PEDRO PAULO BEZERRA MACHADO

Incorporation of enhanced pumped storage in the brazilian national grid considering the expansion of wind farms

São Paulo

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To my family

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"If you set your goals ridiculously high and it's a failure, you will fail above everyone else's success"

- *James Cameron*

ABSTRACT

The energy sector in Brazil is currently introducing a large amount of new renewable sources such as wind and solar power, such sources, being intermittent and non-dispatchable may generate a series of problems in the grid, increasing the amount of wasted energy due to spillage. It is important to counterbalance the intermittency introduced by them in order to maximize its efficiency and reduce the energy wasted. To do so, it is necessary an energy storage facility in order to store exceeding generation energy in certain periods and use it during periods with a smaller availability of energy generated or greater demand. Considering the storage technologies existent today, the most efficient to be used in large scale is through pumped hydroelectric plants (PSP). In Europe, where non-dispatchable sources have been present longer, this technology is already largely used in order to increase the efficiency due to wind, solar and nuclear sources. Through the modeling of the Paraná Basin, and the incorporation of wind generation from different sites in Brazil this work will evaluate the efficiency of this technology in the Brazilian scenario based in the historical data of natural inflows and wind speed in each site. It was then analyzed the operation in cascade of the basin with influence from the pumped stored plant. Since the proposed problem does not have a defined analytic solution, it was necessary to implement an Optimization Algorithm with the simulation routine in order to reach an optimal solution to the problem. Also, the created computer routine had to be flexible, allowing a series of different scenarios to be analyzed. Given the results that were found through the routine, it is possible to evaluate different cases varying either years for the historical data or dimensioning of the PSP, being it an important first step to a deeper evaluation of the insertion of pumped storage plants in Brazil. From this analysis, it is possible to see the benefits a stored facility, such as a Pumped Storage Plant, would generate for the Brazilian electric system.

Keywords: Pumped stored plants. Genetic Algorithm. Hydroelectric plants. Modeling. Evolutionary Algorithm

RESUMO

O setor energético do Brasil está atualmente introduzindo uma grande quantidade de novas fontes renováveis como a solar e a eólica, sendo que essas fontes, sendo intermitentes e não-despacháveis, podem gerar uma série de problemas na rede, aumentando a quantidade de energia desperdiçada devido ao vertimento. É importante controlar o efeito da intermitência introduzida por elas maximizando a eficiência e minimizando a energia desperdiçada. Assim, é necessária a introdução de uma planta de armazenagem de energia, de maneira a armazenar a geração excedente e usá-la em períodos com uma quantidade menor de energia gerada. Considerando as tecnologias de armazenagem existentes hoje, a mais eficiente para ser usada em larga escala é através de plantas hidrelétricas reversíveis. Na Europa, onde as fontes não despacháveis estão presentes há mais tempo, essa tecnologia já é utilizada para aumentar a eficiência devido à presença de fontes eólicas, solares e nucleares. Através da modelagem da Bacia do Paraná e da incorporação da geração eólica em diferentes sítios no Brasil, este trabalho vai avaliar a eficiência dessa tecnologia no cenário brasileiro, baseado nas séries históricas dos fluxos naturais dos rios e nos dados de ventos em cada sítio. Foi analisada então a operação em cascata das hidrelétricas da bacia com a influência das hidrelétricas reversíveis. Uma vez que o problema não possui uma solução analítica definida, foi implementado um algoritmo de otimização com a rotina de simulação para gerar um resultado otimizado do problema. Além disso, a rotina desenvolvida tinha que ser flexível, permitindo analisar uma série de diferentes cenários. Através dos resultados encontrados através da rotina, foi possível avaliar diferentes casos, variando desde o ano base para os dados históricos, até o dimensionamento da planta reversível, sendo este um importante passo para uma avaliação mais profunda da inserção de hidrelétricas reversíveis no Brasil. Desta análise, é possível verificar as melhorias que plantas de armazenagem poderiam trazer ao sistema elétrico brasileiro.

Palavras Chaves: Hidrelétricas Reversíveis. Algoritmo Genético. Plantas Hidrelétricas. Modelagem. Algoritmo Evolutivo.

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1 INTRODUCTION

1.1 Context

Electric energy is the base of any economy in the world. For an economy to grow and develop, it is necessary to expand and be able to supply the country with enough energy so that its industries and commerce have room to expand. The most common way to generate electricity in the world is through thermal plants because of its simplicity. It may be constructed mostly anywhere as well as it can be supplied with its respective fuel. However due to the environmental laws and concerns that have gained room recently, thermal sources are discredited to alternative and renewable sources that are growing in the world's energy matrix.

In the field of renewable sources, the oldest and most used source is the hydroelectric energy that has almost no environmental impact once constructed and with fueled by water, generating no fuel expenses. Also, being a dispatchable source with a small response time, it may be the base of a country energetic matrix. However, due to the impacts generated in its construction and the scarce availability of sites to construct dams in many countries, solar and wind power are also growing in importance in the whole world.

In Brazil it is no different. The base of the Brazilian energy matrix is the hydroelectricity that answers for 68% (EPE, 2014) of all installed power connected to the national interconnected grid. But with new environmental laws, to reduce the flooded area new dams are being classified as run-of-the-river plants reducing drastically the amount of water it may store, being it more subject to the water regime. This creates a few problems to the national grid because firstly the power generation becomes more linked with the wet and dry seasons, which cannot be controlled, and secondly, with the introduction of intermittent sources such as wind and solar power, run-of-the-river plants do not have the same regulation potential as the conventional hydroelectric facilities.

Considering the predicted expansion of the wind farms in the next decade, it is essential to implement a way of regulating and exploring the most of the power generated. A way to do so is through pumped hydroelectric facilities. It consists on pumping water to a superior reservoir in periods of exceeding available power and turbine water from the upper reservoir to the lower reservoirs when there is a need to insert more power in the grid. It is the most efficient way to store energy in a large scale today, you consume exceeding energy generated through the non-dispatchable sources on certain times to pump water into a superior reservoir, storing the electric energy as potential energy and when it is needed, you may turbine it generating the missing energy in the grid.

Through reversible hydroelectric plants it is possible to correct and regulate the oscillations in the grid generated by intermittent sources besides it may store water, avoiding spillage in the dams so that the efficiency of the system is increased. Most of pumped reservoirs in the world have daily cycles meaning that during the peak load of the day water is turbine and in off-peak periods, water may be pumped into the reservoir.

Considering the Brazilian scenario, pumped hydroelectric plants are particularly interesting because it would be able to decrease influence of seasonality in the power generation if an adequate site for a seasonally cycle is available. The problem is that in Brazil there aren't many available locations for the construction of a large-scale reversible reservoir, therefore will be analyzed a technique called Enhanced-Pumped-Storage (EPS). The idea is to combine a pumped storage with a series of dams in cascade, enhancing the power generation of the system through the operation of one reversible reservoir upstream (HUNT, 2014).

1.2 Objectives Of The Work

Considering the Brazilian energy scenario, this work will propose a method to improve the efficiency of the energy matrix in Brazil through the introduction of enhanced pumped storage facilities in an existing energy system.

Taking into account the predicted expansion of wind source of energy, the objective is to improve a hydraulic generation system avoiding wastes of energy, using any excess in pumped machinery allowing storing the exceeding energy in the form of potential energy in way also to counterbalance the intermittency due to wind variation, minimizing the spilled energy in the conventional hydroelectric power plants.

Also, an improvement included in the insertion of pumped facilities to be observed in this work is regarding the daily variation of the load, so reversible hydroelectric power plants may generate energy, injecting power into the grid during peak hours of the day and consume exceeding energy during off-peak periods storing the energy.

It will be to evaluate a more efficient manner of exploring the portfolio of wind and hydraulic sources of energy avoiding unnecessary spillage, minimizing seasonal influence along the years, given by a variable water regime using the real potential data for wind generation in different fields in Brazil and for natural water influxes in the existing dams in the country. To do so, it will be incorporated two Enhanced Pumped Storage plants and then observe their influence and behavior of the system's generation profile after their insertion to evaluate the method's efficiency.

1.3 Methodology

To analyze the system it was developed a partial model of the Brazilian interconnected national grid composed by the Paranaíba Basin, Grande Basin and Paraná Basin, using a routine in *Matlab* to simulate it. Then it was introduced two new pumping facilities, the first called Canastra and connected to the Furnas Dam in the Grande River, and the second called Catalão connected to the Serra do Facão Dam in the São Marcos River (HUNT, 2014).

After the system's modeling, it was implemented a technique of evolutionary optimization through a Genetic Algorithm (GA) to simulate an optimized behavior of the system if the pumped reservoirs were present and using a parallel politic for the conventional reservoirs operation. Initially, using monthly discretization and historical data of the water flux in each dam, the objective is to observe the seasonality influence in the system after the insertion of the reversible reservoirs and compare it to the current system. Then considering the intermittent sources to be inserted, it will be used an hourly discretization and wind data to estimate the generation in the farms and how it could optimize the water use taking into account the intermittence of the wind energy generation.

To calculate the wind generation, it will be used the hourly data of the wind speed in the places where the wind farms are located. Then with the machine's characteristic curve, through a deterministic method, it will be calculated the wind generation in the same period analyzed for the water historical data. Then, using the GA, it will be determined the optimized behavior of the pumps and its benefits compared to a simulation where they were not present.

1.4 Structure Of The Work

This work is structured in 9 chapters, detailed below:

- Chapter 1 – INTRODUCTION: exposes the initial context, the objectives to be achieved, relevance of the work and methodology used.
- Chapter 2 – ELECTRIC ENERGY, OVERVIEW OF BRAZILIAN SCENARIO: in this chapter will be explained the context that surrounds the Brazilian electrical energy system, starting from a brief historical introduction into the next decades expansion plans for the energy sector.
- Chapter 3 - PUMPED STORAGE PLANTS: in this chapter, it will be explained how a pumped storage plant works, and how it could be inserted into the Brazilian context, as well as the system that will be studied in this work.
- Chapter 4 - MODELING OF HYDROELECTRIC PLANTS: it will be explained how the system under analysis was implemented in a computer routine, with the modeling of hydroelectric plants including the pumped facilities. This chapter is the base for the development of the generation analysis of any electric system with hydroelectric plants, supplying with all the generation equations based in the water regime.
- Chapter 5 - WIND FARMS MODELING: It describes the model used to calculate the wind generation profile used later in the simulation as well as details the location, equations used for each wind farm.
- Chapter 6 - SIMULATION AND OPTIMIZATION: After the modeling of the system, it is needed to apply an optimization algorithm that supplies an optimal exit for the simulation. Therefore, it will be explained how the genetic algorithm was applied in this work as well as all the simulation details, with all the constraints and premises.
- Chapter 7 – CASE ANALYSIS: In this chapter will be analyzed the outputs of the simulation, comparing each case among each other, including the cases with or without the Pumped Storage Plants analyzing all of its benefits to the energy generation system.
- Chapter 8 – CONCLUSION: In this last chapter will be taken the final conclusions from the analysis in the chapter before, as well as possible contributions and improvements to be incorporated in the study.

2 ELECTRIC ENERGY, OVERVIEW OF BRAZILIAN SCENARIO

2.1 Energy and Development

Since pre-historical age, the development of human kind has been directly connected to energy consumption. From the primitive man to contemporary man, energy consumption has grown considerably, and comfort has grown in the same proportion. Initially, the energy consumption was mainly from the food we needed to survive, but as time went by, there came new discoveries and other forms, direct and indirect, of energy consumption. For example, when men discovered fire and its use to cook and warm environments making it more comfortable, then the animal energy used for agriculture when we started to domesticate animals and so on. In Figure 2.1 it is possible to see the connection between the human stages of development and the energy consumption and how it grew along each period of history.

Source: (COOK, 1976)

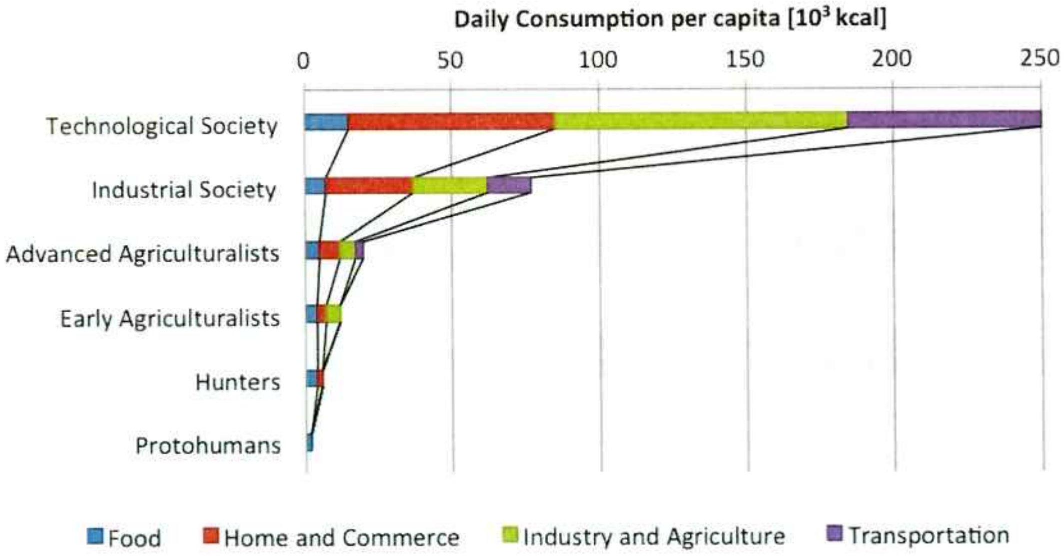

Figure 2.1 – Human stages of development and energy consumption

With the industrial revolution that started in the end of the XVIII century, and the invention of new machinery that were moved by steam and coal, the energy consumption per capita grew considerably and so has since then. In the end of the XIX century, electricity became an important form of energy to now become essential to a country's economy and to the comfort of any person. Today it is present mostly in any activity.

Notice that from primitive stages, daily consumption of energy grew from around 2.000 kcal to a current 250.000 kcal. Thanks to the combustion motors, that are used for commerce, transportation and so many other activities in the daily life besides power plants and heating that allows a more comfortable life to everyone, the energy demand has grown and keeps growing constantly, being always necessary to improve the methods to generate and supply the energy the world demands.

In the last decades with the technology revolution and the process of globalization, the industries and companies have expanded into different areas of the globe and together with the rapid population growth; the process of energy consumption in the whole world was accelerated. As it is possible to see in Figure 2.2 world's consumption of energy grew almost 56% while the population growth for the same period was 37% (THE WORLD BANK, 2015) showing how other factors connected to the new technologies was important to raise the energy rate of consumption.

Source: (ENERDATA)

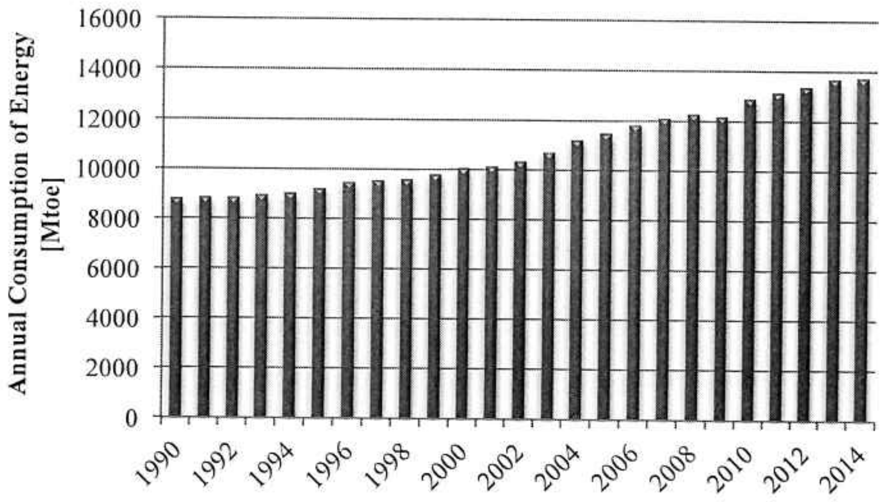

Figure 2.2 – World energy consumption between 1990 and 2014

Unfortunately, not everywhere in the world the rate of energy consumption grew equally. These rates are thinly related to the development level of the country it is analyzed. There are big differences between the rates of a developed country to a poorer country, since they don't usually have the same access to comfort items in daily life and the industrial processes usually aren't as automatized. For example, in the agriculture of developed countries there is a wide use of machinery while in other countries there is still an abundant use of man and animal power.

It is possible to see that comfort has a straight connection with the energy consumption per capita, where the more developed countries with higher Human Development Index (HDI) have higher energy consumptions than countries with lower HDI. It is vital that the supply follows the constant increase in the demand that has been observed in the last decades to keep improving everyone's comfort. But to do so, there have to be taken into account the current concerns such as the environmental factor, because with every development comes a price and there is the duty to attenuate it.

2.2 Energy and Environment

The environment of the world we live in is under constant changes. The alterations may be caused by natural factors that are cyclic or by our society and the impacts our living in the planet causes.

From the XVIII century when the industrial revolution started, the impacts caused by men in the world increased quickly. The main component that represents the pollution men release in the planet is the carbon dioxide (CO_2), which is released while burning an organic material. What initially was emitted mostly over burning wood for cook and heating, with the industry expansion in the XIX century became much more intense and accelerated over time as new industries were established, initially in England. In Figure 2.3 it is possible to see how fast the emissions of CO_2 grew over the last decades until it was realized the problems its consequences.

Most of the emission growth came from the constant increase in the demand of energy and how it has been supplied over the last century. The main source of energy has always been fossil fuels such as coal and oil that when burned release many different pollutants that contributes for the greenhouse effect, accelerating the climate changes and damaging the health of any living being in the planet. One of the consequences was the increase in breathing related diseases in the last decades (WORLD HEALTH ORGANIZATION, 2014).

To change this scenario, constant research has been made into renewable sources, that according to International Energy Agency, is defined as: *"Energy derived from natural processes that are replenished at a faster rate than they are consumed. Solar, wind, geothermal, hydro and some forms of biomass are common sources of renewable energy"* (INTERNATIONAL ENERGY AGENCY, 2014). One of the sectors most affected by this change is the electric sector responsible for the generation and transmission of electric energy because almost every source of energy may be transformed into electricity. Therefore a significant part of the world energy consumption comes in the form of electrical energy.

Source: (THE WORLD BANK, 2015)

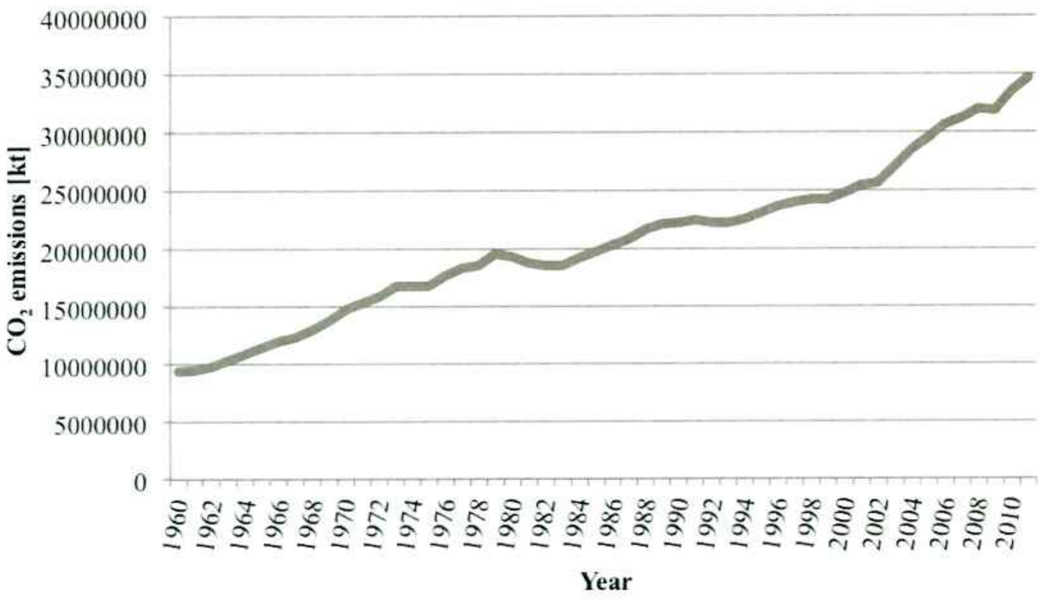

Figure 2.3 – CO_2 emission in the XX and XXI Centuries

Traditionally, thermal sources have been the most used sources to generate electricity, given that they have relatively short implementation time, are cheaper to build and may be installed near to consumer centers. But firstly, due to cost and availability of fuel, the hydro energy has gained room in the XX century since they are characterized for a cheap and clean operation. However, there are a lot of controversies about the hydropower. Once a hydroelectric plant is constructed, the impact in the environment is very little, and there is a free stock of water to move the turbines to generate power, but there are large impacts during its construction.

Considering the Brazilian scenario where the hydro energy is the most important in the electric sector. The constructions of some dams have destroyed large forest areas and it also interrupts the passing of fishes impacting the nearby environments and settlements. The best example of a disastrous hydroelectric plant is the Balbina plant that flooded a huge area of the amazon rainforest without removing the vegetation first. Today due to the rotting of the plants that remained under the water, there is a large emission of methane and the acidity of the water damages the turbines and structures of the plant. Still, if during the planning stage of the construction, all effects are considered correctly, most negative effects may be avoided or reduced.

Searching cheap and clean sources of energy, research into developing the use of wind and solar energy in the electric sector has gained room in the end of the XX century. Looking into Figure 2.4 it is possible to see the increase of the renewable sources share in the world energy generation. Fossil fuel remains the main source of energy around the globe to generate electricity, but after the 90's it is visible the constant increase in the participation of renewable non-hydro sources, such as wind and solar.

Source: (U.S. ENERGY INFORMATION ADMINISTRATION, 2014)

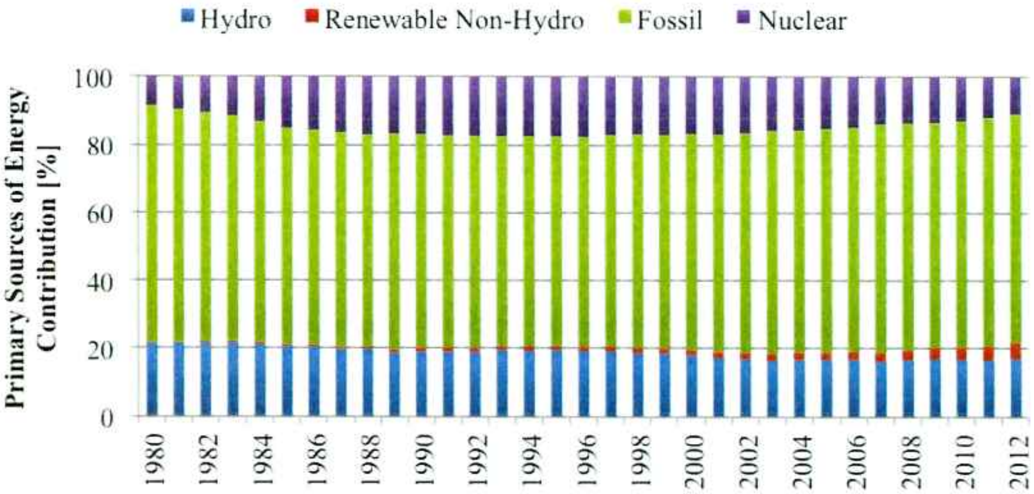

Figure 2.4 – Primary sources of energy participation in the world electricity generation

This increase of renewable share in the energy world matrix coincides with the first movements in favor of pollution reduction, such as the Kyoto Protocol that extended the United Nations Framework Convention on Climate Change (UNFCCC) and was signed in 1997. After its signature in 1997, it is possible to see in Figure 2.4 that the share of the non-hydro renewable sources grew from a participation of 1,50% to 4,96% in 2012 while the fossil participation reduced from 69,6% to 67,2% evidencing the current tendency and how the electric sector has to adapt to it, understanding better how to insert the new sources in the energy distribution system without compromising transmission due to the intermittencies, oscillations and instabilities these sources create.

In the next section will be analyzed the Brazilian scenario with a brief introduction of how the electrical sector was developed along the time and how it's been changing and adapting to the present context.

2.3 The Brazilian Electrical System

2.3.1 Brief Historical Introduction

Electrical energy arrived in Brazil almost simultaneously to the invention of the devices that enabled its use. In 1879, Thomas Edson invented the carbon-powered lamp that lit without use of fire or oil. In the next decade, it became clear that the electrical energy was viable to be applied industrially but it was still unknown a way to transport energy for long distances. Meanwhile, in Brazil, Emperor D. Pedro II inaugurated the first electrical illumination system in Latin America in a railway station.

In 1883, the first thermal electrical plant called Power and Light Station was launched in Rio de Janeiro with an installed power of 52 kW and supplied energy for 39 lamps. In the same year, the first hydroelectric plant was inaugurated in the city of Diamantina, Minas Gerais and used for industrial purposes for the first time.

In 1888, Nikola Tesla was able to generate alternate current that allowed for the electrical energy to be transported longer distances, permitting the use of electricity in a larger scale. As a consequence, in 1890, it was signed between the Prefecture of São Carlos and the company *Malfatti & Huggins* the first contract in Brazil to supply a city with electrical energy. To this purpose, started the construction of the first hydroelectric plant in the state of São Paulo in the river Monjolinho, with an installed power of 100 kW that started operating on July 2nd of 1893.

In only 17 years, after the first power plant, Brazil already had 5 hydroelectric and 6 thermal power plants with a total installed power of 12.085 kW that were mainly controlled by foreign companies such as São Paulo Railway, *Light and Power Empresa Cliente Ltda*, commonly known as LIGHT and was founded in Toronto, Canada. To invest in Brazil, the federal government guaranteed their monopoly in the electrical trams services and energy supply in the city of São Paulo. Other foreign companies were established in other cities with the similar guarantees, but mostly near to Rio de Janeiro and São Paulo and with no interconnection between them.

In the 1920's, the first interconnections began to be built to avoid an energy supply crisis and Amforp developed it. The first barrier was the frequency differences because at the time there wasn't an established standard. It was then patterned the 60 Hz frequency allowing the construction of the first network in Brazil in 66 kV that interconnected 20 power plants summing 50 MW of installed power.

Given the high availability of hydro energy in Brazil, government decided in 1934, through the Water Act, to federalize the rivers, so that they didn't belong anymore to the landowners but to the City, State or Union depending on each case. This made the government owner of every hydro potential in Brazil, which could be granted to third parties through concession or authorizations only. Also, the fares were fixed according to the operational costs and investments.

After the Water Act, the participation of private companies was strongly discouraged so that the government had to intervene in 1945 to solve a strong supply crisis that was happening. A series of state owned companies were founded and charged with the construction of new plants and interconnection of isolated systems. In 1945 was created the CHESF (*Companhia Hidro Elétrica do São Francisco*) charged to construct and operate the plant of Paulo Afonso with 180 MW of installed power and was inaugurated in 1955.

Source: (INSTITUTO DE PESQUISAS TECNOLÓGICAS, 2012).

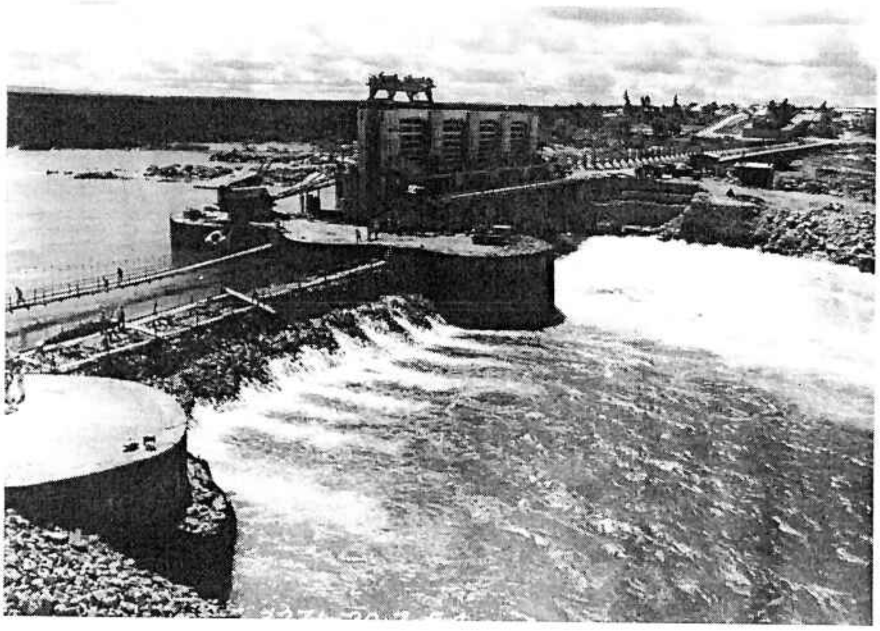

Figure 2.5 – Hydroelectric Plant of Paulo Afonso in 1955

Other companies such as CEMIG – *Centrais Elétricas de Minas Gerais* were founded in the same period. In 1956 began the government of Juscelino Kubitschek that was characterized for the Goals Plan and prioritized the expansion in the electrical energy generation. In 1957 was founded a company named *Central Elétrica de Furnas S. A.* and was charged in the construction of the Furnas power plant in the river Grande. This facility regularized the energy supply in São Paulo and established an interconnection between the systems of Rio de Janeiro, São Paulo and Minas Gerais, starting what would become the National Interconnected System – NIS.

In 1964 began a military dictatorship in Brazil that lasted until 1985. During this period, the federal government bought most of the shares of the energy related corporations and the expansion and operation of the sector were then controlled by a company named *Eletrobras* that acted as a holding company of state and federal firms. During this phase in the history of Brazil, were carried out large state works and many new plants were constructed. Special mention to the Itaipu power plant with an installed power of 14.000 MW that was until 2013 the largest hydroelectric plant in the world, being overcome by the Three Gorges plant in China; Angra I, the first nuclear plant in Brazil located in the state of Rio de Janeiro; but also the Balbina that as mentioned before was an environmental disaster in the middle of the amazon rainforest.

Source: (INSTITUTO DE PESQUISAS TECNOLÓGICAS, 2012)

Figure 2.6 – Construction of the Itaipu Dam

In the 90's with democracy re-established it was conceived a plan to stimulate competition in the sector as a way to cheapen electric energy and separate the activities of generation, transmission and distribution that is operating until nowadays. Many of the state owned companies were privatized except for the transmission lines that remained under control of the State, allowing their exploitation by companies through concession contracts. Together, a series of regulatory actions were to be established through agencies, like the National Electric Energy Agency (*Agência Nacional de Energia Elétrica* – ANEEL) founded in 1997, year that was also founded the National Operator of the System (*Operador Nacional do Sistema* – ONS), responsible for operation and coordination of the NIS.

2.3.2 The National Interconnected System

Considering its dimension, the Brazilian NIS may be considered unique in the world. From Figure 2.7 it is possible to see that the system reaches mostly everywhere in the country except for a few isolated systems in the North region of Brazil in the middle of the Amazon rainforest.

Source: (ONS, 2013).

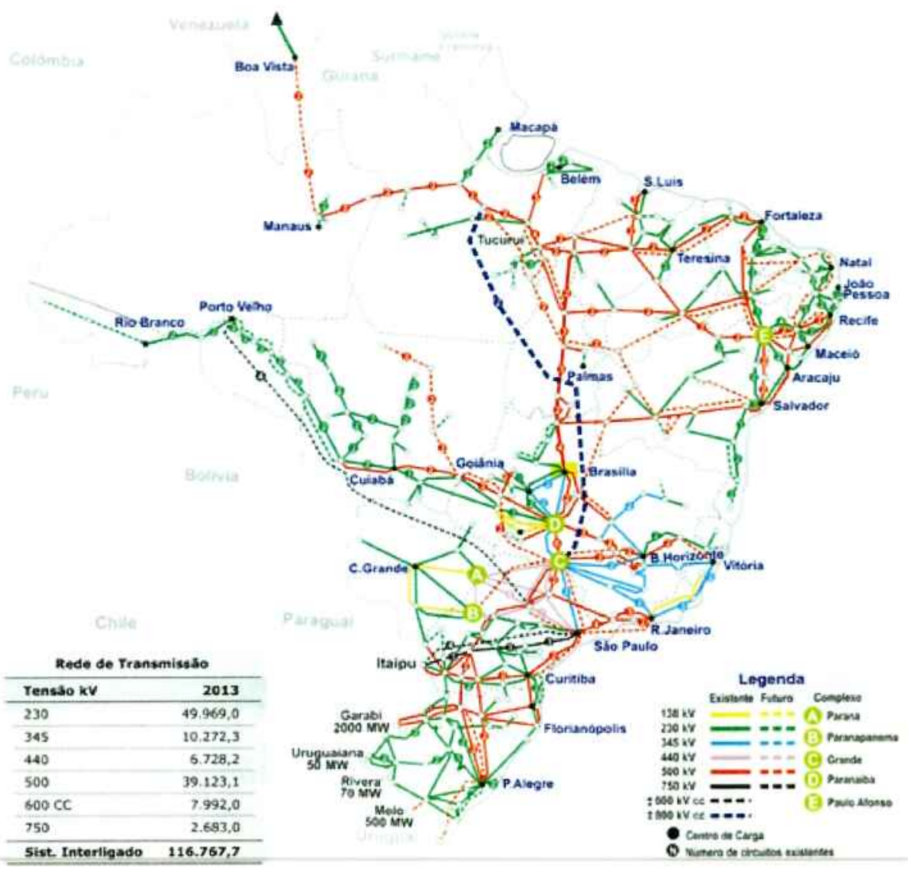

Figure 2.7 – The NIS

In 2013 the NIS had a total of 126.743 MW of installed capacity interconnected and divided in four subsystems: Subsystem Southeast/Centre-West, Subsystem South, Subsystem Northeast, Subsystem North. This year the whole system generated a total of 609,9 TWh (EPE, 2014).

Each subsystem has its own characteristics and limitations. On Table 2.2.1 it is possible to see the generation in each subsystem in 2013 as well as its source. It is important to notice the role each form of energy plays in the national scenario as well as the particularities of each part of Brazil.

Table 2.2.1 – Electrical energy generation in each subsystem in GWh in 2013

Subsystem	Hydraulic	Thermic	Wind	Biomass	Others	Total
SE/CW	168.571,60	53.924,36		3.825,85	2.789,17	229.110,98
SOUTH	78.865,71	12.074,22	845,43	11,34		91.796,70
S/SE/CW	247.437,31	65.998,58	845,43	3.837,19	2.789,17	320.907,68
ITAIPU	88.792,00					88.792,00
S/SE/CW+IT	336.229,31	65.998,58	845,43	3.837,19	2.789,17	409.699,68
NE	34.237,19	23.280,72	2.850,72			60.368,63
N	44.703,91	11.275,25				55.979,16
N+NE	78.941,10	34.555,97	2.850,72			116.347,79
System	415.170,41	100.554,55	3.696,15	3.837,19	2.789,17	526.047,47

Source: (ONS).

Notice that the subsystem S/SE/CW+IT answered for 81% of the total hydraulic in 2013, which in turn answered for 79% of the total electrical energy generation in that year in Brazil. It is important to see the dependence of the whole energy matrix in the hydraulic generation in this subsystem.

This factor is relevant because it implies great distances between the power generation plants and the consumer centers requiring long distance transmission lines. For instance, in the end of 1999 it finished the construction of a transmission line 1.000 km long in 500 kV and maximum interexchange of 1.000 MW that allowed the interconnection of the S/SE/CW subsystems to the N/NE subsystems.

The inauguration of this transmission line increased the reliability of the whole system, because even the Northeast subsystem having a smaller charge connected, generation is still small, demanding power from other subsystems. In Figure 2.8 it is possible to see the importance of the NIS to meet the entire load of the system through the energy balance between each subsystem. One of the problems of the predominance of hydroelectric plants in Brazil is that it is mostly concentered in the S/SE/CW subsystems.

Considering that due to environmental concerns, nowadays most of the new dams are run-of-the-river, having almost no storing capacity, the Brazilian system becomes very dependent on the water regime. Also, hydroelectric plants with the greatest reservoirs capacities are also located in the S/SE/CW subsystems, concentrating both the generation and the storing potentials in the same region.

Source: (ONS).

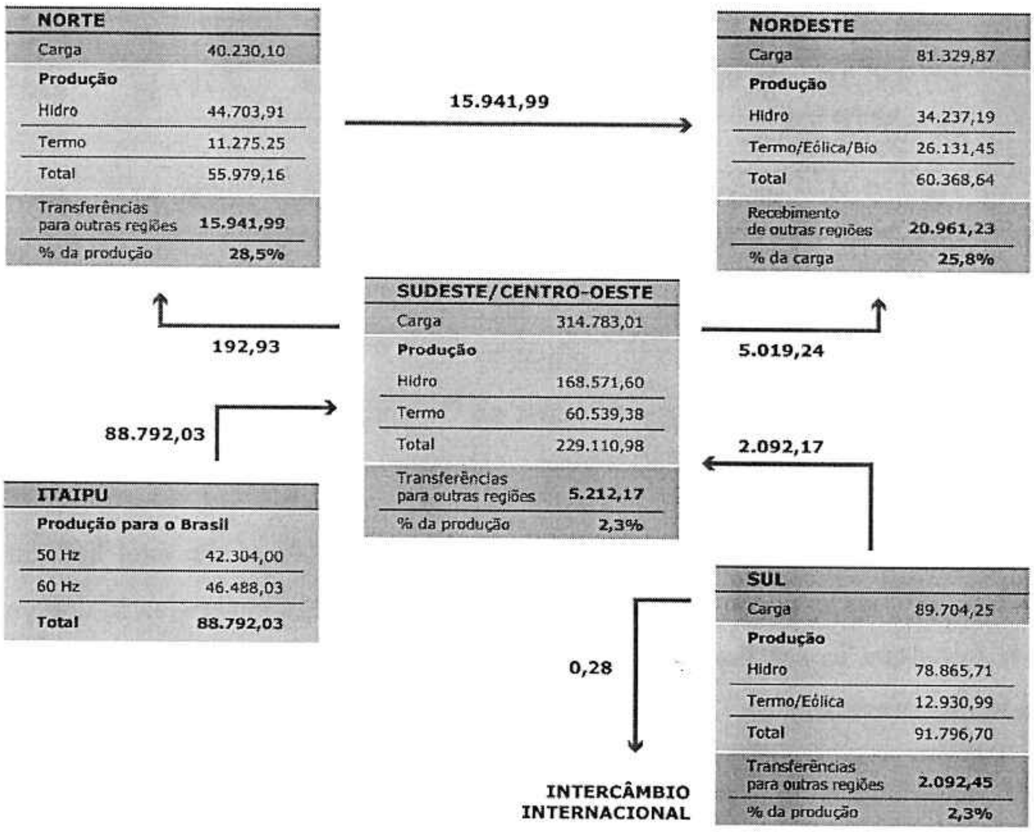

Figure 2.8 – Energy balance in GWh in 2013

The Northeast subsystem however, doesn't have a big expansion potential when it comes to hydropower and at the same time has the best potential in Brazil for wind and solar sources. Therefore, it must be studied a way to explore these potentials in this region, regulating its intermittence and controlling the oscillations they generate in the grid.

The biggest problem with wind and solar sources is that they are both intermittent and non-dispatchable sources. Their generation is dependent on wind and solar energy that arrives, which cannot be predicted with high precision being subjective to unpredictable factors and being impossible to regulate the amount of energy to inject in the grid since. This creates a lot of rumors in the power generation profile. In Figure 2.9 it is possible to see a wind farm generation taken from England as an example of an intermittent source.

To counterbalance these rumors, it is necessary to have a dispatchable source in the grid able to compensate these oscillations; a hydroelectric plant is a perfect example since they have a low response time. The problem in the Brazilian scenario to apply this is that where the intermittent sources are concentered there aren't many available sites of dispatchable power plants to regulate them.

Source: (NEW ELECTRICITY TRADING ARRANGEMENTS).

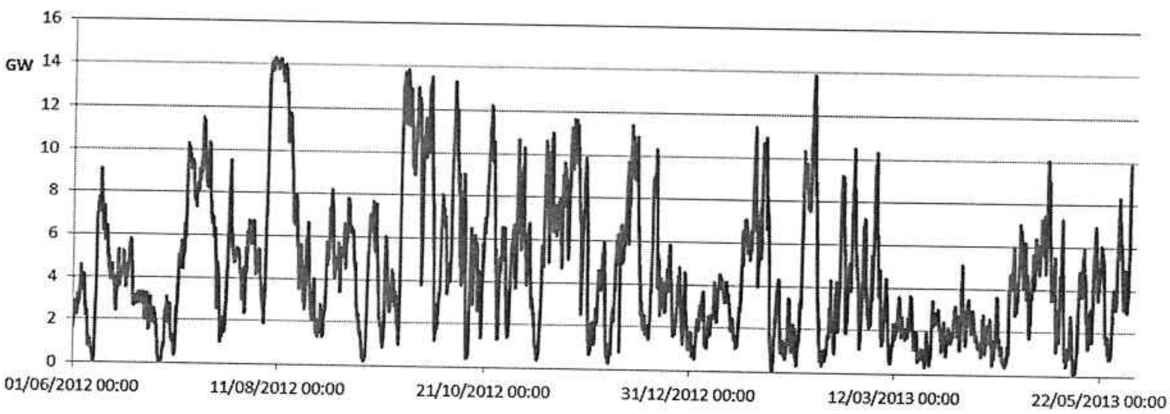

Figure 2.9 – Wind power generation taken from England

As seen on Table 2.2.1, the NE subsystem has an installed power of 34.237,19 MW in hydroelectricity and 23.280,72 MW in thermic power plants, very small potentials compared to the NIS. The scenario becomes more complicated analyzing the sites of the reservoirs in Brazil since they are highly concentrated in the Southeast and Center-West regions; on Table 3.2.2 it is shown the storage capacities of each region in Brazil.

Table 3.2.2 – Storage capacity in each Brazilian subsystem

Region	Maximum Storage Capacity [MW.month]
Southeast / Center-West	205.002
South	19.873
Northeast	51.859
North	14.812

Source: (ONS).

Considering the dimensions and great distance between centers with high wind potential and the storage capacity in Brazil, it is evident that the latter has to be more decentralized so that other renewable sources may be better explored. In the near future, with the predicted expansion of these sources, they won't be able to be used at its maximum if their regulation comes from other subsystems which are limited by long distance transmission lines with physical limitations. Closer alternatives must be found and implemented. That is one of the biggest challenges on incorporating other renewable sources and diversifying the Brazilian energy matrix.

2.3.3 Future Of Energy Generation In Brazil

In 2007 it was confirmed the existence of a large quantity of oil in a pre-salt layer in a great part of the coast of Brazil. Thanks to this great oil basin, it is predicted that until 2024 Brazil will become one of the great oil producers in the world with a daily production of 5 million barrels, exporting 1,5 million barrels a day where 66% of this production would come from the pre-salt layer exploration. But, differently from countries that are great oil exporters, Brazil has a clean energy matrix, 41% of all energy consumed in the country comes from renewable sources, a lot above the world average of 13% (EPE, 2014).

Confirming the predictions, Brazil would become the only big exporter of oil with a clean energy matrix. In the electrical scenario would be no different. According to the decennial plan from 2014 and its prediction for 2023, renewable sources would keep the same current baseline of 83% of the installed power. However, installed power in the NIS is supposed to grow more than 60.000 MW. Looking into Table 2.2.3 there are the predictions for the next decade of the power plants expansion in Brazil.

Table 2.2.3 – Decennial plan for the electric matrix

	2014		2023	
	MW	%	MW	%
Renewable Sources	**110.335**	**83,2**	**164.135**	**83,8**
Hydro	88.661	66,9	116.894	59,7
Wind	5.452	3	22.438	11,5
Others	16.222	11,4	24.802	12,7
Non-Renewable Sources	**22.224**	**16,8**	**31.748**	**16,2**
Total	**132.559**	**100**	**195.883**	**100**

Source: (EPE).

Confirming that said in the section before, wind source is predicted to grow 311% in the next decade being essential to regulate this potential so that no disturbs interfere with the network. Also, for 2015 are predicted auctions that together sum to 12.000 MW of photovoltaic plants, mostly in the northeast region and another considerable part in the southeast. With this programmed expansion of intermittent sources the system will require a more enhanced regulation.

In this scenario, the pumped hydroelectric plants could play an important role considering the success in other countries of using it to regulate and balance the system. It could be mentioned the role Pumped Storage Plants (PSP) play in some countries in Europe such as Spain, Portugal, France, Italy and Germany. Looking into Figure 2.10 it is possible to see all the power installed in the EU plus Norway and Switzerland. There are still projects of PSP plants being developed in these countries specially now with the large expansion of other renewable sources. For example, in Germany there are developments to construct sites that summed together have a potential of 3,5 GW of power and about 14 GWh of storage capacity because of the potential they have to regulate the intermittent sources (VENNEMANN, GRUBER, *et al.*, 2011). Important to notice that in the recent past, wind and solar energy started to play a fundamental role in the German energy matrix, being the country with the largest amount of photovoltaic installed power. Being so, they have a similar concern to the one in Brazil. Most of the wind potential in Germany is located in the north of the country, while the electrical load is mainly to the south. Their idea of using the PSP is to optimize the northern wind potential to generate energy for the south of the country, a similar situation to the one found in Brazil, only in smaller scale and distances.

Source: (VENNEMANN, GRUBER, *et al.*, 2011).

Figure 2.10 – Operational PSP power in GW in Europe

Taking this scenario as an example, it is important for Brazil to look into successful examples to apply it in the national scenario in the near future. So far there aren't concrete projects to construct PSP connected to the NIS but it is a consensus between the engineers and agencies that providences must be taken together with the installation of new renewable plants to guarantee a stable operation of the system. In the next section will be further analyzed the principles of how a PSP works and how exactly they would be able to contribute and be applied. Also taking the consideration of applying an EPS in the current system.

3 PUMPED STORAGE PLANTS

3.1 Overall Scenario of Energy Storage

A Pumped Storage Plant (PSP) is a method of energy storage. One of the greatest problems with electric energy is that it cannot be stored in an easy or financially viable way. So thinking in a large-scale system, all energy generated must be consumed in that same moment or lose it because the grid is not able to absorb large amounts of energy. There have been developed a few methods of energy storage but they are either too expensive, not very efficient or can't yet be used to store large amounts of energy. On Table 3.1 is reported an average efficiency for main technologies of energy storage, the only technology that tops the efficiency of a PSP is Li-ion and lead-acid batteries but have a much smaller storage capacity.

Table 3.1 – Cycle Efficiency of Various Storage Technologies.

Technology	Cycle efficiency
Li-ion	90 ÷ 95%
Lead-acid	80 ÷ 90%
PSP	75 ÷ 80%
VRB	≈75%
NiCd, Ni-metal hydride	70%
AA-CAES	<70%
CAES	42 ÷ 54%
Hydrogen	<40%

Source: (LEONHARD, 2008).

A PSP facility may arrive to more than 1 GW of installed power, storing more than 10 GWh of energy in one site, as other technologies are in a more reduced scale and mostly used for power quality purposes. In Figure 3.1 it is reported a relation between the generation power of main storing technologies and their capacity as well as examples of plants in the world using each technology.

Source: (VENNEMANN, GRUBER, *et al.*, 2011).

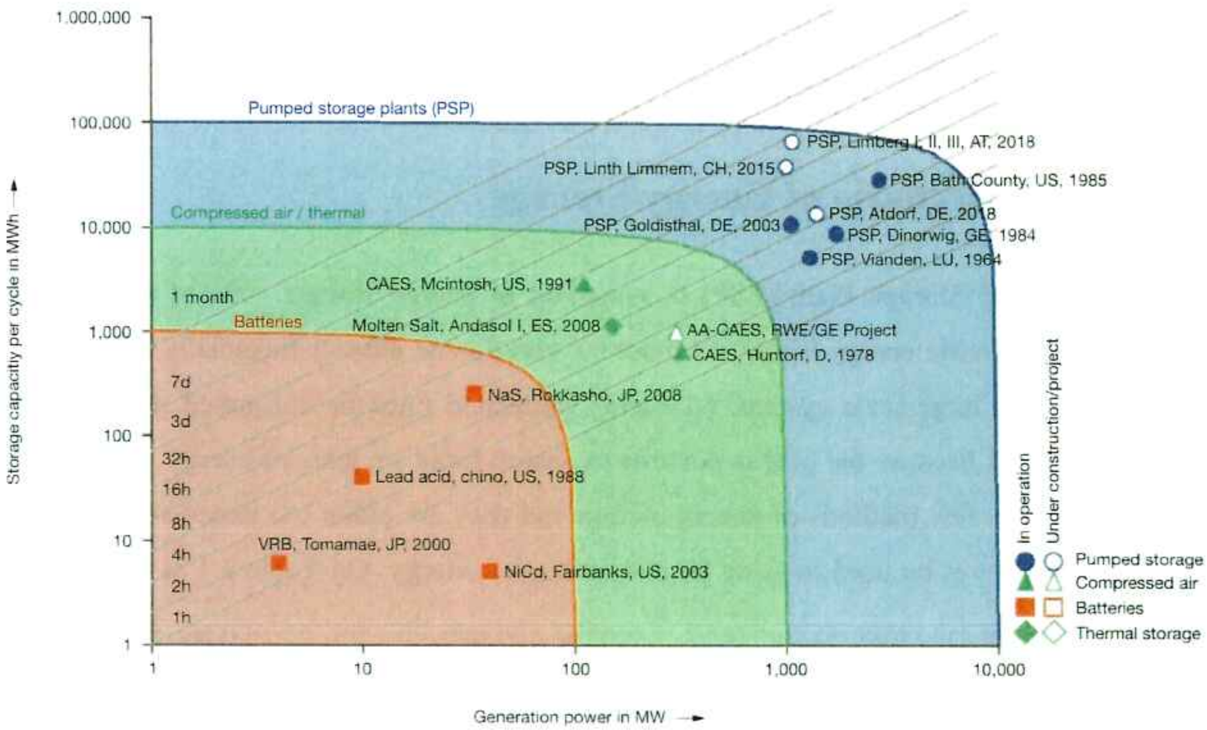

Figure 3.1 – Selected storage sites and projects that represent that represent the state of the art in terms of power and storage capacity [1]

While a PSP is the most capable technology of storing energy, it is also the most economical and convenient in a financial point-of-view. In Figure 3.2 it is reported the compared prices of each technology considering both applications. It may be used for load leveling or for long-term storage, for each one of them it changes the storage capacity and response time so that they have distinct costs and dimensions. In the case it is going to be analyzed in this work, the PSP will be used as a form of long-term storage but with the need

[1] AA-CAES – Advanced Adiabatic CAES, CAES – Compressed Air Energy Storage, NaS – Sodium Sulphur Battery, NiCd – Nickel Cadmium Battery, VRB – Vanadium Redox Flow Battery.

to have a short response time that according to the pumps and turbines available in the market, may vary from a few seconds to a few minutes.

