Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Incorporation of Rationing Effects to Hydrothermal Dispatch Optimization

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***Abstract*--In Brazil, power supply safety criteria is established by the sector regulation, the power supply insufficiency risk must not exceed 5% limit. Thus, the tools that enable agents to model the rationing more accurately became necessary, estimating the impact caused by such kind of event and the future consequences. The official model used by Brazilian electric sector to carry out the expansion planning and medium/long-term operation is based on Stochastic Dual Dynamic Programming technique (SDDP). The main results that this model presents are the monthly evolution projection of Short Run Marginal Cost (SRMC) and hydrothermal dispatch, considering various hydrological scenarios. However, such model does not contain the representation of conjuncture changes occurred during a rationing, such as, for example, demand retraction and thermal dispatch out of merit order. This paper presents a new alternative to estimate rationing effects on power operation planning.**

***Index Terms*--Rationing, Risk Analysis, Power Market, Expansion Planning, Hydrothermal Systems Operation.**

I. Introduction

THE Brazilian electric system is large, comprising more than 100,000 MW installed capacity and approximately 73,000 Km transmission lines between 230 kV and 750 kV, mostly hydroelectric. The hydro plants portion amounts to 82% of electric energy generation matrix. Therefore, the system operation and expansion planning takes into account the great affluence stochasticity in hydroelectric power plants [16]. Currently, the National Electric System Operator or Independent System Operator (ISO) uses studies (5 years ahead) for medium-term operation planning, an optimization model based on Stochastic Dual Dynamic Programming technique to carry out the operation planning called NEWAVE [3]. Such model groups hydroelectric power plants in hydraulic basins having similar hydrological behavior to so-called equivalent energy subsystem. Four equivalent subsystems are used (north, northeast, southeast/mid west and south regions) including monthly operation discretization, which makes available to system operator the major variables projections for each of hydrological scenarios such as, for example:

- ✓ Short Run Marginal Cost (SRMC)
- ✓ Hydraulic and Thermoelectric Generation for submarkets
- ✓ Energy deficits
- ✓ Interchange among equivalent subsystems

Results above are obtained from a simulation, using synthetic hydrologic scenarios generated through a stochastic model called PAR(p) – Periodical Self-regressive Model. The affluence to reservoirs is the sole variable approached in a stochastic manner. Other model input variables are treated in a deterministic manner, which, however, may be subject to change throughout the study. For example:

- ✓ Power demand
- ✓ Generation and transmission expansion timeframe
- ✓ Fuel cost

Models used for hydrothermal system operation planning are intended to meet the estimated demand [1], [2], [4], minimizing the expected value of operation cost along with the study. The operation costs consist of thermoelectric power plants fuel cost and cost allocated to failure to meet the demand, called cost of deficit. Failure to meet the demand is represented by a thermoelectric power plant, called deficit power plant, having equal capacity to failed demand and operation cost equal to economic cost allocated to power rationing [7].

A great problem that Brazilian energy market agents face is the variables projection (SRMC, power plants generation, etc.) in NEWAVE model, when the system is in an electric energy rationing. As the demand curve is a deterministic input variable for NEWAVE model, when the rationing is over, it will not include any consumption restriction effect.

Failing to take into consideration the decrease of power demand, the model extends the restriction period, which may

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take longer than two years, indicating increased SRMC for longer periods in scenarios which power deficit occurs. Such effect has not been noticed in past rationing in Brazil (2001/2002), after its end, SRMC remained low for long period, due to higher reservoir levels and demand reduction caused by consumption restriction.

The modeling currently used by Brazilian electric sector does not contain a power rationing representation, requiring new tools development to assist agents in estimating financial impacts more accurately during the event and in the subsequent years. The purpose of this paper is to emulate, using the own NEWAVE model, the system economic changes that have taken place during rationing. It enables agents to dimension energy demand behavior more accurately in the future.

