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ENERGETIC AND ECONOMIC EFFICIENCY ANALYSIS OF A HYDRAULIC POTENTIAL USING DIFFERENT TYPES OF TURBINES

Bruno Santos Alves Pereira
Pedro Magalhães Sobrinho
José Luz Silveira
Laboratory of Optimization of Energy Systems (LOSE), Guaratinguetá Engineering College (FEG).
Institute of Bioenergy Research (IPBEN), São Paulo State University (UNESP).
Av. Dr. Ariberto Pereira da Cunha, 333 – Guaratinguetá/SP – Brazil.
bsa.pereira@gmail.com
sobrinho@feg.unesp.br
joseluz@feg.unesp.br

Abstract. *The selection of the hydraulic turbine's type for application on a specific hydraulic potential is based on analysis of tables deployed by the manufacturers of the equipment, on function, basically, of the flow and the high of the water drop available at desired place for installation of the hydropower plant. For some tracks of these data, it can be chosen Francis turbine or Kaplan turbine. Analyzing these two types of turbines, for the choice of the type be based on technical and economic discretion, it can be noted that the Francis turbine has a minor investment value comparing with the Kaplan turbine. The comparative analysis of the investment value for the application of each type of turbine versus the quantity of generated power along the year, considering the operational limits of each type of turbine, is the proposal of this job. They will be analyzed situations only using Francis turbines (economically cheaper from the point of view of investment on equipment, but with significant operation restriction due to the flow variation); also using only Kaplan turbines (economically expensive from the point of view of investment on equipment, but presents a wide range of operation in relation of the flow variation); and optimization scenarios of configuration considering the combined application of these two types of turbines at the same hydroelectric dam.*

Keywords: *energy efficiency, technical analysis, economic analysis, hydraulic turbine.*

1. INTRODUCTION

The Brazil's population doubled in period between 1971 and 2008 but the *per capta* energy consumption increased multiplied by 5 in the same period. Besides, the forecast is the Brazilian's electric energy national demand jumps from the 500 TWh in 2010 to 1100 TWh in 2040 (Dale *et al*., 2013), making necessary the expansion of the Brazilian's national energetic matrix in the next 3 decades, specially through the use of the hydraulic potentials still unexplored, mainly at north region of the country (ANEEL, 2008).

The selection of the hydraulic turbine's type to be used on a specific hydraulic potential is based on data of head [m] and flow [m³/s] available at this hydraulic potential installation location (Macintyre, 1983). For some tracks of these data, it can be chosen Francis turbine or Kaplan turbine. Considering that the project of a hydraulic turbine is made based on a fixed optimum value for head and flow, the variation of the flow over time at hydraulic potential installation location influences directly on the turbine's operating mode. A Francis turbine has an implantation cost lower than a Kaplan turbine for the same nominal output power (MME/CEPEL, 2007), however, due its technical features, accepts an instantaneous flow variation regarding to project nominal flow lower than the variation acceptable to a Kaplan turbine with the same nominal output power (Macintyre, 1983 and MME/EPE, 2010).

Thus, for the specific case of a hydraulic potential that presents head and nominal flow values which allow both the application of a Francis turbine or a Kaplan turbine, and is located on a river that presents an accented flow variation throughout the year – due seasonal variables – the choice of the turbine's type to be applied must be done considering a combined analysis of the technical criteria (turbine nominal output power, operating hours amount according the available flow) and economic criteria (income generated by the sale of electricity produced, equipment cost deployment).

The objective of this paper is the analysis of this kind of specific case considering the study of the possible solutions that provide optimization of the cost *versus* benefit relation of the enterprise, including the analysis of an optimum combined application scenario using the two types of turbine previously cited.

The Brazil's energetic matrix is predominantly hydroelectric. From the total installed 130 GW in 2010, about 84 GW (65% of total matrix) were generated by hydroelectric plants (Dale *et al*., 2013). It happens because Brazil has the world's largest potential of hydroelectric development, with about 260,000 MW. The 2030 National Energy Plan estimates that the potential to be availed is about 126,000 MW, wherein more than 70% of this amount is located at

Tocantins/Araguaia's river basin and Amazonas' river basin. The Amazonas' river basin alone had about 106,000 MW of remain potential of hydroelectric development (ANEEL, 2008).

