Simpósio Internacional de Confiabilidade
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THE RELIABILITY OF SOME BRAZILIAN POWER PLANTS USING GAS TURBINES.

1. SUMMARY & PURPOSE

This paper aims to contribute for the proposition of a reliability analysis methodology of thermal power plants using natural gas, for benchmarking purposes, based on analysis by Block Diagrams Reliability.
The work also presents the process of identifying the quantities necessaries to calculate the reliability of equipment, systems and facilities.
It is important to show that the increase in reliability and availability of thermal power plants using natural gas goes in direction to the concept of a sustainable scenario, as well as the need for these thermal plants operate as a supplement when there are restrictions that reduce the hydrological capacity of electricity generated from hydroelectric power plants.
As in many cases the references data were not available, it was used data presented in various databases, such as NERC (North American Electric Reliability Council) [3], OREDA-2002 [4], and others.
This work also presents several benchmarking indicators in the world and offers the most suitable ones for use in Brazil, in addition to carry out a comparison of some Brazilian power plants with average values of the plants covered by the NERC database.

2. INTRODUCTION

A major goal of the power plant operation in Brazil is to reduce the interruption risk in the electricity supply because of the generation system is to be predominantly hydroelectric. The main reasons for the inherent volatility of the hydroelectric system are:
• dependence on hydrological conditions that results in greater risk of electricity supply in addition to price instability;
• reduced ability of annual regularization, ie, over the past years there has been a stagnation of reservoir capacity, which increases the hydrological risk; and
• multiple use of water also leads to outdated values of assured energy from Hydroelectric Power Plants.
The plant operation also reduces the risk of energy deficit by increasing the electric and energy reliability.
The increase in energy reliability is translated through the increased availability of electric power that is independent of the hydrological regime, and also occur increase in electric reliability due to the possibility of plants being installed closer to the center of consumption and therefore with less chance of failures in electric transmission system.
In studies on the reliability of the electrical generation system [1], a forced unnavailability of a generating unit is indicated in terms of forced outage rate and more recently through the forced outage rate equivalent.
In studies on the reliability of the electrical generation system [1], a forced outage of a generating unit is given in terms of forced outage rate and more recently through the forced outage rate equivalent. Further details on these and other performance indicators of plants are provided in section 3.2.
This work aimed to enable the comparison of various indicators between different thermal power plants operating in Brazil and to compare them with other facilities abroad.
There are several criteria for grouping for purposes of benchmarking [11, 12 and 6] and these studies usually have assumed that the best selection criterion for a comparative group of the same level were the fuel and generating capacity for thermal plants that use fuels. More recent studies, however, have felt that other factors such as the operation mode ("base" or "peak"), plant age, etc.., are even more important than fuel or generating capacity. But assuming this requirement that the chosen plants have design features and operation exactly alike, it was not found any plan to set up the group. Therefore, it must find a way to balance the need for a large power plant population in order to achieve and select the same characteristics. Richwine and Curley [11] made studies to identify the most important features, which are listed below:

1. aging
2. turbine criticality
3. fuel firing system
4. boiler circulation system
5. boiler draft type (pressurized vs. balanced vs. converted)

6. turbine manufacturer
7. boiler manufacturer
8. unit size
9. reheats
10. generator manufacturer
11. condenser cooling water type
12. duty cycle

After considering a large number of thermal power plants around the world, Richwine and Curley [11] found that the characteristics they thought to be keys, such as the size and type of fuel, were much less important than others not previously considered. Although each unit must be analyzed individually to find their appropriate peer group, there are some new features that are often identified by the process as the most important. Then, in the present study, it is considered appropriate the division of plants into groups on the base of the project settings, namely: simple cycle, combined cycle and cogeneration, which are briefly described below:

- simple cycle: the power plant consists only of gas turbines that generate energy from the combustion of natural gas and the gas leaving the turbine is sent through a chimney directly into the environment, according to scheme shown in Figure 1.
- combined cycle: in this case the hot gases leaving the gas turbine is recycled in a heat recovery steam generator that generates steam and the steam enters the steam turbine generating more electricity. See Figure 2.
- cogeneration: the power plant generates electricity and provides additional steam or mechanical work for any client, according the scheme in Figure 3.

So with the plants divided into three groups according to their project settings, it was possible to compare the indicators of plants within the same group.

