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Maintenance Schedule Optimization Applied to Large Hydroelectric Plants: Towards a Methodology Encompassing Regulatory Aspects

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ABSTRACT The maintenance schedule planning of hydro plant generating units is a subject of great interest to several agents in the energy industry. A correct approach for this problem can prevent the degradation of physical assets and minimize the probability of forced shutdowns of their equipment. In addition to these factors, due particularities of the Brazilian system, the operational strategies of its agents are also affected by the maintenance schedule of the generating units. This occurs due to the Availability Factor (AFA), which is directly influenced by the hours of maintenance performed at the plant and, in case of a performance below the stipulated in the concession contracts, it can lead to financial losses or administrative sanctions applied by the regulatory agent. With this motivation in mind, the present work proposes a methodology for Generator Maintenance Scheduling (GMS) of a hydroelectric plant, developing a mathematical model to determine the ideal moment to perform maintenance, considering operational restrictions and regulatory aspects of hydroelectric plants. The optimization methodology proposed for this problem is done through mixed-integer linear programming, where the integer variables consist of the operating state and start date of maintenance of each generating unit. In the end, to validate the proposed modeling, a case study is carried out for a real large plant in the Brazilian system.

INDEX TERMS Availability factor, generators units, hydro plants, maintenance scheduling, optimization.

I. INTRODUCTION

Brazil has most of the electricity generated from renewable sources, where generation by Hydroelectric Plants (HP) leads with the highest percentage, reaching 64.9 % of the Brazilian electric matrix [1]. Due to the existence of large plants and spread over the extensive national territory, the National Interconnected System (NIS) was created, which is a coordination and control system, formed by the South, Southeast/Midwest, Northeast and most subsystems from the North, providing energy transmission between subsystems and enabling an economical and secure system.

The hydroelectric plants connected to the NIS and dispatched centrally by the Independent System Operator (ISO) participate in the Energy Reallocation Mechanism (ERM), created due to the hydrological risk existing because of the large territorial extensions of the country, where there are hydrological differences between the regions, with dry and humid periods not coincident [2], [3]. The ERM is a financial mechanism with the objective of sharing hydrological risk among hydroelectric generators, ensuring the optimization of the operation of the hydrothermal system throughout the year [4].

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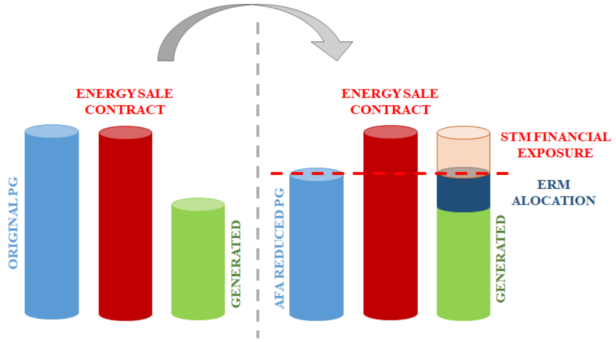

FIGURE 1. **AFA Impact Example.**

Thus, when generators sign energy contracts, they assume the risk of the amount of energy they will generate according to their Physical Guarantee (PG)[12] and may not generate enough energy to meet the contracted amount, in this case, they must purchase energy from other generating agents with energy surplus, valued by the Optimization Energy Tariff (OET), defined annually [3]. In summary, the ERM reallocates the surplus energy from the generation agents that generated above its PG to the ones that generated below [6].

Aiming to guarantee and encourage a quality service by the generators participating in the ERM, the Guaranteed Energy Reduction Mechanism (GERM) was created [3], [7]. The objective of the GERM is to assess whether the plants met their respective generation availability requirements in a given period. The assessment is made for each plant, through a comparison between the expected values (defined in the contract) of scheduled and forced interruption of its generating units, with their respective values verified over time.

In order to evaluate the availability of hydroelectric dams, the GERM uses the Availability Factor (AFA), which is calculated based on the hours of interruptions previously mentioned [2]. The AFA is used to reduce mathematically, that is, only for the purpose of penalty for the sale of energy, the PG of the plants for sharing the hydrological risk in the ERM.

Thus, with the reduction, the agent will be financially impacted, since the plant will need to buy a greater amount of energy from other generators to meet its contractual requirements. Fig. 1 exemplifies the impact of AFA for a generic hydroelectric plant.

As shown in Fig. 1, the hydroelectric plant had its PG reduced by the AFA, due to high interruption hours. After the reduction, the ERM acts by reallocating energy from other plants that generated above its PG. However, as there was a reduction in PG, the agent will not be able to meet its energy sales contracts and will have to acquire this energy deficit in the Short Term Market. This acquisition is valued at the Settlement Price for Differences (SPD), which assumes high values in comparison to OET [3]. Thus, studies related to the Availability Factor have major importance for hydroelectric plants in Brazil, as poor availability performance can cause major financial impacts, as previously discussed.

An alternative to improve the performance of the AFA is strongly related to the reduction of interruptions that occurred due to the plant's responsibility. Generally, these interruptions are caused due to maintenance that must be carried out in the Generating Units (GU's) throughout the year, for their proper functioning. It is worth mentioning that these interruptions are accounted for only when there is an impact on the system, that is, when the disconnection of the GU for maintenance leads to a generation below that required by the system.

Ideally, to mitigate these problems, the mandatory preventive maintenances must be scheduled throughout the year in an optimized way, aiming to minimize penalties that are counted as interruption hours, which negatively impact the hydro plant's Availability Factor values.

Based on the points presented, this work proposes a methodology for Generator Maintenance Scheduling (GMS) of the generating units of a hydroelectric plant. The main goal is to propose an optimization problem to schedule the mandatory preventive maintenance for each GU throughout the year. The proposed optimization modeling focuses on minimizing interruptions penalties, taking into account plant operating restrictions and the duration of each desired maintenance. For this, the operating status of all the generating units is optimized, for all days of the year, as well as the day of beginning of the maintenance previously established.