II. Energy Rationing in Brazil

The main purpose of the electric sector regulatory and commercial framework is to guarantee reliable power supply at fair prices, essential conditions for the country's economic growth.

In theory, it would be possible planning and building an electric system, which is 100% reliable in meeting the demand, including the system served by hydroelectric power plants. The solution for such problem would be the construction of a large number of hydroelectric power plants, being likely that energy availability is less than demand to be met tends to zero.

The problem concerning the solution exposed above is that the more safety is added to the electric system, the energy becomes more expensive. It is then required to find a break-even point between energy cost and system reliability.

In view of aspects previously described and the large hydroelectricity participation in Brazil, electric energy rationing may be considered as natural phenomenon in the Brazilian energy interconnected system.

To optimize the system expansion planning in the long-term along with the hydrothermal dispatch optimization models previously mentioned [17], this paper shows techniques based on genetic algorithms to estimate the best expansion timeframe of hydroelectric and thermal power plants and transmission systems to assure the intended safety criteria.

In the past 25 years, Brazil has faced some energy supply crisis:

- ✓ January through March 1986 – rationing in the South Region, up to 20% restriction in consumption;
- ✓ March 1987 through January 1988 – rationing in regions North and Northeast, approximately 13% restriction in consumption;
- ✓ June 2001 through February 2002 – rationing in regions Southeast and Northeast, 20% restriction in consumption. In North region the consumption restriction reached 15% by December 2001.

South region rationing, in 1986, and North and Northeast regions rationing, in 1987 and 1988, were used as basis for the consumption restriction imposed to some country regions during 2001, the strictest rationing imposed to the country. Actions taken by the Government, the Brazilian Electricity Regulatory Agency (ANEEL) and ISO (National Electricity System Operator) during 2001 rationing will be the directives used in this work to model the effects of a new rationing and estimate its consequences in the electric energy market.

The major cause for 2001 rationing was the structural imbalance between the energy supply and demand, mostly caused by delays in works timeframes and projects cancellation, allied to an unfavorable hydrological condition, mainly in southeast subsystem.

In 2008, Brazil was threatened by another energy rationing caused, once again, by imbalance between energy supply and demand and late rainy season. Such fact reinforces that a tool is required to enable energy market agents measure the effects of a likely rationing and its income and demand future evolution.

III. Hydrothermal Systems Operation Planning

Analyzing past rationing events, in Brazil, it is observed that there is a breach in the operation planning evolution sequence, that is, specific rules created to recover hydroelectric power plant storage and reestablishment of market reliability. Such rules are not implemented to the optimization model, as well as the energy demand behavior after the rationing, rendering difficult the estimate of some important variables, which impact on operation and income of Brazilian electric energy market agents.

Based on 2001 rationing, it was observed some operatives and regulatory actions by ISO and Government, these interferences were incorporated in the model.

Monthly SRMC estimates and dispatch are very important for all system agents as they affect their compensation. Fig. 1 shows spot prices historical, before and after 2001 rationing.

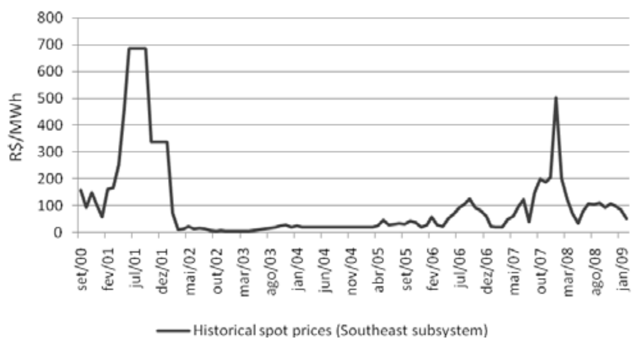

Fig. 1. Spot prices, before and after 2001 rationing.