In this study ten plants and their projects were studied. Of these ten UTEs, five are of the simple cycle, two of combined cycle, two in cogeneration mode and one with two trains in combined cycle and one train in cogeneration. All the plants are of low age, of low operating time and receive natural gas through pipelines.

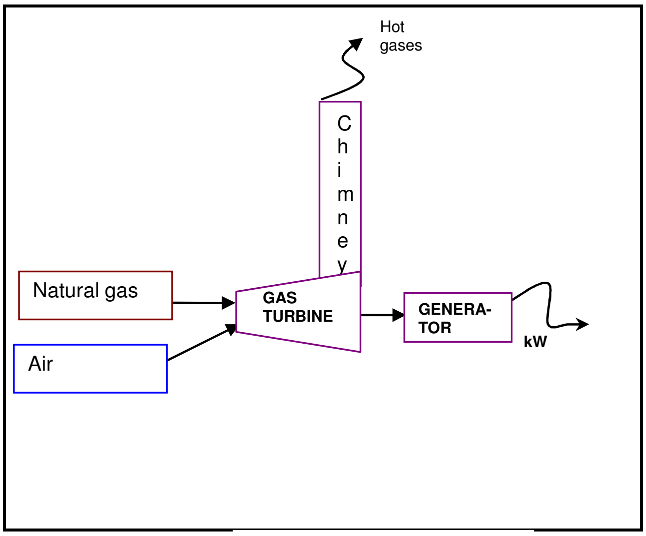

Figure 1- Scheme of simple cycle

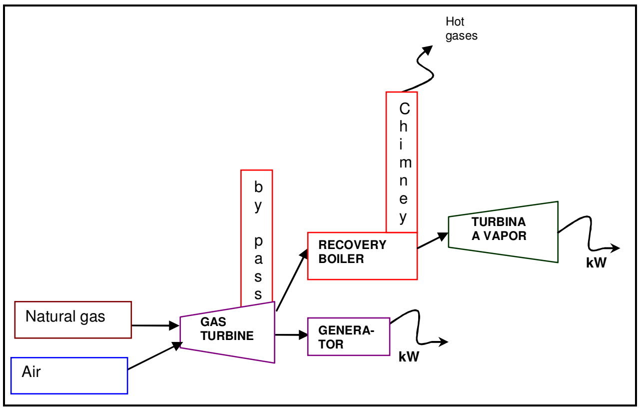

Figure 2- Scheme of combined cycle

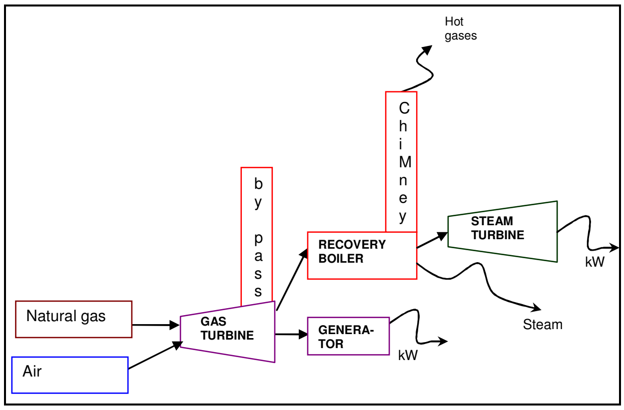

Figure 3- Scheme of cogeneration.

3. METHODOLOGY USED IN THE ANALYSIS OF AVAILABILITY

The identification of the main causes of the unavailability in a thermal power plant is useful for planning engineering and maintenance.

The methodology in this study considers that the average availability is calculated for the case of electricity supply between 80 and 100% of design capacity through the design analysis of each thermal power plant. In other

words, the power plant is considered available only if the generation is over 80% of design capacity.
The methodology used in the study was the analysis of Block Diagrams Reliability. The results were calculated for an operating cycle of 6 years (range that includes the stops for complete maintenance - overhauls - in the gas turbines, steam turbines and heat recovery steam generators). The quantitative assessments of the diagrams were made with the aid of computer program BlockSim version 7.2.0.3 [2].
The calculation of average time to failure (MTTF) and mean time to repair (MTTR) of the failures of various components of each power plant was performed by mapping, or when the failure data were not available by using different databases, such as NERC 1999-2003 [3], OREDA-2002 [4], among others.
It was initially carried out a survey of preventive maintenance schedule for each power plant. Basically this schedule is controlled by the needs identified by gas turbines. From these schedules it was possible to calculate the spent hours in planned outages and the causes of an unavailability, known as " unavailability due to planned outages". Basically this unavailability is generated by the major plant equipments: gas turbines, steam turbines and heat recovery boilers.
An example of the result obtained, for the power plant #1 when operating in combined cycle, without even considering the failures, but only considering the planned outages, is shown in Figure 4.