The importance of this study is evidenced in the case of the Santo Antônio Hydroelectric Plant (SAHP) that caused Santo Antônio Energia (SAE), the concessionaire responsible for the plant, to have a financial impact of approximately R$ 812 million in 2018 [8], due the poor performance of the generating units over the previous years, and consequently, low AFA values.

Thus, the proposed modeling, mentioned above, will be applied using real data from SAHP, considered the fifth largest hydroelectric plant in Brazil, in installed capacity, with 3568 MW and 2424.20 MW of physical guarantee. The entire methodology was developed as part of a Research and Development (R&D) project with SAE, where the main objective is to provide alternatives for a better performance of the SAHP availability, due to the great financial impacts suffered over the past years.

It is important to emphasize that most of the works found, identified in the following session, use heuristic or metaheuristic programming to solve the GMS problems. The need exists because the exact models have low computational efficiency in their application. However, this work seeks to fill this gap, through a deterministic model applied in a real case, a large hydroelectric plant, observing regulatory and constructive aspects.

After this background, the main contributions of this work can be summarized according to the topics below:

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[1] Physical guarantee of a plant corresponds to the fraction allocated to it of the Physical Guarantee of the System [2] and does not depend on its actual generation, is associated with the long-term hydrological conditions of the plant, assuming a specific risk criterion of non-service from the market [5].

[2] Physical Guarantee of the System corresponds to the maximum load that can be met with a risk of non-attendance, obtained through operation simulations, using synthetic series of affluent energy [5].

- Model for obtaining an optimal GU maintenance schedule at a hydroelectric plant;
- Apply GMS to mitigate regulatory penalties, considering operating and maintenance restrictions of the generating units;
- Increase the availability of hydro generation, a renewable source and of low cost, prioritizing maintenance at times when there is not enough affluent flow to operate all the GU's;
- Real case study in a large Brazilian hydroelectric plant.

II. GENERATOR MAINTENANCE SCHEDULING (GMS)

The problem of the generator maintenance scheduling (GMS or GMSP) has been frequently studied, as can be seen in the literature review developed by [9]. According to the authors, this optimization problem is usually NP-hard and can be non-linear and non-convex. The paper emphasizes the importance of improving the maintenance schedule taken in generating units and transmission lines, the main result of which is to avoid unnecessary shutdowns and reduce the probability of forced shutdowns that have high repair costs for the plants.

Two works of great prominence and which are closest to this study, are those of [10] and [11]. In the first work, the authors justify the need to plan the maintenance schedule mainly because of the financial losses of hydroelectric plants caused when the turbines are not available for operation. The work is about a case study of a hydroelectric plant located in Canada and proposes a mixed programming model that considers time windows for maintenance activities, non-linearities and disjunctions of the problem found in the hydroelectric plant, in addition to hydraulic production functions. The researchers opted to simulate the problem through an extended formulation and another by removing sets of unnecessary inequalities, obtaining in the second, better results regarding the computational time of the solution.

The second is a master's dissertation, in which the objective is to model the schedule for the shutdowns of the power transformers of an energy transmission company. The author portrays that there is little research in the literature on the maintenance schedule in transmission companies, so he used as inspiration the studies related to problems of preventive maintenance of generators, the main equipment of the electric power generation companies. This problem was modeled mathematically as a problem of mixed-integer linear programming.

The authors of [10] continue their work on the article [12]. In this study, the authors specifically approach the problem of maintenance planning for generating units of hydroelectric plants, focused on seeking to reduce operating costs. The authors show that the financial impacts on hydroelectric systems are difficult to estimate due to the non-linearity of hydroelectric generation, the uncertainty of water flux, in addition to the diversity of variables and physical restrictions of the system. The problem is solved using the Benders algorithm, but the authors use seven acceleration techniques for the same.

Among the various methods that have been used to solve the GMS problem, the most recent are the study of [13], in which the authors use the General Algebraic Modeling System (GAMS) software to perform the optimization. The study by [14] uses the Discrete Integer Cuckoo Search (DICS) algorithm to solve this problem, a method inspired by nature, being an algorithm based on meta-heuristics. The results of this method are compared to the technique of Genetic Algorithms (GA) and to the Particle Swarm Optimization (PSO), presenting the DICS method the best results. As for the case study presented by [15], the authors present the method they used to elaborate the maintenance schedule for hydroelectric power seeking to maximize profit. It is a study applied in Norway that uses the Benders decomposition principle to program the plant's maintenance schedule in a medium-term horizon of the hydroelectric system planning, at the end the computational performance for this type of problem is discussed through this case study.

Other studies carried out in previous years are found, especially the works of [16] and [17], which use the meta-heuristic method Simulated Annealing (SA) to solve maintenance schedule planning optimization problem, an easily applicable model. The [18] works, on the other hand, compare the results found using the Genetic Algorithm (GA) model with hybrid models of GA with SA. The article developed by [19] proposes two different solutions, the first is through the Ant Colony Optimization (ACO) heuristic methods and the second, also by the SA method. In the work of [14] the algorithm known as Discrete Integer Cuckoo Search (DICS) is used, the author comments that his results show to be better than other algorithms used for this same type of problem. There is also the thesis of [20] which brings an extensive explanation about the problems of GMS and meta-heuristics to be used. Last but not least, the book titled "Maintenance, modeling and optimization", by the authors [21] presents a review of the problem formulation and solution techniques.

III. AVAILABILITY FACTOR (AFA)

A. FORMULATION

As previously mentioned, the AFA is used to evaluate the generation availability of each hydroelectric plant, treated in the GERM with the aim of mathematically reducing the plant PG, financially impacting the agent responsible for the hydro plant. The AFA uses unavailability indicators for each GU of the hydroelectric plant related to shutdowns or limited power operation. The indicators can be classified as forced or scheduled stops, usually caused by equipment maintenance.

