Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia

COPPE UFRJ

# SMALL-SIGNAL SECURITY ASSESSMENT CONSIDERING MINIMUM REDISPATCH

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Tese de Doutorado apresentada ao Programa de Pós-graduação em Engenharia Elétrica, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Doutor em Engenharia Elétrica.

Orientadores: Glauco Nery Taranto
Sergio Gomes Junior

Rio de Janeiro
Julho de 2017

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TESE SUBMETIDA AO CORPO DOCENTE DO INSTITUTO ALBERTO LUIZ COIMBRA DE PÓS-GRADUAÇÃO E PESQUISA DE ENGENHARIA (COPPE) DA UNIVERSIDADE FEDERAL DO RIO DE JANEIRO COMO PARTE DOS REQUISITOS NECESSÁRIOS PARA A OBTENÇÃO DO GRAU DE DOUTOR EM CIÊNCIAS EM ENGENHARIA ELÉTRICA.

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RIO DE JANEIRO, RJ – BRASIL
JULHO DE 2017

Parreiras, Thiago José Masseran Antunes

Small-signal Security Assessment Considering Minimum Redispatch / Thiago José Masseran Antunes Parreiras. – Rio de Janeiro: UFRJ/COPPE, 2017.

XV, 143 p.: il.; 29, 7cm.

Orientadores: Glauco Nery Taranto

Sergio Gomes Junior

Tese (doutorado) – UFRJ/COPPE / Programa de Engenharia Elétrica, 2017.

Referências Bibliográficas: p. 113 – 118.

1. Power system stability. 2. Small-signal security assessment. 3. Small-signal security boundary. 4. Oscillation damping control. I. Taranto, Glauco Nery *et al.* II. Universidade Federal do Rio de Janeiro, COPPE, Programa de Engenharia Elétrica. III. Título.

*This work is dedicated to all my relatives, for everything that they always provided to me, for all the support that they always gave to me, because they have been by my side, in all the moments of my life, especially, when I most needed.*

*Thank you very much!*

*"One does not make friends. One recognizes them."*
*Garth Henrichs*

*"If I have seen further, that is because I stood on the shoulders of giants."*
*Isaac Newton*

# Acknowledgment

I thank God for my existence and for all the blessings that He always provides to me, my mother, Maria Helena Masseran, my father, Nivaldo Parreiras, my sister, Viviane Masseran, and all my family, which always supported me in all the moments of my life, and all my friends that helped me during this journey in this graduation.

I would like to thank all the professors that participated of my academic formation during this doctoral course and, especially, I thank professor Glauco Nery Taranto, from Electrical Engineering Program (PEE) of Alberto Luiz Coimbra Institute of Graduation and Engineering Research (COPPE), which was my advisor in this work.

I also thank all my work friends and colleagues from Energetic Research Company (EPE) and from Electrical Energy Research Center (CEPEL), especially, my friends Nicolas Abreu and Tiago Amaral, for all the help that they gave to me during this graduation, and, more especially, I would like to thank researcher Sergio Gomes Junior, which was my coadvisor during this doctoral course, providing all the support to the development of the researches made and described in this doctoral thesis.

Finally, I thank the National Council for Scientific and Technological Development (CNPq) for the financial support, which allowed the realization of an interchange in Norway, through the Science Without Borders program, at the Norwegian University of Science and Technology (NTNU), which was important to the success of the researches made in this thesis, and, especially, I thank professor Kjetil Uhlen, which was my advisor during this interchange period, and my friend Knut Bjorsvik for all the help that he gave to me during the realization of the work in this interchange.

Resumo da Tese apresentada à COPPE/UFRJ como parte dos requisitos necessários para a obtenção do grau de Doutor em Ciências (D.Sc.)

AVALIAÇÃO DE SEGURANÇA A PEQUENOS SINAIS CONSIDERANDO REDESPACHO MÍNIMO

Thiago José Masseran Antunes Parreiras

Julho/2017

Orientadores: Glauco Nery Taranto
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Programa: Engenharia Elétrica

Este trabalho apresenta uma revisão dos principais conceitos relacionados à estabilidade eletromecânica de sistemas de potência e das características associadas às avaliações de segurança de tensão, transitória e a pequenos sinais (VSA, TSA e SSA). A última é o foco desta pesquisa.

O desenvolvimento de novas ferramentas de avaliação de segurança a pequenos sinais e suas implementações computacionais no programa PacDyn, do Centro de Pesquisas de Energia Elétrica (CEPEL), são descritos.

Um método para determinação de redespacho mínimo em sistemas de potência usando sensibilidades de geração (CSBGRES) é proposto. Este é um método de otimização que considera um fator de amortecimento desejado para modos de oscilação como restrição.

O método CSBGRES pode ser utilizado para a determinação de margens de segurança a pequenos sinais ou de medidas corretivas, visando a melhoria do comportamento dinâmico de sistemas de potência.

Abstract of Thesis presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Doctor of Science (D.Sc.)

SMALL-SIGNAL SECURITY ASSESSMENT CONSIDERING MINIMUM REDISPATCH

Thiago José Masseran Antunes Parreiras

July/2017

Advisors: Glauco Nery Taranto
Sergio Gomes Junior

Department: Electrical Engineering

This work presents a review of the main concepts related to electromechanical stability of power systems and of characteristics associated to the voltage, transient and small-signal security assessments (VSA, TSA and SSA). The last one is the focus of this research.

The development of new tools for small-signal security assessment and their computational implementations in software PacDyn, from Electrical Energy Research Center (CEPEL), are described.

A method for determining minimum redispatch for power systems using generation sensitivities (CSBGRES) is proposed. This is an optimization method that considers a desired damping factor for oscillation modes as constraint.

The CSBGRES method can be utilized for the determination of small-signal security margins or of corrective measures, aiming at the dynamic behavior improvement of power systems.

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# Chapter 1

# Introduction

This chapter will describe the main topics covered by this work, containing the motivations, objectives and contributions of this research. This thesis is focusing on power system stability, small-signal security assessment and determination of corrective measures to improve the system dynamic behavior.

## 1.1 Contextualization

Different kind of studies must be done in the expansion and operation planning of power systems, in order to forecast possible problems in the energy supply to the consumers. These studies are related to power flow, fault and electromechanical stability analyses, among others.

Power flow analyses are concerned with the study of system steady-state conditions, aiming at the determination of bus voltage levels. Active and reactive power flow in branches of the electrical grid are also determined [1].

Fault analyses consist of studying short-circuit levels to which system equipment are submitted, in order to adequate their capability so they can resist to high electrical currents, without suffering any damage. Capability of circuit breakers are also identified in this evaluation [2].

Electromechanical stability analyses are concerned with the study of system dynamic behaviors when disturbances occur in the electrical grid, aiming at the identification of undesired transient or stability problems [3, 4].

Issues that can be detected through power system stability analyses are related to loss of synchronism between power plants or poorly damped oscillations in the electrical grid [4].

Disturbances considered in these analyses are events that may happen in the grid, such as: short-circuits, equipment trip-outs or shunt switching [3, 4].

Small variations are also evaluated, such as: load modifying during a day, control system set-point changing, power plant redispatches or automatic generation control (AGC) and coordinated voltage control (CVC) actions [3, 4].

Computational programs capable of performing these studies for large-scale power systems are extremely important. The Electrical Energy Research Center (CEPEL) develops these kinds of software. Some of them can be highlighted, such as: ANAREDE [5], ANAFAS [6], ANATEM [7] and PacDyn [8].

ANAREDE is a software able to perform power flow analyses, giving important information about steady-state conditions of electrical grids [5].

ANAFAS is a software capable of performing fault analyses, giving important information about short-circuit levels of electrical grids [6].

ANATEM is a software able to perform transient stability analyses, giving important information about system dynamic behavior, considering occurrences of large disturbances in its electrical grid [7].

PacDyn is a software capable of performing small-signal stability analyses, giving important information about system dynamic behavior, regarding natural oscillations and control systems [8].

The pursuit of an adequate, continuous and secure supply of electrical energy is increasing worldwide, each day more. Power system analyses are needed to improve system planning and operation, increasing its robustness and minimizing risks of failure in this process.

Power system security assessments arise in this context. Voltage security assessment (VSA) is concerned with bus voltage levels, transient security assessment (TSA) is concerned with transient dynamic behavior and small-signal security assessment (SSA) is concerned with dynamic behavior in face of small disturbances [9].

Some academic publications about VSA, TSA and SSA will be reviewed and several concepts and methodologies related to these analyses will be studied [10–17].

## 1.2 Research Motivations

First motivation of this research is the fact that concepts of power system security assessment are not well defined in the academy, needing a better organization.

Second motivation is the lack of methodologies and computational tools for small-signal security assessment. The development of new SSA features is important.

Third motivation of this work is the lack of discussion regarding solutions for security problems that may be detected in power system monitoring.

These are the main reasons for choosing small-signal security assessment as the theme of this doctoral thesis.

## 1.3 Thesis Contributions

This work presents a description of power system security assessment, reviewing and organizing its basic concepts. Besides, new tools for SSA were developed, considering its applications in real-time operation and planning studies.

This research studies methods and corrective measures that can be used to increase the damping factor of power system oscillations, considering control tuning and plant redispatches.

On-line control tuning is not a practice currently adopted by operators, but, in a future, this solution could be feasible.

On the other hand, power plant redispatches are more reasonable to be adopted as a solution of oscillation problems in a real-time operation.

The main contribution of this thesis is a mathematical development of algorithm capable of determining a minimum redispatch for power system, based on Hopf bifurcation analysis [18–33], which uses generation sensitivities and considers a damping factor criteria for oscillation modes.

This algorithm can be used to determine small-signal security margins and corrective measures to improve the dynamic behavior of power systems.

The redispatch algorithm and SSA tools proposed in this work represent an advance in the state of art of power system security assessment. The planning and operation of power systems can be improved using these developments.

## 1.4 Thesis Structure

This thesis is divided in chapters as follow:

• Chapter 1 – Introduction: In this chapter, the main topics of this research were described, including the motivations and contributions of this thesis;

• Chapter 2 – Power System Stability: In this chapter, the basic concepts of power system stability will be reviewed, focusing on the small-signal stability;

• Chapter 3 – State of Art and Concepts: In this chapter, the actual state of art related to the power system security assessment will be presented;

• Chapter 4 – Security Assessment Theory: In this chapter, the main concepts of power system security assessment will be reviewed, focusing on SSA;

• Chapter 5 – Hopf Bifurcation Study: In this chapter, the method for determination of minimum redispatch for power systems will be presented;

• Chapter 6 – Tests and Results: In this chapter, the methods and computational tools developed in this thesis will be tested in example systems;

• Chapter 7 – Conclusion: In this chapter, the conclusions of the thesis will be made, evidencing the benefits brought by the proposed methods.

## 1.5 Published Papers

Through the research and methods proposed in this thesis, the following papers were produced and published:

• PARREIRAS, T. J. M. A., GOMES JUNIOR, S., TARANTO, G. N., LEITE NETTO, N. A. R., AMARAL, T. S., UHLEN, K., "Avaliação de Segurança a Pequenos Sinais de Sistemas de Potência com o PacDyn", *XXIII Seminário Nacional de Produção e Transmissão de Energia Elétrica - SNPTEE*, october, 2015;

• PARREIRAS, T. J. M. A., GOMES JUNIOR, S., TARANTO, G. N., "Damping Nomogram Method for Small-Signal Security Assessment of Power Systems", *IEEE Latin America Transactions*, may, 2017.

## 1.6 Submitted Papers

Through the research and methods proposed in this thesis, the following paper was produced and submitted to publication:

• PARREIRAS, T. J. M. A., GOMES JUNIOR, S., TARANTO, G. N., UHLEN, K., "Closest Security Boundary for Improving Oscillation Damping through Generation Redispatch using Eigenvalue Sensitivities", *IEEE Transactions on Power Systems*, june, 2017.

## 1.7 Related Dissertations

The following master dissertations are related to the work made in the development of this doctoral thesis:

• BJORSVIK, K., *A Scheme for Creating a Small-Signal On-line Dynamic Security Assessment Tool – Using PSS/E and PacDyn*, M. Sc. dissertation, NTNU, Trondheim, Sor-Trondelag, Norway, 2016;

• LEITE NETTO, N. A. R., *Novas Ferramentas para a Análise de Segurança Estática e Dinâmica de Sistemas de Potência*, M. Sc. dissertation, COPPE/UFRJ, Rio de Janeiro, Rio de Janeiro, Brazil, 2016.

## 1.8 Final Considerations

Power flow, fault and electromechanical stability analyses should be done for the planning and operation of electrical power systems. These studies were briefly described in this chapter.

Research motivations and thesis contributions were presented. This work is focusing on the small-signal security assessment and development of a method for determining of minimum redispatch for power systems.

The thesis structure with chapter descriptions and lists of produced papers were also presented, finishing this chapter.

# Chapter 2

# Power System Stability

This chapter will review the basic concepts related to power system stability analyses, focusing on the rotor angle stability. The transient and small-signal stability analyses will be described in this topic.

## 2.1 Basic Concepts

Electromechanical stability analyses are concerned with the dynamic behavior of power systems, before, during and after the occurrence of faults or disturbances in their electrical grid [4, 34].

Stability problems can be identified in these analyses. Redispatches and control tuning may be used to solve these problems [4, 34].

Operative constraints necessary to avoid stability problems can be obtained in the operation planning and reinforcements needed to improve the system dynamic behavior can be determined in the expansion planning.

Software capable of performing stability analyses of large-scale power systems are necessary to study real electrical systems. ANATEM [7] and PacDyn [8], developed by CEPEL, are examples of these kinds of software.

Power system stability can be divided into voltage stability, frequency stability and rotor angle stability. Figure 2.1 illustrates this division [4, 35].

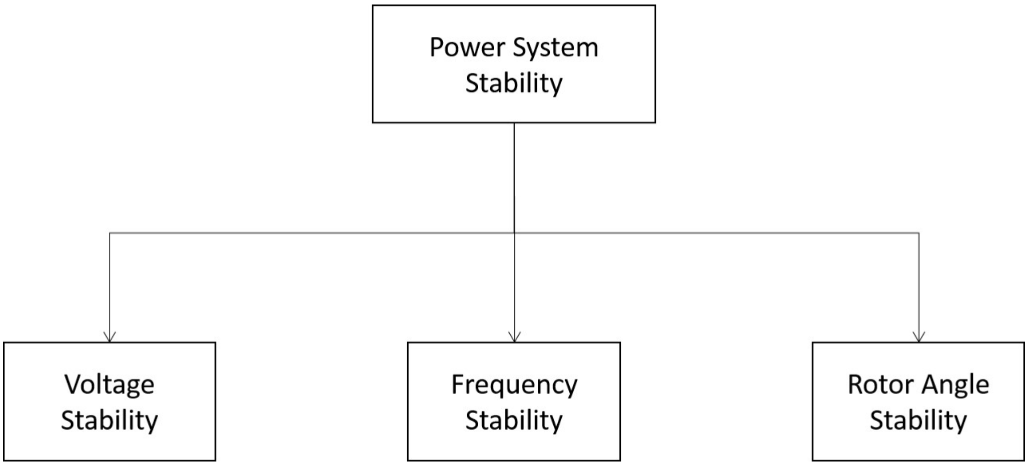


Figure 2.1: Power system stability division.

Voltage stability analyses are concerned with the bus voltage levels, considering contingencies and several disturbances, in order to determine the system capability of coming back to an acceptable operating point [34–36].

These studies are directly related to the transmission system capability and verifies abrupt voltage drops or voltage collapse [34, 35].

Frequency stability analyses are concerned with the system capability of keeping its frequency in acceptable value after the occurrence of large disturbances which may cause large unbalance between load and generation [34, 35].

Rotor angle stability analyses are concerned with the dynamic behavior of generators upon the occurrence of disturbances in the electrical grid [34, 35].

These studies are directly related to the mechanical and electromagnetic torques applied to power plant rotors [34, 35].

Rotor angle stability can be subdivided into transient stability and small-signal stability, as shown in figure 2.2 [4, 35].

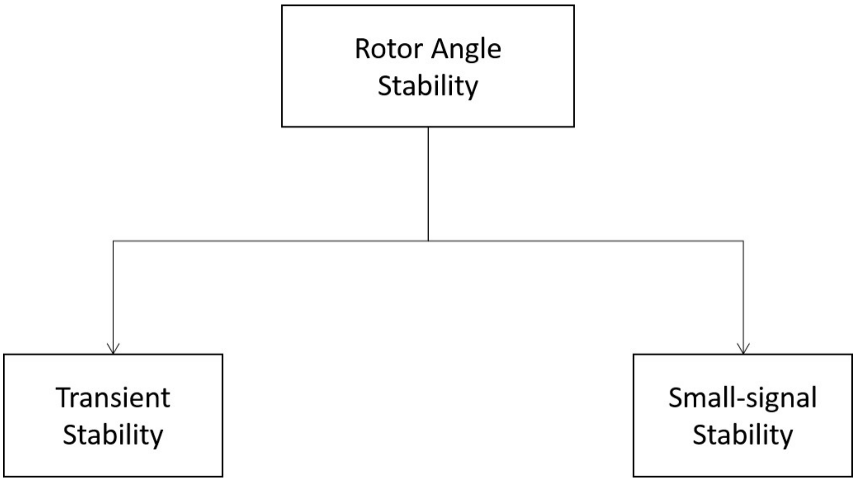


Figure 2.2: Rotor angle stability subdivision.

Power systems are considered stable when they have acceptable oscillatory and non-oscillatory stability. The oscillatory stability is related to damping factor of system natural oscillations and the non-oscillatory stability is related to maintenance of synchronism between the power plants [4, 34].

## 2.2 Transient Stability

Transient stability analyses are concerned with the determination of system dynamic behavior in face of large disturbances in the electrical grid, such as: short-circuits, equipment trip-outs, loss of generation, load rejection and others [4, 34].

The dynamic behavior of the load angle and rotor speed of power plants can be observed, in order to verify the maintenance of synchronism between the system machines and the oscillation damping factor [4, 34, 35].

Power systems of order $n$ can be mathematically described through $n$ differential equations of first order. These equations represent dynamic behavior and are necessary to model these systems. The state variable vector $x$ is defined according to this equation set [4, 34].

These systems also have algebraic equations, which are related to electrical grid or control systems and are also needed in this modelling. The algebraic variable vector $r$ can be defined according to this equation set [4, 34].

### 2.2.1 Non-linear System Modelling

The mathematical model of power systems can be described through equations (2.1), (2.2) and (2.3), including an input variable vector $u$ and an output variable vector $y$, according to references [4, 34, 37].

$$\dot{x} = f\left(x, r, u\right) \tag{2.1}$$

$$0 = g\left(x, r, u\right) \tag{2.2}$$

$$y = h\left(x, r, u\right) \tag{2.3}$$

Where:

$x$ = State variable vector;

$r$ = Algebraic variable vector;

$u$ = Input variable vector;

$y$ = Output variable vector;

$\dot{x}$ = State variable derivative vector;

$f$ = Differential equation set;

$g$ = Algebraic equation set;

$h$ = Output equation set.

The analysis of power system transients is mainly focused on time response simulations of large disturbances in its electrical grid, obtained through using the mathematical model described before.

A software is needed for the analysis of large-scale power systems, as the Brazilian interconnected power system. ANATEM [7] can be used in this study.

