# Evaluation of Integration of Pumped Storage Units in an Isolated Network

Paul David Brown

Faculty of Engineering, University of Porto

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Universidade do Porto

Faculdade de Engenharia

FEUP

Orienting Professor:
Prof. João Abel Peças Lopes

# Outline

# Introduction

This work focuses on

- Pumped storage
- Isolated (island) systems
- Large renewable resources available

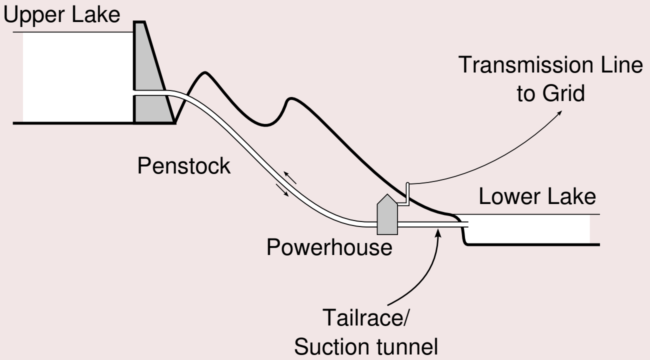
It approaches from two angles:

- Dynamic performance (frequency regulation)
- Optimization of capacity to install

# Pumped Storage

Energy is stored by moving water to a higher elevation

## Typical station



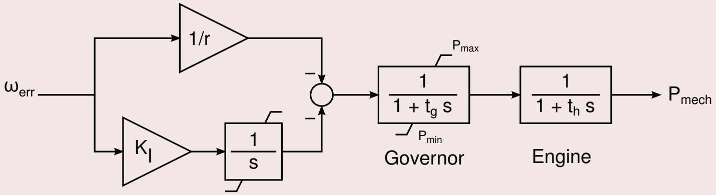
# Dynamic Behavior Analysis

Dynamic Behavior Analysis

# Frequency Regulation

- Imbalance between power produced and consumed leads to frequency deviations.
- Frequency control/load following must respond

## Typical control loop




- New equilibrium frequency (w/o integral action):

$$\frac{\Delta f}{f_{base}} = r \cdot \frac{\Delta P}{P_{base}}$$

# Reserve Criteria: Problem

**Define minimum of extra online capacity**

$$P_{reserve} = \sum_i P_i^{max} + P_{renewable} - P_{load} > 1.5 \cdot \Delta P_{max}$$

- Usual spinning reserve criteria guarantee that generation is available to be able to restore equilibrium after a disturbance
- BUT this does not guarantee at what frequency the system will settle
- If frequency drops too much, other generating units will begin to be lost, making the problem worse!

# Reserve Criteria: Proposed Solution

- A new reserve criterion requires sufficient frequency-regulating capacity to be able to restore equilibrium above a minimum frequency
- Shedding of pumped storage can be used to compensate power imbalance instead of additional generation capacity reserve

## Define minimum of regulating capacity

$$P_{base} > \frac{f_{base}}{\Delta f_{max}} \cdot a \cdot r \cdot (\Delta P_{max} - P_{shed}) + P_{genlost}$$

- New criteria may reduce the use of renewable resources in order to gain security
- Inclusion of pumped storage allows increased use of renewable resources while maintaining security

# Evaluation through Simulation

- Dynamic simulation shows system frequency and behavior following a disturbance
- Need to choose:
  - Platform: EuroSTAG
  - Models: machines, controls, protection
  - Scenario(s): Off-peak w/ large renewable production
  - Disturbances: Faults, machine trips, load increase

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# Capacity Optimization

Capacity Optimization

# Basic Idea

Questions to answer:

- Should we install pumped storage?
- If so, how much?
- What impact will it make on system operation?
- Can it allow us to take more advantage of renewable resources?