The entire Amazonas' river basin presents an accented seasonality in terms of level of its rivers due to a number of geographic and climatic features of the region. The drought level average is about half of the annual flow level for all of the rivers of the basin (MMA/ANA, 2005). In 2005, the largest drought of the last 103 years hit the west of Amazon causing some rivers a lower of 6 cm per day. Four years later the same region was desolated by a flood of historical proportions, overcoming the historic records at Manus's harbor – including the overcoming of the historic record of 29.68 m for the Negro river (Marengo *et. al.*, 2010).

Soito and Freitas (2011) bring an evaluation study about the expansion of the hydroelectric dams at Amazonas' river basin listing the possibilities, impacts and vulnerabilities of hydroelectric energy adaptation in the face of the climatic changes and social-environmental demands. The sustainable use of Amazonas' river basin in hydroelectric potential is considered through the economic and technological possibilities of the energy generation sector, the integration with the neighbor countries, the new arrangement of the regulatory market and the integrated management of the reservoirs. The work brings indicators that show the Amazonas' river basin as the "new Brazil's hydroelectric frontier" in the face of the almost complete exhaustion of the hydroelectric potentials in all other regions of the country.

Westin *et al*. (2014) present an analysis of the differences and main contributions of the IEA (Integrated Environmental Assessments) and SEA (Strategic Environmental Assessments) tools application, used by the National Water Agency on its Hydrous Resources Strategic Plan for the decision making process on Brazil's energetic sector, especially regarding to the hydroelectric potential exploration of the Amazonas' river basin and the Tocantins/Araguaia's river basin. Three different studies about hydroelectric dam implantation at Tocantins/Araguaia's river basin are analyzed: the Hydrous Resources Strategic Plan for the Tocantins/Araguaia's river basin using the SAE methodology, the IEA of the Tocantins' river basin and the IEA of the Araguaia's river basin, making a comparative analysis of their methodologies, scenarios, results and recommendations.

Elbatran *et al*. (2015) does a revision of the low head micro-hydropower turbines studies for application at rural and remote areas, through an approach focused on categorization, performance, operation and cost. The work brings technical discussions about advantages and disadvantages of the reaction turbines use compared to action turbines use, recommendations, technical solutions and a case study of a cross-flow turbine application. Efficiency features for each type of cited turbine are analyzed as well as significant factors that may influence the operation and performance of these turbines, giving a turbine's type selection guide more suitable for applications in low head micro-hydropower projects.

Santolin *et al*. (2011), based on the technical and economic analysis of the flow permanency curve, present a method for dimensioning of the small hydropower installed capacity considering the following technical and economic parameters: type and dimensions of the turbine, complete machine cost, turbine implantation level (with the goal of avoid the occurrence of the cavitation phenomenon), energy annual production, IRR (Internal Rate of Return) and NPV (Net Present Value). The proposed method was tested through the analysis of three hydropower plants with different flow permanency curves, indicating that the simultaneous analysis of the considered parameters allow the adoption of a project more suitable from the technical viability and enterprise profitability point of view.

Aggidis and Zidonis (2014) present a technology capable of accelerate the development of hydraulic turbines through the full automation of the prototypes models initial tests process, promoting the conversion of the collected data in hill curves charts that allow ready comparison of the prototype's performances. The initial tests procedures are illustrated for both action turbines and reaction turbines and the hill curves charts reached may be used for a quickly evaluation and initial turbine model prototype performance comparison before proceeding to a more expensive and slow stage of turbine model selection.

Cordova *et al*. (2014) describe a performance and energetic optimization evaluation system for real time operation of Itá (SC) hydropower plant. They were measured parameters such as losses, efficiency and turbine's output flow – the most important and challenging parameter to be controlled for real time operation of the system – to allow that system gives a real time optimization that has the purpose of water's efficient use. The benefits described and detailed on the work are applicable for other hydropower plants specially those ones with multiple generating units that have distinct operational features.

Thus, it is evident the need of a study that approach a technical and economic combined analysis of applications that cover the use of these two types of turbines, considering scenarios of exclusive application of one type or another and scenarios that search an optimum combined application of these two types of turbines. This combined analysis it would be made possible through the development of a computational tool – with easy user's interaction and fast numerical response capacity – that provides an embracing analysis of the possible solutions for a specific case study.

2. EFFICIENCY ANALYSIS STRUCTURE

The selection of the hydraulic turbine's type to be used on a specific hydraulic potential is based on data of head [m] and flow [m³/s] available at this hydraulic potential installation location (Macintyre, 1983) and it may be done through the application of specific selection charts – as showed on Fig. 1 – usually developed by the own equipment's manufacturer.