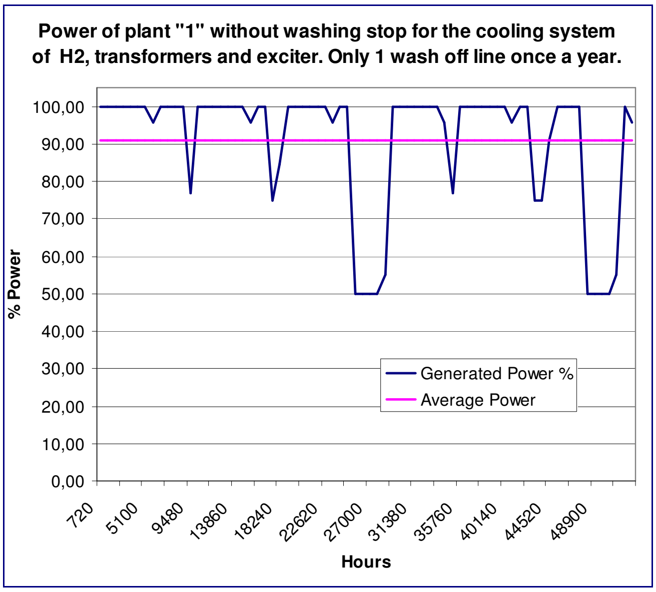

Figure 4- Availability of UTE #1 whereas it is not necessary to stop for washing the cooling system of electrical transformers. The average capacity is 90.44% of the maximum capacity of power plant

3.1 Steps

From this survey, it is initiated the assessment phase of failure frequency in meeting the electricity demand (between 80-100% capacity) of power plant, following the steps:

3.1.1-Step 1: identifying the logical paths of success

This step identifies the combinations involving failure and success of the generating units of UTE. Each of these combinations is a logical path of success in meeting the demand. To determine these paths, it was used a spreadsheet, prepared in Microsoft Excel V.2003 [9]. As entries are provided the demands and the capacity of generating units, and as output, the power actually produced. Table 1 shows the spreadsheet for a power plant #6 operating in combined cycle, as is sketched in Figure 5. In this table are shown the percentage of power in relation to the total power for each arrangement. In the column sources index varies between **0** and **1** reflecting the power stage, where **0** means that the source is not producing anything and **1** means 100% capacity. In the column Energy Production the index **0** means that the arrangement does NOT meet the power indicated in the column, while the index **1** means that the arrangement meets the power indicated in the column.

Table 1- Spreadsheet: Example of use for a thermal power plant operating in combined cycle

	SOURCES			ENERGY PRODUCTION				
	TG-1	HRSG12	TV-1	(%)	100%	90%	75%	ALL
1-A	1	1	1	100,00%	1	1	1	1
1-B	1	0	0	65,57%	0	1	1	0
1-C	0,5	0,5	0,5	50,00%	0	1	1	0
1-D	0,75	0,75	0,75	75,00%	0	1	1	0
1-E	0,8	0,8	0,8	80,00%	0	1	1	0

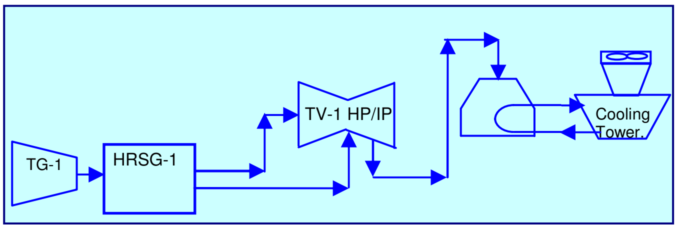

Figure 5- Schematic of the combined cycle in the power plant #6.

3.1.2-Step 2: determination of minimum logical paths

Among the logical paths of success identified in Step 1, they are used in the study only those whose withdrawal of one of its generating units prevents that the demands to be less than 80% of the maximum capacity of UTE. The Table 2 presents the paths obtained for the minimum case of UTE #6 listed above. This Table 2 shows for each type of arrangement which the minimum percentage of energy generated in relation to the ability of UTE. In this case were obtained only 2 minimal arrangements.