Numerical integration methods are needed to determine time responses through the equations (2.1), (2.2) and (2.3). One of these methods is the numerical integration using trapezoidal approximation.

The dynamic behavior of power systems in face of disturbances can be verified through these time response simulations.

## 2.3 Small-signal Stability

Small-signal stability analyses are concerned with the system dynamic behavior in face of small disturbances in its electrical grid, such as: dispatch variations, load variations and controller set-point modification and others [4, 34].

The non-linear power systems are linearized in this study, which enables the use of linear control techniques and modal analysis. These tools help to determine characteristics of the system dynamic behavior [4, 34].

Modes of power systems can be determined through using modal analysis techniques. These modes represent the dynamic behavior of the system and have information about its small-signal stability. They may represent natural oscillations of power systems, being called oscillation modes [4, 34].

Control systems can be tuned using modal analysis techniques, in order to improve the system dynamic behavior. Power system stabilizers (PSS) and power oscillation damper (POD) are examples of controllers that may be used to increase the damping factor of oscillation modes [4, 34].

A software is needed for performing modal analysis of large-scale power systems, as the Brazilian power system. PacDyn [8] can be used in this study.

### 2.3.1 System Model Linearization

Non-linear power system model can be linearized around its initial operating point $(x_0, r_0, u_0)$ to obtain linear approximate model, which is represented by equations (2.4) and (2.5), according to [4, 34, 37]. This is called descriptor system model.

$$\begin{bmatrix} \Delta\dot{x} \\ 0 \\ \Delta y \end{bmatrix} = J_{(x_0,r_0,u_0)} \cdot \begin{bmatrix} \Delta x \\ \Delta r \\ \Delta u \end{bmatrix} \tag{2.4}$$

$$\begin{bmatrix} \Delta\dot{x} \\ 0 \\ \Delta y \end{bmatrix} = \begin{bmatrix} \frac{\partial f}{\partial x} & \frac{\partial f}{\partial r} & \frac{\partial f}{\partial u} \\ \frac{\partial g}{\partial x} & \frac{\partial g}{\partial r} & \frac{\partial g}{\partial u} \\ \frac{\partial h}{\partial x} & \frac{\partial h}{\partial r} & \frac{\partial h}{\partial u} \end{bmatrix}_{(x_0,r_0,u_0)} \cdot \begin{bmatrix} \Delta x \\ \Delta r \\ \Delta u \end{bmatrix} \tag{2.5}$$

Where:

$\Delta x$ = State variable deviation vector;

$\Delta r$ = Algebraic variable deviation vector;

$\Delta u$ = Input variable deviation vector;

$\Delta y$ = Output variable deviation vector;

$\Delta\dot{x}$ = State variable derivative deviation vector;

$J_{(x_0,r_0,u_0)}$ = System jacobian matrix in $(x_0, r_0, u_0)$;

$\frac{\partial f}{\partial x}$ = Function $f$ derivatives with respect to vector $x$;

$\frac{\partial f}{\partial r}$ = Function $f$ derivatives with respect to vector $r$;

$\frac{\partial f}{\partial u}$ = Function $f$ derivatives with respect to vector $u$;

$\frac{\partial g}{\partial x}$ = Function $g$ derivatives with respect to vector $x$;

$\frac{\partial g}{\partial r}$ = Function $g$ derivatives with respect to vector $r$;

$\frac{\partial g}{\partial u}$ = Function $g$ derivatives with respect to vector $u$;

$\frac{\partial h}{\partial x}$ = Function $h$ derivatives with respect to vector $x$;

$\frac{\partial h}{\partial r}$ = Function $h$ derivatives with respect to vector $r$;

$\frac{\partial h}{\partial u}$ = Function $h$ derivatives with respect to vector $u$;

$$\begin{bmatrix} \frac{\partial f}{\partial x} & \frac{\partial f}{\partial r} & \frac{\partial f}{\partial u} \\ \frac{\partial g}{\partial x} & \frac{\partial g}{\partial r} & \frac{\partial g}{\partial u} \\ \frac{\partial h}{\partial x} & \frac{\partial h}{\partial r} & \frac{\partial h}{\partial u} \end{bmatrix}_{(x_0,r_0,u_0)} = \text{Detailed system jacobian matrix.}$$

Algebraic variables can be eliminated from the model through mathematical manipulations. This new model is represented by equations (2.6) and (2.7), according to [4, 34, 37, 38], and is called state space model.

$$\Delta\dot{x} = A.\Delta x + B.\Delta u \tag{2.6}$$

$$\Delta y = C.\Delta x + D.\Delta u \tag{2.7}$$

Where:

$\Delta x$ = State variable deviation vector;

$\Delta u$ = Input variable deviation vector;

$\Delta y$ = Output variable deviation vector;

$\Delta\dot{x}$ = State variable derivative deviation vector;

$A$ = State transition matrix;

$B$ = System input matrix;

$C$ = System output matrix;

$D$ = Direct transfer matrix.

System modes can be obtained through the eigenvalues of matrix $A$ and represent the system dynamic behavior in face of small disturbances. These modes may represent characteristics of power system natural oscillations [4, 34].

The oscillation modes related to electromechanical dynamics can be divided into: intra-plant modes, local modes, inter-area modes and multi-machine modes.

Intra-plant modes represent oscillations between generating units of a single power plant. Local modes represent oscillations of a power plant against all other system machines. Inter-area modes represent oscillations between power plants of some areas against others. Multi-machine modes represent oscillations between several machines of several areas.

### 2.3.2 Eigenvalues and Eigenvectors

Eigenvalues and eigenvectors of the matrix $A$ can be determined through equations (2.8) and (2.9), according to [4, 34, 37–39].

$$A.v = \lambda.v \tag{2.8}$$

$$w.A = w.\lambda \tag{2.9}$$

Where:

$A$ = State matrix;

$v$ = Right eigenvector;

$w$ = Left eigenvector;

$\lambda$ = Eigenvalue.

Equations (2.10), (2.11), (2.12) and (2.13) can be obtained through mathematical manipulations, according to [4, 34].

$$A.v - \lambda.v = 0 \tag{2.10}$$

$$\left(A - \lambda.I\right).v = 0 \tag{2.11}$$

$$w.A - w.\lambda = 0 \tag{2.12}$$

$$w.\left(A - \lambda.I\right) = 0 \tag{2.13}$$

Where:

$A$ = State matrix;

$v$ = Right eigenvector;

$w$ = Left eigenvector;

$\lambda$ = Eigenvalue;

$I$ = Identity matrix.

The matrix $A - \lambda \cdot I$ must be singular, so eigenvalues can be obtained. The system characteristic equation is presented in equation (2.14), according to [4, 34].

$$\det\left(A - \lambda.I\right) = 0 \tag{2.14}$$

Where:

$A$ = State matrix;

$\lambda$ = Eigenvalue;

$I$ = Identity matrix;

det = Determinant of the matrix $A - \lambda.I$.

A $n$ order system will have $n$ eigenvalues. This system will also have $n$ right and left eigenvectors related to each one of these eigenvalues. They can be obtained through equations (2.15) and (2.16), according to [4, 34].

$$(A - \lambda_i.I)\,.v_i = 0 \tag{2.15}$$

$$w_i.\,(A - \lambda_i.I) = 0 \tag{2.16}$$

Where:

$A$ = State matrix;

$v_i$ = Right eigenvector associated to mode $i$;

$w_i$ = Left eigenvector associated to mode $i$;

$\lambda_i$ = System mode $i$;

$I$ = Identity matrix.

These eigenvalues and eigenvectors have important information about the natural oscillations that may appear in power systems [4, 34].

### 2.3.3 Participation Factors and Mode Shapes

Participation factors represent the contribution of each system state variable for the appearance of modes in its model [4, 34].

These factors can be obtained through the multiplication of elements of the right eigenvector matrix $\Phi$ and left eigenvector matrix $\Psi$ and their calculation is shown in equations (2.17) and (2.18), according to [4, 34].

$$P = \begin{bmatrix} P_1 & \cdots & P_i & \cdots & P_n \end{bmatrix} \tag{2.17}$$

$$P_i = \begin{bmatrix} P_{1i} \\ \vdots \\ P_{ii} \\ \vdots \\ P_{ni} \end{bmatrix} = \begin{bmatrix} \Phi_{1i}.\Psi_{i1} \\ \vdots \\ \Phi_{ii}.\Psi_{ii} \\ \vdots \\ \Phi_{ni}.\Psi_{in} \end{bmatrix} \tag{2.18}$$

Where:

$P$ = Participation factor matrix;

$P_1$ = Participation factor vector for mode 1;

$P_i$ = Participation factors vector for mode $i$;

$P_n$ = Participation factors vector for mode $n$;

$P_{1i}$ = Participation factor of state variable 1 for mode $i$;

$P_{ii}$ = Participation factor of state variable $i$ for mode $i$;

$P_{ni}$ = Participation factor of state variable $n$ for mode $i$;

$\Phi_{1i}$ = Element of right eigenvector matrix related to state variable 1 and mode $i$;

$\Phi_{ii}$ = Element of right eigenvector matrix related to state variable $i$ and mode $i$;

$\Phi_{ni}$ = Element of right eigenvector matrix related to state variable $n$ and mode $i$;

$\Psi_{i1}$ = Element of left eigenvector matrix related to state variable 1 and mode $i$;

$\Psi_{i1}$ = Element of left eigenvector matrix related to state variable $i$ and mode $i$;

$\Psi_{in}$ = Element of left eigenvector matrix related to state variable $n$ and mode $i$.

The participation factors can be used to determine the system mode origins, which can be related to power flow equations, control system equations or electromechanical interactions [4, 34].

Electromechanical oscillation modes present high participation factors for rotor angles and rotor speeds [4, 34].

Mode shapes are the graphics obtained through plotting elements of right eigenvector matrix $\Phi$. They are related to a desired state variable and a mode and their calculation is shown in equations (2.19) and (2.20), according to [4, 34].

$$\Phi = \begin{bmatrix} \Phi_1 & \cdots & \Phi_i & \cdots & \Phi_n \end{bmatrix} \tag{2.19}$$

$$\Phi_i = \begin{bmatrix} \Phi_{1i} \\ \vdots \\ \Phi_{ii} \\ \vdots \\ \Phi_{ni} \end{bmatrix} \tag{2.20}$$

Where:

$\Phi$ = Right eigenvector matrix;

$\Phi_1$ = Right eigenvector related to mode 1;

$\Phi_i$ = Right eigenvector related to mode $i$;

$\Phi_n$ = Right eigenvector related to mode $n$;

$\Phi_{1i}$ = Element of right eigenvector matrix related to state variable 1 and mode $i$;

$\Phi_{ii}$ = Element of right eigenvector matrix related to state variable $i$ and mode $i$;

$\Phi_{ni}$ = Element of right eigenvector matrix related to state variable $n$ and mode $i$.

The mode shapes can be used to determine if system variables oscillate in a coherent or non-coherent way, when a small disturbance occurs in the electrical grid [4, 34]. Figure 2.3 illustrates examples of mode shapes.

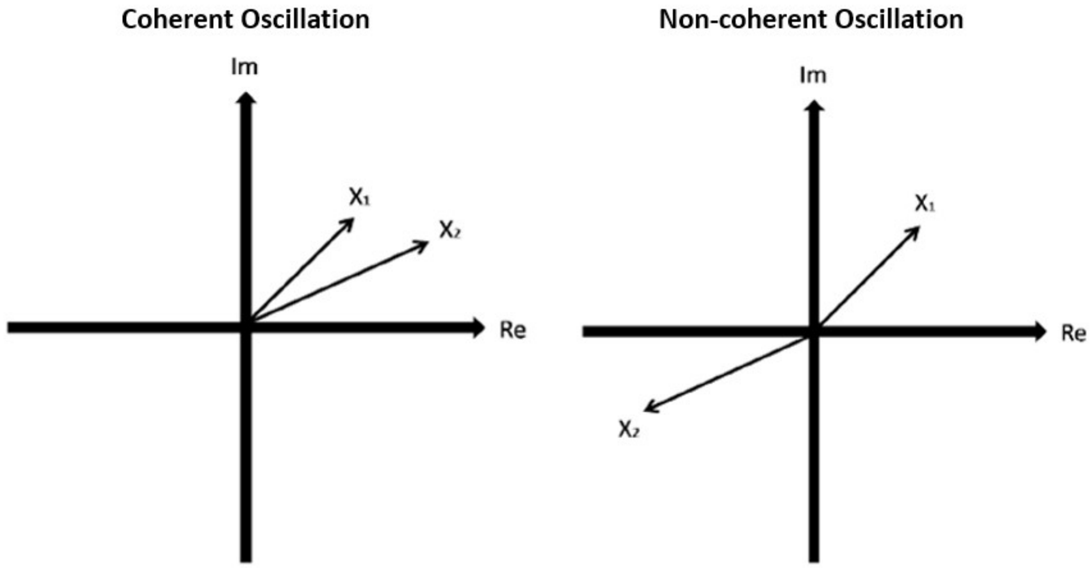


Figure 2.3: Schematic examples of mode shapes.

Coherent oscillations are those in which variables behave similarly and present oscillations almost in phase. Non-coherent oscillations are those in which variables have opposite behaviors and present oscillations almost in counter-phase [4, 34].

Rotor speed mode shapes are very important to electromechanical oscillation modes, enabling the determination of their types, such as: intra-plant modes, local modes, inter-area modes or multi-machine modes [4, 34].

### 2.3.4 Residue, Controlability and Observability

A variable linear transformation can be performed, in order to obtain a new state transition matrix $\Lambda$ and modal state variables $z$ for power systems [4, 34].

This similarity transformation is represented through equations (2.21) and (2.22). The new state transition matrix $\Lambda$ will have a diagonal form, if the system presents $n$ distinct eigenvalues [4, 34].

$$x = \Phi.z \tag{2.21}$$

$$\Lambda = \Phi^{-1}.A.\Phi = \begin{bmatrix} \lambda_1 & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & \lambda_i & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & \lambda_n \end{bmatrix} \tag{2.22}$$

Where:

$x$ = Original state variable vector;

$z$ = Modal state variable vector;

$A$ = Original state transition matrix;

$\Phi$ = Right eigenvector matrix;

$\Lambda$ = Modal state transition matrix;

$\lambda_1$ = System mode 1;

$\lambda_i$ = System mode $i$;

$\lambda_n$ = System mode $n$.

Each modal state variable is directly related to a system mode, which defines its dynamic behavior. The original state variables can be obtained through linear combinations of the modal state variables [4, 34].

This similarity transformation can be expanded to the input matrix $B$, output matrix $C$ and direct transfer matrix $D$, yielding a new state space model for the power system, which is represented in equations (2.23), (2.24), (2.25), (2.26), (2.27) and (2.28), according to [4, 34].

$$x = \Phi.z \tag{2.23}$$

$$\Lambda = \Phi^{-1}.A.\Phi \tag{2.24}$$

$$B' = \Phi^{-1}.B \tag{2.25}$$

$$C' = C.\Phi \tag{2.26}$$

$$\Delta\dot{z} = \Lambda.\Delta z + B'.\Delta u \tag{2.27}$$

$$\Delta y = C'.\Delta z + D.\Delta u \tag{2.28}$$

Where:

$x$ = Original state variable vector;

$z$ = Modal state variable vector;

$A$ = Original state transition matrix;

$\Phi$ = Right eigenvector matrix;

$\Lambda$ = Modal state transient matrix;

$B$ = Original input matrix;

$B'$ = Modal input matrix;

$C$ = Original output matrix;

$C'$ = Modal output matrix;

$D$ = Direct transfer matrix;

$\Delta u$ = Input variable deviation vector;

$\Delta y$ = Output variable deviation vector;

$\Delta z$ = Modal state variable deviation vector;

$\Delta\dot{z}$ = Modal state variable derivative deviation vector.

If there are no direct transfer terms in the system, the matrix $D$ will be null and its model can be represented through equations (2.29) and (2.30). A transfer function [40] relating the input and output of the system can be obtained applying the Laplace transform in this new model, which is shown in equation (2.31).

$$\Delta\dot{z} = \Lambda.\Delta z + B'.\Delta u \tag{2.29}$$

$$\Delta y = C'.\Delta z \tag{2.30}$$

$$\frac{\Delta Y(s)}{\Delta U(s)} = C'.(s.I - A)^{-1}.B' \tag{2.31}$$

Where:

$\Lambda$ = Modal state transition matrix;

$B'$ = Modal input matrix;

$C'$ = Modal output matrix;

$\Delta u$ = Input variable deviation vector;

$\Delta y$ = Output variable deviation vector;

$\Delta z$ = Modal state variable deviation vector;

$\Delta\dot{z}$ = Modal state variable derivative deviation vector;

$\Delta Y(s)$ = Laplace transform of output variable deviation vector;

$\Delta U(s)$ = Laplace transform of input variable deviation vector;

$\frac{\Delta Y(s)}{\Delta U(s)}$ = Transfer function matrix relating input and output variables.

If the system has only one input and one output variables (SISO system), equation (2.31) can be rewritten through equations (2.32) and (2.33).

$$\frac{\Delta Y(s)}{\Delta U(s)} = c'.(s.I - A)^{-1}.b' \tag{2.32}$$

$$\frac{\Delta Y\left(s\right)}{\Delta U\left(s\right)}=\sum_{i=1}^{n}\frac{c_i'.b_i'}{s-\lambda_i}=\sum_{i=1}^{n}\frac{R_i}{s-\lambda_i} \tag{2.33}$$

Where:

$\Lambda$ = Modal state transition matrix;

$b'$ = Modal input vector;

$c'$ = Modal output vector;

$b_i'$ = Element $i$ of input variable deviation vector;

$c_i'$ = Element $i$ of output variable deviation vector;

$R_i$ = Residue related to mode $i$ in transfer function $\frac{\Delta Y(s)}{\Delta U(s)}$;

$\Delta Y\left(s\right)$ = Laplace transform of output variable deviation vector;

$\Delta U\left(s\right)$ = Laplace transform of input variable deviation vector;

$\frac{\Delta Y(s)}{\Delta U(s)}$ = Transfer function matrix relating input and output variables.

Controlability factor can be defined as an input variable capability of exciting a system mode and can be determined through equation (2.34), according to [4, 34].

$$Ctrl_i=b'=\Psi_i.b \tag{2.34}$$

Where:

$Ctrl_i$ = Controlability factor of mode $i$;

$b_i'$ = Element $i$ of modal input vector;

$\Psi_i$ = Left eigenvector related to mode $i$;

$b$ = Original input vector.

Observability factor can be defined as an output variable capability of reflecting a mode dynamic and can be obtained through equation (2.35), according to [4, 34].

$$Obsv_i = c' = c.\Phi_i \tag{2.35}$$

Where:

$Obsv_i$ = Observability factor of mode $i$;

$c'_i$ = Element $i$ of modal output vector;

$\Phi_i$ = Right eigenvector related to mode $i$;

$c$ = Original output vector.