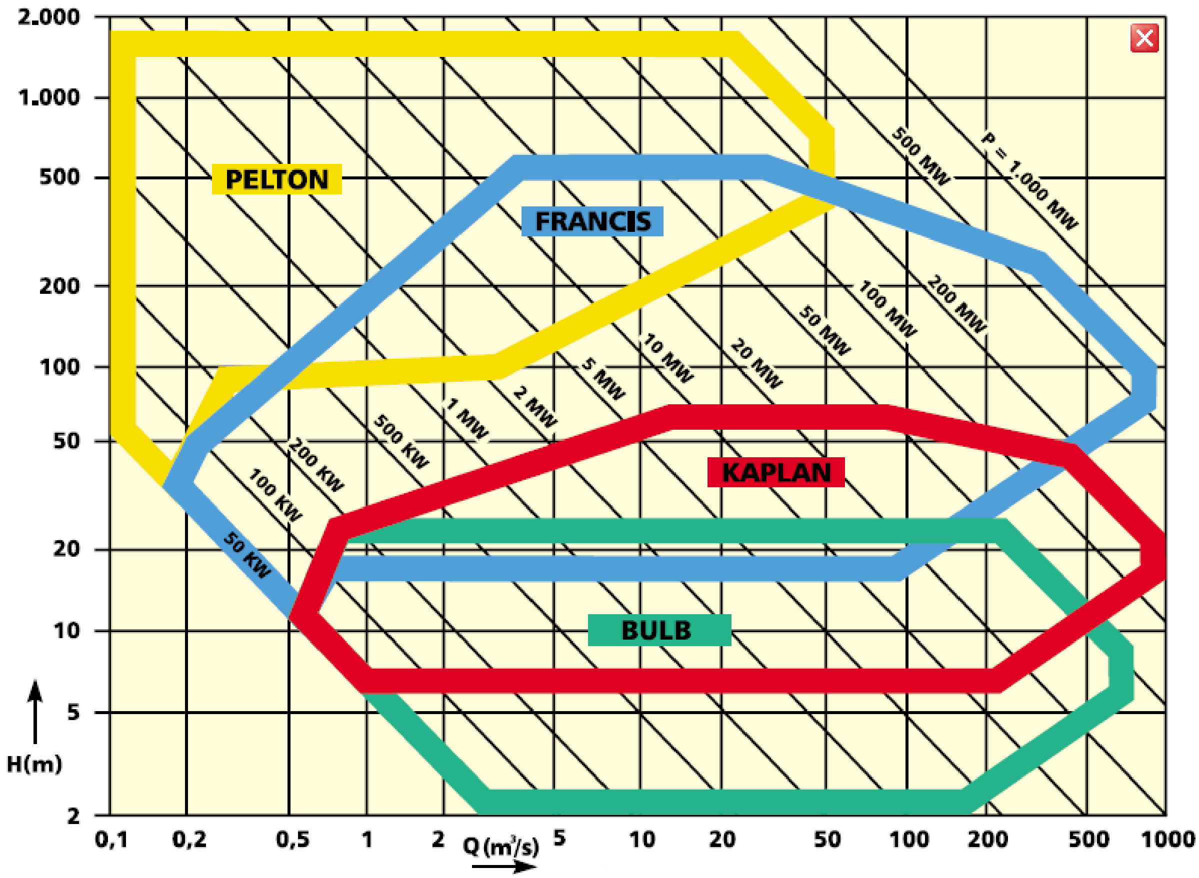

Figure 1. Hydraulic turbine selection chart.

Analyzing this kind of turbine's selection chart it realizes that for some regions of the chart there is an overlapping of two or more types of turbines that are possible to be applied. The focus of this work is the chart's region that indicates the possibility of the application of both Francis turbine and Kaplan turbine – this is, the region located between the head values of 20 m and 70 m and between the nominal flow values of 1.5 m³/s and 600 m³/s.

With the data of head and nominal flow available at location of the hydraulic potential installation, it is possible the calculation of the hydraulic turbine's output power through the Eq. 1 indicated below (Macintyre, 1983).

$$W = 9{,}8.Q.H.\eta \quad (1)$$

Where W is the hydraulic output power [kW], Q is the nominal flow [m³/s], H is the head at location of the installation [m] and η is the efficiency of the turbine.

