Simulation Application to Hydropower Systems Management and Design in a Market Environment

A. Perea, J. M. Latorre, *Member, IEEE*, A. Ramos, S. Cerisola, R. Bellido, and E. López

Abstract**—This paper presents a mixed approach to schedule and assess the design of hydropower systems. It is composed of a simulation tool that considers the full detail of the operation of the system, while it follows as closer as possible the objectives proposed by a medium term mathematical programming model that considers the whole hydrothermal system in the electricity market. The simulation tool also allows considering forced outages, to permit the assessment of different design options for new assets or for considering the repowering of old ones. The test case considered in this paper is a realistic one, in which different price profiles and power capacity scenarios are evaluated. Finally the maximum generation flow and number of turbines of a new hydro power plant is assessed considering the reduction of spills and the energy production against installation costs.**

Index Terms**-- Hydroelectric power plants, discrete simulation, hydro reservoirs management, electric power scheduling.**

I. Introduction

Hydro power plants play a key role in electric power systems, due to their low operating costs and their flexibility in real time operation. Furthermore, being a renewable source of energy, environmental concerns support the use of hydro power.

Simulation allows considering complex behavior in hydro plant operation at low computational costs compared with other approaches, like mathematical modeling that may involve increased solution times due to the use of integer or nonlinear expressions. In our simulation model, nearly optimal results are obtained by following the guide of longer term hydrothermal mathematical programming models to propose initial reservoir management that is later adapted to fit the peculiarities of the river basin.

In this paper we describe a simulation model based on discrete time step, specially focusing on the stochastic nature of hydro inflows, generators forced outages and the simulation considering energy market prices. This model may have different purposes: a common use is to obtain near-optimal production schedules that are physically feasible, without performing an explicit optimization; another approach is to use simulation to evaluate the costs of performing maintenance duties in different periods; it can be used to carry out reliability analysis; and finally, simulation can also be used to test different design options when considering river basin construction or expansion.

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II. State of the Art

In the literature, two approaches can be found to tackle the task of planning the operation of the hydro plants: mathematical programming and simulation. In the first methodology, [4] proposes a mixed integer model, where discharge function for each reservoir are represented by piecewise linear functions, and binary variables are used to separate different non-convex regions in these discharge functions. In this case, the objective function is to minimize the penalties due to violating maximum or minimum volumes in the reservoirs, changing abruptly outflows and releasing high volumes of water. Other mathematical programming models include the nonlinear problems [9], network flows [2], and stochastic optimization [5][1]. It can be found in [3] a review of the mathematical programming models used for planning the operation of river basin.

Considering the simulation approach, the objective has been mainly the reliability assessment of the power systems. For instance, [7] performs a simulation of the whole hydrothermal system in order to asses its service reliability. It evaluates different reliability indices by sampling outages of power plants and network buses, as well as determining water inflows and demand levels. This sampling procedure is enclosed in a discrete simulation. In [8] and [10] simulation model considers the transmission network but not the hydro scheme, with the same aim of computing reliability measures. An hourly sequential simulation model is developed, sampling the outages of power plant and transmission elements. Additionally, variance reduction techniques are applied to obtain a more efficient simulation process.

In contrast with these works, the model described in this paper performs a sequential simulation with the objective of prescribing a near-optimal operation. The main objective is set by a longer-term mathematical programming that cannot consider the hydro system in full detail, but provides a goal that incorporates the economic sense of the electric system operation. The simulation model then takes into account all the details of the reservoirs, adapting the overall decisions to a

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more realistic framework.

The management of a hydroelectric cannot be performed separately, but integrated into a larger optimization process to cover demand with the participation of the generation technologies comprised in the generation mix.

To obtain accurate results from the simulation tool, it requires the guidance from a medium term model, MHE. This stochastic programming model provides criteria for the optimal management of the yearly and multiannual reservoirs. MHE computes these optimal schedules employing a simplified market model, and considering the hydro inflows series provided by the clustering tool called ARBOLES.

The optimal management criteria are transferred to the simulator by means of production and pumping tables, which tell it initially how to behave under certain circumstances like water reserves or rain inflows. However, the simulation tool can also another kind of criteria different from the previous one, like guiding curves and flow limits.