There are five main features of energy storage technologies:

1) the charging and discharging power;
2) the storage capacity;
3) the ramp-up time;
4) the whole cycle storage efficiency;
5) the specific storage costs.

Source: (LEONHARD, 2008)

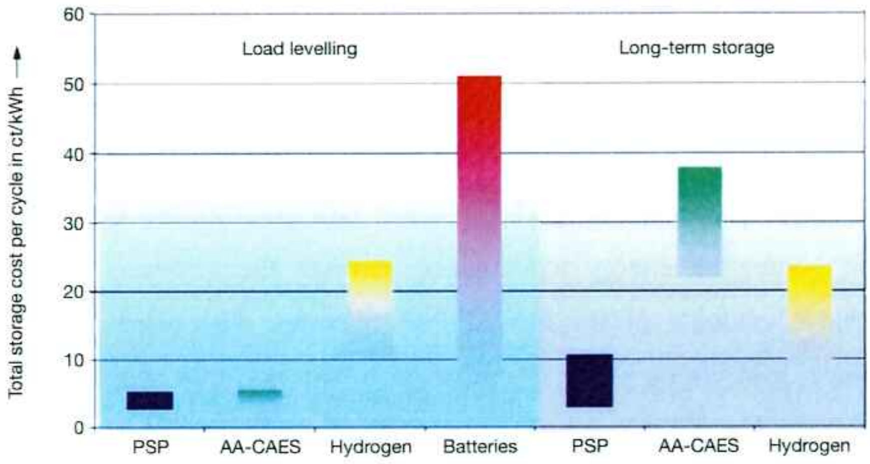

Figure 3.2 – Energy Storage Costs

In the next section will be explained the principles on how a PSP operates and why it is convenient to be applied together with intermittent sources such as wind and solar considering its characteristics that as mentioned before have the highest charging and discharging power, the biggest storage capacity, a short ramp-up time, of the best whole cycle storage efficiency and specific storage costs.

3.2 Operation of a PSP

A pumped storage plant (PSP), also called as a reversible hydroelectric plant, consists of a dam, that could be a conventional hydroelectric and an upper reservoir connected to it. It may be attached through underground tubing that has a turbine and a pumping machine allowing the water to go both ways. In some cases they have different tubes for each direction of the water flux. One of the main needs of the PSP is to have a big height difference between each reservoir so that the energy storage is maximized in the superior one. The energy stored in a reservoir is based in the Equation 3.1 so the bigger the fall, the more energy is generated, since more potential energy is converted into electrical energy.

$$E = Vol_{res}.\rho.g.H_{res} \tag{3.1}$$

The principle of operating a PSP is that when there is a spare amount of energy in the grid, it will use that energy to pump water to an upper reservoir, while in moments when it is needed to inject more power in the grid, the water will go from the upper reservoir to the lower reservoir, generating energy when going through the turbines. In Figure 3.3 it is represented a basic example of the how a PSP operates. The plant is connected into a transmission power grid with a power flux that goes both ways, to supply the pumps during the pumping mode and to inject in the grid during the generating mode.

Source: (EURELECTRIC).

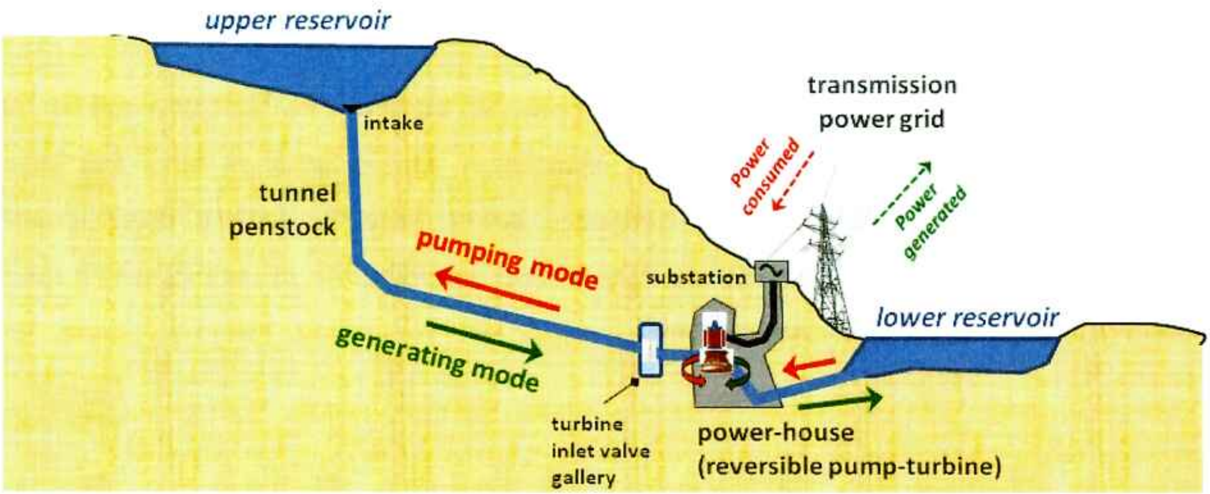

Figure 3.3 – Working principle of a pumped-storage power plant

Here an analogy can be made between the working process of a PSP and a residential photovoltaic plant. In a small solar installation there is the connection of the building to the grid that allows the place to absorb power from it, but at the same time, if they are generating more energy than consuming, the power flux may invert sense and the house starts to supply the grid with energy. It is common as well to have batteries in way to store the energy that was generated and use it in periods with less sun exposure. The same works for a PSP, only in a much larger scale.

Considering now the scenario of a PSP working with the wind farms of the grid. In an electrical system, there are different levels of electrical loads along the day, having a peak value, around 4 pm in Brazil, and the lowest values that are in the middle of the night when the electrical load connected is the smallest considering that most industries are with its machinery turned off. At the same time, along the night there is usually more wind than in the day, so that wind farms generate more energy at night, during the off-peak period. Also, for every dam in the system there is a minimum water flux that must go through it for navigation, environmental purposes. Considering the future scenario with a rapid expansion of wind farms in Brazil, their generation may surplus the load at night in a subsystem, so that hydro plants are obliged to spill water from their reservoirs so to keep a minimum flux of the river, wasting water that could turbine to generate energy.

Source: (EPE, 2014).

Figure 3.4 – Example of PSP scheme operation with storage of intermittent renewable sources.

With PSP facilities, this could be avoided, because the dams would turbine the water producing the power flow required by the system at night and keeping the minimum flow of the river while the surplus energy generated by the wind farms would supply the pumps of a PSP, storing its energy in their upper reservoir. Clearly this would avoid spillage and improve the overall efficiency of the system.

The other function it could accomplish is on regulating the comportment of the system along the day. Considering a wind generation profile such as the one in Figure 2.9, the PSP could generate or absorb energy with a very short response time compensating the intermittence of the wind sources, as well as solar. In Figure 3.4 there is an example of how a PSP could operate to compensate the same profile from Figure 2.9.

That would be possible in the cases when there is a surplus of power so that the generation that comes from non-dispatchable sources is greater than the load connected. In Figure 3.5 it is possible to see a graph of how the storage would work considering a constant load and the reallocation of the surplus to compensate it.

Source: (EPE, 2014).

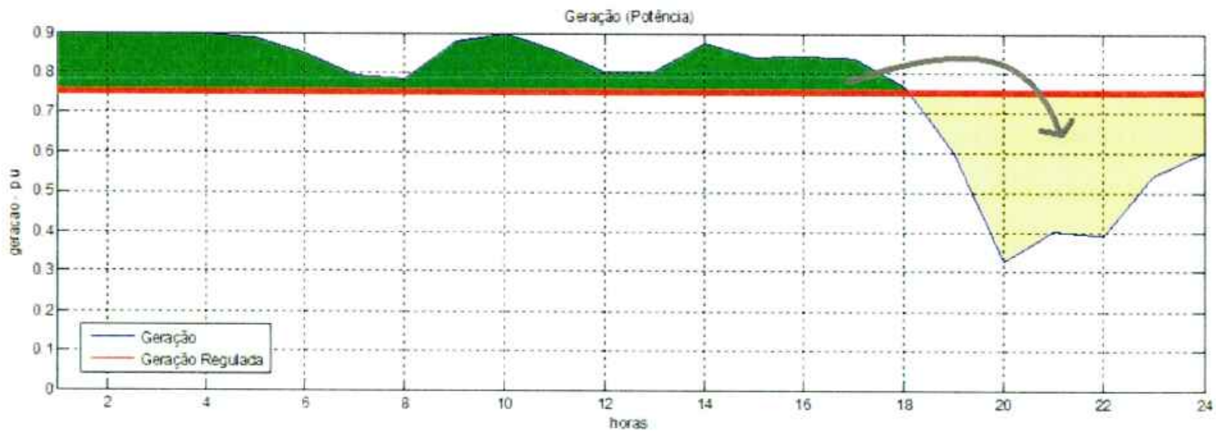

Figure 3.5 – Regulation of wind resources

This way, the average generation would be the red line in the graph, compensating the period with the lower generation with the energy surplus of the peak generation period.

Considering now the operation modes of the facility, there are a few different working scenarios for the PSP:

- Two separate units, one for generation and another for pumping;

- Two units combined for generation and pumping: in this mode the operating mode must be switched, this may be through a clutch operated in repose, through a starting turbine or through a synchronized torque converter;
- One unit for pumping and generation: in this case it must be used a reversible turbine-pump that may operate with fixed or variable speed. It has four operating modes available:
    i. Turbine mode;
    ii. Pump mode, no converter (fixed speed);
    iii. Pump mode, with converter (variable speed);
    iv. Synchronous compensator with converter;

In this work will be considered a reversible unit capable of operating as a pump or turbine so to reverse the operation with a short ramp-up time. On Table 3.2, there are some examples of PSP facilities around the globe with its main characteristics.

However, in the simulations in the shortest discretization period, of an hour, the response time of pumped plants won't be taken into consideration, as if it was instantaneous.

Table 3.2 – Examples of PSP in the world

PLANT	LOCATION	POWER	DROP	OBS.
	France	720 MW	250 m	
	Japan	30 MW	150 m	Only sea pumped hydroelectric plant in the world
	France	730 MW	1150 m	Has an affluent in the upper reservoir that allows to generate another 250 GWh
	United States of America	1,872 MW	111 m	Was the largest PSP in the world when built

3.3 Enhanced Pumped Storage

A PSP usually has a big height difference between the upper and lower reservoir so that the energy generated during the turbine mode is worth the investment and the storage is maximized. However, in Brazil there aren't many available sites to construct a PSP because there are almost no mountains or Alps in the country.

In 1982, the Energy Company of São Paulo (CESP – *Companhia Energética de São Paulo*) studied the possibility of building a PSP in the state and came with a few alternatives [(CESP, 2014)]. At the time to enable the project, they established the following pre-requirements:

- Fall > 300 m;
- Minimum Power 1.000 MW;
- 14 hours of generation a day;

This way there were three possible sites in São Paulo at the time: Serra do Mar, Mantiqueira and Serra Geral. But none of these pre-studies evolved any further. Nowadays, with the scarce availability of sites to build any traditional PSP and the need to regulate the expansion of intermittent sources, as well as decentralize the storage potential, Julian Hunt, Marcos Freitas and Amaro Pereira Junior proposed to implement a concept called *Enhanced Pumped Storage* (EPS). Through the combination of a large-scale pumped-storage site and a series of dams in cascade, it would be possible to maximize the generation with a smaller reservoir. *"A large-scale pumped-storage site, built close to the top of a river can change the flow regime of the river and thus change the seasonal hydroelectric power generation of the whole river"* (HUNT JD.).

This would be particularly useful in the Brazilian scenario. During the construction of the NIS, considering the base in the hydro energy, it was designed to combine a series of run-of-the-river dams with others reservoir dams in the Brazilian watersheds so that a constant amount of electricity could be generated along the year. Therefore, during the wet period, the reservoirs would fill up storing water for the dry period when they are emptied. But with the constant increase in the power demand and the exhaustion of available sites to build new reservoirs, this model is almost weary. If twenty years ago it had storage potential to reach the load for a couple of years, today, all the stored energy is able to supply the current load only for a few months.

Nowadays most of the unexplored hydro potential of Brazil is located in the north region, where is located the Amazon rainforest and also a subsystem with the smallest load connected to it, according to Figure 2.8. However this region is characterized by its flatness so that to build reservoir dams, it would require a very large flooded area and wouldn't be able to store a high amount of energy. Therefore due to environmental restrictions, plants under construction in the region are run-of-the-river dams with close to none storage capacity. Also, knowing that the climate in the North varies with the period of the year having very distinct wet and dry seasons, the plants are very subject to it, having a low efficiency due to the variable water regime.

Right now is under construction the hydroelectric plant of Belo Monte, located in the Xingu River, that will have a total capacity of *11.000 MW* (NORTE ENERGIA, 2010), being the largest hydroelectric plant in Brazil, remembering that Itaipu, that has *14.000 MW* of power, is a bi-national facility operated by Brazil and Paraguay. However, the plant will generate, on average, much less power than the installed capacity due to the water regime.

Now, considering a scenario with the presence of an EPS located in a more centralized place of the country, it would allow to store the energy generated in the north region in the wet season, and then use it during the dry periods for the whole country. Besides, it would allow the regulation of the intermittent sources that are under construction or predicted in auctions for the NE subsystem. A location that would allow this is in the beginning of the Parana Basin. So according to (HUNT, 2014), there are two available sites that incorporates all of this conditions, one in the Grande River and another in the Paranaíba River, the former using Furnas dam as the lower reservoir and constructing the upper reservoir in the hills of Canastra and the latter using Serra do Facão dam as lower reservoir and building an upper reservoir in Catalão.

Taking into account the geological characteristics of both sites, it is possible to come with the aspects of each reservoir. On Table 3.3 there are the main features of both reservoirs. These two sites are interesting given their high ratio of energy stored per flooded area, specially Canastra. That is possible given that both regions are in the form of a valley, allowing it to store more water in a smaller area. This also is beneficial considering that it allows smaller losses due to evaporation, raising even more the efficiency of the EPS. The location is also convenient given the more centralized location in Brazil, as it can be seen in Figure 3.6, it would contribute to a more decentralized energy storage, facilitating the regulation of a growing NE subsystem as well as the traditional reason to construct PSP that is the additional peak load generation capacity.

Table 3.3 – Data of the EPS sites to be implemented

Reservoir	Canastra	Catalão
Technical Aspects		
Minimum Altitude	1050	900
Maximum Altitude (m)	1250	950
Lower Reservoir Altitude (m)	768	756
Maximum Fall (m)	482	194
Useful volume (km^3)	17,22	5,22
Energetic Aspects		
Storage capacity (TWh)	19,83	2,51
NIS storage ratio (%)	22,16	3,5
6 months generation (GW)	10,65	1,68
Belo Monte Distance (km)	2242	1855
Environmental Aspects		
Flooded Area (km^2)	132,2	228,79
Energy storage seasonally/area required (MWh/m^2)	0,3467	0,0322
Natural Reserve	Yes	No

Source: (HUNT, 2014).

Considering these two places to build an EPS, they would influence the generation profile of the whole Parana Basin that all together has a total of *20.795 MW* of installed power. In Figure 3.7 is represented the existing system that composes the Paranaíba, Grande and the Paraná Basins as well as the two pumped storage. Altogether, there are twenty-one dams, ten conventional with reservoir and eleven run-of-the-river dams.

Source: (Google maps).

Figure 3.6 – Location of the EPS sites to be implemented in Brazil[2]

In this work will be studied how the system would react, should the two EPS facilities be located as in Figure 3.7. Given the data of both reservoirs, to see how they are convenient, it is important to compare it with other sites in the Brazilian system. Given the data of other six reservoirs of the NIS (Table 3.4), it is possible to see that those chosen to construct the EPS have great characteristics from the energetic and environmental points of view when compared to existing storage reservoirs in Brazil.

[2] A = Catalão, B = Canastra, C = Belo Monte

Source: (HUNT, 2014).

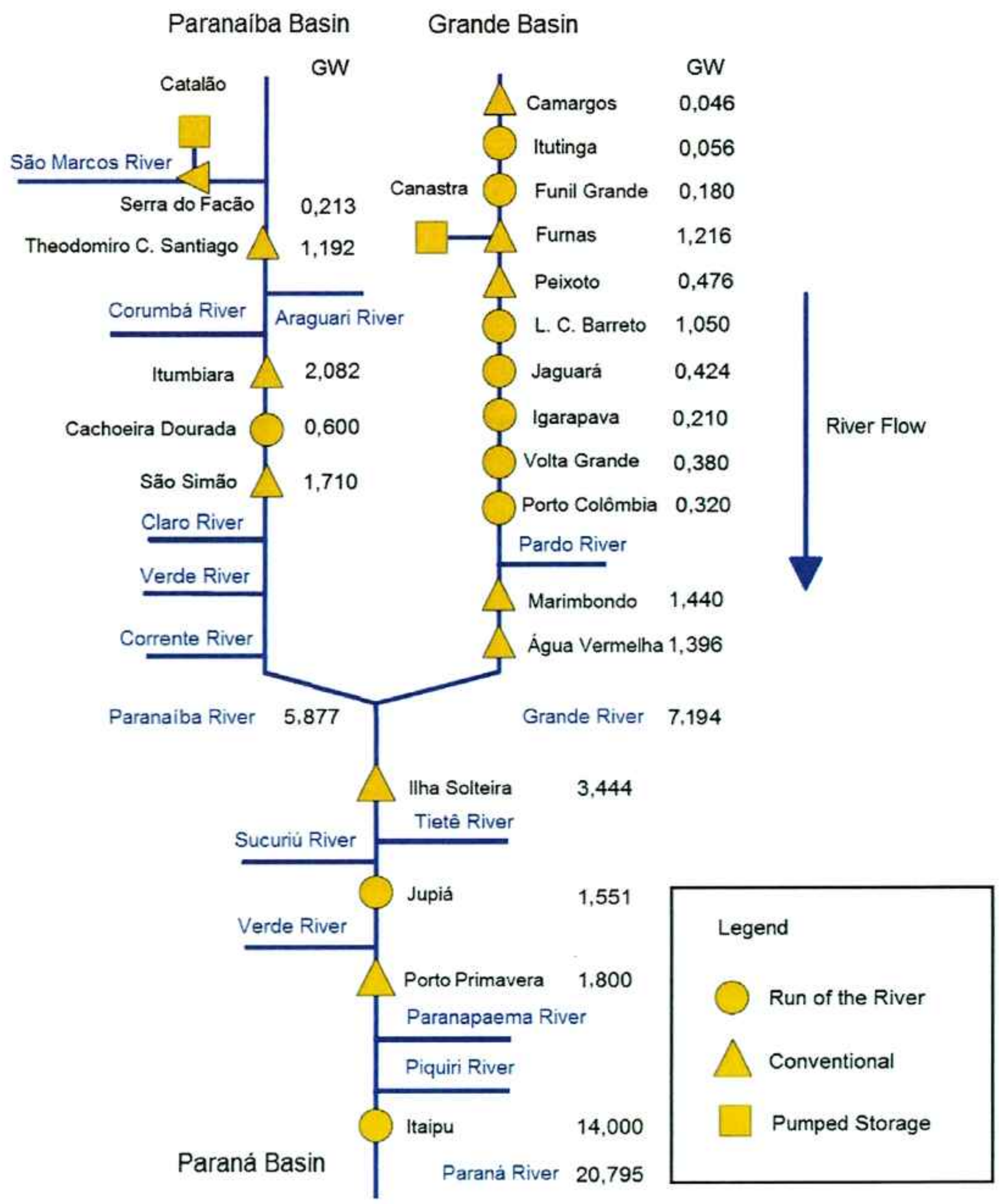

Figure 3.7 – Diagram of dams in the Paraná, Paranaiba and Grande Watersheds with two proposed Enhanced-Pumped-Storage schemes.

Table 3.4 – Efective Storage Reservoirs in Brazil

Reservoir	Furnas	Serra do Facão	Nova Ponte	Três Marias	Bento Munhoz	Serra da Mesa
Technical Aspects						
Average height (m)	761,1	747,0	800,8	563,6	752,2	445,7
Height Variation (m)	18,0	23,5	39,6	23,3	42,0	42,7
Dam Height (m)	127	92	141	75	160	154
Useful volume (km^3)	17,22	5,20	10,38	15,30	5,60	43,25
Energetic Aspects						
EARmax (TWh)	25,716	4,827	16,773	11,742	4,406	4,723
SIN storage ratio (%)	12,24	2,30	7,99	5,59	2,10	2,25
Environmental Aspects						
Flooded Área (km^2)	1440	219	442	1040	167	1784
Energy stored seasonally/area required (MWh/m^2)	0,0179	0,022	0,0379	0,0113	0,0264	0,0026

Source: (HUNT, 2014).

In the next chapter will be explained how it was established the model for the system in Figure 3.7 so to simulate the system after inserting two EPS. This tool will permit a full energetic analysis, comparing the generation profile of the whole system, its influence in power availability as well as how it will help regulating intermittent sources.

4 MODELING OF HYDROELECTRIC PLANTS

Modeling of hydroelectric plants is a process in which plants are represented through a series of mathematical equations. This way, it is possible to calculate the energy generated by these plants based on a series of information that are associated to their operation (SILVA FILHO, 2003). So, the first thing is to define the entries and the exits of this model.

Considering that this work is focused on the energetic aspects of the electrical system, the mathematical model developed consists on the generation function of the plant, this is, a function that relates measurable variables to the energy generated. The measurable variables are the volume of stored water, turbine flow and spilled flow. Through these variables, illustrated in Figure 4.1, it is possible to determine the generated energy in the plant.

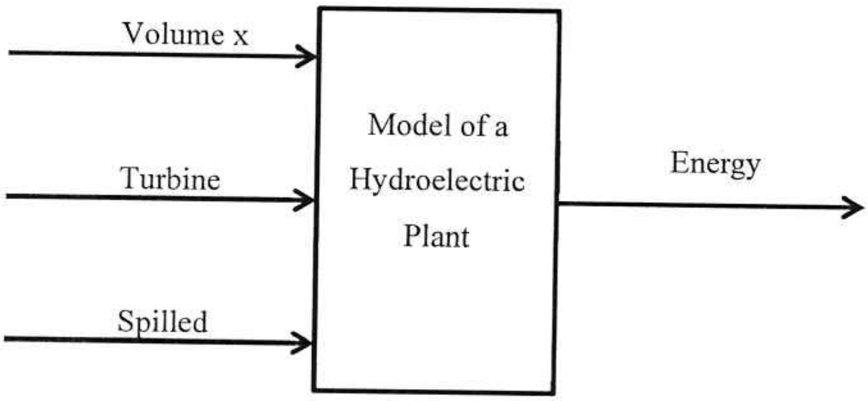

Figure 4.1 - Model of a Hydroelectric Plant

To be able to understand the model, in the next section, every component of a hydroelectric plant will be explained in details, as well as every variable associated to the transformation of hydraulic energy into electrical energy.

Then, in Section 4.2 it is described the modeling of energy losses through evaporation. In Section 4.3, it is shown how the series of inflows are calculated. Finally, in Section 4.4 it is shown the meaning of every variable used in the study. Considering that the EPS to be implemented do not exist in the system, a few approximations were made to include them in the model of the system, this will be explained in Section 4.5.

4.1 Generation Function Of Hydroelectric Plants

The mathematical model of a hydroelectric plant is going to be explained using Figure 4.2. According to this figure, it is possible to list a few components of a plant:

- A dam to dam the water, consequently forming a reservoir that raises the height of the drop of water as well as having, for some plants, an important role in the regulation of natural water inflow. The reservoirs with this potential are called accumulation reservoir and its volume may have a daily, weekly, monthly, annual or even multiannual regulation potential.
- An adduction channel that conducts the stored water in the reservoir to the turbines. Usually, in the entry of an adduction channel there is a structure composed by bars to avoid that objects enter the channel damaging the turbines. There are also floodgates that allow the isolation of the turbines for maintenance.
- A spillway in which the exceeding water, that won't be used in the energy generation and can't be stored, returns into the river. This may also be used to keep a minimum flow downstream of the river in cases of a low load profile.
- A machine house where are located the turbines, the generators and every equipment responsible for the transformation of potential hydraulic energy into electrical energy.
- An escape channel that conducts the water back into the river.

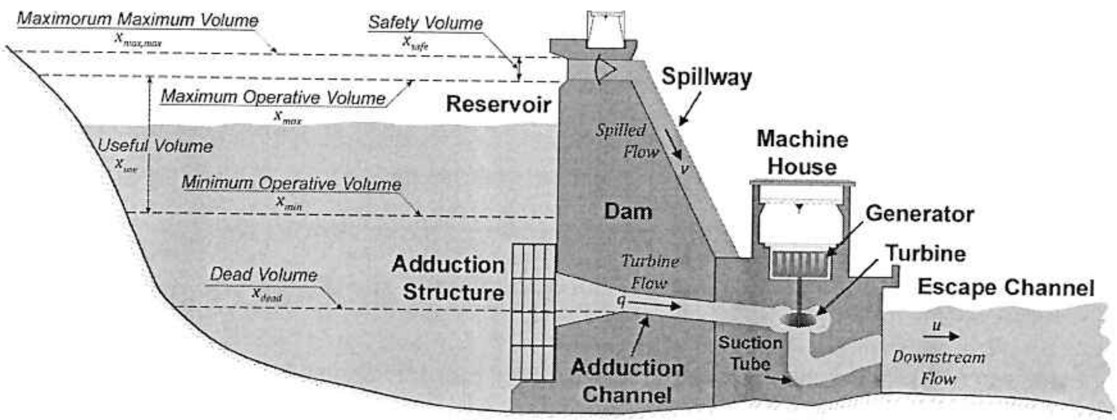

Figure 4.2 – Scheme of a hydroelectric plant

To represent some limitations of the reservoir and water fluxes that go through different parts of the plant, there are some variables to define:

- x_{dead}: it is the dead volume of the reservoir, measured in hm^3. It is the amount of water stored bellow the adduction channel minimum level and can't be removed from the reservoir.
- x_{min}: it is the minimum operative volume, in hm^3. It is the minimum amount necessary so that the plant can generate energy, it is usually associated to the minimum height in which the turbine can operate or the minimum level so that the reservoir may keep its adduction structures submerged. Usually it is equal to the dead volume.
- x_{max}: it is the maximum operative volume, in hm^3. It is the maximum volume that the reservoir stored in normal working conditions.
- x_{use}: it is the useful volume, in hm^3. It is the difference between the maximum and minimum volumes.
- $x_{max,max}$: it is the maximorum maximum volume, in hm^3. It is the extreme amount of water the reservoir may store without compromising the dam's structure. It is reached only under abnormal operating conditions and it won't be considered in the study.
- x_{safe}: it is the safety volume, in hm^3. It is the difference between the maximorum maximum volume and the maximum operative volume.
- q: it is the turbine flow, in m^3/s. It is the flow that actually generates energy, flowing from the reservoir into the machine's house through the adduction channel, rotating the turbines and triggering the generators.
- v: it is the spilled flow, in m^3/s. It is the flow that goes straight from the reservoir to the river through the spillway without generating energy. It is seen as a waste that may be necessary to satisfy minimum downstream flow of the river.
- u: it is the downstream flow, in m^3/s. It is the sum of the turbine and spilled flow.

The amount of electric energy generated by a certain amount of water x is the result of the transformation of the potential energy of this mass of water into electrical energy. Being e_e and e_p the electrical and potential energy, it may be written:

$$e_e \propto e_p \tag{4.1}$$

Knowing that the potential energy e_p is calculated as:

$$e_p = m \cdot g \cdot h \tag{4.2}$$

being *m* the mass of the volume *x* of water, in kg, *g* the acceleration due to gravity, equals to 9,81 m/s^2, and *h* the height from which the water will fall to generate energy, in *m*. During the work, instead of using the mass of water, it will be used its volume *x* calculated as follows:

$$m = \rho \cdot x \tag{4.3}$$

where ρ is the specific mass of water, equals to $10^3\ kg/m^3$. This way, (4.2) may be rewritten:

$$e_p = \rho \cdot g \cdot h \cdot x \tag{4.4}$$

Also, it is possible to associate a dimensionless coefficient η, that considerate the efficiency of the turbine and generator in the energy transformation process:

$$e_e = \eta \cdot \rho \cdot g \cdot h \cdot x \tag{4.5}$$

Equation 4.5 specifies the electric energy that a volume *x* of water generates when it goes through the turbines. However, usually it is known the flow *q* that goes through the turbines and is desired to know the power generated by its generators. Considering that the volume *x* takes Δt to product the amount of energy e_e, it is possible to determine the average power dividing Equation 4.5 by Δt.

$$\frac{e_e}{\Delta t} = \eta \cdot \rho \cdot g \cdot h \cdot \frac{x}{\Delta t} \tag{4.6}$$

The energy divided by a time interval Δt specifies the average rate of energy transformation, in other words, the average power. Also, the volume divided by a time interval specifies the average flux of water through the turbines, defined before as *q*. Imposing time interval tend to zero, there is:

$$\lim_{\Delta t \to 0} \frac{e_e}{\Delta t} = \eta \cdot \rho \cdot g \cdot h \cdot \lim_{\Delta t \to 0} \frac{x}{\Delta t} \tag{4.7}$$

$$p(t) = \eta \cdot \rho \cdot g \cdot h \cdot q(t) \tag{4.8}$$

defining the instantaneous power *p(t)* in *Watts* and the turbine instantaneous flow *q(t)* in m^3/s. Observe that all the variables in Equation 4.8 are expressed using the International System.

Analyzing the Equation 4.8, it is seen that *g* and ρ are constants. Therefore to be able to define a hydraulic generation function of a hydroelectric plant such as the one from Figure 4.1, the values of η and *h* must be determined from the entries of the model. Besides, the turbine flow $q(t)$ must have a superior limit q_{max} based on the maximum power that can be generated by the plant taking into account the model entries and the characteristics of the turbines and generators. In the next sections, the expressions of η, h and q_{max} are going to be determined.

4.1.1 Height h

The height h from Equation 4.8 is the height in m from which the water effectively falls when generating energy. It is known as the liquid drop height and will be called h_l. This value is determined by the difference between the gross drop height h_g and the hydraulic losses height h_{loss}.

4.1.1.1 Gross Drop Height

The gross drop height of a hydroelectric plant is a function of the upstream and downstream water levels. To establish a common reference to every plant, these levels are expressed based in the level zero of the Brazilian Institute of Geography and Statistics (BIGS) that refers to the sea level.

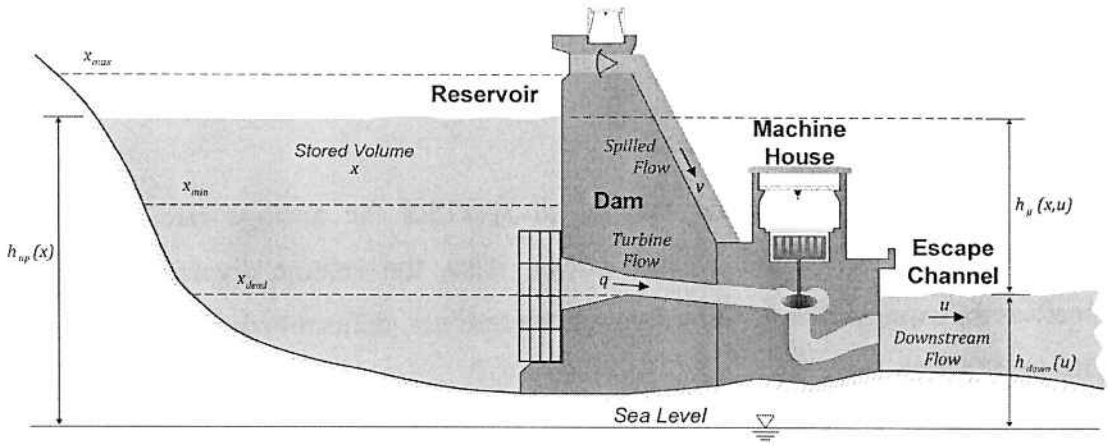

Figure 4.3 – Gross drop height

The upstream level is a non-linear function of the total volume of water stored in the reservoir x, in hm^3. This function is defined as $h_{up}(x)$ and depends on the geographic conditions in which the reservoir was built.

The downstream level is also a non-linear function, but differently from the upstream function, it depends on the downstream water flow u, in m^3/s. This function will be called

$h_{down}(u)$ and it depends on the escape channel of the plant as well as the characteristics of the downstream river of the dam.

Both these functions are known based on the auctions data that are supplied by EPE for the models NEWAVE and MSUI to calculate the energy physical guarantees of the electrical plants. (EPE, 2014). They are calculated based on measures in the location of the dam or through computer models capable of describing the characteristics of the region and processing models of hydrodynamics. In Brazil it is adopted polynomials up to the fourth degree to represent both upstream and downstream levels of the plants.

So, the gross drop height depends both on the stored volume of water x and of the downstream flow u:

$$h_g(x, u) = h_{up}(x) - h_{down}(u) \tag{4.9}$$

4.1.1.2 Hydraulic Losses Height

Due to friction between the water and the plant's structures, there is a loss of energy. There are six main structures that create this friction:

- Adduction structure;
- Entry of the adduction channel;
- Adduction channel;
- Turbine's helix;
- Turbine;
- Suction tube;

To calculate the losses, the last three are considered in an indirect way, being incorporated in the turbine's efficiency. The others are directly considered to calculate the hydraulic losses.

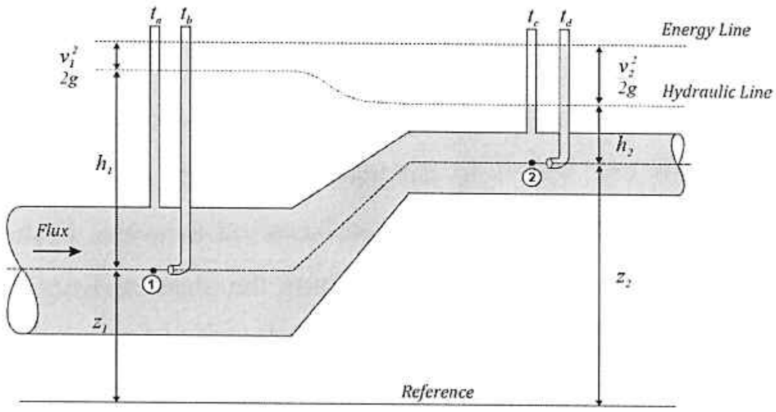

Figure 4.4 – Flux through a tube

The losses due to the adduction structure, the entry of the adduction channel and the adduction channel may be calculated using the *Bernoulli Equation*. (MUNSON, YOUNG e OKIISHI, 1998) Based in Figure 4.4 the equation may be written as:

$$z_1 + h_1 + \frac{V_1^2}{2 \cdot g} = z_2 + h_2 + \frac{V_2^2}{2 \cdot g} \tag{4.10}$$

in which z_1 is the elevation at point 1, in *m*; h_1 is the static pressure at point 1, in *m*; V_1 is the water speed at point 1, in *m/s*; *g* is the acceleration due to gravity, equals to 9,81 m/s^2; z_2 is the elevation at point 2, in *m*; h_2 is the static pressure at point 2, in *m*; V_2 is the water speed at point 2, in *m/s*. All the elevations are calculated based on a common reference.

Considering the existence of hydraulic losses between points 1 and 2, the hydraulic losses height h_{loss}, in *m*, may be introduced in (4.10) as follows:

$$z_1 + h_1 + \frac{V_1^2}{2 \cdot g} = z_2 + h_2 + \frac{V_2^2}{2 \cdot g} + h_{loss} \tag{4.11}$$

Applying the Bernoulli Equation to a hydroelectric plant, once between the entrance of the adduction channel (point a) and the entrance of the turbine's helix (point b), and a second time between the point b and the exit of the dam (point c), there is:

$$z_a + h_a + \frac{V_a^2}{2 \cdot g} = z_b + h_b + \frac{V_b^2}{2 \cdot g} + h_{loss} \tag{4.12}$$

Isolating the losses height:

$$h_{loss} = z_a + h_a + \frac{V_a^2}{2 \cdot g} - \left(z_b + h_b + \frac{V_b^2}{2 \cdot g}\right) \tag{4.13}$$

Now, applying again the Bernoulli Equation between points b and c and considering the hydraulic losses of this part null since it is considered in the efficiency of the turbine, there is:

$$z_b + h_b + \frac{V_b^2}{2 \cdot g} = z_c + h_c + \frac{V_c^2}{2 \cdot g} \tag{4.14}$$

Combining (4.13) with (4.14):

$$h_{loss} = z_a + h_a + \frac{V_a^2}{2 \cdot g} - \left(z_c + h_c + \frac{V_c^2}{2 \cdot g}\right) \tag{5.15}$$

Despite that h_a and h_c may be measured directly, it is more adequate using the model variables to express them:

$$\begin{cases} h_a = h_{up}(x) - z_a \\ h_c = h_{down}(u) - z_c \end{cases} \tag{4.16}$$

Rewriting Equation 4.15 using Equation 4.16, the height of hydraulic losses may be written as:

$$h_{loss} = h_{up}(x) - h_{down}(u) + \frac{V_a^2 - V_c^2}{2 \cdot g} \tag{4.17}$$

Therefore, it is seen that the greater the height difference between the upstream and downstream levels, or the greater the difference between the flux speed in the entrance of the adduction channel and the exit of the suction tube[3], the greater the hydraulic loss.

However, this resulting equation is not very practical because the speeds V_a and V_c aren't usually measured. So, depending on the objectives of the operation and the available data, the hydraulic losses h_l may be estimated according to the three following models.

---

[3] V_c is alway greater than V_a

i. Constant hydraulic losses:

This is the simplest model and also the least precise. The hydraulic losses are considered constant and equal to an average value. This model is used when there isn't enough information to calculate the hydraulic losses in a more precise way.

$$h_{loss} = \text{constant} \tag{4.18}$$

ii. Hydraulic losses proportional to the gross drop height:

Considering Equation 4.16, this model considers the hydraulic losses directly proportional to the gross drop height, therefore, it is neglected the variation regarding the speed of the water.

$$h_{loss}(x, u) = k \cdot h_b(x, u) \tag{4.19}$$

where k is a constant positive number that depends on the plant in study.

iii. Hydraulic losses proportional to the square of the turbine flow

This model, also based on Equation 4.16, neglects the gross drop height but depends on the square of the turbine water flow q, which is directly related to the water speed.

$$h_{loss}(q) = k \cdot q^2 \tag{4.20}$$

In this study, the hydraulic losses will be assumed constant and variable between each hydroelectric plant according to their own characteristics.

4.1.1.3 Liquid Drop Height h_l

This is the searched height that is applied in Equation 4.8. It is the height from which the water effectively drops when generating energy. The drop height is calculated based on the height difference between the gross drop height h_g and the hydraulic losses height h_{loss}. Considering that the study in case will consider h_{loss} constant, the liquid drop height may be determined combining the Equations 4.9 and 4.18 and written as:

$$h_l(x,q,v) = h_{up}(x) - h_{down}(u) - h_{loss}{}^4 \tag{4.21}$$

4.1.2 Efficiency η

The efficiency η refers to the combined efficiency of the turbine and generator. Depending on the available data and precision desired by the plant's model, the efficiency may be modeled in different ways. In this case, considering that the study in matter is a long-term study, it may be considered constant and equal to an average efficiency η_{aver}.

However, looking into the catalogs and the available data, it is common not to find the efficiency of the plants, but a parameter called *specific producibility*, *sp*. To explain this parameter, Equation 4.8 is rewritten bellow:

$$p(t) = \eta \cdot \rho \cdot g \cdot h \cdot q(t) \tag{4.22}$$

Considering a constant efficiency, the equation has now three constant parameters: ρ, g and η_{aver}. The specific producibility *sp* is then defined as a multiplication of these three parameters. However, considering that all parameters are expressed in the International System of measures, *p(t)* would be expressed in *Watts*, which isn't usual for a hydroelectric plant, where usually it is expressed in *MW*, i.e. 10^6 *Watts*. To keep the coherency between unities, *sp* is divided by 10^6 so that Equation 4.22 gives a result in *MW*.

$$sp = \frac{\rho \cdot g}{10^6} \cdot \eta_{aver} \left[\frac{MW}{(\frac{m^3}{s}) \cdot m}\right] \tag{4.23}$$

or replacing ρ and g by its values:

$$sp = 9{,}81 \times 10^{-3} \cdot \eta_{aver} \tag{4.24}$$

Rewriting the Equation 4.22 to use *sp* and noticing now that the power *p(t)* is expressed in *MW*.

$$p(t) = sp \cdot h_l \cdot q(t) \quad [MW] \tag{4.25}$$

---

[4] u is the total downstream flow, therefore the sum of the boosted flow q and the spilled flow v.

4.1.3 Maximum Swallowing q_{max}

The maximum swallowing q_{max} of a hydroelectric plant refers to the maximum flow that may be boosted by every turbine of the plant at the same time. Together with the calculation of q_{max} is calculated the maximum power p_{max} that may be generated by the plant.

Considering that in a same plant there may be different machines, turbines and/or generators, the plant could be divided into sets of machines composed by a number n_{mach} of identical machines. For each set j, $j=1,\ldots, n_{conj}$, first is calculated the maximum swallowing and the maximum power of one of its machines and then multiplied by the number of machines in the set. The sum of the maximum swallowing of every set is the total maximum swallowing of the plant.

The maximum swallowing of a turbine is defined by the boost flow when its vanes are 100% open. From what was seen in the section before, the turbine flow varies in function of the liquid drop height, the bigger the drop, bigger the flow. Therefore, the maximum swallowing of a turbine is function of the liquid drop height.

However, the maximum swallowing of a machine $q_{max,mach}$ must also consider the generator's limitations. The generator has a maximum power that can generate, known as *effective power* or *nominal power* ($p_{ef,mach}$), in *MW*. Once specified the drop height, to assure the integrity of the generator it must be assured that the power generated by the turbine is smaller than the effective power of the generator. Depending on the liquid drop height, different situations may occur:

- If the liquid drop height is too low, even with the vanes completely open, the power generated by the turbine may be smaller than the effective power of the generator. In this case, the maximum power generated by a set is the turbine's power with an opening of 100%; the generator cannot generate its effective power because the turbine can't supply it. In this case, the turbine is limiting the set's operation.
- If the liquid drop height is big, the power generated by the turbine with the vanes completely open may be greater than the effective power of the generator. In this case, the maximum power generated by a set is the generator's power; its vanes cannot be open 100% to protect the generator. In this case, the generator is limiting the set's operation.

The situation described above may be seen in Figure 4.5. It is distinguished the regions where the turbine or the generator limits the operation of the set. When the turbine is limiting the operation, the maximum swallowing is with the vanes completely open. As the drop height is relatively low, the power generated by the turbine is lower than the generator effective power. So, the maximum power of the set is the maximum power the turbine may generate, such is indicated in the graph of the maximum power of the set. In the region where the generator limits the set's operation, the turbine must close its vanes so that the power supplied doesn't exceed the effective power of the generator.

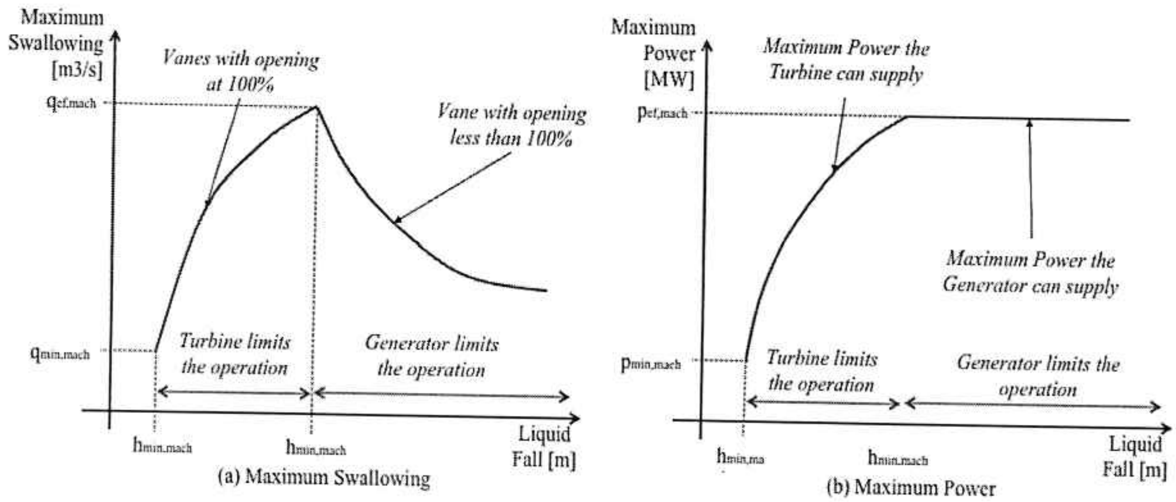

Figure 4.5 – Maximum swallowing and power in function of the Liquid Fall

In the case of the Brazilian plants, there are three functions specified for the curves shown in Figure 4.5:

- $q_{max,tur}$: the maximum swallowing of the turbine for drop falls smaller than the effective drop height, when the turbine is limiting the set's operation.
- $q_{max,gen}$: the maximum swallowing of the turbine for drop falls greater than the effective drop height, in this case the generator is limiting the set's operation.
- $p_{max,tur}$: the maximum power of the set for drop heights smaller than the effective drop height.

So, the maximum swallowing and power of the set turbine/generator is given:

$$q_{max,mach} = \begin{cases} q_{max,tur}, \text{ if } h_l < h_{ef,mach} \\ q_{max,gen}, \text{ if } h_l \geq h_{ef,mach} \end{cases} \quad (4.26)$$

$$p_{max,mach} = \begin{cases} p_{max,tur}, \text{if } h_l < h_{ef,mach} \\ p_{ef} \quad\quad , \text{if } h_l \geq h_{ef,mach} \end{cases} \tag{4.27}$$

where:

- $q_{max,mach}$: maximum swallowing of the set turbine/generator in m^3/s.
- $p_{max,mach}$: maximum power of the set turbine/generator, in MW.
- $q_{ef,mach}$: effective swallowing of the turbine in m^3/s.
- $p_{ef,mach}$: effective power of the generator, in MW.
- $h_{ef,mach}$: effective liquid drop height of the turbine, in m.
- $h_{l,mach}$: liquid drop height, in m.

To express the functions $q_{max,tur}$, $q_{max,gen}$ and $p_{max,tur}$ will be used a simplified modeling expressed on Equations 4.28 and 4.29.

$$q_{max,mach} = \begin{cases} q_{max,tur} = \left(\frac{h_l}{h_{ef,mach}}\right)^{\alpha} \cdot q_{ef,mach} , \text{if } h_l < h_{ef,mach} \\ q_{max,gen} = \left(\frac{h_l}{h_{ef,mach}}\right)^{-1} \cdot q_{ef,mach} , \text{if } h_l \geq h_{ef,mach} \end{cases} \tag{4.28}$$

$$p_{max,mach} = \begin{cases} p_{max,tur} = \left(\frac{h_l}{h_{ef,mach}}\right)^{\beta} \cdot p_{ef,mach} , \text{if } h_l < h_{ef,mach} \\ p_{ef,mach} \quad\quad\quad\quad\quad\quad\quad\quad , \text{if } h_l \geq h_{ef,mach} \end{cases} \tag{4.29}$$

where α and β are coefficients that depend on the type of turbine:

- $\alpha = 0{,}5$ and $\beta = 1{,}5$ for turbines type Francis and Pelton;
- $\alpha = 0{,}2$ and $\beta = 1{,}2$ for turbines type Kaplan;

In the system under study, represented in Figure 3.7, it is known that for every dam, there is only one type of turbine, therefore considering the proposed equations above there will be only one set of machines per plant and the maximum swallowing and power of each plant will be the number of machines multiplied by the maximum swallowing and power of one machine.