The main purpose of hydrothermal system operation planning is to determine generation targets to meet the demand, minimize the expected value of operation cost along with the study [5], [6]. The operation cost consists of thermoelectric power plants fuel cost and cost allocated to failure to meet the demand, cost of deficit. The approach to settle this problem is based on Stochastic Dual Dynamic Programming (SDDP) [8], [14], [15], [17], [18], [19], [20].

This section points out the important concepts to understand the proposed methodology.

A. Demand Levels

The demand curve to be met by a subsystem during a certain month of the study, daily, weekly and monthly seasonality. For medium and long-term planning, focus of present work, the time discretization has a monthly basis [7]. Three load stages are considered during the month to include on-peak, shoulder and off-peak demand effect.

The demand levels are represented by: (i) depth, which is the p.u. value of monthly average demand to be met at the stage under analysis; (ii) duration, p.u. value of stage time during the month. The sum of depth-duration products, considering the appropriate corrections to units, provides the total energy consumed by that subsystem during the month in question.

B. Deficit Stages

The system operation cost during a certain period is based on the following portions: (i) the sum of operation cost of thermal power plants; (ii) cost afforded by failure to meet demand; (iii) future cost regarding current operation decision duly deduced at a certain interest rate.

The energy deficit is modeled as a thermal power plant with infinite capacity and high cost for each subsystem.

Four stages with different costs have been considered to represent different deficit severity:

- ✓ Stage 1: Up to 5% of demand share
- ✓ Stage 2: 5 to 10% of demand share
- ✓ Stage 3: 10 to 20% of demand share
- ✓ Stage 4: Above 20%

Therefore, it is possible to rank deficits of different severity degrees for the system.

C. Model Outputs

The price of differences settlement (PLD) is the amount paid for the energy in the short-term market or spot price [9], [10], [21]. The value is calculated weekly by the Electric Power Trading Chamber (CCEE) and its upper and lower limits are determined annually by the regulatory agency, Brazilian Electricity Regulatory Agency (ANEEL) [11]. PLD calculation basis is the Operation Marginal Cost and, therefore, SRMC estimates for several scenarios are very important for agents' analysis.

Another important model output is the monthly energy deficit for each demand stage, deficit stage and hydrologic scenario. Through the analysis of such variable, it is possible to establish criteria to identify the start up of energy rationing.

It should be also pointed out the estimate of stored energy evolution for each equivalent subsystem in each hydrological scenario. The stored energy reflects the water volume in the reservoirs within the equivalent subsystems.

Finally, the model provides the monthly estimate for each hydrologic scenario of hydraulic, thermal and interchange generation for each demand level.

D. Rationing Problem in Hydroelectric Base Systems

As for systems with hydroelectric predominance, the energy rationing is characterized by the fact that the system has availability to meet the demand required in the short-time, at any demand stage, with no need to cut, but has no capacity to meet the system in longer periods (weeks, months). In view of such scenario, the foreseen affluent flows (weeks, months) added the energy stored in the reservoirs are not sufficient to meet the energy demand during the same period.

Upon execution of NEWAVE model with official data provided by ISO [11] it may be observed that some synthetic hydrologic scenarios present deficit in some months. Within such scenarios, the calculated values of short run marginal costs do not portray the system operation reality in the event of rationing, decrease of demand curve and dispatch of thermal power plants out of merit order would occur in this series.

The high deficit value indicates that, for such hydrologic scenarios, the rationing should be started, dramatically changing the solution adopted for the model.

In view of this problem, it is not possible for the investor to have a reliable forecast of amount paid for the energy in the short-term market, as well as the power generated and other important variables for the analysis in view of possible rationing scenario.

IV. Proposed Methodology

It should be considered that due to impact cause to society as a whole, the rationing besides the electric and energetic aspect is also a political problem. From this point view, during such event, the system operation, as well as the energy pricing in the short-term market, is carried out under an exceptional regimen.