III. Simulation Model

The simulation model described in this section is a medium term model included in the general set of models used in the electric power plant scheduling. It receives longer term instructions about the optimal way to allocate water use through the year from the previously mentioned model MHE, in the form of production and pumping tables. This longer term model takes into account the whole hydrothermal power system, so as to be able to properly schedule each hydro section. It considers the uncertainty in the hydro inflows series through different scenarios, and estimates the market price for the future.

The simulation model consists of two main parts: the basin elements representation and the simulation algorithm, which are described in the following two sections.

River basin elements can be divided into three main categories: reservoirs, power plants and channels. Reservoirs are by far the most important elements in the management of the basin from a hydrological point of view. Power plants just place water from one point in the river basin into another, but they perform no modification on the water flows that run through them. They differ from channels in that they produce energy, which from the simulation point of view is a byproduct and not a relevant hydrological event. The only modification to the water management imposed by both power plants and channels is forced by the maximum flow that can run through them.

For the reservoir management, it uses the production flow read from the MHE tables to propose an initial management. If no table is available for a reservoir, which is the case of the smaller reservoirs, it uses an alternative rule which guides the reservoir towards an objective reserve volume, prescribed for each reservoir, which may be the maximum volume for small reservoirs in dry areas, for instance.

This initial proposal is checked against the rest of physical restrictions, like volume or flow limits. Also they are affected by economic or ecological restrictions, which may limit the volumes where it is safe or profitable to operate. This is expressed by means of guiding curves that delimit volume areas with different production flow limits, upper and lower. An example of guiding curves can be seen in Figure 1, where the black curves delimit the tighter operation area which is primarily desired by the operator, while the gray lines mark a secondary and wider one. This provides a flexible way to adapt the initial outflow proposal, especially on the reservoirs that have no MHE table, which depart with an initial rougher decision. Reservoirs with a MHE table may find these guiding curves useless, because the impose restrictions that are inherently considered in the MHE model.

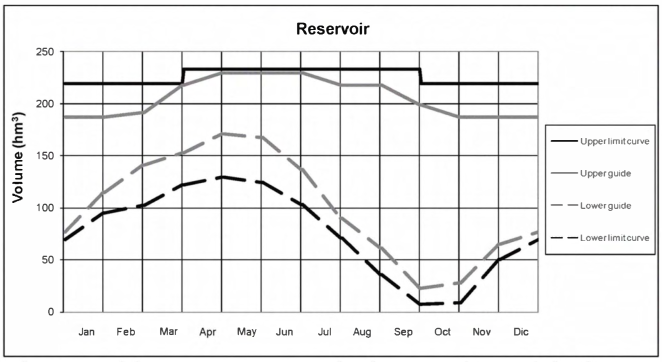

Figure 1. Guiding curves for a reservoir with production and irrigation use

A. Simulation method

The general idea of the simulation method is to carry on reservoir management as close to longer term instructions as possible. In order to do so, the simulation method performs three passes, in which it first computes the initial behaviour in a disaggregate way, then checks what can it do to avoid undesired situations (like water spills and lack of outflows), and finally reallocates water flow to correct these situations. The modification in the water flows affect the unused space in the reservoirs, that can be use to retain or release water in upstream points in the river basin to help alleviate problems downstream. Thus, these computations are performed locally in each individual river basin element, but considering the whole river structure in a general way, keeping a record of what is needed downstream and what can be modified upstream.

These simulations can use two different types of hydro series as water inflow. One type of series comes from historical data from past years, used to recover past situations with all the detail and correlation among different physical locations. The other type of series are synthetic ones based on a subset of the historical series, usually chosen upon a hydrological point of view (for instance, the series corresponding to the most dry years). These synthetic series are computed as the mean of the historical series in the subset, modulating the year inflow profile with monthly coefficients to modify the expected inflows.

The simulation tool also considers forced outages, which are internally generated by means of random sampling. These unplanned outages are assigned to each hydro unit sampling daily the outages for the following day, considering the outage rate and the present availability of the unit.

IV. Simulation Tool

For the analysis presented in this paper, a simulation tool is used. This tool has been developed based on Object Oriented Programming, due to the fairly independent computations required for each basin element. This allows the representation of the basin as a set of objects that interact with each other in each simulation pass in a very limited way: the water flows, and the spillages and lack of agreed outflows.