The calculation of the maximum swallowing of a plant, once defined the stored volume in the reservoir, x, and the total downstream flow, u, is not direct because the variables in case are mutually dependent. To calculate the maximum swallowing of the plant, q_{max}, it is necessary to know the liquid drop height, that to calculate is necessary to know the downstream level, which depends on the turbine flow of the plant, unknown because the maximum swallowing is unknown. Therefore it is necessary to use an iterative process:

I. Initial step:

a. Using the stored water volume in the reservoir, x, calculate the upstream level of the plant, $h_{mon}(x)$.

b. The downstream total flow of the plant is considered equal to the desired flow, u, which is given.

c. Calculate the downstream level, $h_{jus}(u)$.

d. The turbine flow of the set of machines j, $q_{set,j}$, is determined in a proportional way to the effective swallowing of the set, so that the sum of the turbine flows of each set is equal to the total downstream flow desired.

e. The turbine flow of one machine of the set of machines j, $q_{mach,j}$, is made equal to the turbine flow of the set, $q_{set,j}$, divided by the number of machines of the set, $n_{mach,j}$.

f. Calculate the liquid drop height of each set of machines j, for $j=1,...,n_{set}$:

$$h_{l,j} = h_{up}(x) - h_{down}(u) - h_{losses} \tag{4.30}$$

II. Iterative Process:

a. While Δh_l is significant[5]:

i. With the current liquid drop height value of the set of machines j, $j=1,...,n_{set}$, it is calculated the maximum swallowing of a machine of the set, $q_{max,mach,j}$, using Equation 4.28;

ii. It is calculated the maximum swallowing of the set j, $j=1,...,n_{set}$, using the number of machines in the set, $n_{mach,j}$:

$$q_{max,set,j} = n_{mach,j} \cdot q_{max,mach,j} \tag{4.31}$$

iii. It is calculated the maximum swallowing of the plant, using the number of sets of machines, n_{set}:

[5] Here is adopted a precision parameter, meaning that for Δh_l greater than this parameter, the iterative process continues, for example 10^{-3}.

$$q_{max} = \sum_{j=1}^{n_{set}} q_{max,set,j} \tag{4.32}$$

iv. If $q_{max}>u$, it is made $u=q_{max}$ and $q=q_{max}$. In this case, it is supposed that the downstream flow will be the maximum turbine flow;

v. If $q_{max}<u$, it is made $q=q_{max}$. In this case there will be spillage;

vi. It is calculated the liquid drop height of every set of machines j, $j=1,\dots,n_{set}$, corresponding to the new values of the turbine flow:

$$h_{l,new,j} = h_{up}(x) - h_{down}(u) - h_{losses} \tag{4.33}$$

vii. It is calculated Δh_l:

$$\Delta h_l = \max_{1\le j\le n_{set}} \left\{ \left| \frac{h_{l,new,j} - h_{l,j}}{h_{l,j}} \right| \right\} \tag{4.34}$$

viii. The value of $h_{l,j}$ from the step before is updated:

$$h_{l,j} = h_{l,new,j} \tag{4.35}$$

III. Calculation of the maximum power:

a. With the final values of $h_{l,j}$, $j=1,\dots,n_{set}$, from the step II, it is determined the maximum power of the machines of each set of machines, $p_{max,mach,j}$, through Equation 4.29.

b. It is calculated the maximum power of the plant, p_{max}:

$$p_{max} = \sum_{j=1}^{n_{set}} n_{mach,j} \cdot p_{max,mach,j} \tag{4.36}$$

When Δh_l arrives to a value within the adopted parameter for the precision, the iterative process is finished, and the final values of the maximum swallowing of the plant, q_{max}, and maximum power of the plant, p_{max}, is known.

4.1.4 Maximum Continuous Generation $p_{max,con}$

The maximum continuous generation of a hydroelectric plant is defined as the maximum power that the plant may generate considering the maximum power related to the status of the reservoir, p_{max}, the maximum capacity factor, fc_{max}, the scheduled maintenance rate, t_{maint} and the forced unavailability rate, t_{unav}.

The maximum power related to the reservoir condition, p_{max}, is the one determined in the section before, that considers the loss of power due to the reduction of the drop height caused by the emptying of the reservoir.

The maximum capacity factor, fc_{max}, is defined as the maximum power that a plant may product in relation to its effective power. In this study, with the data given for each plant, $fc_{max} = 1$ for every plant.

The scheduled maintenance rate, t_{maint}, indicates the percentage of time in which the plant is off for maintenance of its machines.

The forced unavailability rate, t_{unav}, indicates the percentage of time in which the plant is off due to faults in its machines.

So, the maximum continuous generation is determined as follows:

$$p_{max,con} = p_{max} \cdot fc_{max} \cdot (1 - t_{maint}) \cdot (1 - t_{unav}) \quad (4.37)$$

For example, considering the Itaipu plant, knowing that $fc_{max} = 1$; $t_{maint}=8,263\%$ and $t_{unav}=3,115\%$ and assuming conditions where $p_{max}=0,75*P_{nom}=0,75*14.000\ MW$, it is possible to calculate the maximum continuous power of the plant:

$$p_{max,con} = 0,75 \cdot 14.000 \cdot 1 \cdot (1 - 0,08263) \cdot (1 - 0,03115) = 9.332,3\ \text{MW}$$

This means that during a certain time of simulation, given a certain value of x and u, even though the plant may supply a maximum power of $p_{max}=10.500\ MW$, it can't guarantee during the whole period due to the maintenance chronogram, the forced unavailability and the maximum capacity factor, being it able to supply a continuous generation of $9.332,3\ MW$ in the interval.

4.2 Evaporation Losses

Evaporation is the physical process in which a liquid goes to the gaseous state. When talking about meteorology, evaporation refers to the transformation of water from the liquid state into a gaseous state due to solar irradiation, air temperature, wind and to vapor's pressure.

During the energetic operation of hydroelectric plants, evaporation models are required to evaluate the energy losses due to evaporation of stored water in the reservoirs, since it can't be used to generate energy.

In the study in case, the evaporation losses may be modeled through twelve evaporation coefficients, one for each month of the year, $ec_{January}$, $ec_{February}$, ..., $ec_{December}$, expressed in *mm*. The area of the reservoir in a certain month then multiplies its respective coefficient to find the evaporated volume x_{ev}, in hm^3. Just like the upstream and downstream water levels, the area of the reservoir in Brazil is calculated through a polynomial that goes up to the fourth degree and is specified for every reservoir in the country. This polynomial is function of the upstream water level. So, the evaporated volume in a certain month may be calculated:

$$x_{ev} = 10^{-3} \cdot ec_{month} \cdot a_{reser}\left(h_{up}(x)\right) \qquad [hm^3] \qquad (4.38)$$

For example, in the case of the Porto Primavera plant, it is available the following data:

- Evaporation Coefficients (*mm*):

  $ec_{Jan}= 9$ $ec_{Feb}=18$ $ec_{Mar}=27$ $ec_{Apr}=37$ $ec_{May}=68$ $ec_{Jun}=63$

  $ec_{Jul}=43$ $ec_{Aug}=37$ $ec_{Sept}=38$ $ec_{Oct}=14$ $ec_{Nov}=13$ $ec_{Dec}=10$

- The upstream level polynomial:

$$h_{up}(x) = 2{,}3917\times10^{2} + 2{,}5\times10^{-3} \cdot x - 1{,}2596\times10^{-7} \cdot x^{2}$$
$$+3{,}0481\times10^{-12} \cdot x^{3} - 2{,}5711\times10^{-17} \cdot x^{4}$$

- The reservoir's area polynomial:

$$a_{res}\left(h_{up}\right) = -4{,}8569\times10^{4} + 2{,}7949\times10^{2} \cdot h_{up} - 3{,}232\times10^{-1} \cdot {h_{up}}^{2}$$

Considering now that the reservoir in February is full, $x=14.400\ hm^3$, it is possible to determine the evaporated volume that month:

- Upstream level:

$$h_{up}(14.400) = 257\ m$$

- Reservoir's area:

$$a_{res}(257) = 1912{,}8\ km^2$$

- Evaporated volume:

$$x_{ev} = 10^{-3} \cdot 18 \cdot 1912{,}8 = 34{,}43\ hm^3$$

Considering the Furnas plant, it is possible to plot the graph of the evaporated volume as a function of the upstream level for a certain month, given the polynomials and the coefficients.

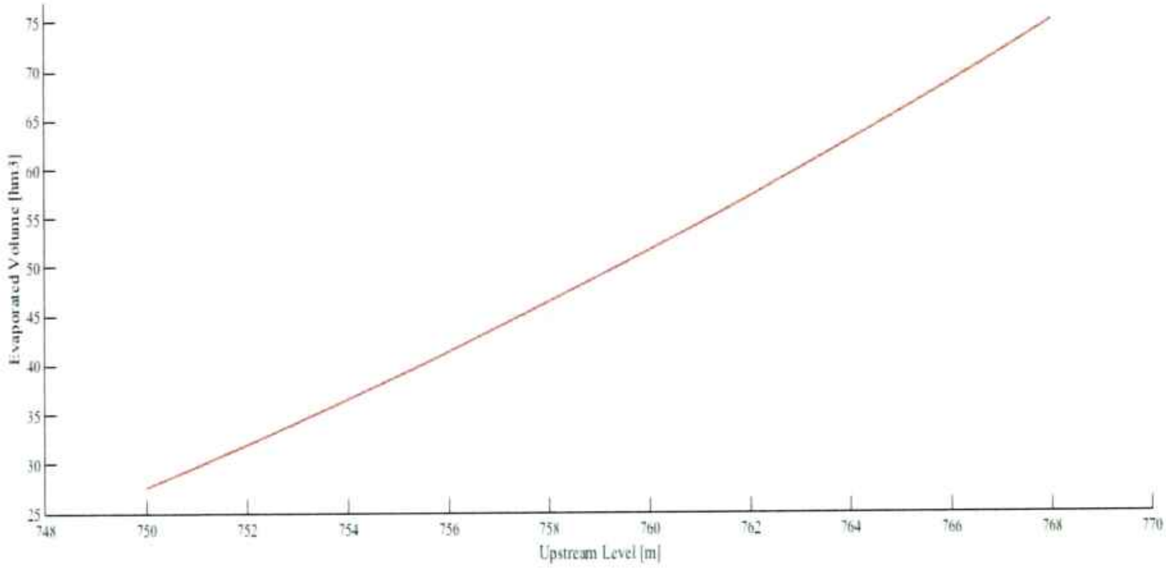

Figure 4.6 – Evaporated Volume in the Furnas plant in May

An approximation that has been made in the model was the use of the mirror area of the reservoir in the beginning of the month to calculate the total evaporated volume. This has been made to easy the converging process during the iterative process and because the model used for the evaporation losses is already an approximated model.

In the case of the study with hourly discretization, it was decided to use the average monthly loss per hour to calculate the water balance in each discretization period. So that the evaporation losses is constant for every hour of the month:

$$x_{ev}(\text{hour}) = {x_{ev}(\text{month})}\Big/{\text{days}(\text{month}) \cdot 24\text{h}} \tag{4.39}$$

4.3 Series of Inflows

The series of inflows represent the average flux of water in measuring posts in certain discretization periods. In Brazil there is a historical record of inflows upstream to the main plants of the NIS since 1931. This record is called "historical series".

The historical series show the natural water flux, that is, the inflow there would be in the dam without the influence of any other dams upstream. The historical series may be found with a monthly discretization or daily discretization. In the optimization and simulations used in this study, it will be used both.

In the first study, made to observe the influence of the EPS in the seasonality problem of the NIS was used the monthly data of the inflows, since the horizon of study was made on a monthly basis for a long period of observation.

In the second study, to see the effects the EPS could have in the correction of intermittent sources, it was used the daily data, which was then transformed into an hourly discretization, given the high variability of the wind along a day (ONS, 2013).

To be able to see the high variability of the inflow in a dam along the years, in Figure 4.7 it is represented the whole historical inflow in the Furnas dam with its average for every year. It is possible to see the variability of the inflows along the years, how due to uncontrollable factors, there may be a shortage of water such as the one observable in the 50's for example or an abundant inflow such as in the early 80's.

Source: (ONS, 2013).

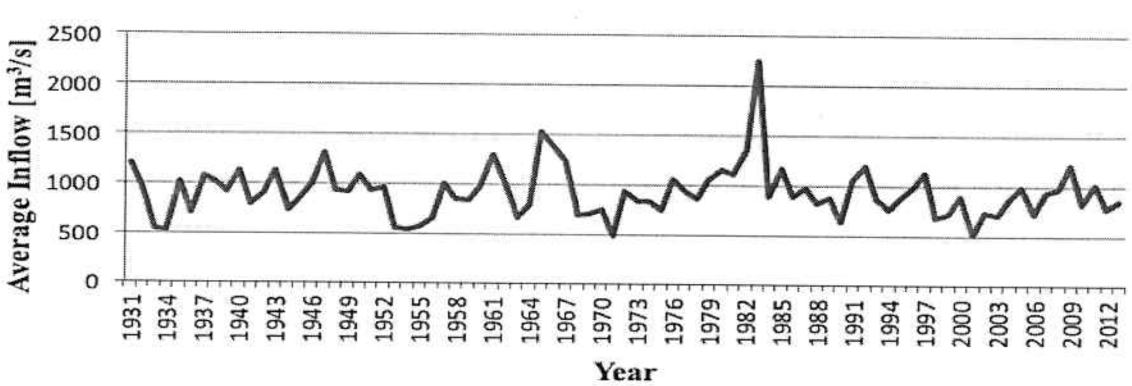

Figure 4.7 – Yearly Average inflow in the Furnas dam

The same may be done for one year to see the influence of seasonality in the inflow of the dam, for example, considering the year 1952, also in the Furnas dam, it is possible to see two very well defined seasons of the year, a wet season from January to April and a dry season in the rest of the year. Also, since this represents the natural inflow in 1952, notice, from Figure 4.7 that it was a year with a shortage of water compared to the historical average.

Source: (ONS, 2013)

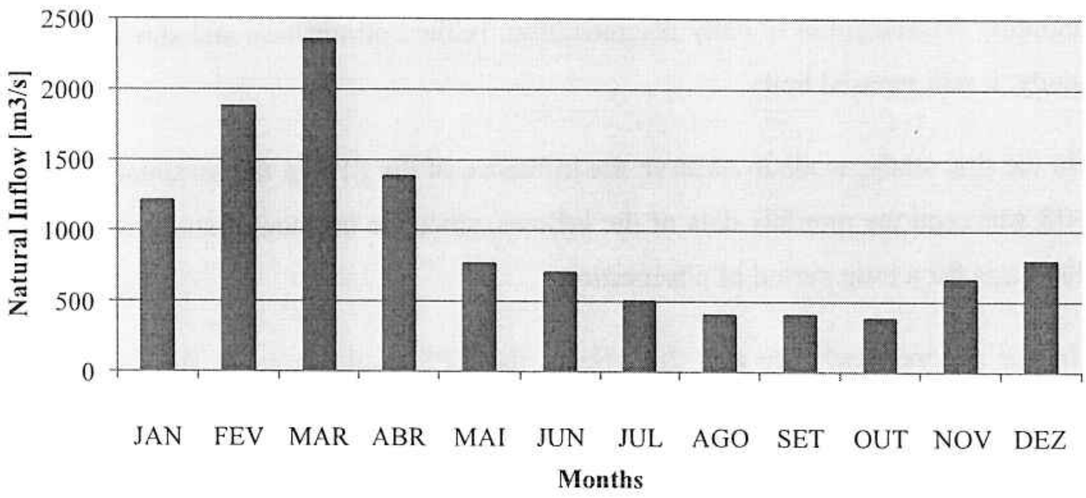

Figure 4.8 – Monthly Average inflow in the Furnas dam in 1952

In the study in case, it will be analyzed the effect of dams connected in cascade. Therefore, the total downstream flow of one dam affects the inflow of every dam in the same basin. Now will be explained how the total inflow of the downstream dams is calculated taking into account the influence of the upstream dams.

Considering a system with 4 dams such as the one in Figure 4.9, and being $y_{nat,i}$ the natural inflow in the dam i, y_i the total inflow in dam i and $y_{inc,\,i}$ an incremental inflow in the dam i. In the dams 1 and 2, there are no other dams upstream, therefore $y_1=y_{nat,\,1}$ and $y_2=y_{nat,\,2}$ and the incremental portions, $y_{inc,1}$ and $y_{inc,2}$ are null. While dams 3 and 4 depend on the downstream flow created by plants 1 and 2, if they operate as run-of-the-river, their inflow will also be equal to the natural inflow since in this case $u_1=y_1$ and $u_2=y_2$.

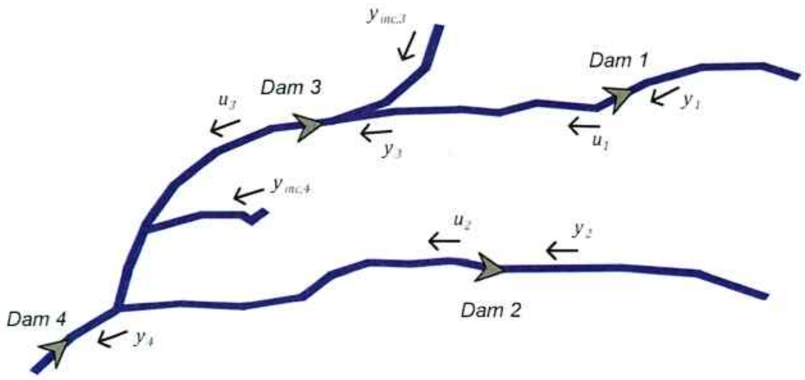

Figure 4.9 – System to calculate the incremental inflow

Since this condition is not always true, the flow y_3 may be determined as the sum of the downstream flow at dam 1, u_1, and the incremental portion of dam 3, $y_{inc,3}$. The following calculations are made:

$$y_{inc,3} = y_{nat,3} - y_{nat,1}$$

$$y_3 = u_1 + y_{inc,3}$$

Notice that the incremental flow may not be altered through the operation of the reservoirs; therefore it is called a non-controllable flow. So, dam 3 has a portion of controllable flow that comes from dam 1, u_1 and a portion of uncontrollable flow.

In dam 4, the situation is more complex because its inflow is affected by the operation of dams 2 and 3. In a general way, the inflow of any dam i, y_i, may be determined with the following equations:

$$y_{inc,i} = y_{nat,i} - \sum_{j\in\Omega} y_{nat,j} \tag{4.40}$$

$$y_i = y_{inc,i} + \sum_{j\in\Omega} u_j \tag{4.41}$$

where Ω is the set of dams upstream to dam i.

This equating was used in the Matlab model established to calculate the inflow to every dam in the system taking into account the historical data of natural inflows supplied by ONS and the reservoir operation of the upstream plants.

In the monthly analysis it is correct to say that the monthly average inflow may be calculated as explained above, however, with an hourly discretization, the inflow of a dam does not depend on the outflow of the upstream basins in the same period, but from periods before. Considering that the plants are distant from each other, it may take a few hours or days for the water going through one dam to arrive to the next downstream dam. However, in this study, it was chosen to not take into account the transit time for the water, therefore:

$$y_i(hour) = y_{inc,i}(hour) + \sum_{j \in \Omega} u_j(hour) \tag{4.42}$$

It was an approximation to simplify the iterative process, and a possible improvement to be added to this study in the future.

4.4 Variables Used In The Studies

Once it will be used a simulation using an optimization algorithm and the modeling explained in this section, there are many different variables to describe the mathematical model established for the hydroelectric plants, the inflows, turbine and spilled flows, the stored volumes, generated power, etc.

To simplify and make it clearer, in this section will be explained the main variables and their respective units:

- **Volumes**: in the model will be used the minimum, maximum and evaporated volumes, all of them expressed in hm^3.
- **Heights**: the variables such as, upstream and downstream level, liquid and gross drop, hydraulic losses are all expressed in *m*.
- **Flows**: the inflow, boosted, spilled, downstream flows are always expressed in m^3/s.
- **Power**: the variables that represent power, such as the maximum power of the plant are expressed in *MW*. However for the variables that represent the average in the discretization period are expressed in *MW.aver* or $\overline{MW}$.
- **Energy**: The variables that represent the energy, such as the stored energy in a reservoir, or the generated energy in a month are expressed in *GWh*.
- **Time**: the variables that represent time, such as the duration of the discretization periods are expressed in *s (seconds)*.

In this work, the horizon of study will be divided in intervals of same duration Δt that may be an hour or a month according to the study in matter, but always expressed in *s (seconds)*. So given an interval Δt, the flow used in it will be the average for that period, always using the standard unit adopted. The same is applied to the volumes, the evaporated volume, even though it varies in along the interval with the area of the reservoir, will be considered the average volume in the month with its respective average area to calculate the total evaporated volume.

Now considering that the variables associated to the hydric balance equation are all in average values, it is adopted that at a certain time *t*, the volume stored in the reservoir $x(t)$ will refer to the volume in that reservoir in the beginning of that interval. Therefore to calculate the volume after one step Δt, it is used the following equation:

$$x(t+1) = x(t) + \frac{\Delta t}{10^6} \cdot (y(t) - u(t)) - x_{ev}(t) \tag{4.43}$$ [6]

$$u(t) = q(t) + v(t) \tag{4.44}$$

The Equation 4.43 says that the volume stored in the beginning of interval *t+1* will be equal to the volume in the beginning of interval *t*, plus the difference between the average values of how much water inflows to the plant and how much flow out of the plant plus the lost volume due to evaporation. This way the volumes in the beginning of each interval may be determined based on the average flows in the intervals Δt.

While Equation 4.44 says that the outflow of a dam is given by the sum of the boosted flow that goes through the turbines and the spilled flow.

[6] The factor $\Delta t/10^6$ is present due to the conversion of water flow, expressed in m^3/s to volume units, expressed in hm^3.

4.5 The Pumped Storage Plants Model

To model a PSP inserted in the system according to Figure 3.7, it was used the same structure presented in the sections before. However, due to their inexistence, there weren't available data such as polynomials or evaporation coefficients.

It was decided, considering the focus of this work, to approximate its model using the same evaporation coefficients as the ones available for the lower reservoir given its proximity. Therefore, PSP called Canastra used the same evaporation coefficients from Furnas and PSP Catalão used the same from Serra do Facão.

As for the polynomials, since it is not the scope of this work to establish a geological model of the vale in which they would be built, it was decided to use a rough approximation with a first-degree polynomial for both the area of the reservoir, and for its height. To do so, it was considered that both wouldn't have any dead volume, and that the flooded area indicated on Table 3.3 is with its respective maximum storage volume.

To illustrate better, in Figure 4.10 there is a representation of how Canastra reservoir would be, the same logic can be applied to the Catalão reservoir with its respective data.

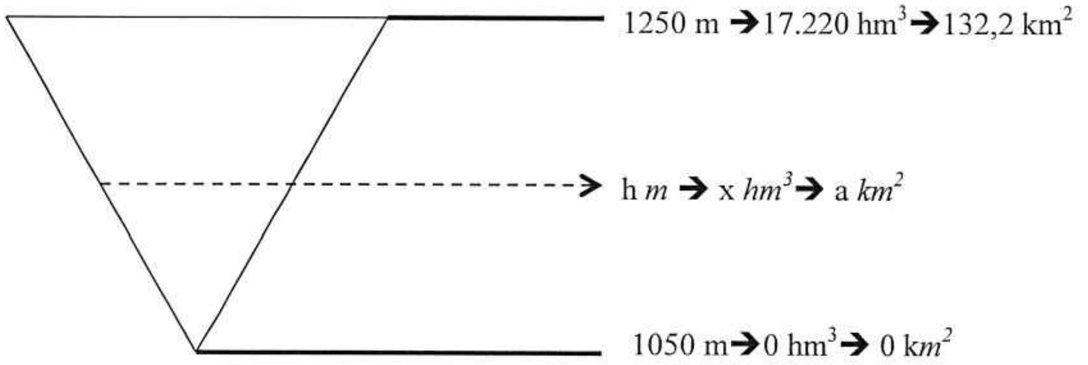

Figure 4.10 – Geometric model of the Canastra PSP

So, the polynomials established for the Canastra EPS were:

$$h_{up}(x) = 1{,}05\times10^{3} + 1{,}16\times10^{-2}\cdot x \quad (4.45)$$

$$a_{res}(h_{up}) = -6{,}9405\times10^{2} + 6{,}61\times10^{-1}\cdot h_{up} \quad (4.46)$$

While for the Catalão EPS, considering a maximum height of *950 m* with a respective area of *228,79 km²* and volume of *5.220 hm³*, and a minimum height of *900 m* with no volume in the reservoir or flooded area, the following polynomials are established:

$$h_{up}(x) = 900 + 9{,}578\times10^{-3} \cdot x \tag{4.47}$$

$$a_{res}(h_{up}) = -4{,}1184\times10^{3} + 4{,}576 \cdot h_{up} \tag{4.48}$$

Another consideration made about the EPS plants, was the limiting of the flows in the plants. To do so, it was used the equations (4.49) and (4.50) with the maximum power established by (HUNT, 2014) and maximum drop to calculate the maximum flow for each EPS. The generation efficiency was established at an approximate value of η_{gen_pump} = *91%* for the Catalão plant and η_{gen_pump} = *89%* for the Canastra plant taking into account an average from existing PSP in the world while the pumping efficiency was considered η_{cons_pump} = *85%* for both plants.

The generation function of the pumps is shown in Equation 4.49 while the power consumed for pumping is shown in Equation 4.50.

$$p_{gen_{pump}} = \frac{9{,}81 \cdot \eta_{gen\_pump} \cdot \Delta h \cdot q_{pump}}{10^3} \text{ [MW]} \tag{4.49}$$

$$p_{cons_{pump}} = \frac{9{,}81 \cdot \Delta h \cdot q_{pump}}{10^3 \cdot \eta_{cons\_pump}} \text{ [MW]} \tag{4.50}$$

For its generation maximum power was established the same, since it is proportional to the flow that goes through its turbines, it was decided to leave it as previously considered in Section 3.3, *5.500 MW* for the Canastra EPS and *400 MW* for the Catalão EPS but it could be sized through another optimization process considering the financial factors to dimension it. The same was considered for the pumping maximum power.

Also, considering that the water flow goes into or out of the EPS, it's been adopted the following referential:

$$\begin{cases} \text{pump flow} > 0 \rightarrow \text{Fill} \\ \text{pump flow} < 0 \rightarrow \text{Empty} \end{cases} \tag{4.51}$$

Through Equations 4.49 and 4.50, it is possible to see that according to the referential used in the study, the power consumed will be negative, once the pump flow is also negative, meanwhile, the power generated will always be positive, so it can be added to the total generation of the system.

5 WIND FARMS MODELING

In this chapter will be explained basic theoretical concepts regarding the wind power generation, as well as the locations and specific data for each wind farm that is later used in the simulation with hourly discretization.

5.1 Theoretical Principles of a Wind Farm

The electrical energy generation from a wind farm works through the transformation of kinetic energy from a moving mass of air into mechanical energy in the axis connected to the rotor of a wind turbine. Therefore, the first step into determining the power generated in a wind farm consist in knowing the amount of energy that comes with the wind, then, the transformation of kinetic energy into mechanical energy depends on the aerodynamic profile of the blades. After that, the energy generator located in the wind turbine is responsible for converting the mechanical energy into electrical energy.

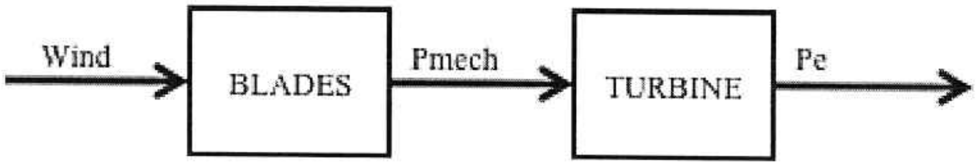

Figure 5.1 – Wind Conversion to Electrical Power

It is evident that the efficiency of a wind farm is mainly connected to its capability on absorbing the kinetic energy from the air and converting it into mechanical energy. For that, it is important to comprehend all the distinct forces that are induced in the components of a turbine, which greatly depend on the average speed of the wind.

According to (FADIGAS, 2011), the power contained in the wind is given by:

$$P = \frac{\rho \cdot A \cdot v^3}{2} \qquad (5.1)$$

where:

- ρ is the specific mass of the air given in kg/m^3;
- A is the capture area of the wind, given in m^3;
- V is wind speed, given in m/s;

However, not all the kinetic energy is transformed into mechanical energy, according to the continuity equation, it is possible to verify that the maximum energy that may be extracted from the wind into the turbine axis is *59,3%*, which corresponds to the theoretical power coefficient, *Cp*.

$$P_{mech} = \frac{\rho \cdot A \cdot v^3}{2} \cdot Cp \tag{5.2}$$

But considering that the efficiency of the conversion is always smaller than a theoretical value, since it depends on many physical characteristics of the blades and turbine, the value used for *Cp* is always smaller than 59,3%.

Then the electrical energy generation, it must be considered the set turbine and generator efficiency, given by η.

$$P_e = \eta \cdot \frac{\rho \cdot A \cdot v^3}{2} \cdot Cp \tag{5.3}$$

To maximize the electrical power generation, the wind turbines operate in a way to maximize *Cp*, having the blade tip speed (λ) and blade angle (β) in an optimal operation point. Another important factor is the wind density and its variation along the seasons of the year, as well as the turbine height. For that, the wind turbine manufacturers provide the power curve for different air densities.

Each wind turbine is designed to maximize the electrical energy generated from the wind kinetic energy. The maximum electrical energy generated is denominated henceforward as the nominal power of the wind turbine, and the wind speed in which it is achieved is known as the nominal wind speed. Usually, the wind nominal speed is between *12 m/s* and *15 m/s*.

To begin generating energy, the turbine requires a minimum wind speed known as cut-in speed ($V_{cut\text{-}in}$) that is usually around *2,5* to *3 m/s*. The turbine also has a maximum speed in which it can work, known as the cut-out speed ($V_{cut\text{-}out}$), around *25 m/s*, if a turbine operates at a wind speed higher than the cut speed, it may damage the generator due to the mechanical loads that will arise.

Considering the physical limits of an air generator, each manufacturer is able to plot the performance characteristic curve given by the graph "wind speed x output power", also known as the power curve of the wind generator.

5.2 Wind Resources Evaluation

The main variable to evaluate to know a wind potential in a region is the wind speed, and with a good knowledge of wind characteristics, it is possible to predict with a high precision the average wind generation profile prior to the operation giving a high operative security as well as maximizing the electrical energy production.

There are a lot of factors that influences the wind profile in a certain region such as geography, terrain roughness, temperature, atmospheric pressure, relative humidity, air density and the measurement height. All these factors must be considered to evaluate the wind productivity of a certain farm and to optimize the position the air generators, as well as choosing for the best turbine in the known conditions.

In this work will be considered certain wind farms where it was already decided for the optimal model of the turbine as well as its placement (WITZLER, 2015), not being the aim of this work to optimize the placement and evaluation of wind resources.

5.3 Wind Generation Function

There are many ways to determine the electrical energy generation from a wind farm. It may be done through:

- A series of measurement data;
- The histogram of wind speed;
- Statistical techniques;

In this work will be used a series of wind speed data, where it was either measured or reconstructed based in the local characteristics of the site, such as the wind direction, humidity, pressure and temperature (WITZLER, 2015) and then deterministically.

To calculate the average electrical power generated given by a series of *N* data of average wind speed in an interval Δt, it is used the Equation 5.4.

$$\overline{P_e} = \frac{1}{N} \cdot \sum_{i=1}^{N} P_e(v_i) \tag{5.4}$$

where $P_e(v_i)$ is the electrical power in function of the wind speed extracted from the power curve of the wind turbine.

Considering the discretization period Δt, it is possible to calculate the energy generated:

$$E_g = \frac{1}{N} \cdot \sum_{i=1}^{N} P_e(v_i) \cdot \Delta t \tag{5.5}$$

A wind farm however, may have many turbines so that altogether they have a certain amount of installed power. Each turbine has a certain factor of losses, that the manufacturers establish at an acceptable level of *5%*. Besides that, there are other losses factors between the energy generation in the turbine and the energy injected in the grid. Therefore, the energy generated in a farm, measured in the substation is not equal to the sum of energy of each turbine.

To be added to the losses there is also the availability factor of the farm, usually between *97%* and *99%* so that the annual generation is lowered by it. The unavailable period of the plant refers to hours in which it is under maintenance for preventive or corrective measures.

This way, the annual energy generated by a wind farm may be calculated by the following equation:

$$E_{g(year)} = \sum E_g(hour) \cdot AF \cdot (1 - losses) \cdot NT \tag{5.6}$$

where:

- AF is the availability factor
- NT is the number of turbines

Another way to determine the generated energy is considering the capacity factor of a wind farm, *CF*.

$$E_{g(year)} = P_n \cdot CF \cdot 8760 \text{ [MWh]} \tag{5.7}$$

where *8760* is the number of hours in a year and P_n is the nominal power of the wind farm.

The capacity factor indicates the effective generation potential of the farm. It is defined as the ratio between the energy effectively generated, also known as physical guarantee, and the maximum energy it could be generated in case the turbine always generated its nominal power. So, the *CF* can be defined by:

$$CF = \frac{E_g(year)}{P_n \cdot 8760} = \frac{P_{avg}}{P_n} \tag{5.8}$$

5.4 Wind Turbine Data

For the calculation of wind generation, it was used a class of wind turbine for four different wind farms to arrive to a generation profile in p.u.

The turbine used was a V100 2.0 MW – Class II from the manufacturer Vestas. The technical characteristics are shown on Table 5.1.

Table 5.1 – Technical Data of the Wind Turbine

Turbine V100 2.0MW		
Nominal Power	[MW]	2
Cut-In	[m/s]	3
Nominal Speed	[m/s]	12
Cut-out	[m/s]	20
Frequency	[Hz]	60
Blades		
Length	[m]	49
Tower		
Height	[m]	125

This wind generator possesses an induction generator with nominal power of *2.000 kW* and the following power curve.

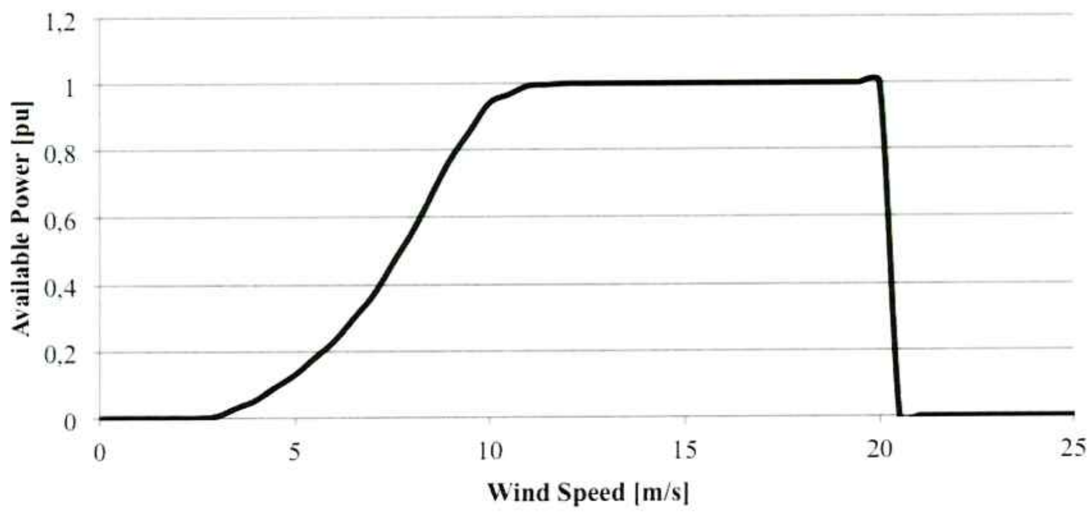

Figure 5.2 – Power Curve of a V100 Wind Turbine

5.5 Region of Study

Based in the Brazilian wind potential, it was decided to use four distinct regions to base the wind farms. On Figure 5.3, the yellow dots represent the wind farms already existent and the projects for the next auctions, located in the Brazilian territory.

Figure 5.3 – Wind Farms distribution in Brazil

That considered, the four locations for the wind generation profile study are located in the states of Ceará, Rio Grande do Norte, Bahia and Rio Grande do Sul. Each region already has a certain power installed as it can be seen on Table 5.2.

Table 5.2 – Current Installed Power in each region

State	Power [MW]	Physical Guarantee [MW.avg]
RN	2.752,05	1.416,1
CE	1.806,93	727,69
BA	1.602,27	869,62
RS	1.405,8	603,83

In the study however, it won't be considered the current potential, but the future predicted expansion of the wind source of energy in the Brazilian energy matrix. Therefore, it was considered the wind data from four different fields, one in each state, and the total installed wind power equal to a multiplying factor of the total hydro installed power.

The fields used for the study and its respective coordinates are given bellow.

Table 5.3 – Fields of Study

Field	State	Coordinates		Name
1	CE	-3,42295	-39,042664	Paracuru, Ceará, Brazil
2	RN	-5,088892	-36,549969	Macau, Rio Grande do Norte, Brazil
3	BA	-11,536543	-41,157532	Morro do Chapeu, Bahia, Brazil
4	RS	-30,86451	-55,725403	Coxilha Negra, Rio Grande do Sul, Brazil

It was considered that the total installed wind power was about *20%* of the total hydroelectric power based in generous consideration on the future expansion scenario of the Brazilian energy matrix. Considering that in the system under study, the total nominal power of the conventional hydroelectric plant is *33.788 MW*, it was used a total wind installed power of *3.378 MW*. Then, this nominal power was divided among the four fields proportionally to the current power on each state, arriving to the resulting installed power per field. After that it was considered a constant capacity factor equal to the current value, arriving to the field's physical guarantee, according to Equation 5.9.

$$CF = \frac{\text{Physical Guarantee [MW]}}{\text{Installed Power [MW]}} \tag{5.9}$$

Applying the Equation 5.9 to each field's nominal power, it is possible to arrive to the following data.

Table 5.4 – Power Data for each Field

Field	Power (MW)	CF	Physical Guarantee (MW)
1	1.229	0,51	632,16
2	807	0,40	324,85
3	715	0,54	388,21
4	628	0,43	269,56

Then, using the wind data for each field in a certain period (WITZLER, 2015) it is possible to trace the generation profile of each field given the power curve of a wind turbine. Since the total wind power installed is a variable, it was decided to use the generation profile in p.u. based in the plant's physical guarantee.

Since the intention is using the total wind generation profile, the four profiles were added altogether to trace the final wind generation profile in the period under analysis.

Using an hourly discretization, totalizing *8760* points, it was traced the following wind profile for the year 1991.

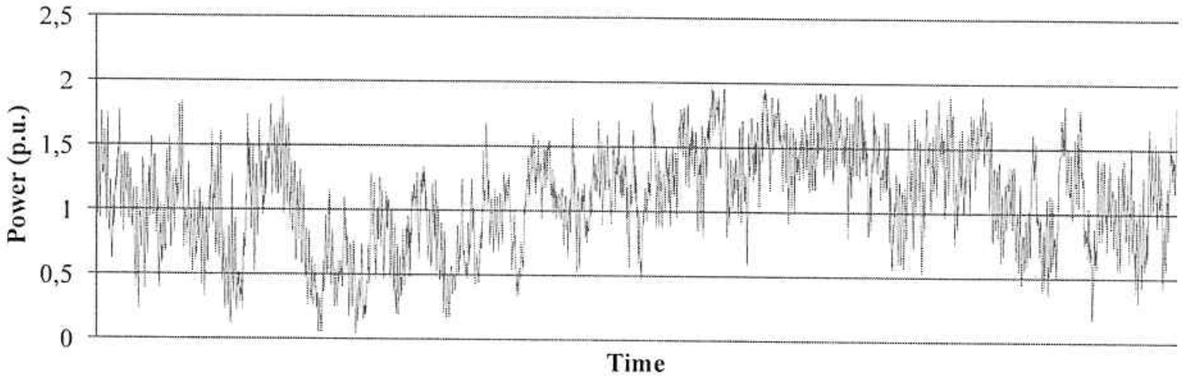

Figure 5.4 – Wind Profile in the year 1991

Dividing the wind profile between each field, it arrives to:

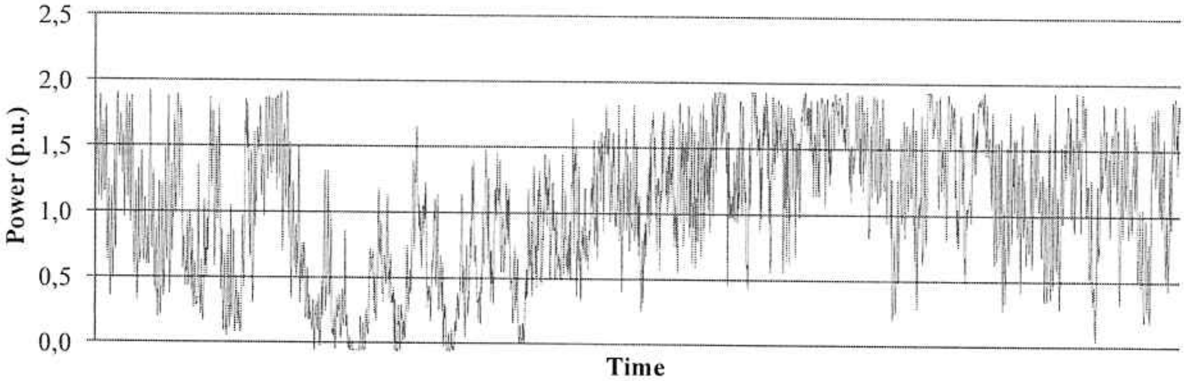

Figure 5.5 – Wind Profile in Paracuru (CE) in 1991

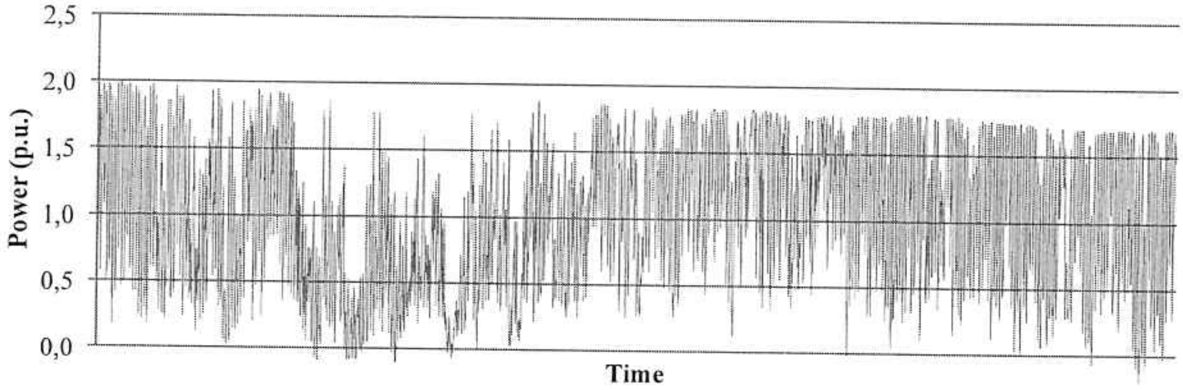

Figure 5.6 – Wind profile in Macau (RN) in 1991

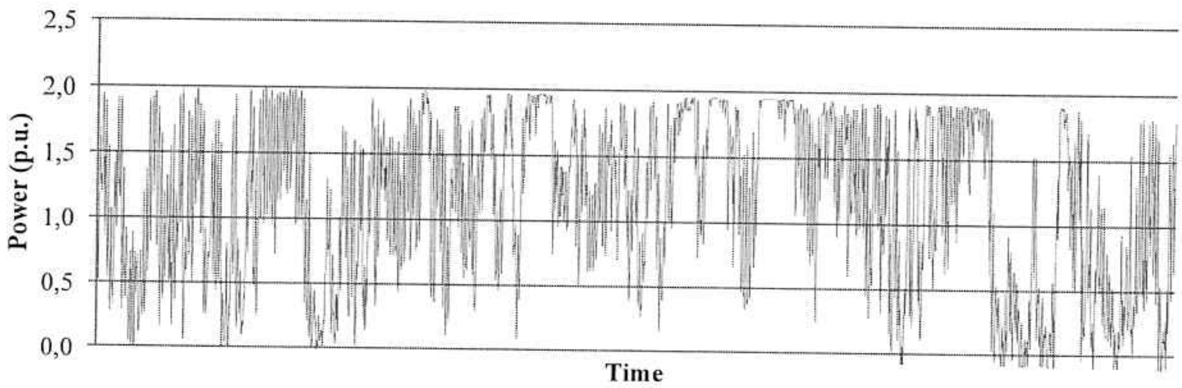

Figure 5.7 – Wind Profile in Morro do Chapéu (BA) in 1991

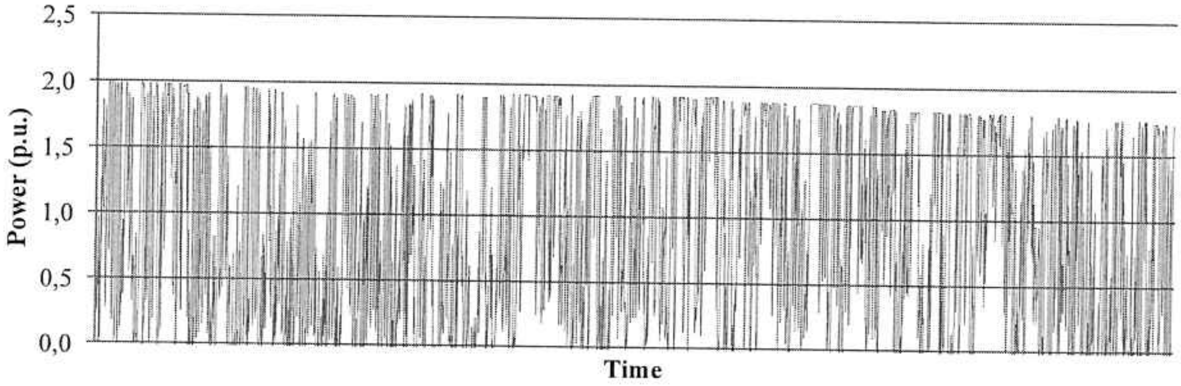

Figure 5.8 – Wind Profile in Coxilha Negra (RS) in 1991

Remembering that the graphs are in function of the physical guarantee of each field. The same procedure could be traced for any year between 1940 and 2010. During the study, other years may be used where indicated.

6 SIMULATION AND OPTIMIZATION

Nowadays with the great expansion of computers and the constant development of better and faster processors, the computer simulation and optimization has become an essential tool in almost every field of work. Many professionals, from doctors to artists, to have better and faster results in studies or to automatize any task, largely use it.

Simulations made by computers are basically a routine that following a series of rules and constraints have to supply a final result given the initial conditions. This is the model established in Chapter 4, where given a set of entries to the system, it should supply the final result that in the case under study is the energy generation in the period under study. Remembering that since it is required an iterative process to arrive to final results, the computer is essential to accelerate the process, since for large systems it unviable to do the calculations otherwise.

Together with simulation routines it is common to write an optimization algorithm that is capable of giving the best result given an unknown variable as entry that also has to be determined. For example it may be used to dimension a hydroelectric plant given an objective function that could be the energy generation, or the best financial scenario, considering the revenue it would generate and the initial investment it is required.

The optimization algorithms are particularly useful considering complex problems with non linear equations that don't have direct answers. However it is important to know that many optimization algorithms not necessarily supply the best result possible, but they give very efficient results what so ever.

In this work will be used an optimization process known as Genetic Algorithm that gives the best local result for a certain period of simulation. This algorithm and how it was applied in this study is explained in Section 6.1.

In Brazil, many companies have developed very efficient simulation tools together with optimization algorithms such as MSUI and Newave. However, it was necessary to completely build a new tool to allow the insertion of pumped facilities, which do not exist in the current context. Besides, a self-written tool allows a better manipulation of simulation conditions, creating a powerful way to apply it in the context under study.

It was chosen to use the software Matlab as a platform to write the model given the previous knowledge of the platform and the amenities given the pre-existing functions in the platform. Also since the problem is a complex system composed by non linear equations, it was also easier to rewrite the genetic algorithm than use the built-in tool available by the software.

6.1 The Genetic Algorithm

6.1.1 Introduction

Genetic algorithm is a heuristic search based in the process of natural evolution; it is largely used in search and optimization problems. It is part of a class of algorithms named Evolutionary Algorithms (EA) that finds its solution using natural evolution techniques such as inheritance, mutation, crossover and selection.

In EA, there is an initial population of possible solutions that may be generated randomly, called first generation. This population consists of a pre-determined number of individuals that contains a set of properties (chromosomes) that are going to be evaluated. In the iterations, it will produce an exit for each individual that is the value of the objective function; it may be a maximization or minimization objective function depending on the case under study.

After calculating the objective function, also known as fitness, for every individual in the initial population, the first generation goes through a recombining process where it is subject to the genetic operators: inheritance, selection, crossover and mutation. After that, the fitness for the new generation formed will also be calculated and so on iteratively until the stopping criteria is achieved.

In the Genetic Algorithm (GA) that was developed, it was decided to use a selection method called Biased Roulette Wheel Selection. It consists on creating a roulette wheel where the probability of selecting a certain individual for the next generation depends on its fitness value, so the better the result of an individual, greater the probability of selecting him for the next generation because the size of its respective slice is also bigger, but noticing that any individual may be selected. To visualize the idea of the selection, in Figure 6.1 it is represented the same idea in the form of a cumulative curve of weighted values associated with each discrete position considering a population of M individuals.

So a random number r is picked from an uniform probability distribution in $[0,1]$ and entered in the Cumulative Distribution Function (*CDF*) axis picking the corresponding discreete position on the horizontal axis and its respective individual where the variable ψ

represents the normalized fitness value of individual *m*. (CHICCO, 2010), This way, the chosen individual may be present in the next generation.

