A Multi-Area Approach to Evaluate the Brazilian Power System Capacity to Supply the Peak Load Demand Using Detailed Simulation Model of Power Plants Operation

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Abstract—In hydro dominated systems, such as the Brazilian system, the evaluation of the adequacy of the generating system to supply the maximum power demand (peak load) should consider the variation of the output capacity of the hydropower plants with respect to the inflows to the reservoirs, which are also random. This parameter, referred as “available power” depends on the volume of water stored in the hydro plant reservoir and the inflow scenarios. Currently, the available power of each hydro plant in the Brazilian system is calculated by an approximated approach which extrapolates the percentage of water volume stored in the equivalent reservoirs to the reservoir of each hydro plant. This paper analyses the impact of using a methodology based on an individualized model, which represents the detailed operation of hydro plants considering the optimum policy calculated for the aggregated system, to calculate the available power of hydropower plants; thus, parameters such as the water head and the stored volume of the reservoirs are considered individually for each hydro plant. This methodology to estimate the available power is then used in a multi-area approach to evaluate the capacity of the generation system to supply the peak load. The system interconnected operation was performed by an optimization model that minimizes the total power deficit of the whole system (risk sharing approach). In order to assess the impact of the optimized interconnected operation, two other criteria were analyzed: minimization of the power deficit of the subsystem with the highest power deficit in absolute terms, and minimization of the power deficit of the subsystem with the highest power deficit in terms of percentage of its maximum power demand. The proposed methodology is applied to the configuration of the Brazilian Ten-Year Energy Expansion Plan 2020.

Keywords — adequacy analysis; multi-area analysis; hydrothermal systems; simulation and optimization; expansion planning; peak load; available power.

I. INTRODUCTION

The expansion planning is one of the foundations of the current model of the Brazilian power sector. Thus, the Ten-Year Energy Expansion Plan (PDE), annually published, provides an indicative schedule of the generation and transmission expansion, including the main interconnections reinforcements among subsystems, in order to ensure adequate energy supply to the projected growth of the energy demand.

The objective of the generation expansion planning is to minimize the investment and expected operation costs over the planning horizon, taking into account an adequacy reliability criterion. In the case of the Brazilian generating system, the expansion plan is obtained when: (i) the expansion marginal cost is equal to the expected operation marginal costs (economic criterion); and (ii) the annual energy deficit risk is less or equal to 5%.

The studies performed in the Ten-Year Energy Expansion Plan utilizes the computation model NEWAVE \cite{1,2} that simulates the system operation (based on stochastic dual dynamic programming) considering 2,000 hydrological scenarios to represent in detail the stochasticity of water inflows to the reservoirs of the hydropower plants. The hydropower plants are represented in the NEWAVE through energy equivalent reservoirs, i.e., the model aggregates the hydro plants belonging to the same river basin (or hydro plants from nearby river basins with similar inflows behavior). Also, in the NEWAVE model, the interconnection capacities among river basins or subsystems are taken into account. Therefore, from the energy point of view, the representation by equivalent reservoirs is adequate to assess the adequacy of the generation system to supply the projected energy demand in the long-term operation planning.

The Ten-Year Energy Expansion Plan also evaluates the capacity of the generation system to supply the maximum power demand (peak load), in terms of adequacy. For this evaluation it is necessary to assess the output capacity of each power plant. In thermal power systems, this output capacity is subject to equipment random forced outages. However, in hydro dominated systems, such as the Brazilian one, another key parameter is the variation of the output capacity of the hydropower plants with respect to the inflows to the reservoirs, which are also random. This parameter, referred as “available power” depends on the volume of water stored in the hydro plant reservoir and the inflow scenarios. The Ten-Year Energy Expansion Plans have been adopting an approximated approach to calculate the available power of each hydro plant, which has been estimated by using information of the...
equivalent reservoirs that are directly extrapolated to the reservoir of each hydro plant [3,4].

The purposes of this paper are: (i) to analyse the impact of using a methodology based on an individualized model, which represents the detailed operation of hydro plants considering the optimum policy calculated for the aggregated system, to calculate the available power of hydropower plants; thus, parameters such as the water head and the stored volume of the reservoirs are considered individually for each hydro plant; and (ii) to use the previous mentioned methodology to estimate the available power into a multi-area approach to evaluate the capacity of the generation system to supply the peak load. The system interconnected operation is performed by an optimization model that minimizes the total power deficit of the whole system (risk sharing approach). In order to assess the impact of the optimized interconnected operation, two other criteria are analyzed: minimization of the power deficit of the subsystem with the highest power deficit in absolute terms, and minimization of the power deficit of the subsystem with the highest power deficit in terms of percentage of its maximum power demand. Also, for simplicity, equipment random forced outages are not directly considered. Numerical results obtained for a real configuration of the Brazilian system considering a ten-year horizon are presented and discussed.