Transfer function residue can be defined as a system mode influence in output variable dynamic behavior when this mode is excited by input variable and can be determined through equation (2.36), according to [4, 34].

$$R_i = Ctrl_i.Obsv_i = c'.b' = c.\Phi_i.\Psi_i.b \tag{2.36}$$

Where:

$R_i$ = Residue related to mode $i$ in transfer function $\frac{\Delta Y(s)}{\Delta U(s)}$;

$Ctrl_i$ = Controlability factor of mode $i$;

$Obsv_i$ = Observability factor of mode $i$;

$c'_i$ = Element $i$ of modal output vector;

$b'_i$ = Element $i$ of modal input vector;

$c$ = Original output vector;

$b$ = Original input vector;

$\Phi_i$ = Right eigenvector related to mode $i$;

$\Psi_i$ = Left eigenvector related to mode $i$.

The modal analysis is very important to small-signal stability of power systems. This analysis enables the identification of equipment most responsible for causing undesired oscillations and the improvement of their damping factors through control system tuning, such as: PSS or POD.

### 2.3.5 Control System Design

Power system stabilizers (PSS) can be used to increase the damping factor of electromechanical oscillation modes. Module and phase compensation are needed in PSS tuning, according to [34, 41, 42].

Nyquist diagrams can be used to design control systems, as PSS, and determine these compensations. These diagrams analyze the open loop system, in order to evaluate the closed loop dynamic behavior [34, 41, 42].

Figure 2.4 represents a power system model, where $G(s)$ considers a generator, its automatic voltage regulator (AVR), its speed governor (GOV) and other system equipment. $PSS(s)$ is the transfer function of a power system stabilizer, which is used in a negative feedback [34, 41, 42].

System input variable is the voltage reference signal $V_{\text{ref}}$, output variable is the rotor speed $WW$ and $V_{\text{pss}}$ is the stabilization signal [34, 41, 42].

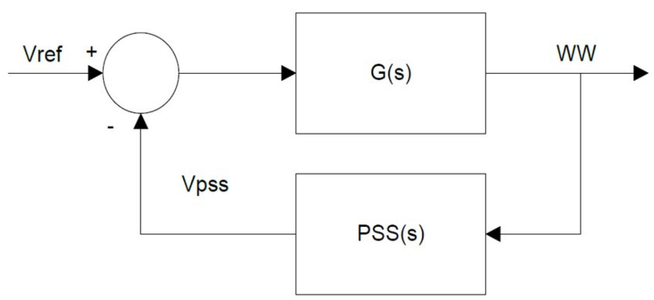


Figure 2.4: Transfer function $G(s)$ with feedback through $PSS(s)$.

$PSS(s)$ can be decomposed into a WASHOUT block and the function $Comp(s)$, which is responsible for module and phase compensation of the stabilizer, according to equations (2.37) and (2.38).

$$PSS(s) = Comp(s).\left(\frac{T_w.s}{1+T_w.s}\right) \tag{2.37}$$

$$Comp(s) = K_{pss}.\left(\frac{1+T.s}{1+\alpha.T.s}\right)^{nb} \tag{2.38}$$

Where:

$PSS(s)$ = Transfer function of power system stabilizer;

$Comp(s)$ = Transfer function of module and phase compensation;

$T_w$ = WASHOUT block time constant;

$K_{pss}$ = Gain of $Comp(s)$;

$\alpha$ = Phase parameter of $Comp(s)$;

$T$ = Frequency parameter of $Comp(s)$.

Function module $M$ and phase $\phi$ for the mode frequency $\omega$ can be obtained through a traditional Nyquist diagram (with damping factor of 0%) of transfer function $G(s).\left(\frac{T_w.s}{1+T_w.s}\right)$ [4, 34, 42], as can be seen in figure 2.5.

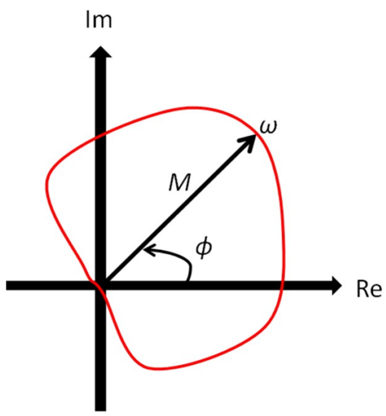


Figure 2.5: Schematic Nyquist diagram for the range $0 \leq \omega < \infty$.

$Comp(s)$ parameters can be obtained, so the compensated Nyquist diagram can involve the point $-1$ of the complex plane, counterclockwise. Then, system will become stable, according to Nyquist criteria [34, 40, 42]. This module and phase compensations can be observed in figure 2.6.

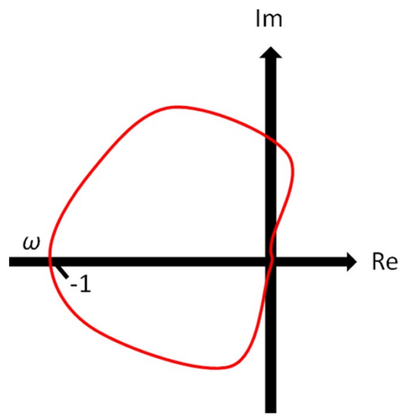


Figure 2.6: Nyquist diagram with module and phase compensation.

Gain and phase margins must be considered in compensation to ensure a satisfactory damping factor for the mode of interest [34, 40, 42].

The phase and frequency parameters of $Comp(s)$ can be determined through equations (2.39), (2.40) and (2.41), according to [34, 40, 42].

$$\phi_{adv} = 180^\circ - \phi \tag{2.39}$$

$$\sin\left(\frac{\phi_{adv}}{nb}\right) = \frac{1-\alpha}{1+\alpha} \tag{2.40}$$

$$\omega = \frac{1}{T.\sqrt{\alpha}} \tag{2.41}$$

Where:

$\phi_{adv}$ = Desired phase advance;

$\phi$ = Phase of open loop system for frequency $\omega$;

$nb$ = Number of lead-lag blocks used in compensation;

$\omega$ = Frequency of system mode;

$\alpha$ = Phase parameter of $Comp(s)$;

$T$ = Frequency parameter of $Comp(s)$.

Module compensation can be determined through the Nyquist diagram with phase compensation. The new module $M_{comp}$ for mode frequency $\omega$ can be obtained in this new diagram, as can be seen in figure 2.7.

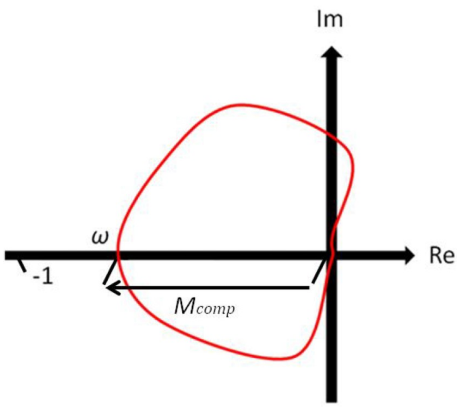


Figure 2.7: Nyquist diagram with phase compensation.

The gain $K_{pss}$ can be obtained through the module $M_{comp}$, as can be seen in equation (2.42), according to [34, 40, 42].

$$K_{pss} = \frac{1}{M_{comp}} \tag{2.42}$$

Where:

$K_{pss}$ = Gain of $PSS(s)$;

$M_{comp}$ = Module of phase compensated transfer function for the mode frequency $\omega$.

This equationing is related to control system design using traditional Nyquist diagram, which is not the only way to project controllers.

Other formulations for tuning control systems or loops can be performed through using Nyquist diagrams with damping factor [41, 42].

These other methods allow positioning complex pole pair in a desired location in complex plane, ensuring a desired damping factor and frequency for the oscillation mode of interest, according to [41, 42].

## 2.4 Final Considerations

Power system electromechanical stability was briefly described in this chapter, including a transient and small-signal stability analyses review.

Modal analysis principles were presented, including the concepts of eigenvalues, eigenvectors, participation factors, mode shapes, controlability, observability and transfer functions residues.

Control system design was discussed and a basic methodology for control tuning was also presented, finishing this chapter.

# Chapter 3

# State of Art and Concepts

This chapter will present the power system security assessment state of art, including a literature review about concepts of voltage, transient and small-signal security assessments (VSA, TSA and SSA).

## 3.1 DSA Tools and Techniques

DSA tools and techniques are described in [14]. Several stability analyses should be done in a DSA, such as: voltage, frequency and rotor angle stability [14].

Developments related to voltage and transient security assessment (VSA and TSA) are presented in [14]. The main applications in DSA field are: operation planning analysis, available transmission capability (ATC) determination and on-line security assessment of power systems [14].

The voltage stability is related to power system ability of keeping acceptable bus voltage levels under normal operation and contingency situations [14].

Voltage security assessment consists of evaluating system voltage stability and should have important characteristics, such as: critical contingency list to be consider, properly voltage security analysis and corrective measures to improve power system behaviors [14].

On-line transient security assessment is a computational challenge due to the high processing time in the determination of time response simulations of large-scale power systems, according to [14].

TSA tools should use adequate technique, as time responses and Prony analysis [43], for determining oscillation damping factors, through a fast computational processing with minimum human interference [14].

Transient security assessment tools should have important characteristics, such as: critical contingency list to be consider and properly transient security analysis to determine system security margins [14].

The criteria of DSA tools are related to oscillation damping factors and transient voltages, in order to determine these security margins, according to [14].

## 3.2 On-line DSA Method

Methods for performing on-line DSA are presented in [11], such as: second kick method, fast second kick method and free mode second kick method.

These methods are based on calculation of kinetic energy injected in the system, in order to determine stability or security margins of power systems [11].

Power systems are operating, each day more, under stressed scenarios and close to their limits. Power system security assessments are very important in this context, to ensure a safe system operation [11].

On-line transient security assessment can be divided into three steps, according to [11]: critical contingency selection, TSA considering these contingencies and determination of power system security limits.

Implementations of on-line DSA are based on time responses and should have important characteristics, such as: system dynamic behavior evaluation, stability margin determination, calculation of stability margin sensitivities with respect to power system key variables [11].

The second kick method for on-line DSA consists of applying two artificial short-circuits in the power system and verifying the kinetic energy variation of certain power plants, aiming at the transient energy margin determination [11].

The fast second kick method is defined through mathematical manipulations in the original second kick method, in order to enable a faster computational determination of the transient energy margin [11].

The free mode second kick method is presented in [11], which is a variation of the original second kick method and fast second kick method.

This new method aims at determining the kinetic energy margin, deleting the need of mode of disturbance (MOD) information, which is a machine set where the oscillation of interest is more observable [11].

A variable replacement is used to eliminate the MOD information from the second kick method and a Newton-Raphson algorithm is utilized to determine system kinetic energy and stability margins [11].

## 3.3 DSA Tool in an EMS

Off-line stability analyses are used for determining power system stability limits, but they are very conservative studies and, many times, consider scenarios in which the system may never operate [10].

On-line methods are better for the determination of these stability limits, because they are based on the analysis of the actual system operating point [10].

On-line dynamic security assessment is very important in this context, for determining these limits and improving power system reliability [10].

Some characteristics of on-line DSA are presented in [10], such as: critical contingency selection, time responses simulations, power transfer limit determination and parallel processing use to increase simulation speed.

This on-line security assessment aims at the periodic monitoring of power system state to ensure a secure operation [10].

Methods for calculating stability margins based on transient energy determination are also presented in [10], which enable faster simulations.

The basic requirements to on-line DSA implementations are described in [10], such as: critical contingencies selection, contingency analyses, power system modelling, algorithms for evaluating transient stability, and power system monitoring.

On-line DSA should supply important information about the system operation, as well as, power transfer limits and security margins [10].

## 3.4 SSA Tools and Characteristics

A small-signal security assessment tool is presented in [16]. The small-signal stability analyses determine important information about power system dynamic behavior and characteristics, according to [16].

This study is performed through the power system model linearization and its modal analysis, which enables the determination of bad damped oscillations [16].

SSA is directly related to small-signal stability analyses. This assessment includes contingency evaluation and bad damped oscillation mode determination [16].

The main motivations to a SSA tool development are presented in [16], such as: poorly damped oscillation mode determination, controller design for improving mode damping factors, small-signal security level determination and a possible on-line small-signal security assessment.

The basic requirements for a SSA tool implementation are defined in [16], such as: power system model linearization, eigensolvers to calculate modes, small-signal stability criteria, friendly interface development with result presentation.

This implementation of a SSA tool can be divided into two steps, according to [16]: eigenvalues or modes calculation and security assessment execution.

SSA tools have two important objectives, according to [16]: power system security margin determination and small-signal stability limit calculation.

These stability limits and security margins can be obtained through indexes, which are calculated considering damping factor criteria [16].

A relation between power transfer levels practiced in electrical systems and these security indexes can be defined and used to ensure a safe operation [16].

Small-signal security assessment tools should have some features, according to [16], such as: full eigensolvers, partial eigensolvers, time response simulations, frequency response simulations, small-signal security indexes, small-signal stability limits and system oscillation mode monitoring.

## 3.5 SSA Numerical Index

A SSA numerical index is proposed in [17], in order to represent qualitative small-signal security assessment results, identifying the system security.

The main objective of SSA consists of determining system critical modes, which could represent undesired oscillations in its electrical grid [17].

Oscillation problems can be identified through modal analysis tools, which are capable of calculating system modes, identifying the critical ones [17].

Small-signal security assessment is related to small-signal stability and should consider a critical contingency list to be evaluated [17].

The monitored power system will be defined as secure if mode damping factors are greater than the desired minimum damping factor, according to [17].

The power system will be considered insecure if, at least, one mode presents undesired damping factor [17].

A SSA index for power system is proposed in [17], which is called SSSI. This index can be determined through equations (3.1) and (3.2).

$$SSSI = min\left(1, max\left(\frac{\xi_i}{\xi_{min_d}}\right)^{-n}\right), \xi_i > \xi_{min_d} \tag{3.1}$$

$$SSSI = 1, \xi_i \leq \xi_{min_d} \tag{3.2}$$

Where:

$n$ = SSSI security index norm;

$\xi_i$ = Damping factor of mode $\lambda_i$;

$\xi_{min_d}$ = Desired minimum damping factor.

## 3.6 DSA in Planning and Operation

Results of initial experiences using a DSA computational tool are presented in [15]. The DSA is an important part of power system security assessment, which should be based on fast time response simulations and contingency analysis [15].

Dynamic security assessments should consider a criteria related to voltage, transient and small-signal stability analyses, according to [15].

The power system security assessment must be used in order to optimize system operation and should have some objectives, such as: load forecast, resource storage, power transfer planning, static and dynamic security assessment [15].

These security assessments should have a criteria related to: critical contingency analysis, equipment charging limits, desired minimum damping factor, transient stability margins, dynamic limits for frequency and voltage deviation [15].

A DSA tool prototype is proposed in [15], which has graphical interface, application platform and computational device.

This DSA prototype was used to monitor a power system in [15]. The tool was capable of determining the system security index and identifying the critical contingencies for its operation [15].

This computational tool was used in an EMS/SCADA and the results obtained through the detailed power system model and from monitoring data were coherent, once the same problems were detected in both situations [15].

The prototype security index consists of a scale from 0 to 1, where 0 represents a secure system operation and 1 represents a insecure operation. The intermediary values represent different system security levels [15].

## 3.7 Static and Dynamic Security

An integration between software ANAREDE [5] and ANATEM [7], both from CEPEL, is presented in [12], which can be used for performing static and dynamic security assessment of power system (SDSA).

The Brazilian interconnected power system may operate in several different power transfer scenarios between its electrical areas, which is a serious challenge for the system operators, according to [12].

The voltage, transient and small-signal security assessments should be performed to increase the robustness of the Brazilian system planning and operation, due to this important characteristic [12].

Power flow and transient stability data are needed for performing off-line SDSA, which should be used for the analysis of several feasible operation scenarios, so the system security can be evaluated [12].

On-line SDSA uses the actual operating point data, instead of analyzing several scenarios of the system. These data are obtained through the power system EMS/SCADA, according to [12].

Computational performance of on-line SDSA tools is very important for obtaining useful results for the system operator. The parallel processing is an interesting technique to be used in this context [12].

SDSA results can be observed through nomograms, which are orthogonal projections of the security regions. These regions are three-dimensional, relating the dispatches of three generating groups to the security criteria [12].

The dispatches of these generating groups are modified for the creation of different scenarios that must be evaluated in SDSA. The criteria of this security assessment are related to steady-state and dynamic limits recommended by the Electrical System National Operator (ONS) [12].

## 3.8 Oscillation Monitoring in SDSA

The importance of voltage and transient security assessments is discussed in [13], which can be used to improve the power system planning and operation.

VSA and DSA tools can be utilized to determine the relative position of power system operating points in relation to security region borders, which can be graphically observed through the nomograms [13].

Impact of detailed power plant representation in software ANAREDE [5] and ANATEM [7] is also discussed in [13], which can modify SDSA results.

Oscillation damping monitoring implementation is presented in [13], in order to adequate the dynamic security assessment results to the criteria recommended by the Brazilian power system operator.

This detailed representation of generating units can have a significant influence in VSA and DSA results, modifying the power system security regions determined through a SDSA execution, according to [13].

## 3.9 Final Considerations

The actual power system security assessment state of art were briefly described in this chapter, including a voltage, transient and small-signal security assessments literature review.

Critical contingencies and several scenarios should be evaluated in these security assessment, in order to determine power system security margins.

Security indexes and nomograms can be obtained as results of static and dynamic security assessment, according to the literature review made in this chapter.

# Chapter 4

# Security Assessment Theory

This chapter will present the main concepts related to the voltage, transient and small-signal security assessments. SSA methods will be proposed and their computational implementation will be described.

## 4.1 Basic Concepts

The concern and pursuit of an adequate, continuous and secure electrical energy supply are increasing worldwide.

Several power system analyses are needed to ensure a robust planning and operation, enabling the system to operate in different scenarios, many times very stressed, with minimized risks of failures.

An adequate security level is extremely important so the system can operate with continuity and robustness, ensuring the energy supply [9, 12–14, 44].

Power system security assessment appears in this context, where the bus voltage levels (VSA), transient dynamic behavior (TSA) and small-signal stability analysis (SSA) are evaluated, according to [9, 12–14, 44].

These security assessments consist of evaluating several scenarios and critical contingencies for the power system of interest, aiming at the determination of critical operating points [12–17].

The processing time of these evaluations is a challenge. TSA, for example, is very time consuming. Some methods are presented in the literature, trying to deal with this problem, as the extended equal area criterion (EEAC) [45].

Stability margins [11], security indexes [17] and security regions [12, 13] can be obtained through the power system security assessments.

Power system stability margins can be obtained through the determination of transient kinetic energy margin, according to [11].

A numerical small-signal security index is presented in [17], called SSSI.

The security regions determined through static and dynamic security assessment of power system can be viewed by using nomograms, according to [12, 13].

Figure 4.1 illustrates a nomogram that can be used in voltage and transient security assessments of power systems.