The specific velocities [rpm] of the Francis turbines and Kaplan turbines are given, respectively, by the following Eq. 2 and Eq. 3 (Simone, 2000),

$$rot(F) = \frac{2300}{\sqrt{H}} \quad (2)$$

$$rot(K) = \frac{3100}{\sqrt{H}} \quad (3)$$

The deployment costs estimations for Francis turbines and Kaplan turbines [thousands R$] are given by the Eq. 4 and Eq. 5 below (MME/CEPEL, 2007).

$$C(F) = -0{,}0011.\left[\frac{W}{rot(F)}\right]^2 + 18{,}162.\left[\frac{W}{rot(F)}\right] + 3279 \quad (4)$$

$$C(K) = -0{,}0058.\left[\frac{W}{rot(F)}\right]^2 + 40{,}609.\left[\frac{W}{rot(F)}\right] + 3122{,}5 \quad (5)$$

The calculation of the monthly income generated by the hydraulic turbine operation is given by the Eq. 6 below.

$$inc_m(j) = eep.W_m(j).op_m(j) \quad (6)$$

Where j is the index related to the month, inc_m is the income [R$], *epp* is the sell price of the electric energy to the dealership [R$/kW], W_m is the hydraulic output power [kW] and op_m is the monthly turbine's operating hours [h].

Hydraulic turbines have an operating limit relative to the available flow compared to the nominal flow of the project. For Francis turbines this operating limit is 60% of the nominal flow value (Mello Júnior, 2000), this is, the turbine will must be turned off if the available flow is lower than 60% of the nominal flow. For Kaplan turbines this operating limit is 35% (MME/EPE, 2010).

The mathematical model developed for this work – created using LINGO® programming language – provides that in the case of monthly flow available for the first turbine is lower than the its operating limit this turbine will be turned off and this flow will be directed to all other turbines. This algorithm will extend successively to all other turbines of the hydropower plant, so that ensures the maximum possible operation of the last turbines.

The target of the developed mathematical model is the calculation of an objective function that maximizes the generated income after a whole year in relation to each turbine's implantation cost, thus indicating the optimum configuration of the turbine's type – if Francis or Kaplan – for each generating unit of the hydropower plant.

The objective function will be given by the Eq. 7 below.

$$max = \sum_{i=1}^{n}[Y(i).\lambda(i) - Y(i).\varphi(i)] \quad (7)$$

Where i is the index related to the generating unit, *max* is the optimum value calculated from the income obtained from the energy generation [R$], λ is the total annual income [R$], φ is the turbine's implantation cost [R$] and Y is the Boolean variable that will indicate the turbine's type to be applied for each generating unit.

3. CASE STUDY

The developed mathematical model was applied for the SINOP hydropower plant case study – expected for the Teles Pires river, in the northern of Mato Grosso State and located at Amazonas' river basin – that provides the application of 3 Kaplan turbines with 24.5 m of available head, 596.20 m³/s of unitary nominal flow and 400 MW of optimum total installed power (MME/EPE, 2010).

They were adopted 95% and 96% as efficiency values for Francis turbines and Kaplan turbines, respectively (Macintyre, 1983 and MME/EPE, 2010).

The utilized values for monthly flows were the average flows of Teles Pires river at location of the installation, during the period between 1931 January and 2006 December (MME/EPE, 2010).

The adopted electricity sell price was 259.19 R$/MWh (CCEE, 2015) while the adopted monthly operating hour load was 660 h.

It was made the application of the mathematical model for the analysis of three different scenarios: all 3 generating units using Kaplan turbines (according real project), all 3 generating units using Francis turbines and finally an optimized combined application scenario with these two types of turbines.

4. RESULTS AND DISCUSSION

The optimum scenario calculated by the mathematical model was the application of two Kaplan turbines for the number 1 and number 2 generating units and one Francis turbine for the number 3 generating unit.

As the efficiency values of these two types of turbines are different each other, there was a little deviation on the total output installed power values for each studied scenarios.

These total output installed power values [MW] are shown by Fig. 2 below.