II. CURRENT APPROACH TO EVALUATE THE SYSTEM CAPACITY TO SUPPLY THE PEAK LOAD [3,4]

Initially, it is necessary to estimate the available power of each power plant, which depends on the plant type, as described below:

**Hydro Plants with Reservoir** - The system operation simulation using the NEWAVE model provides, for each historical inflow sequence and month of the planning horizon, the stored energy in the equivalent reservoir of each subsystem. It is assumed that all reservoirs within a subsystem are operated in parallel, i.e., the storage of the equivalent reservoir (as a percentage of its maximum storage capacity) is directly extrapolated to the reservoirs of the hydro plants located in that subsystem. The upstream level is obtained by the volume polynomial. The difference between the upstream level and the tailwater level is the net water head of the reservoir. After determining the net water head of the reservoir for each hydrological scenario and month, the respective available power is calculated (discounting the values associated to the forced and programmed outages).

**Run-of-the-River Hydro Plants** – To these kinds of hydro plants, the variation of water head is not considered in long-term studies. Thus, the available power is given by the installed power capacity discounting the forced and programmed outage rates.

**Hydro Plants with Strong Seasonality** – Rivers located in the Northern region of Brazil present a huge seasonality of inflows. The main new hydro generation projects under construction/studies in Brazil are located in this region, e.g. Jirau and Santo Antônio hydro plants, Belo Monte hydro plant and the power plants of the Teles Pires and Tapajós basins. All these hydro plants are run-of-river. For each historical inflow sequence and month, the available power is given by their power generation associated to the heavy load level provided by the NEWAVE model.

**Plants that are Not Dispatched by the Brazilian National System Operator (including solar, wind and biomass)** - The available power of these plants is the average value of its monthly energy generation.

**Thermal Plants** - The available power is the installed power capacity discounting the forced and programmed outage rates.

The analysis is done in two steps, single area and multi-area evaluations. In the single area evaluation, a power balance is carried out for the whole system assuming that there are no interchange constraints among subsystems, i.e., the total available power of the Brazilian interconnected system (SIN) is compared with the instantaneous coincident maximum power demand of the SIN. In turn, in the multi-area evaluation, a power balance is initially carried out for each subsystem. If there are subsystems with power deficit, a heuristic procedure is performed to attempt to minimize the deficits: firstly, South and the Southeast subsystems are allowed to interchange power, and the same applies to the North and Northeast subsystems; if deficits still persists, the heuristic procedure allows interchange power between the pairs South/Southeast and North/Northeast subsystems.

III. DETAILED SIMULATION MODEL OF POWER PLANTS OPERATION

One of the objectives of the operation planning of the Brazilian hydrothermal system is to determine a strategic operation that, for each period of planning, produces generation targets to the plants of the system in order to minimize the expected total operational cost over the planning horizon. The NEWAVE model is officially adopted in the ten-year energy expansion plan studies. This model represents the hydro plants through energy equivalent reservoirs, i.e., it aggregates several hydro plants of a same river basin (or hydro plants of nearby river basins with similar inflows behavior). However, for some studies it is necessary to address figures for each hydro plant, which is provided by the SUISHI model [1,5], a detailed simulation model of hydro plants operation in an interconnected hydrothermal system, like the Brazilian system.

The solution process of the SUISHI model is divided into two steps that are solved iteratively: the first step optimizes the hydrothermal balance between subsystems, and the second step simulates the operation of individualized hydro plants. The problem solved in the first step is equivalent to the problem solved by NEWAVE during its final simulation of the system operation. In this step, the objective of SUISHI is to define generation targets for each thermal plant and to each equivalent reservoir by solving an optimization problem which aims at minimizing the sum of the present and future costs, subject to certain constraints, such as water balance, demand supply, maximum storage, maximum hydro generation and cost-to-go function obtained by a simulation of the NEWAVE model.