With this abstract representation of a river basin, the consideration of a new one is greatly simplified. There are two main steps to be taken in this process:

- First, the river basin topology has to be described, including the type of each element and the connections amongst them. This includes reporting the power plant associated to each reservoir, which reservoir receives the spills from each reservoir, the channels linking elements in the basin, or which power plants that share their penstock, for instance.
- Then, the individual technical characteristic of the elements of the river basin have to be provided. For example, this means supplying the maximum outflow of each power plant, the coefficients of the conversion function from water flow to energy produced, the maximum and minimum volume curves, the management strategies and guiding curves for each reservoir.

The simulation tool builds upon Excel workbooks, which hold the input data needed to represent the river basin structure and the individual elements data. This interface allows the user to easily interact with the system, providing the input data and analyzing the output results of the simulations performed. The core of the tool is coded in Visual Basic for Application, and uses the somewhat limited features of this language to implement the Object Orientation paradigm.

V. Application to Hydroelectric Management

Many hydroelectric management tasks require the assessment of simulations, in order to take into account the stochasticity of inflows and outages, as well as to consider a lot of details that cannot be contemplated so precisely during the optimization software execution.

With regard to management, these tasks mainly include yearly and weekly planning of the hydro production, but also include more rare scope analysis as exceptional circumstances, like water floods or droughts, location of the best period to carry out maintenance or refurbishment, assessment for domestic or international outflow agreements, etc.

With regard to design, sizing of new reservoirs, powerhouses, channels, etc, and additional investments as repowering and technical modifications can be evaluated employing this simulation approach that provides a measure to support the decision process. The test of river elements designs is performed in the following section.

This section presents a case study of the management, for hydrothermal scenarios, of a large reservoir with yearly operation. This kind of reservoirs plays a key role in the river basin, as they are the most representative. Thus, they drive the overall management in order to reduce total generation costs and reduce the use of other generation technologies that are more expensive or more polluting.

Four production tables have been generated with MHE considering two different kinds of assumptions:

- Two different degrees of installed thermal capacity.
- Similar or very different prices for peak and off-peak hours

When combining these two aspects, four cases are analyzed:

- Case 1, with reduced installed capacity and similar generation costs for peak and off-peak hours. This will be considered the base case.
- Case 2, with reduced installed capacity and more different peak and off-peak generation costs.
- Case 3, with increased installed capacity and similar generation costs for peak and off-peak hours.
- Case 4, with increased installed capacity and more different peak and off-peak generation costs.

With the tables generated by MHE for these four cases, the simulator has been run providing the detailed hydro operation under the corresponding circumstances.

The river basin used in this section does not correspond to a real river basin, although it has been created starting from situations very close to real ones. As such, it contains realistic river configurations that prove the capabilities of the simulation model proposed. More particularly, the hydroelectric scheme that has been simulated comprises 9 reservoirs and their corresponding power plants. Reservoirs are ruled by management strategies according to their respective sizes, being the larger ones ruled by the production tables and the smaller ones by heuristic guide curves.

The curves of the evolution of the main reservoir in the river basin are shown, for each of the cases previously described, in Figure 2, Figure 3, Figure 4 and Figure 5, respectively. These simulations have been performed for 24 series of historical data, in daily basis and consecutively considered. Increased installed thermal capacity allows hydro production to be free for its concentrated allocation in high demand months. Instead, reduced installed thermal capacity induces a more flat hydro production, in order to meet demand all year along

On the other hand, when prices for peak and off-peak are more different (cases 2 and 4), the evolution of the reservoir follows a tighter area all the years (especially during the summer). In this situation, the similar prices for peak and off-peak of cases 1 and 3 causes them to be more insensitive to where the hydro generation is allocated.

A final remark is that the behaviour of the reservoir is quite different from year to year in winter, where the variability of inflows drives the reservoir through wider areas of the reservoir volume. Contrarily, the reservoir during summer cannot perform such ample movements, due to the reduced inflows during this season, and hence this area is restricted to more constrained ranges of reservoir volumes.