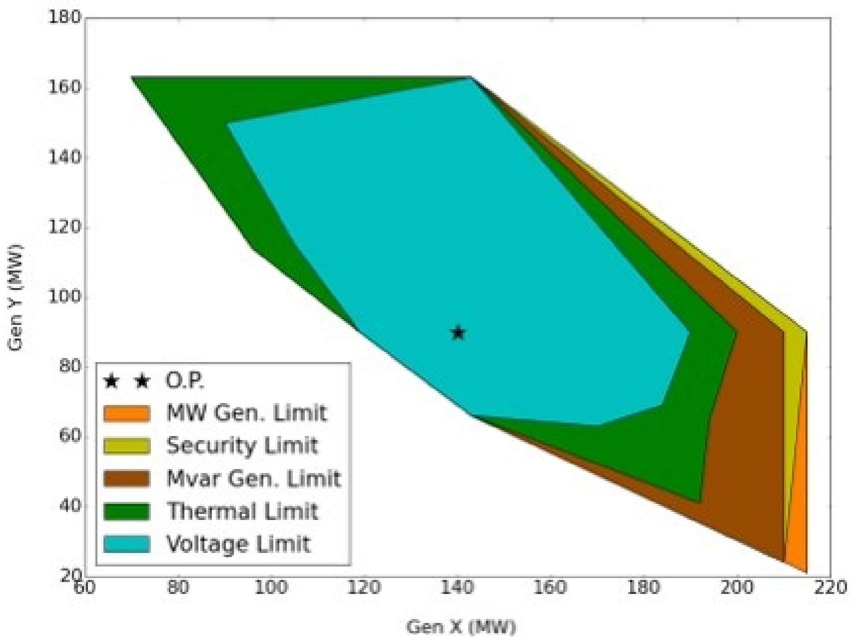


Figure 4.1: Schematic example of a SDSA nomogram.

Five security regions are defined in the schematic SDSA nomogram: blue, green, brown, yellow and orange.

Blue region represents the secure operating points. Outside, there were voltage violations in the system.

Green region represents the operating points with only voltage violations. Outside, there were voltage and charging limit violations.

Brown region represents the operating points with voltage and charging limit violations. Outside, there were also reactive compensation limit violations.

Yellow region represents the operating points with all already mentioned violations. Outside, there were also stability limit violations.

Lastly, orange region represents the operating points all the four mentioned violations. Outside, the power flow calculations were not convergent, considering a normal operation of the system.

## 4.2 Power System VSA and TSA

Voltage security assessment (VSA) is directly related to voltage stability concepts and consists of determining and evaluating bus voltage levels.

VSA should consider system normal operation and critical contingency situations, in order to determine the power system security.

Operating point will be considered secure if no critical contingencies are capable of leading the system to undesired bus voltage levels, which could cause interruptions in electrical energy supply.

A VSA criteria, in general, are related to limits of: under-voltage, over-voltage, generator active power, reactive power reserve, equipment charging and voltage stability margins [12–14].

The off-line VSA should use power flow data and a contingency list, in order to evaluate the system, determining its security regions [12, 13].

The on-line VSA uses EMS/SCADA data as power flow information and should be executed during system operation, aiming to obtain the security regions [12, 13].

Figure 4.2 presents a scheme for off-line VSA tools [12, 13].

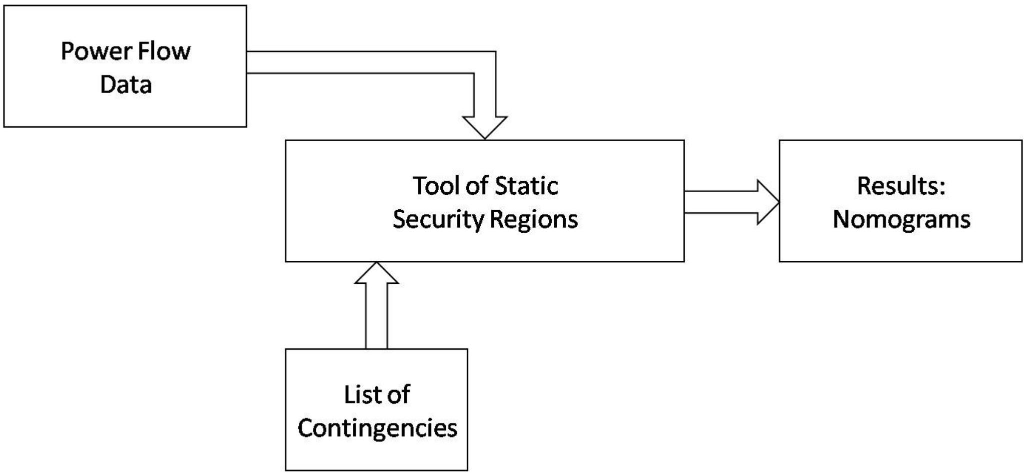


Figure 4.2: Off-line voltage security assessment scheme.

Figure 4.3 presents a scheme for on-line VSA tools [12, 13].

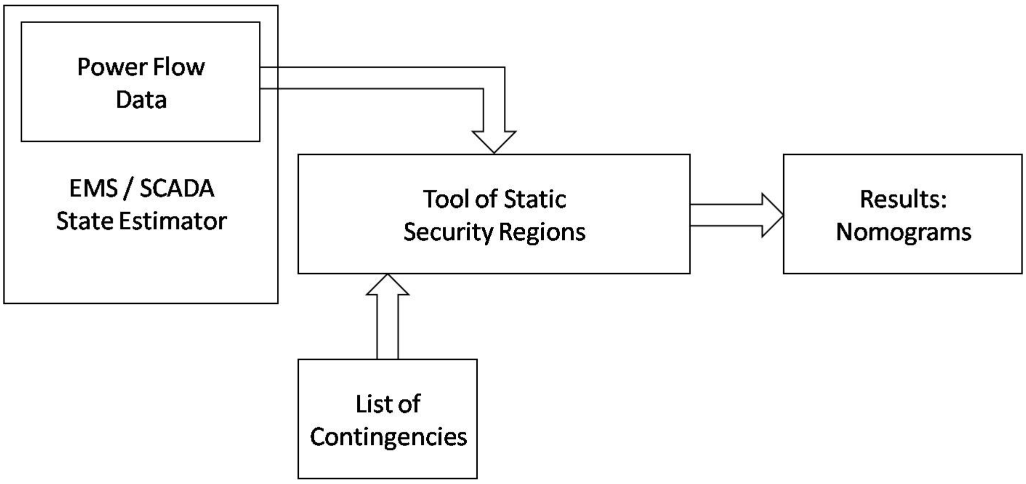


Figure 4.3: On-line voltage security assessment scheme.

Transient security assessment (TSA) is directly related to transient stability concepts and consists of determining and evaluating system dynamic behavior.

TSA should perform non-linear time responses for critical contingency situations, in order to determine the power system security.

Operating point will be considered secure if no critical contingencies are capable of leading the system to loss of synchronism between the power plants.

A TSA criteria, in general, are related to limits of: under-voltage, over-voltage, generator active power, reactive power reserve, equipment charging and transient stability margins [12–15].

The off-line TSA should use power flow data, dynamic data and a contingency list, in order to evaluate the system, determining its security regions [12, 13].

The on-line TSA uses EMS/SCADA data as power flow information and should also be executed during system operation, aiming to obtain the security regions [12, 13].

Figure 4.4 presents a scheme for off-line TSA tools [12, 13].

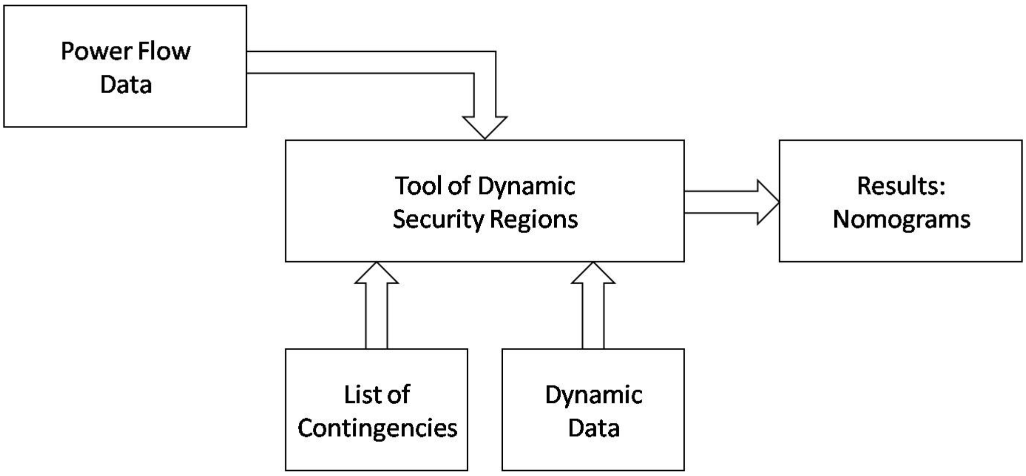


Figure 4.4: Off-line transient security assessment scheme.

Figure 4.5 presents a scheme for on-line TSA tools [12, 13].

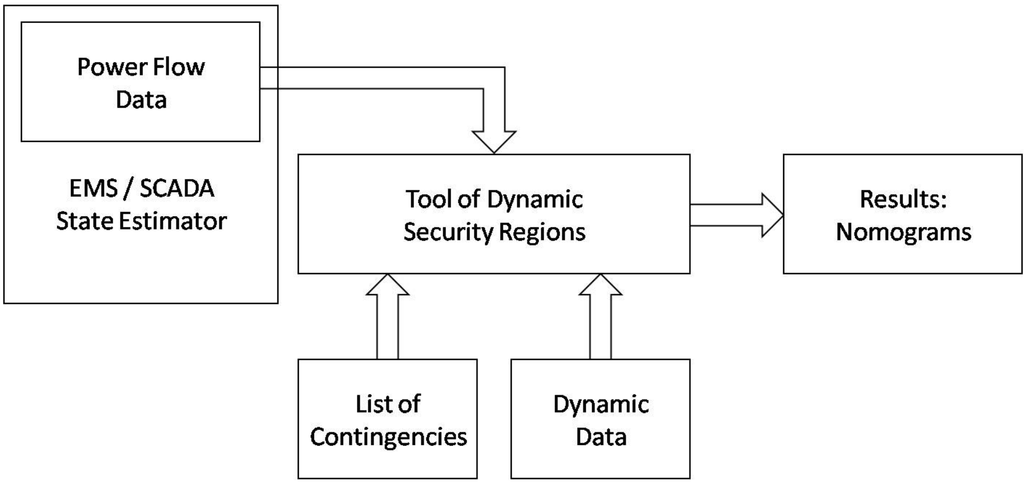


Figure 4.5: On-line transient security assessment scheme.

The power plants must be divided into three generator groups and their dispatches should be modified in order to obtain several system operation scenarios that will be evaluated in VSA or TSA [12, 13].

This generator group definition and processing time for large-scale power systems are challenges for VSA and TSA tool developers [12, 13].

All the scenarios are evaluated by the security assessment tool, aiming to determine the system security regions and their nomograms [12, 13].

Figures 4.6, 4.7 and 4.8 present illustrative nomograms example [12, 13].

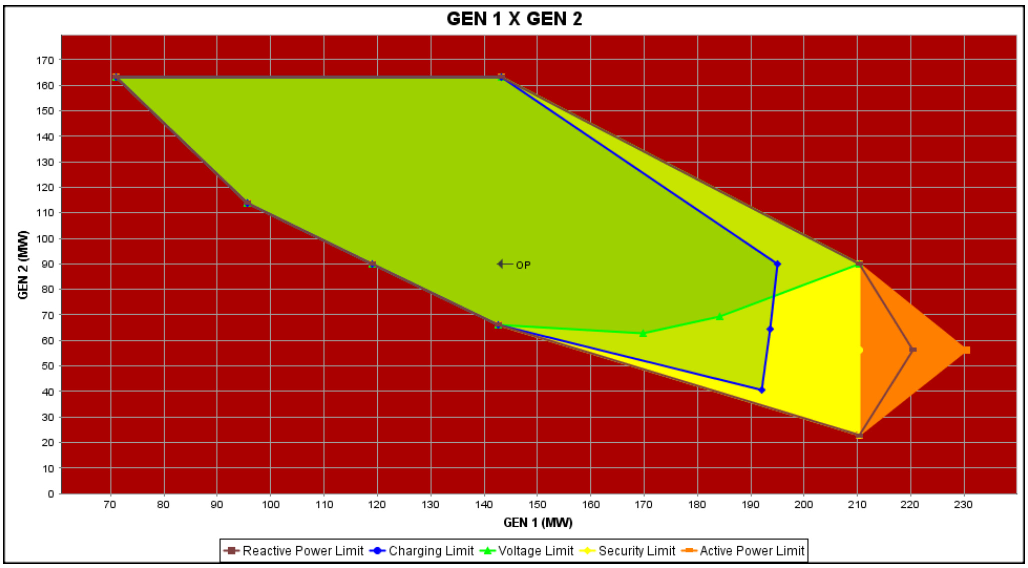


Figure 4.6: Nomogram relating *Gen* 1 and *Gen* 2 generation groups.

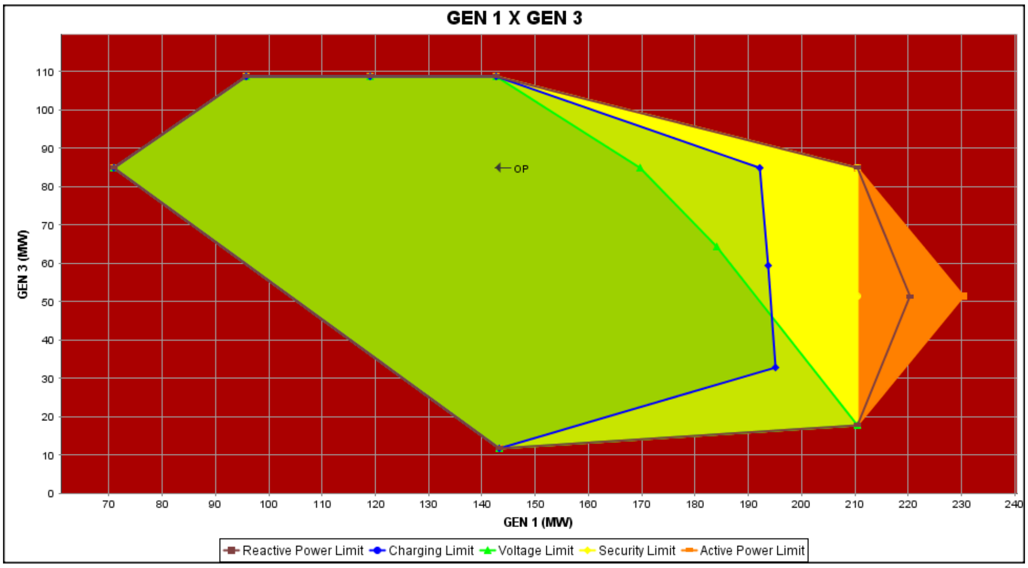


Figure 4.7: Nomogram relating *Gen* 1 and *Gen* 3 generation groups.

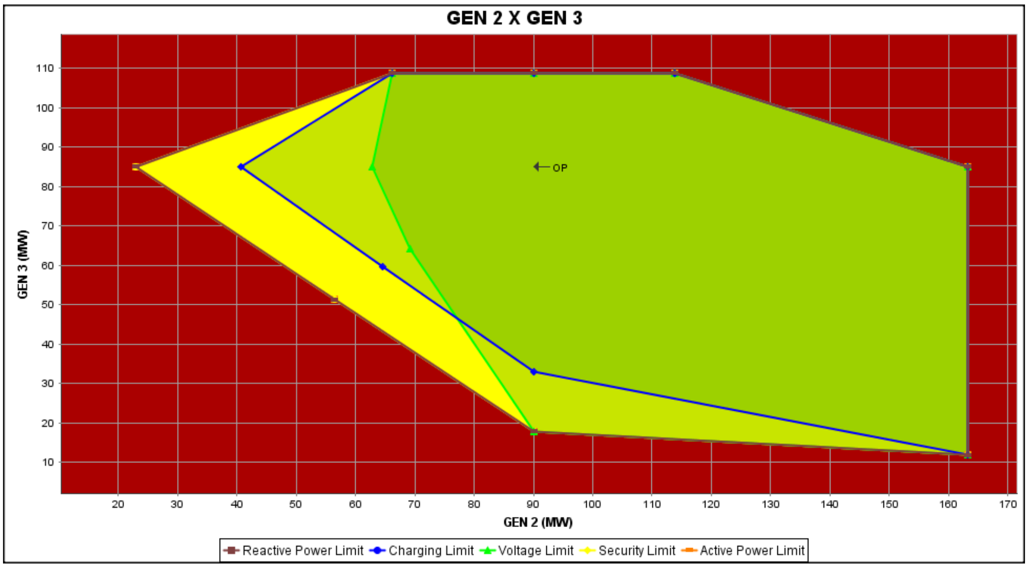


Figure 4.8: Nomogram relating *Gen* 2 and *Gen* 3 generation groups.

Green border represents voltage limits, blue border represents charging limits, brown border represents reactive power reserve limits, yellow border represents voltage (VSA) or transient (TSA) stability limits, and orange border represents power flow convergence limits for system normal operation.

Dark green region represents secure operating points, light green region represents operating points with one violation, yellow region represents operating points with more than one violation, orange region represents operating points with contingency issues, and red region represents operating points with normal operation issues.

The nomograms present power system security regions and can be used to identify the relative position of actual operating point in relation to the security limits, improving system planning and operation.

Power system planning studies can use the nomograms to recommend new equipment for the system, trying to improve its security.

Power system operation studies can use the nomograms to determine operative measures for the system, trying to keep its security.

## 4.3 Power System SSA

Small-signal security assessment (SSA) is directly related to small-signal stability concepts and consists of determining and evaluating system dynamic behavior, in face of small disturbances.

SSA should perform modal analysis and consider critical contingency situations, in order to calculate oscillation modes and determine system security.

Operating point will be considered secure if no oscillation mode presents undesired damping factor, which represents small-signal stability problems. This analysis should be done for system normal operation and contingency situations.

A SSA criteria are related with damping factors presented by system oscillation modes, which should be higher than a desired minimum value [12, 13, 16, 17].

The off-line SSA should use power flow data, dynamic data and a contingency list, in order to evaluate the system, calculating its oscillation modes and determining its security regions or root-locus contours [12, 13, 16, 17].

The on-line SSA uses EMS/SCADA data as power flow information and should also be executed during system operation, aiming to obtain the security regions, root-locus contours or on-line monitoring of oscillations [12, 13, 16, 17].

Figure 4.9 presents a scheme for off-line SSA tools [12, 13, 16, 17].

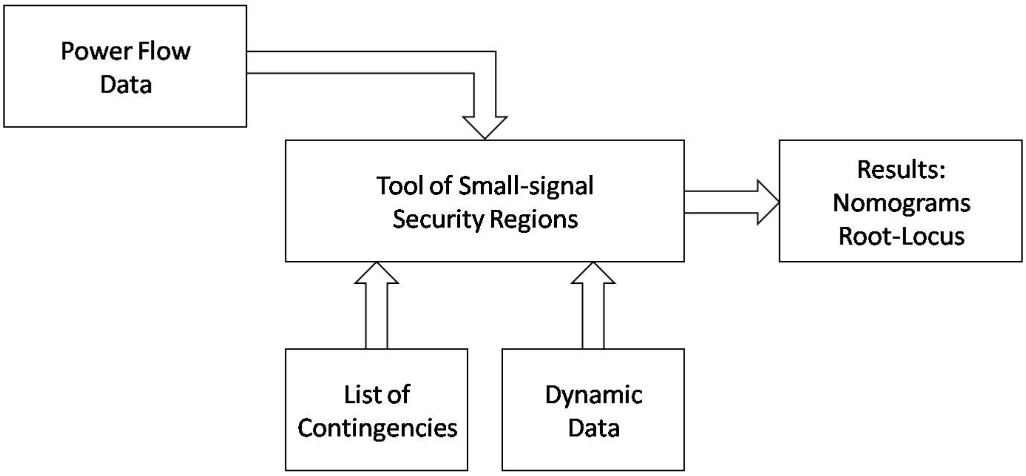


Figure 4.9: Off-line small-signal security assessment scheme.