# Basic Idea

Approach:

- Treat variety of renewable production by using scenarios and optimizing each scenario within constraints of available storage capacity
- Real power capacity and energy capacity considered independently
- Generate scenarios through fuzzy clustering
- Formulate the problem using linear programming

# Mathematical Formulation (1)

## Objective function

Minimize the expected daily cost of operation and amortization:

$$\text{minimize } t \cdot \sum_{i,j,k} p_i \cdot C_{T,k} \cdot P_{i,j,k} + a \cdot C_{E_{max}} \cdot E_{max} + a \cdot C_{P_{max}} \cdot Pg_{max}$$

# Mathematical Formulation (2)

## Constraints

$$0 \leq E_{i,j} \leq E_{max}$$

$$0 \leq Pg_{i,j} \leq Pg_{max}$$

$$0 \leq Pp_{i,j} \leq Pp_{max}$$

$$0 \leq Edump_{i,j}$$

$$0 \leq Pcurtail_{i,j}$$

$$E_{i,j+1} = E_{i,j} + t \cdot \eta_p \cdot Pp_{i,j} - t \cdot \frac{Pg_{i,j}}{\eta_g} - Edump_{i,j}$$

$$E_{i,0} = E_{i,n}$$

$$Pg_{max} = Pp_{max}$$

# Mathematical Formulation (3)

## More Constraints

$$0 \leq P_{i,j,k} \leq PParcelMax_k$$

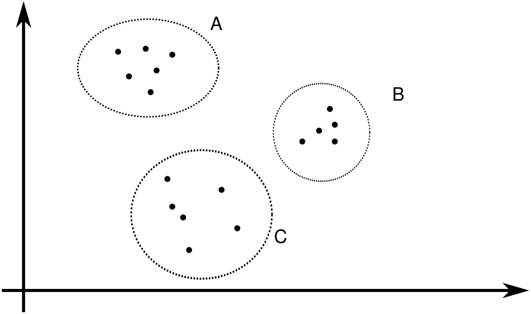
$$\sum_k P_{i,j,k} + Pg_{i,k} - Pp_{i,j} = Pload_{i,j} - (Phydro_{i,j} + Pwind_{i,j} - Pcurtailed_{i,j})$$

$$\sum_k P_{i,j,k} \geq \frac{1.5 \cdot UnitSize \cdot TechMin}{1 - TechMin}$$

$$\sum_k P_{i,j,k} \geq TechMin \cdot (RegFactor(TechMin \cdot UnitSize - Pp_{i,j} + Pg_{i,j}) + ThermUnitSize)$$

# Overview of Fuzzy Clustering

- Clustering seeks to discover natural groupings in a data set
- Fuzzy clustering assigns each data point to a cluster with some membership value $0 \leq X_i \leq 1$



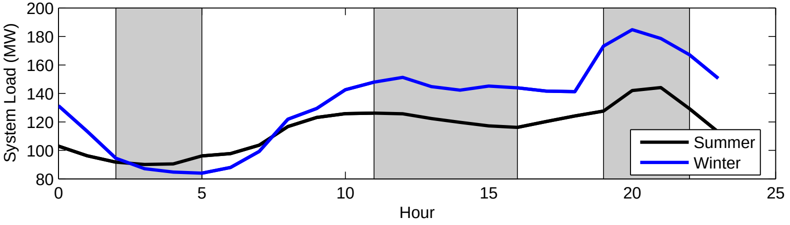
# Scenario Generation

Scenarios are defined by a series of 24 hourly values for *NetLoad*:

$$NetLoad = TotalLoad - HydroProduction - WindProduction$$

Three time periods are used to characterize the net load curve:

- Off-peak, usually minimum load, between 3 and 5 AM.
- Peak, usually maximum load, between 8 and 10 PM.
- Intermediate, the mid-day period in which load rises to an intermediate peak, between 12 noon and 4 PM.



# Test System

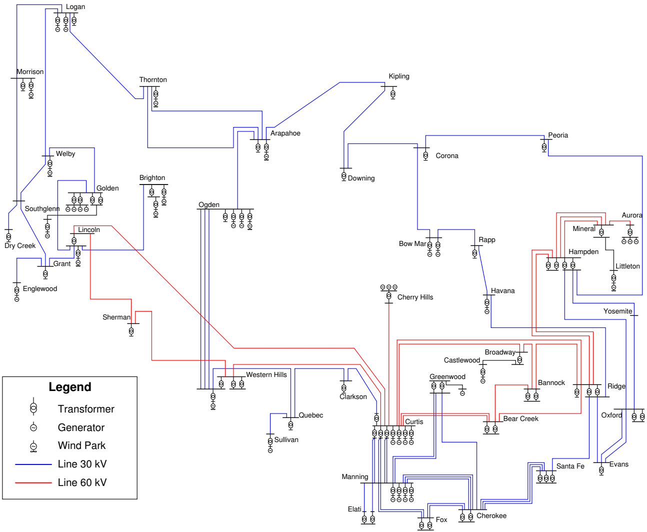
Test System

# System Overview

A test system based on a real system was created to apply and test these ideas

- Typical peak load: 180 MW
- Typical off-peak load: 80 MW
- Generation capacity
    - Thermal (diesel): 220 MW
    - Hydro: 50 MW
    - Wind: 60 MW
- Production and load both exhibit seasonality, especially hydro production