The unavailability assessed by ISO is determined by means of the Equivalent Scheduled Shutdown Rate (ESSR) and the Verified Equivalent Forced Shutdown Rate (EFSRv). Thus, for each plant dispatched by ISO, the ESDR and EFDR rates must be calculated monthly, according to (1) and (2).

$$ESSR = \frac{\sum_{j=1}^{60}\sum_{i=1}^{n} P_i \cdot (HSS + EHSS)_{ij}}{\sum_{j=1}^{60}\sum_{i=1}^{n} P_i \cdot (HP)_{ij}} \tag{1}$$

$$EFSRv = \frac{\sum_{j=1}^{60}\sum_{i=1}^{n} P_i \cdot (HFS + EHFS)_{ij}}{\sum_{j=1}^{60}\sum_{i=1}^{n} P_i \cdot (HFS + EHFS + HS + HE)_{ij}} \tag{2}$$

where:

i	Index of the generating unit in commercial operation;
n	Number of generating units in commercial operation;
j	Month index;
P	Installed power of the generating unit i;
HSS	Hours of Scheduled Shutdown of unit i in month j;
$EHSS$	Equivalent Hours of Scheduled Shutdown of the unit i in month j (the unit operates with limited nominal power, associated with a scheduled condition);
HP	Hours of the month j for unit i;
HFS	Hours of Forced Shutdown of unit i in month j;
$EHFS$	Equivalent Hours of Forced Shutdown of the unit i in month j (the unit operates with limited nominal power, associated with a forced condition);
HS	Hours in Service of the unit i in the month j (number of hours equivalent in service plus the number of hours in which the unit operates synchronized to the system, without power restriction);
HE	Number of hours of shutdown due to external conditions and/or shutdown due to systemic interest of the unit i in month j.

Analyzing the equations, it is possible to see which indicators are subject to change, optimization and planning so that the rates are lower. In (1), specifically in the numerator, the number of hours is directly associated with the scheduled maintenance of the generating units present in the hydroelectric plant. Thus, it is extremely important that an optimized planning of these maintenance is carried out, considering all the influencing factors, for example, seasonality of the inflow in the reservoirs and operational limitation of the generating units.

In the Equation (2), the HE indicator depends on external conditions, making it impossible for the agent to interfere. And the HFS and EHFS indicators, which indicate forced or corrective maintenance, are at first not flexible to change either. However, the use of tools that assist in maintenance management can influence and decrease the likelihood of shutdowns or forced conditions leading to an operation with limited power.

It is also worth noting that new studies on this subject are suggested, especially in the context of scenario projections of forced shutdowns. The mathematical model proposed in the next session is able to receive possible corrective maintenance as an input parameter. In this case, the days with expected forced shutdowns will have a limited number of GU's available for operation.

Finally, it is possible to perform the calculation of the AFA given according to the verified ESSR and EFSR rates and the reference values established in the contract, as presented in (3), (4) and (5).

$$Av = (1 - ESSR) \cdot (1 - EFSRv) \tag{3}$$

$$Ar = (1 - SS) \cdot (1 - EFSR) \tag{4}$$

$$AFA = \frac{Av}{Ar} \tag{5}$$

where:

Av	Verified Availability Index;
Ar	Reference Availability Index;
SS	Scheduled Shutdown in contract;
$EFSR$	Equivalent Forced Shutdown Rate in contract;

B. AFA IMPACTS

As previously discussed, the AFA will impact hydroelectric plants that do not meet their availability requirements. For this purpose, the plant's PG will be mathematically reduced, increasing its exposure in the Short Term Market. Thus, the calculation is given as presented in (6).

$$PGv = \min(PG,\ PG \cdot AFA) \tag{6}$$

where:

PGv	Verified Physical Guarantee;
PG	Contractual Physical Guarantee.

Therefore, if the AFA is less than one, the evaluated hydroelectric plant will have its physical guarantee reduced. Therefore, the agent will be financially impacted, as the plant in question will need to purchase energy from other generators to meet its energy sales contracts.

IV. PROPOSED METHODOLOGY

A. PROBLEM OVERVIEW

As previously discussed, the main objective of the work is to find an optimal maintenance schedule for the generating units of a hydroelectric plant, in order to reduce the penalties caused by scheduled shutdowns in inappropriate periods. Penalties occur when the Independent System Operator demands power generation and the turbines are unavailable for operation due to both preventive and corrective maintenance, and then the agent is penalized as it is affecting the entire NIS. In addition, the new schedule must meet all the necessary maintenance of each generating unit in order to prevent possible undesirable breakdowns and interruptions.

In order to better clarify the penalty rules, Fig. 2 presents a flowchart that demonstrates the effect of the penalty for unavailability, specifically for plants in the Northern region of Brazil. In summary, when the plant has GU's inoperative due to internal operational planning and spilled flow, then there is a penalty. The accounting will be proportional to the number of hours disconnected in this period, which may be hours of scheduled or forced maintenance, computed respectively by the HSS and HFS indexes.

In addition, even with all the turbines in operation, the plant is still subject to penalty in the following case, if spillage occurs and some GU is not operating at maximum capacity due to the responsibility of the plant. In this case, the penalty will be proportional to the difference in the maximum operating potential with the actual occurred and accounted for during the period of time that this occurred.

Therefore, as seen in Fig. 2, if there is spilled flow, but not caused by the plant's responsibility, there will be no penalty. In case of spillage and this is caused by the plant's operational criteria, it will be penalized. Thus, the objective is to schedule all maintenance in an annual horizon, in order to avoid water spillage caused by the plant, reducing penalties in the HSS index, and consequently in the AFA, reducing the plant's exposure in the short-term market.

B. MATHEMATICAL FORMULATION OF THE PROBLEM

The mathematical model developed aims to optimize the planning of the maintenance schedule for generating units of a hydroelectric plant. The problem involves binary and real variables, in addition to restrictions related to time and space, thus categorizing itself into a Mixed-Integer Linear Programming (MILP) problem.

The objective is to optimize the planning of the operation and the beginning of the maintenance of each turbine, represented by the sub-index t. In addition, respecting the restrictions of the problem, in order to minimize the flow and, consequently, reduce the financial impact caused by the AFA to the hydroelectric plant.