The modeling currently used does not comprise such representation, being required the development of new tools which assist the agents to accurately estimate the financial impacts during the event and in the subsequent years. This is the purpose hereof.

Some assumptions were defined to incorporate the rationing scenario to NEWAVE model, based on the supply crisis and electric energy rationing in SIN during year 2001 [12]. Such assumptions are detailed below.

The Flowchart of Fig. 1 below summarizes the proposed algorithm.

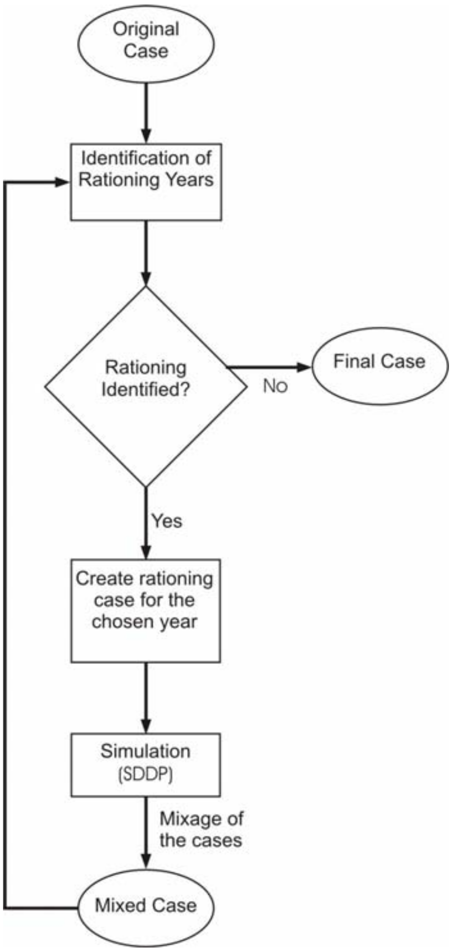

Fig. 1. Proposed Algorithm.

A. Identification of Years with Probable Energy Rationing

The study case prepared by the National Electricity System Operator (ISO) is used as data input. Newave model is executed and generates results for 2000 hydrologic scenarios on a monthly basis for a five-year study (from year 2007 through year 2011). In the present work, the study period started in January 2007 and terminated in December 2011. In view of affluences' seasonality in hydrographic basis and the rationing experience in 2001, it may be understood that May is the most likely month in which the Brazilian Government will interfere through market regulatory mechanisms to minimize the effects of a new rationing.

Thus, for each hydrological scenario, deficits above 5% of demand for three consecutive months are sought within the same year of study. Whenever such condition occurs, it is identified as being the year with probable occurrence of rationing. This procedure was adopted because deficits lower than 5% do not characterize rationing scenarios, since there are other ways to cope with this situation.

The following criteria was used for this paper: (i) occurrence of three consecutive deficits during the wet period (from November through April), rationing will be decreed in the next May; (ii) occurrence of three consecutive deficits during the dry period (from April through October), rationing will be decreed in May of same year.

B. Rationing Scenarios

In step A, n years are identified as probable occurrence of rationing and n new study cases are created based on Base Case.

In step B, each of *n* new study cases is processed through the operation planning model.

The assumptions used to create each *n* study case are described below:

1) Study Period

The study will always start in the month of April of year in question. For example, if it verified that in base case used in this paper (January 2007 through December 2011), there is a probable deficit during year 2008 and 2009, two new study cases are generated comprising, respectively, the following periods:

- ✓ From April 2008 through December 2011
- ✓ From April 2009 through December 2011

In accordance with the foregoing, each new study case operates as if ISO was facing rationing and required new optimal operation planning due to change in model input data.

2) Initial Volume

Initial power stored in each subsystem in the beginning of the study will make use of the month of April average of series that indicate rationing for the year in question.