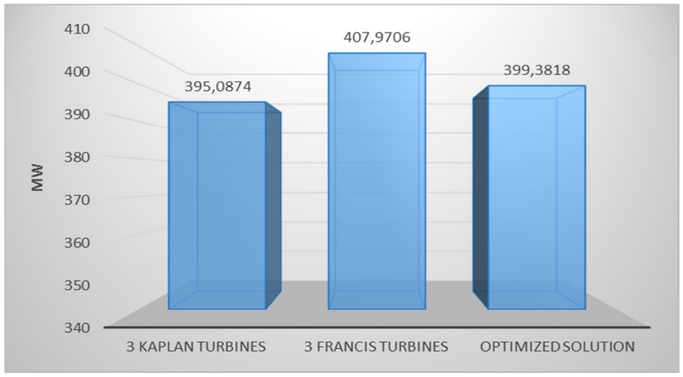

Figure 2. Total output installed power for each studied scenario.

The total deployment cost [millions R$] for implantation of the turbines for each studied scenario, calculated based on each turbine's output power and specific velocity, are shown by Fig. 3 below.

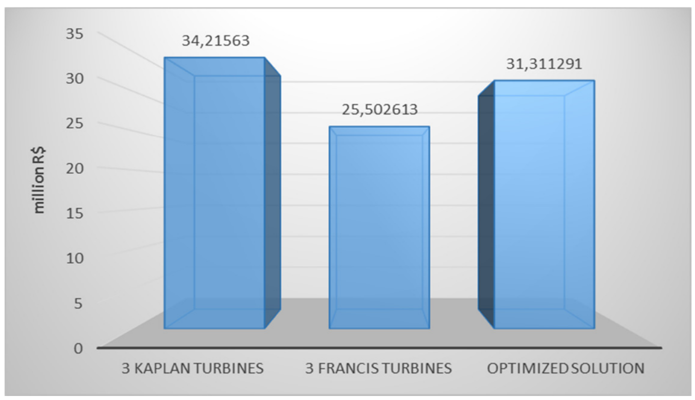

Figure 3. Total deployment cost for each studied scenario.

The total annual income amount generated by turbines operating [millions R$] and the obtained values for objective function [millions R$] after one year of operation for each one of 3 studied scenarios are shown by Fig. 4 below.

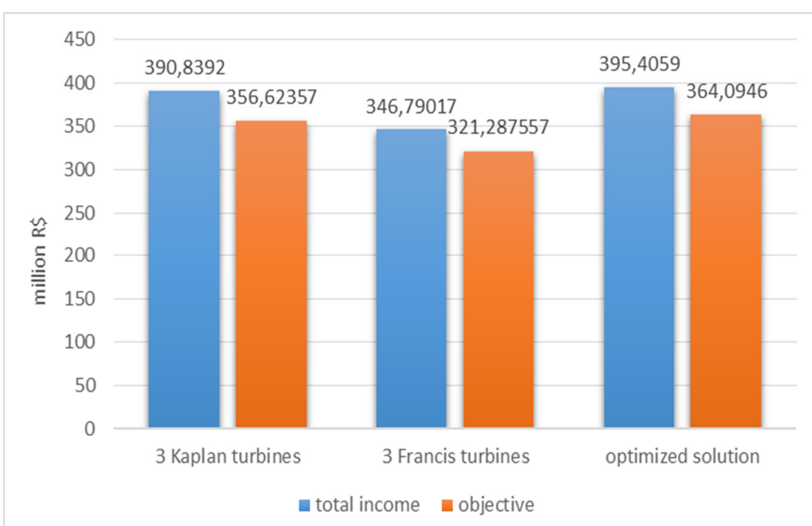

Figure 4. Total annual income amount and objective function values for each studied scenario.

The operation factors for each turbine of each one of 3 studied scenarios are presented – according Fig. 5, Fig. 6 and Fig. 7, respectively – in function of month-to-month available flows. On the developed mathematical model, these operation factors are multiplied by turbine's operating hours load. Thus, the generating units that present operation factor equal to 1 will be their operation hours load equal to 660 h.