Table 2 - Operating Mode 1: Scenarios that satisfy the minimum production of 80% of the capacity of any plant UTE #6.

				ENERGY PRODUCTION			
	TG-1	HRSG1	TV-1	(%)	100%	90%	80%
1-A	1	1	1	100,00%	1	1	1
1-C	1	0,5	0,5	82,79%	0	0	1

For each minimum arrangement of unit #6 they were also considered , if necessary, sub-arrangements which provide the partial failure condition of the cooling tower from the Steam Turbine Condenser, Transformer Generator and Exciter.

These sub-arrangements consider the following faults in the case of unit #6:

1- Failure of the recirculation pumps from the cooling tower for ST (Stema Turbine);

2- Failure of one cell of a Cooling Tower for ST;

Taking in consideration that in the cooling tower design, it was made an overestimation of the order of 20%, ie, there is an extra cell in the cooling tower, so the failure of a cell of the same does not imply a reduction of the power of ST. For the case of two cells stop the operation, it was used the hypothesis that the power of ST would be reduced by 25%, falling to 63.075 MW, which means reducing the power of the whole plant up to 8.61% or falling to 91.39% of the total power provided to the unit #6.

Table 3 presents the results used in the simulation of the cooling tower system, noting that they were generated 6 arrangements which were later converted into block diagrams.

Table 3 - Operating Mode: Sub-arrangements considered for the Cooling Towers system of unit #6

Arrangement	Cooling Tower Configuration for TV		Configuration of the Extraction Pump for the condenser of TV			
Minimum 1A	Cooling Tower	Pump 1	Pump 2	Pump 1	Pump 2	TV-1 power	Power of the unit
1	4	1	1	1	1	100%	100%
2	4	1	1	1	0	50%	85%
3	3	1	0	1	1	75,00%	92,70%
4	3	1	0	1	0	50%	85%
5	2	1	1	1	1	50,00%	85%
6	2	1	0	1	0	50,00%	85%

3.1.3- Step 3: identification of the logical minimum arrangements

The meeting, in parallel, of the obtained minimum logical paths in Step 2, it forms a logical arrangement that represents the minimum simplified logic configuration of the generation system of the power plant from the point of view of reliability analysis.

As an example, in the case of unit #6, it was identified only one minimum logical arrangement, shown in Figure 6, considering the different combinations of demand.

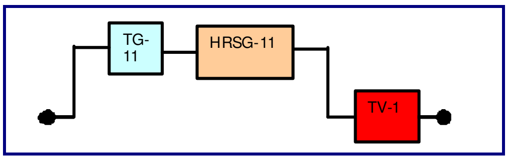

Figure 6- Minimum Logical arrangement that meets the hypotheses of this study for the unit #6.

3.1.4-Step 4: identification of block diagrams reliability

So they are presented 6 reliability block diagrams that adequately represent the system of the unit #6. These diagrams were quantified with the support of computational reliability analysis BlockSim version 7.0.3 [2]. The results represent the mean values for each year of the operational cycle of 6 years and considering the main equipment, including pumps, tanks deaerators, turbines, boilers, etc..

It is important to stand out that in the preparation of reliability block diagrams, it was considered all active components (pumps, control valves, etc..) that show the highest rates of failure and directly impact the supply of electricity. The events "Failure of Gas Turbine", "Failure of Recovery Boilers" and "Failure of Steam Turbine" include failures of the equipment itself, failures in instrumentation and control associated with the process.

To be correctly represented the success logic of the generate system of a thermal power plant in a reliability block diagram, it is necessary to detail the possibility of loss of outside and inside electric power system in all reliability block diagram of power plants.

The Figure 7 shows the reliability block diagram for the combined cycle of the unit #6. For example, the Figure 8 shows the cooling system of such unit.

The average availability was calculated in 2 ways: without considering the influence of natural gas supply and considering this influence.

In addition to availability, they are obtained some other data. As an example, the chart of failures for specific blocks, such as the set of gas turbine, shown in Figure 9.