The maintenance and optimized operation schedule is done on a daily basis, where each day is represented by the sub-index d. Therefore, modeling consists of minimizing the daily sum of the spilled flow. Thus, the proposed methodology for the generator maintenance scheduling problem is formulated by (7) - (14).

$$min \;\; Z = \sum_{d=1}^{D} s_d \tag{7}$$

Subject to:

$$q_d = \sum_{g=1}^{G} x_{g,d} \cdot \bar{q}_{g,d} \qquad \forall\, d \in D \tag{8}$$

$$q_d + s_d = u_d \qquad \forall\, d \in D \tag{9}$$

$$\sum_{d=1}^{M_g-1} y_{g,d} = P_g \qquad \forall\, g \in G \tag{10}$$

$$(y_{g,d} = 0) \vee \left(\sum_{s=0}^{M_g-1} x_{g,d+s} = 0 \right) \qquad \forall\, g \in G, \quad d = 1, 2, 3, \ldots, D - M_g + 1 \tag{11}$$

$$\sum_{d=1}^{D} y_{g,d} \leq N \qquad \forall g \in G \tag{12}$$

$$x_{g,d}, y_{g,d} \in [0, 1] \cap \mathbb{Z} \tag{13}$$

$$q_d, s_d \geq 0 \tag{14}$$

where:

G	Number of generating units;
D	Number of days;
s_d	Spilled flow by the plant on d day (m^3/s);
q_d	Turbined Flow by the plant on d day (m^3/s);
$\bar{q}_{g,d}$	Maximum turbined flow of the g unit on d day (m^3/s);
u_d	Affluent flow forecast for the day d (m^3/s);
$x_{g,d}$	Operating mode of the unit g in d day;
$y_{g,d}$	Day in which the maintenance action of unit g will start
M_g	Maintenance duration of g unit;
P_g	Number of maintenance periods of unit g;
N	Maximum simultaneous maintenance starts.

In this problem, the objective function, represented by (7), aims to minimize the spilled flow of the plant, because when this occurs, the hydroelectric plant suffers significant financial losses. This process seeks to use as much of the water as possible in the river through the turbined flow (generation of energy) of the available generating units. Maintenance planning takes place at daily time intervals for each generating unit. This objective function is subject to the following restrictions:

- *Turbined Flow Constraint:* Presented in (9), each generating unit, when available (state indicated by the variable $x_{g,d} = 1$) will always turbine to its maximum potential, resulting in the total daily turbined flow of the entire plant, according to (8). The defluent flow, which is the turbined flow plus the spilled flow, must always be equal to the affluent flow of the river for every day of the planned period.
- *Maintenance Period Constraint:* The number of maintenance carried out for each turbine must be equal to the number of planned maintenance for this turbine, represented in (10).
- *Duration of Maintenance and Continuity Restriction:* All generating units must be shut down for the period corresponding to the duration of their maintenance (M_g). In addition, when maintenance is started, it must occur continuously (without interruptions) until the planned period is met, that is, the maintenance cannot be aborted or concluded before scheduled. These two premises will be met in a single constraint, expressed in (11). This constraint is a Disjunctive Constraint, which says either $y_{g,d} = 0$ or the sum $\sum_{s=0}^{M_g-1} x_{g,d+s} = 0$,

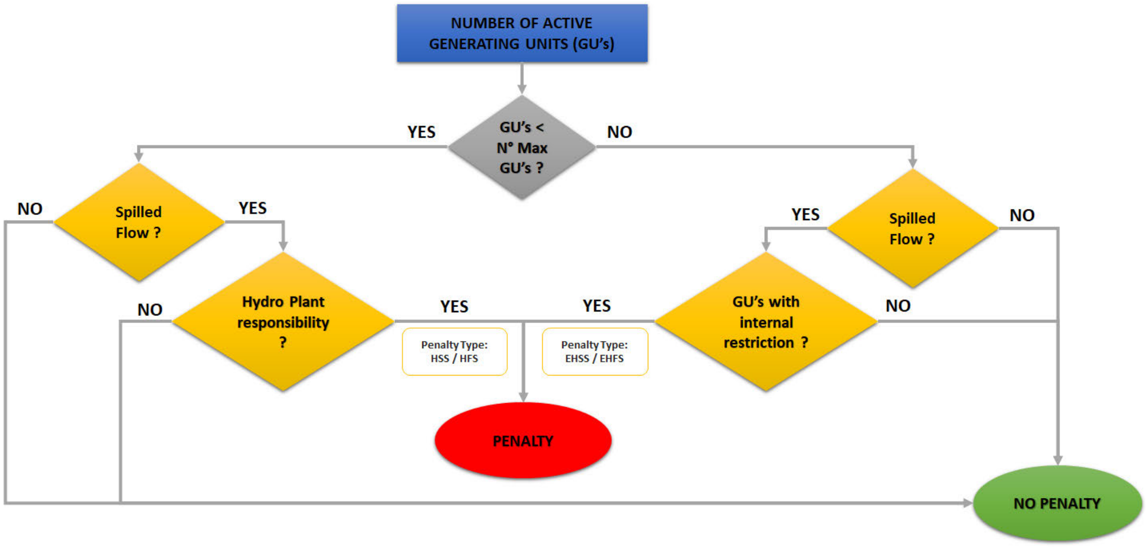

FIGURE 2. **Flowchart of the Operation of Penalties in Relation to the Shutdowns.**

but not simultaneously. This constraint is applied to all turbines declared in the problem.

- *Limit of Maintenance Starting Simultaneously Constraint:* Presented by (12), it indicates that the sum of $y_{g,d}$ starts on d day is limited by a scalar. The restriction is important in order to represent limitations of the hydroelectric plant maintenance team.
- *Canalization Constraints:* These constraints limit the problem variables. For binary variables, $x_{g,d}$ and $y_{g,d}$, is indicated in (13) and for the spilled flow s_d, in (14).