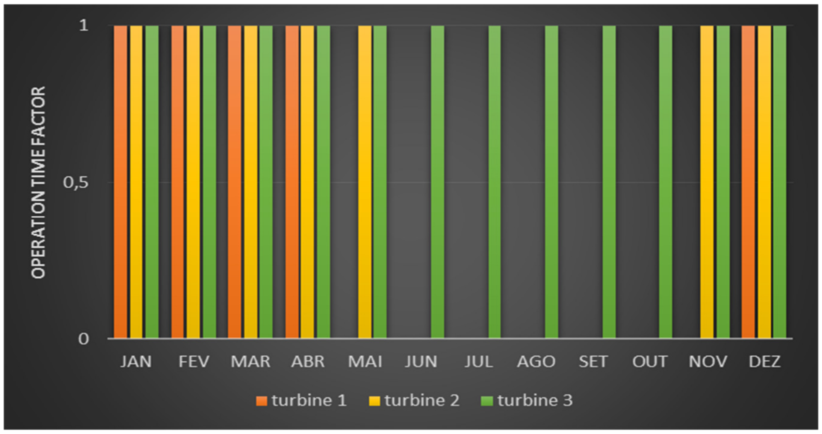

Figure 5. Francis turbine scenario's monthly operation hours.

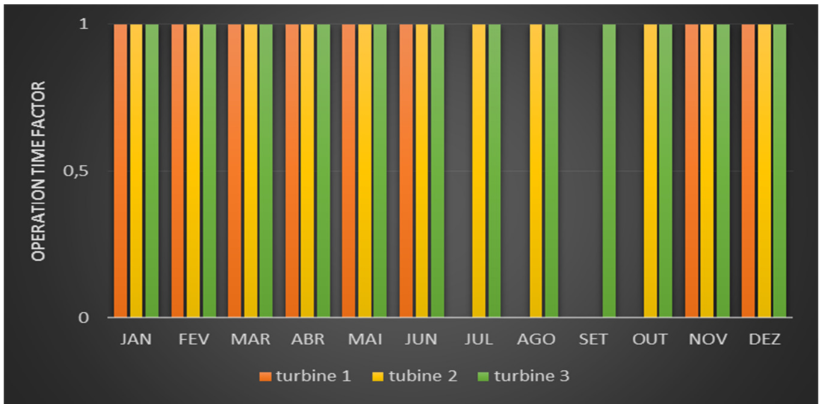

Figure 6. Kaplan turbine scenario's monthly operation hours.

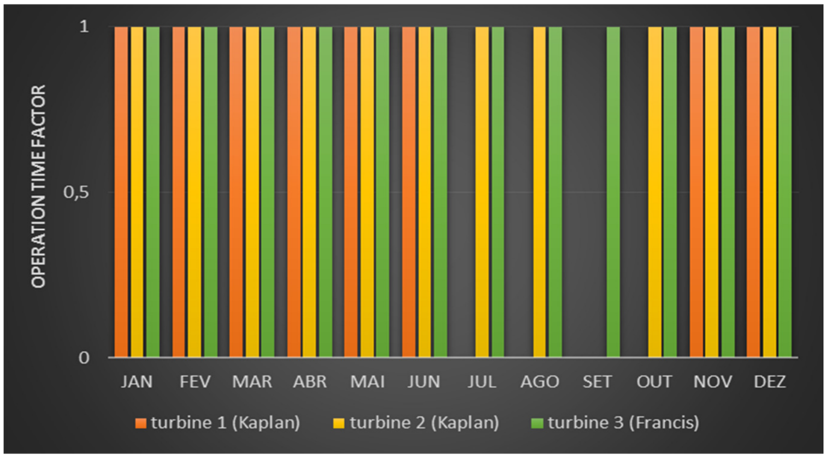

Figure 7. Optimized combined turbine type scenario's monthly operation hours.

5. CONCLUSION

The fact of the mathematical model developed as this work's proposal have shown an optimum solution – for the combination of the UHE SINOP turbines types – that indicates the application of Kaplan turbines for the number 1 and number 2 generating units and Francis turbine for the number 3 generating unit, matches with the expected practical results, once the model initiates from #1 generating unit the comparison between the available flow and the nominal flow of the project.

As the studied case has 3 generating units, the number 1 generating unit will be more impacted by the flow variation and, this way, the mathematical model identified optimum usage condition of a Kaplan turbine for this generating unit. This reasoning is analog for all other generating units, which causes that number 3 generating unit be less impacted by the flow variation – once that may counts with the residual flows from number 1 and number 2 generating units – and that's why receives an application of a Francis turbine.

The optimum solution proposed by the mathematical model presents a deployment equipment cost 1.2% more expensive than 3 Kaplan turbines scenario and 14.0% more expensive than 3 Francis turbines scenario. On the other hand, presents a value for the objective function 2.1% higher than 3 Kaplan turbines scenario and 13.3% higher than 3 Francis turbines scenario.

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