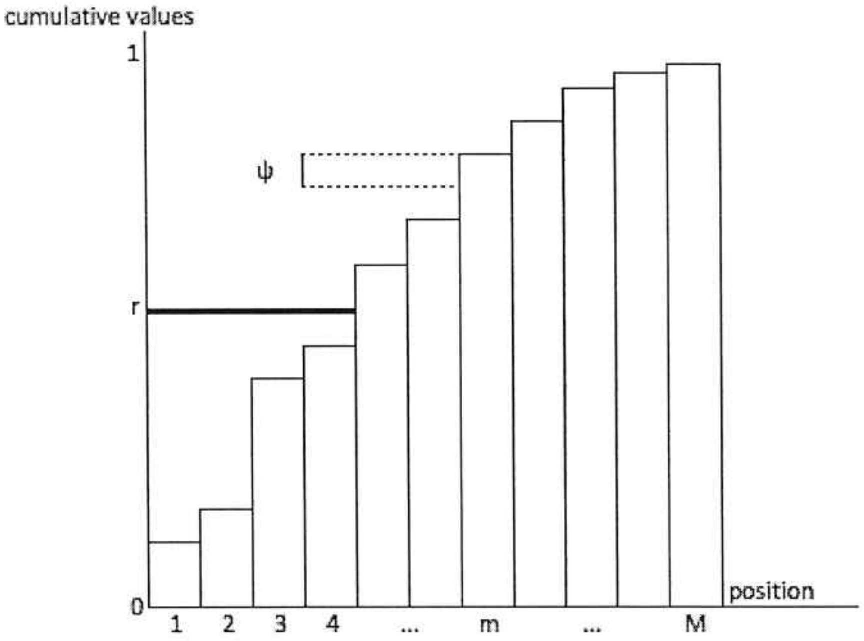

Figure 6.1 – Roulette wheel selection from a cumulative distribution

Once the individuals that are going to be part of the next generation are selected (beware that a same individual may be selected more than once), they go through the genetic operators (crossover and mutation) to create the next generation. To easier visualize the operations, it will be used a set of binary strings, and in the next subsection will be explained exactly how it was applied in this work. First important thing is that for each operator, there is its respective probability of occurring, $p_{crossover}$ and $p_{mutation}$, and it is an entry of the simulation.

Crossover is an operation between a pair of chromosomes next to each other. It will happen only if a random number r extracted from a uniform probability distribution in $[0,1]$ is smaller than the crossover probability, $p_{crossover}$. If this condition is satisfied, a point of the chromosome is picked and their branches are exchanged, like in Figure 6.2.

Figure 6.2 – Crossover

Mutation operation is an exceptional event in natural reproduction of species; it is when a gene is transformed, sometimes for no apparent reason and it has a low probability of happening. In the algorithm, it works similarly to the crossover operation. A random number r is extracted from a uniform probability distribution in *[0,1]* and if it is smaller than the mutation probability, $p_{mutation}$, the gene is mutated to a new random element, or in a binary example, it will be inverted:

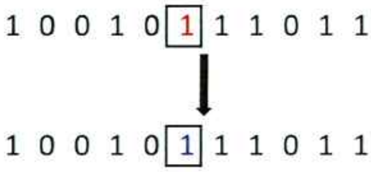

Figure 6.3 – Mutation

There are other operators that could be used in the GA as well, but in this work will only be used the three described above: selection, crossover and mutation. In each iteration, the individual with the best objective function is compared to the one in previous generations, updating the overall best individual in case of an improvement and storing its data since it is the best result so far.

A stop criterion that may be used, considering that the fitness value desired is unknown, is the total maximum number of iterations and the maximum number of iterations with no improvement. Meaning that as an entry to the GA there is an absolute maximum number of iterations it may calculate, n_{MAX}, and another smaller number that if after n_{no_improv} iterations, no better results were found, the algorithm also stops giving the optimal result found until that point.

6.1.2 Genetic Algorithm Applied in the Study

The system under analysis is composed of twenty-three hydroelectric plants, being eleven run-of-the-river dams, ten with conventional reservoirs and two EPS. Knowing that the main objective of this work is to study the effects of an EPS in the generation profile, the unknown variable is the average water flux in an interval Δt in each pumped storage facilities; therefore they compose the individuals of the population.

Considering that there will be two distinct study cases, first with a monthly discretization and second with an hourly discretization, each population will be composed by parameters of each EPS and the water flux going into each reservoir in each period. Therefore, considering a horizon of study of Y years, M months, D days and H hours, in case of an hourly discretization, and a population composed by N individuals, it will be represented through a matrix $[N \times Y \times M \times D \times H \times EPS]$. In case of a monthly study, the only difference is that it will be a four dimensions matrix $[N \times Y \times M \times EPS]$. From now on, when mentioned a variable in a period t of the study, it will refer to the time coefficients of each study, so, in the hourly study, it will refer to the year, month, day and hour of that study, and for the monthly study, it will refer to its current year and month.

	1	**2**	**...**	**h**	**...**	**24**
EPS 1	*pop(n,Y,M,D,1,1)*	*pop(n,Y,M,D,2,1)*	...	*pop(n,Y,M,D,h,1)*	...	*pop(n,Y,M,D,24,1)*
EPS 2	*pop(n,Y,M,D,1,2)*	*pop(n,Y,M,D,2,2)*	...	*pop(n,Y,M,D,h,2)*	...	*pop(n,Y,M,D,24,2)*

Figure 6.4 – Format of the individual n in the population under study in the year Y, month M and day D

The variable *pop* however, does not give the absolute flow in the pumps, but a coefficient that multiplies the arriving water flow in the dam of the lower reservoir in the period under analysis, Furnas in case of the Canastra EPS (EPS 1) and Serra do Facão in case of the Catalão EPS (EPS 2), given by a variable Y. So the average flow in t for an individual n is given by:

$$\begin{cases} \text{Pump flow}(t,1) = \text{pop}(n,t,1) \times Y(t,\text{Furnas}) \\ \text{Pump flow}(t,2) = \text{pop}(n,t,2) \times Y(t,\text{S. Facao}) \end{cases} \tag{6.1}$$

To generate the population it was used the *rand* function from *Matlab* so that the variable *pop* belongs to the interval *[0; 0,5]*. However, considering that there are dry months when the sense of the water flow in the pumps should invert as well as peak hours for the load along a day, it comes multiplied by *(-1/0,5)* so that it belongs to the interval *[0; 1,0]* like shown in Figure 6.5.

```
for i  = 1 : size(pop,3)
     if ismember(i,dry)==1
          pop(:,:,i,:,:,:) = pop(:,:,i,:,:,:)*(-1/0.5);
     end
 end

 for i = 1 : size(pop,5)
     if ismember(i,Peak_hours)
         pop(:,:,:,:,i,:) = abs(pop(:,:,:,:,i,:))*(-1);
     else
         pop(:,:,:,:,i,:) = abs(pop(:,:,:,:,i,:));
     end
 end
```

Figure 6.5 – Code with the dry period and peak hours consideration for the population

It is important to notice however, that during the simulation, coefficients may be changed and overwritten based on constraints of the system's model to optimize the water use in the system and attend the demand of energy.

When applying genetic operators of crossover and mutation, it was chosen to pick one random point of crossing in each dimension of the population using the *Matlab* function *randi* that gives a random integer, then, after verifying the success of crossing such as described in Section 6.1.1, a branch exchange is made. The code for the crossing operation with a six dimensions matrix, used in the Hourly Analysis is shown in Annex A within the Genetic Algorithm written.

For the mutation operation, it was decided to verify its occurrence for every bit of every individual, if an extracted random number r is smaller than $p_{mutation}$, that bit will be overwritten by a new number created exactly like the initial population, through the *rand* function. The code written for the mutation operation, taking as base the hourly analysis with a six dimensions matrix is shown in Annex A within the GA written.

In the system under study, the objective function is to maximize the energy generated and stored in the end of the period under analysis as well as minimize the spillage of water.

$$E_{balance}(t) = \sum_{t=1}^{T} E_{generated}(t) + E_{stored}(t+1) - \sum_{t=1}^{T} E_{spilled}(t) \tag{6.2}$$

$$E_{generated}(t) = E_{gen}(t) - E_{load}(t) \tag{6.3}$$

$$E_{stored}(t+1) = \sum_{j\in\Theta}^{N} \left\{ Vol_j(t+1) \cdot 9{,}81\times10^3 \cdot h_{j_{up}}(t+1) - E_{j_{dead-volume}} \right\} \tag{6.4}$$

where Θ represents the set with all the hydroelectric plants with conventional reservoirs in the system and the EPS.

Also, considering the possibility of not attending or exceeding the demand of energy within a precision figure ε, it was defined a different penalization for each case.

$$\begin{cases} \text{if} \left|E_{generated}(t)\right| < \varepsilon \rightarrow E_{generated}(t) = 0 \\ \text{if } E_{generated}(t) < -\varepsilon \rightarrow E_{generated}(t) = E_{generated}(t)\times1\times10^{20} \\ \text{if } E_{generated}(t) > \varepsilon \rightarrow E_{generated}(t) = E_{generated}(t)\times0{,}25 \end{cases} \tag{6.5}$$

Through this penalization, it is possible to represent the additional cost that comes when the load cannot be supplied with the system under analysis, and in the case of not existing another source of energy; it is needed to cut part of the load. Observe that when the load isn't satisfied, $E_{generated}$ will be a negative figure, that through the penalization becomes more negative and when generation surplus the load, the benefits that comes from it is smaller given the uncertainty of the existence of an exceeding load in a near system that could absorb the power surplus. This will be shown better in Chapter 1 that presents the simulation results.

Now to normalize the fitness function for each string, $i=1,...N$, to use in the bias roulette wheel selection described in the section before, since the objective is maximization, it becomes:

$$\psi_i = \frac{\sum_{t=1}^{T} E_{balance_i}(t)}{\sum_i^N \sum_{t=1}^{T} E_{balance_i}(t)} \tag{6.6}$$

In every iteration, the fitness function is calculated and based in a bias roulette wheel selection, and then applied evolutionary operators, the next generation is built so that a new iteration begins, repeating all the process. In Figure 6.6 it is possible to see the whole iterative process applied in the study, considering the output of the model, and the GA used.

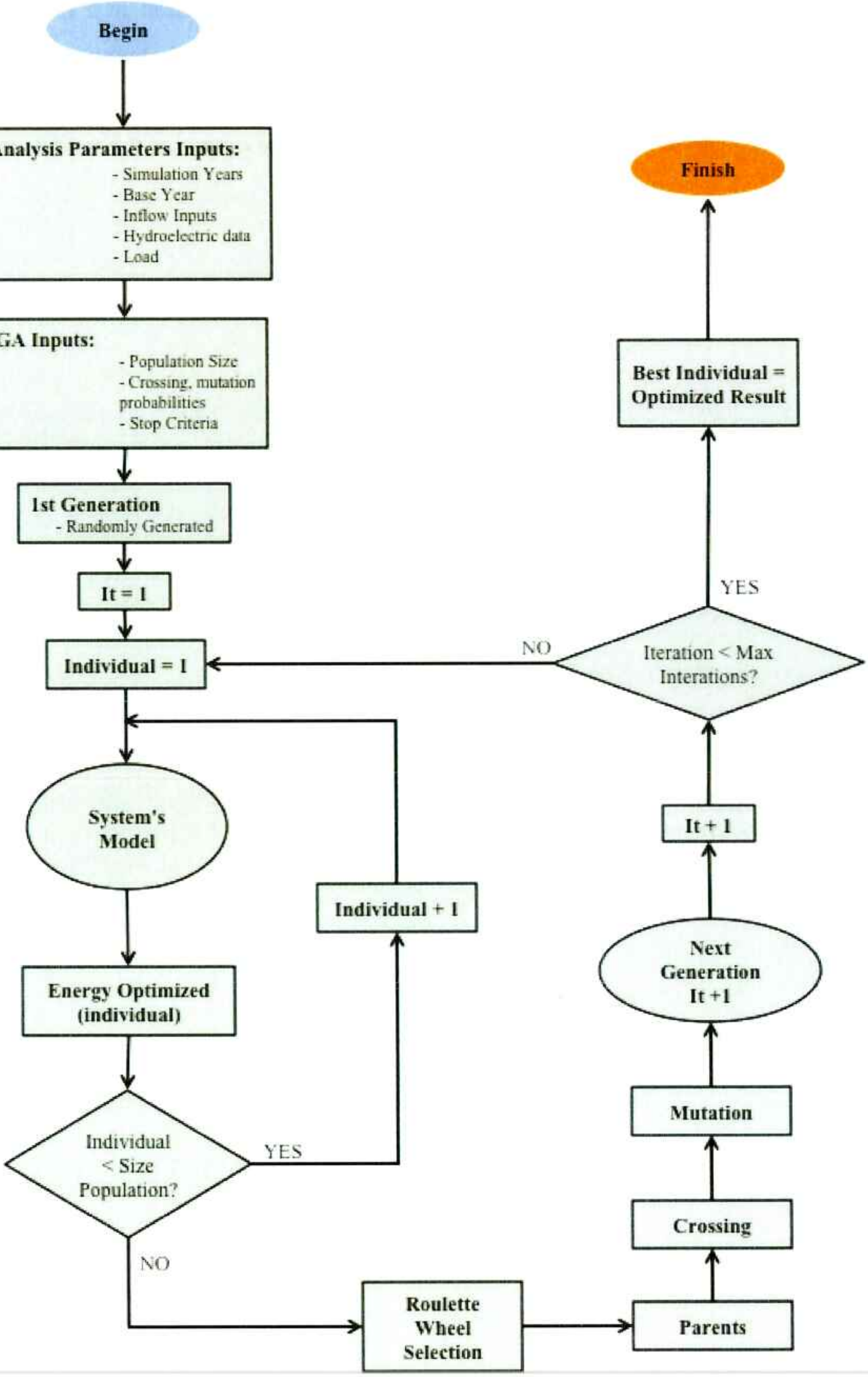

Figure 6.6 – Block Diagram with the GA applied in the simulation

In the next section will be explained all the simulation process applied to the modeling described on Section 4, which is inserted inside the block "System's Model" from Figure 6.6.

6.2 Simulation Model in the Seasonal Analysis

During the study it will be used two different time basis for the analysis, a monthly discretization for a seasonal analysis and another hourly discretization to deeply simulate the effects of the intermittency of wind energy in the system's generation. In this subsection it will be explained the procedure for the seasonal analysis with monthly discretization, while in Section 6.3 it will be explained the modifications implemented to habilitate an hourly analysis with incorporation of wind farms.

Considering the model established in Section 4, where a generation function was built based in water flows that go through the dam and the reservoir volume, it allows to determine the power generated in each plant during the period under study. However, to do so, it is necessary to know the values of the water fluxes.

To represent the hydraulic system of the study, a few considerations are made:

i. Each plant is represented individually, so that its modeling data matches its real physical characteristics;
ii. The system is considered static, so that over the simulation time, the installed capacity of the system and the demanding loads are always equal.
iii. The system is modeled under a single busbar, so that it looks as if all the generation units were connected to one single knot in which was concentrated the entire load. This way the transmission restrictions are not taken into account.

For every simulation, it must be provided a certain load to which the system is connected. It was decided to use a range of different loads to see the behavior of the system in each case. To facilitate, given the size of the system, it was decided to use a load in terms of the installed nominal power of the whole system under study, for example, a load of *50%* of P_{nom}, remembering that it is being used the average power during a certain discretization period.

The focus of this simulation is to calculate the water fluxes in each dam including the pumped reservoirs, so the demand is met. There are infinite ways to do so, because a different water flux in an upstream dam implicates in a different water flux on every downstream dam and therefore on a different generation profile in every plant downstream. In Figure 6.7 it is represented the block diagram that shows the variables use as inputs in the study as well as the optimized variables. The pumped flow here is considered linked to the inflow of the plant, as entry for the optimizable variable, which is the downstream flow in each plant.

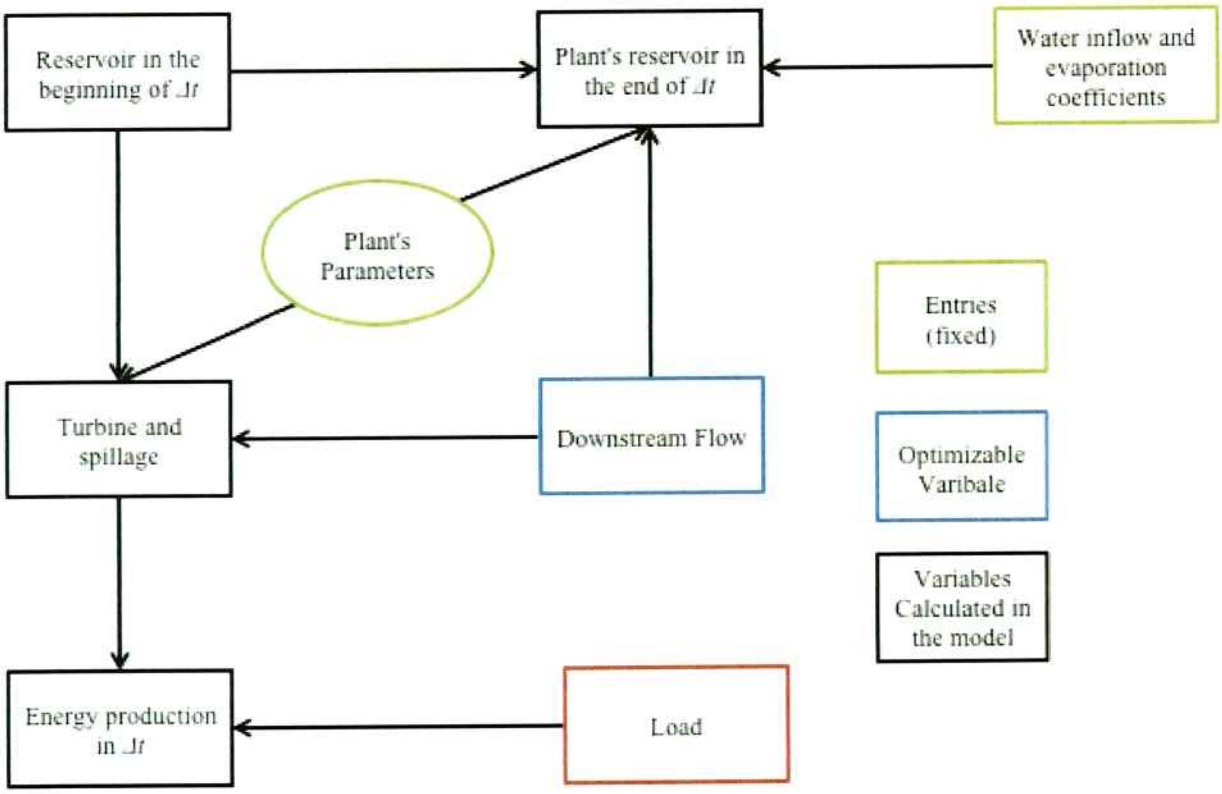

Figure 6.7 – Block diagram of the simulation and optimization process in the Seasonal Analysis

There are five different operational conditions that must be supplied to the simulation model. The process is expressed in Figure 6.8.

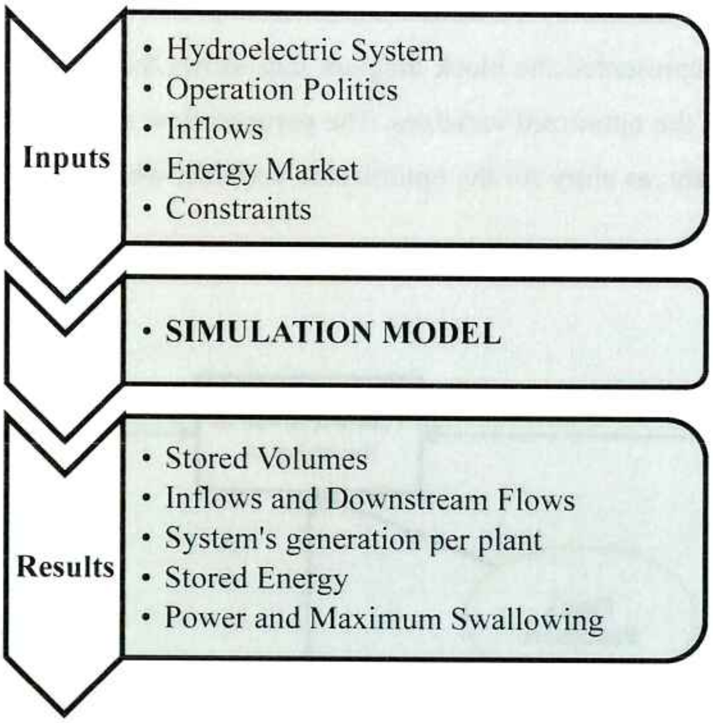

Figure 6.8 – Simulation model process

6.2.1 Operational Conditions

Five different operational conditions are inputs described bellow:

6.2.1.1 Hydroelectric System

This condition consists on the physical characteristics of every plant in the system that is being studied. Therefore, in this case, it consists in every plant in Figure 3.7, each with its own characteristics. They are found in a file named *hidrexp1.dat*, an entry to simulation softwares used by companies in the energy sector such as MSUI and Newave. Before every auction, this file is made public to enable energetic studies (EPE, 2014). In Annex B there is all data available in the file referring to the system under study, while in Annex C it is explained how to read the file.

6.2.1.2 Operation Politics

This establishes how conventional dams will work between them. Since they have reservoirs, their levels and the downstream flow of the dam highly influence the downstream dams and its respective generation, so it is important to have a defined operation politic for the reservoirs to maximize the generation profile of the system.

In case of run-of-the-river dams, there is practically no direct control over the reservoir's volume variation; therefore, the downstream flow will be equal to the inflow minus evaporation losses maintaining a constant volume along the period under study.

In this work, it will be used a parallel operation politic. It consists on operating the whole system as one, so that all the conventional reservoirs are seen as one reservoir for the whole system, this way they are all operated in the same ratio. To do so, a linkage factor, denoted by λ, $0<\lambda<1$, is established so that the volume variation of every plant is a function of this factor.

This is not the most efficient way to demonstrate an optimized operation of reservoirs because it operates every volume variation in the same ratio, without taking into account the position in the river; however, it permits to illustrate main aspects of the system's behavior. In the future, a deeper study could use another optimization process for the operation politics of the reservoirs. In (SILVA FILHO, 2003), is proposed a method based in the establishment of a function $f(\lambda)$ for each plant, based on a cloud of points of the reservoir's energy level in function of the whole system's level and then through a technique called *Mountain Method* it is written the function $f(\lambda)$.

The parallel operation politic establishes that every conventional reservoir in the system will be at a relative level of its useful volume. For example, if for a certain period, $\lambda=0,5$, this means that all the plants with reservoirs have 50% of its useful volume filled. So, the volume of the reservoirs can be written as a function of λ as follows:

$$x(\lambda) = x_{min} + \lambda \cdot (x_{max} - x_{min}) \tag{6.7}$$

being x_{min} the minimum operative volume of the plant, that corresponds to the dead-volume and x_{max} the maximum operative volume of the plant.

The emptying/filling politic of the reservoirs is determined based on Equation 6.7 so that when $\lambda=0$ it means the reservoirs are empty, or with its minimum operative volume, and when $\lambda=1$, the reservoirs are at its maximum operative volume. This way, the emptying and filling of reservoirs is done proportionally to the storing capacity of the reservoirs so that all of them have the same relative volume λ and the turbine water is exactly what is necessary to attend the electrical load.

A constraint that must be established is that λ must belong to the interval $[0,1]$. So if during the simulation, λ becomes smaller than 0, that means that the reservoirs are already empty and if the load hasn't been reached by the generation, the hydroelectric system won't be able to attend to it sufficiently so that this system will require energy from other systems or energy sources or in the worst case scenario, has to disconect part of the load. Now if λ becomes greater than 1, it means that the reservoirs are full and if the load has already been reached there won't be any more room to store the water excess, therefore, there will be spillage of water in the dams with reservoir creating a possible spilled energy. In both cases, λ is edited and made equal to its limits, either 0 or 1.

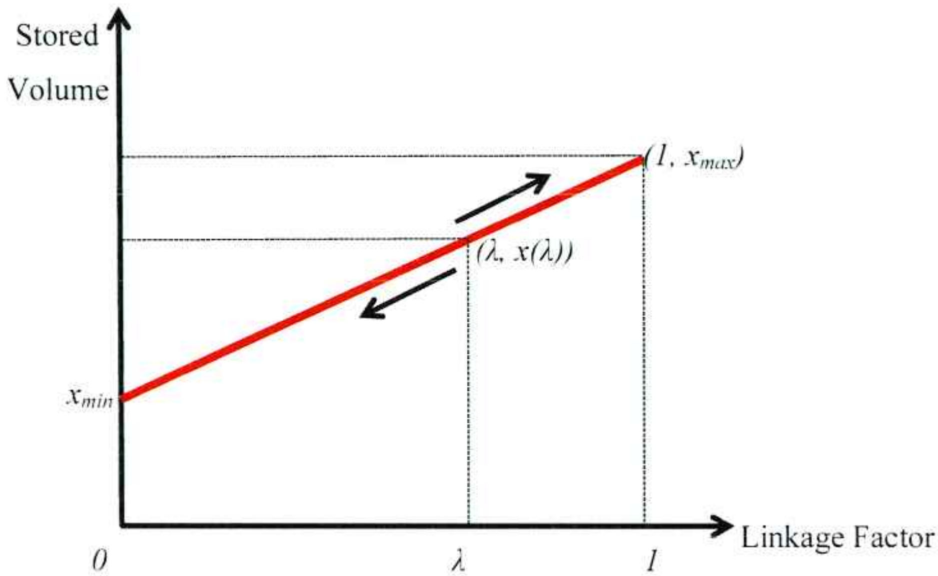

Figure 6.9 – Parallel politic of operation

Through this politic of operation, there is a simple way to manage the reservoirs allowing the decision of filling or emptying the reservoirs to be taken based in an integrated way of every reservoir in the system under study since they are a function of a global parameter. However, as explained before, this isn't the most optimized way to manage the reservoirs, in a real system, the upstream reservoirs are emptied more often to regulate the downstream water flux so that the downstream reservoirs are kept more filled, increasing its energy production since the drop height will be bigger.

6.2.1.3 Inflows

To define the inflow of every plant in the system, it is necessary to specify the year in which the simulation will start, a variable defined as *year_start* in the *Matlab* routine. Based in historical data, available from 1933 to 2013, simulation will take place in a user-defined year for a period of *T* years. The inflow register is automatically loaded by the *Matlab* routine for every plant that composes the system.

For the seasonal analysis, it is used the monthly average of the natural inflow in the period.

6.2.1.4 Energy Market

For every simulation, it is necessary to define the energy market that the system must attend to. This is done through an average of power connected to the system in terms of the nominal installed power of the system.

In the simulations, the load will be given as a percentage factor, and the system will be tested for a series of different scenarios of energy market to compare the results. This parameter will be known now forward as *D(t)*, as for demand.

In this case with a seasonal analysis and monthly discretization, it was established two base levels of demand. Based on data for the electrical load in Brazil along 2014 (ONS, 2015) and the installed capacity, it was possible to establish two approximate levels for the load of this system as a coefficient that multiplies the installed power capacity.

On Table 6.1 it is possible to see the electrical load in the national grid along 2014, on January, February, March, September, October, November and December, the electrical load was above the yearly average. It was then decided to define these as the months for the peak load in the year, while April, May, June, July and August are months off peak.

Table 6.1 – Monthly electrical load in 2014

	Load (MW.avg)
Jan	67.944
Feb	69.870
Mar	66.355
Apr	64.900
May	62.938
Jun	61.510
Jul	61.528
Aug	63.168
Sep	65.328
Oct	67.147
Nov	66.472
Dec	65.632
Avg	65.233

(ONS, 2015)

Considering that in 2014 there was a total of 126.743 MW of installed power, the coefficients for the load are then calculated, dividing the approximate load in the month by the installed capacity in the NIS. Establishing only two levels of load, it is possible to come with the result shown in Figure 6.10, being decided a coefficient of 0,528 for the peak months and 0,489 for off peak months.

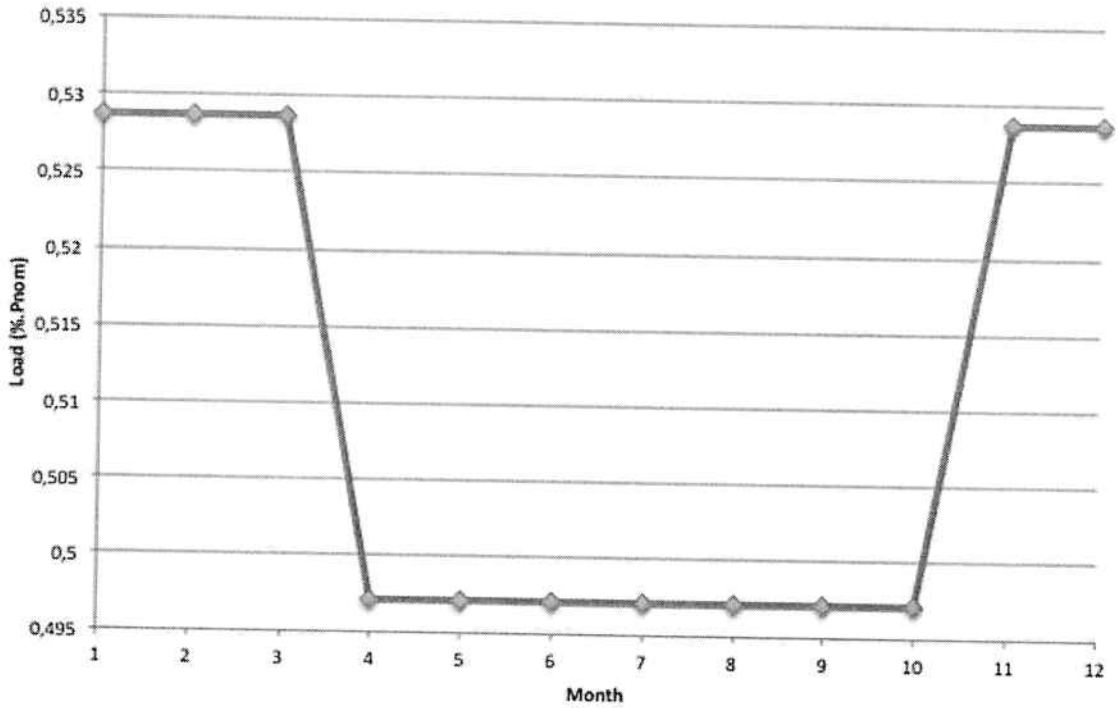

Figure 6.10 – Monthly load level

6.2.1.5 Constraints

To establish a realistic model of the system, a series of constraints must be previously established. The following were included in the *Matlab* routine written:

- Minimum and maximum volume of every reservoir;
- Minimum and maximum downstream flow on every dam;
- Maximum turbine flow given by the maximum swallowing determined as described in Section 4.1.3;
- Maximum continuous generation, determined as described in Section 4.1.4;
- Storage of the predicted spillage volume due to maximum swallowing if there is room in the reservoir;
- Determination of the pumped water flow in case of missing or exceeding the energy generation;

Once every constraint and parameter described above has been implemented, the program is able to run and start an iterative process for each individual of the population determined in the Genetic Algorithm.

6.2.2 Iterative Process

Given all the entry parameters described above, the next step is the simulation model that works through an iterative process to find the correct linkage factor so that the demand is reached by the generation using the initial available volumes and the natural inflows given by the historical series. Then, considering the constraints established, an iterative process starts to find the λ required. The process is schematized in Figure 6.11.

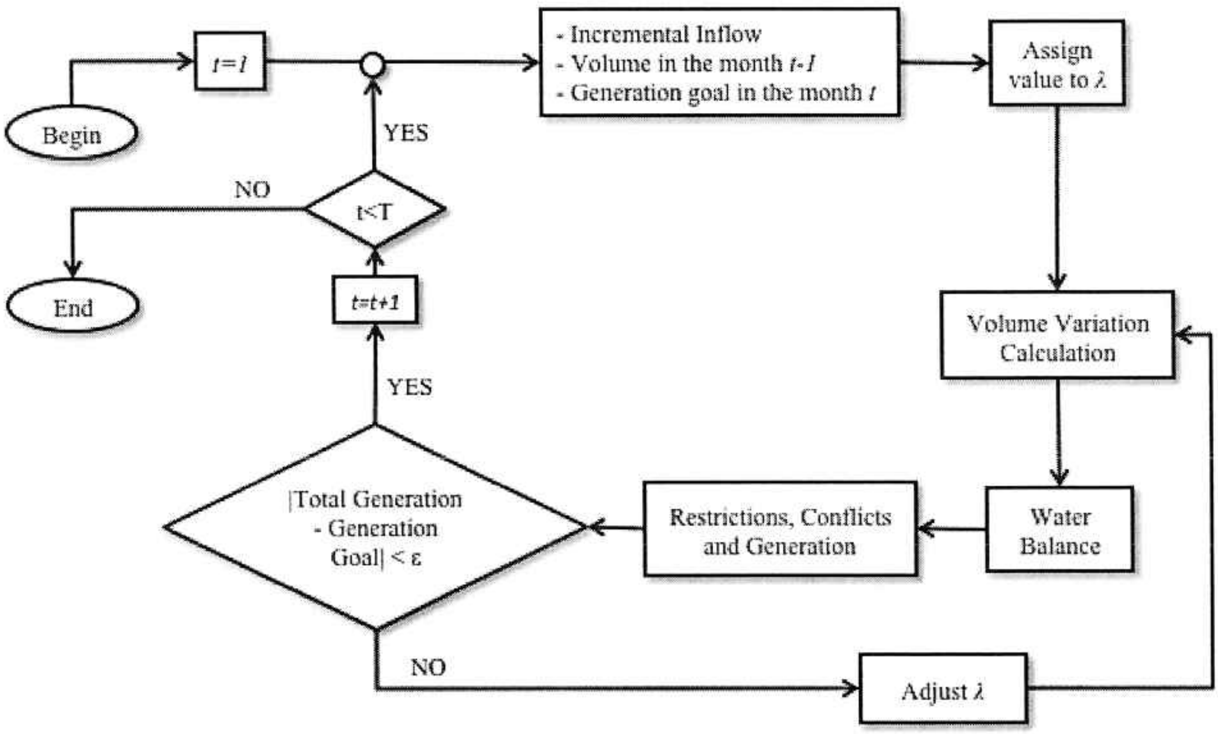

Figure 6.11 – Algorithm for the iterative process

Initially it is necessary to establish a number of periods T that is going to be simulated, this variable is called *time_simulation* in the program.

In the interval t:

1. First step is to update the natural inflows, as well as the incremental inflow, the initial volume in the reservoir and the generation goal of the system. Considering the plants with an EPS, it is necessary to update the incremental inflow with the current pumped flow that comes from the GA:

$$\mathrm{Y(year, month, plant) = Y(year, month, plant)}$$

$$\mathrm{-pump\_flow(year, month, plant)} \quad (6.8)$$

2. The second step is to assign an initial value to λ. The initial value of λ, λ_0 is made equal to the stored energy in the system, in p.u..

$$\lambda_0(t) = \frac{E_{stored}(t)}{E_{stored}^{max}} \quad (6.9)$$

3. The third step is calculate the volume variation. Based in Equation 6.7, it is found the volume stored for each plant in the end of the interval t.
4. The fourth step is the water balance. Since the volumes in the end of the interval are known from the third step, it is possible to calculate the outflow of each plant based in the Equation 5.3.
5. The fifth step include restrictions, conflicts and generation.
   - Generation Limits:

     In this case it is necessary to determine the maximum continuous average generation for each plant in the interval t. This value is represented by the variable p_{max_con} that is determined as demonstrated in Section 4.1.4. This way the maximum generation of a plant in the interval t is limited by p_{max_con}.
   - Outflow Limits:

     From the input data in the file *hidrexp1.dat* it is known the minimum outflow that every plant in the system must respect. Therefore, even though there isn't enough demand to request the minimum outflow, there must be spillage to attend this constraint. This is due to navigation, environmental and political purposes. The same is applied to maximum outflow in the plant that is limited also due to its spillage characteristics.
   - Spillage Avoidance:

     During the calculation of p_{max_con}, it is calculated the spillage based in the maximum swallowing of the plant, q_{max}, according to the iterative process explained in Section 4.1.3. However, in the cases of plants with reservoirs, to avoid unnecessary spillage when the outflow required based in the linkage factor λ is greater than q_{max}, the predicted spillage volume may be stored respecting the volume limits of the reservoir. The algorithm in Figure 6.12 was followed to optimize the spillage in one plant.

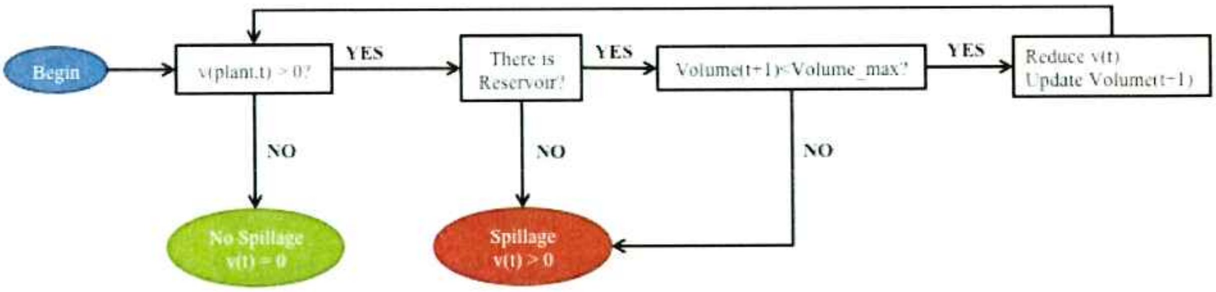

Figure 6.12 – Spillage avoidance algorithm

6. The sixth step is to calculate the total generation of the system through the generation function defined in Section 4.1 by Equation 4.8 for each plant. The total average generation by the hydroelectric plants in the interval t will be indicated as $H(t)$.
7. The seventh step is to compare the total generation with the goal established in the beginning given a precision figure ε. When the generation is different to the production goal, λ may be altered in two different ways:
   - Generation Excess: In the case in which the hydroelectric generation $H(t)$ is greater than the demand $D(t)$, it is necessary to raise λ to store the exceeding water, reducing the turbine flow and generation. In case λ is equal to one, that means reservoirs are already full and in case there is still an excess of water, it will be spilled.
   - Generation Deficit: In the case where the hydroelectric generation $H(t)$ is smaller than the demand $D(t)$, it is necessary to reduce λ so that the turbine flow increases, as well as the generation. In case λ reduces to zero, it means the reservoirs are empty and if the total generation is still smaller than the demand, there will be a supply deficit.

8. The eighth step is to adjust λ when comparison between the generation and the demand is not within the precision figure ε. To do so, it was used Equation 6.10.

$$\lambda = \lambda + \alpha \cdot \frac{H(t) - D(t)}{D(t)} \tag{6.10}$$

where α is a positive constant that determines the intensity of the variation of λ. It was decided not to use a constant value for α, but a function on the amount of iterations realized so far in this iterative process. This was decided after a non-convergence problem in the algorithm. There were many cases that during the iterations, the values for *H(t)* oscilated around *D(t)*, therefore, the bigger amount of iterations realized to that point, the bigger had to be the precision to adjust λ, so that the generated power arrived within a precision figure of the demand. It was also established a maximum amount of iterations equals to twenty with the condition of having a generation bigger than the demand, to speed up the simulations.

6.2.3 Results

After the simulation reaches the final interval *t* it will save all the workspace into a file *.m*. Its name will take into consideration the entry parameters established as explained in Figure 6.13.

SeasAnal->LoadSP [1] WP [2] Vol [3] _Volpump [4] _GApop [5] m [6] c [7] It_ [8] - [9] _Year [10] - [11]

1 - The summer peak load
2 - The winter peak load
3 - Initial volume in the conventional reservoirs
4 - Initial volume in the pumped reservoirs
5 - Size of the population of the GA
6 - Propability of mutation
7 - Probability of crossing
8 - Total maximum number of iterations of the GA
9 - Maximum number of iterations with no improvement in the GA
10 - Initial year of the simulation
11 - Final year of the simulation

Figure 6.13 – Name of the exit file of the simulation

To facilitate the analysis, it was written a routine called *Graphs.m* that supplies a series of graphs to illustrate the behavior of the system. The outputs of the routine are the following graphs:

1) Power generation in each plant of the Grande Basin in p.u.;
2) Power generation in each plant of the Paranaiba Basin in p.u.;
3) Power generation in each plant of the Parana Basin in p.u.;
4) Water flows in each plant of the Grande Basin;
5) Water flows in each plant of the Paranaiba Basin;
6) Water flows in each plant of the Parana Basin;
7) Power x Demand graph;
8) Energy storage level of the whole system in p.u.;
9) Energy storage level of the conventional reservoirs in p.u.;
10) Energy storage in each pumped reservoirs in p.u.;
11) Water flow in the Canastra EPS;
12) Water flow in the Catalão EPS;

6.3 Simulation Model in the Hourly Analysis with Wind Farms

The simulation procedure established in Section 6.2 for the seasonal analysis with monthly discretization is used with the same approximations and premises for the daily analysis with hourly discretization but with a few modifications. In this case, every variable of the system's model is organized into a five dimensions matrix organized in (*year* x *month* x *day* x *hour* x *plant*) as explained before in Section 6.1.2.

Considering that it will be incorporated a certain amount of wind farms into the system, and being it a non-dispatchable source of energy, the block diagram for the simulation may be represented as follows in Figure 6.14. So that the wind generation will be directly incorporated into the energy production, reducing the load the hydroelectric system must attend.

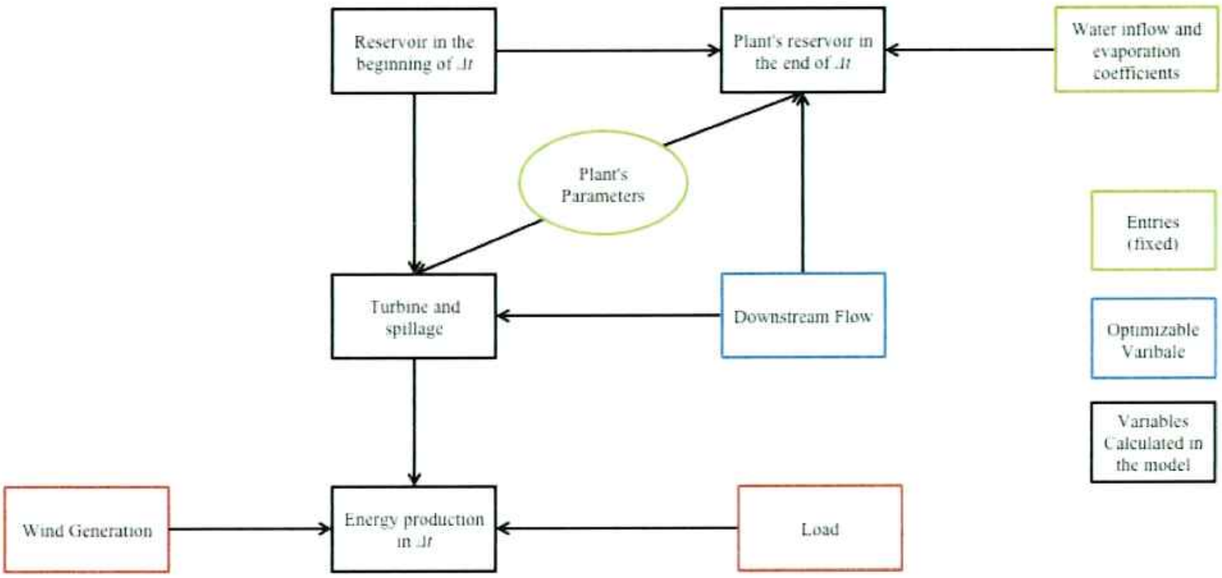

Figure 6.14 – Block diagram for the daily simulation with hourly discretization

Comparing the operational conditions of this simulation to those explained before, the only differences concern the inflow data and the energy market.

It is available the daily average inflow in every plant of the system under analysis after 1973 (EPE, 2014). So it was considered a constant inflow for every plant in the system along each day that is equal to its daily average data available. Here an approximation was made considering the operation in cascade.

In the monthly analysis it is correct to say that the monthly average inflow may be calculated as explained before, however, with an hourly discretization, the inflow of a dam does not depend on the outflow of the upstream basins in the same period, but from periods before. Considering that the plants are distant from each other, it may take a few hours or even days for the water going through one dam to arrive to the next downstream dam. However, in this study, it was chosen to not take into account the transit time for the water, therefore:

$$y_i(\text{hour}) = y_{inc,i}(\text{hour}) + \sum_{j \in \Omega} u_j(\text{hour}) \quad (6.11)$$

It was an approximation to simplify the iterative process, and a possible improvement to be added in the future.

Considering the energy market, since there is a fluctuation of the load along the day, it was considered two different load levels along a day that varies with the season of the year, as it was described in Subsection 6.2.1.4. To do so, four variables were created:

- *summer_peak*: represents the peak load along the day in the summer season;
- *summer_offpeak*: represents the off peak load during the day in the summer season;
- *winter_peak*: represents the peak load in the day during the winter season;
- *winter_offpeak*: represents the off peak load in the day during the winter season;

Based in the daily load profile in Brazil, it is possible to see that the peak load happens in the afternoon between 12 o'clock and 18 o'clock with a load around 1,4 times greater than the daily average (ONS, 2013). In Figure 6.15 it is shown a typical day load profile in the Southeast / Center-West subsystem in a summer day.

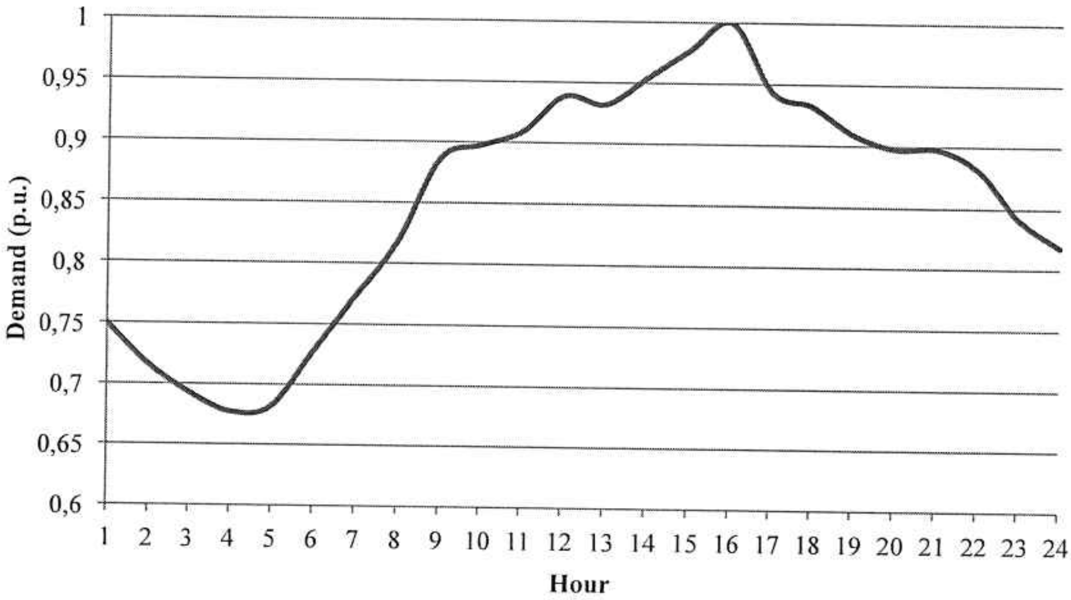

Figure 6.15 – Typical Daily load in the Southeast/Center-West subsystem in the Summer

Considering now that the average load is equal to 1 p.u. it is possible to calculate the off peak average coefficient given a peak load of 1,4 p.u., between 12 and 18 o'clock:

$$D_{\text{off peak}}(\text{hour}) = \frac{24-\sum_{\text{hour}=12}^{18} D_{\text{peak}}(\text{hour})}{17} \tag{6.12}$$

This way, it was possible to determine the following load profile that will be taken as base for every day of the year according to each month's own characteristics.

$$\begin{cases} D_{\text{peak}}(\text{hour}) = 1{,}4 \times D_{\text{avg}}(\text{day}) \\ D_{\text{off peak}}(\text{hour}) = 0{,}8667 \times D_{\text{avg}}(\text{day}) \end{cases} \tag{6.13}$$

In Figure 6.16 is represented the approximation used for the daily load profile in the simulations. A peak load 40% greater than the average along 6 hours of the day, and an off-peak load 13,3% smaller than the average along the rest of the day.