# System Oneline



# Results of Dynamic Behavior Analysis

Results of Dynamic Behavior Analysis

# Verification of Minimum Frequency Prediction

To verify the simplified expression that predicts the minimum frequency after a disturbance:

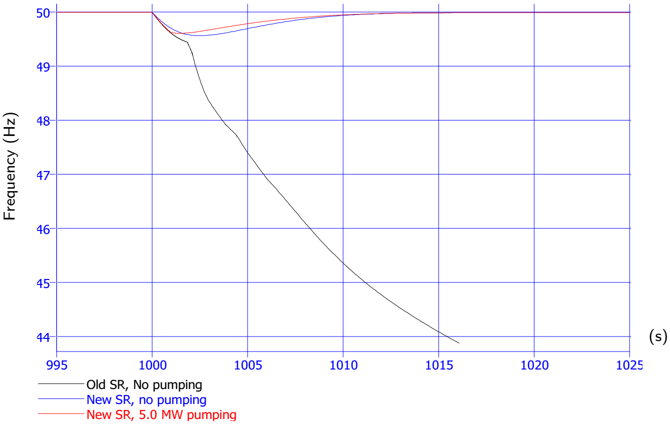
- All protective devices disabled
- Simulate scenarios over a range of unit commitments and disturbances (step in load)
- Compare minimum frequency predicted by expression to simulation results

Results for $a = 0.85$ shown at right

| | | | | |
|---|---|---|---|---|
| $P_{base}$ | 47.9 | | | |
| $\Delta P$ | 4.1 | 8.2 | 12.3 | 16.4 |
| $\Delta f$ - observed | 0.2 | 0.4 | 0.59 | 0.78 |
| $\Delta f$ - predicted | 0.22 | 0.44 | 0.65 | 0.87 |
| $\Delta f$ - error | 0.02 | 0.04 | 0.06 | 0.09 |
| $P_{base}$ | 55.1 | | | |
| $\Delta P$ | 4.1 | 8.2 | 12.3 | 16.4 |
| $\Delta f$ - observed | 0.19 | 0.37 | 0.54 | 0.73 |
| $\Delta f$ - predicted | 0.19 | 0.38 | 0.57 | 0.76 |
| $\Delta f$ - error | 0.00 | 0.01 | 0.03 | 0.03 |
| $P_{base}$ | 60.1 | | | |
| $\Delta P$ | 4.1 | 8.2 | 12.3 | 16.4 |
| $\Delta f$ - observed | 0.17 | 0.34 | 0.50 | 0.66 |
| $\Delta f$ - predicted | 0.17 | 0.35 | 0.52 | 0.70 |
| $\Delta f$ - error | 0.00 | 0.00 | 0.02 | 0.03 |
| $P_{base}$ | 76.6 | | | |
| $\Delta P$ | 4.1 | 8.2 | 12.3 | 16.4 |
| $\Delta f$ - observed | 0.14 | 0.27 | 0.41 | 0.54 |
| $\Delta f$ - predicted | 0.14 | 0.27 | 0.41 | 0.55 |
| $\Delta f$ - error | 0.00 | 0.00 | 0.00 | 0.01 |