In the second step, a heuristic approach tries to allocate the hydro generation targets of each equivalent reservoir (defined in the first step) to the respective hydro power plants. Such
The depletion of reservoirs is based on priorities (built-in or defined by user) and operative levels (defined by user);
2. It attempts to keep all reservoirs within a subsystem in the same operative level;
3. The effect of a reservoir depletion over the downstream reservoirs are taken into account;
4. It aims to maintain empty the upper operative level of reservoirs in order to absorb high inflows (flood control), thus minimizing spillways;
5. It aims at maintaining full the lower operative level of reservoirs to avoid excessive power loss due to low net water head.

After the operation simulation, two different situations may occur: success or fail in the target allocation of hydro generation defined on the optimization step. The fail occurs when the sum of individualized energy generation of a subsystem is lower (generation deficit) or higher (generation excess) than the target defined by the optimization step. When a generation deficit occurs, the SUISHI model redefines the maximum hydro generation constraint in order to reduce the hydro generation target for the equivalent reservoir to be established in the optimization step. On the other hand, when a generation excess occurs, the model decreases the maximum storage energy constraint in order to force a higher hydro generation target to be established in the optimization step. The iterative process goes on until convergence occurs.

Figure 1 illustrates the iterative process performed by the SUISHI model.

**IV. PROPOSED APPROACH**

In order to evaluate the capacity of the Brazilian generation system to supply the peak load, it is necessary to determine the available power of each hydro plant for each inflow sequence and for each month of the planning horizon. In this paper, the individualized SUISHI model, described in the previous section and which represents the detailed operation of hydro plants considering the optimum policy calculated for the aggregated system, is used to calculate the available power of hydro plants. Thus, parameters such as the water head and the stored volume of the reservoirs are considered individually for each hydro plant.

To calculate the available power of each hydro plant in the proposed approach, it is assumed that the amount of water available for a hydro plant \(Q_{AV}\) is given by the total amount of water stored in its own reservoir plus the amount of water that may come from the depletion of upstream reservoirs. The amount of water that may pass through its turbines is limited to its maximum discharge \(Q_{MAX}\). Thus the available power of a hydro plant \(P_{AV}\) is calculated by the equation below:

\[
P_{AV}(MW) = \text{Minimum}(Q_{AV}, Q_{MAX}) \times H \times \rho
\]

Where \(H\) is the net water head of the hydro power plant and \(\rho\) is its average efficiency. All these variables are provided by the SUISHI model.

Once the available power for each hydro plant and for each hydrological scenario and month has been obtained, it is possible to evaluate the capacity of the generation system to supply the peak load in a multi-area approach. In this paper, the system interconnected operation is performed by an optimization model that minimizes the total power deficit of the whole system (risk sharing approach). In order to assess the impact of the optimized interconnected operation, two other criteria are analyzed: minimization of the power deficit of the subsystem with the highest power deficit in absolute terms, and minimization of the power deficit of the subsystem with the highest power deficit in terms of percentage of its maximum power demand. Also, for simplicity, equipment random forced outages are not directly considered.

**Criterion 1: minimization of the total power deficit of the whole system (risk sharing approach)**

For each inflow scenario and month of the planning horizon, the following linear programming model is solved:

\[
\text{Minimize } \sum_{i=1}^{NS} \text{Def}_i
\]

subject to:

\[
\sum_{i \neq j} f_{ij} + \text{Def}_i \geq D_i - P_i \quad i = 1, \ldots, NS
\]

\[
f_{ij} \leq F_{ij} \quad i = 1, \ldots, NS; \quad j = 1, \ldots, NS; \quad i \neq j
\]

\[
\text{Def}_i \geq 0 \quad i = 1, \ldots, NS
\]

where:

\(NS\) – number of subsystem;
Def_i – power deficit in subsystem i;
f_{ij} – power interchange from subsystem i to subsystem j;
P_i – available power in subsystem i;
D_i – peak load of subsystem i;
F_{ij} – transmission power capacity from subsystem i to subsystem j;

Equation (2) is the objective function representing the criterion of minimization of the total power deficit. Equation (3) represents the power balance of subsystem i. Equation (4) limits the power interchange between subsystems and equation (5) limits the power deficit to non-negative values.

The term \( P_i \) is given by the sum of the available power of all power plants (hydro, thermal etc) within subsystem i. In this sum the available power of hydro plants with reservoir, run-of-the river hydro plants and hydro plants with strong seasonality is determined by equation (1). For plants that are not dispatched by the Brazilian National System Operator (including solar, wind and biomass) and for thermal power plants the available power is calculated as described in section II.

