MonaLisa

Firm energy calculation for Hydropower plants

Overview

Several countries adopt the concept of firm energy in their contractual arrangements. The usual definition is the measure of power supplies that are guaranteed to be delivered under terms defined by contract. In contrast, Non-firm Energy is the Electrical energy that may be interrupted either by the provider or the receiver by giving notice to the other party as specified in a contract.

The meaning of firm power depends on the context in which it is used, and may have different meanings to different parties. It can be synonymous with firm energy, mean capacity to provide firm energy, or both.

The objective of MonaLisa is to calculate the firm energy, defined as the amount of energy that can be generated given the region's worst historical water conditions. It is energy produced on a guaranteed basis. It thus has a physical meaning.

Output results can be used to evaluate the cost/benefit ration of projects or the reliability of supply of signed contracts. The hydro operation is modelled in detail, through water balance equations for hydro plants in different arrangements of cascades, non linear production factor, evaporation, and possibility of adding energy transportation constraints.

MonaLisa has been extensively used for the analysis of new hydro projects, verification of the long-term supply adequacy and investigation of the benefits of the reinforcement of some important transmission lines, such as the 1,000 MW, 1,300 km North-South “line” in Brazil. The firm energy contribution of large scale (>3,000 MW) hydropower projects, located in tributaries of the Amazon River, has also been analysed with MonaLisa.

Methodology and modelling

MonaLisa solves one large-size non linear optimisation problem. The problem is formulated in AMPL (A Mathematical Programming Language) and solved by any commercially available non-linear packages, such as Knitro or Loqo.

MonaLisa has a detailed operation of the hydro plants covering the following options:

- Complex hydrologic topologies
- Use of historic or synthetic inflows (e.g. generated by GESS)
- Different options for modelling the hydro power function, such as:
  - Constant hydro production factor
  - Variable production function using head × storage, tailwater elevation × total discharge and hydraulic losses × turbined discharge polynomial
  - Convex Hull approximation of the non-linear hydropower function through construction of hyperplanes
- Transportation capacity limits between regions, with the following options:
  - user defined values for each pair of from-to region and in each direction
  - unconstrained capacity (infinite capacity)
  - null (no transfer) capacity
- Limits on total amount of energy exported or exported to/from neighbouring regions
- Minimum water discharge constraints and irrigation values
- Installed capacity constraints

The formulation of the mathematical problem is the following:

$$\text{Maximise} \sum_{k=1}^{K} E_k$$

subject to

a) water balance equation

$$v_{t+1,i} = v_{t,i} + a_{t,i} + \sum_{m \in M_i} [u_{t,m} + w_{t,m}] - u_{t,i} - w_{t,i} - e_{ti}(v_{t,i}, v_{t+1,i}) - r_{ti}$$

b) maximum turbined flows and storage

$$v_{ti} \le \overline{v}_i$$
$$u_{ti} \le \overline{u}_i$$

c) installed capacity

$$u_{ti} \cdot \rho_i \cdot h_{ti} \le \overline{p}_i \cdot \delta_t$$

d) net head difference

$$h_{ti} = p_{1i}(v_{ti}, v_{t+1,i}) - p_{2i}(\underline{u}_{ti}, w_{ti}) - hl_i(\underline{u}_{ti})$$

e) firm energy calculation of each region

$$E_k \cdot \delta_t \le \sum_{i \in Y_k} [u_{ti} \cdot \rho_i \cdot h_{ti}] + \sum_{j \in W_k} [f_{tjk} - \underline{f}_{tkj}]$$
$$f_{tjk} \le \overline{f}_{jk} \times \delta_t$$

for $t = 1, \ldots, T$; $i = 1, \ldots, I$; $k = 1, \ldots, K$

v_{ti}, u_{ti}, $a_{t,i}$, s_{ti}, e_{ti}, r_{ti} — respectively: (i) volumes of the water stored in the reservoirs, (ii) turbined, volumes (iii) natural inflow volumes, (iv) spilled volumes, (v) evaporated volumes and (vi) irrigation volumes

$\rho \cdot h_t$ — production factor (MWh/m^3) of plant, where $\rho = 3.6 \cdot g\ (m/s^2) \cdot \eta$ (turbine-generator efficiency) and h_t is the head of plant in stage t (m)

$p_1(.)$ — reservoir head × storage polynomial (function of $0.5 \cdot [v_t + v_{t+1}]$)

$p_2(.)$ — tail-water head × outflow polynomial (function of $0.5 \cdot [v_t + v_{t+1}]$)

hl — head of hydraulic losses (m)

$\overline{p}$ — installed capacity (MW)

δ_t — number of hours of month of stage t; $\overline{p} \times \delta t$ is the maximum power production (in MWh)

E_k — firm energy of region k

Y_k, W_k — set of hydro plants and regions connected to region k, respectively

f_{tjk} — flow of energy from region j to region k in stage t

Model Input and Output

Input

- Historical inflow sequences
- Hydrological topology
- Technical characteristics of hydro power plants such as minimum storage, maximum storage, head × storage relationship, installed capacity, operational constraints (such as minimum flow requirements and irrigation values), and others
- Definition of Systems and energy transportation limits among them

Output

The following results are produced by MonaLisa that contain relevant information regarding the system operation in each month or week of the study horizon. These results are ready to be plotted in Excel, with the use of the User Interface Graph Module:

- Firm energy capacity of the hydropower plants
- Identification of the “critical period” associated to the period of hydrological stress of the system
- Reservoirs stored volumes
- Turbined volumes
- Spilled volumes
- Energy production in each stage
- Energy interchange flows between systems

Graphical User Interface

All mentioned options are defined in the Graphical User-interface of MonaLisa. Input data may be imported directly from SDDP.