# Effect of New Criteria & Pumped Storage

Simulation of loss of a thermal unit

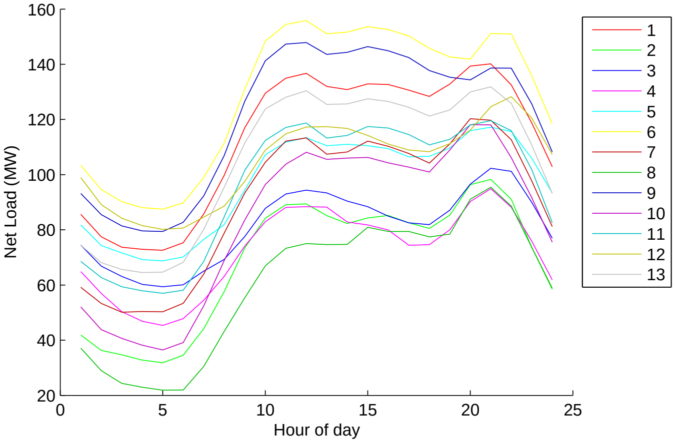


# Results of Capacity Optimization

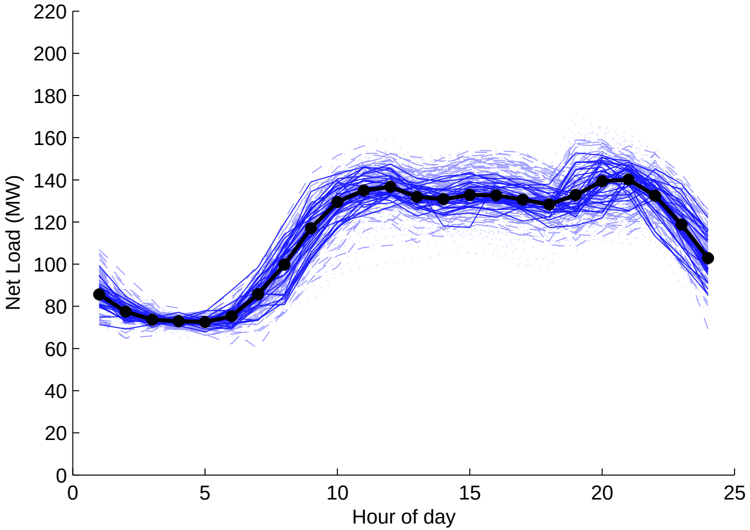
Results of Capacity Optimization

# Clustering Results

Generating thirteen scenarios results in the following curves for *NetLoad*:



# A Typical Cluster

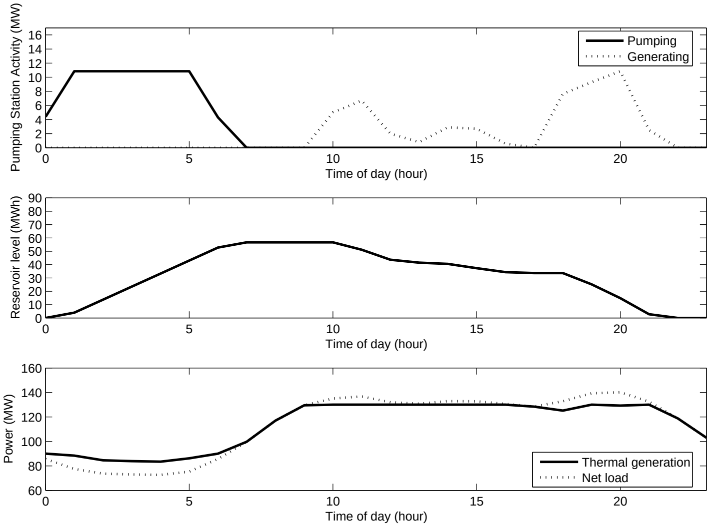


# Global Results

| Limit | Value |
|---|---|
| $P_{max}$ | 10.9 MW |
| $E_{max}$ | 80.2 MWh |

- Total project cost: 5.07 million EUR
- Amortized cost: 881 EUR/day
- Fuel cost savings: 1363 EUR/day (0.6% of total)
- Avg. daily curtailment of renewable reduced from 25.8 MWh to 10.2 MWh

# Typical Scenario Results



# Conclusions

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# Achievements

- Pumped storage proposed to
  - allow increased use of renewable resources in isolated systems
  - improve dynamic performance of island system
- Pumped storage included in security criteria
- Optimization of pumped storage capacity is done including dynamic security criteria and stochastic model of load and renewable production through fuzzy clustering

# Future Prospects

- Pumped storage stations in energy and reserve markets
- Other storage technologies may better meet needs for reserve in improving dynamic performance
- Optimization of operating strategy

# The End

Thank You!