Figure 4.10 presents a scheme for on-line SSA tools [12, 13, 16, 17].

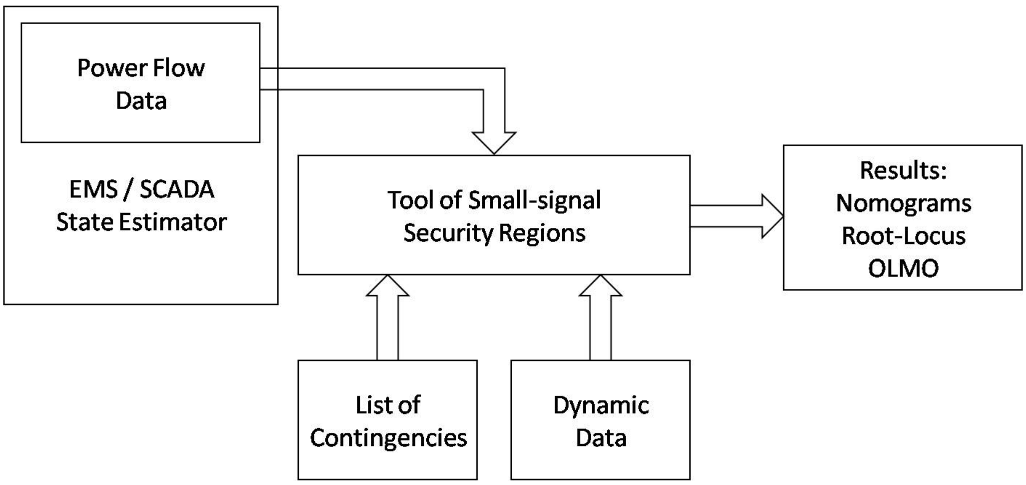


Figure 4.10: On-line small-signal security assessment scheme.

The thesis is proposing three SSA methods: damping nomogram method (DNM), root-locus method (RLM) and on-line monitoring of oscillations (OLMO).

### 4.3.1 Damping Nomogram Method

Damping nomogram method (DNM) consists of determining small-signal security regions for power systems, based on mode damping factors [9, 46–48].

The power plants must also be divided into three generator groups and their dispatches should be modified in order to obtain several system operation scenarios that will be evaluated in this SSA method.

All the scenarios are evaluated by the security assessment tool, aiming to determine the system small-signal security regions and their nomograms.

These SSA nomograms present the small-signal security regions, based on the minimum mode damping factor of each operating point, and can be used to identify the relative position of actual scenario in relation to the security limits, improving power system planning and operation.

Figure 4.11 illustrates a nomogram that can be used in small-signal security assessments of power systems.

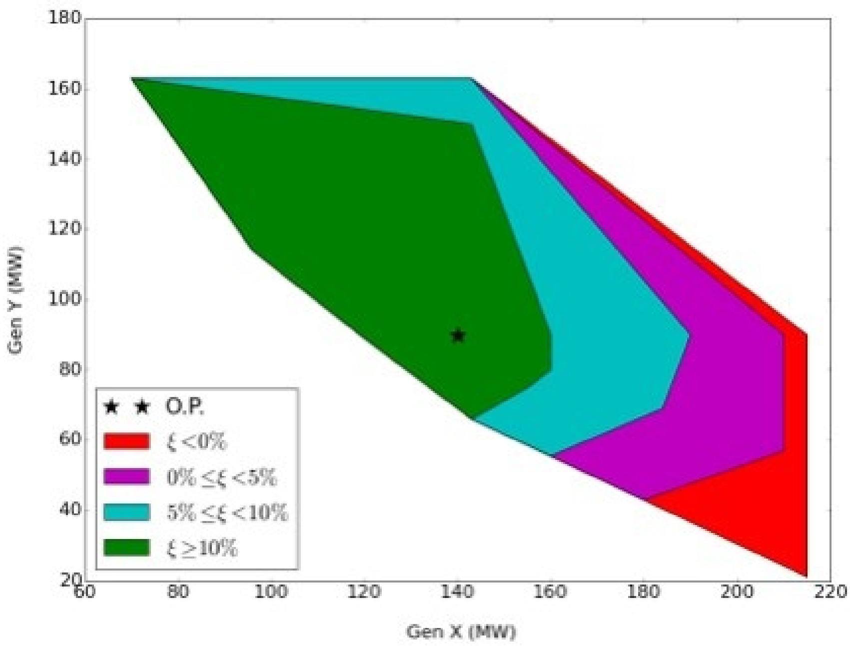


Figure 4.11: Schematic example of a SSA nomogram.

Five security regions are defined in the schematic SSA nomogram: green, blue, purple, red and white.

Green region represents the operating points defined as secure and stable, with minimum damping factor higher or equal to 10%.

Blue region represents the operating points defined as secure and stable, with minimum damping factor lower than 10% and higher or equal to 5%.

Purple region represents the operating points defined as insecure and stable, with minimum damping factor lower than 5% and higher or equal to 0%.

Red region represents the operating points defined as insecure and unstable, with minimum damping factor lower than 0% (negative damping factors), which represents instability in face of small disturbances.

Lastly, white region represents the operating points where power flow calculations were not convergent, considering a normal operation of the system.

Power system planning studies can use the SSA nomograms to recommend new equipment for the system or a new control tuning, trying to improve its security.

Power system operation studies can use the nomograms to determine operative measures for the system, as redispatches, trying to keep its security.

### 4.3.2 Root-locus Method

Root-locus method (RLM) consists of determining root-locus contours for power systems, considering load flow parameter variation [46, 47, 49].

These root-locus contours obtained through load flow parameter variation already exist, as can be seen in [49]. The proposed SSA method uses this kind of evaluation, in order to obtain small-signal security margins.

Important power flow variables can be used in this root-locus analysis, such as bus loads and plant dispatches.

The DNM analysis considers proportional redispatches for the power plants of the same generator group, during the scenario creation.

The RLM analysis can consider any proportion for plant redispatches and is applicable to a more detailed SSA evaluation.

Figure 4.12 presents an illustrative SSA root-locus, showing an oscillation mode displacement in complex plane caused by a load flow parameter variation.

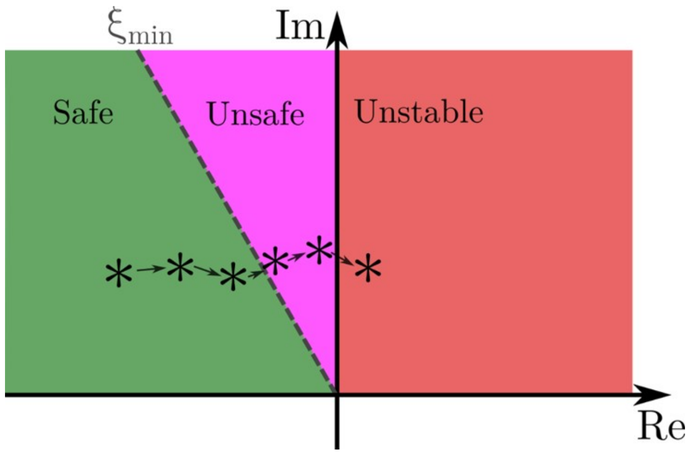


Figure 4.12: Schematic SSA root-locus example.

Figure 4.13 presents the same information as figure 4.12, showing a mapping of the mode damping factor in function of a parameter variation [16, 17].

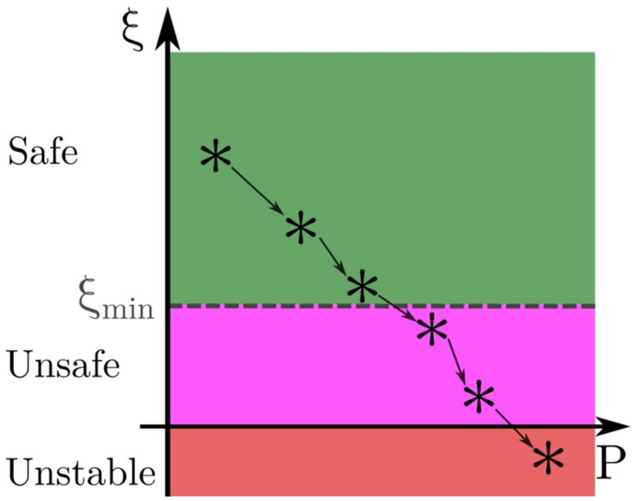


Figure 4.13: Mode damping factor mapping.

First RLM application consists of verifying system robustness and determining variation amount of parameter set that would produce poorly damped oscillations.

Load increasing with correspondent redispatch should be used in this case, in order to determine how much these loads can increase before a problem occurs.

Second RLM application consists of determining corrective measures to improve system dynamic behavior, increasing critical mode damping factors.

Power plant redispatches, terminal voltages and reactive power compensation should be used in this case, in order to obtain a better operating point.

Contingency analysis could also be considered in the RLM, yielding different root-locus contours for each one of these emergency situations.

### 4.3.3 On-line Monitoring of Oscillations

On-line monitoring of oscillations (OLMO) consists of monitoring small-signal stability of power systems, during their operations [47].

This monitoring is based on modal analysis, determining system oscillation modes and their damping factors, in order to detect possible oscillation problems.

Frequencies and damping factors of oscillation modes are monitored in the OLMO, which represent power system natural oscillations.

System will be considered secure if the monitored modes present damping factors higher than a desired minimum value. Otherwise, the system will be considered insecure, presenting poorly damped oscillations.

Security criteria used in OLMO are focusing on damping factors: 5% may be consider as a security limit and 0% is the stability limit.

Figure 4.14 illustrates OLMO of a secure power system, where monitored mode is always presenting a damping factor higher than the minimum desired.

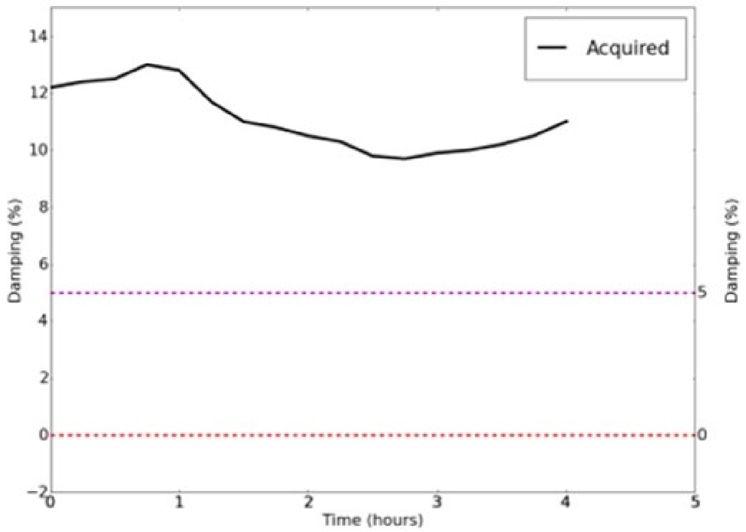


Figure 4.14: Schematic OLMO of a secure system.

Figure 4.15 illustrates OLMO of an insecure power system, where monitored mode is violating the security criteria in some operating points.

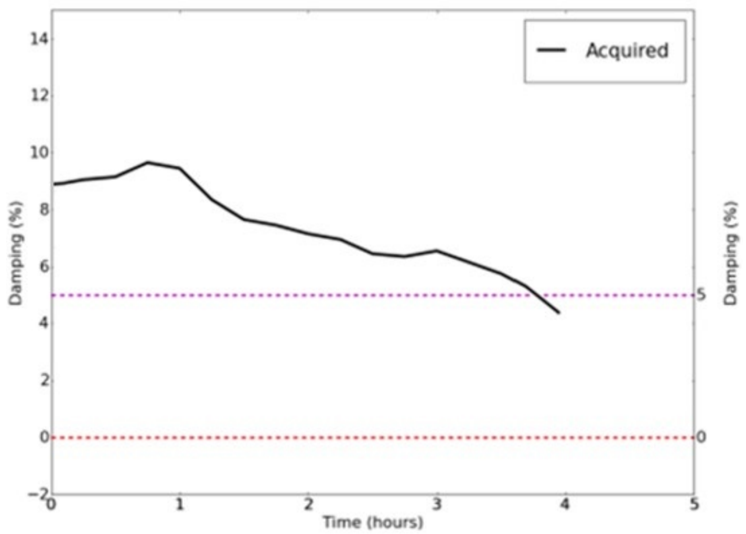


Figure 4.15: Schematic OLMO of an insecure system.

The OLMO may consider a method to forecast frequency and damping factor of important system modes, in order to preview future oscillation problems.

This forecasting may be related to simple extrapolation based on previous measurements or more complex methods based on load curve estimates.

Figure 4.16 illustrates OLMO of a secure power system, with forecasting, where monitored mode is always presenting a damping factor higher than the minimum desired, in measured and foreseen operating points.

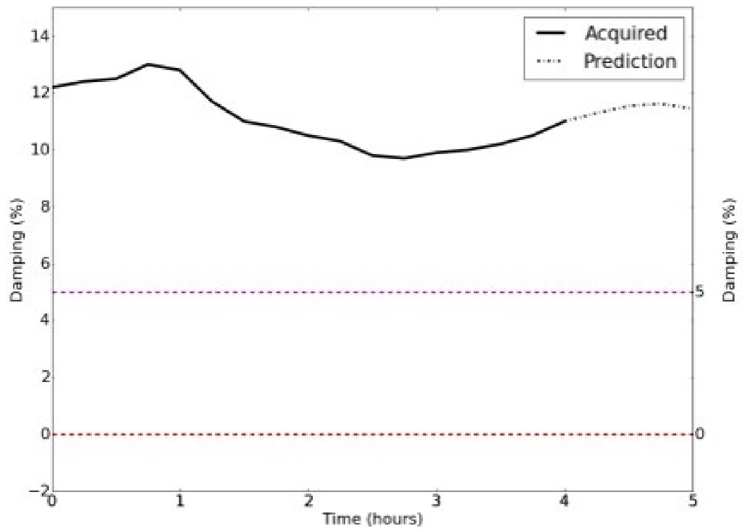


Figure 4.16: Schematic OLMO of a secure system with forecasting.

Figure 4.17 illustrates OLMO of an insecure power system, with forecasting, where monitored oscillation mode is violating the small-signal security criteria in some measured or foreseen operating point.

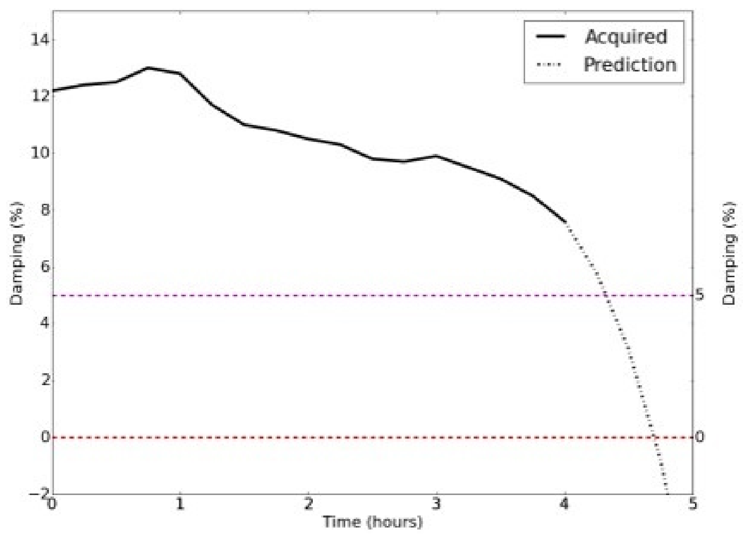


Figure 4.17: Schematic OLMO of an insecure system with forecasting.

The OLMO can also consider critical contingencies, in order to monitor the system modes of the normal operation scenarios and emergency situations.

Corrective measures can be used in power system, aiming to keep a secure operation, increasing damping factors of critical oscillation modes.

Figure 4.18 illustrates OLMO of a power system, where a security violation was foreseen and a corrective measure was used to keep a secure system operation, through increasing monitored mode damping factor.

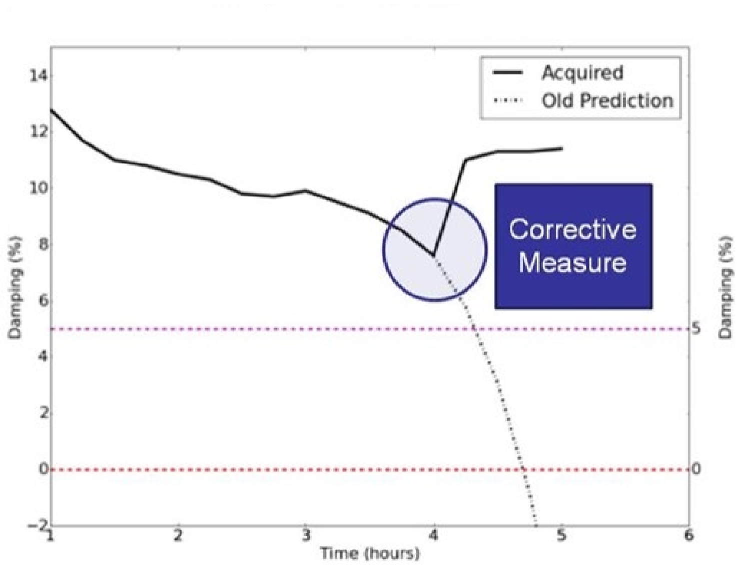


Figure 4.18: Schematic OLMO with forecasting and corrective measure.

Oscillation mode dynamic behaviors can be modified through using corrective measures in power systems, which are used to increase mode damping factors and can be related to automatic or operator actions.

Automatic actions can be related to supervisory control system utilization or power system stabilizer tuning. Adaptive control systems can also be used, in order to improve power system dynamic behavior.

Operator actions can be related to manual control system tuning or power plant redispatches, aiming to obtain better damping factor for monitored modes and keeping the system inside the security limits [44].

Nowadays, there are methods and strategies for power system monitoring based on phase measurement units (PMU) utilization [50].

The OLMO uses the steady-state and dynamic power system model, differently from these methods, which are based on real-time measurements [50].

PMU methods are more accurate and direct, since they do not depend on power system model. On the other hand, OLMO depends on the state estimator and system model data base. However, OLMO enables the forecasting, which can be used for corrective measure determination.

Then, OLMO could be used with PMU methods, in order to validate power system models and have forecasting tools, in order to improve system monitoring and determine corrective measures whenever needed.

Parallel processing may be utilized in OLMO tools, for improving computational performance to run eigensolver, specially for real-time applications [51].

## 4.4 Computational Implementations

The damping nomogram method and on-line monitoring of oscillations were implemented in software PacDyn [8], from CEPEL. These developments will be described following. The root-locus method, already existent [49], was not focused in this work, therefore, its implementation will not be described.

### 4.4.1 Damping Nomogram Method

Damping nomogram method was implemented in software PacDyn [8] and can be used to determine small-signal security regions for power systems.

