represented as a mixed-integer linear program (MILP)

$$\begin{aligned} \text{minimize} \quad & f^T x + g^T y \\ \text{subject to} \quad & Ax + By \leq b \\ & x \in \mathbb{R}^n \\ & y \in \{0, 1\}^m \end{aligned}$$

- **Constraints**: Power balance, fixed reserves, production limits, ramping limits, etc.
- **Variables**: Production levels, reserve levels, on/off decisions, etc.

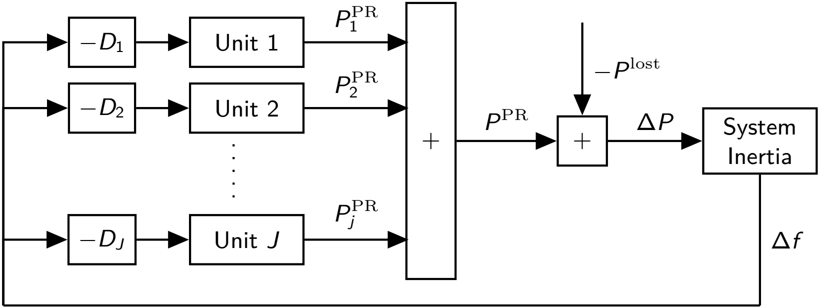
The solution of the MILP provides a ≈24-hours ahead production plan with a ≈5-minute resolution.

System Frequency



- Primary reserves are critical to avoid power outages (and blackouts) when a generator trips: $\Delta P = P^{\mathrm{PR}}(t) - P^{\mathrm{lost}}$.

System Dynamics



- Primary reserves are activated automatically at a local level via proportional control
- System frequency and the activation of primary reserves are coupled through a closed-loop system
- Differential equation form: $F(t, f, f', P^{\mathrm{PR}}) = 0$

Minimum Frequency Constraint

In power systems it is critical that $f(t) \geq \underline{f}$ for some minimum frequency $\underline{f}$.

$$f'(t) = K\left(P^{\mathrm{PR}}(t) - P^{\mathrm{lost}}\right)$$

- **Large interconnected systems**: Large and (approximately) constant system inertia. Production planning with a fixed amount of primary reserve is sufficient.
- **Small isolated power systems**: Small and varying system inertia. Production planning with explicit constraints for the minimum frequency is required.

The constraint $f(t) \geq \underline{f}$ is highly non-linear. This makes it intractable to handle using mixed-integer linear programming.

Alternative Formulation

The minimum frequency constraint

$$f(t) \geq \underline{f}$$

may be expressed as

$$E^{\mathrm{PR}}(t) + \Delta E^{\mathrm{rot}} \geq P^{\mathrm{lost}} t$$

- $E^{\mathrm{PR}}(t) = \int_0^{\mathrm{t}} P^{\mathrm{PR}}(\tau) d\tau$ is the energy contribution from the activation of primary reserves
- ΔE^{rot} is the energy contribution from the system inertia (the rotating masses of the generators slow down when the frequency drops to $\underline{f}$)
- $P^{\mathrm{lost}} t$ is the energy lost as a result of the generator trip