3) Demand Curve Change

Rationing in Brazil during 2001 showed a severe decrease in power demand curve. Demand curve has not returned to the original levels when the rationing was over, but a progressive recovery along some years. Such phenomenon may be explained by the economic impact that the rationing and energy efficiency gain have caused.

In new study cases, the demand curve of each subsystem is changed in accordance with the standard behavior observed during 2001 rationing.

For each equivalent subsystem it was carried out a study comparing the demand curve estimated before 2001 rationing to the demand curve effectively carried out. Therefore, it was possible to find out a multiplying factor between the real demand curve and the estimated one for each rationing month. Fig. 2 shows the estimated monthly demand curve and the realized one in the southeast subsystem, where a strong demand decrees in the month of April is observed.

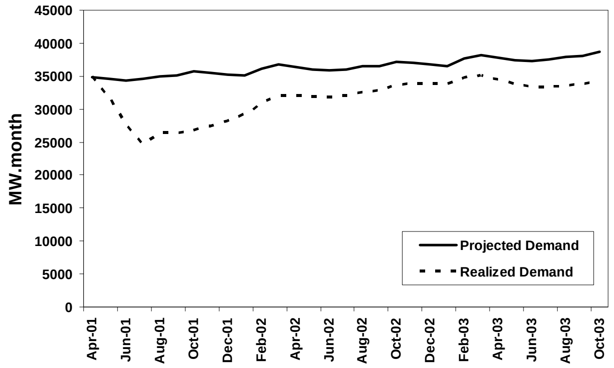

Fig. 2. Projected and Realized Demand Curves in 2001

Fig. 2 shows the relation factor between the estimated and realized demand curve. Based on that, the market decrease factors for each of the four subsystems were extracted.

Finally, for each *n* new study cases, the market decrease factors are applied. Thus, it is managed to obtain the major effect of Short Run Marginal Cost (SRMC) decrease during the rationing period. The inclusion of such result is unprecedented as from this work.

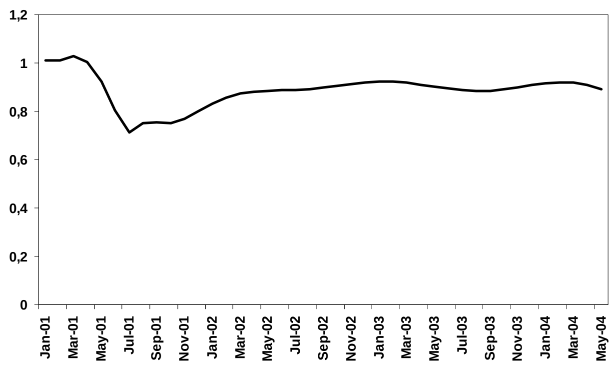

Fig. 3. Real / Estimated Relation in Southeast Market

4) Thermal Power Plants Dispatch

To supplement the regulatory interference representation imposed by ISO, during the rationing period, thermal power plants are dispatched at full load "ad referendum" of operation planning model. That is, all thermal power plants of equivalent subsystems, in which rationing probability was detected, dispatched maximum power during ten months as of the rationing start up [13]. This is the period in which one believes the rainfall is capable of assuring the recovery of reservoirs and the month of May was chosen since it is when the dry season begins.

Out of the rationing period, all thermal power plants must operate identically to the original case. In Fig. 4, the southeast subsystem thermoelectric generation is verified in regard to base case and in the event of rationing during 2009.