These regions are based on damping factors of system modes, which can be calculated through QR [52, 53] or DPSE [54] methods.

QR method [52, 53] is capable of determining all the modes of a power system, while, DPSE [54] only calculates a mode set of interest.

A communication between software ANAREDE [5] and PacDyn [8] was developed for the creation of scenarios to be evaluated in DNM.

Figure 4.19 presents the algorithm used by ANAREDE [5] to define the operating point list necessary in this SSA method.

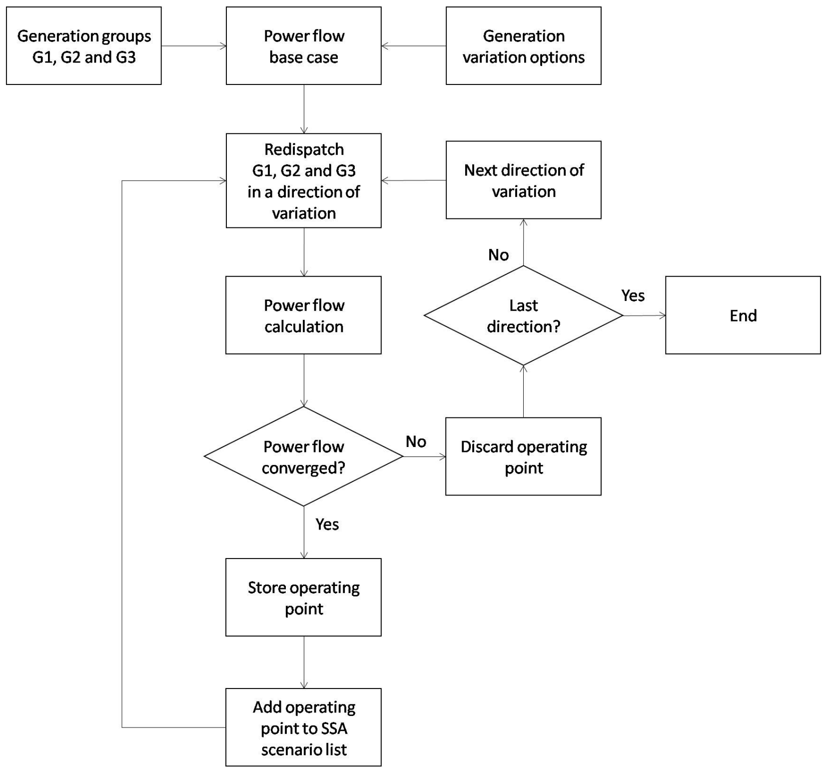


Figure 4.19: SSA scenario creation algorithm.

PacDyn [8] uses this communication with ANAREDE [5] for creating several scenarios to be evaluated in SSA.

Modes are obtained through QR [52, 53] or DPSE [54] methods, for all operating points, considering system normal operation and contingency situations.

Then, mode damping factors are verified, in order to determine the small-signal security regions, defining the SSA nomograms.

There are three nomograms for system normal operation and other three nomograms for the critical contingency situations.

Figure 4.20 presents the damping nomogram method algorithm, implemented in PacDyn [8] for SSA executions.

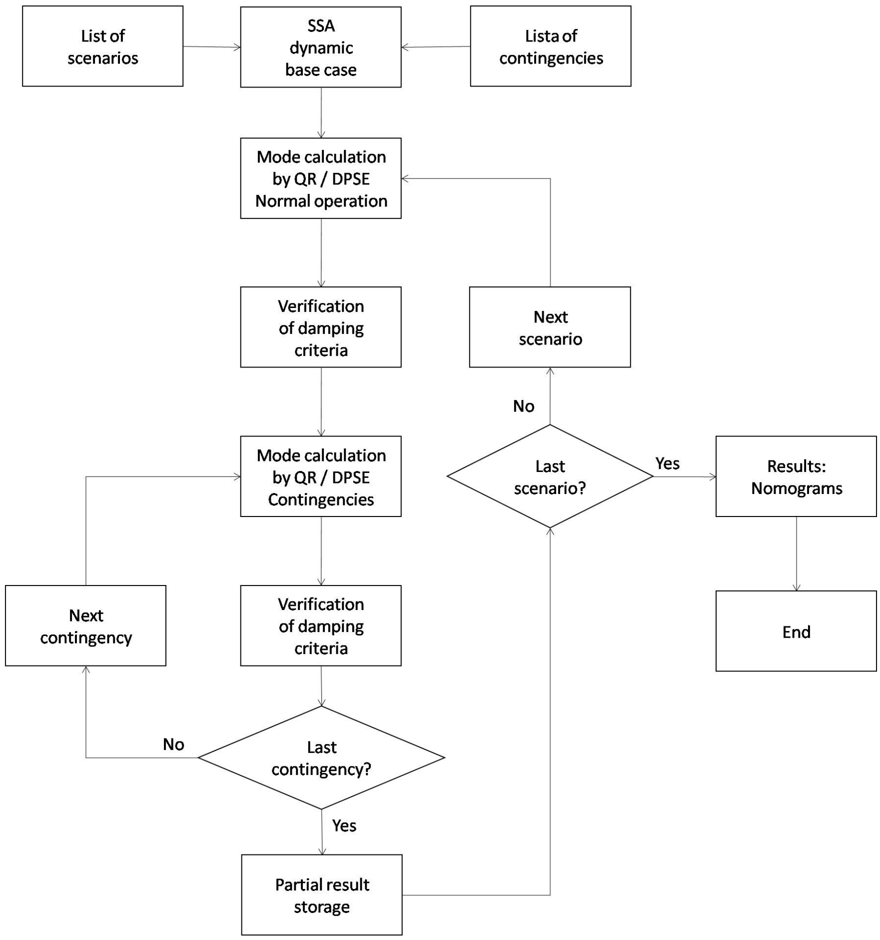


Figure 4.20: Damping nomogram method algorithm.

### 4.4.2 On-line Monitoring of Oscillations

On-line monitoring of oscillations was implemented in software PacDyn [8] and can be used to execute small-signal stability monitoring of power systems.

PacDyn monitors a mode set, which is calculated through using DPSE [54] method, considering system normal operation and contingency situations.

The software stays monitoring system steady-state data. When an EMS/SCADA updates these data, PacDyn [8] updates mode calculation, running DPSE [54] again, and obtains new frequencies and damping factors for monitored modes.

The OLMO results and their graphical views are also updated. These results are frequency and damping factor graphics over the time.

OLMO feature implemented in PacDyn [8] has several functions of this software available for using, such as: mode view in complex plane, linear time responses, frequency responses, root-locus calculations, sensitivities calculations, from among other modal analysis tools.

Figure 4.21 presents the OLMO algorithm, implemented in PacDyn [8] for small-signal stability monitoring.

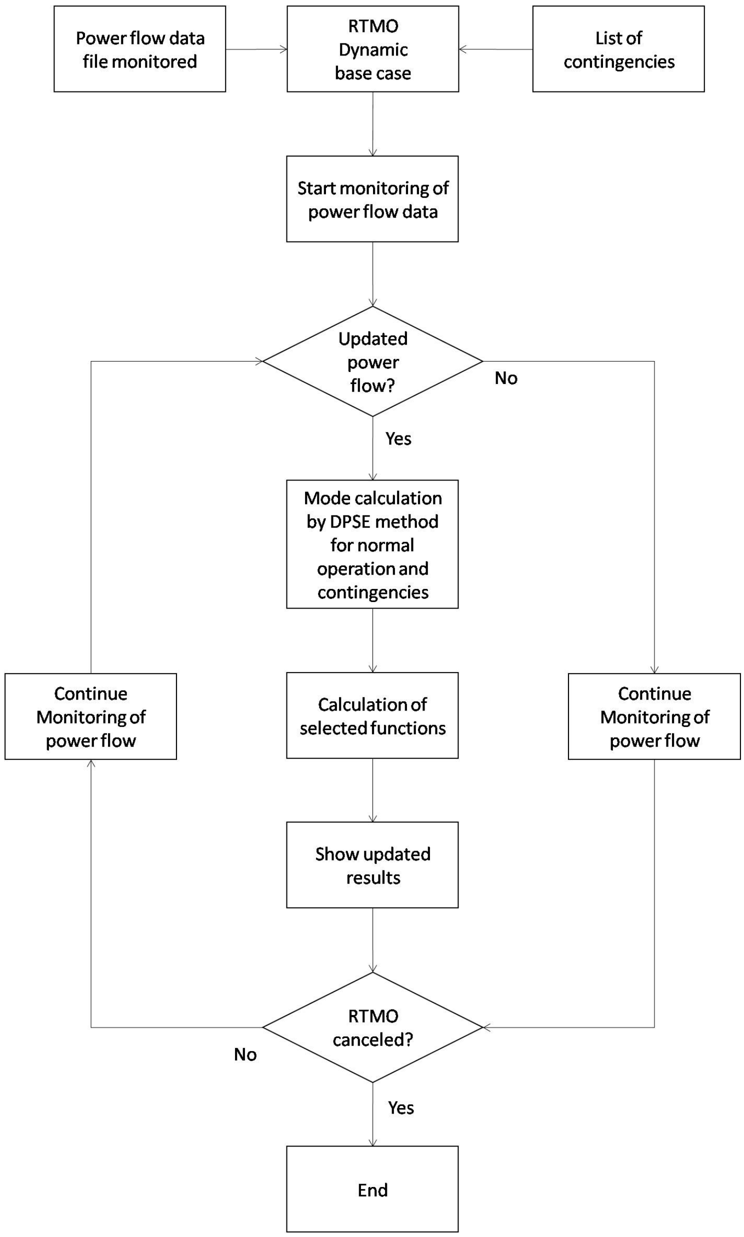


Figure 4.21: OLMO algorithm.

## 4.5 Final Considerations

Main concepts of voltage, transient and small-signal security assessment were briefly described in this chapter, focusing on SSA.

The damping nomogram method (DNM), root-locus method (RLM) and on-line monitoring of oscillations (OLMO) were proposed for SSA execution.

Computational implementations of the DNM and OLMO in software PacDyn [8] were presented, finishing this chapter.

# Chapter 5

# Hopf Bifurcation Application

This chapter will make a Hopf bifurcation literature review and will propose a method for power plant redispatches, considering a mode damping factor criteria. Generation sensitivity calculation will also be presented.

## 5.1 Hopf Bifurcation Analysis

Power system stability analysis aims at evaluating system dynamic behavior in face of disturbances, in order to detect possible focus of instability [4].

Hopf bifurcation analysis consists of determining specific situations of power systems, where their dynamic behaviors change [24].

System Hopf bifurcation points, considering small-signal stability analysis, are those where oscillation modes are positioned at the imaginary axis [24].

These situations represent the small-signal stability limits, which separates stable operating points from the unstable ones [24].

Several applications of Hopf bifurcation analysis for determining stability issues in power systems are presented in [18–33]. Parameter modifications that could lead them to a stability problem are calculated.

Some applications consider control system parameter variations, as presented in [18–20]. Other applications, however, are concerned with power flow parameter variations, as proposed in [29–33].

A method for determining minimum redispatch for power systems will be presented in this thesis, which considers a damping factor criteria for oscillation modes. This method is an extension of the algorithm proposed in [18–20].

An algorithm that uses optimization techniques and a predictor-corrector procedure is presented in [29], which can be utilized to detect power system bifurcations, including the Hopf bifurcations.

The method proposed in [29] is concerned with critical oscillation mode calculation and is applied to dynamic voltage security assessment, where modifications in the electrical grid and redispatches are considered for problem mitigation.

Power system bifurcation analysis is presented in [30], which considers several load situations. System demands are the parameters used in this study, for determining these bifurcations.

Methodology to control Hopf bifurcations through set-point modification of power systems is presented in [31], which uses reactive compensation, tap tuning, load shedding, plant terminal voltage changing, among others.

Method for determining the minimum distance to a Hopf bifurcation of power system is proposed in [32], which is based on genetic algorithm utilization. Active and reactive load variations were considered in the analysis.

An analysis of generation redispatch effects in system stability margins is presented in [33], where the Hopf bifurcation and load uncertainties are considered.

The methodologies presented in [29–33] are directly related to the research made in this work. However, they are quite different from the minimum redispatch method proposed by this thesis.

The proposed method is unique and uses optimization techniques and a mode damping factor criteria to determine, directly, a new dispatch for power systems.

## 5.2 Closest Hopf Bifurcation Review

Hopf bifurcation analysis applications are proposed in [18–20] for determining the lowest control parameter variation capable of making a specific system oscillation mode $\lambda$ present a desired damping factor $\xi_d$.

The situation, determined by using this method for desired damping factor of 0%, can be defined as the closest Hopf bifurcation of power systems.

Optimization techniques are used in [18–20], in order to minimize an objective function, which ensures the minimum parameter variations.

This function is the normalized square difference sum of chosen parameters [18–20], known as euclidean norm, which is presented in equation (5.1).

$$f_{obj}\left(p\right) = \sum_{i=1}^{n} \left( \frac{p_i - p_{i0}}{p_{i0}} \right)^2 \tag{5.1}$$

Where:

$f_{obj}$ = Objective function;

$n$ = Number of chosen parameters;

$p$ = Chosen parameter vector;

$p_i$ = Parameter $i$ value;

$p_{i0}$ = Parameter $i$ initial value.

This optimization method must consider some boundary conditions, according to [18–20], as can be seen in equations (5.2), (5.3), (5.4), (5.5) and (5.6).

$$Min f_{obj}\left(p\right) \tag{5.2}$$

S.t.:

$$f\left(x_0, p\right) = 0 \tag{5.3}$$

$$\left(\lambda.T - J\left(x_0, p\right)\right).v = 0 \tag{5.4}$$

$$c.v - 1 = 0 \tag{5.5}$$

$$B\left(\sigma, \omega\right) = \sigma + \frac{\xi_d}{\sqrt{1 - \xi_d^2}}.\omega \tag{5.6}$$

Where:

$f_{obj}$ = Objective function;

$p$ = Chosen parameter vector;

$x_0$ = System variable vector;

$T$ = Expanded identity, containing 1 in diagonal elements related to state variables and 0 in those related to the algebraic variables;

$J$ = System jacobian matrix;

$v$ = Right eigenvector;

$c$ = Sparse line vector used for normalization of $p$;

$\sigma$ = Mode real component;

$\omega$ = Mode imaginary component;

$\xi_d$ = Desired damping factor;

$f$ = Vector including power flow equations and equipment initialization equations;

$B$ = Function representing the desired relation between $\sigma$ and $\omega$.

The Lagrange method can be used to solve this optimization problem. A lagrangian function $LF$ is defined in equation (5.7) and must be minimized for obtaining the optimal solution [18–20].

$$MinLF = f_{obj}\left(p\right) + l^{t}.h\left(x,p\right) \tag{5.7}$$

Where:

$LF$ = Lagrangian function;

$f_{obj}$ = Objective function;

$l$ = Lagrangian multiplier vector;

$h$ = Function representing equality constrains;

$p$ = Chosen parameter vector;

$x$ = Vector containing independent variables, except vectors $p$ and $l$.

The solution is obtained when the lagrangian function gradient is null ($\nabla LF = 0$), which is represented by equations (5.8), (5.9) and (5.10), according to [18–20].

$$\frac{\partial LF}{\partial x} = l^{t}.\frac{\partial h}{\partial x} = 0 \tag{5.8}$$

$$\frac{\partial LF}{\partial p} = \frac{\partial f_{obj}}{\partial p} + l^{t}.\frac{\partial h}{\partial p} = 0 \tag{5.9}$$

$$\frac{\partial LF}{\partial l} = h = 0 \tag{5.10}$$

Where:

$l$ = Lagrangian multiplier vector;

$p$ = Chosen parameter vector;

$x$ = Vector containing independent variables, except vectors $p$ and $l$;

$h$ = Function representing equality constrains;

$\frac{\partial LF}{\partial x}$ = Lagrangian function derivative with respect to vector $x$;

$\frac{\partial LF}{\partial p}$ = Lagrangian function derivative with respect to vector $p$;

$\frac{\partial LF}{\partial l}$ = Lagrangian function derivative with respect to vector $l$;

$\frac{\partial h}{\partial x}$ = Function $h$ derivative with respect to vector $x$;

$\frac{\partial f_{obj}}{\partial p}$ = Objective function derivative with respect to vector $p$;

$\frac{\partial h}{\partial p}$ = Function $h$ derivative with respect to vector $p$.

The non-linear system defined in equations (5.8), (5.9) and (5.10) can be solved through using Newton-Raphson method. Then, the equations (5.11), (5.12) and (5.13) can be defined [18–20].

$$l^t.\frac{\partial^2 h}{\partial x^2}.\Delta x + l^t.\frac{\partial^2 h}{\partial p \partial x}.\Delta p + \left(\frac{\partial h}{\partial x}\right)^t.\Delta l = \Delta\frac{\partial LF}{\partial x} \tag{5.11}$$

$$l^t.\frac{\partial^2 h}{\partial x \partial p}.\Delta x + \left(\frac{\partial^2 f_{obj}}{\partial p^2} + l^t.\frac{\partial^2 h}{\partial p^2}\right).\Delta p + \left(\frac{\partial h}{\partial p}\right)^t.\Delta l = \Delta\frac{\partial LF}{\partial p} \tag{5.12}$$

$$\frac{\partial h}{\partial x}.\Delta x + \frac{\partial h}{\partial p}.\Delta p = \Delta\frac{\partial LF}{\partial l} \tag{5.13}$$

Where:

$\Delta l$ = Lagrangian multiplier variation vector;

$\Delta p$ = Chosen parameter variation vector;

$\Delta x$ = Variation vector containing independent variables, except vectors $p$ and $l$;

$\Delta\frac{\partial LF}{\partial x}$ = Variation of lagrangian function derivative with respect to vector $x$;

$\Delta\frac{\partial LF}{\partial p}$ = Variation of lagrangian function derivative with respect to vector $p$;

$\Delta\frac{\partial LF}{\partial l}$ = Variation of lagrangian function derivative with respect to vector $l$;

$\frac{\partial^2 h}{\partial x^2}$ = Second order derivative of function $h$ with respect to vector $x$;

$\frac{\partial^2 h}{\partial p \partial x}$ = Second order derivative of function $h$ with respect to vectors $x$ and $p$;

$\frac{\partial h}{\partial x}$ = Function $h$ derivative with respect to vector $x$;

$\frac{\partial^2 h}{\partial x \partial p}$ = Second order derivative of function $h$ with respect to vectors $p$ and $x$;

$\frac{\partial^2 f_{obj}}{\partial p^2}$ = Second order derivative of objective function with respect to vector $p$;

$\frac{\partial^2 h}{\partial p^2}$ = Second order derivative of function $h$ with respect to vector $p$;

$\frac{\partial f_{obj}}{\partial p}$ = Objective function derivative with respect to vector $p$;

$\frac{\partial h}{\partial p}$ = Function $h$ derivative with respect to vector $p$.

Using this equationing in an iterative algorithm, the closest security boundary in control parameter space can be defined, according to [18–20].

This method can be used to determine the minimum parameter variation capable of making a system mode present a desired damping factor [18–20].

Mathematical difficulties arise when considering power flow parameter variation in the method proposed in [18–20], such as plant dispatches.

This thesis solved these mathematical issues in a different way, defining a minimum redispatch method, which will be described in this chapter.