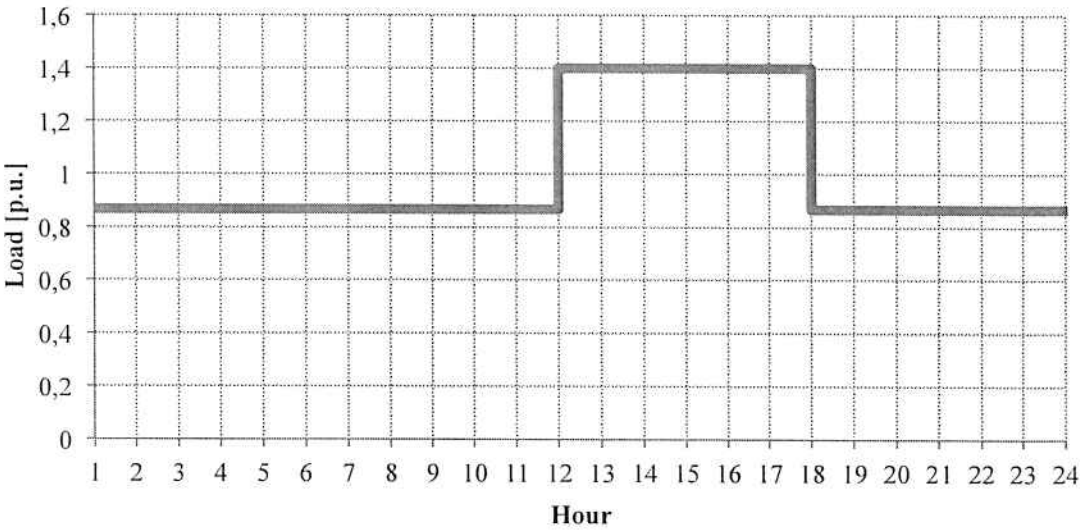

Figure 6.16 – Daily load profile

After that, the same iterative procedure used to calculate the monthly average generation was used to calculate the hourly average generation with the same entries, only in a different discretization period. After that it was incorporated the wind farms generation directly into the energy generated. This happens because the wind generation is a non-dispatchable source, so all the energy generated that isn't consumed would be wasted. Therefore, the most efficient solution takes the wind energy as being 100% consumed.

Here it was included the energy consumed by an EPS to pump the water up in the reservoir. Being *P(t)* the amount of energy consumed in *t* in this aim, the load that the hydroelectric power plants must attend is:

$$H(t) = D(t) - W(t) + P(t) \tag{6.14}$$

where *W(t)* represents the wind power generation in the period *t*, calculated as in Section 5.

7 CASE ANALYSIS

In this chapter, it will be analyzed the output of the simulations, comparing them among each other. The first step will be a Seasonal Analysis, discretized monthly, after that it will be analyzed the one year discretized hourly including the wind power generation effects, always comparing the cases with and without the pumped storage reservoirs.

It is important to understand that the following graphs referring to the system's reservoir are always in terms of useful energy, calculated according to Equation 7.1 and 7.2, except where made explicit that is regarding a volume measure.

$$E_{min} = \rho \cdot Vol_{min} \cdot g \cdot h_{min} \quad (7.1)$$

$$E_{useful} = \rho \cdot Vol \cdot g \cdot h - E_{min} \quad (7.2)$$

given that ρ is the water density, *1.000 kg/m³* and g is the acceleration due to gravity, *9,81 m/s²*.

Then, to calculate the stored energy in p.u., it is used the maximum useful stored energy as base given by Equation 7.3.

$$E_{useful_{max}} = \rho \cdot g \cdot (Vol_{max} \cdot h_{max} - Vol_{min} \cdot h_{min}) \quad (7.3)$$

To use energy instead of volume is useful since a big reservoir upstream in the basin can store more energy due to its higher height than a same size reservoir with lower heights downstream to the basin.

Bellow is reproduced one more time the system under analysis, showing every dam in the system as well as the pumped-storage reservoirs that were included in the analysis.

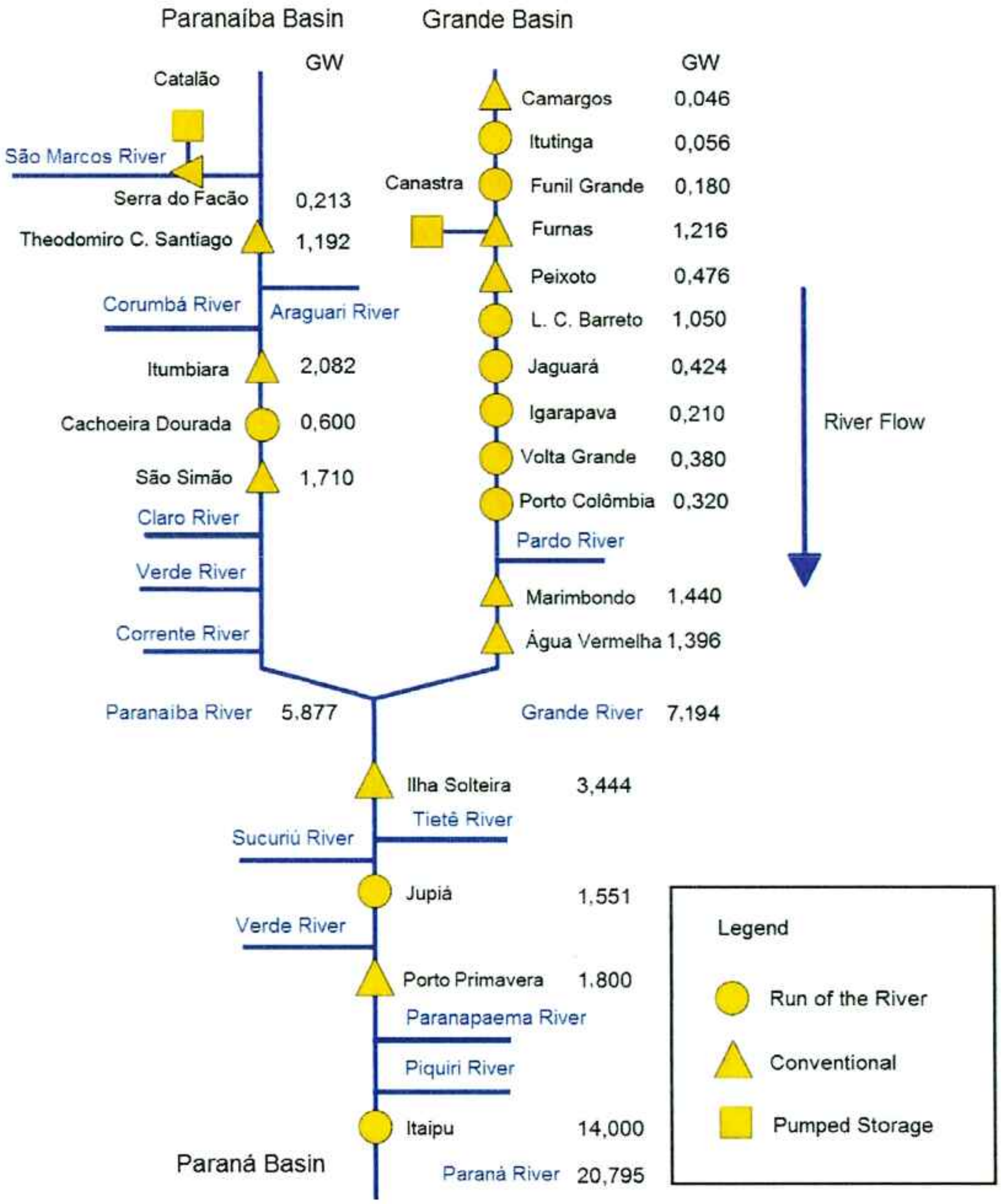

Figure 7.1 – Diagram of dams in the Paraná, Paranaíba and Grande Watersheds with two proposed Enhanced-Pumped-Storage schemes.

7.1 Seasonal Analysis Output

Considering the load determined in Chapter 6, the first case will consider the critical period from 1949 to 1958 when there was a very severe drought in Brazil, and how the system would behave if a similar drought happened. This period is particularly interesting to analyze because of the reduced inflow of the system. The first subsection will show the behavior of the system without the EPS facilities and then compare it after their inclusion in the section after.

This case was useful to test the model established in Chapters 4. It allowed verifying the inflow in every dam in the system, analyzing its behavior and testing the water balance to look for inconstancies. However, the real benefits of a PSP are regarding the daily load in order to attend the demand.

This cases, discretized monthly are, anyhow, useful to understand better the system's behavior and how the PSP works.

7.1.1 Case Without EPS Facilities

Considering the case without EPS facilities, given by the filename: *SeasAnal_Load52.8.48.9_Vol99.9_Year1949-1958.mat*, there is no need to apply the optimization algorithm since it is a deterministic solution, only applying the established model.

It is important to understand the drought that existed at the time under analysis. Observing the graph with the reservoir levels in the system altogether, shown in Figure 7.3, it evident that after 1954, due to the severe drought existent, the reservoirs emptied themselves, not being able to supply all the demand as it can be seen in Figure 7.2.

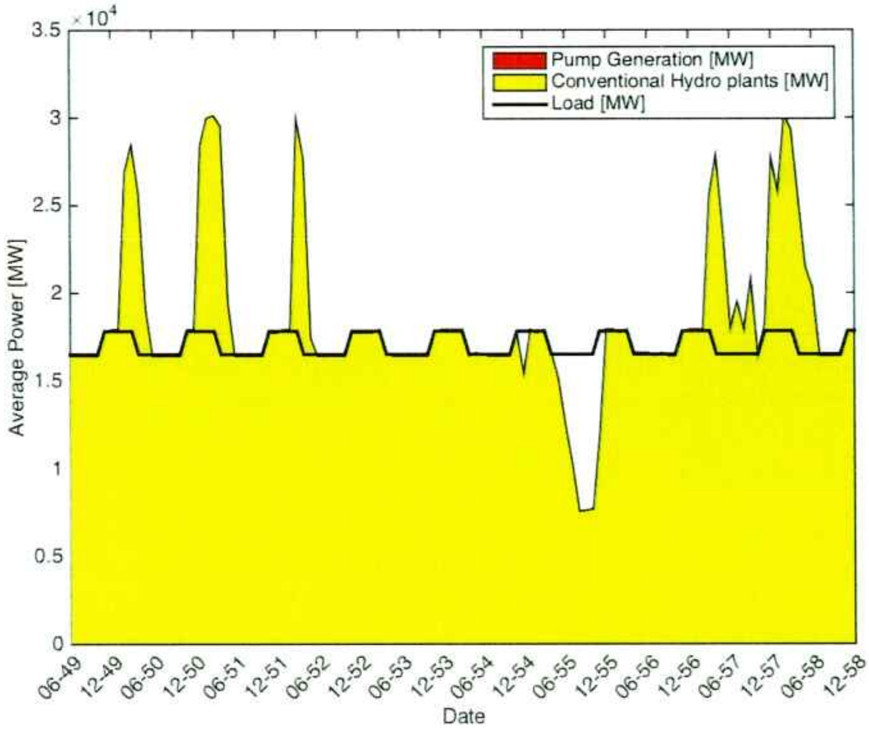

Figure 7.2 – Power x Demand Graph (Case with no EPS)

Due to the lack of generation in the period, it would be needed to cut part of the load, requiring a rationing measure to avoid the whole collapse of the system.

In Figure 7.3, it is possible to observe the operation politics of the reservoir, emptying them during the dry period of the year and filling in the wet period. In the end of

1954, it still manages to generate the required load and fill-up the reservoir, but not the amount needed to attend the demand in the following dry period requiring the rationing measure due to a lack of generation.

Before this drought began, in Figure 7.2, it is observed an excess of generation when compared to the load. This happens only when the reservoirs are full as it can be seen in Figure 7.3, and this system, in case it can't be sent to another electrical system, will be spilled, meaning it is wasted.

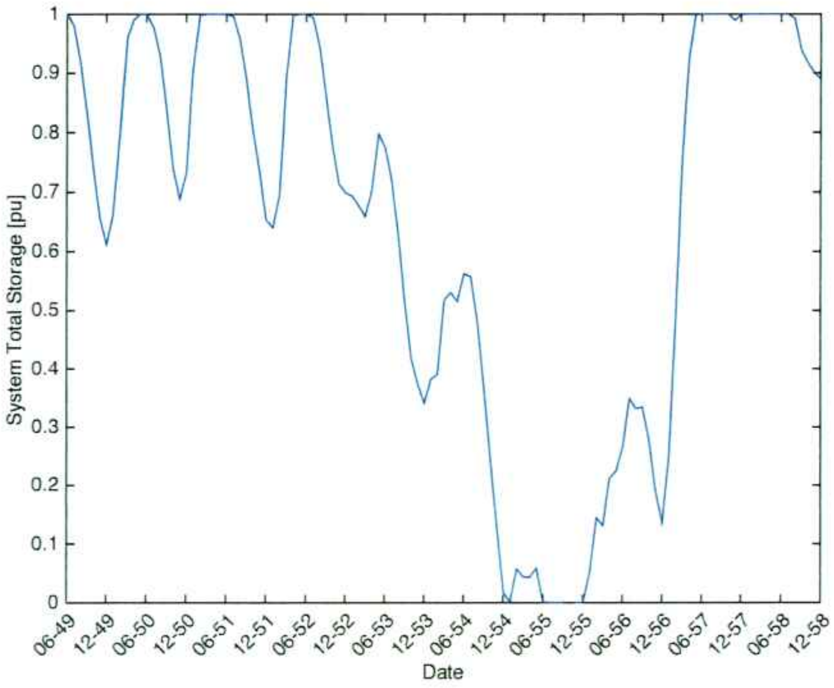

Figure 7.3 – Storage of the whole system

In Figure 7.4 is represented the water flows in the Ilha Solteira Dam as well as its reservoir level along the period of analysis. Here is evident the drought of the system, when the inflow, represented by the orange line, of the dam after 1952 doesn't increase enough in the wet period, its reservoir starts to empty.

Ilha Solteira is a good example among the twenty-one hydroelectric plants because it is the first in the Parana River after the joining of the Grande and Paranaiba rivers, and also for the fact that it has a large conventional reservoir. Looking into the Furnas hydroelectric power plant, which has the biggest reservoir in this system is also useful to observe its behavior.

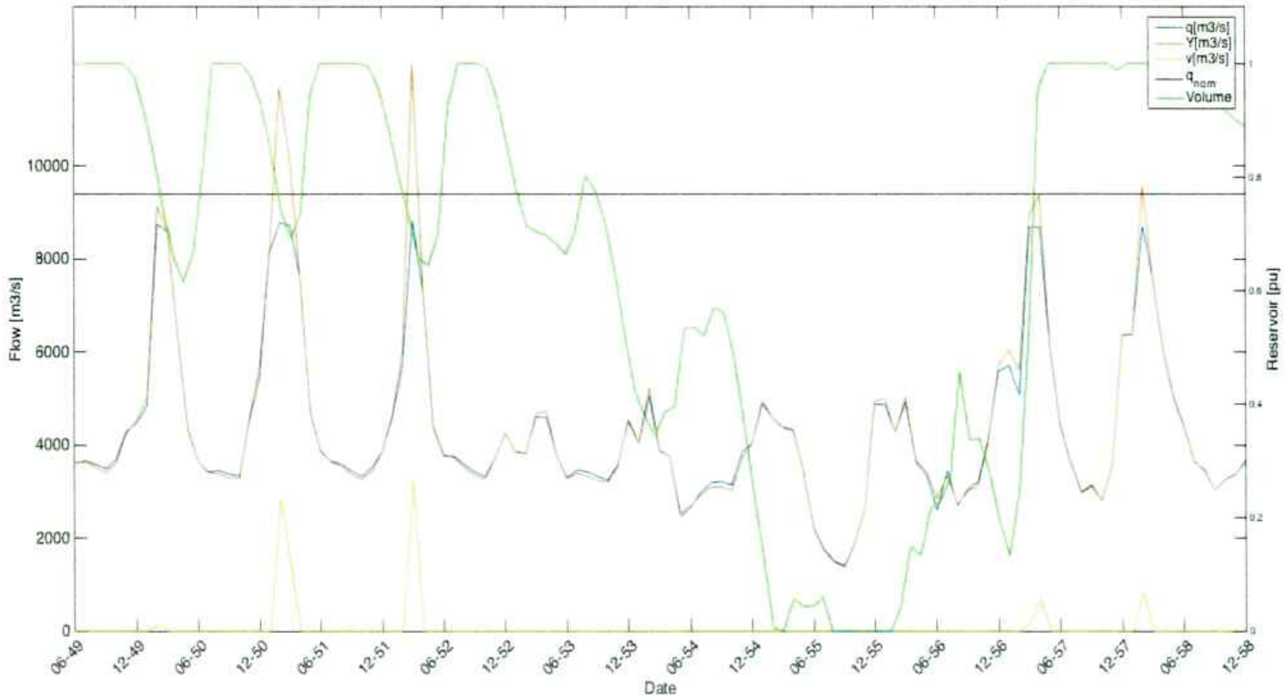

Figure 7.4 – Water Flow and Reservoir Level in the Ilha Solteira Dam (Case with no EPS)

For a matter of comparison is also shown the water flow in the São Simão Hydroelectric Power Plant in the Paranaiba River to show the effect of the drought in all three rivers of the system. However, it is possible to see that the effect in the Paranaiba River was reduced when compared to the Grande River, having a more stable inflow in its last dam, and having a more severe drought later, starting in the dry period of 1954 when there was a drastically reduction in the inflow of the plant.

In Figure 7.6 it also evident the drought of the system after 1952, allowing concluding that it affects all hydroelectric power plants. The system tries to store the maximum amount of energy, observe that after the drought began, there is no more spillage in either dams. Observing the generating power of the Parana Basin, that has the largest installed power, it is evident the effect the drought has in the power generation profile.

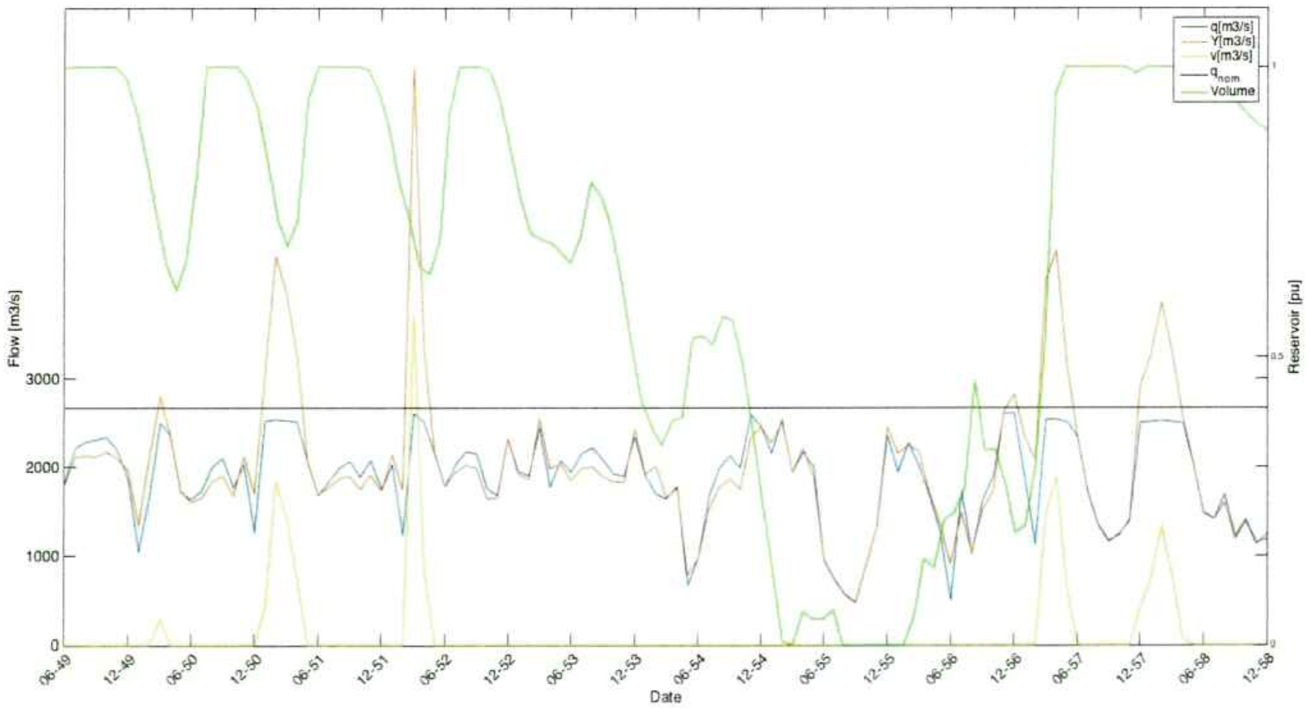

Figure 7.5 – Water Flow and Reservoir Level in the São Simão Dam (Case with no EPS)

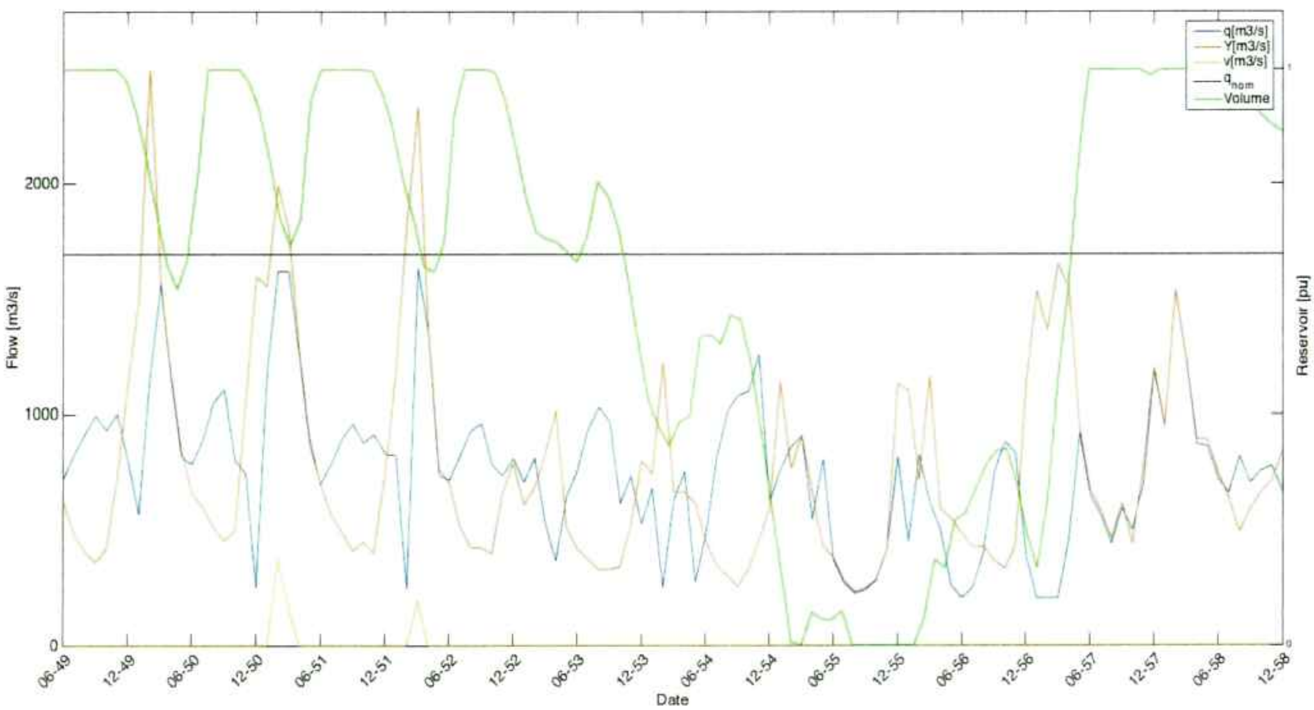

Figure 7.6 – Water flow and Reservoir Level of the Furnas Dam (Case with no EPS)

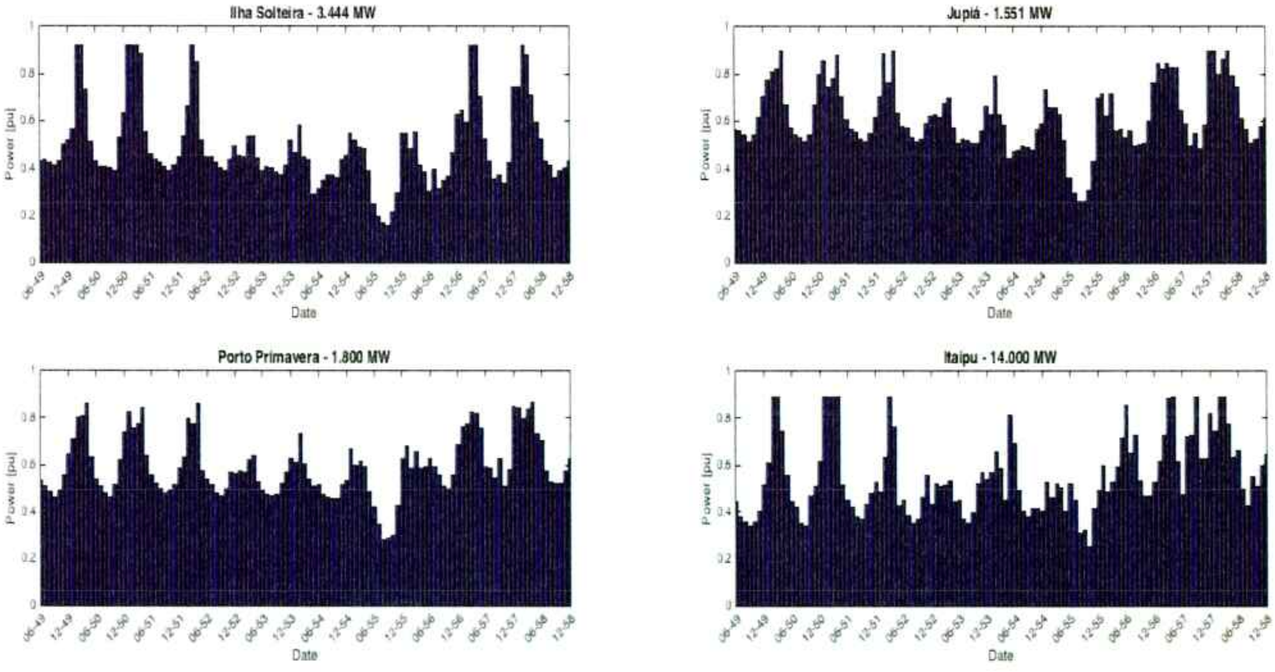

Figure 7.7 – Power Generation Profile in the Parana Basin

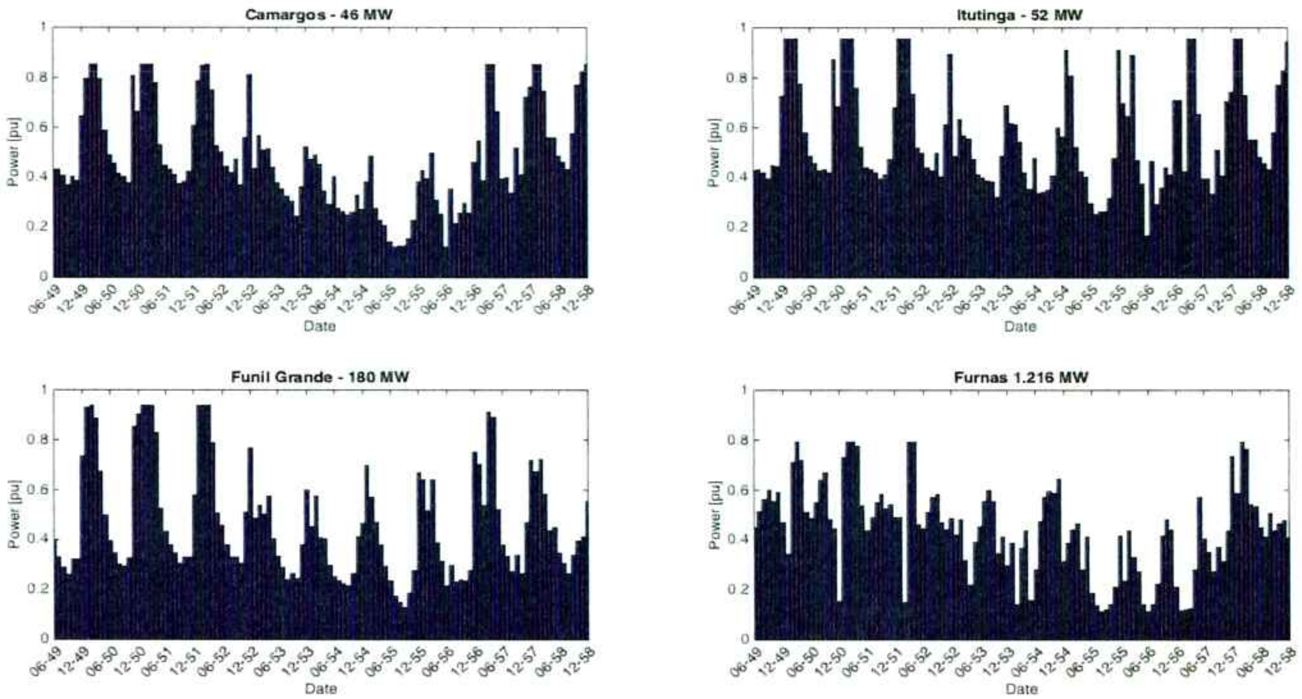

Figure 7.8 – Power Generation in the Grande River

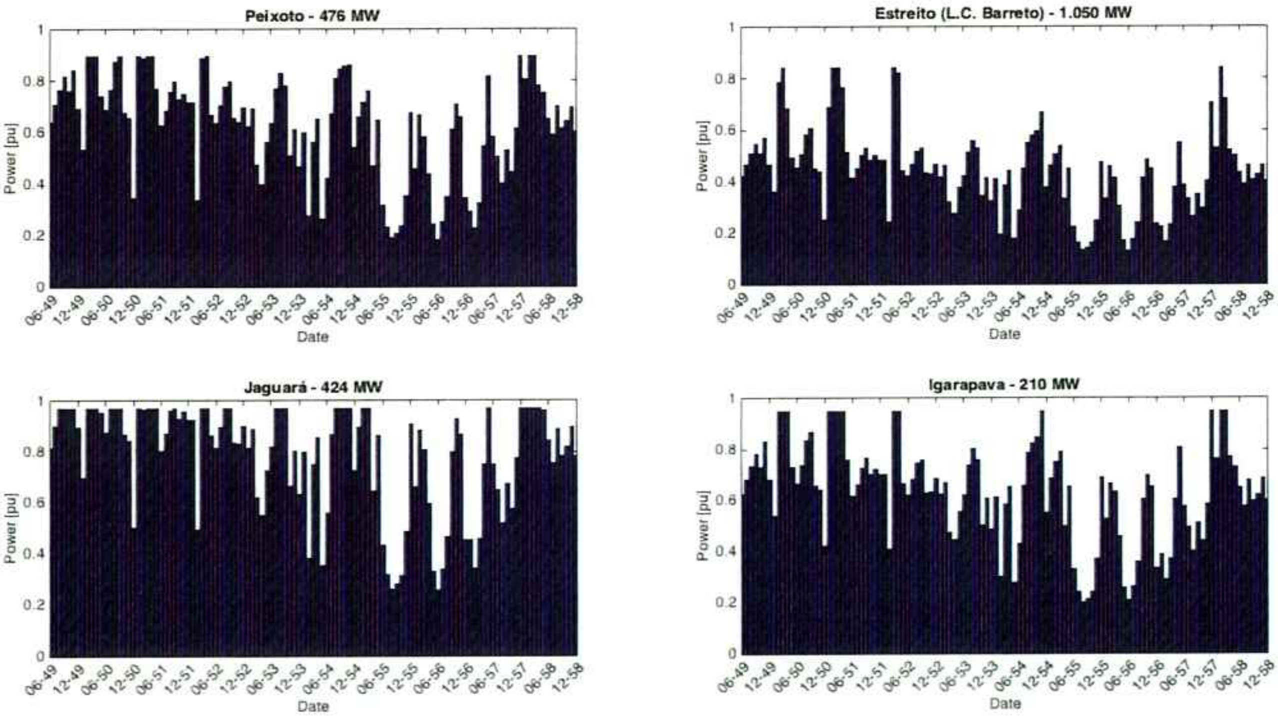

Figure 7.9 – Generation Profile in the Grande River

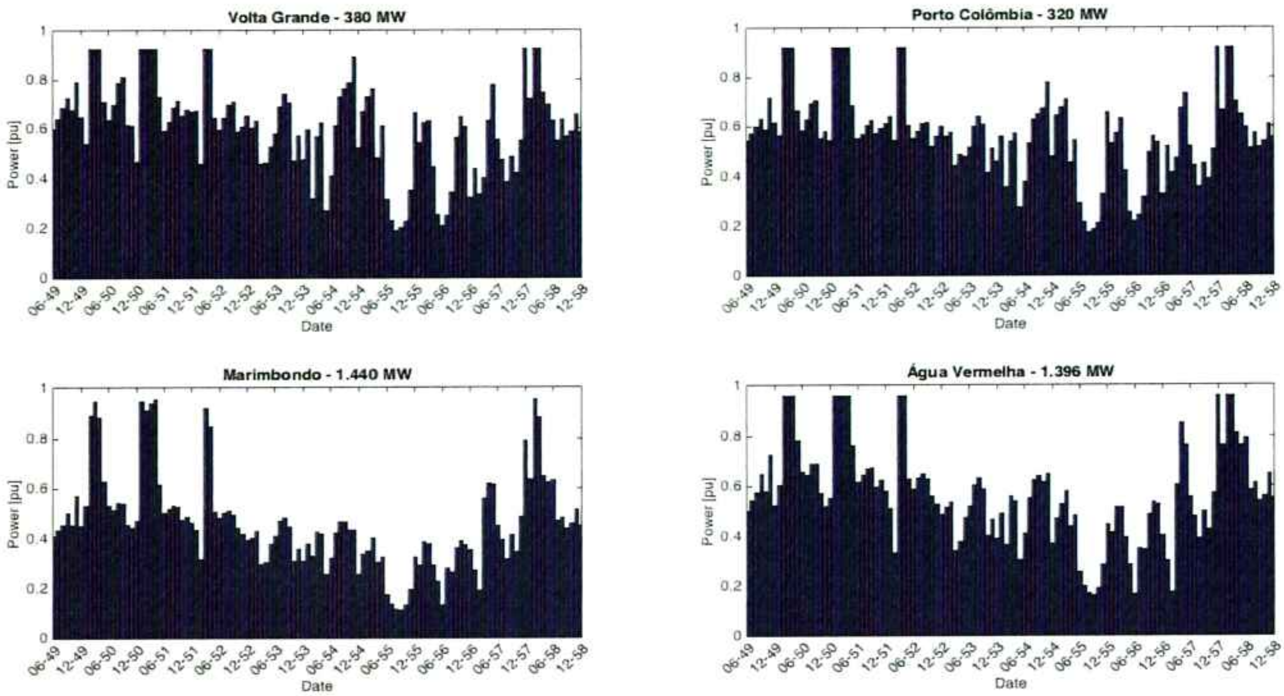

Figure 7.10 – Generation Profile in the Grande River

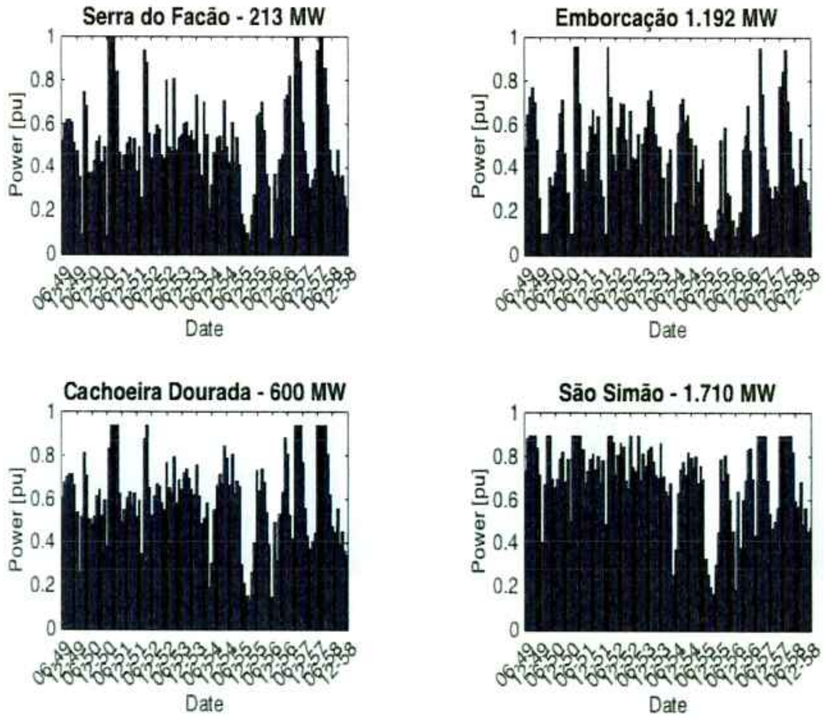

Figure 7.11 – Generation Profile in the Paranaiba River

Looking into the generation profile, after the drought began, in 1952, it is possible to see that all four plants in the Paraná Basin, as well as in the other basins keep an average generation near to the period previously to the beginning of the drought. In 1954 however, the reservoirs reach its minimum volume during the dry season, creating a short period where the generation doesn't manage to reach the load. However, since the reservoirs emptied in the end of the dry season of the year, the cut was still small so that when the wet season began, it managed to still store some water. In Figure 7.3 it is possible to see the small increase in the system's reservoirs after December 1954, but insufficient to store enough energy to endure the next dry season.

Since, there was no more regulation capacity in the power plants, they all worked as run-of-the-river dams, not storing any water and being totally dependent on the natural inflow of the river.

In 1956 the drought begins to give signs that it is coming to an end. Observing the water flow graphs in each dam, it is possible to observe that it starts to become closer to its regular behavior and the system manages to attend the required demand and also store enough water to endure a dry season in 1956 so that in 1957 a season more humid than average begins and all the reservoirs in the system fill up to its maximum volume.

So, looking into this horizon of 10 years, it is possible to see the effects of the drought that happened in that decade, causing a shortage of energy in the system demanding the cut of load. Besides, it was possible to see the system's behavior, operation politics of the reservoirs and the effects of seasonality along a year.

In the next subsection will be considered the same scenario, however starting with more energy in the system, since it is included two EPS with its reservoir full.

7.1.2 Case 1 - Inclusion of the EPS

Given the previous scenario when during the 1950's a severe drought caused a shortage of energy, it will be analyzed in this case the system including both EPS facilities, one connected to the Furnas Dam, called Canastra, and another one connected to the Serra do Facão Dam, called Catalão. Through their insertion, increasing the system's initial energy and the storage capacity, it is possible to be a first starting point in the system's analysis to test the modeling established for the pumped facilities, as well as the Optimization Algorithm.

The first case will take as base the following output file: *SeasAnal_Load52.8.48.9_Vol99.9_Volpump99.9_GApop30m0.05c0.47It_500-100_Year1949-1958.mat*. It is considered that all reservoirs are full in the beginning of the analysis and for this case it was established a population of 30 individuals with an absolute maximum number of iterations at 500 and the same load level from the previous case without the EPS facilities.

Firstly, looking into the total power per demand graph of the system, it is possible to see that this time there is no shortage of energy, and the system is able to supply all the demanded energy along all the period under analysis.

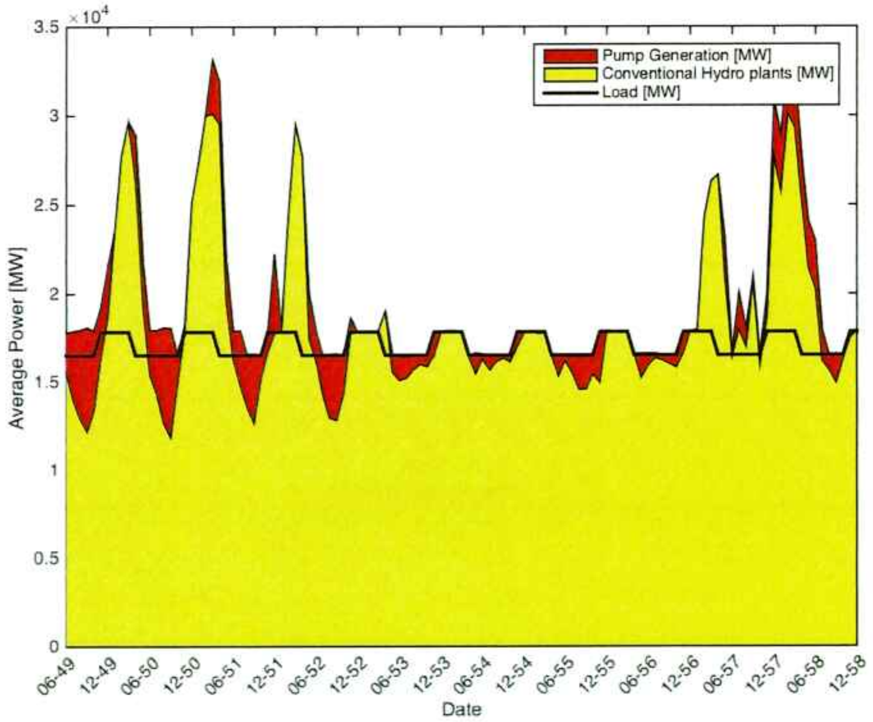

Figure 7.12 – Power x Demand Graph (Case 1)

Observe that here it wasn't taken into account the energy needed by the pumped storage plants to pump the water up to their reservoir, since it was considered that this energy would come from the exceeding energy of a different system.

In 1951, even though there is an exceeding generation of energy, that may need to be spilled since all reservoirs are full according to Figure 7.14, the EPS are still generating energy instead of consuming. This was due to the premise adopted in this scenario where the energy consumption was not taken into account as a constraint.

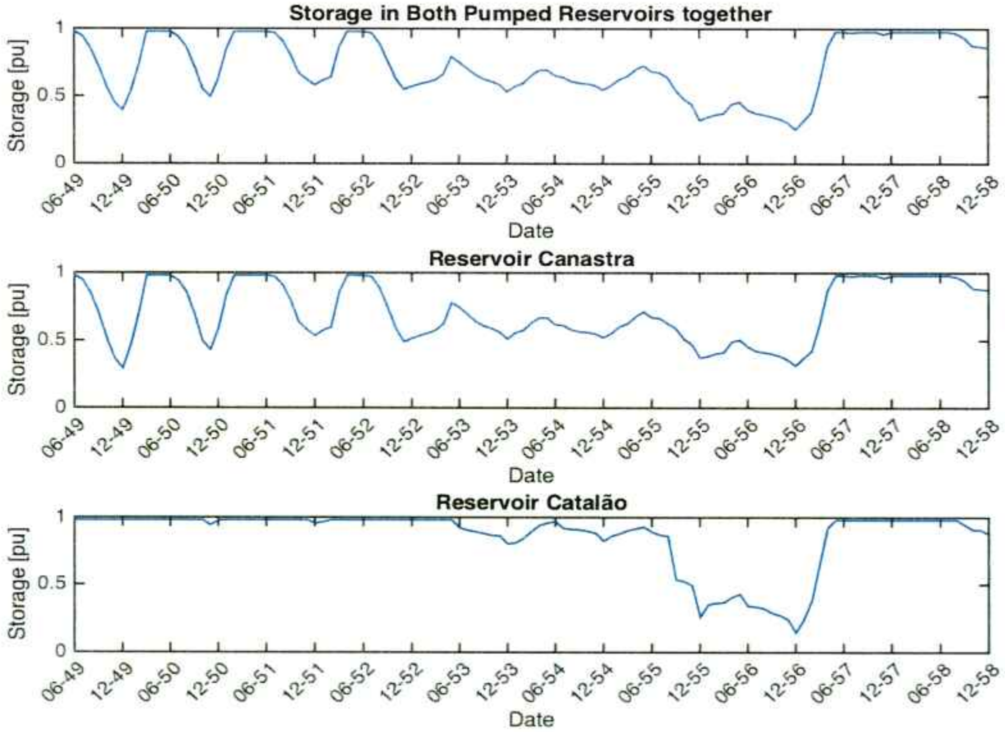

Figure 7.13 – Reservoir level in the EPS (Case 1)

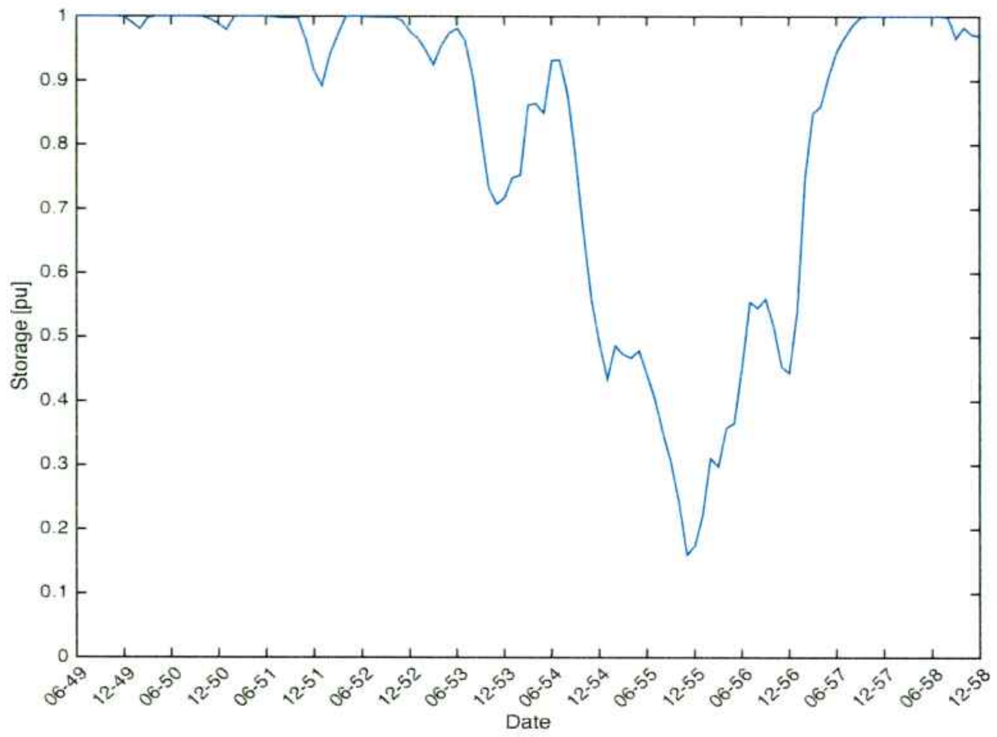

Figure 7.14 – Conventional Reservoir Total Storage (Case 1)

It is possible to observe through the two figures above that the pumped reservoir are emptying themselves in order to attend the demand in the beginning, allowing the conventional reservoirs to stay filled attending a minimum water flow due to its filled reservoir and the physical need of the river.

Then, when the drought begins around 1953 the pumped reservoirs do not fill until its limit, staying with about 60% of its capacity while the conventional reservoirs empty themselves to supply the required load. This way, the pumped facilities work as a backup reservoir being upstream in the river and its volume supplies almost every power plant in all three rivers. Also, with the inferior reservoir emptier, the gross drop between the reservoirs is increased, maximizing the generation by the EPS, being an interesting measure to generate more energy in a period of drought.

Also, notice that due to the very large volume capacity difference between the two EPS, the storage pattern of the two reservoirs combined follows the same pattern of the Canastra Reservoir.

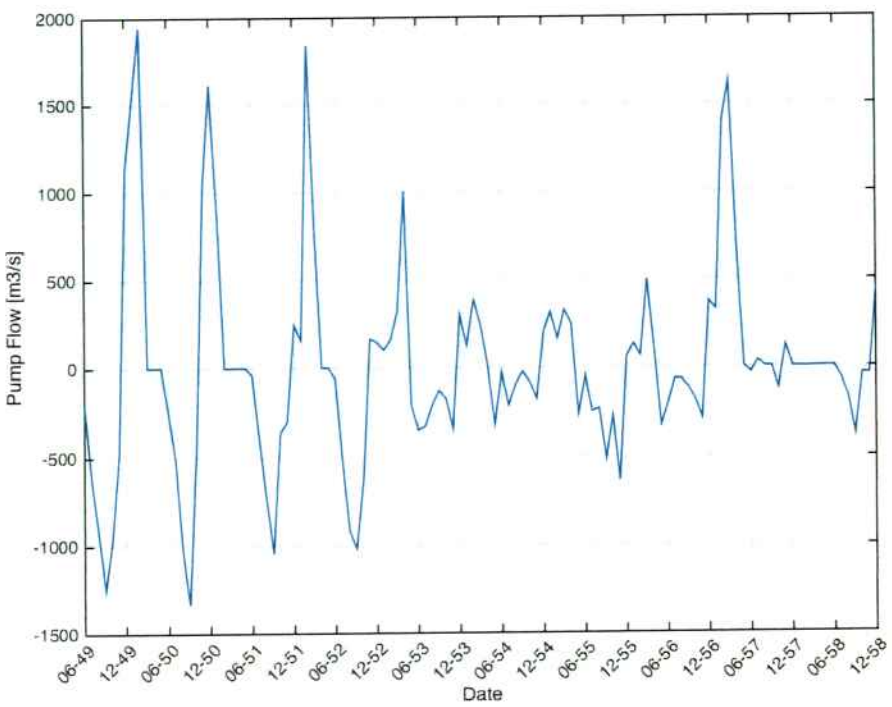

Figure 7.15 – Pumped water flow in the Canastra EPS (Case 1)

Here it is possible to see the water flow variation in the pumps of the reservoir, determining its generation profile as well as the volume variation shown in Figure 7.13.