Disjunctive constraints of this nature are often encountered in maintenance scheduling problems, as they are applicable when the problem has disjoint viable regions. In the problem presented, the disjunctive constraint can be replaced by a set of linear inequalities using the aid of Big-M, being represented in (15). Big-M is represented by 'M' appearing on the right side of this constraint, which in this case is equal to the duration of each maintenance period M_g, of the respective unit g. Therefore, it meets the maintenance duration and continuity restrictions at the same time.

$$\sum_{s=0}^{M_g-1} x_{g,d+s} \leq M_g \cdot (1 - y_{g,d}) \qquad \forall\, g \in G,$$
$$d = 1, 2, 3, \ldots, D - M_g + 1 \qquad (15)$$

The proposed optimization considers that the GU's in operation will turbine the maximum available on the day, thus, the dimension of the problem is reduced, since the turbine flow of each GU is not a variable. However, in order to respect the restriction presented in (9), unnecessary spilled flow may occur, since connecting an available GU would violate the restriction, given that the respective unit would necessarily generate it's maximum available on the day. In this case, an improvement is made in the optimal result obtained by the optimization in (7) - (14), in order to circumvent this situation and achieve the minimum spilled flow, according to the flowchart shown in Fig. 3.

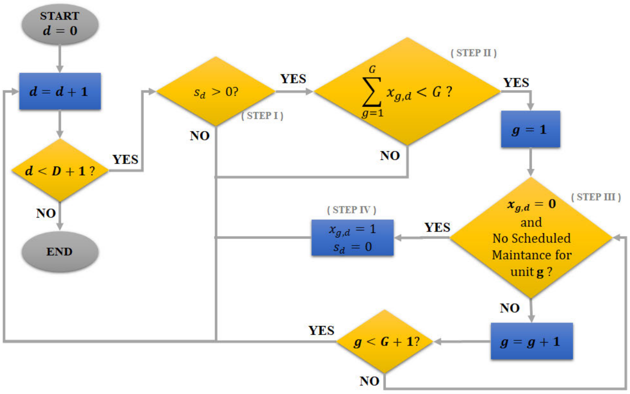

FIGURE 3. **Flowchart for Post-Optimization Adjustment.**

With the result obtained in the proposed optimization ((7) - (14)), the adjustment process begins. Firstly, for each day d, it is verified whether there is spillage **(STEP I)** and available units **(STEP II)**, i.e., if there is an unnecessary spilled flow. If confirmed, a generating unit is selected to operate, which must not be operating or in scheduled maintenance **(STEP III)**, that is, fully available. Therefore, modifying the operating status of this unit does not affect the result previously found in the optimization for the other units, it only adjusts the unnecessary spilled flow. In this case, this generating unit operates below its total daily capacity, turbine what was being spilled, leading to a daily operation without spillage **(STEP IV)**. After the adjustment for the d day, the process continues for the next day.

The flowchart presented in Fig. 4, summarizes the entire process proposed in this work to obtain a maintenance schedule.

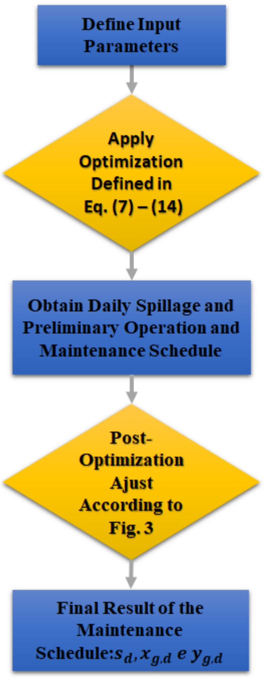

FIGURE 4. General Flowchart of the Proposed Methodology.

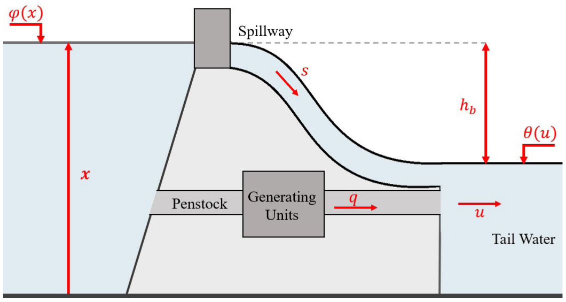

FIGURE 5. Components of a Hydroelectric Plant.

In summary, the consideration of maximum capacity and the adjustment made after optimization affects the optimal result found initially without changing the solution viability. However, given the dimension of the problem and knowing that the objective is to minimize spillage, the adjusted result found is suitable for the main objective, since it leads to a reduced spill operation, avoiding regulatory penalties.

C. MAXIMUM TURBINED FLOW

Considering the formulation of the problem presented in the previous item, some components related to the hydrothermal system need to be known. These components will be used to calculate the maximum turbined flow parameter for each generating unit, which is being used in the (8) constraint of the problem, Figure 5 illustrates these components.

The calculations necessary to find the maximum turbined flow of each GU are presented in 5 steps described below:

Step 1: Find the daily Water Level of Upstream Reservoir in meters (m), represented by $\varphi(x)_d$, a non-linear polynomial of 4^o degree. In (16) is presented this polynomial, where x is the volume in the reservoir in m^3 on d day and a, b, c, d, e are the coefficients of this function, obtained empirically through constructive parameters of the hydro plant [22]. In some cases, the level of upstream is found through operating rules specific to each plant.

$$\varphi(x)_d = a + b \cdot x_d + c \cdot x_d^2 + d \cdot x_d^3 + e \cdot x_d^4 \tag{16}$$

Step 2: Find the daily Downstream Level of the Reservoir in meters (m), represented by $\theta(u)_d$ and also called the tailrace elevation. For its calculation a Polynomial of 4^o degree, presented in (17) is also used, in which the coefficients (a, b, c, d, e) of this function, made available by the hydroelectric plant, and the defluent flow (turbined flow + spilled flow) represented by u in m^3/s [22].

$$\theta(u)_d = a + b \cdot u_d + c \cdot u_d^2 + d \cdot u_d^3 + e \cdot u_d^4 \tag{17}$$

Step 3: Find the daily Gross Fall valuein meters (m), represented by hb_d. Its value is found from the value of Downstream Level and Water Level of Upstream of the Reservoir represented by (18).