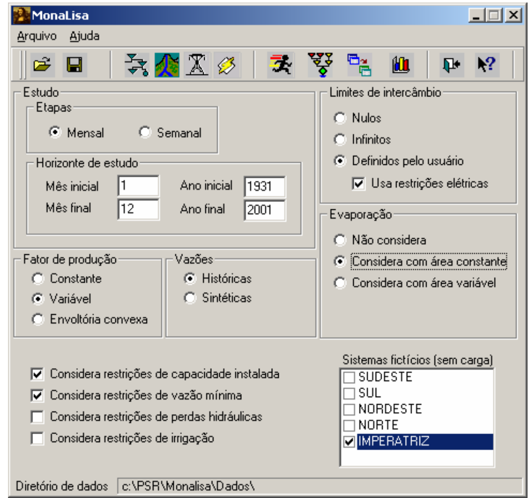

Fig. 1: MonaLisa GUI Main Screen

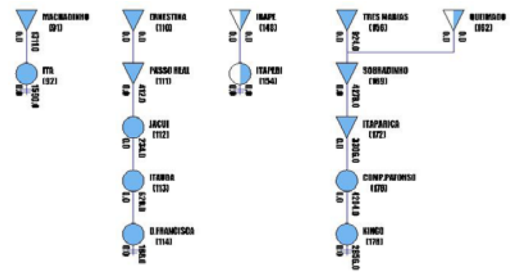

Fig. 2: VisualiSation of the hydro topology

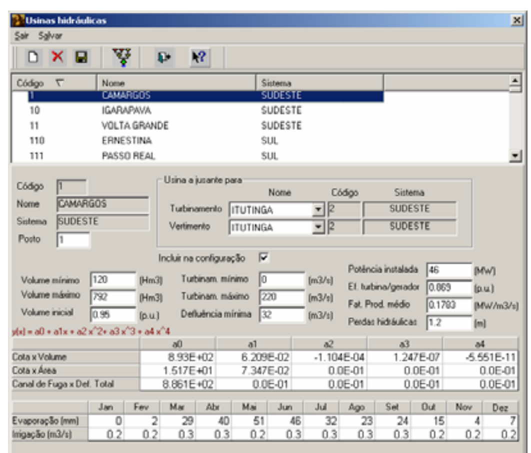

Fig. 3: Technical parameters of the hydro

Integration with external models

MonaLisa imports data from both the SDDP model and the Newave model. Newave is the energy planning model used by ONS - the Brazilian Dispatch Centre.

Applications of the model

MonaLisa has been used by investors interested in measuring the firm power availability of their hydro projects.

It has been also used in consultancy works for the Brazilian Government to verify the adequacy of the supply, *vis a vis* to the load requirements. It has also been used to independently calculate the Firm Energy Certificates of the hydro plants of Brazil. The values calculated by MonaLisa were benchmarked with the official ones, published by ANEEL – the electricity regulatory authority. They have indicated that the official certificates granted to the hydro plants were overestimated.

This result was later confirmed in the report delivered by the Commission created by the Federal Government of Brazil in order to analyse the reasons for the 2001 energy crisis (rationing).

MonaLisa has been used to investigate the increase of the overall Brazilian system caused by the duplication of the 1000 MW North-South circuit of 1300 km.

Currently MonaLisa is being extensively used to analyse different development alternatives for the construction of two hydro plants totalling about 7,000 MW in the Madeira River – one of the tributaries of the Amazon River.

MonaLisa has been used to calculate the increase of the firm energy supply of the Brazilian system that would take place in the Belo Monte Complex (a giant project whose engineering project spanned from 5,500 MW to 11,000 MW).

Example Case Study

Results with MonaLisa for the existing hydro plants of Brazil (reference in Portuguese *Kelman, J. ; Kelman, R. ; Pereira, Mario V F. Energia Firme de Sistemas Hidrelétricos e Usos Múltiplos dos Recursos Hídricos. RBRH Revista Brasileira de Recursos Hídricos, v. 9, n. 1, p. 189-198, 2004)* showed that the calculated firm energy was 1,200 MW (3% smaller) than the sum of the assured energy certificates of these plants, as shown next.

Case	Brazilian Firm energy (mean GW)*
(A) Official value (Aneel)	38.1
(B) Calculated with Monalisa with non-linear hydro power production function, energy transportation limits, evaporation, irrigation & minimum flow requirements.	36.9
Difference (B) – (A)	-1.2
Ratio (B)/(A)	97%

* Data from 2001 static configuration

This means that there will be a new energy rationing in case the worst historic hydrology happens again in the future. A revision of the methodology was proposed, ensuring that the resulting firm energy considers both the hypothesis of the worst drought observed in the past and the decreasing availability of water for energy production, due to other uses.

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