## 5.3 Generation Sensitivities

A method for calculating oscillation mode sensitivities with respect to power plant dispatches was developed, which was called generation sensitivities.

These sensitivities can be mathematically defined as the derivative of oscillation mode $\lambda$ with respect to active power dispatched by specific power plant $P$.

The analytical determination of these derivatives is very complex, once many jacobian elements depend on power plant dispatches.

Then, a numerical method was used for determining the generation sensitivities. Small positive and negative variations ($P + \Delta P$ and $P - \Delta P$) are applied in a specific power plant dispatch and oscillation modes are obtained for both situations ($\lambda_{+\Delta P}$ and $\lambda_{-\Delta P}$), using DPSE method [54].

Other system plants take on opposite dispatch variation, proportionally to their nominal capability (MVA base), ensuring the load-generation balance.

The generation sensitivity can be obtained through a first order approximation, which is represented by equations (5.14), (5.15) and (5.16)

$$\frac{\partial \lambda}{\partial P} \approx \frac{\Delta \lambda}{\Delta P'}, \Delta P' \to 0 \tag{5.14}$$

$$\Delta P' = 2.\Delta P \tag{5.15}$$

$$\frac{\partial \lambda}{\partial P} \approx \frac{\lambda_{+\Delta P} - \lambda_{-\Delta P}}{2.\Delta P} \tag{5.16}$$

Where:

$\frac{\partial \lambda}{\partial P}$ = Generation sensitivity of mode with respect to dispatch;

$\Delta \lambda$ = Oscillation mode variation;

$\Delta P'$ = Total dispatch variation;

$\Delta P$ = Absolute dispatch value used in positive and negative variations;

$\lambda_{+\Delta P}$ = Oscillation mode for dispatch $P + \Delta P$;

$\lambda_{-\Delta P}$ = Oscillation mode for dispatch $P - \Delta P$.

If $\Delta P$ is very small, numerical problems may happen in power flow solution. Otherwise, if $\Delta P$ is very high, the sensitivity calculation loses accuracy. In this thesis, $\Delta P$ was considered equal to 0.1 per unit in system power base.

Generation sensitivities can be used for selecting power plants to be used in the redispatch method that will be proposed in this thesis.

## 5.4 Hopf Bifurcation for Redispatch

Hopf bifurcation analysis can also be applied for determining a minimum power plant redispatch capable of making a specific system oscillation mode $\lambda$ present a desired damping factor $\xi_d$.

This new application was called the closest security boundary for generation redispatch using eigenvalue sensitivities (CSBGRES method).

Similarly to the method presented in [18–20], optimization techniques can be used to minimize an objective function, which ensures the minimum dispatch variation for system power plants.

Several system jacobian elements, power flow and equipment initialization equations change in function of plant dispatches, which is a challenge.

Other mathematical issues are related to the discontinuous control of power flow model, which should be considered in the method.

A new optimization problem can be proposed, which avoids these difficulties using a different approach. This formulation is presented through equations (5.17), (5.18) and (5.19), where a mode damping factor criteria and a load-generation balance equation (without including loss variations) are considered as constraints.

$$Min f_{obj}\left(P\right) = \sum_{i=1}^{n} \left(P_i - P_{i_0}\right)^2 \tag{5.17}$$

S.t.:

$$\sigma\left(P\right) + \frac{\xi_d}{\sqrt{1-\xi_d^2}}.\omega\left(P\right) = 0 \tag{5.18}$$

$$\sum_{i=1}^{m} P_i - \sum_{i=1}^{m} P_{i_0} = 0 \tag{5.19}$$

Where:

$f_{obj}$ = Objective function;

$P$ = Active power vector;

$P_i$ = Power plant $i$ dispatch;

$P_{i_0}$ = Power plant $i$ initial dispatch;

$n$ = Number of chosen power plants;

$m$ = Total number of system power plants;

$\sigma(P)$ = Mode real component;

$\omega(P)$ = Mode imaginary component;

$\xi_d$ = Desired damping factor.

The variables $\sigma$ and $\omega$ were considered independent variables in the optimization method presented in [18–20]. In the equationing of this thesis, these variables depend on the power plant dispatches, being dependent variables.

These $\sigma$ and $\omega$ characteristics enable the CSBGRES method development, which is the main contribution of this thesis.

The Lagrange method can be used again to solve this new optimization problem. A lagrangian function $LF$ is defined in equation (5.20) and must be minimized for obtaining the optimal solution.

$$MinLF = \sum_{i=1}^{n} (P_i - P_{i_0})^2 + l_1. \left( \sigma(P) + \frac{\xi_d}{\sqrt{1-\xi_d^2}}.\omega(P) \right) + l_2. \left( \sum_{i=1}^{m} P_i - \sum_{i=1}^{m} P_{i_0} \right) \tag{5.20}$$

Where:

$LF$ = Lagrangian function;

$P$ = Active power vector;

$P_i$ = Power plant $i$ dispatch;

$P_{i_0}$ = Power plant $i$ initial dispatch;

$n$ = Number of chosen power plants;

$m$ = Total number of system power plants;

$\sigma(P)$ = Mode real component;

$\omega(P)$ = Mode imaginary component;

$\xi_d$ = Desired damping factor;

$l_1$ = First lagrangian multiplier;

$l_2$ = Second lagrangian multiplier.

Similarly to [18–20], the solution is obtained when the lagrangian function gradient is null ($\nabla LF = 0$), which is represented by equations (5.21), (5.22) and (5.23).

$$\frac{\partial LF}{\partial P} = 2\left(P - P_0\right) + l_1.\left(\frac{\partial \sigma}{\partial P} + \frac{\xi_d}{\sqrt{1-\xi_d^2}}.\frac{\partial \omega}{\partial P}\right) + l_2 = 0 \tag{5.21}$$

$$\frac{\partial LF}{\partial l_1} = \sigma + \frac{\xi_d}{\sqrt{1-\xi_d^2}}.\omega = 0 \tag{5.22}$$

$$\frac{\partial LF}{\partial l_2} = \sum_{i=1}^{m} P_i - \sum_{i=1}^{m} P_{i_0} = 0 \tag{5.23}$$

Where:

$P$ = Active power vector;

$P_i$ = Power plant $i$ dispatch;

$P_{i_0}$ = Power plant $i$ initial dispatch;

$n$ = Number of chosen power plants;

$m$ = Total number of system power plants;

$\sigma(P)$ = Mode real component;

$\omega(P)$ = Mode imaginary component;

$\xi_d$ = Desired damping factor;

$l_1$ = First lagrangian multiplier;

$l_2$ = Second lagrangian multiplier;

$\frac{\partial LF}{\partial P}$ = Lagrangian function derivative with respect to vector $P$;

$\frac{\partial LF}{\partial l_1}$ = Lagrangian function derivative with respect to multiplier $l_1$;

$\frac{\partial LF}{\partial l_2}$ = Lagrangian function derivative with respect to multiplier $l_2$;

$\frac{\partial \sigma}{\partial P}$ = Derivative of mode real component with respect to vector $P$;

$\frac{\partial \omega}{\partial P}$ = Derivative of mode imaginary component with respect to vector $P$.

The derivatives $\frac{\partial \sigma}{\partial P}$ and $\frac{\partial \omega}{\partial P}$ can be obtained through the generation sensitivities of mode $\lambda$ with respect to vector $P$, according to equations (5.24) and (5.25).

$$\frac{\partial \sigma}{\partial P} = Re\left\{\frac{\partial \lambda}{\partial P}\right\} \tag{5.24}$$

$$\frac{\partial \omega}{\partial P} = Im\left\{\frac{\partial \lambda}{\partial P}\right\} \tag{5.25}$$

Where:

$\frac{\partial \lambda}{\partial P}$ = Generation sensitivity of mode $\lambda$ with respect to vector $P$;

$\frac{\partial \sigma}{\partial P}$ = Derivative of mode real component with respect to vector $P$;

$\frac{\partial \omega}{\partial P}$ = Derivative of mode imaginary component with respect to vector $P$.

Similarly to [18–20], the non-linear system defined in equations (5.21), (5.22) and (5.23) can be solved through using Newton-Raphson method. Then, the equations(5.26), (5.27) and (5.28) can be defined.

$$2.\Delta P + \left( \frac{\partial \sigma}{\partial P} + \frac{\xi_d}{\sqrt{1-\xi_d^2}} . \frac{\partial \omega}{\partial P} \right) .\Delta l_1 + \Delta l_2 = \Delta \frac{\partial LF}{\partial P} \tag{5.26}$$

$$\left( \frac{\partial \sigma}{\partial P} + \frac{\xi_d}{\sqrt{1-\xi_d^2}} . \frac{\partial \omega}{\partial P} \right) .\Delta P = \Delta \frac{\partial LF}{\partial l_1} \tag{5.27}$$

$$\Delta P = \Delta \frac{\partial LF}{\partial l_2} \tag{5.28}$$

Where:

$\Delta P$ = Active power variation vector;

$\Delta l_1$ = First lagrangian multiplier variation;

$\Delta l_2$ = Second lagrangian multiplier variation;

$\xi_d$ = Desired damping factor;

$\Delta \frac{\partial LF}{\partial P}$ = Variation of lagrangian function derivative with respect to vector $P$;

$\Delta \frac{\partial LF}{\partial l_1}$ = Variation of lagrangian function derivative with respect to first lagrangian multiplier;

$\Delta \frac{\partial LF}{\partial l_2}$ = Variation of lagrangian function derivative with respect to second lagrangian multiplier;

$\frac{\partial \sigma}{\partial P}$ = Derivative of mode real component with respect to vector $P$;

$\frac{\partial \omega}{\partial P}$ = Derivative of mode imaginary component with respect to vector $P$.

The second derivative of mode $\lambda$ with respect to vector $P$ was not considered for the simplification of this optimization problem. Then, a dishonest Newton-Raphson method is used here, instead of the traditional one.

Maximum and minimum limits must be consider for the active power vector $P$. Variable replacement can be done, aiming at their implementations.

Similarly to [18–20], the vector $P$ can be replaced by an auxiliary vector $a$ through using equations (5.29) and (5.30).

$$P = \frac{P_{max} + P_{min}}{2} + \frac{P_{max} - P_{min}}{2}.\sin(a) \tag{5.29}$$

$$a = \arcsin\left(\frac{P - \frac{P_{max}+P_{min}}{2}}{\frac{P_{max}-P_{min}}{2}}\right) \tag{5.30}$$

Where:

$P$ = Active power vector;

$P_{max}$ = Maximum active power vector;

$P_{min}$ = Minimum active power vector;

$a$ = Auxiliary vector.

All the derivatives with respect to vector $P$ must be replaced by the ones with respect to auxiliary vector $a$ through using correction factors $f_1$ and $f_2$, which are defined in equations (5.31) and (5.32).

$$f_1 = \frac{\partial P}{\partial a} = \frac{P_{max} - P_{min}}{2}.\cos(a) \tag{5.31}$$

$$f_2 = \frac{\partial^2 P}{\partial a^2} = -\frac{P_{max} - P_{min}}{2}.\sin(a) \tag{5.32}$$

Where:

$P$ = Active power vector;

$P_{max}$ = Maximum active power vector;

$P_{min}$ = Minimum active power vector;

$a$ = Auxiliary vector;

$f_1$ = Correction factor representing vector $P$ derivative with respect to vector $a$;

$f_2$ = Correction factor representing vector $P$ second order derivative with respect to vector $a$;

$\frac{\partial P}{\partial a}$ = Vector $P$ derivative with respect to vector $a$;

$\frac{\partial^2 P}{\partial a^2}$ = Vector $P$ second order derivative with respect to vector $a$.

Correction factors $f_1$ and $f_2$ should be used in linearized system shown in equations (5.26), (5.27) and (5.28), so the optimization problem can be modelled in function of vector $a$, instead of vector $P$.

This new system can be defined through equations (5.33), (5.34) and (5.35).

$$\left(2.f_1^2 + \left(2.\left(P - P_0\right) + l_1.\left(\frac{\partial \sigma}{\partial P} + \frac{\xi_d}{\sqrt{1-\xi_d^2}}.\frac{\partial \omega}{\partial P}\right) + l_2\right) f_2\right).\Delta a$$
$$+f_1.\left(\frac{\partial \sigma}{\partial P} + \frac{\xi_d}{\sqrt{1-\xi_d^2}}.\frac{\partial \omega}{\partial P}\right).\Delta l_1 + f_1.\Delta l_2 = f_1.\Delta\frac{\partial LF}{\partial P} \tag{5.33}$$

$$f_1.\left(\frac{\partial \sigma}{\partial P} + \frac{\xi_d}{\sqrt{1-\xi_d^2}}.\frac{\partial \omega}{\partial P}\right).\Delta a = \Delta\frac{\partial LF}{\partial l_1} \tag{5.34}$$

$$f_1.\Delta a = \Delta\frac{\partial LF}{\partial l_2} \tag{5.35}$$

Where:

$\Delta a$ = Auxiliary vector variation;

$\Delta l_1$ = First lagrangian multiplier variation;

$\Delta l_2$ = Second lagrangian multiplier variation;

$\xi_d$ = Desired damping factor;

$\Delta\frac{\partial LF}{\partial P}$ = Variation of lagrangian function derivative with respect to vector $P$;

$\Delta\frac{\partial LF}{\partial l_1}$ = Variation of lagrangian function derivative with respect to first lagrangian multiplier;

$\Delta\frac{\partial LF}{\partial l_2}$ = Variation of lagrangian function derivative with respect to second lagrangian multiplier;

$\frac{\partial \sigma}{\partial P}$ = Derivative of mode real component with respect to vector $P$;

$\frac{\partial \omega}{\partial P}$ = Derivative of mode imaginary component with respect to vector $P$;

$P$ = Active power vector;

$P_0$ = Initial active power vector;

$l_1$ = First lagrangian multiplier used in the method;

$l_2$ = Second lagrangian multiplier used in the method;

$f_1$ = Correction factor representing vector $P$ derivative with respect to vector $a$;

$f_2$ = Correction factor representing vector $P$ second order derivative with respect to vector $a$.

Using this equationing in an iterative algorithm, the closest security boundary for generation redispatch using eigenvalue sensitivities can be defined.

The CSBGRES method can be used to determine minimum redispatches capable of making a system mode present a desired damping factor.

Computational implementation of the method should use step-length controls in desired damping factor and active power variations, in order to keep mode track and improve algorithm convergence.

The proposed method can be applied to determine power system security margins or possible corrective measures to improve its dynamic behavior.

## 5.5 Computational Implementations

The generation sensitivity calculation and CSBGRES method were implemented in software PacDyn [8]. These developments will be described following.

### 5.5.1 Generation Sensitivities

Generation sensitivity calculation was implemented in software PacDyn [8], using equations (5.14) and (5.16), and can be used to determine system mode displacement trend in complex plane in function of power plant dispatches.

These sensitivities can also be used to select the power plants to be utilized in CSBGRES method for minimum redispatches.

This development was made through programming an iterative algorithm that runs the calculation defined in equations (5.14) and (5.16) for each power plant.

Software ANAREDE [5] is used for the several power flow executions needed to obtain the generation sensitivities.

The results are phasors that show this displacement trend in complex plane of the mode of interest, when modifying power plant dispatches.

This numerical method used in this computational implementation is generic and can be utilized to determine the sensitivities of oscillation modes with respect to any parameter of electrical power systems.

Figure 5.1 presents the generation sensitivity calculation algorithm, implemented in PacDyn [8] for obtaining a first order relation between system oscillation mode and power plant dispatches.

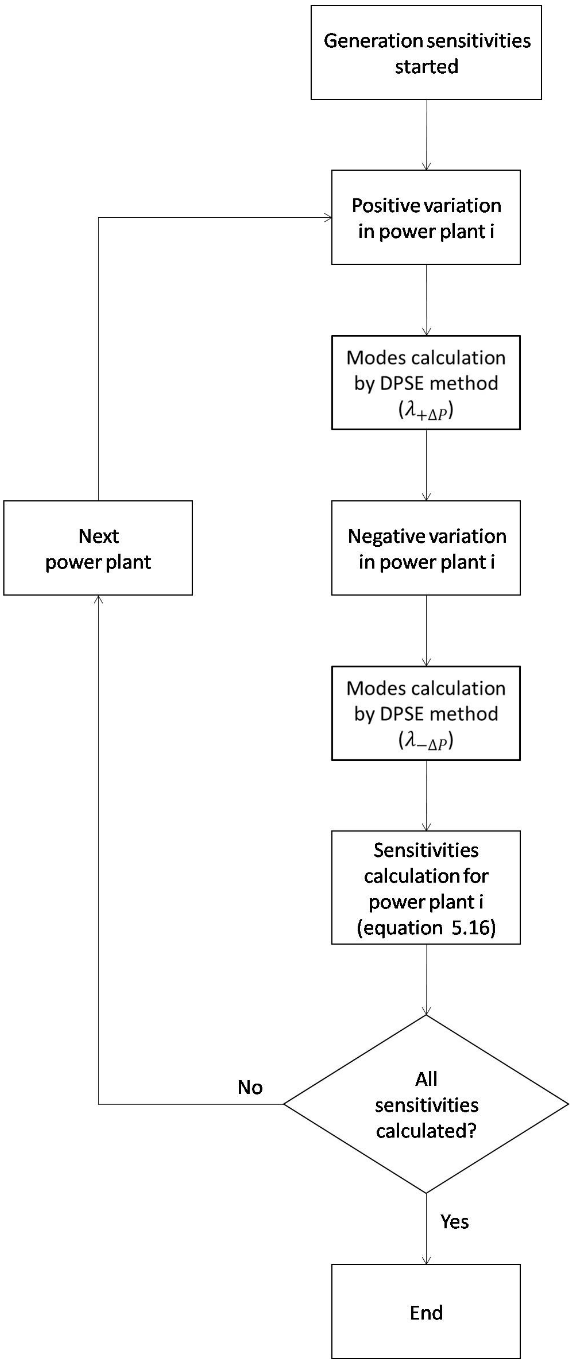


Figure 5.1: Generation sensitivity calculation algorithm.

### 5.5.2 Hopf Bifurcation for Redispatch

The CSBGRES method was implemented in software PacDyn [8], using equations (5.26), (5.27) and (5.28), and can be used to determine minimum redispatch to achieve a desired damping factor for a system mode.

This development was made through programming an iterative algorithm that runs the calculation defined in equations (5.26), (5.27) and (5.28), which is based on dishonest Newton-Raphson method.

The algorithm is an alternating method, similar to a predictor-corrector process.

Power flow calculation and mode determination are made considering the dispatches of actual iteration, using ANAREDE [5] and PacDyn [8].

If the desired damping factor was not reached, a new Newton-Raphson iteration is executed to determine power plant dispatch variations.

This alternating procedure is repeated until desired damping factor is reached for the mode of interest and the minimum redispatch is obtained.

Convergence verification is made through a comparison between the mode damping factor and the desired value. If this difference is lower than a tolerance, which is 0.1% in this work, the process is convergent.

Losses variations are taken on by the power plants selected to be used in the method.

This numerical procedure used in this computational implementation is generic and can be utilized to consider the variation of any power system parameter, in order to obtain its security margins.

Figure 5.2 presents the CSBGRES method algorithm, implemented in PacDyn [8] for determining minimum dispatches for power systems, considering a damping factor criteria for oscillation modes.