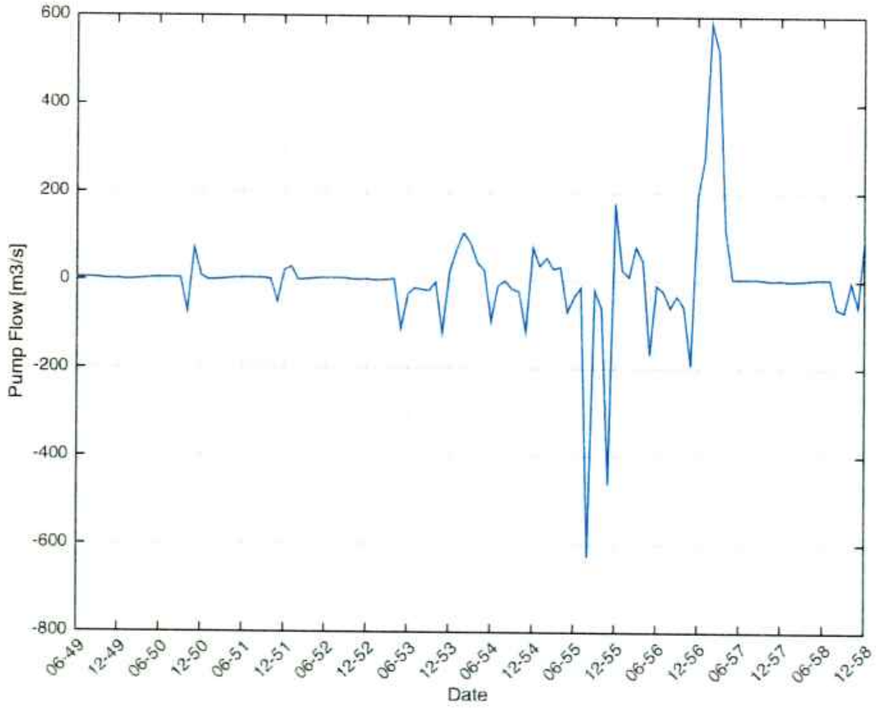

Figure 7.16 – Pumped Water Flow in the Catalão EPS (Case 1)

Looking into the water flows in the Furnas Power Plant, and comparing it to the case without an EPS facility, it is possible to see that the outflow of the dam is more variable, because due to the water that is pumped, less water arrives to the reservoir in the dam in some periods. For example in the end of 1949, looking into Figure 7.15, there is a large volume of water going into the PSP, due to this, as it can be seen in Figure 7.17, the volume that goes through the turbine is very low and still greater than the inflow arriving to the dam, emptying a little the plant's reservoir. However, this allows the system to achieve its generation goal at all times during the studied period.

Also, for certain periods, given the large generation coming from the EPS and the required minimum flow in the dam, it is observed in the end of 1949 until the beginning of 1950 and then in the end of 1956 and July 1957, the minimum flow going through the turbine. Meanwhile in this period, the EPS are also alternating between pumping and generation modes minimizing the spillage of water due to a full reservoir in the end of 1949 and would consume the exceeding generation at the time.

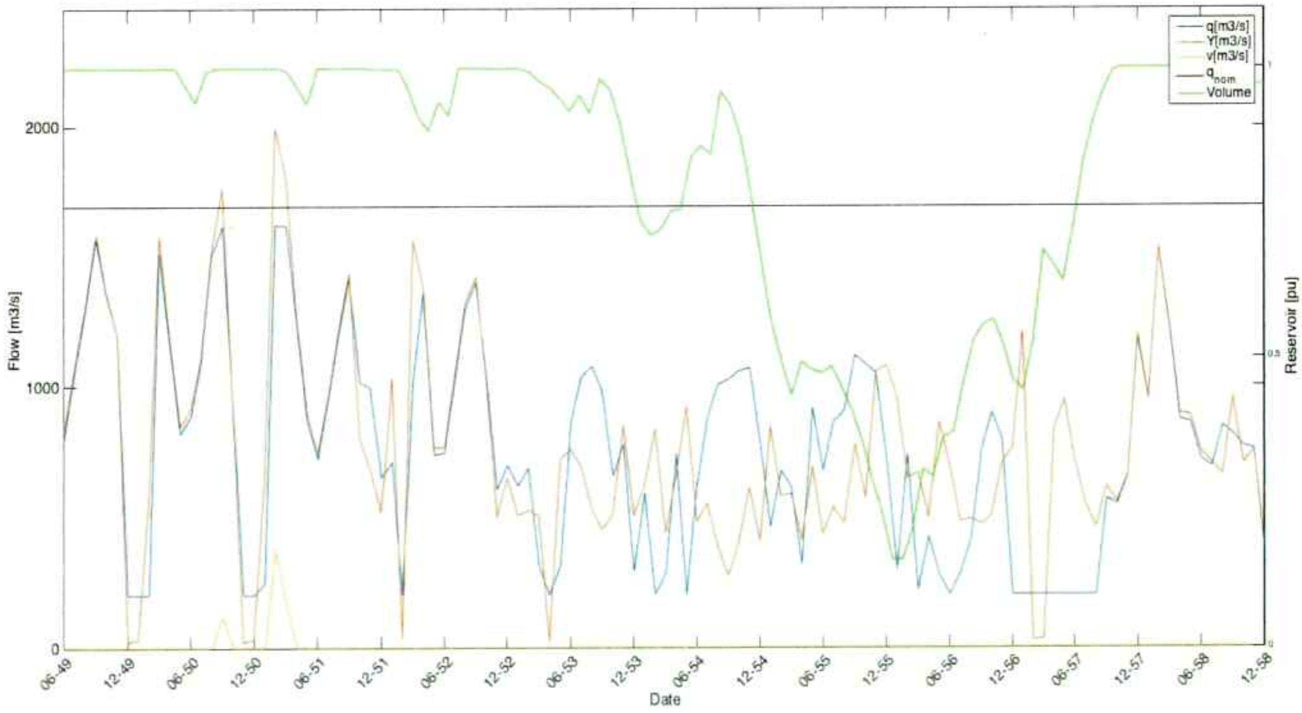

Figure 7.17 – Water flow in the Furnas Dam (Case 1)

In case of the Catalão EPS, since its storage capacity is much smaller, it has a smaller regulation capacity, also, it is linked to a much smaller hydroelectric power plant, Serra do Facão with an installed capacity of *213 MW*. Therefore, it doesn't affect that much the system as a whole like the Canastra EPS. In 1951, was a very humid period having a big inflow that had to be spilled since the Catalão EPS was already full. And looking into the system's storage in that period, it was still full, being it before the drought, creating the possible spilled energy from Figure 7.12.

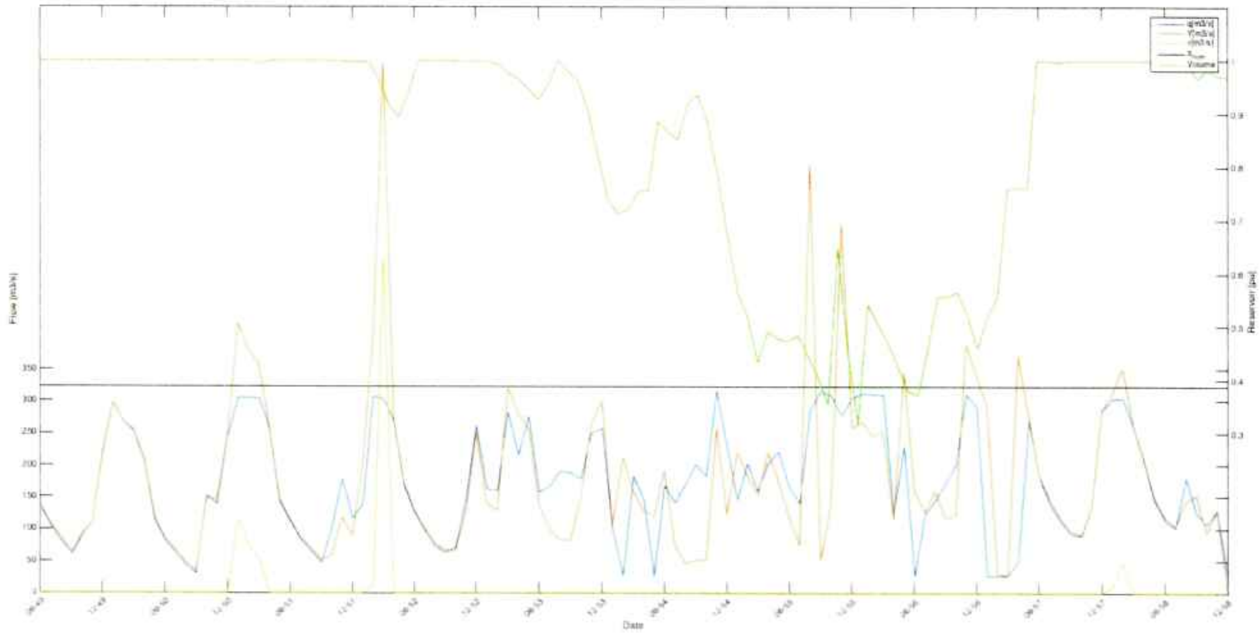

Figure 7.18 – Water flow in the Serra do Facão Dam (Case 1)

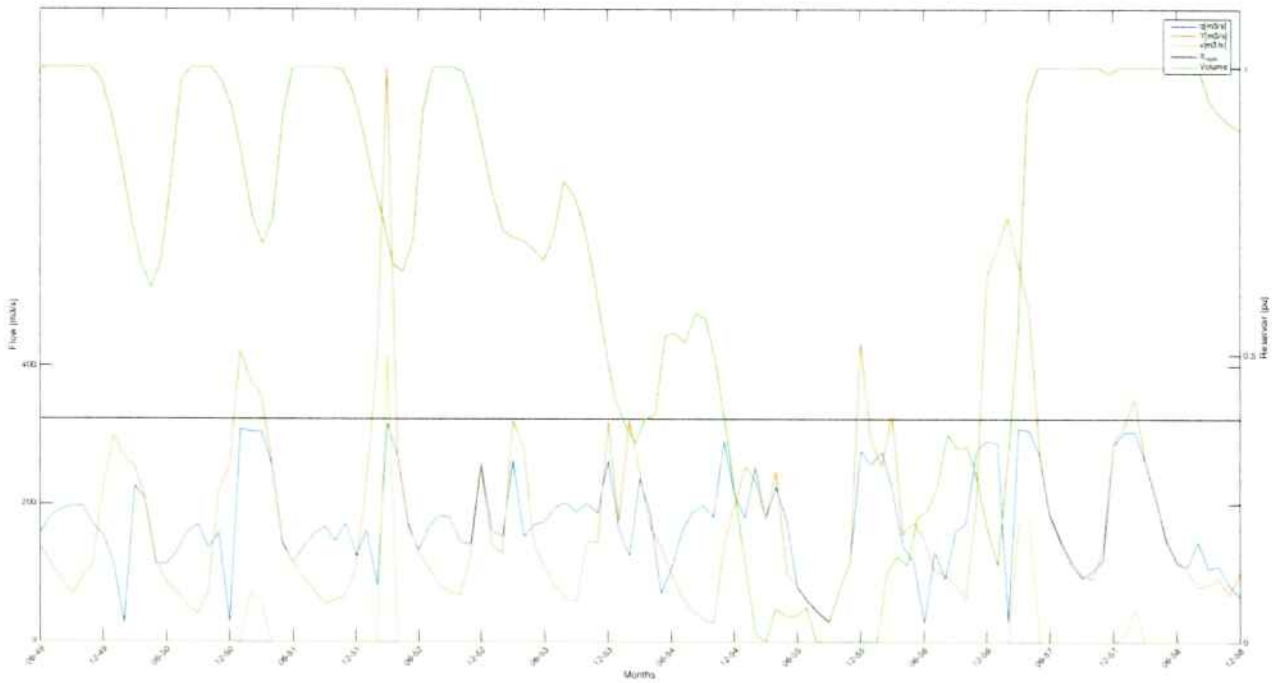

Figure 7.19 – Water flow in the Serra do Facão Dam (Case with no EPS)

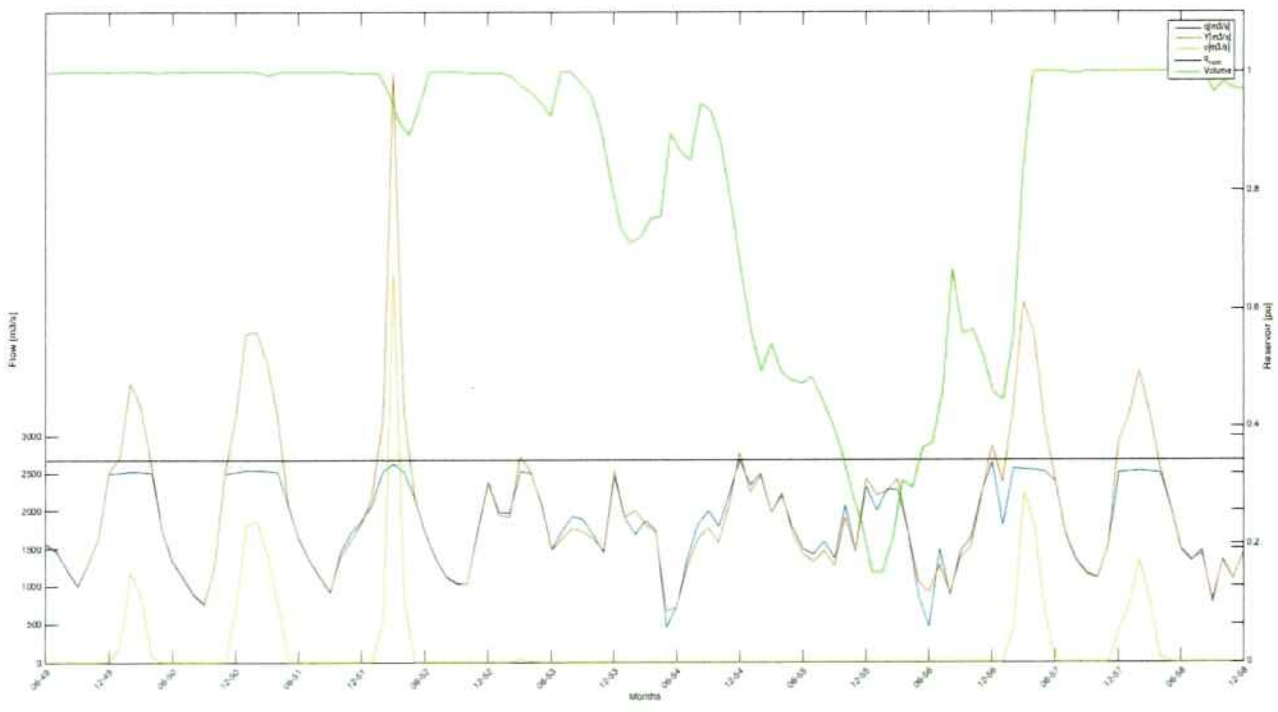

Figure 7.20 – Water flow in the São Simão dam

From a seasonal point of view, the creation of an EPS wouldn't have much difference from simply creating a new hydroelectric dam in the river, increasing greatly the storage capacity of the system. Besides, this case only proved that through a higher storage capacity in the system, it would be able to ensure the system's demand in a severe drought as it was predicted.

It was considered the 1950's decade only since it was the highest drought in the historical series, being easier to see this effect.

In the next section it will be analyzed in the hourly point of view where the daily peak of load may be compensated by the stored energy at night.

7.2 Hourly Analysis Output

In this analysis context, it was decided to evaluate only the system as one, not seeing each plant individually. Being so, the graphs shown bellow will take only the system altogether, not showing the individual generation aspects of conventional hydroelectric power plants.

Also, from now on, the hydraulic system from Figure 7.1 is incorporated with the four different wind farms described in Chapter 5. In every case it will be considered that the wind farms have a physical guarantee of 10% of the installed hydroelectric power being equal to 3.379 MW. It was then established the following division among the four fields with installed capacity and physical guarantee.

Table 7.1 – Installed Capacity in each Wind Farm

Field	Power (MW)	CF	Physical Guarantee (MW)
1	2.570	0,51	1322,44
2	1.687	0,40	679,56
3	1.496	0,54	812,10
4	1.313	0,43	563,89

Initially was adopted a premise where the energy consumption from the plants was not considered as a constraint for it to work. The next case will show the results from this premise. However, they were not satisfactory since the energy consumption constraint is too important to evaluate the uses and benefits of an EPS.

Then, it was decided to simulate a new case where it was incorporated the constraint where the EPS would be able to pump water only from the exceeding energy in the same system.

Lastly, it was created a stress case, where the wind generation was increased, the peak and off-peak load difference and also the minimum outflow at the dams with reservoir. Besides, instead of considering the reservoir capacity established by (HUNT, 2014), it was used a much smaller reservoir in order to use it in a daily basis. In its section will be explained how it was dimensioned.

7.2.1 Case 2 – Without Energy Consumption Constraint

The first case with an hourly discretization has the file *HourAnal-Load_M_P0.5808M_OffP0.5379H_P1.4H_OffP0.86667_Vol50_Volpump50_GApop4m0.055c0.475It_5-2_Year1989-1989.mat* as base, where it was used the nominal load as described in Chapter 6. Besides that, it was considered the reservoirs to be half full at the beginning of the analysis that was taken place with the inflows and wind generation from 1989. Another consideration about this case is that it was not considered the energy available in the system as a constraint for an EPS to pump water. It was considered that if it was available it would be consumed when it was possible, however, if according to the pumped flow determined in the GA, it was required a larger amount of energy than available, it was supposed this energy would come from another source.

First analyzing the power generation profile of a year, in Figure 7.21 is represented the graph with the analysis during the whole period. It is hard to analyze the whole period because of the amount of data. There are 4 different areas as it is explained in the legend. Light blue represents the energy from the system that was consumed by an EPS to pump water to the superior reservoirs which is assumed to come from the wind source when available, dark blue is energy generated from wind sources to attend the load, red represents power generation from EPS plants, green is the power generation from conventional hydroelectric power plants from the system and they are all linked to the black line that represent instantaneous demand.

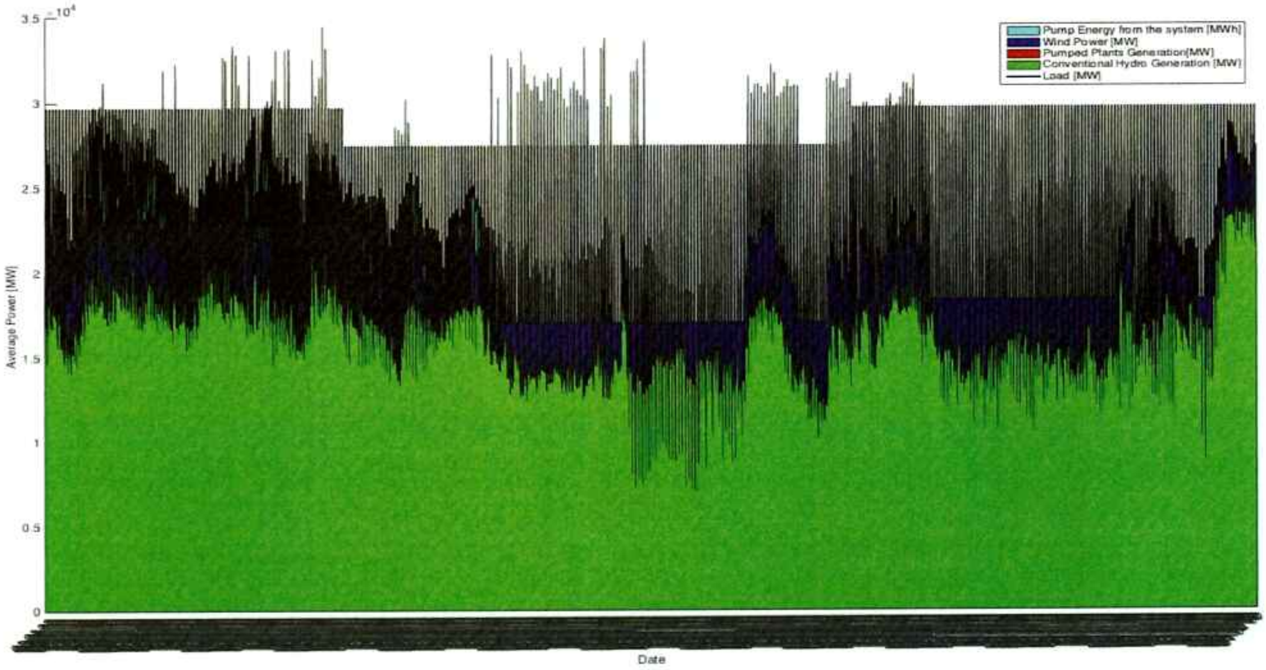

Figure 7.21 – Power Generation Profile and Demand (Case 2)

To facilitate the analysis, it is useful to zoom into certain periods. In Figure 7.22 is represented the generation profile in the first week of May. It is possible to see the peak load represented and components of generation profile. Observe how the pumped facilities reverse their flow sense in order to compensate and reach the required load. While after the peak hours of the day, it starts to pump water in order to fill the reservoir. In Figure 7.23 it is possible to see the reservoir variation along the same week, how it empties during the peak hours of the day and fills in the remaining periods. It is also represented the water fluxes at Canastra EPS that is responsible for most of the generation by pumped plants. Its sense follows the demand profile as predicted in order supplying all demand and managing to store maximum of water possible, spilling only when required.

They lowered the amount of energy that was spilled by the system, there is still some spillage in the off-peak hours however in this period, but it would be greater without the EPS.

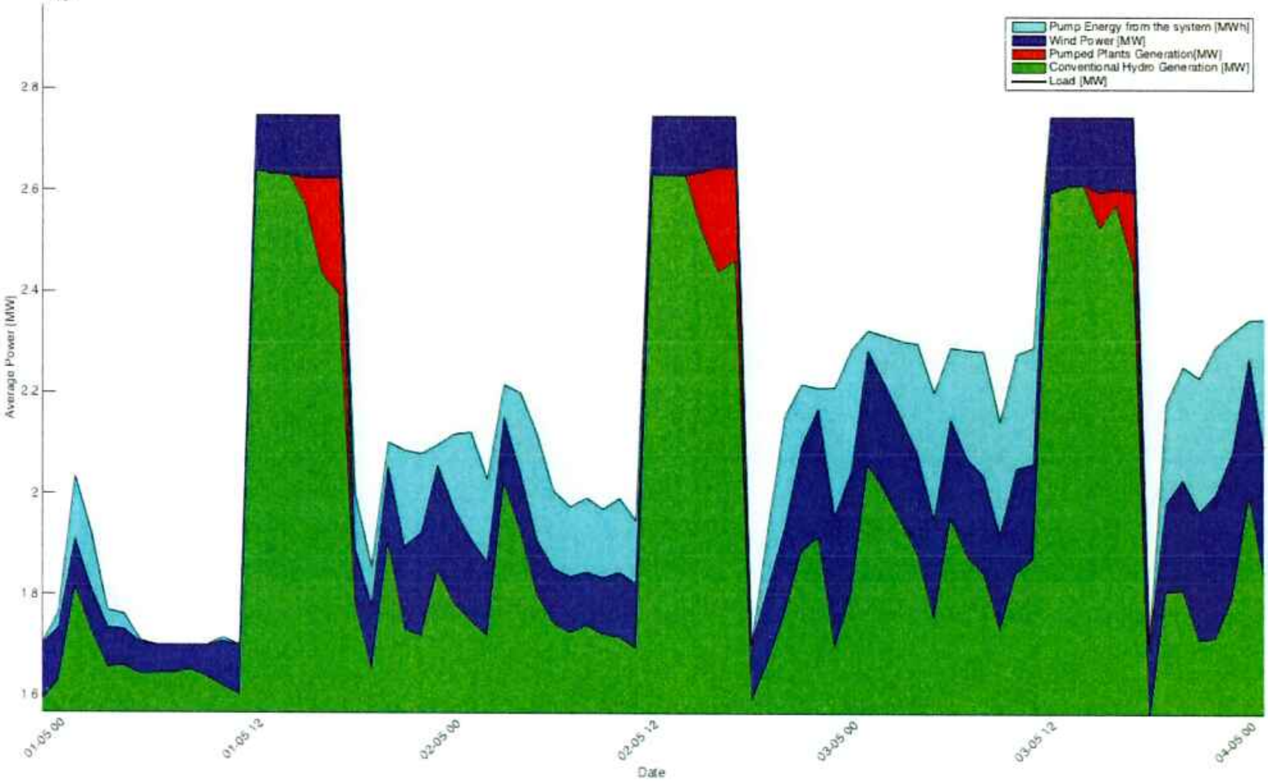

Figure 7.22 – Generation Profile in the first week of May (Case 2)

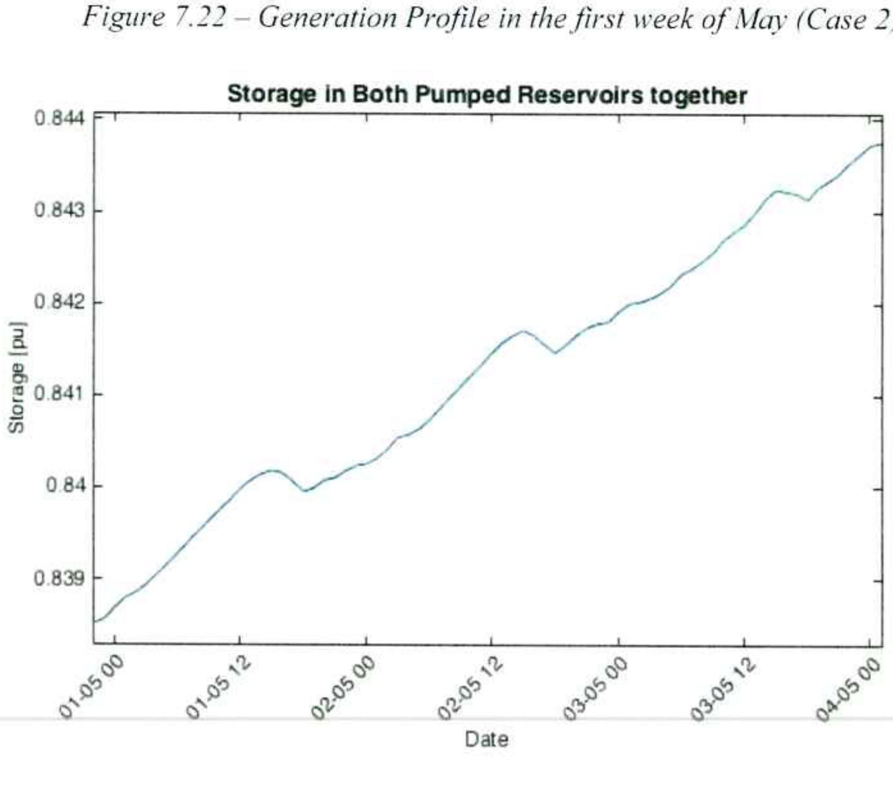

Figure 7.23 – EPS Reservoirs in the first week of May (Case 2)

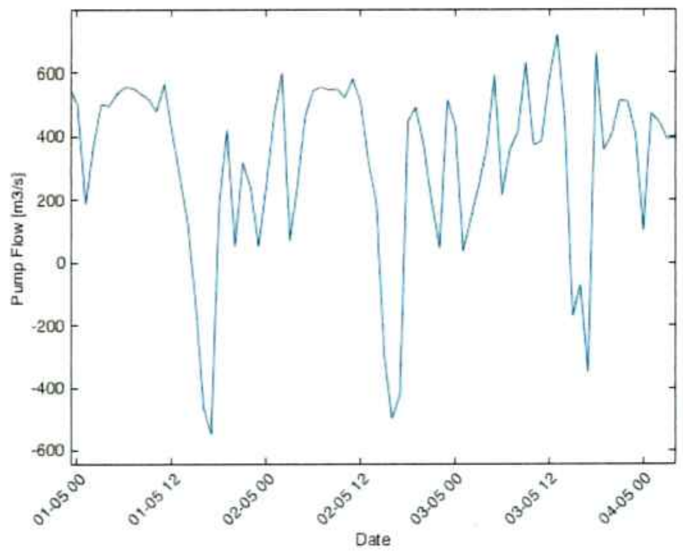

Figure 7.24 – Pump Flow at Canastra EPS in the first week of may (Case 2)

Taking another period to analyze, for example, between October 16th and October 23rd it is also possible to see the results. It is the same situation presented before, however during this period, being the end of the dry period of the year, the pumps are not emptying themselves as easily as before, trying to store the maximum amount of volume to avoid an eventual shortage of energy.

Also it is noticeable that Canastra EPS is always operating close to its nominal capacity during this period, but, since it was not constrained the availability of energy for pumping in this case and it is demanding an amount that should come from a near system, since at some times it is pumping in the peak hours and as it can be seen in Figure 7.27, it doesn't use any available energy from the same system since its generation is reaching exactly the required load at this time.

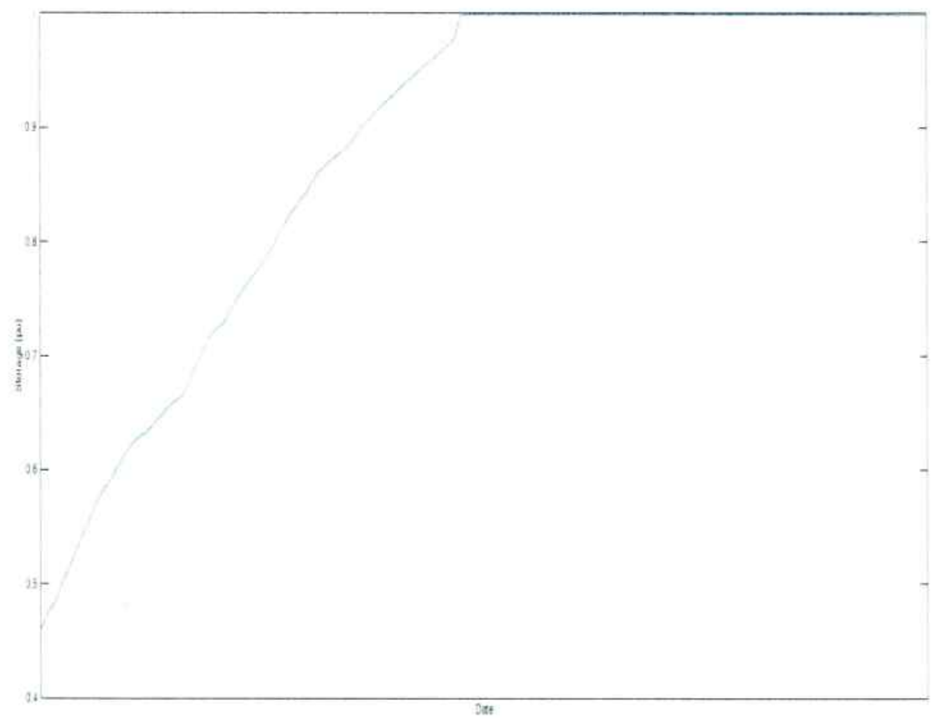

Figure 7.25 – Canastra Reservoir Level along the year of study (Case 2)

It is important to analyze the amount of energy available at the network in order to have a more real situation where it is not used an infinite amount of energy in order to store in the PSP. In the next case it was established a constraint where all the energy consumed by the pumps must come from the system itself.

This case however is a starting point to begin understanding the daily behavior of a system with the EPS facilities installed.

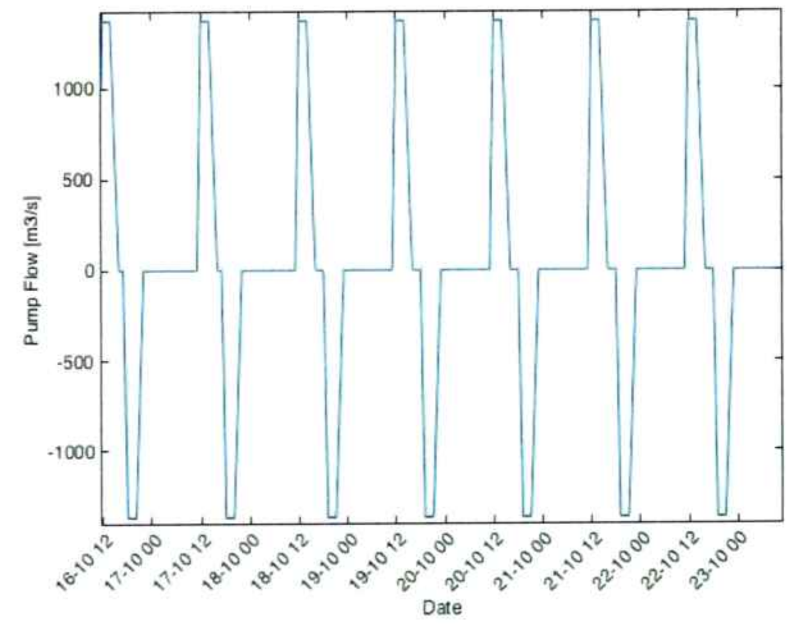

Figure 7.26 – Water flow at Canastra EPS between October 16th and October 23rd (Case 2)

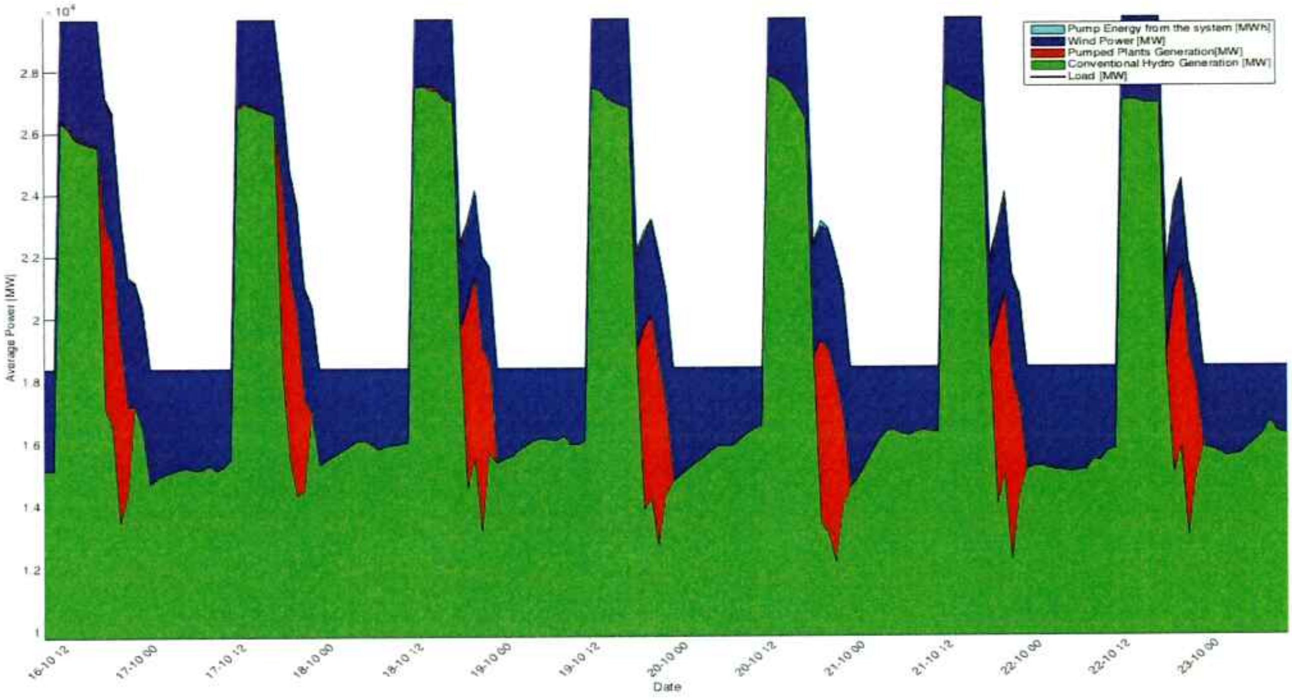

Figure 7.27 – Generation Profile between October 16th and October 22nd (Case 2)

It is already evident that their presences collaborate to fill the power generation in way to compensate the intermittent energy created from the wind sources, represented by the blue area in Figure 7.27.

In Figure 7.21, it possible to observe a series of peaks superior to the demand (recognizable by its horizontal profile with two levels along the year), this happened due to an iterative problem where after it didn't converge onto the exact demand load. As it can be seen in Figure 7.28 the reservoirs were not full and the system still wasted energy. In the next case after limiting the power consumption by the pumps on the energy available at this system, the iterative process should converge more easily.

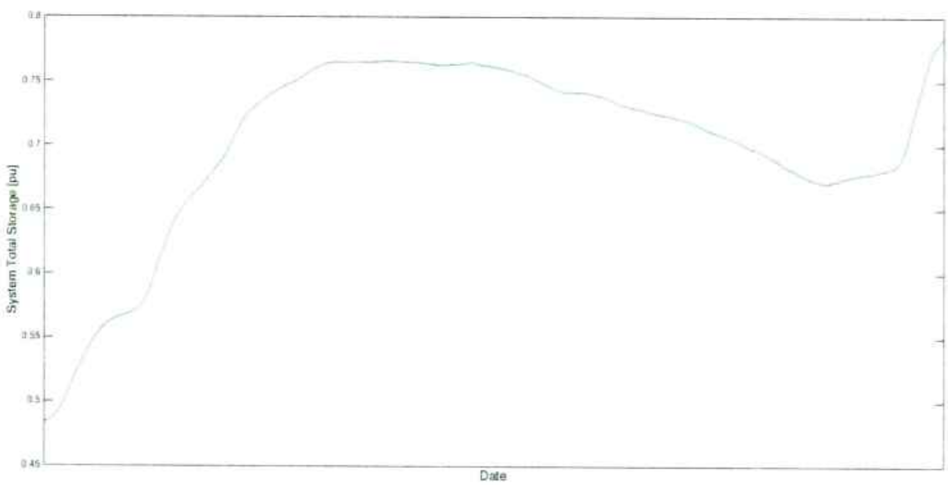

Figure 7.28 – Total storage of the system (Case 2)

Also, to compare with the wind generation, in Figure 7.29, it is noticeable how the pumps work according to the profile of wind generation, following its ups and downs in the first half of the year. When the wind generation is high the pumps work in way to store the energy while when it goes down, there is a decrease in the pumped flow and also an inversion of the operating sense.

Looking into Figure 7.30 with the wind profile in the first week of May, it is noticeable how the wind profile is complementary to the daily load. During the night, usually it winds more, so that the generation from wind farms is increased as it can be seen by peaks registered around midnight. However, at the same time, it is an off-peak period of the day. This way, it is beneficial for the system to store this extra amount of power that comes from wind farms. In Figure 7.24 with the pumping flow at Canastra, the pumps reverse their sense at night, storing the extra energy coming from the wind farms in a way that it can use in the next day to attend a load peak.

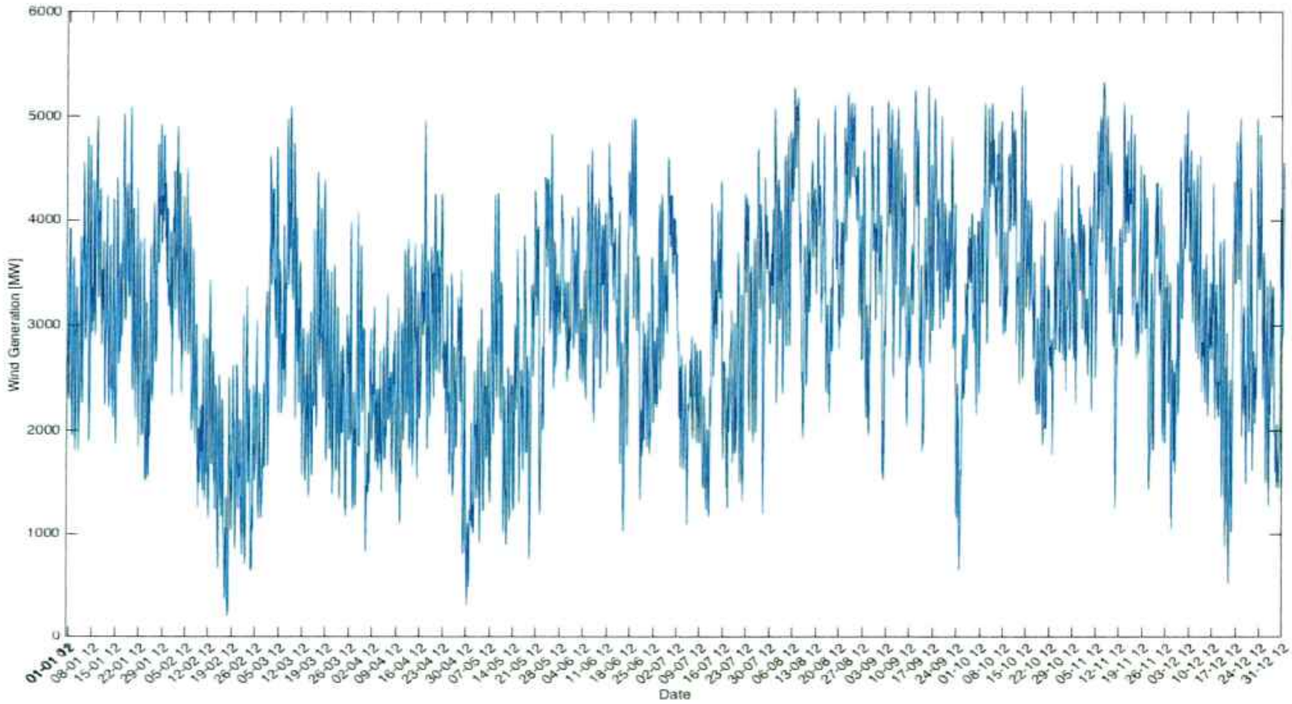

Figure 7.29 – Wind Generation Profile in 1989 (Case 2)

When it arrives to the end of June, the Canastra EPS starts to operate always near to its nominal capacity according to Figure 7.33, oscillating between pumping and generation modes. This happened because as it can be seen in Figure 7.25, its reservoir filled completely.

Now considering that in this case there isn't an energy consumption constraint, it is logical that it compensates to be always filled, pumping the maximum amount of energy and then when it is full to switch onto generation mode, so that in average the reservoir stays always filled.

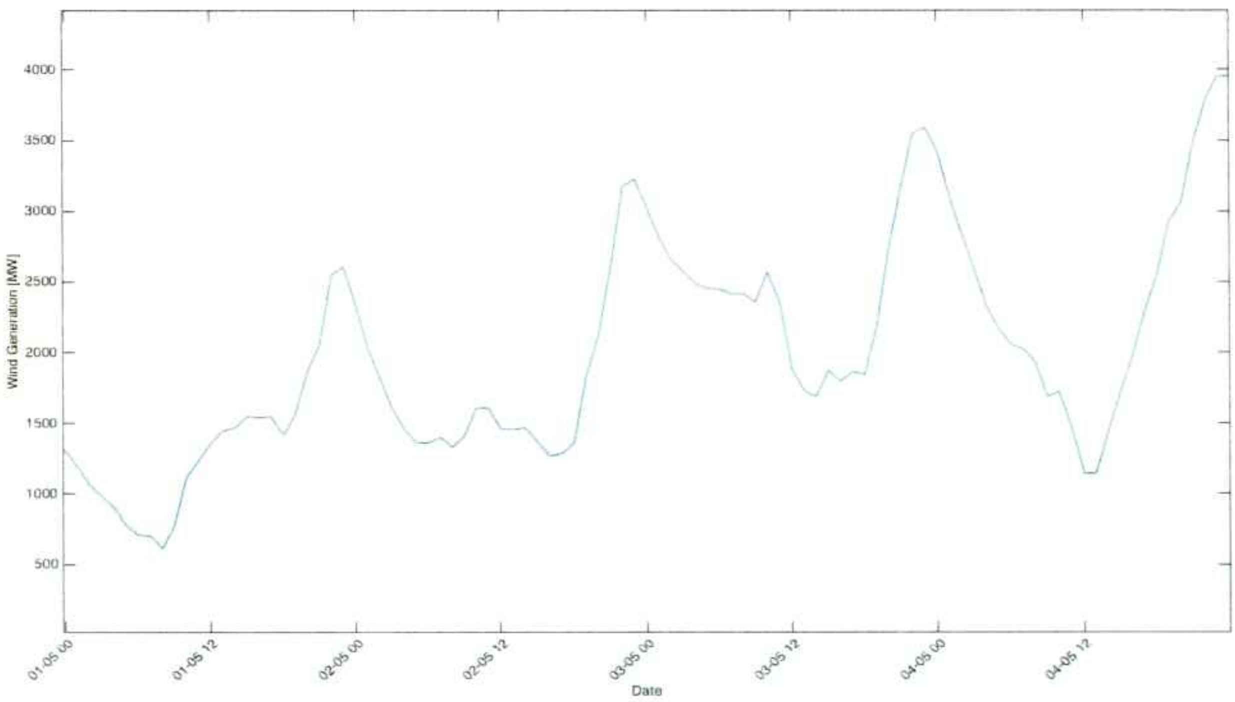

Figure 7.30 – Wind generation profile in the first week of May (Case 2)

The same cannot be said about the Catalão EPS. As it can be seen in Figure 7.31, it reaches its maximum volume only in the end of the year when its pumped flow also starts to be more constant to its maximum nominal capacity.

Looking into the seasonal influence along the year, it is also recognizable two very distinct seasons in the pumped flow profile. Ignoring the last half of the year in the case of Canastra, given its abnormal behavior due to the unconstrained power consumption by the pumps, in the wet season, in the beginning of the year, the pump-turbine unity of both EPS are operating with higher fluxes given that there is a more abundant arrival of water. And they operate in generation mode only to compensate the peak loads along the day; meanwhile, in the remaining hours, it is pumping water and storing energy for the dry season.

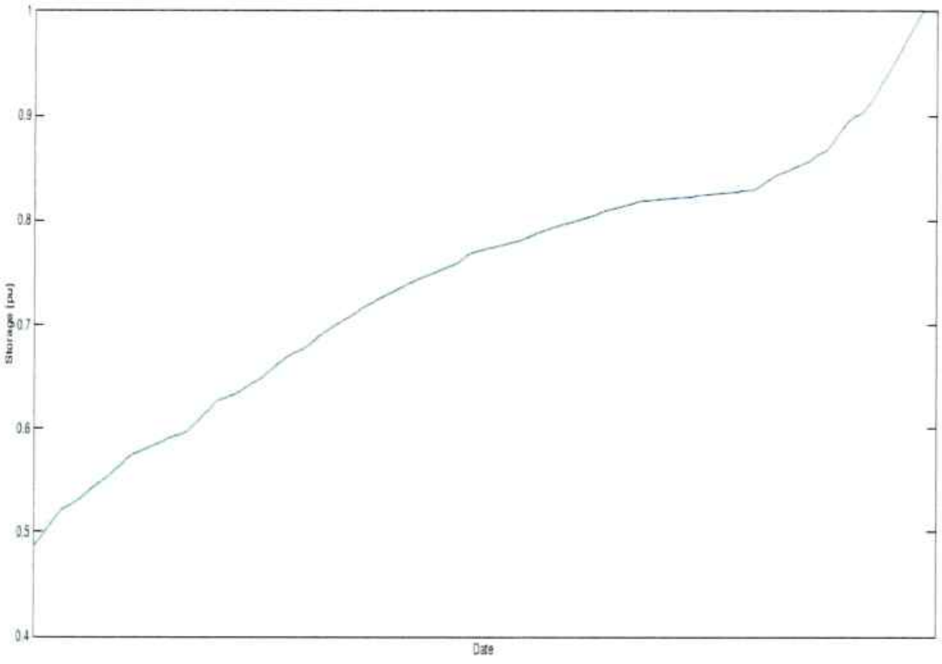

Figure 7.31 – Catalão Storage Level along the whole year of study (Case 2)

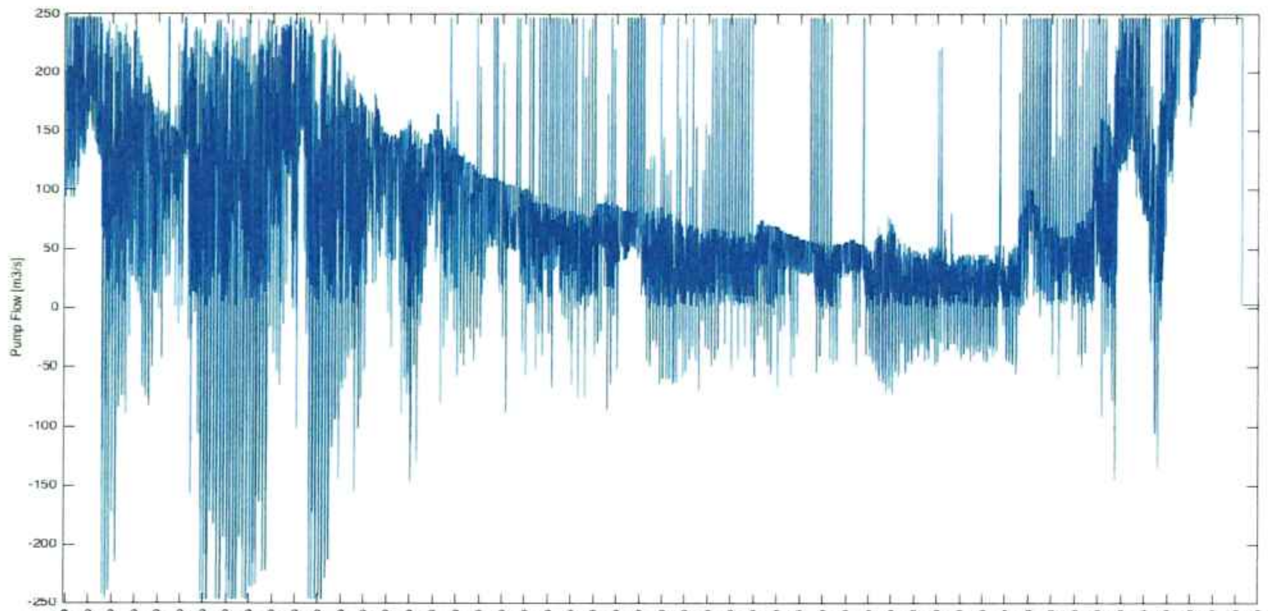

Figure 7.32 – Pump flow at Catalão (Case 2)

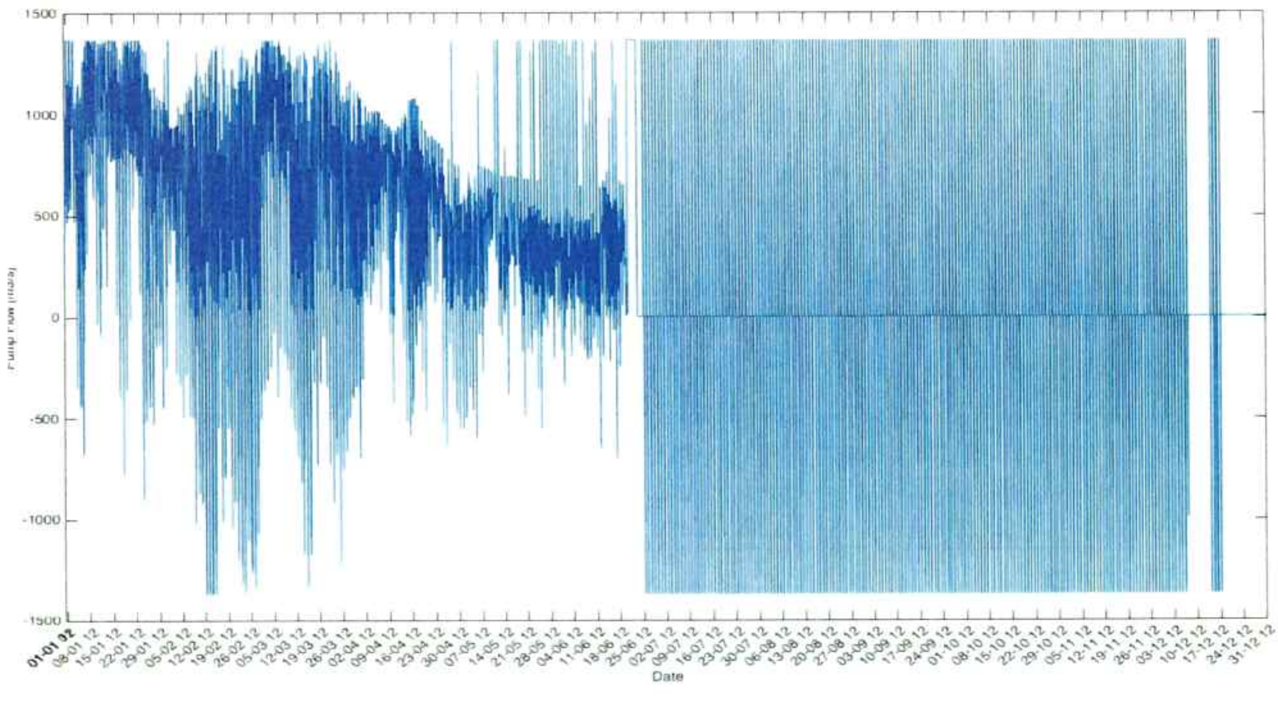

Figure 7.33 – Pump flow at Canastra (Case 2)

When the dry season arrives, considering that the system is managing to attend most of the load as it can be seen in Figure 7.34, both EPS continue to store water, only at a smaller rate as it is visible in the pump flow graphs of both facilities.