Criterion 2: minimization of the power deficit of the subsystem with the highest power deficit in absolute terms

For each inflow scenario and month of the planning horizon, a linear programming model similar to (2)-(5) is solved, but replacing the equation (2) by equation (6) and adding the equation (7).

\[
\text{Minimize} \quad (\text{Def}_{\text{max}})
\]

\[
\text{Def}_{\text{max}} \geq 0 \quad i = 1, \ldots, NS
\]

where \( \text{Def}_{\text{max}} \) represents the power deficit of the subsystem with the highest power deficit.

Criterion 3: minimization of the power deficit of the subsystem with the highest power deficit in terms of percentage of its maximum power demand

For each inflow scenario and month of the planning horizon, a linear programming model similar to (2)-(5) is solved, but replacing the equation (2) by equation (8) and adding the equation (9).

\[
\text{Minimize} \quad (\text{Def\%}_{\text{max}})
\]

\[
\text{Def\%}_{\text{max}} - \text{Def}_i / D_i \geq 0 \quad i = 1, \ldots, NS
\]

where \( \text{Def\%}_{\text{max}} \) is the power deficit of the subsystem with the highest power deficit in percentage terms.

V. NUMERICAL RESULTS

This section presents the numerical results obtained for the real configuration adopted in the Brazilian Ten-Year Energy Expansion Plan 2020 [3].

The Brazilian interconnected power system has been divided into 9 subsystems: Southeast (SE/CO), South (S), Northeast (NE), North (N), Itaipu (IT), Acre/Rondônia (AC/RO), Manaus (Man), Belo Monte (BM) and Teles Pires/Tapajós (TP). The main load centers are located in the first four subsystems while the others are typically energy exporters. Taking this feature in association with the fact that the hydro plants available powers are calculated separately by SUISHI model, it allows to simplify the system representation by aggregating subsystems IT, AC/RO and TP into the SE/CO subsystem and BM and Man subsystems into the N subsystem. It is also necessary to aggregate the transmission limits between SE/CO and S subsystems, as showed in Figure 2.

Table 1 presents the peak load for each subsystem in the last month of the planning horizon (December 2020). The Southeast subsystem is the main load center concentrating about 59% of the total Brazilian peak load. The South and Northeast concentrate about 15% of the peak load while the North subsystem concentrates only 10%.

![Fig. 2. Schematic diagram adopted in the case study (source: [4])](image)

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>MW %</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southeast</td>
<td>66,700</td>
<td>59</td>
</tr>
<tr>
<td>South</td>
<td>17,803</td>
<td>16</td>
</tr>
<tr>
<td>Northeast</td>
<td>17,502</td>
<td>15</td>
</tr>
<tr>
<td>North</td>
<td>11,645</td>
<td>10</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>113,650</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Figure 3 presents the duration curve for the total available power of the Brazilian hydro plants obtained by the proposed (red curve) and the current (blue curve) approaches. Each curve presents the results for 77 historical inflow sequences and 120 months, resulting in 9,240 points plotted in ascending order. It is possible to observe that the accurate total available power, calculated by the proposed approach is always lower than that figure calculated by the current approach.
Fig. 3. Duration curve for the Brazilian available hydro power

Figures 4, 5, 6 and 7 present the duration curve of the power balance for the subsystems Southeast, South, Northeast and North, respectively. In each figure, the blue curve represents the power balance duration curve by using a single area approach, i.e., the available power within a subsystem minus its peak load. The red curve represents the resulting power balance duration curve by using a multi-area methodology adopting a risk sharing approach, (Criterion 1). Again, each curve presents the results for the 77 historical inflow series and 120 months.

From Figure 4 it is observed that the probability of power deficit in the Southeast subsystem considering only its own generation is about 2.2%. Also, Southeast subsystem has a high probability of exporting power to others subsystems (region where the red curve is below the blue curve). Nevertheless, considering the interchange of power from others subsystems under a risk sharing approach, the probability of power deficit is reduced to 0.90%.

Figure 5 shows that the South subsystem benefited dramatically from the interconnected operation under a risk sharing scheme: its power deficit probability drops from 33% (single area approach) to only 1.9%.

In turn, the probability of power deficit of the Northeast subsystem decreases from 1.5% to 0.2% when the risk sharing scheme is considered (see Figure 6). Similarly to the Southeast subsystem, the Northeast subsystem has a high probability to export power (region where the red curve is below the blue curve).

Finally the North subsystem (Figure 7) has a probability of power deficit reduced from about 15% to 1.5%.