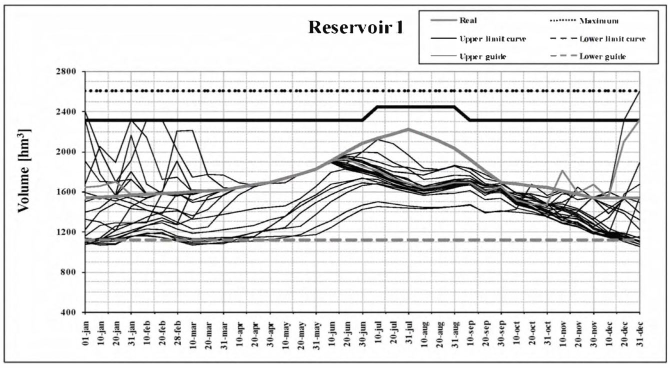

Figure 2. Case 1

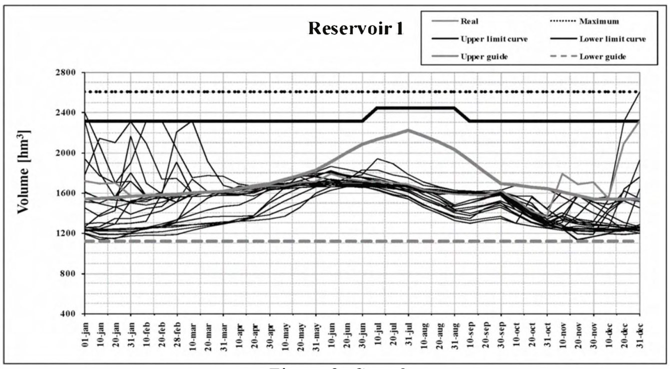

Figure 3. Case 2

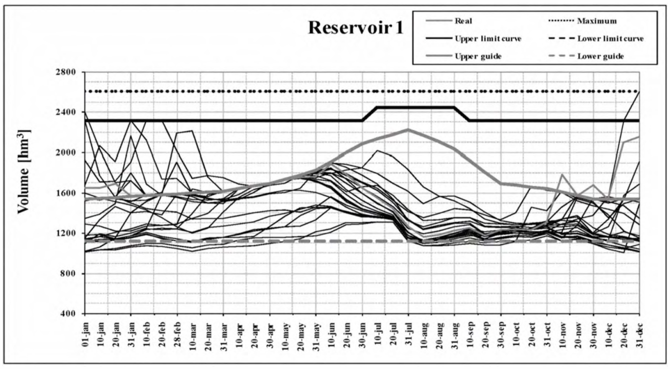

Figure 4. Case 3

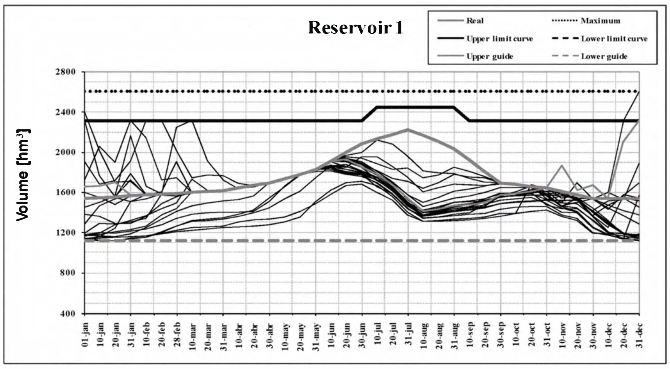

Figure 5. Case 4

VI. APPLICATION TO HYDROELECTRIC SCHEME DESIGN

The design of a hydroelectric scheme comprises a great number of variables that include economic, technical, environmental and social decisions. This set of decisions has to be evaluated through the management of the elements of the basin, considering the sets of plausible hydro inflows series and units outages that the system will find during its lifetime. These sets of inflows and units outages will usually be obtained statistically from historical information of the same series.

Due to the interconnected nature of the operation of river basins, the design of a single element cannot be performed on its own. Instead, the whole set of basin elements has to be taken into account in their final layout, considering both the existing elements and the different design alternatives that are being analyzed. These design alternatives include the power and number of turbines, the possibility of installing pumping turbines, the maximal outflow of turbines, reservoir dimensions, and other similar factors, that should be evaluated in order to attain the best design option.

Several examples design support are presented in [11] considering applications to the choice of the maximum generation capacity and the installation of pumping units. This approach allows comparing the effects of different alternatives considering normal operation.

In this paper, these results are improved by including the unavailability caused by the unexpected outage of generation units. This way, the real operation of generators can be more closely simulated, and the operation and economic results will provide a more accurate vision of the expected results of each alternative.

As a first step, unexpected outage of units is sampled randomly for each day from a uniform distribution. A more exact probability distribution for outages could be fitted employing statistical analysis of historical information, although this study has not been performed in this paper.