Such as it was seen in the seasonal analysis, the inclusion of the EPS is showing to be an effective way to store energy to attend a drier season, as well as to balance the peak loads along the day. However an important constraint was ignored in both cases, which was the energy consumption by the pumps. In the next case it will be considered that the EPS is only able to pump water into its superior reservoir in case of an availability of energy in this same system.

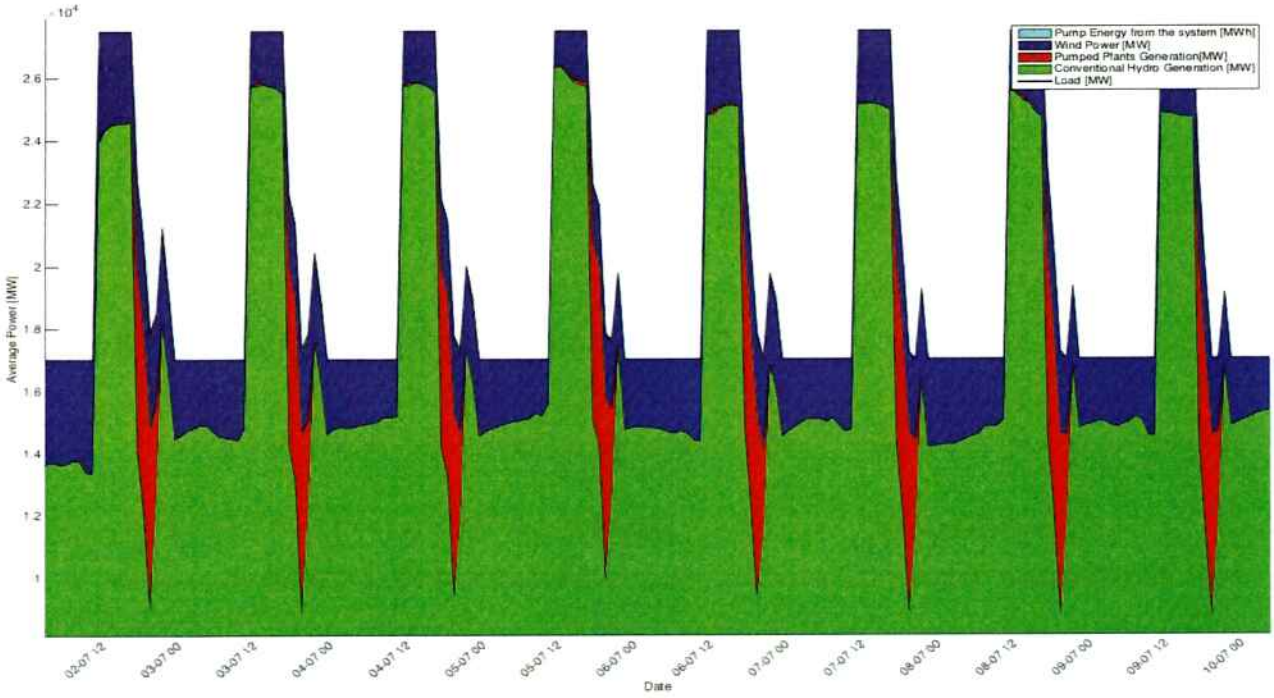

Figure 7.34 – Generation and Demand profile in July (Case 2)

7.2.2 Case 3 – Including the Energy consumption constraint

In this case it will be considered the output from *HourAnal-Load_M_P0.5544M_OffP0.51345H_P1.4H_OffP0.86667_Vol50_Volpump50_GApop4m0.035c0.483It_5-3_Year1990-1990.mat.*

It was taken a population of four individuals and with a maximum of 5 iterations using data from 1990. Both conventional and pumped reservoirs were with 50% of its volume in the beginning of the simulations and it was used a load 5% greater than the nominal load established before to observe better the effects of a PSP in a daily profile.

Also, after the analysis of Case 2, it was observed that without constraining the used energy by an EPS produced unsatisfactory results since, as it can be seen in Figure 7.26, Canastra operates at full capacity always filling itself along the study. It was then decided to include this constraint, given by $E_{cons\_pump}(t)$ in the next cases. The energy balance equation becomes:

$$E_{balance}(t) = W(t) + H(t) + E_{gen_{pump}}(t) - E_{cons_{pump}}(t) \geq D(t) \qquad (7.4)$$

where $W(t)$ is the Wind Generation, $H(t)$ is the Conventional Hydroelectric Generation, and $D(t)$ the load the system must attend to.

This was an important constraint established in the model allowing a deeper study of the benefits in including an EPS in the system.

All this considered, after five iterations the following optimized results were found.

Figure 7.35 represents the generation profile along the whole year 1990 and in the subsequent graph it is zoomed into a week of February. In this graph it is represented in red the energy generated by the EPS, in dark blue the energy from wind farms, in light blue, the energy consumed by the EPS and in green the energy generated from conventional hydroelectric plants. The total power generated is represented by a dashed line and it is given by Equation 7.5.

$$E_{gen_{total}}(t) = W(t) + H(t) + E_{gen_{pump}}(t) + E_{cons_{pump}}(t) \qquad (7.5)$$

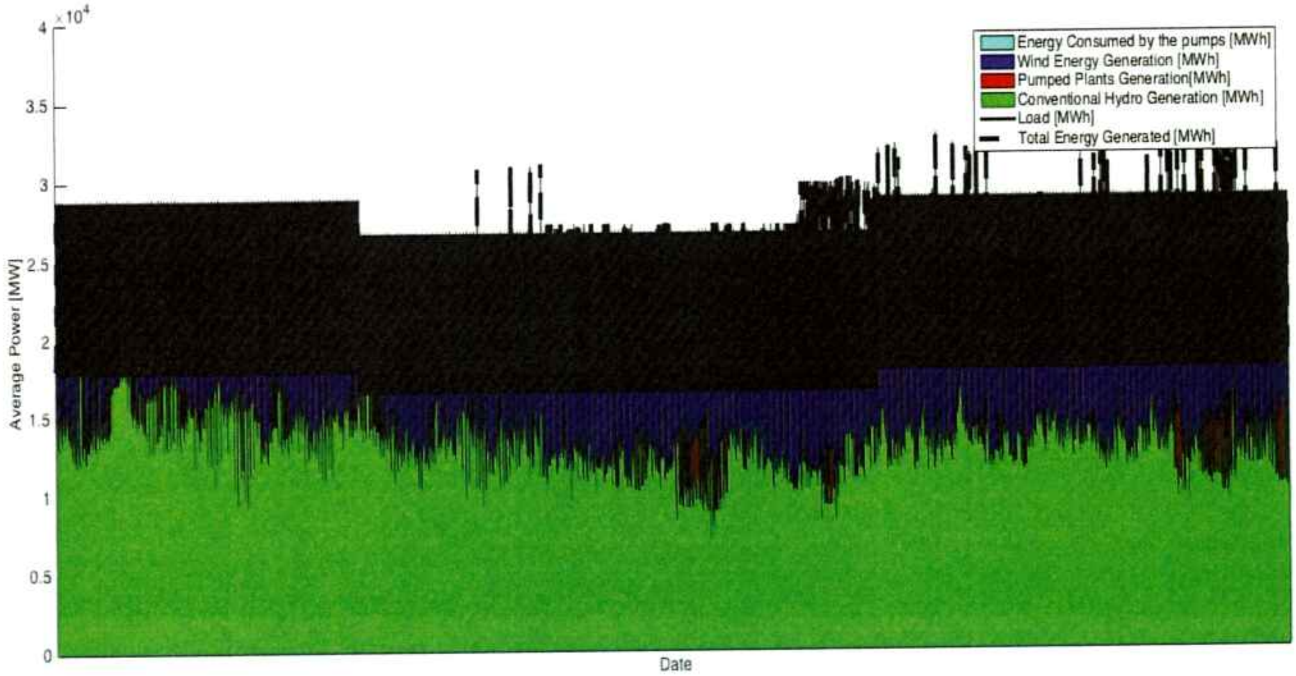

Figure 7.35 – Generation Profile in 1990 (Case 3)

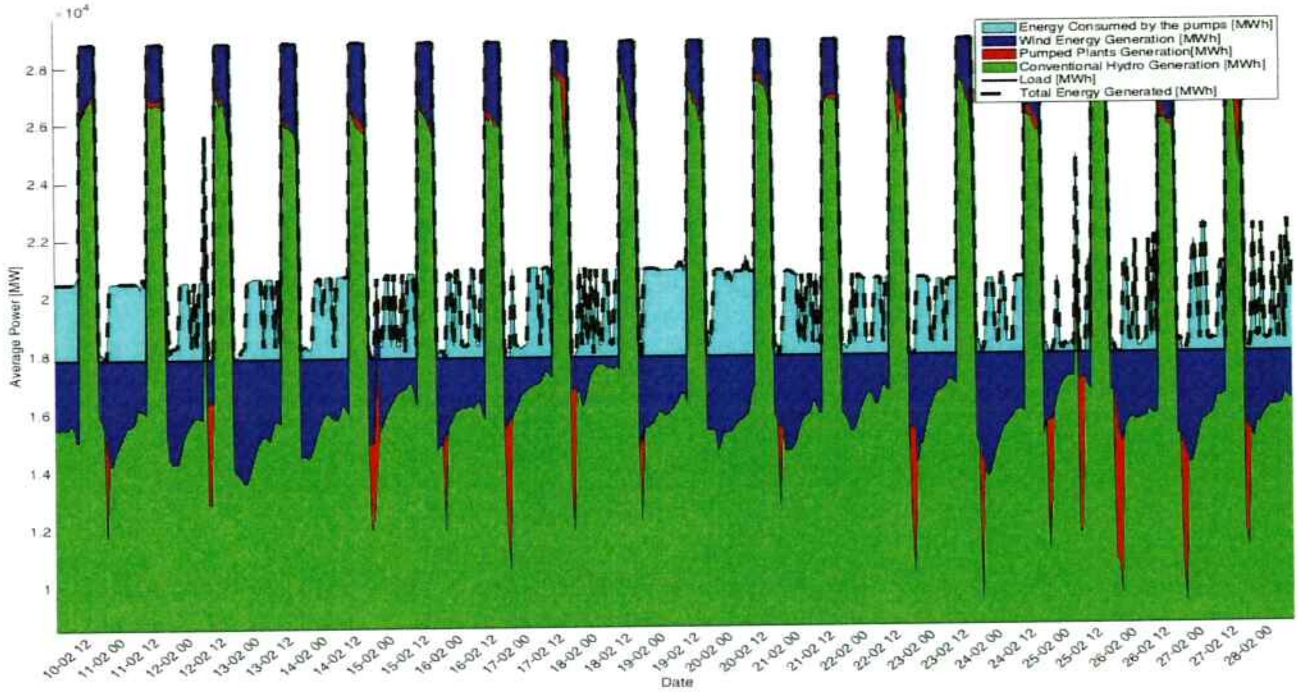

Figure 7.36 – Generation Profile in February

Looking into Figure 7.36, it is represented the main functionality aspect of a PSP. Along the night, when the winds are more intense and load is smaller, the EPS is consuming energy, and the conventional hydroelectric plant added to the wind sources supply this load added by the pumping consumption. This way, in the following day, during the peak hour when the wind generation is much smaller, as it can be seen by the dark blue area, the EPS is able to change its operational sense and supply the system in way to attend all the required load.

Also, comparing to the previous case that was taken place in 1989, this case also shows that the wind generation profile has a tendency of generation peak at night.

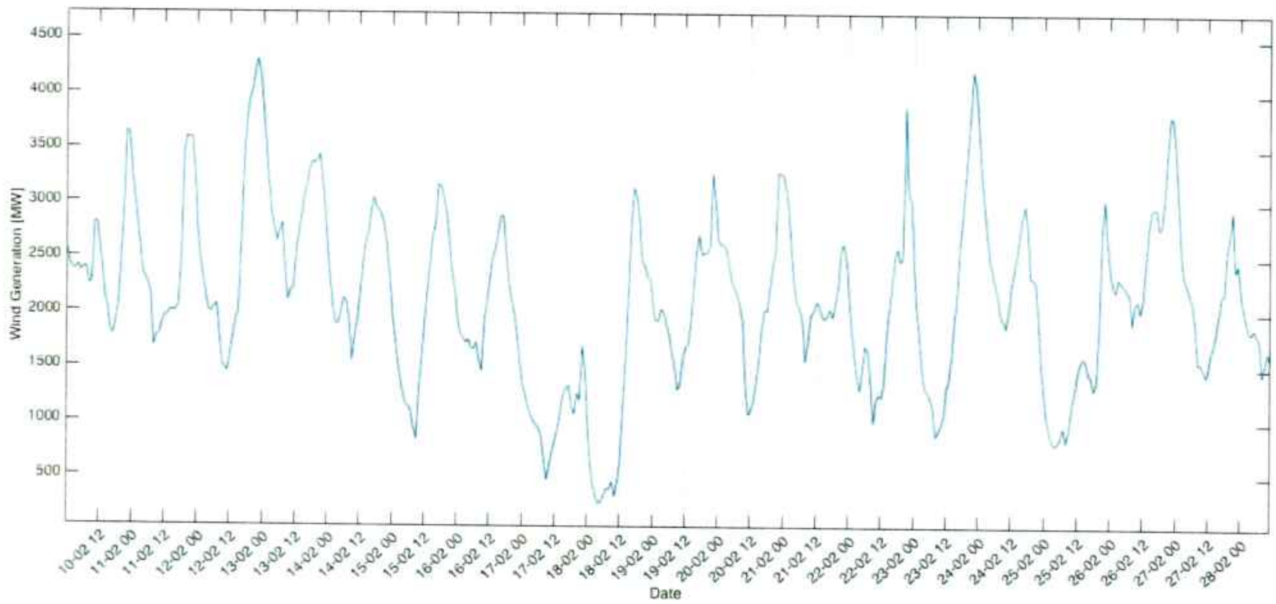

Figure 7.37 – Wind Generation Profile in February

At the same period, the pumping sense at Catalão and Canastra work in way to compensate the generation from the wind sources, creating the generation/consume profile established in Figure 7.36. It is interesting as well that both EPS keep a flux of water when pumping more stable and much bellow the nominal capacity of the plant, meanwhile when generating energy it has peaks of generation with a flow very close to its nominal capacity.

This happens because of the availability of energy in which the pumps depend and is mostly variable according to the wind profile. For example, it is noticeable that on

February 18th, near to midnight, there is big drop in the wind generation, getting close to zero.

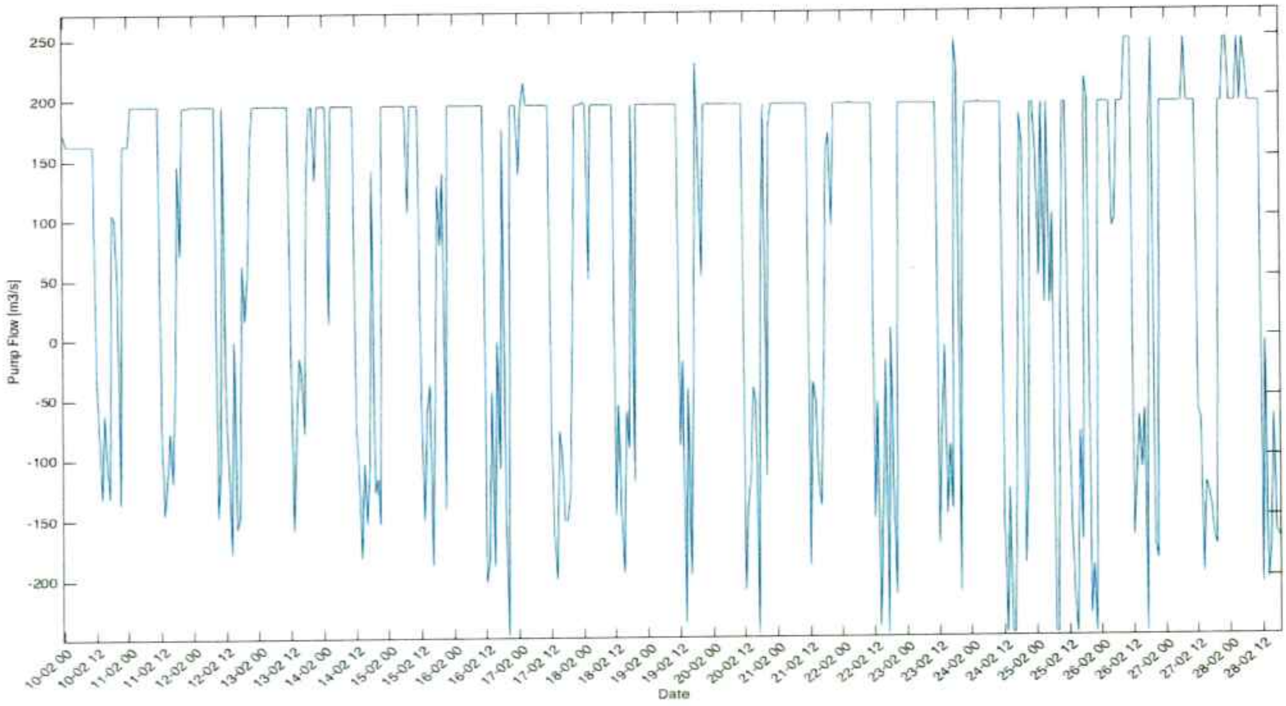

Figure 7.38 – – Pumped water flow at Catalão in February (Case 3)

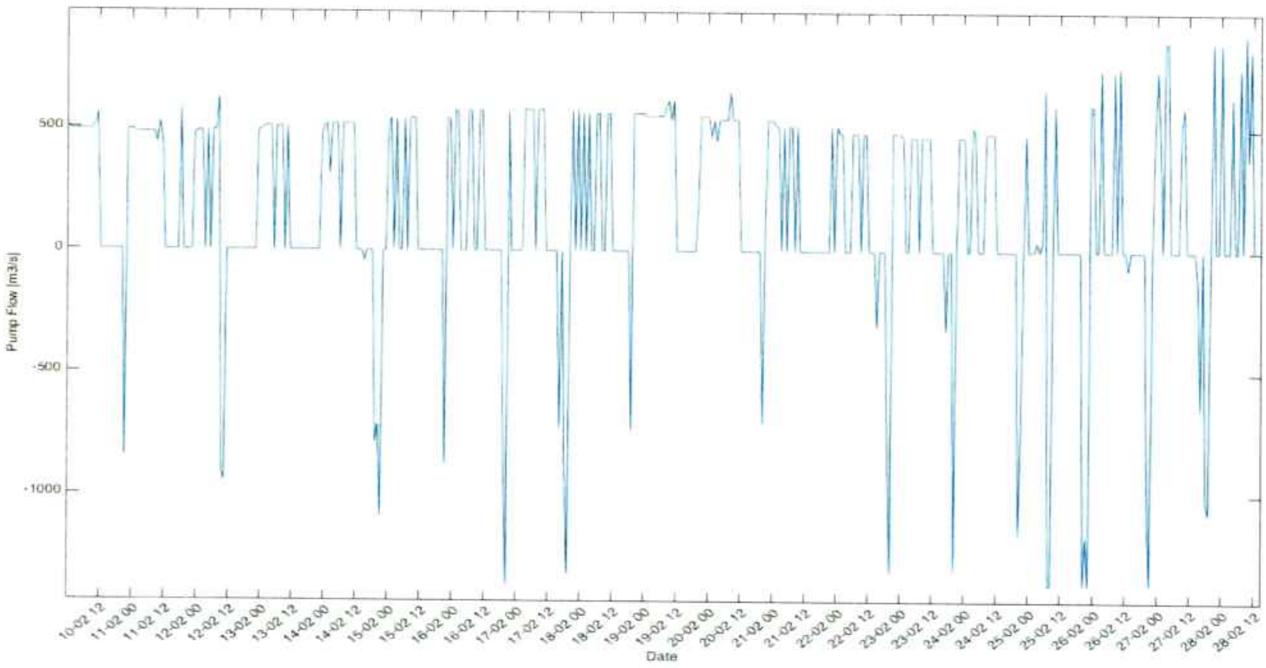

Figure 7.39 – Pumped Water Flow at Canastra in February (Case 3)

When that happens, both EPS, including Canastra, which was turned off in the previous hour, inverted their working sense with a high flux going through the turbines to generate the amount of energy required to compensate a decrease in the wind generation. Observe that this happened not only in the peak-hours, but since the wind generation was bellowing average also at night it is observed a generation by both EPS.

The same effect can be observed along the year for a few times given the high variability of the wind generation and the volatility of the EPS to adjust to a variable generation profile.

Looking into the one year horizon of the EPS operation, it is possible to see at Canastra that most of the time it is operating in way to fill the reservoir, always storing more energy than consuming, which happens mostly in the peak hours of the day. This is due to the size of the reservoir that was dimensioned by (HUNT, 2014) to be a yearly cycle reservoir.

However, from May on, it is possible to notice an increase in the turbine mode of the EPS while the pumping operation mode is reduced given it is in a dry season of the year and it becomes important as a backup reservoir for the whole system.

A similar effect happens at Catalão, that when the dry season begins, it reduces its pumping mode keeping oscillating between both modes, but always emptying its reservoir more than filling.

This can be verified seeing both the tendency of the pump flow in the facilities as well as its reservoir level in that period represented in Figure 7.43 and Figure 7.44, how they decrease in the dry period allowing the conventional reservoirs to remain stabilized in this season.

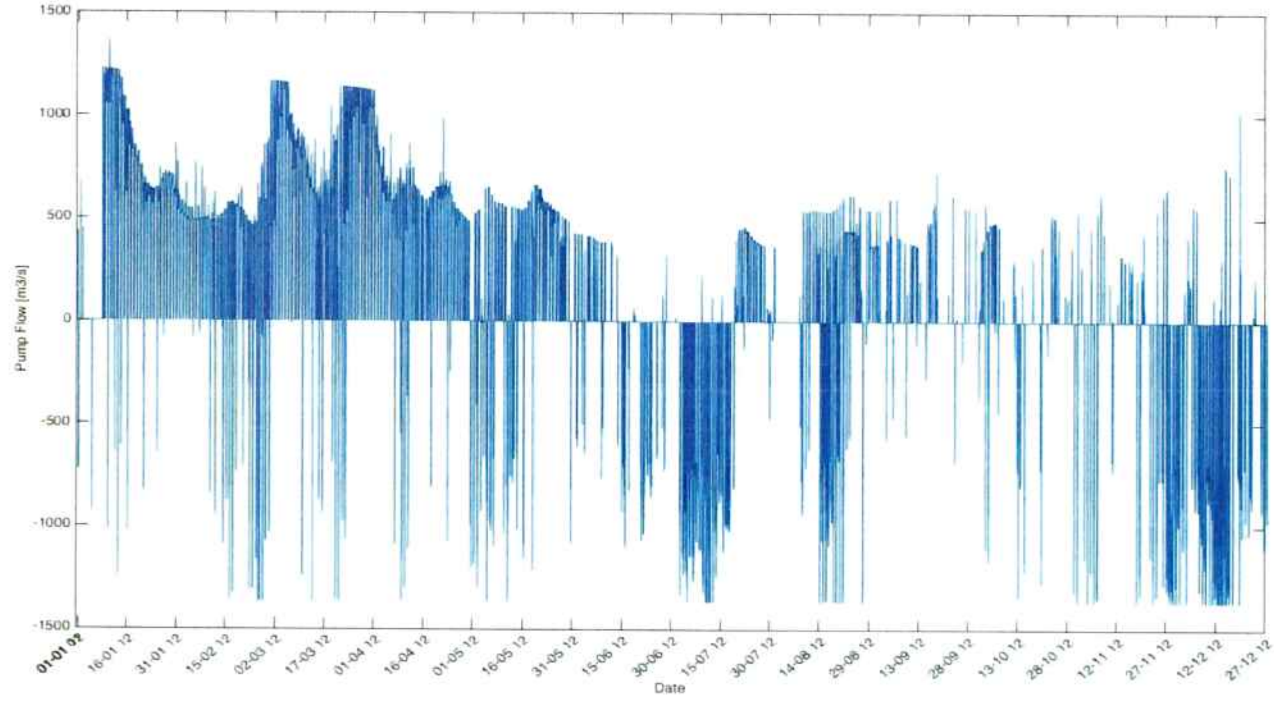

Figure 7.40 – Pumped flow at Canastra (Case 3)

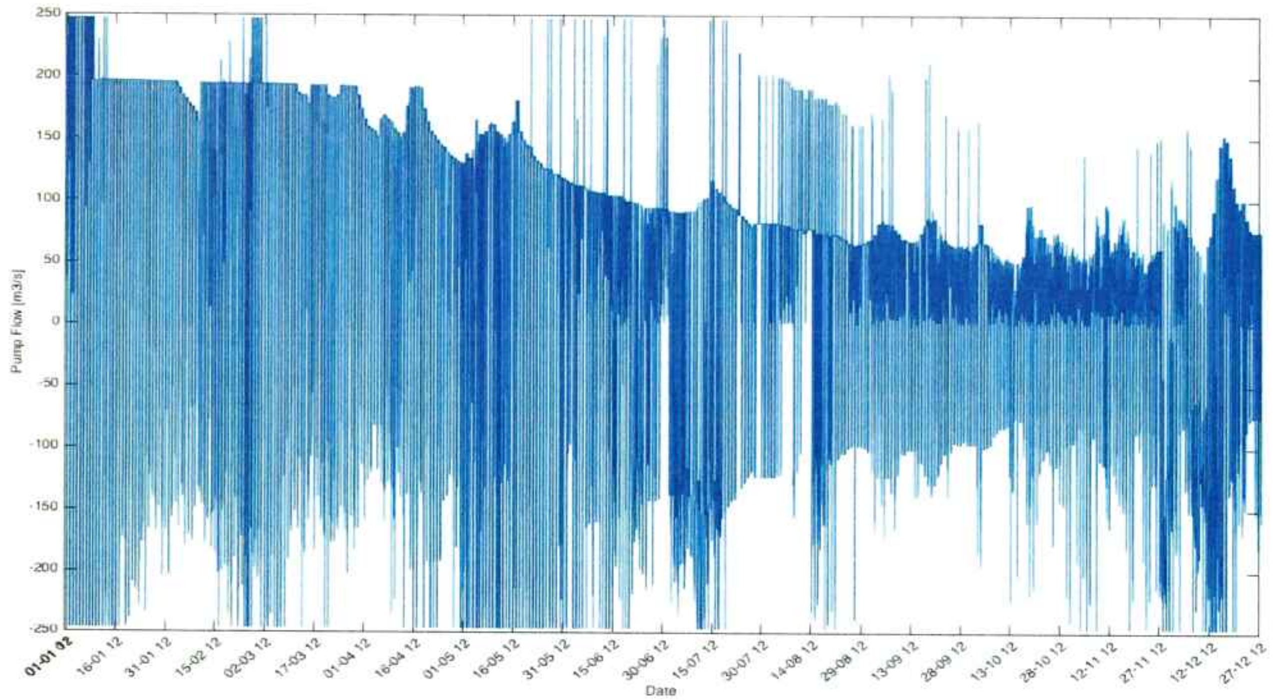

Figure 7.41 – Pumped flow at Catalão (Case 3)

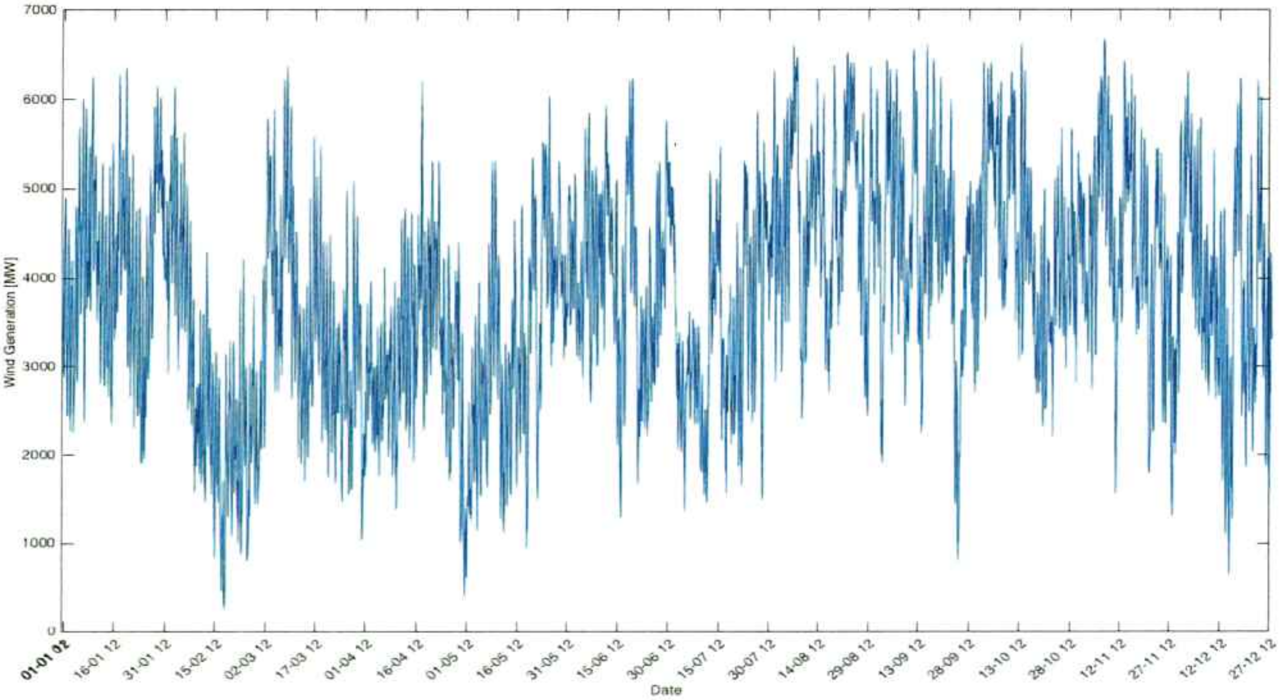

Figure 7.42 – Wind generation profile in 1990 (Case 3)

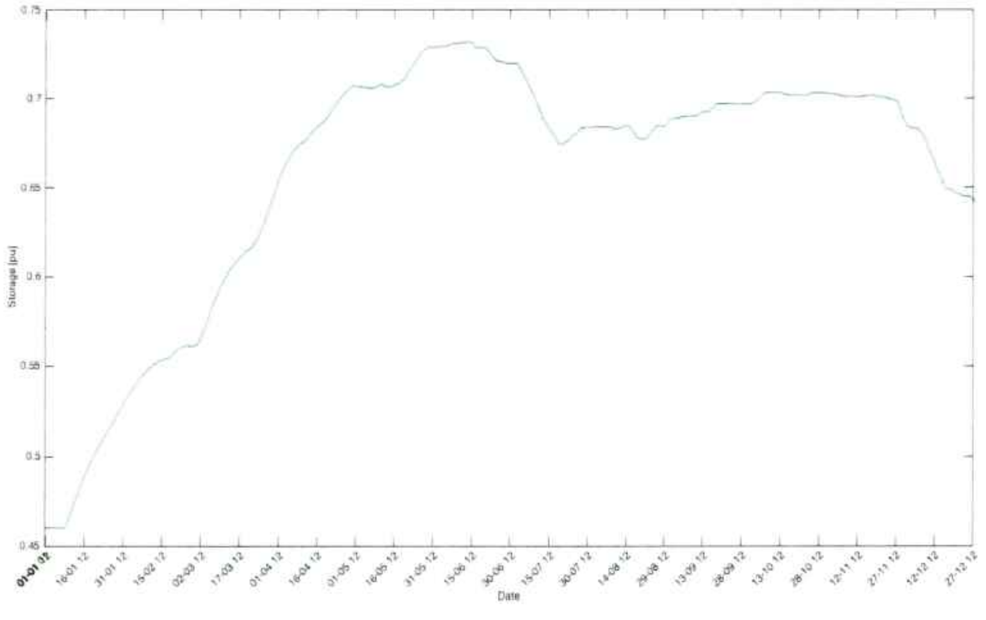

Figure 7.43 – Reservoir Level at Canastra EPS (Case 3)

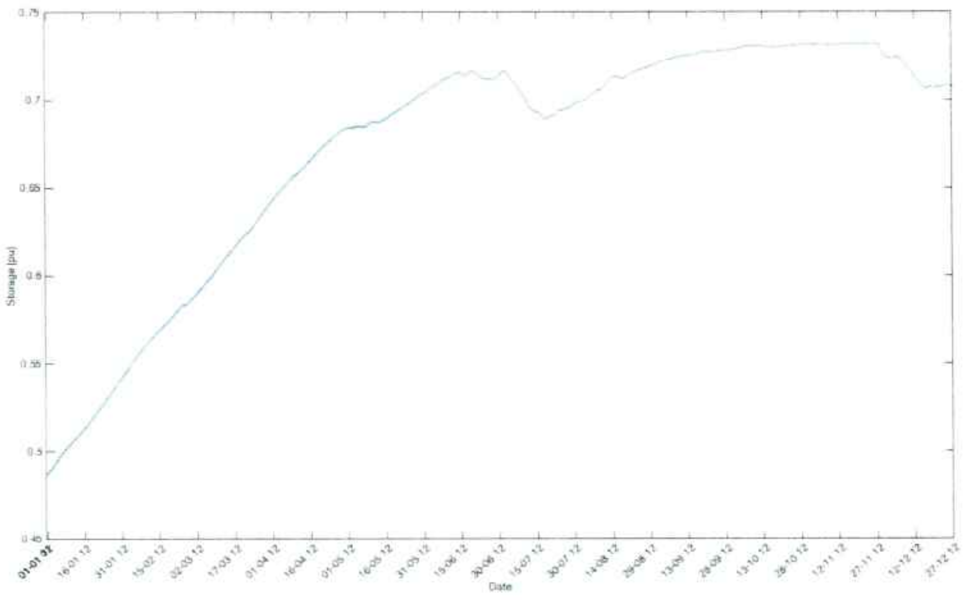

Figure 7.44 – Reservoir Level at Catalão EPS (Case 3)

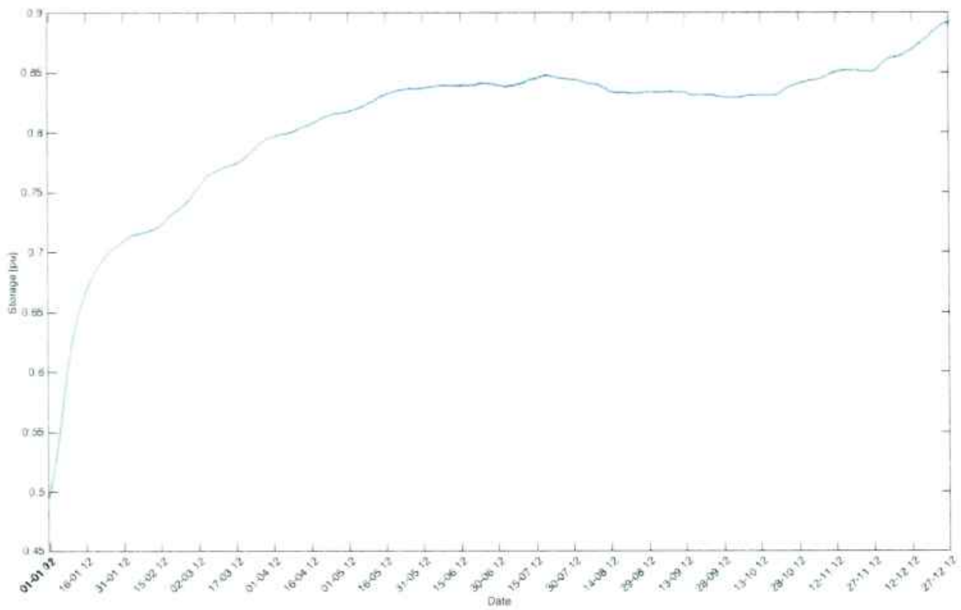

Figure 7.45 – Conventional Reservoir Storage (Case 3)

Highlighting another great decrease in the wind generation profile that happened in the first week of May.

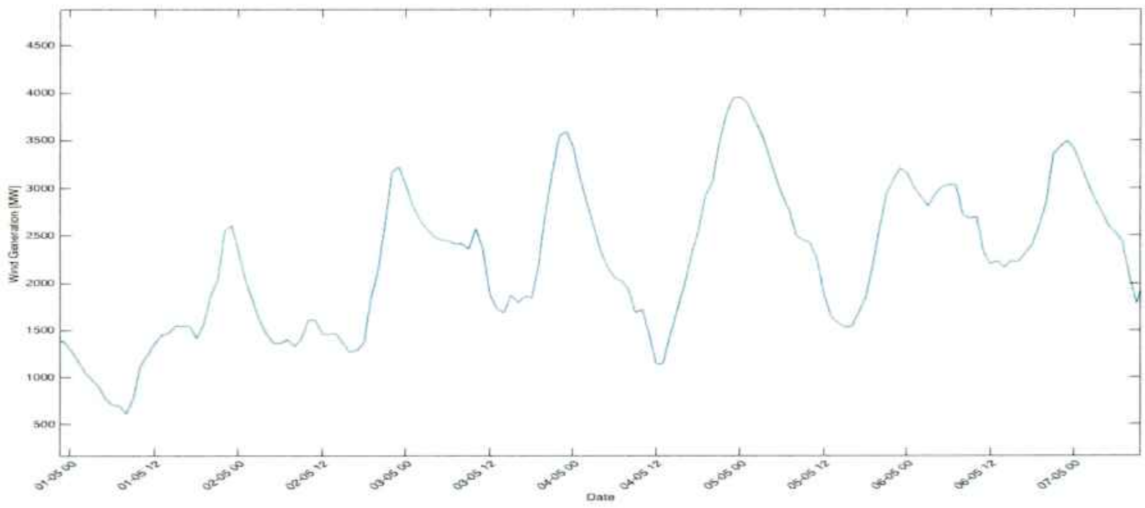

Figure 7.46 – Wind generation in the first week of May

On May 1st, the wind generation arrived to almost 500 MW, noticing that its physical guarantee is of 3.379 MW, a value much bellow the predicted average generation.

To counterbalance that it is possible to see in Figure 7.40 and Figure 7.41 that both EPS had peaks of water flow in way to generate energy, however, the side effect at Catalão was much reduced since its capacity is smaller, and Canastra has a greater potential to fill the energy deficit from wind generation.

Taking another example along the year, now in July, in the middle of the dry season, it is possible to observe a diverse behavior of the pumps.

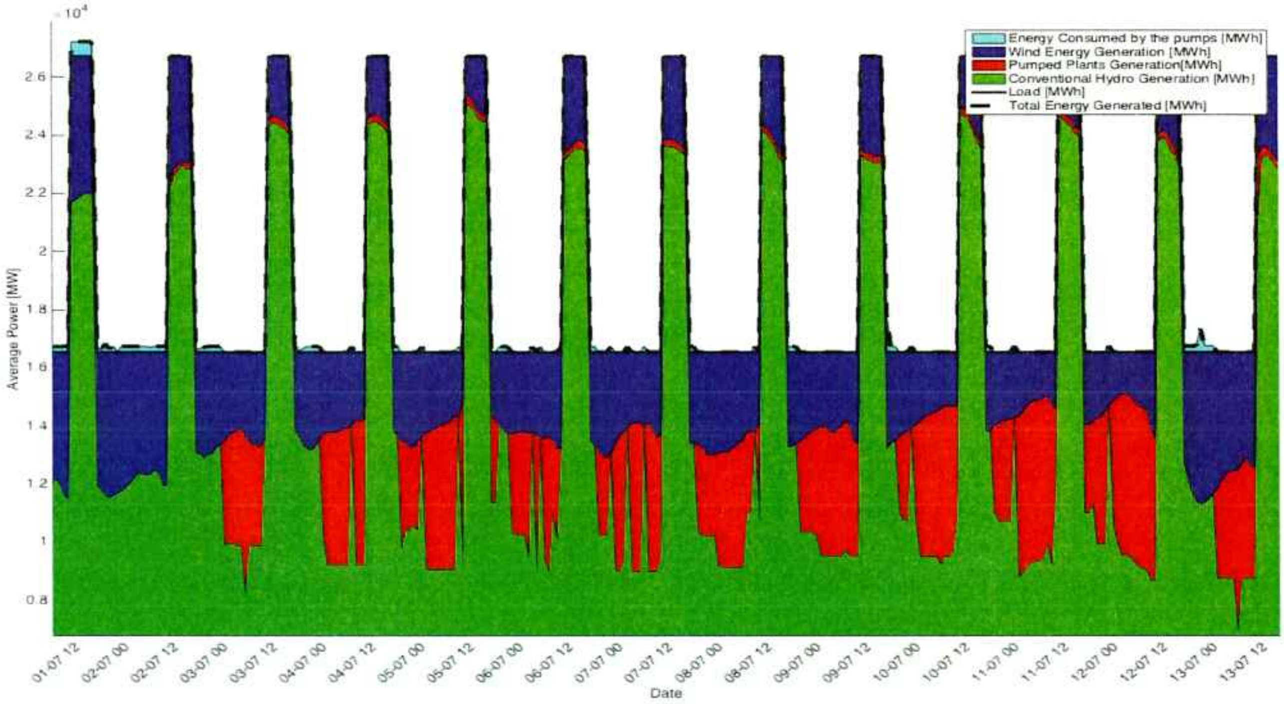

Figure 7.47 – Power x Demand in July (Case 3)

Due to the dry period, the pumps start to work constantly to regulate the generation and sparing at most the conventional hydroelectric plants. Since the inflow is smaller in this period, the operation politics adopted in this case allowed the EPS to empty themselves, increasing its generation along all the dry period, noticeable by Figure 7.47 while the conventional reservoirs kept a constant level, since their generation reduced in the same ration as the inflow at the dam.

Going into the next dry month, looking into August, from figures indicating the reservoir level, it is possible to see that they stabilize, around the same value from the end of July. Since it was a dry period, it was expected for all the dams to keep the same profile or emptying themselves in order to attend the load. However, as it can be seen in Figure 7.42, the wind generation profile is complementary to the water regime, so that in part of the dry period, the generation from wind farms is greater compensating the smaller generation from hydroelectric plants, managing to keep their reservoir more stable.

Given 1990 was a regular year regarding the water fluxes in the river, it is clear from the system reservoir levels that managed to attend a load 5% superior to its estimated value, as well as end the period under analysis with a higher reservoir level. Given the three reservoirs graphs, Canastra, Catalão and the whole system's storage, in the end of the year, since the system isn't completely filled, it gives a preference on emptying the EPS first keeping every conventional reservoir filled at most for the future.

Looking into the power generation profile at this period in December, the reservoirs are filling and the EPS generating and emptying. The observed effect in the generation profile is that even in off-peak periods of the day, both EPS are generating instead of storing energy, meanwhile, the hydroelectric plants are supplying less than normally and storing more energy. Then in the peak hours they are allowing a greater downstream flow in way to reach the required generation in the period.

So, the system is operating in way to store the maximum amount of water in the conventional reservoirs given that Catalão and Canastra are above 70%, this way, supplying their inferior reservoir, they are generating a large amount of power from the water flux going through their turbines and at the same time supplying a large volume of water to the inferior dams, regulating their inflow so that they manage to generate enough energy for the load and also stock up their reservoirs as it can be seen in Figure 7.45, how the conventional reservoirs are filling up in the end of the year and both EPS are emptying according to Figure 7.43 and Figure 7.44.

Also, after December 10th, it occurred a convergence problem since the generation was superior to what was required even though there was room in the system's reservoirs.

This convergence problem was due to a small amount of iterations made for this case and only observed in some random points of the simulation so that its impact in the overall objective function was not very significant. During the simulation it was saved and analyzed intermediate results that had worst results due to a bad operation of the pumped reservoirs and didn't attend the required load, as well as points where there was a waste of energy such as the one verified in Figure 7.48 when generation suppressed the load.

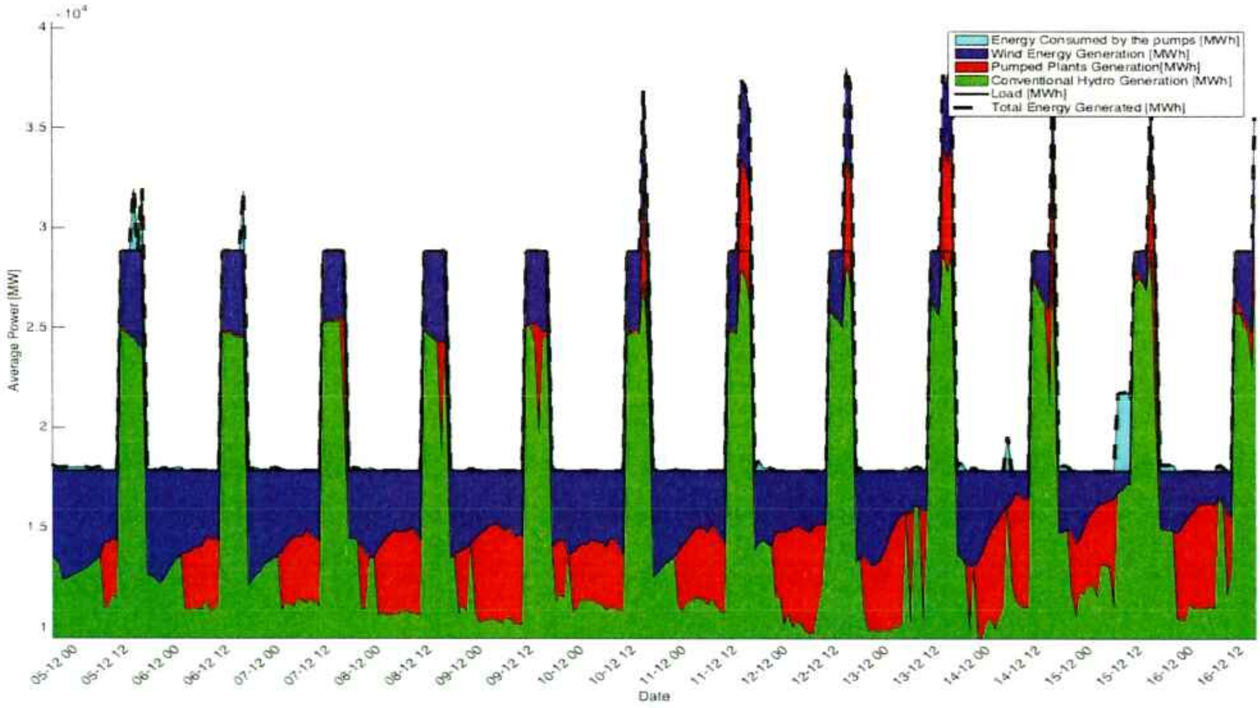

Figure 7.48 – Generation Profile in December 1990 (Case 3)

The operation in this particular case after including the constraint regarding the energy consume in the pumping operation was much clearer, elaborating a more efficient manner to operate an EPS thinking on both a seasonal cycle, storing energy for dry seasons of the year, working as a backup reservoir and also to regulate the peak demands along a day.