The comparison of the results obtained by criteria 1, 2 and 3 are presented in Figures 8, 9, 10 and 11, for subsystems Southeast, South, Northeast and North, respectively. These Figures show the segment of the duration curve in which the
power balance is negative (power deficit occurs). The segment of these curves in which the power balance is non negative (deficit null) are very similar for the three criteria, following the shape of the red curves presented previously in Figures 4, 5, 6 and 7.

From Figure 8 it is noted that the maximum power deficit of the Southeast subsystem is about 8,900 MW for criteria 1 (red curve) and 3 (green curve), and about 4,200 MW for criterion 2 (blue curve). The probability of power deficit is about 0.9% for criterion 1, which increases to 2.7% for criteria 2 and 3. Besides, criterion 3 presents tendency of greater deficits than criteria 1 and 2.

![Power Balance Duration Curve (Southeast)](image)

Fig. 8. Comparison of results obtained by the three criteria (Southeast subsystem).

Figure 9 shows the maximum power deficit of South subsystem: 10,100 MW for criterion 1, reducing to 5,200 MW for criterion 2 and reducing even more to 4,300 MW for criterion 3. On the other hand, the probabilities of power deficit are: 1.9% (criterion 1), 3.1% (criterion 2) and 3.0% (criterion 3).

The Northeast subsystem (Figure 10) presents maximum power deficit of about 2,400 MW for criterion 1 which increases to about 4,900 MW and 4,700 MW for criteria 2 and 3 respectively. In turn, the probability of power deficit in criterion 1 is 0.2%, increasing to 1.9% for criterion 2 and 1.8% for criterion 3.

The North subsystem presents the same value of maximum power deficit for the three criteria: about 6,100 MW (see Figure 11). The probability of deficit for criterion 1 is about 1.5%, increasing to about 2.6% for criteria 2 and 3.

Comparing the results presented in Figures 8, 9, 10 and 11 it can be observed a reduction of larger power deficits for the Southeast, South (expressive reduction for both) and North (slight reduction) subsystems, while the Northeast subsystem presents an expressive increase of larger deficits, when changing from criterion 1 (risk sharing) to criterion 2 (minimization of the power deficit of the subsystem with the highest power deficit in absolute terms).

In turn, when changing from criterion 1 to criterion 3 (minimization of the power deficit of the subsystem with the highest power deficit in terms of percentage of its maximum power demand) the deficits of the Southeast and Northeast subsystem increase substantially, while the deficits of the South and North subsystems decrease.

Finally, in all subsystems, the probabilities of power deficit were the smaller when applying criterion 1 thus highlighting...
the benefits of an interconnected operation under a risk sharing approach.

VI. CONCLUSIONS

In hydro dominated systems, such as the Brazilian system, the evaluation of the adequacy of the generating system to supply the peak load should consider the variation of the output capacity of the hydropower plants with respect to the inflows to the reservoirs, which are also random. This parameter, referred as “available power” depends on the volume of water stored in the hydropower plants; thus, parameters such as the water head and the stored volume of the reservoirs are considered individually for each hydropower plant. This methodology to estimate the available power was used in a multi-area approach to evaluate the capacity of the generating system to supply the peak load. The system interconnected operation was performed by an optimization model that minimizes the total power deficit of the whole system (risk sharing approach). In order to assess the impact of the optimized interconnected operation, two other criteria were analyzed: minimization of the power deficit of the subsystem with the highest power deficit in absolute terms, and minimization of the power deficit of the subsystem with the highest power deficit in terms of percentage of its maximum power demand. The proposed methodology was applied in the real configuration adopted in the Brazilian Ten-Year Energy Expansion Plan 2020.

Regarding the adoption of an individualized model, the results shows that the total available power of all hydro plants is smaller when compared with the value obtained by extrapolating results of the equivalent reservoirs, thus meaning that the available power obtained by the current approach is optimistic.

Regarding the multi-area evaluation based on an optimization model, in all subsystems, the probabilities of power deficit were smaller when applying criterion 1 thus highlighting the benefits of an interconnected operation under a risk sharing approach.

The results obtained from the proposed approach encourages its further development aiming to be adopted for the multi-area evaluation of adequacy of the Brazilian generating system to supply its peak load, based on detailed simulation model of individualized power plants operation and optimization techniques. Additionally, the impact of equipment random forced outages on the proposed methodology should be assessed, using, for example, the methodologies described in references [6-10].

REFERENCES