$$hb_d = \varphi(x)_d - \theta(u)_d \tag{18}$$

Step 4: Find the value of the daily Net Head in meters (m), defined by the difference between the height of the gross fall and the penstock head loss, represented by hl_d in (20) [23]. The penstock head loss ph_d, which is usually associated with the water friction of water on the penstock wall, can be represented according to (19), where k is a constant that expresses the characteristic of the penstock in s^2/m^5 [24].

$$ph_d = k \cdot {q^2}_d \tag{19}$$

$$hl_d = hb_d - ph_d \tag{20}$$

Step 5: Maximum daily turbine flow ($\overline{q}_d$) of each GU as (21): It consists of finding the maximum flow associated with the generation power as a function of the net head hl_d [22]. It will be necessary to consult the function called 'Hill Chart', which has this name due to its format. It will provide the necessary information to find the maximum turbined flow of each GU given a fixed net head and the respective power of the generating unit.

$$\overline{q}_d = \overline{q}(hl_d)_d \tag{21}$$

An example of 'Hill Chart', can be seen in Fig. 6, represented in the form of contour lines. It can be noted that given a height of net fall and varying the turbine flow, the performance linked to power also varies. In this case the yield is varying from a minimum value (Point A), passing through a maximum value (Point B) and reaching an intermediate value (Point C), when the turbine flow reaches its maximum. The curvature noted through Point A to C is due to the interdependence between the three axes.

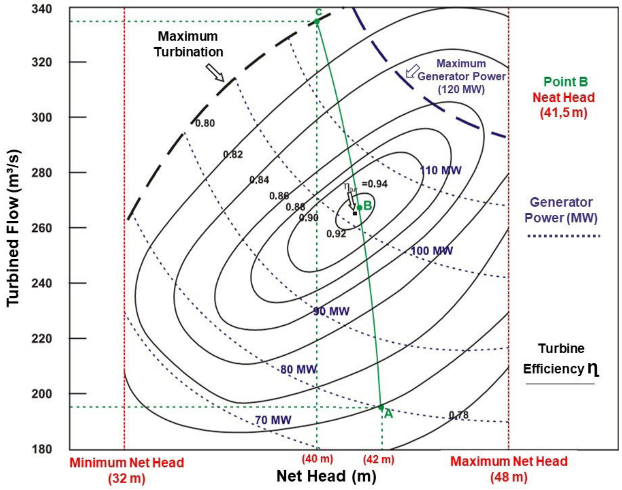

FIGURE 6. Hill Chart.

V. CASE STUDY

The proposed method will be applied at the Santo Antônio Hydroeletric Plant (SAHP) using real data from the plant in order to obtain significant and substantiated results, validating the mathematical model developed.

A. GENERAL DATA

As previously mentioned, SAHP is a large power plant with the reduced reservoir model (run-of-river plant) and is located on the Madeira River in the city Porto Velho of the state of Rondônia - Brazil. The concessionaire responsible for the implementation, operation and sale of energy generated of the SAHP is Santo Antônio Energia (SAE).

The SAHP started operating on March 30, 2012, but only reached full generation with all turbines in commercial operation in January 2017. Totaling 3568 MW of installed power and 2424.20 average MW of physical guarantee, being considered the fifth largest hydro generator from the country. The plant has 50 Bulb type turbines each. With an average power of 71.3 MW, divided into two groups, 24 4-bladed turbines (GU 1-24) and 26 5-bladed turbines (GU 1-26).

The motivation for applying the study at SAHP is related to the financial losses that SAE has suffered in recent years due to low Availability Factor values. As shown in Fig. 7. The low performance of AFA is directly associated with maintenance planning, as previously explained.

B. OPERATIONAL DATA

The affluent flow of the SAHP is a relevant data to be analyzed for the maintenance planning of the GU's. Since it is interesting to allocate the maintenance in the periods of low flow of the plant avoiding overflow. In the case of SAHP this period is well defined, characteristic of the Madeira River where the plant is located. The Fig. 8 shows the average affluent flow of the plant that is equivalent to defluent flow, since it is a run-of-river plant.

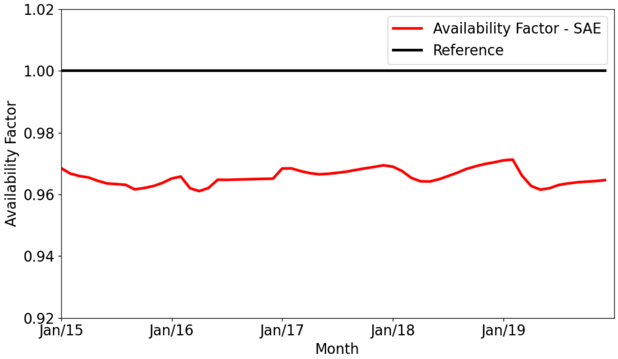

FIGURE 7. Availability Factor and SAE Generating Units - 2015/2019.

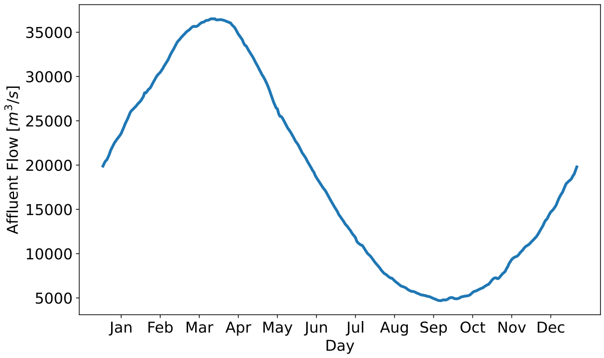

FIGURE 8. Affluent Flow - Santo Antônio Hydroelectric Power Plant.

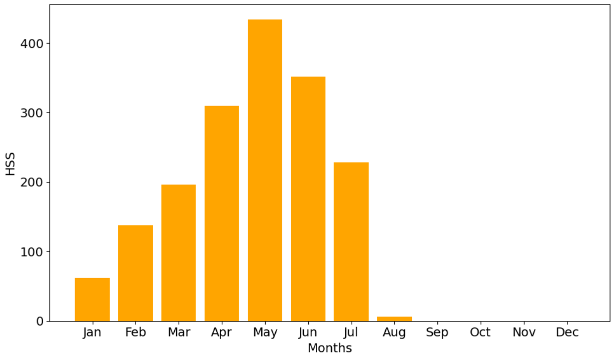

FIGURE 9. Average HSS Indicator.