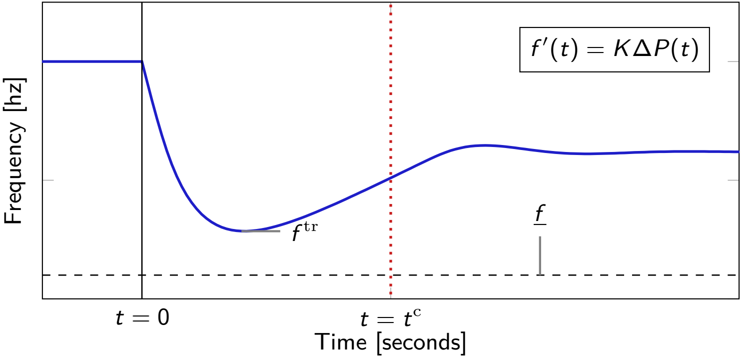
Sufficient Conditions

- We require the minimum frequency to occur no later than time t^{c}

$$P^{\mathrm{PR}}(t^{\mathrm{c}}) \geq P^{\mathrm{lost}}$$

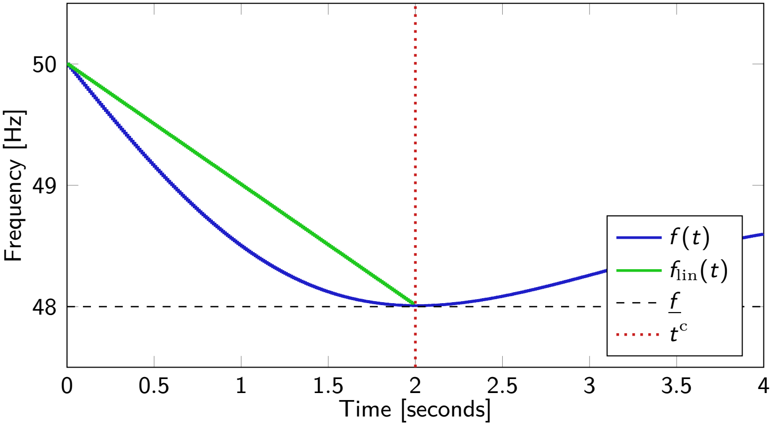
- Consequently, $f(t) \leq \underline{f}$ only needs to hold for $t \leq t^{\mathrm{c}}$, i.e.

$$E^{\mathrm{PR}}(t) + \Delta E^{\mathrm{rot}} \geq P^{\mathrm{lost}} t, \quad t \leq t^{\mathrm{c}}$$

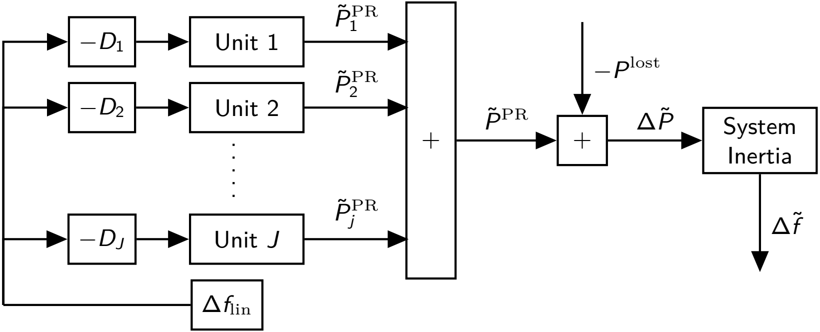


Frequency Bound

- The affine function that contains $(0, f^{\mathrm{nom}})$ and $(t^{\mathrm{c}}, \underline{f})$ is an upper bound for $f(t)$ for $t \leq t^{\mathrm{tr}}$.



Breaking the Loop



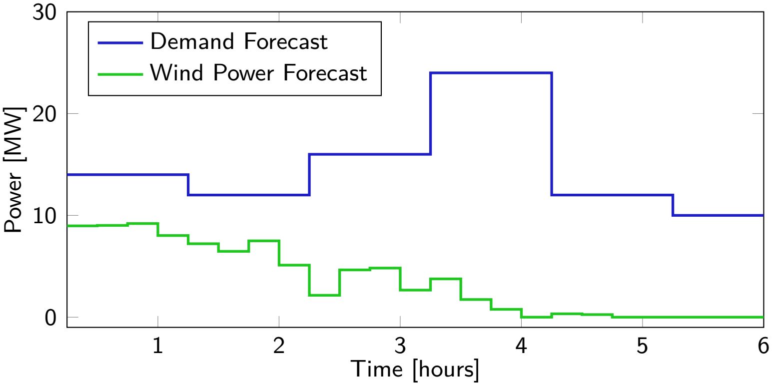
- Lower bound property: $\tilde{P}^{\mathrm{PR}}(t) \leq P^{\mathrm{PR}}(t), \quad t \leq t^{\mathrm{tr}}$
- We can use $\tilde{P}^{\mathrm{PR}}(t)$ to formulate conservative sufficient conditions for the minimum frequency constraint
- $\tilde{P}^{\mathrm{PR}}(t)$ is determined by simulation or in actual experiments

Optimal Reserve Planning Problem

Optimal reserve planning problem (ORPP):

- Production planning optimization problem with (conservative) minimum frequency constraints
- Implemented in OPL studio and solved via CPLEX
- Identification experiments are currently being conducted in the Faroe Islands
- The ORPP will be tested in the Faroe Islands this year
- Compared to a conventional production and reserve planning problem (BLUC)