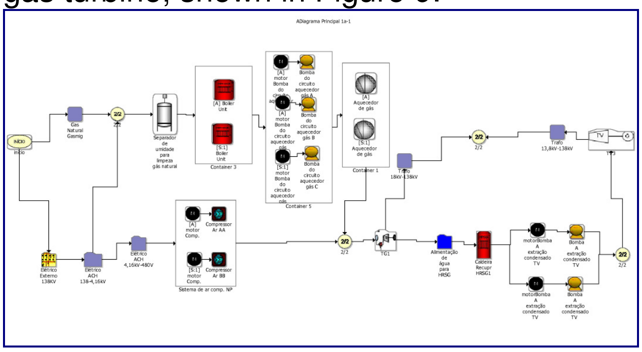

Figure 7- Reliability Block Diagram for the Unit #6.

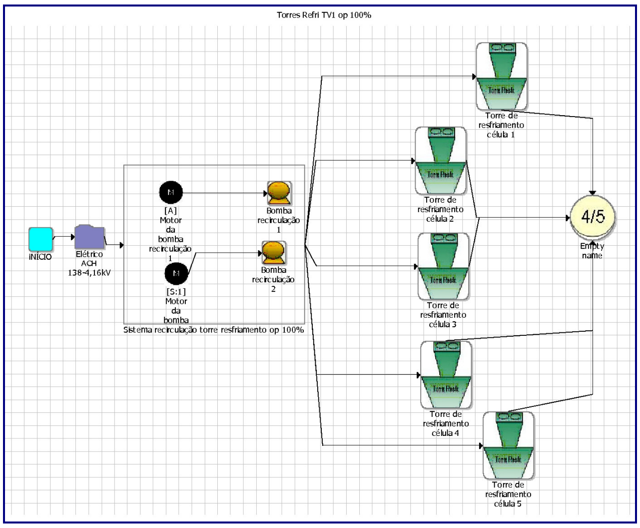

Figure 8- Reliability Block Diagram of the Cooling Tower System for the unit #6.

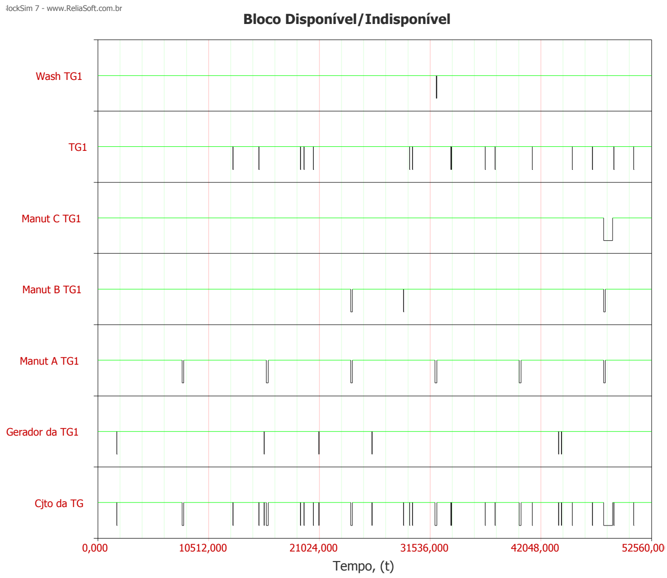

Figure 9- Graph showing the shutdowns of a Gas Turbine, calculated by BlockSim, considering the maintenance, wash off line and failures for the unit #6.

----- Time in operation -----Time in repair

The actual availability should be calculated annually based on reports by operational indicators SF (Service Factor), AF (Availability Factor), EAF (Equivalent Availability Factor), EFOR (Equivalent Forced Outage Rate), among others, which are presented in Table 4. These indicators, and many others, are defined in IEEE-762-2006 [8].

Table 4 - Indicators proposed for this study.

AGE-age

NCF-Net Capacity Factor

GCF- Gross Capacity Factor

SF- Service factor

NOF- Net Output Factor

AF– Availability Factor

EAF– Equivalent Available Factor

FOR– Forced Outage Rate

EFOR– Equivalent Forced Outage Rate

EFORd- Equivalent Forced Outage Rate demand

SOF-Schedule Outage Rate

FOF- Forced Outage Factor

SR- Starting Reliability

ART- Average Run time

FOA- Forced Outage – Automatic Trip

FOM- Forced Outage Manual Shutdown

AL- Average Load

MTBF– Mean Time Between Failure

MTTR– Mean Time to Repair

Reliability

For example, it is presented the definition of the indicator "factor service", which provides how much has been operating the power plant. For a thermoelectric power plant that uses a single generating unit, the definition of SF is:

$$SF = \frac{SH}{PH}$$

where:

- *SH* expresses the number of hours the unit operated.
- *PH* expresses the number of hours in the period which the unit remains in the active state (See Figures 10 and 11).