Its operation together with the wind source it allowed a very precise and manner to regulate a non-dispatchable source also produced the most efficient results, being extendable to any other source of the kind such as solar energy from photovoltaic plants and tidal power plants.

A more expressive consideration about the use of an EPS to store off-peak energy and generate during peak loads of the day will be presented in the next case.

7.2.3 Case 4 – Stress case

In this case it will be considered a smaller reservoir, an increased wind power, and a higher minimum outflow in the dams. This was made to stress the dams and verify the functionality of an EPS in a daily cycle.

To dimension the reservoir it was considered the installed power of the EPS and the duration of its storage cycle, then its energy storage level was calculated as follows:

$$E_{stored_{max}} = T_{cycle} \cdot P_{inst} \quad (7.6)$$

After that, it was calculated its maximum volume level, assuming to be no dead-volume in the pumped storage reservoir, therefore its minimum volume is zero.

$$V_{max} = \frac{E_{stored_{max}} \cdot 3600}{\rho \cdot g \cdot h_{max}} \quad (7.7)$$

Considered this, it arrived to the following inputs for the Catalão and Canastra EPS.

Table 7.2 – Stress Case inputs for each EPS

	Min Energy [GWh]	Max Energy [GWh]	Min Volume [hm3]	Max Volume [hm3]
Canastra	0	132	0	38,75
Catalão	0	9,6	0	3,71

Besides, it was considered a greater load, with a longer peak period. Therefore, the load considered was 5% greater in peak hours, which lasted from 1pm to 8pm.

Using this data as input, it was possible to analyze how an EPS helps regulating peak and off-peak loads. The reported exit is found in the following file: *HourAnal-Load_M_P0.528M_OffP0.489H_P1.47H_OffP0.86667_Vol50_Volpump2_GApop4m0.035 c0.483It_5-3_Year1990-1990.mat*.

In Figure 7.49, it possible to see the daily profile of the demand. Along off-peak period in the day, each EPS is pumping water up the reservoir, consuming an exceeding wind energy represented by the light blue color. Then, in the peak hours, it is able to empty its reservoir generating energy to fill the demand peak. Its reservoir level profile is represented in Figure 7.50. Even though it is not emptying itself completely, it is already possible to observe its effects in the power generation profile, regulating the demand through an exceeding energy due to the higher wind profile in the off-peak hours.

As in the previous case it works together with the wind profile, looking into February 2nd and 3rd, it is possible to see, through the dark and light blue area, that the wind generation was smaller than on February 19th, for example. Due to this, the pumps do not pump as much water since there was not a large exceeding amount of energy in the system. And it only turbine water during the peak hours, emptying the reservoir.

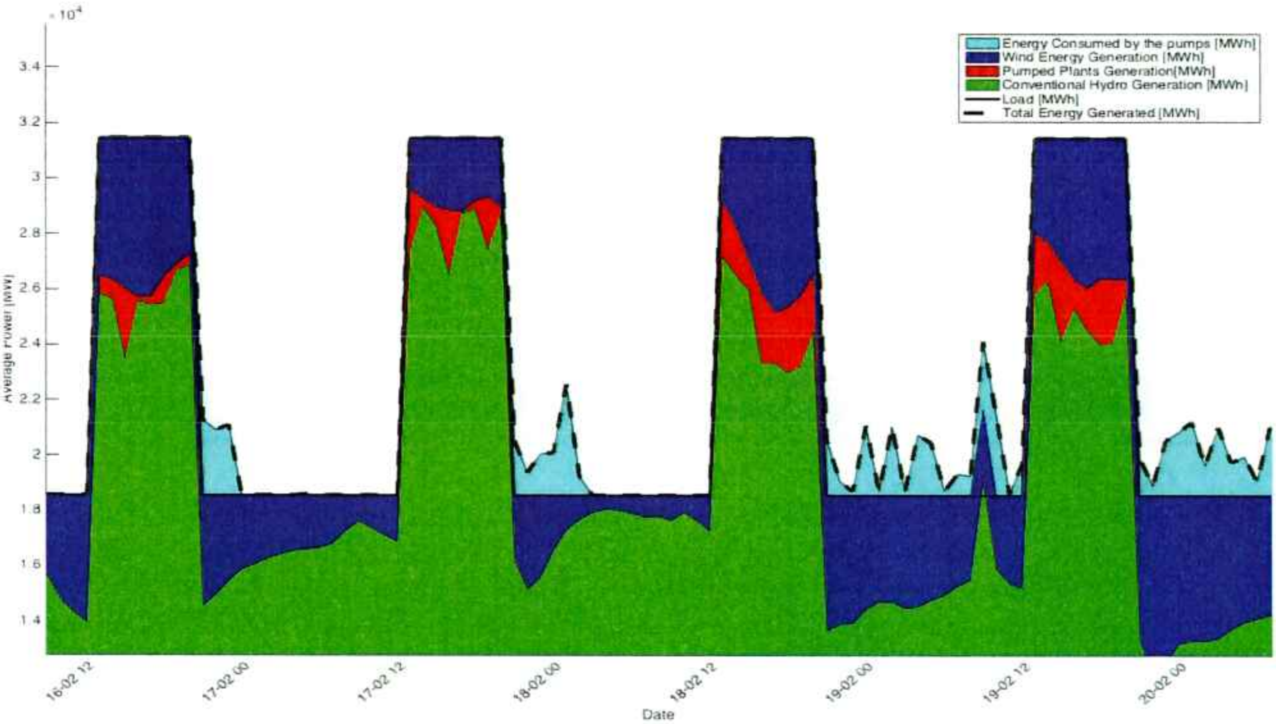

Figure 7.49 – Power x Demand in February (Case 4)

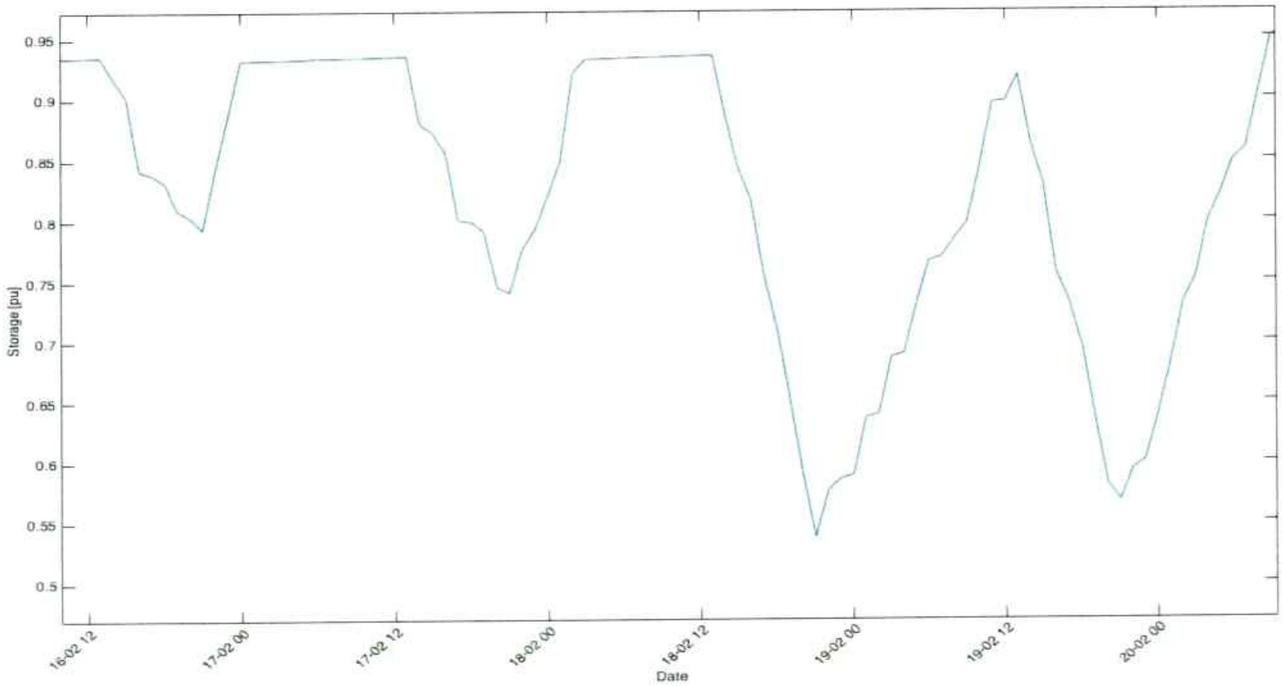

Figure 7.50 – Pumped Reservoir level in February (Case 4)

Now, looking into a regular winter day, when less water is inflowing to the dams and there is also a larger wind generation, the both EPS work more often being established a more defined daily cycle, however there is also much less available energy since the hydroelectric power plants have a much lower generation profile.

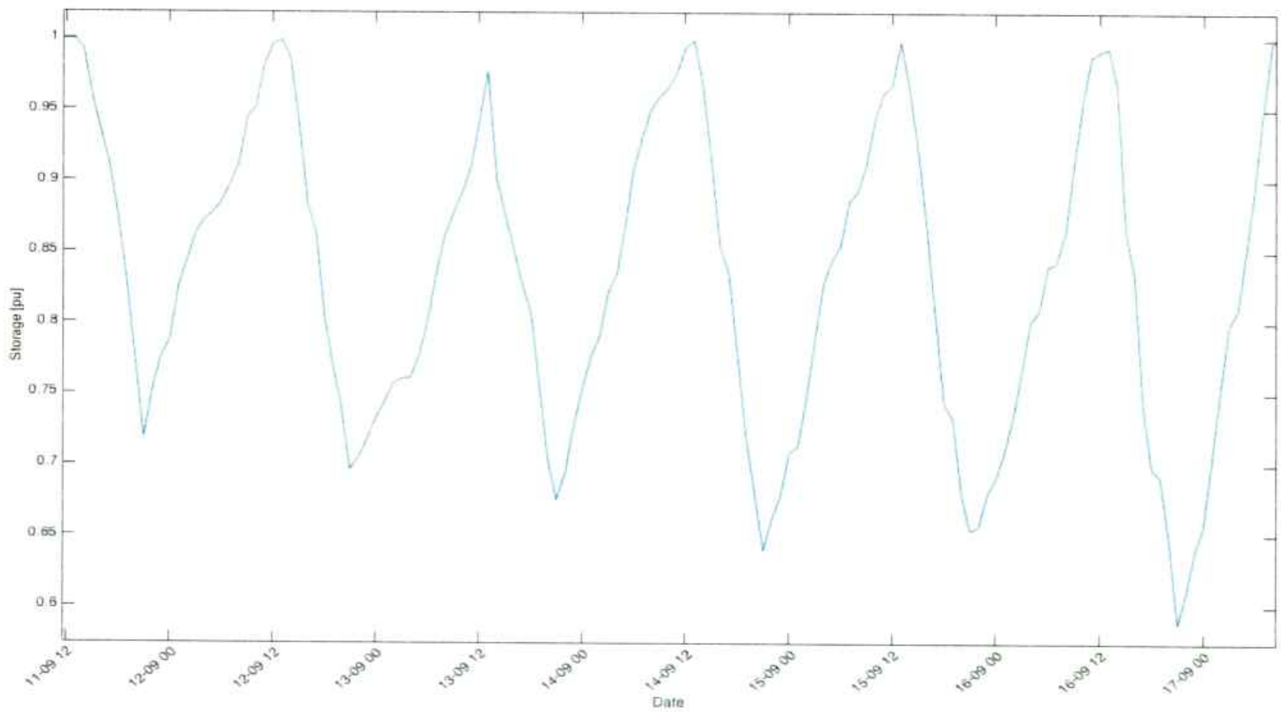

Figure 7.51 – Pumped Reservoir level in September (Case 4)

At this period, considering the generation profile however, there is still a lot of energy spilled, given that the available generated energy is above demand, making it to be spilled. Looking at the times, it is possible to see that it happened when the pumped reservoirs were completely full. To avoid this spillage it would be necessary either a larger reservoir, or a smaller generation from conventional hydroelectric plants. But given its minimum outflow level that was established 50% higher than nominal, this constrains its minimum generation, that added to the wind generation, creates an exceeding amount.

But it is also possible to compare this result with a case without an EPS. Later it will be plotted the spilled energy in comparison between Case 3 and Case 4 and how it managed to avoid it through the EPS.

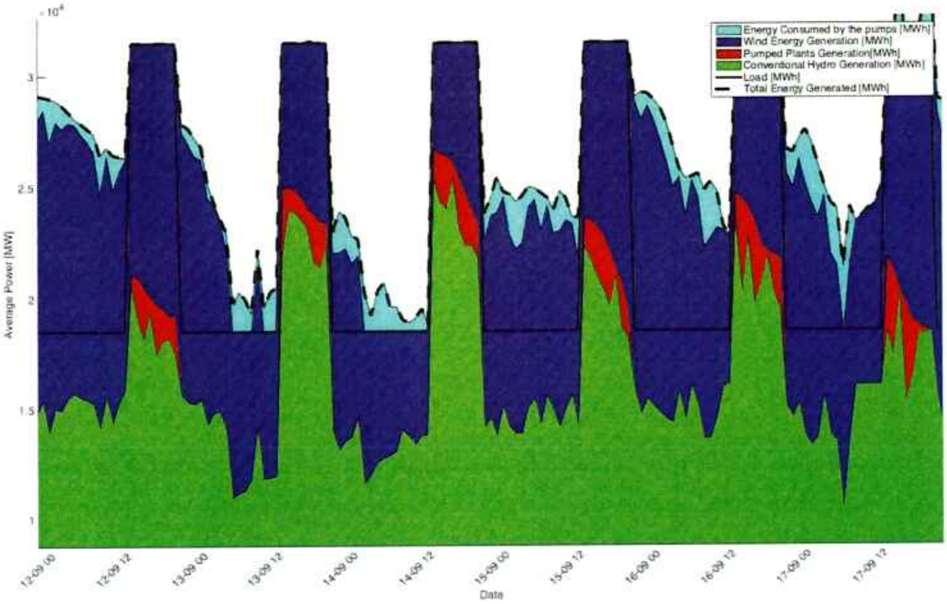

Figure 7.52 – Power x Demand Profile in September (Case 4)

Observing the daily cycle, it was possible to see how it could be implemented, in a much smaller scale, a pumped storage facility to counterbalance the wind generation profile and store an exceeding energy from off-peak periods to use it during the peak loads of the day. Bellow is reported the pumped flow of each EPS in order to established the energy and reservoir profile from the graphs above.

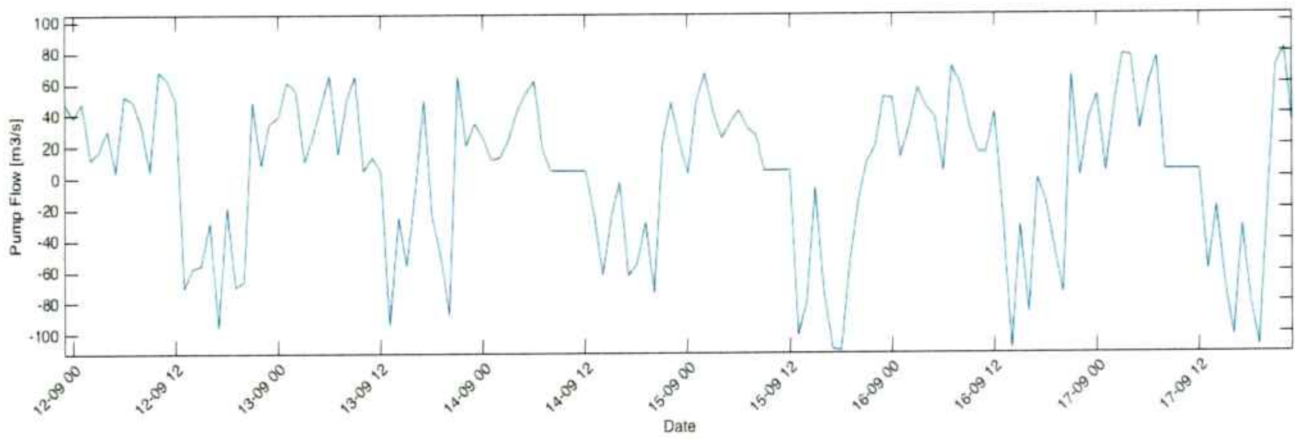

Figure 7.53 – Pump flow at Catalão in September (Case 4)

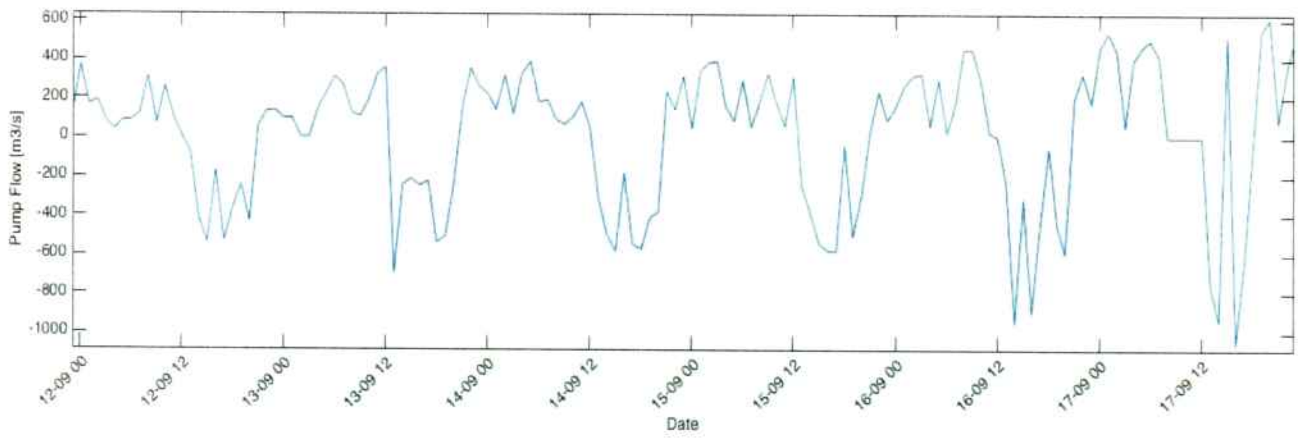

Figure 7.54 – Pump flow at Canastra in September (Case 4)

Now, given the stress case, it was also simulated a case without any EPS with the same load from the Stress Case, in the hourly analysis to compare the amount of energy spilled between each case only to present how much difference it could make.

In Figure 7.55 it is reported a comparison between each case. It was calculated the total amount of power generated in each case, subtracted by the consumptions in the pumps, as in Equation 7.4. Then, by subtracting the load, it gets to the wasted energy.

$$E_{wasted}(t) = E_{balance}(t) - D(t) \tag{7.8}$$

To make it easier to visualize, it was then generated a cumulative curve of the E_{wasted} of each case.

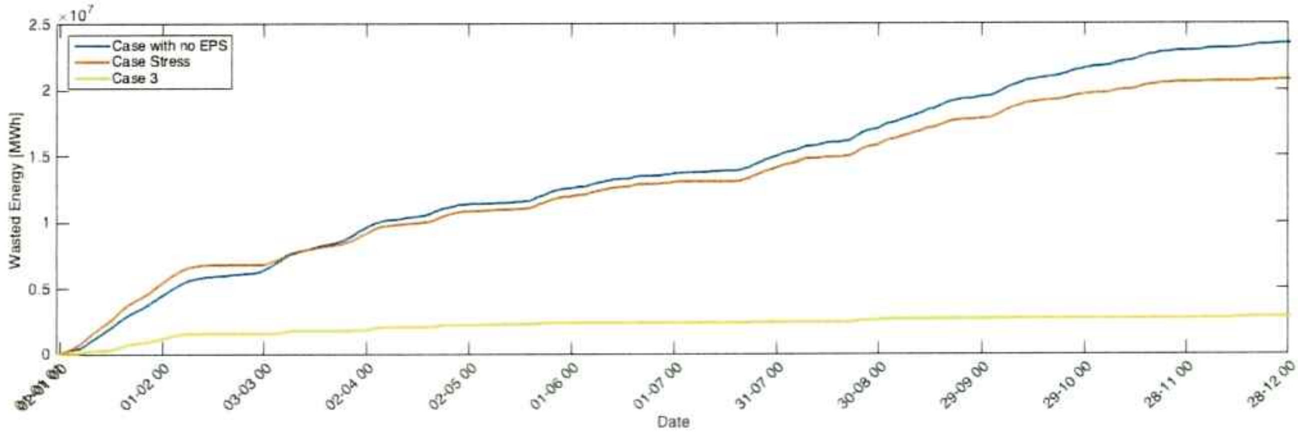

Figure 7.55 – Wasted Energy Cumulative Curve

Also, comparing the total amount of energy wasted to the total amount generated in each case, it arrives to the result reported on Table 7.3.

Table 7.3 – Final results balance

	Energy Generated [TWh]	Energy Consumed [TWh]	Energy Wasted [TWh]	Energy Wasted / Energy Generated	Final Energy Stored [TWh]
No EPS	217	193,43	23,57	10,86%	104,0
Case 3	185	182,19	2,81	1,52%	144,6
Case 4 - Stress	222	200,25	21,75	9,80%	104,5

Looking into the table it is possible to compare the improvements on the amount of energy wasted for each case. As it was predicted, the larger the EPS reservoir, the better results it would supply. Then, in case 3 where it was considered two EPS that together summed 22,34 TWh of storage capacity, managed to spill only 1,52% of all energy generated in the period, a great improvement from the 10,86% of wasted energy from the case without an EPS.

Meanwhile, in the stress case that included a small scale EPS in the system, it already showed an improvement of 1% in the wasted energy.

Considering that the Energy Consumed column includes both the electrical load and the pumping energy consumed, it was expected for Case 4 to have the highest amount of energy consumed due to the higher load used as input for this case, as well as the amount used for pumping. The result can only be compared among the three cases when looking into the last column since its load levels are different.

Besides, comparing the Stress case with the case without the EPS plant, the amount of energy stored in the end is also superior with the EPS, since less water was spilled, being stored in the system's reservoirs.

8 CONCLUSION

In the presented work it was able to develop a flexible methodology to analyze and study various scenarios in the Brazilian electric energy system. It was decided since the beginning of the study to make it as flexible as possible allowing infinite different scenarios, leaving as entry variables data such as electrical load, plants characteristics, the year under study to pick both water inflow in the rivers of the system as well as the wind generation data.

Regarding the model established for the system, it became an automatic and flexible model, allowing it to be a contribution for future studies in energy generation scenarios, being possible to adapt it to any different system given its input is organized by the MSUI file, which is able to mount the system and interactions between each power plant. Besides, the wind generation tool used allows the study of any farm given its wind speed historical data and the turbine specifications.

Then, through the genetic algorithm that was implemented it allowed an optimized result that also contributes for the model automation, not needing any intervention while the study is being conducted. It also allowed a study of optimal operation politics for the Pumped Storage Plants, that since they do not it exist in the Brazilian matrix, it is important to deeply understand its behavior in the country's particular context to optimize at all times its operation given the current meteorological scenario.

After both the simulation algorithm and the modeling were implemented it got to an optimized result of how to operate two PSP considering its interaction with the seasonality effects in hydro generation as well as with intermittency from wind farms. Besides, the establishment of a fitness function to minimize spillage was useful to improve the system's efficiency, converting almost all the potential energy stored in the water of the system into electrical energy thanks to each PSP that was able to store energy and avoid spillage in each dam.

Considering the routine written in *Matlab*, even being written for this specific case and system, its adaptation into other systems and basins is very simple being useful for a deeper study in the energy scenario in Brazil, including a possible expansion of this particular system including the nearby rivers where there are also other hydroelectric plants.

Given the results presented in Chapter 1, after the simulations it was possible to analyze a few different scenarios, first through a decade of generation, where the presence of two EPS, showed how the increased storage capacity upstream the river helps stabilize the whole generation profile given a period of drought. However, this didn't prove the efficiency of an PSP since in the same case, a conventional reservoir located at that point would create a very similar behavior. It was important though as kick-start point for the modeling allowing t verify the water balance equations and to get familiar with a more simplified model of the system until the establishment of a more complex case when with a smaller discretization period.

Then, through the incorporation of wind farms it showed an efficient to manage and operate the reservoirs allowing it to store peak wind generation that showed to be present in the middle of the night and use it along the next day to regulate the peak load in the afternoon. Considering the overall efficiency of a PSP that is between 70% and 80%, it is according to the literature review one of the most efficient storage methods, and also the only method that allows a large storage in the form of potential energy.

Besides, its presence along the year, managed to regulate the water flows in the system along the dry season, so that most conventional reservoirs remained at a constant level when normally it would empty.

In general, the case analysis allowed observing the influence and effects of an EPS in a portfolio of hydro and wind generation and how it would be beneficial for the system its inclusion, allowing a peak regulation through storage of wind power. Considering the future scenario in Brazil where wind generation is constantly growing and latest auctions started to introduce photovoltaic power plants mainly in the Northeast subsystem, the intermittency from these renewable sources will need a regulation, and since hydroelectric power is the main component in the Brazilian energy matrix, a pumped storage plant becomes a good alternative to it.

To implement this concept in the Brazilian energy matrix however, there are a few modifications and circumstances that must be taken into account. In this work it was not considered the dimensioning of an EPS, being taken from (HUNT, 2014) and after considered a stress case with a daily cycle, in the future it is essential a precise planning in the energy generation to dimension it based in financial constraints to produce a maximized return based in its generation and construction investments. Given the size of the reservoir, specifically Canastra, and its installed power, it is a very large investment, also because the capex of an EPS, given examples around the world, may get to R$ 7.000,00/kW installed, while a conventional hydroelectric plant has an approximate capex of R$ 4.500,00/kW. Besides, an EPS is not a generation facility, in the long term, it will consume more energy than generate, since its cycle has an efficiency of about 70%.

To implement such a facility in Brazil will need a review in the electrical energy legislation, to make the operation business of an EPS interesting. Nowadays, considering the liberal energy market in Brazil, there is no legislation predicted that would make interesting from the financial point of view such an investment. But considering the benefits it would bring into the generation profile in the country, it would be interesting for all renewable generation a storage facility, diminishing its generation risks due to the unpredictability of the meteorological scenario as well. An alternative would be including an EPS in terms of the Energy Reallocation Mechanism that exists today to diminish the generation risks for hydroelectric generators from a financial point of view, but this is a point that must be carefully studied in the future, since it is the base for any investment in the generation profile.

Regarding improvement points for this work. It was adopted a series of constraints that could be improved.

The main aspect regards the operation politics of reservoirs, since in this work was adopted a parallel operation politic. In the future it is essential to adopt a more optimized operation, including the position in the river of each reservoir, to operate an upstream plant not only to optimize itself but also every downstream facility.

Another important matter regards the water transit time that was ignored in this work. Since each plant is distant from each other, in a daily basis it would be necessary to incorporate a transit time between each dam enhancing the interaction between dams.

A problem that happened with the simulation in an hourly basis was due to simulation time. Considering there were 8760 points of analysis, the simulation time was very long, for each individual of a population, to arrive to a final energy balance, the simulation took about fifty minutes. For this reason it was not possible to use large populations with much iteration. An essential improvement in this work is regarding the simulation time optimization. Reviewing the created routine to optimize even more, allowing the system to converge into the required generation, would speed the simulation, allowing more iteration in the Genetic Algorithm, supplying better results.

Overall, this work allowed being a kick-start into this theme in the Brazilian energy matrix, given its inexistence in the matrix today. It already proved that even though the energy consumption is increased due to pumping, it allows a smaller waste of energy allowing so that the system's reservoir are kept more filled. But there is still a lot of work to be done in this theme, so that PSP may be used in the Brazilian energy matrix.

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ANNEX A – Genetic Algorithm Code

```
%% GENETIC ALGORITHM - HOURLY ANALYSIS

%amount of points of the chromosome where the crossing will take place

Cross_bits_day = 1;
Cross_bits_month = 1;
Cross_bits_year = 1;
Cross_bits_hour = 1;


%% create first generation

% pop = [n_ga, year, month, day, hour, EPS]
pop = rand(size_pop,year_simulation,month_simulation,31,24,2);


for i = 1 : size(pop,5)
     if ismember(i,Peak_hours)
         pop(:,:,:,:,i,:) = abs(pop(:,:,:,:,i,:))*(-1);
     else
         pop(:,:,:,:,i,:) = abs(pop(:,:,:,:,i,:));
     end
 end

for i1=1 : size_pop %individual
    for i2 = 1 : year_simulation %year
        for i3 = 1 : month_simulation %month
            for i4 = 1 : 31 %day
                for i5 = 1 : 24 %hour
                    for i6 = 1 : 2 %EPS
                        if ismember(i5,Peak_hours)&&ismember(i3,dry)

                  pop(i1,i2,i3,i4,i5,i6)=pop(i1,i2,i3,i4,i5,i6)*1.5;

                        end
                    end
                end
            end
        end
    end
end

clear i1 i2 i3 i4 i5 i6

it = 0;
stop = 0;
count = 0;


while stop~=1
    it = it+1;
    disp('Iteracao')
    disp(it)

    for n_ga = 1 : size_pop
        disp('Individuo')
        disp(n_ga);
```

```
        % calculate the energy balance of the system for the given
        % population

        modeling;
        Energy_opt(n_ga) = Energy_bal; %#ok<SAGROW>

    end

    [en_elit,pop_elit] = max(Energy_opt);

    pop_elit = pop(pop_elit,:,:,:,:,:);

    if it == 1
        pop_best = pop_elit;
        en_best = en_elit;
        count=count+1;
    else if en_elit>en_best
            en_best = en_elit;
            pop_best = pop_elit;
            count = 0;
        else
            count = count+1;
        end
    end

    disp(en_elit);

    %% Genetic Operators

    %% Selection
    new_pop = zeros(size_pop,year_simulation,month_simulation,31,24,2);
    select_pop = zeros(size_pop,1);

    fitness = Energy_opt./sum(Energy_opt);

    for aux = 1 : size_pop
        select_pop(aux) = RouletteWheelSelection(fitness);
    end

    parents = zeros(size_pop,year_simulation,month_simulation,31,24,2);

    for aux = 1 : size(select_pop,1)
        parents(aux,:,:,:,:,:) = pop(select_pop(aux),:,:,:,:,:);
    end

    %% Crossing

    for aux = 1 : 2 : size_pop
        for aux2 = 1 : size(new_pop,6)
            if year_simulation>1
                r_cross_year = rand;
                if r_cross_year < p_cross %year crossing
                    bit_cross_year = randi(year_simulation-
1,1,Cross_bits_year);

                    bit_cross_year = [bit_cross_year year_simulation];
```

```
                    bit_cross_year = sort(bit_cross_year);
                    for aux3 = 1 : Cross_bits_year
                        new_pop(aux,1:bit_cross_year(aux3),:,:,:,aux2)
= parents(aux,1:bit_cross_year(aux3),:,:,:,aux2);

new_pop(aux,bit_cross_year(aux3)+1:bit_cross_year(aux3+1),:,:,:,aux2) =
parents(aux+1,bit_cross_year(aux3)+1:bit_cross_year(aux3+1),:,:,:,aux2)
;


new_pop(aux+1,1:bit_cross_year(aux3),:,:,:,aux2) =
parents(aux+1,1:bit_cross_year(aux3),:,:,:,aux2);

new_pop(aux+1,bit_cross_year(aux3)+1:bit_cross_year(aux3+1),:,:,:,aux2)
=
parents(aux,bit_cross_year(aux3)+1:bit_cross_year(aux3+1),:,:,:,aux2);
                    end
                end
            end

            r_cross_month = rand;
            if r_cross_month < p_cross

                bit_cross_month = randi(month_simulation-
1,1,Cross_bits_month);

                bit_cross_month = [bit_cross_month month_simulation];
                bit_cross_month = sort(bit_cross_month);

                for aux3 = 1 : Cross_bits_month

                    new_pop(aux,:,1:bit_cross_month(aux3),:,:,aux2) =
parents(aux,:,1:bit_cross_month(aux3),:,:,aux2);
                    new_pop(aux,:,bit_cross_month(aux3)+1 :
bit_cross_month(aux3+1), :, :, aux2) = parents(aux+1, :,
bit_cross_month(aux3)+1 : bit_cross_month(aux3+1), :, :, aux2);

                    new_pop(aux+1,:,1:bit_cross_month(aux3),:,:,aux2) =
parents(aux+1,:,1:bit_cross_month(aux3),:,:,aux2);
                    new_pop(aux+1,:, bit_cross_month(aux3)+1 :
bit_cross_month(aux3+1), :, :,aux2) = parents(aux, :,
bit_cross_month(aux3)+1 : bit_cross_month(aux3+1), :, :,aux2);

                end
            end

            r_cross_day = rand;
            if r_cross_day < p_cross

                bit_cross_day = randi(31-1,1,Cross_bits_day);
                bit_cross_day = [bit_cross_day 31];
                bit_cross_day = sort(bit_cross_day);

                for aux3 = 1 : Cross_bits_day

                        new_pop(aux,:,:,1:bit_cross_day(aux3),:,aux2) =
```

```
                    parents(aux,:,:,1:bit_cross_day(aux3),:,aux2);

new_pop(aux,:,:,bit_cross_day(aux3)+1:bit_cross_day(aux3+1),:,aux2) =
parents(aux+1,:,:,bit_cross_day(aux3)+1:bit_cross_day(aux3+1),:,aux2);

                    new_pop(aux+1,:,:,1:bit_cross_day(aux3),:,aux2) =
parents(aux+1,:,:,1:bit_cross_day(aux3),:,aux2);

new_pop(aux+1,:,:,bit_cross_day(aux3)+1:bit_cross_day(aux3+1),:,aux2) =
parents(aux,:,:,bit_cross_day(aux3)+1:bit_cross_day(aux3+1),:,aux2);

                end
            end

            r_cross_hour = rand;
            if r_cross_hour < p_cross
                bit_cross_hour = randi(24-1,1,Cross_bits_hour);
                bit_cross_hour = [bit_cross_hour 24]; %#ok<AGROW>
                bit_cross_hour = sort(bit_cross_hour);

                for aux3 = 1 : Cross_bits_day

                    new_pop(aux,:,:,:,1:bit_cross_hour(aux3),aux2) =
parents(aux,:,:,:,1:bit_cross_hour(aux3),aux2);

new_pop(aux,:,:,:,bit_cross_hour(aux3)+1:bit_cross_hour(aux3+1),aux2) =
parents(aux+1,:,:,:,bit_cross_hour(aux3)+1:bit_cross_hour(aux3+1),aux2)
;

                    new_pop(aux+1,:,:,:,1:bit_cross_hour(aux3),aux2) =
parents(aux+1,:,:,:,1:bit_cross_hour(aux3),aux2);

new_pop(aux+1,:,:,:,bit_cross_hour(aux3)+1:bit_cross_hour(aux3+1),aux2)
=
parents(aux,:,:,:,bit_cross_hour(aux3)+1:bit_cross_hour(aux3+1),aux2);

                end
            end
        end
    end



    %% Mutation
    for aux = 1 : size_pop %each individual
        for aux2 = 1 : size(new_pop,2) %each year
            for aux3 = 1 : size(new_pop,3) %each month
                for aux4 = 1 : size(new_pop,4) %each day
                    for aux5 =1 : size(new_pop,5) %each hour
                        for aux6 = 1 : size(new_pop,6) %each EPS
                            r_mut = rand;
                            if r_mut < p_mut

                        new_pop(aux,aux2,aux3,aux4,aux5,aux6)=rand;

                                if ismember(aux5,Peak_hours)
```

```
                                    new_pop(aux,aux2,aux3,aux4,aux5,:)
= abs(new_pop(aux,aux2,aux3,aux4,aux5,:))*(-1);
                                else
                                    new_pop(aux,aux2,aux3,aux4,aux5,:)
= abs(new_pop(aux,aux2,aux3,aux4,aux5,:));
                                end
                            end
                        end
                    end
                end
            end
        end
    end


    %% updating new population
    pop = new_pop;

    %% Stoping Criteria

    % absolute maximum amount of iterations
    if it==n_it
        stop=1;
    end

    %certain amount of iterations without improvements
    if count == n_it_2
        stop=1;
    end

end


pop = pop_best;
n_ga = 1; %#ok<NASGU>
modeling;

clear n_ga n_it2 n_vol_ot n_power_ot r_cross r_mut stop
```

ANNEX B – Hydroelectric Plants Data (Hidrexp1.dat)

620 ITAIPU	2	14000.0	20	15	67	0	92.03.115	117.0	2.03	2839	100.0	8.263	8.263	8.263	8.263	8.263	8.263	8.263	8.263	8.263	8.263	8.263	8.263	29000.0	220.0	1350.0	29000.0	220.0	1350.0	29000.0	220.0	1350.0	1	90.0	29000.
913 I.SOLTEIRA	2	3444.0	20	10	34	914	90.00.802	41.5	1.10	1387	281.2	7.233	7.233	7.233	7.233	7.233	7.233	7.233	7.233	7.233	7.233	7.233	7.233	18085.3	325.4	1097.0	20068.4	327.2	1166.4	21060.0	328.0	1196.1	1	90.0	15543.
914 I. SOLTEIRA EQV	2	4251.50	25	11	44	919	90.00.816	41.5	1.10	1552	281.1	7.466	7.466	7.466	7.466	7.466	7.466	7.466	7.466	7.466	7.466	7.466	7.466	29564.0	325.4	1788.4	32809.3	327.2	1905.1	34432.0	328.0	1955.0	1	90.0	25467.
919 JUPIA	2	1551.2	14	9	45	926	89.02.073	21.3	0.31	4000	257.9	7.248	7.248	7.248	7.248	7.248	7.248	7.248	7.248	7.248	7.248	7.248	7.248	3354.0	280.0	327.0	3354.0	280.0	327.0	3354.0	280.0	327.0	2	90.0	3354.0
926 P. PRIMAVERA	2	1540.0	14	11	46	620	93.10.715	19.0	0.36	5500	238.3	4.443	4.443	4.443	4.443	4.443	4.443	4.443	4.443	4.443	4.443	4.443	4.443	14400.0	257.0	1914.2	14400.0	257.0	1914.2	14400.0	257.0	1914.2	2	90.0	14400.
1207 CAMARGOS	2	46.0	2	1	1	1208	86.93.253	24.6	0.32	34	886.1	11.77	11.77	11.77	11.77	11.77	11.77	11.77	11.77	11.77	11.77	11.77	11.77	120.0	899.0	23.9	568.0	909.7	61.0	792.0	913.0	73.4	2	90.0	419.0
1208 ITUTINGA	2	52.0	4	1	2	1212	89.91.745	25.0	0.55	34	857.7	2.497	2.497	2.497	2.497	2.497	2.497	2.497	2.497	2.497	2.497	2.497	2.497	11.0	886.0	1.6	11.0	886.0	1.6	11.0	886.0	1.6	2	90.0	11.0
1212 FUNIL-GRANDE	2	180.0	3	2	3	1221	90.01.141	34.9	0.84	68	768.0	4.844	4.844	4.844	4.844	4.844	4.844	4.844	4.844	4.844	4.844	4.844	4.844	304.0	808.0	37.7	304.0	808.0	37.7	304.0	808.0	37.7	2	90.0	304.0
1221 FURNAS	2	1312.0	8	4	6	1222	88.09.081	89.8	1.04	204	672.9	12.57	12.57	12.57	12.57	12.57	12.57	12.57	12.57	12.57	12.57	12.57	12.57	5733.0	750.0	530.1	17211.0	763.6	1186.1	22950.0	768.0	1442.1	1	90.0	6173.8
1222 M. DE MORAES	2	478.0	10	8	7	1223	85.05.879	43.2	0.35	225	622.0	4.768	4.768	4.768	4.768	4.768	4.768	4.768	4.768	4.768	4.768	4.768	4.768	3422.5	663.5	234.6	3834.2	665.3	254.0	4040.0	666.1	263.6	1	90.0	3422.5
1223 ESTREITO	2	1104.0	6	3	8	1224	90.04.221	61.7	0.97	226	557.8	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	1423.0	622.5	46.5	1423.0	622.5	46.5	1423.0	622.5	46.5	1	90.0	1423.0
1224 JAGUARA	2	424.0	4	3	9	1225	91.00.405	44.1	0.62	235	512.6	2.753	2.753	2.753	2.753	2.753	2.753	2.753	2.753	2.753	2.753	2.753	2.753	450.0	558.5	33.9	450.0	558.5	33.9	450.0	558.5	33.9	1	90.0	450.0
1225 IGARAPAVA	2	210.0	5	4	10	1226	92.04.448	15.7	0.30	239	494.8	0.733	0.733	0.733	0.733	0.733	0.733	0.733	0.733	0.733	0.733	0.733	0.733	480.0	512.0	52.0	480.0	512.0	52.0	480.0	512.0	52.0	2	90.0	480.0
1226 VOLTA GRANDE	2	380.0	4	3	11	1227	92.03.893	26.6	0.21	253	467.3	3.744	3.744	3.744	3.744	3.744	3.744	3.744	3.744	3.744	3.744	3.744	3.744	2244.0	494.9	201.6	2244.0	494.9	201.6	2244.0	494.9	201.6	2	90.0	2244.0
1227 P. COLOMBIA	2	328.0	4	3	12	1240	89.02.223	18.9	0.45	245	443.4	6.001	6.001	6.001	6.001	6.001	6.001	6.001	6.001	6.001	6.001	6.001	6.001	1524.0	467.2	143.9	1524.0	467.2	143.9	1524.0	467.2	143.9	2	90.0	1524.0
1240 MARIMBONDO	2	1488.0	8	4	17	1241	87.00.984	59.2	1.02	418	382.8	3.873	3.873	3.873	3.873	3.873	3.873	3.873	3.873	3.873	3.873	3.873	3.873	890.0	426.0	119.8	4221.3	441.4	345.0	5887.0	445.7	427.3	1	90.0	1175.1
1241 A. VERMELHA	2	1396.2	6	3	18	913	90.00.590	53.5	0.63	484	326.4	3.569	3.569	3.569	3.569	3.569	3.569	3.569	3.569	3.569	3.569	3.569	3.569	5856.0	373.3	399.7	9302.0	380.5	566.2	11025.0	383.3	643.5	1	90.0	5856.0
1493 SERRA DO FACAO	2	212.58	2	2	487	1505	91.00.000	73.7	1.86	27	675.8	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1752.0	732.5	89.1	4050.0	750.0	175.6	5199.0	756.0	212.2	1	90.0	2777.0
1505 EMBORCACAO	2	1192.0	4	2	24	1513	89.01.051	130.3	1.77	100	521.9	3.092	3.092	3.092	3.092	3.092	3.092	3.092	3.092	3.092	3.092	3.092	3.092	4669.0	615.0	150.0	13373.0	650.4	373.8	17725.0	661.0	477.7	1	90.0	10627.
1513 ITUMBIARA	2	2082.0	6	3	31	1514	90.01.290	80.2	1.01	261	435.6	5.414	5.414	5.414	5.414	5.414	5.414	5.414	5.414	5.414	5.414	5.414	5.414	4573.0	495.0	272.7	12875.7	514.0	621.6	17027.0	520.0	796.9	1	90.0	6915.6
1514 CACH.DOURADA	2	658.0	10	8	32	1515	89.01.491	30.0	0.65	20	401.1	4.404	4.404	4.404	4.404	4.404	4.404	4.404	4.404	4.404	4.404	4.404	4.404	460.0	434.1	69.0	460.0	434.1	69.0	460.0	434.1	69.0	2	90.0	460.0
1515 SAO SIMAO	2	1710.0	6	5	33	913	92.06.015	70.9	0.45	450	328.1	4.682	4.682	4.682	4.682	4.682	4.682	4.682	4.682	4.682	4.682	4.682	4.682	7000.0	390.5	407.6	10693.3	397.8	575.5	12540.0	401.0	665.2	1	90.0	7000.0

ANNEX C – User Guide MSUI

MSUI

Modelo de Simulação a Usinas Individualizadas

Versão 3.2

MANUAL DO USUÁRIO

Outubro/2009

Eletrobrás

3. Arquivo de Dados Característicos de Usinas Hidroelétricas do Sistema Existente - HIDROSE

Nome do Arquivo: ....**HIDROSE.DAT**

Tipo de Entrada: ....Permanente, Formatado

Tipo de Acesso: ....Seqüencial

Este arquivo contempla as usinas existentes no sistema. As usinas em expansão serão contempladas no arquivo de mesmo formato, HIDREXP1.DAT (casos dinâmico ou dinâmico transformado em estático).

Campos de Informação

Tipo	Nome	Formato	Descrição
I*4	CDHD Col. 1	I4	Código da usina. Um valor negativo significa retirada da usina nos campos de mês e ano de entrada em operação do reservatório. Nesse caso, os demais dados da usina não são lidos pelo MSUI. É obrigatório existir uma usina com código positivo no sistema existente.
A12	NMHD Col. 6	A12	Nome da usina hidroelétrica.
I*4	ISBHD Col. 19	I2	Número do subsistema a que pertence a usina hidroelétrica.
R*4	PHD Col. 22	F7.1	Potência Instalada da usina hidroelétrica em MW.
I*4	NUTHD Col. 30	I2	Número total de unidades.
I*4	NUBHD Col. 33	I2	Número de unidades de base. Corresponde ao número de unidades necessário para gerar a energia firme da usina.
I*4	CDPSHD Col. 36	I8	Código do posto hidrológico. Identifica o posto onde estão gravadas as vazões naturais afluentes ao aproveitamento.
I*4	CDJSHD Col. 45	I4	Código da usina de jusante.
I*4 ou R * 4	RNDHD Col. 49	I3 ou F5.2	Rendimento do conjunto turbina-gerador, em %.

Este registro continua na próxima página.

Campos de Informação (continuação)

Tipo	Nome	Formato	Descrição
R*4	IFHD Col. 54	F5.1	Taxa equivalente de indisponibilidade forçada, em %.
R*4	QDRHD Col. 60	F6.1	Queda de referência, em metros.
R*4	PRDHD Col. 67	F6.1	Perda hidráulica média, em metros.
I*4	VZHDMN Col. 74	I4	Vazão mínima defluente, em m^3/s. Corresponde à menor vazão com que a usina deverá operar no horário fora de ponta, exceto quando a vazão afluente for necessariamente inferior à mesma. Pode ser necessária por motivos ambientais, de navegação ou operacionais das unidades geradoras (submergência mínima das turbinas).
R*4	NJHDMD Col. 79	F6.1	Nível médio do canal de fuga, em metros.
R*4	IPHDM(12) Col. 86	F5.1	Índices mensais de Indisponibilidade Programada, em %.
R*4	VLHDMN Col. 158	F7.1	Volume mínimo, em hm^3.
R*4	CTHDMN Col. 166	F6.1	Cota mínima, em metros.
R*4	ARHDMN Col. 173	F6.1	Área mínima, em km^2.
R*4	VLHD Col. 180	F7.1	Volume intermediário, em hm^3. Necessário apenas para a simulação do MODDHT.
R*4	CTHD Col. 188	F6.1	Cota intermediária, em metros. Necessário apenas para a simulação do MODDHT.
R*4	ARHD Col. 195	F6.1	Área intermediária, em km2 Necessário apenas para a simulação do MODDHT.

Este registro continua na próxima página.

Campos de Informação (continuação)

Tipo	Nome	Formato	Descrição
R*4	VLHDMX Col. 202	F7.1	Volume máximo, em hm^3.
R*4	CTHDMX Col. 210	F6.1	Cota máxima, em metros.
R*4	ARHDMX Col. 217	F6.1	Área máxima, em km^2.
I*2	NTURB Col. 224	I4	Tipo de Turbina: 1: Turbinas Francis 2: Turbinas Kaplan ou Bulbo 3: Turbinas Pelton
R*4	FCMAXL Col. 228	F4.2	Fator de capacidade máximo em %. Utilizado apenas pelo modelo MODDHT.
R*4	VSPILL Col. 234	F6.1	Volume de vertimento em hm^3 Só será possível o vertimento quando o volume do reservatório estiver acima deste valor. Corresponde ao volume na cota da soleira do vertedouro.
I*4	IVIN Col. 241	I4	Volume inicial (Percentagem do volume útil). Default: Volume inicial = 0.
I*2	NDGL Col. 246	I1	Não disponível.
R*4	QMINV Col. 248	F5.0	Vazão mínima defluente durante enchimento de volume morto. Só considerado no HIDREXP1.DAT.
I*2	IDSVCF Col. 254	I1	Opção de consideração da influência do desvio d'água no nível do canal de fuga. 0 – Não considera; 1 – Considera.
I*4	IPSTQINT Col. 256	I3	Código do posto de vazões intermediárias com influência no nível do canal de fuga. 0 – Não considera; Caso contrário – Código do posto.