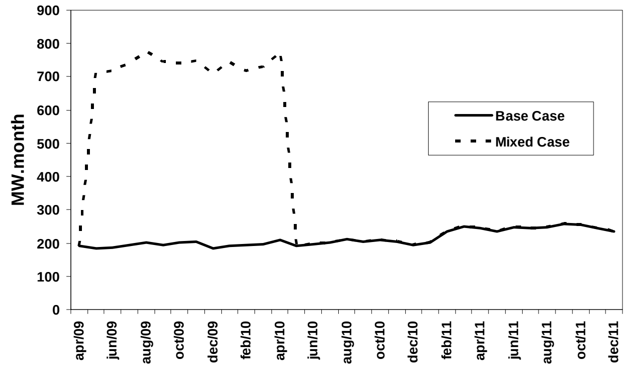

Fig. 4. Total Thermal Generation of Southeast Subsystem with Rationing in 2009

C. Merge of Results (or Mixed Case)

After execution of NEWAVE model for all *n* new study cases, the results corresponding to 2000 hydrologic scenarios considered for each month of the study must comprise not only the base case estimates, but also the estimates obtained for each probable year of rationing. Such data set was called mixed results.

In possession of simulation results for the base case and all *n* rationing cases it was possible to accomplish the mixing of results. As final result, a matrix was obtained whose dimension is given by the number of months in the simulation *versus* the number of synthetic hydrological scenarios (2000).

This mix is done as follows: for each simulated rationing case it was necessary to identify the synthetic series of affluent energies behaving similarly to synthetic series of the original case identified by the rationing. Thus, the minimum square technical was used. Fig. 5 shows two series of maximum likelihood of cases: base and rationing during 2009.

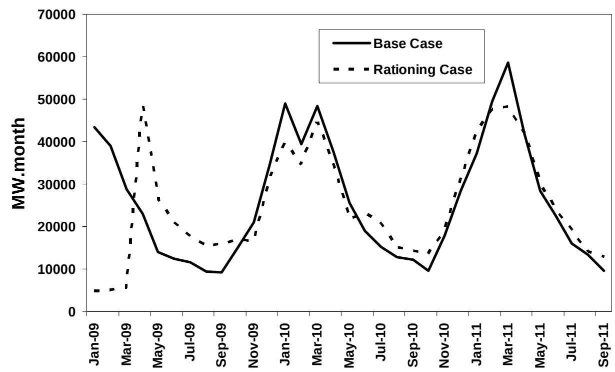

Fig. 5. Comparison between two series identified as similar

The following procedure was adopted for the synthetic series of the two cases identified: all variables of interest values (SRMC, Hydraulic Generation, Thermal Generation, Deficit and Stored Energy) in the original case series were replaced by values found in the respective rationing case series, as of the date of rationing beginning.

During the rationing period, the value was set at R$540,00/MWh (Price Cap) specially for the Short Run

Marginal Cost.

V. RESULTS

As previously indicated, the base study case used for this paper is the official case ISO made available to generation, distribution and transmission agents (January 2007). It was taken into account the number of 146 hydroelectric power plants and 86 thermal power plants. Amongst such number, it is comprised power plants already existing at the time of the study startup (January 2007) and power plants which started operating during the study (from January 2007 through December 2011). Fig. 6 shows the energy demand curve for the 4 equivalent subsystems for all study months.

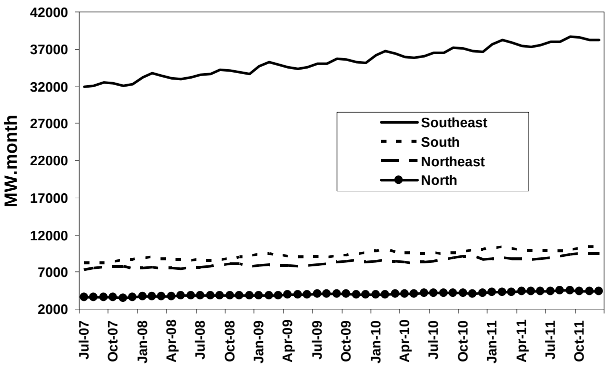

Fig. 6. Energy Market for Base Study Case

As from the base case, it was verified the possible occurrence of energy rationing during years 2008, 2009, 2010 and 2011, thus, 4 new study cases have been generated. Fig. 7 shows the comparison between the markets of southeast subsystem between the study base case and the 2009's rationing case. This figure shows that the present model can reproduce the phenomenon of energy rationing in the same way of 2001 (Fig. 2).