It is important to highlight that the Scheduled Shutdown Hours are not included in the calculation of the AFA when there is no spilled flow. That is, when the operation of the disconnected GU's is not necessary for the NIS. The Fig. 9 shows the average of the HSS indicator from 2017 to 2019. It is noted that in periods of low flow (between July and December) the value of the indicator is low or even null. This shows that the hours of scheduled maintenance were not accounted in the HSS indicator, unlike the high flow period where more GU's must be in operation to turbine the entire flow.

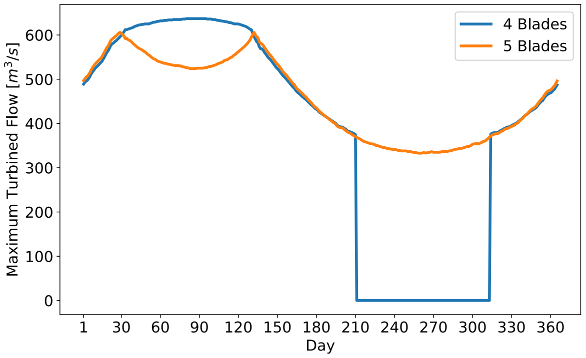

FIGURE 10. Maximum Turbocharged Flow per GU - 4 and 5 blades.

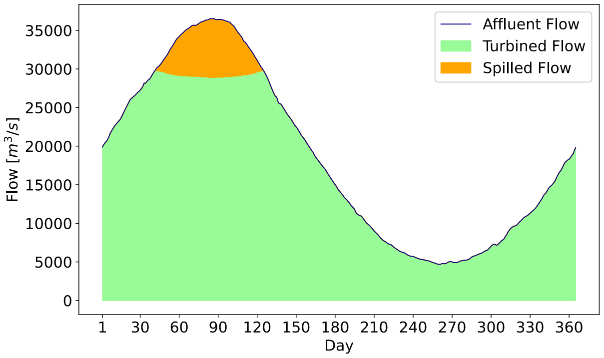

FIGURE 11. Turbine and Spill Flow Throughout the Year.

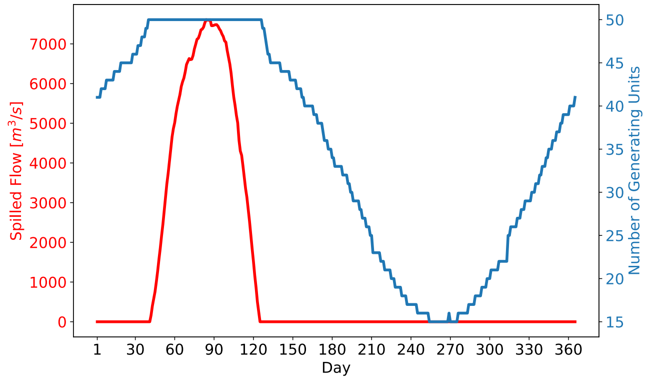

FIGURE 12. Spilled Flow and Number of GU's in Operation.

It is worth mentioning that in the month of July, belonging to the low flow period, the value of the HSS indicator is high. This is due to the inadequate planning of preventive maintenance or sudden problems that caused the need for corrective maintenance. Thus, the objective of the proposed model is precisely to minimize the occurrence of these shutdowns during the year with an optimal maintenance schedule.

Due to the different characteristics between the two groups of generating units, turbines with 4 and 5 blades, each group has a maximum turbine flow calculated according to the methodology presented in Section IV-C. Thus, the Fig. 10 shows the maximum turbine curves for each group.

C. MAINTENANCE DATA

The maintenance schedule to be attended by the Santo Antônio Hydroelectric Plant is a diversified and extensive schedule. Where some turbines have only one type of maintenance to be performed and others seven different types of maintenance. Table 1 shows the duration in days of maintenance for each GU.

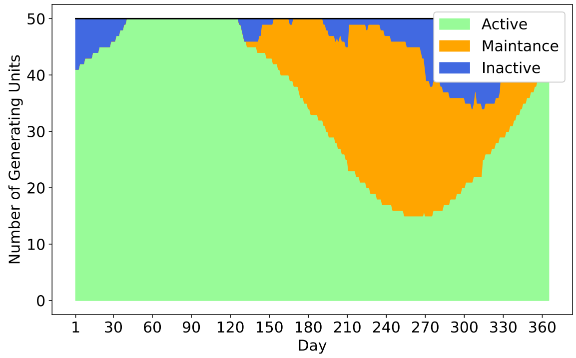

FIGURE 13. Number of GU's in Operation, Maintenance and Inactive.

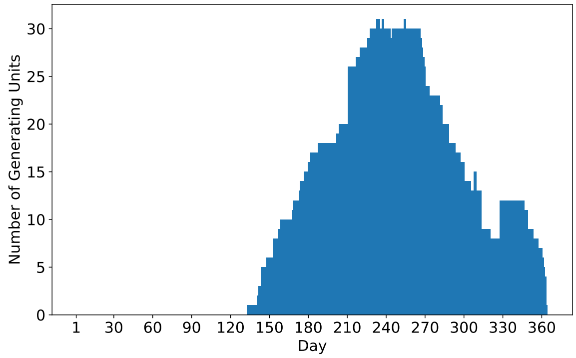

FIGURE 14. GU's in Maintenance.

TABLE 1. Maintenance Duration in Days.