Case Study

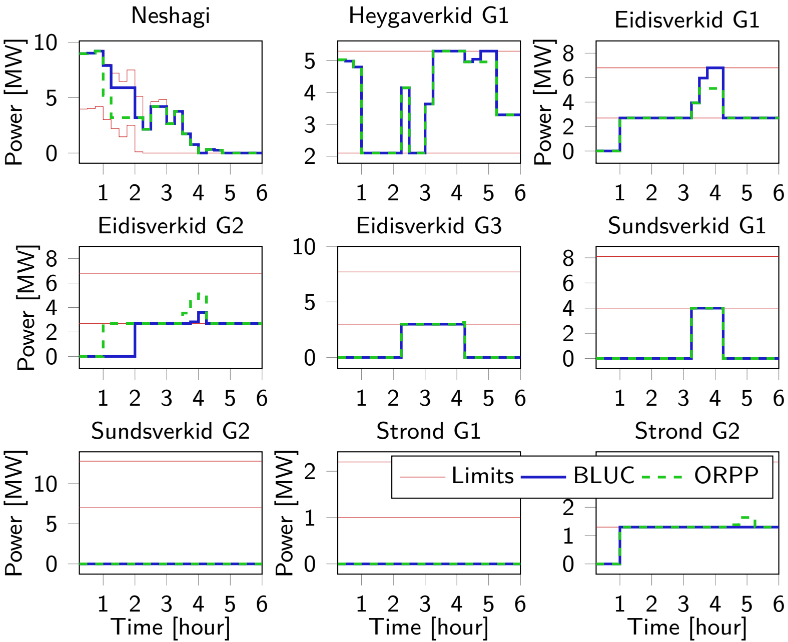


- 6-hours ahead production plan with a 15-minute resolution
- 9-generators available
- Nominal frequency $f^{\mathrm{nom}} = 50$Hz; minimum frequency $\underline{f} = 48$Hz

Generator Specifications

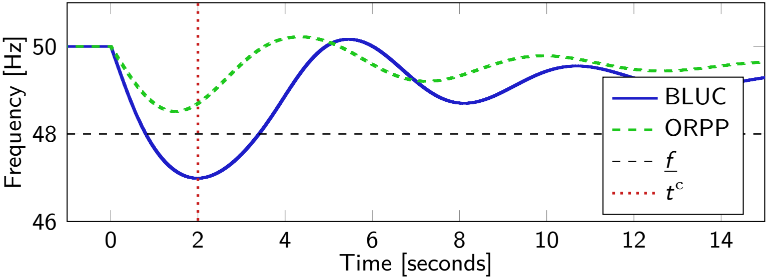
Plants listed in ascending order with respect to their marginal production costs

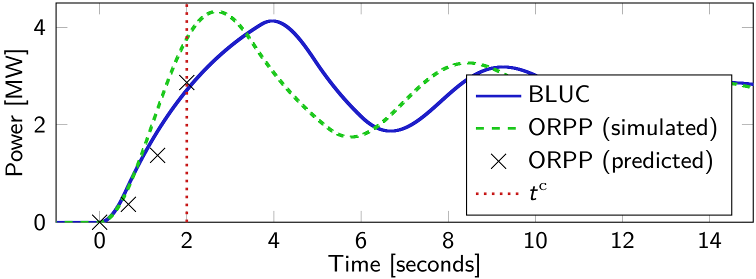
Plant	Type	#Gen.	Inertia	Contingency
Neshagi	Wind Farm	1	None	0
Heygaverkid	Hydro	1	Small	0
Eidisverkid	Hydro	3	Large	1
Sundsverkid	Diesel	2	Large	1
Strond	Diesel	2	Small	1



Neshagi
Heygaverkid G1
Eidisverkid G1
Eidisverkid G2
Eidisverkid G3
Sundsverkid G1
Sundsverkid G2
Strond G1
Strond G2
Power [MW]
Time [hour]
Limits
BLUC
ORPP

Simulation: Edisverkid G1 trips at time $t = 1$ hour





Conclusions and Future Work

The optimal reserve planning problem [1]:

- Production planning tool for small isolated power systems
- Provides a systematic way to trade-off security and costs
- Can be used to analyse the effect of integrating new power generators in the system
- Limited by a number of assumptions: no transmission capacity constraints, no-transmission losses, only frequency-independent loads, etc.

Related model predictive control (MPC) problems:

- Economic dispatch of secondary reserves via MPC [2]
- Efficient re-optimization of the production planning problem via MPC [3]

Thanks! Questions and Comments?

References

- L. E. Sokoler, P. Vinter, R. Bærentsen, K. Edlund, and J. B. Jørgensen, "Contingency-Constrained Unit Commitment for Island Operation," *IEEE Transactions on Power Systems*, p. submitted, 2015.
- L. E. Sokoler, K. Edlund, and J. B. Jørgensen, "Application of Economic MPC to Frequency Control in a Single-Area Power System," in *2015 IEEE 54th Annual Conference on Decision and Control (CDC)*, 2015, p. submitted.
- P. Dinesen, L. E. Sokoler, and J. B. Jørgensen, "Unit Commitment and Economic Model Predictive Control for Optimal Operation of Power Systems," Master's Thesis, DTU Compute, Technical University of Denmark, 2015.