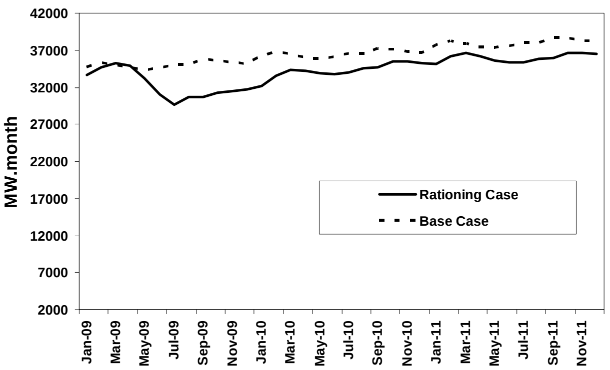

Fig. 7. Demand depletion in 2009 rationing case.

After usage of operation planning model for the four new study cases, results have been mixed and presented below.

Fig. 8 shows a comparison between the average evolution amongst the 2000 series of the Operation Marginal Cost along the months for the original case and the mixed case for Southeast subsystem. It is noticeable that SRMC evolution for the Study Base Case and the mixed case (considering rationing) are quite alike in average. However, for risk analysis purpose, the distribution function of SRMC for each study month presents major changes

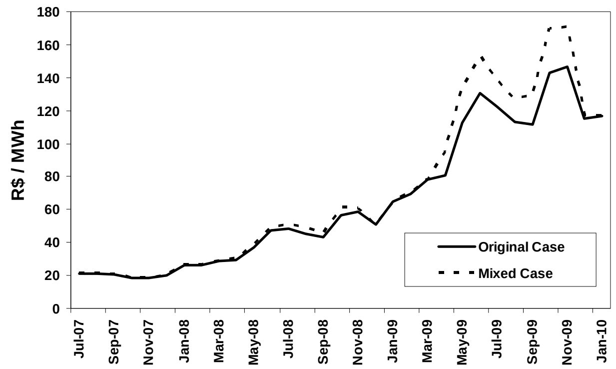

Fig. 8. Comparison between average SRMC of Original Case and Final Mixed Case in the Southeast.

Fig. 9 shows the analogue analysis for total thermal generation of southeast subsystem.

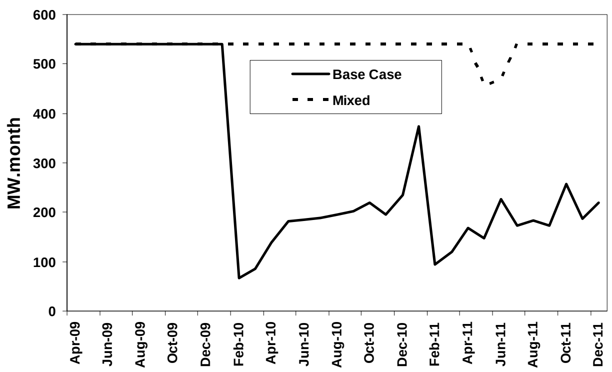

Fig. 9. Comparison between GTERM average from Original case and Final Mixed Case.

VI. CONCLUSIONS

The representation of operatives and regulatory actions adopted during energy rationing events in computer models for hydrothermal systems operation planning in Brazil has been investigated and a way to model it was proposed in this article.

The proposed methodology consists in replace the scenarios with rationing, in original case, by new scenarios where the operatives, regulatory actions and future demand behavior are represented. The results from mixed matrix are more realistic when compared with expected system operation during and after a rationing event.

The main variable of interest for agents analysis, the SRMC, was the more sensitive in view of rationing scenarios.

A computer model was developed to allow agents adjust the algorithms, such as, for example:

- Criteria for identification of years of probable rationing;
- Demand behavior before, during and after rationing event

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