Name	MD	Name	MD	Name	MD
GU01	145	GU18	33	GU35	26
GU02	181	GU19	2	GU36	206
GU03	78	GU20	71	GU37	50
GU04	141	GU21	25	GU38	57
GU05	45	GU22	159	GU39	36
GU06	60	GU23	56	GU40	22
GU07	28	GU24	73	GU41	116
GU08	110	GU25	142	GU42	95
GU09	161	GU26	67	GU43	44
GU10	59	GU27	124	GU44	54
GU11	173	GU28	29	GU45	38
GU12	60	GU29	58	GU46	63
GU13	112	GU30	96	GU47	43
GU14	57	GU31	67	GU48	156
GU15	63	GU32	130	GU49	89
GU16	2	GU33	58	GU50	61
GU17	90	GU34	36		

In order to minimize the computational effort for the solution, since the problem has 50 generating units, maintenance was grouped by turbine. A previous study was carried out to analyze the feasibility of this planning option. Therefore, the duration of the maintenance period in days planned for the year 2021 is shown in Table 1.

VI. RESULTS AND DISCUSSION

With the data presented previously, the problem to be solved consists of 36866 binary variables, 366 real variables and 15084 restrictions. The proposed optimization model was developed in Python using the Gurobi solver and was sim-

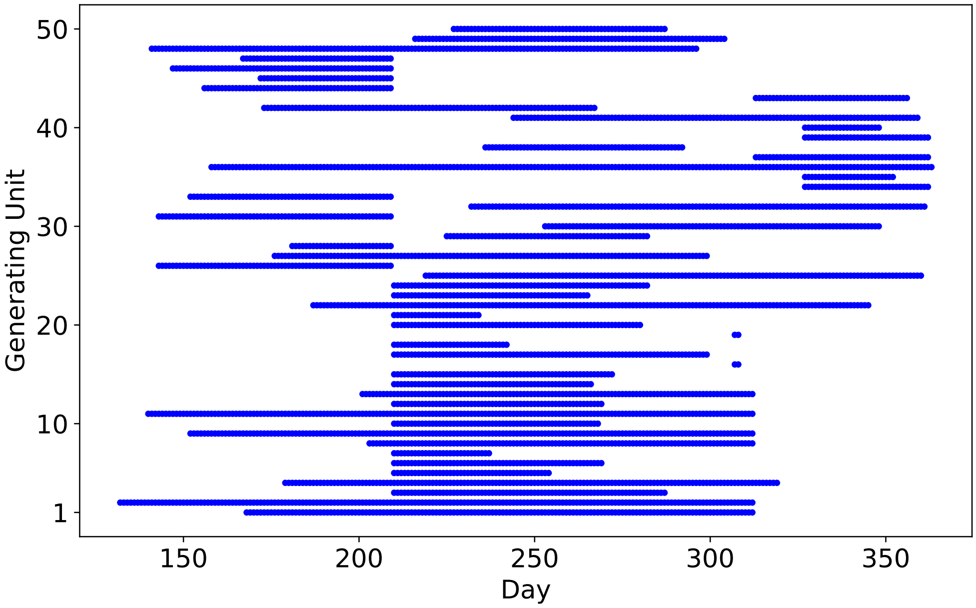

FIGURE 15. Final Maintenance Calendar.

ulated on a computer with the following configuration: Intel®Core i5-3210M Processor with 2.50 GHz and 12 GB of RAM, Windows. The simulation was carried out in approximately 20 minutes.

First, the Fig. 11 shows the total turbine volume by the plant throughout the year. It can be observed that only in the period of high flow there was a spill. However, observing the Fig. 12, when there was a spill all the generating units were in full operation. That is, the plant does not have the capacity to turbine the entire affluent flow. Thus, as explained by the Fig. 2, there will be no penalty for the plant due to maintenance stoppages as two situation have occurred:

- All affluent flow was turbine by the GU's, zero spilled flow - **no penalty**;
- Positive spilled flow, however, all GU's operating without limitations - **no penalty**.

Thus, it can be said that the scheduling of the optimized maintenance was satisfactory. Respecting all necessary maintenance, being possible to operate properly throughout the year and avoiding unwanted penalties.

The Fig. 13 shows the number of GU's in operation (green), maintenance (yellow) and inactive (blue) throughout the year. As expected, there is a greater number of active units in periods of high flow, reaching all 50 GU's active. Then this number decreases as the affluent flow decreases and therefore maintenance is initiated. In addition, no maintenance starts at the beginning of the year. Due to the continuity restriction, after starting maintenance, the GU should only be available again after the end of the maintenance activity. Therefore, in order to avoid penalties for spilled flow in the high flow period, the maintenances only start after this period.

In addition, also in Fig. 13, it is possible to observe that most of the time where there is maintenance, there are still inactive turbines, so the optimized schedule has the flexibility to avoid spillage, in case the maintenance of any unit generator lasts longer than necessary. The Fig. 14, on the other hand, shows the number of maintenance performed each day. It can be seen that the peak of simultaneous maintenance occurs in the low flow period.

Finally, in order to complement the analysis of the results, the Fig. 15 shows the general maintenance schedule. It shows the start day and duration for the maintenance performed in each GU. As shown previously, maintenance starts after the high flow period in order to reduce the penalties for overflow.

Furthermore, another highlight in Fig. 15 is the beginning of majority of the maintenance of the 4-bladed GU's (GU 1 to 24) start on day 211. Exactly when these GU's are unable to turbine due to the operational fall restrictions caused by the low flow, according to the curve presented in 10.

VII. CONCLUSION

This article presented a MILP optimization model to solve the problem of scheduling the maintenance of generating units of hydroelectric plants. The optimized schedule is carried out on a daily basis with an annual horizon.

The proposed model considered regulatory aspects. Operational restrictions, duration and maintenance limitations were also considered in order to minimize spilled flow by the plant, aiming to reduce financial penalties, as presented along the article.

The main motivation for the article is evidenced by the Santo Antônio Hydroeletric Plant situation previously shown. Thus, the proposed optimization was applied using real data from the plant, demonstrating its applicability in large problems.

With the results obtained, the mandatory maintenance was scheduled throughout the year, respecting their respective duration. In addition, the optimization eliminated any penalty.

Since there was only a spill in the high flow period where the plant operates at full capacity, therefore, not being penalized.

Thus, it can be said that the proposed model was applied satisfactorily, being validated with a real case and meeting the objective of reducing regulatory penalties. In addition to being of great relevance for large Brazilian hydroelectric plants.

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