This section presents some theoretical studies in order to decide the number of units of a virtual power plant when the size of its corresponding reservoir is already decided or fixed. Considered alternatives vary the number of units of this power plant, from 1 to 4. The increase in the number of turbines alleviates the problems caused by unavalabilities, whether they are planned of unplanned, that could lead to water spills at the reservoir or limited generation capacity in economic opportune moments. On the other hand, the increase in the number of turbines also increases the investment costs, especially in the case of underground power plants or where the power plant installations are located at restricted space sites.

For the first analyzed case each generator group has a maximum flow capacity of 200 m^3/s, while the maximum power generation of each group is 48 MW. Thus, the four cases (1a to 4a) study situations of 200, 400, 600 and 800 m^3/s, and correspondingly 48, 96, 144 and 192 MW.

Each design option has been simulated considering 24 historic series of daily hydro inflows and unplanned outage rates of 5%. Note that for the results presented, consecutive years have been employed, as this is a design phase where the continuous behaviour is the objective of the analysis. Were this an management analysis of the real operation, it would have considered several series starting from the same initial point which represents the actual known situation, and these series would have to fir the expected future evolution of inflows starting from now.

Table 1 shows the effect of the different alternatives analyzed in the flow that is generated and spilled. As it can be expected, as more turbines are installed, more generation can be produced and less water is spilled. This result shows how the unavailabilities loose effect on the reliability of the whole power plant as there are more parallel turbines that can substitute the failed ones.

Table 1. Generated and spilled flows

Case	Maximum output flow [m^3/s]	Generation flow [hm^3/year]	Spilled flow [hm^3/year]
1a	200	2007	1079
2a	400	2446	641
3a	600	2623	464
4a	800	2725	363

The first additional group makes the spills reduce by approximately 40% whereas increasing production by a 20%. Further increases produce less steep changes, and may collide with the investment costs of new turbines. In fact, the installation of the fourth group might not be profitable as the spill reduction resulting from this improvement is a mere 9% while production increases 5%. This might no justify the investment costs that have to be carried for a new turbine.

Another aspect that can be considered is the modification of the production pattern due to more generation capacity. The simulator allows computing the production performed during peak and valley (off-peak) hours, whose results are presented in Table 2. This permits to evaluate the production distribution between peak and valley, placing valley production in the peak hours as more turbines are available. As well, as less production being spilled, this raises the benefits obtained by both increasing the price paid for the produced energy and reducing the loss of incomes derived of spills. Again, this increase of benefits reduces as more turbines are available as unavailabilities loose their negative effect when multiple series element can substitute each other. A balance has to be reached matching the diminishing benefit increase that has been observed due to more turbines being installed, against the increase in investment cost of installing these turbines.

Table 2. Energy production results

Case	Generation energy Total	Peak	Off-peak	Spilled energy [GWh/year]
	[GWh/year]			
Case 1	155	107	48	83
Case 2	189	153	35	49
Case 3	202	177	25	36
Case 4	210	190	20	28

But this also serves for quantification of the magnitude of the spills and thus permits an economic valuation of the investment required to double the output capacity of the turbine against the reduction of losses in the spills. The simulator can then help in this economic assessment providing a technical evaluation of the design options, whether the spills, the power output, or any other suitable metric.

The post-process of this information with the financial counterpart provides support for the design process. Simulation results from the four considered cases allow valuing the incomes from each of them. Without further economic evaluation, it can be seen that the improvements obtained from increasing from 600 to 800 m3/s are relatively low compared with the increase from less turbines. In the case that the investment costs did not prove economically unjustified this last flow capability, further analysis would be needed to show if this is the best option and not a greater amount.

Once the optimal output flow for the power plant has been decided, the specific design of the amount of generator groups is performed. From the previously presented study, plus additional economic valuation of the investment costs, it can be considered that the optimal output flow is 600 m^3/s. This is the starting point for this last phase of the design. The design options considered in cases 1b to 4b are to include 1 to 4 identical groups with a total output flow of 600 m^3/s. The numerical results of these simulations, performed for the same 24 hydro inflows series and outage rates as for the previous study, are presented in Table 3. That table shows the joint data of output flows and energy production.