3.2 Data obtained from world database

Since the indicators are calculated from several hourly factors, events classes and failure rates, it is emphasized that the important thing is that the survey methodology of these values is standardized, so it is possibly compare them with available performance in international database.

3.2.1 - Standardization mapping the failure rates and hourly values that make up the indicators.

In order to standardize the survey, it is necessary first define the current state of the plant, defined as one of the blocks shown in Figure 10, established by the IEEE Std 762-2006 [8] also used the NERC (North American Electric Reliability Council). The definition of each of these blocks is presented in references [8 e13].

It is important that the operator can identify the type of shutdown or reduction in capacity that occurs in a power plant. The definition of the outages types and reductions in capacity is given in references [8 e14].

It is important to note that the database system ORAP ® ("Operational Reliability Analysis Program) uses a similar classification, which has minor differences with regard to the planned stops, which for the IEEE and NERC are forced (for class 3 ORAP® is the planned stop). These differences can be observed in Figure 11.

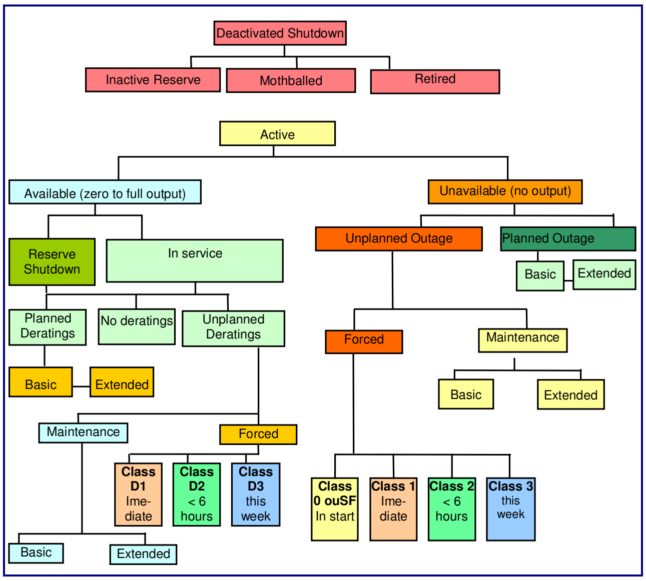

Figure 10- Possible states for a thermal power plant [8]

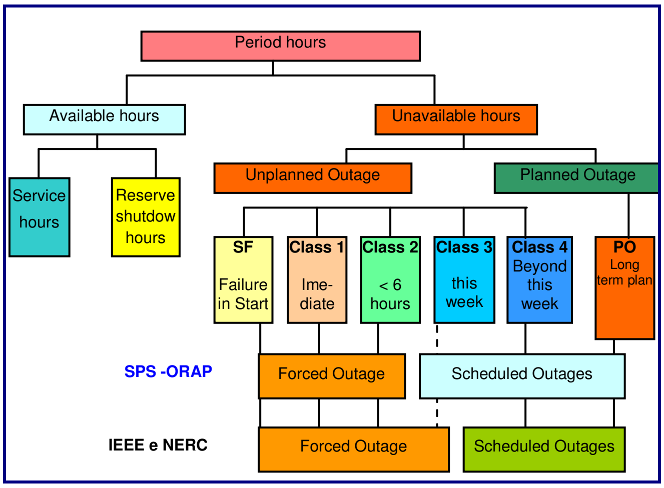

Figure 11- Possible states for a power plant, comparison between IEEE / SPS-NERC and Orap [10].

4. RESULTS

Next are presented the results of availability and service factor for the plants studied.

4.1 Results obtained from design data

The values of the calculated availability by means of the Block Diagram method, for plants operating in simple cycle in the range

of 6 years, as detailed in item 3, are presented in Table 5. In this case the availability was calculated to provide between 80-100% of the capacity of the power plant.
The Table 6 presents the results for the combined cycle power plants and cogeneration.

Table 5 - Availability calculated from the design of thermal power plants in simple cycle.