Table 3. Results for an output flow of 600 m^3/s

Case	No. of units	Generated flow	Spilled flow	Generation energy Total	Peak	Off-peak	Spilled energy
		[hm3/year]		[GWh/year]			
1b	1	2454	632	189	158	31	49
2b	2	2610	478	201	177	24	37
3b	3	2615	473	202	178	24	36
4b	4	2659	428	205	180	25	33

This last phase of design can be assessed in the following manner: considering the total output flow previously decided, the higher the number of groups, the higher the power available. It can be seen, though, that the advantage of installing more units can be substantial when adding the second one (case 1b to 2b), but from that point on, the improvement increase lowers. That is, for the third and fourth case, the generated flow increase compared to the increase from the first to the second is a 31%, and for the spills reduction this figure is a 32%. So when the economic impact of investment costs is considered, the option which would be more probably selected would be to choose the configuration of 2 generation units, unless there were other additional incomes to be considered, like the ancillary services payments or the consideration of additional turbines for quick replacement in case of long-time outages.

VII. Conclusions

This paper describes a simulation model that provides a physically feasible production scheduling for river basins, based upon the solution of the longer term mathematical programming model MHE and taking into account the special features of real river basins.

This simulation model belongs to the set of models applied regularly to hydroelectric energy management at Iberdrola Generación, for the short, medium and long term. It is also used for different kind of analysis like maintenance or improvement works planning, ecological flows, international river agreements, droughts, and other similar issues that may arise in the management of a hydroelectric scheme. The new features like the outage sampling and the link to the medium term hydrothermal model MHE have allowed to occasionally apply it to support the design of modifications to current elements or new hydroelectric schemes. This support can be provided by the valuation of different choices like number and size of power turbines and pumping units, reservoir size, minimum flow, channels for driving tributary rivers, etc, and also the effect that may have the unplanned unavailabilities of the generation units.

This model is applied in this paper to two cases: first to evaluate the management of hydro reservoirs, coordinated with the thermal interaction provided the medium term model MHE, and then to a design related one considering the effect of the unplanned outage when designing the output flow of a hydroelectric power plant and the number of turbines installed on it. Both of them have been applied to realistic river basins and show the real use and capabilities of this simulation tool.

VIII. References

[1] Escudero, L. F., J.L. de la Fuente, C. García, F.J. Prieto, "A Parallel Computing Approach for Solving Multistage Networks", *Annals of Operations Research*, Vol. 90, pp. 131-160, 1999.

[2] Heredia, F.J., N. Nabona, "Optimum short-term Hydrothermal Scheduling with Spinning Reserve through Network Flows", *IEEE Transactions on Power Systems*, Vol. 10, No 3, pp. 1642-1651, August 1995.

[3] Labadie, J. W., "Optimal Operation of Multireservoir Systems: State-of-the-Art Review", *Journal of Water Resources Planning and Management*, Vol. 30, No 2, pp. 93-111, March/April 2004.

[4] Needham, J.T., D.W. Watkins, J.R. Lund, S.K. Nanda, "Linear Programming for Flood Control in the Iowa and Des Moines Rivers", *Journal of Water Resources Planning and Management*, Vol. 126, No 3, pp. 118-127, May/June 2000.

[5] Pereira, M., L. Pinto, "Multistage Stochastic Optimization Applied to Energy Planning", *Mathematical Programming*, Vol. 52, 1991.

[6] Piekutowski, M. R., T. Litwinowitcz , R. J Frowd, "Optimal Short-term Scheduling for a Large-scale Cascaded Hydro System", *IEEE Trans. On Power Systems*, Vol. 9, No 2, pp. 805-811, 1994.

[7] Roman, J., R. N. Allan, "Reliability Assesment of Hydro-thermal Composite Systems by Means of Stochastic Simulation Techniques", *Reliability Engineering & System Safety*, Vol. 46, No 1, pp 33-47, 1994.

[8] Sankarakrishnan, A., R. Billinton, "Sequential Monte Carlo Simulation for Composite Power System Reliability Analysis with Time Varying Loads", IEEE/PES Winter Meeting 1995.

[9] Sjelvgren, D., H. Brannlund, T.S. Dillon, "Large-scale Non-linear Programming Applied to Operations Planning", *Journal of Electrical Power & Energy Systems*, Vol. 11, No 3, pp. 213-217, July 1989.

[10] Van Hecke, J. et al., "Sequential Probabilistic Methods for Power System Operation and Planning", CIGRE TF38.03.13, *Elektra* No 179, August 1998

[11] Perea, A., J.M. Latorre, A. Ramos, S. Cerisola, R. Bellido, "Simulation applications to hydropower systems management and design", presented at 11ª Conferencia Hispano-Lusa de Ingeniería Eléctrica. Zaragoza, Spain, July 2009.

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