	Availability (AF)				
	1	2	3(*)	4(*)	5(*)
Average 5 years	95,4.	85,37	96,17	85,37	94,7
GE7FA [5]	89,3				
ORAP data from EPRI report [6]			95,4		

(*) Using aero derivative turbines.

Table 6 - Availability calculated from the design of thermal power plants in combined cycle and cogeneration.

	Availability (AF)					
	Combined Cycle			Cogeneration		
	6	7	8(**)	9	10	8(**)
Average 5 years	94,37.	78	86,09	91,92	65,05	85.63

(**) Unit operates with 2 trains on the combined cycle and cogeneration train 1

4.2 Results obtained from actual data

As cited earlier, it is important to analyze the service factor (SF) because many of these plants have not been operated due to various factors such as lack of natural gas (until 2007), availability of hydroelectric power, among others. The actual data for the service factor can be seen in Table 7, for some years.

Table 7 - Service Factor for power plant in simple cycle, combined cycle and cogeneration.

	Service Factor for simple cycle (SF)				
	1	2	3(*)	4(*)	5(*)
2006	62	9,9	3,45	---	1,34
2007	20	14,5	9,26	3,51	0,48

	Service Factor for combined cycle and cogeneration (SF)					
	Combined Cycle			Cogeneration		
	6	7	8(**)	9	10	8(**)
2006	58,27	---	6,64/0,77	0	15,56	28,16
2007	25,45	---	5,81/0,61	44,51	36,98	21,72

The Table 8 presents the results of the actual availability calculated from the operational reports.

Note that the availability results from the project are reference values used primarily as a basis for availability targets for the average of 5 years. The calculation of these values is important for setting availability targets for certain plants because each case its project will not permit to reach the goals of the group average.

Table 8 - Real availability in simple cycle, combined cycle and cogeneration.

	Real Availability for simple cycle (AF)				
	1	2	3(*)	4(*)	5(*)
2006	---	---	99,94	---	89,2
2007	---	---	99,34	---	97,38
2008	---	---		90,61	87,16

	Real Availability for combined cycle and cogeneration (AF)					
	Combined Cycle			Cogeneration		
	6	7	8(**)	9	10	8(**)
2003-7	.93,24	---	---	100	---	---
2007	---	---	---	99,98	66,68	---
2008	---	---	---	95,34	71,95	---

5. CONCLUSIONS

The result of reliability analysis, using the block diagram, has shown that the design of some thermal plants was made with the philosophy of getting a good availability, since there is redundancy in the most appropriate equipment In others plants there are scope to achieve better reliability since the redundancies necessaries be implanted.
A comparison of the average availability of the power plants with the average values of combined cycle power plant from NERC for the period 2002-2006, showed higher values for the single plant #6, whereas in some others power plants could not acquire these actual data. For the simple cycle (could not get the value of the actual availability for plants #1 e #2) the availability for the thermal plants #4 and #5 was smaller than the average value of the NERC for the past 5 years, but higher for the power plant 3.
It should be noted that the average age of the plants NERC (2002-2006) is 9.72 years, while the average age of power plant studied is 5 years until 12/2007. Also should be considered that these numbers are still partly because the Brazilian power plants only in recent years operate continuously. It has been shown that the external electric net

system which the power plants flawed, it contributes to reduce the power plant availability, except in the cases of the few who can make islanding (power plants #8 and #10).
Originally this study intended to provide to the power plant managers, the stage of each plant at the end of 2007, in terms of comparative performance with other plants in Brazil and in the world.
From these data, it was made a recommendation to the power plant owner to make efforts to standardize the data acquired by operators, in order to be possible in future to compare performance with worldwide data through the use of all indicators. Many indicators could not be raised for all thermal plants, including one of them did not provide data to calculate any of the indicators provided.
There are two types of data groups to be recorded:
- those that can be collected automatically, such as: gross electricity generated, consumed energy, etc.. These data can be obtained from systems such as DCS (Distributed Control System) or a tool for data management in real time and,
- operating records of state of the system , such as records of corrective maintenance, preventive forced outages, among others.
In the case of data that can be obtained from the DCS or tools for data management, efforts should be made to avoid to re-enter them, because this work, in addition to being expensive frequently leads to mistakes. For the records and description of events, it is suggested to use the international standards established by the IEEE Std 762-2006 [19].
Since 2009, most of these thermal plants is in the process of accession of the ORAP® system.

6. REFERENCES

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