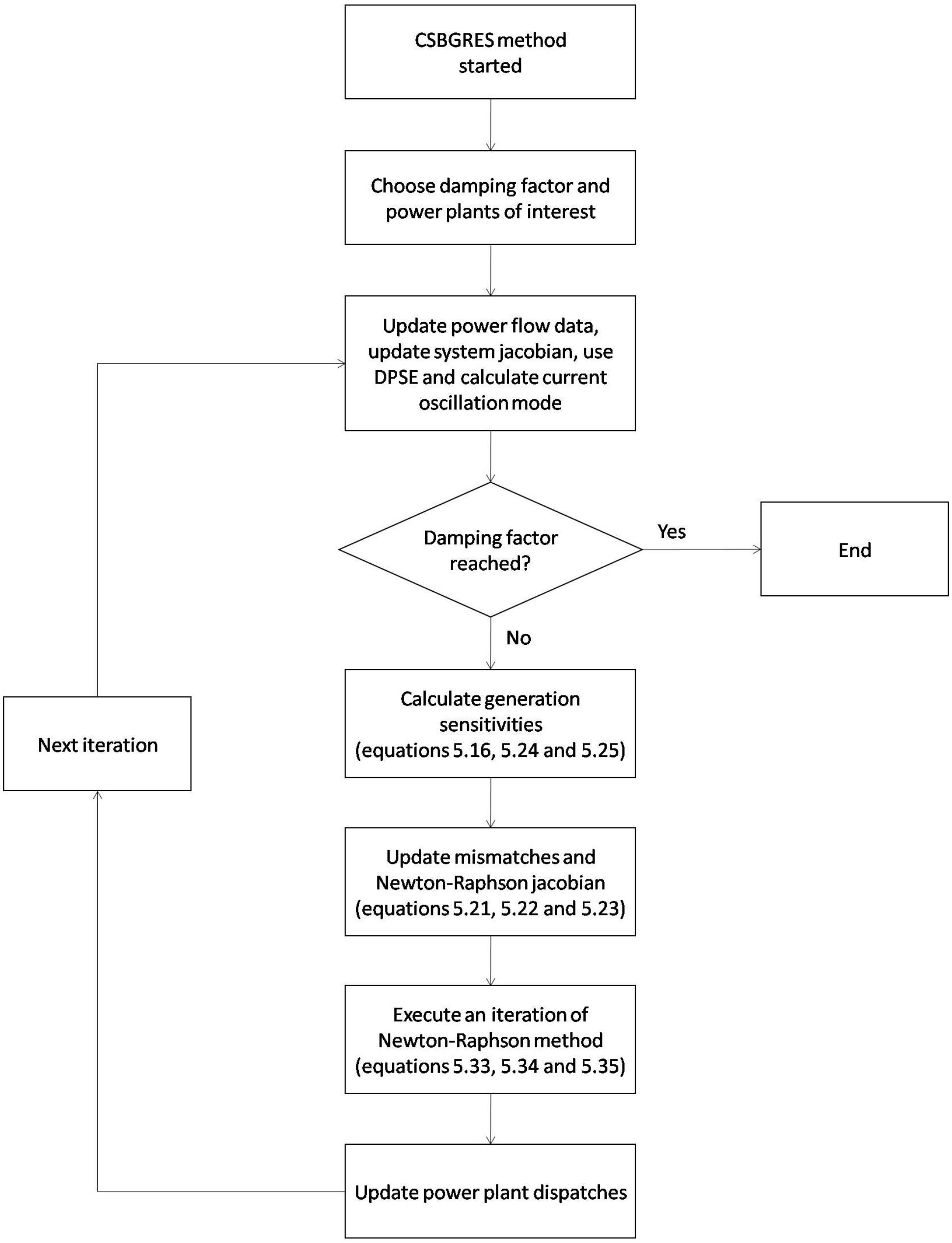


Figure 5.2: CSBGRES method algorithm.

## 5.6 Final Considerations

Hopf bifurcation analysis and the closest security boundary in control parameter space algorithm were reviewed in this chapter.

A generation sensitivity calculation was developed and can be used to determine mode displacement trend in complex plane in function of power plant dispatches and select machines to be used in system redispatch.

The CSBGRES method was also developed and can be used to obtain minimum redispatches for power plants needed to achieve a desired damping factor for a specific system mode.

# Chapter 6

# Tests and Results

This chapter will perform tests and simulations using the methods developed in this thesis. Results will be evaluated, in order to highlight the benefits obtained through applying these methods in power system analyses.

## 6.1 SAGE System Results

Damping nomogram method (DNM) was tested in a Brazilian equivalent system (appendix A), containing about 65 buses and 29 machines (related to Itaipu, South and Southeast power plants).

Power flow base case from the energy management open system (SAGE) [55], developed by CEPEL, was used in this analysis.

Figure 6.1 [56] presents the single-line diagram of SAGE system, showing interconnections between three electrical areas.

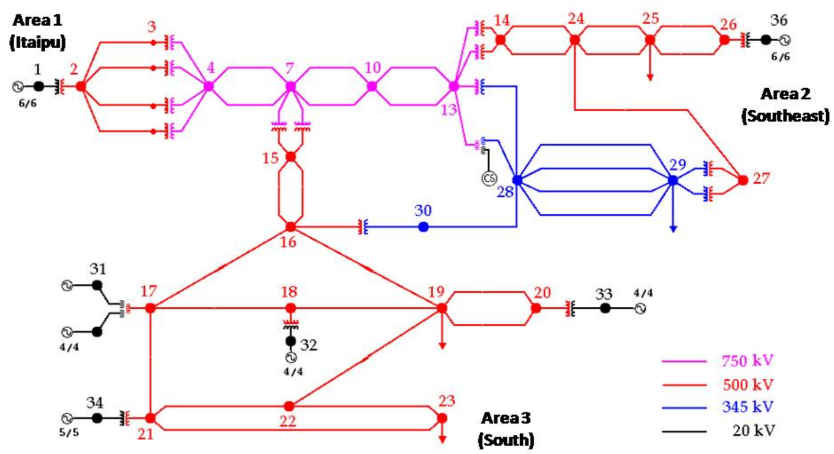


Figure 6.1: SAGE system single-line diagram.

Power plants of area 1 were chosen to form the generation group 1, power plants of area 2 were chosen to form the generation group 2 and the other power plants were chosen to form the generation group 3.

Ten redispatch directions were used for creating scenarios to be evaluated. Two outages were considered as contingencies: of transmission line inside area 3, and interchanging line between areas 1 and 2.

Figure 6.2 to 6.13 present DNM results with oscillation modes obtained through QR [52, 53] and DPSE [54] methods, considering system normal operation and contingency situations.

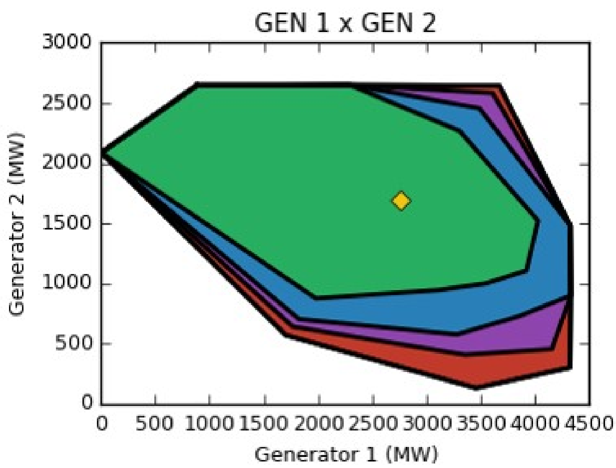


Figure 6.2: Gen 1 x Gen 2 nomogram for system normal operation using QR.

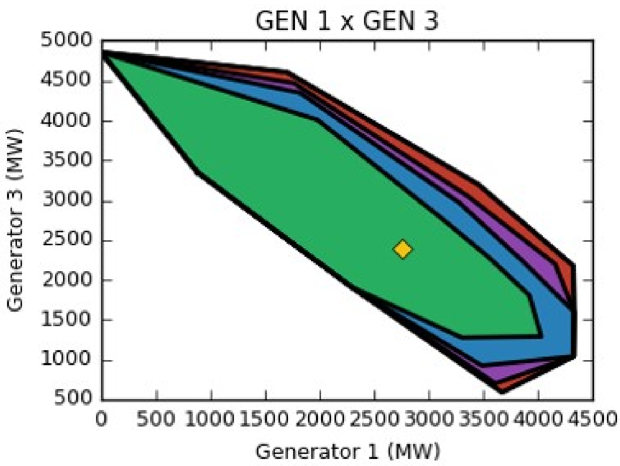


Figure 6.3: Gen 1 x Gen 3 nomogram for system normal operation using QR.

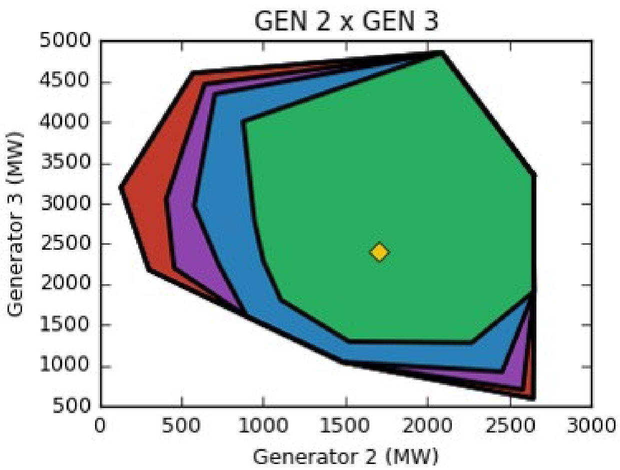


Figure 6.4: Gen 2 x Gen 3 nomogram for system normal operation using QR.

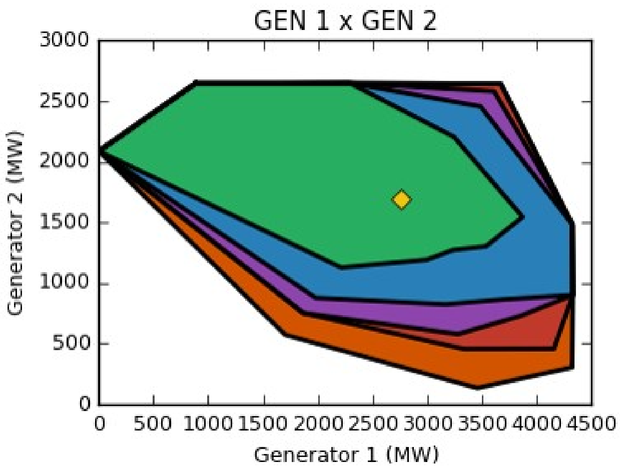


Figure 6.5: Gen 1 x Gen 2 nomogram for contingency situations using QR.

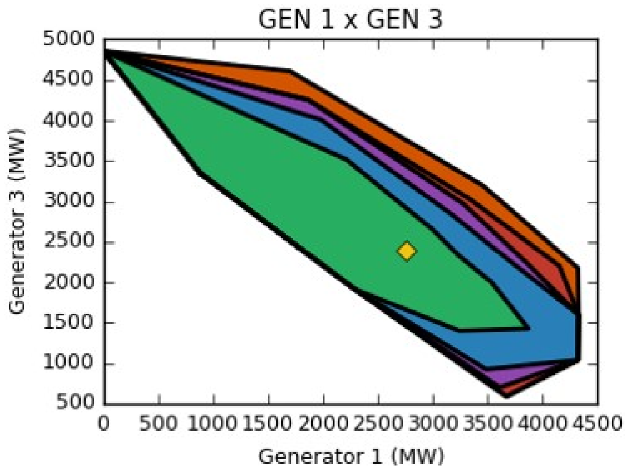


Figure 6.6: Gen 1 x Gen 3 nomogram for contingency situations using QR.

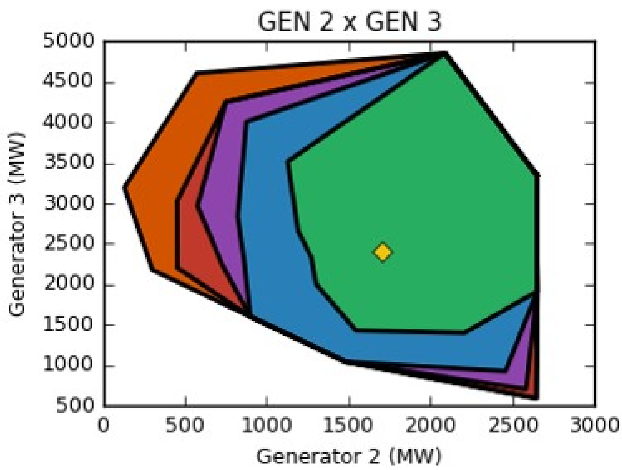


Figure 6.7: Gen 2 x Gen 3 nomogram for contingency situations using QR.

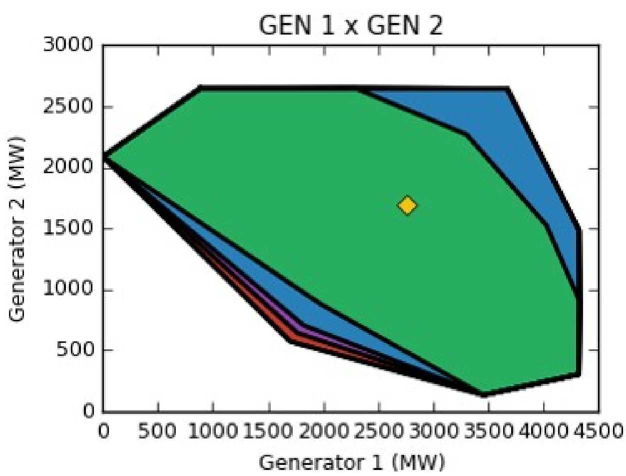


Figure 6.8: Gen 1 x Gen 2 nomogram for system normal operation using DPSE.

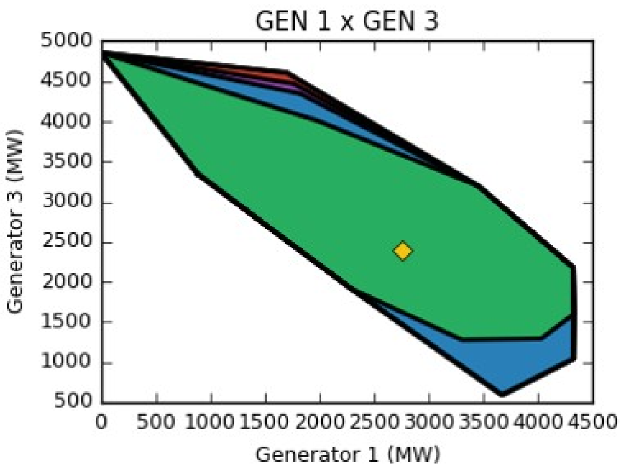


Figure 6.9: Gen 1 x Gen 3 nomogram for system normal operation using DPSE.

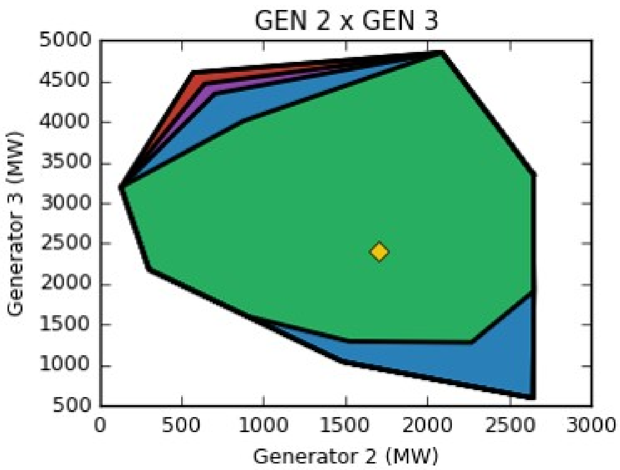


Figure 6.10: Gen 2 x Gen 3 nomogram for system normal operation using DPSE.

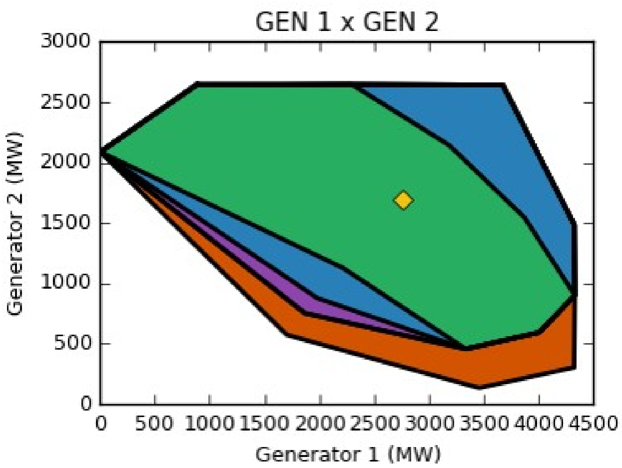


Figure 6.11: Gen 1 x Gen 2 nomogram for contingency situations using DPSE.

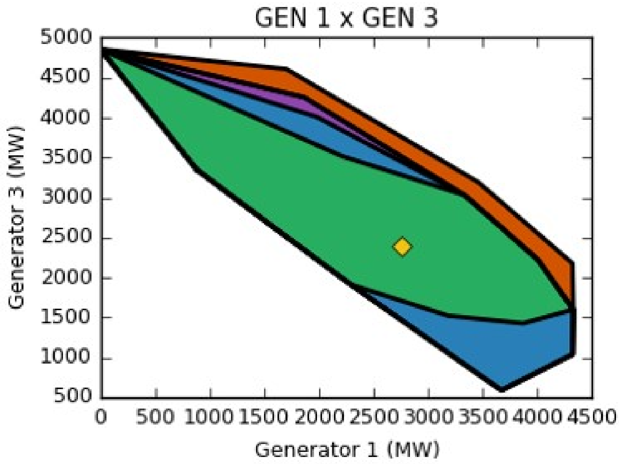


Figure 6.12: Gen 1 x Gen 3 nomogram for contingency situations using DPSE.

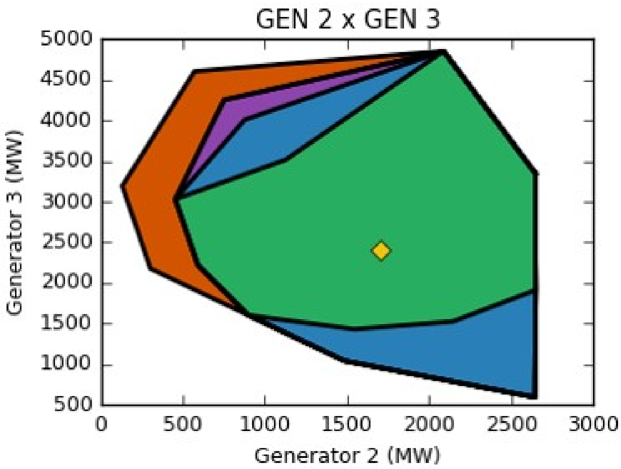


Figure 6.13: Gen 2 x Gen 3 nomogram for contingency situations using DPSE.

Small-signal security regions can be obtained through DNM, which can be observed using a set of nomograms. The distance of actual operating point (yellow dot) to the security borders can be determined.

The influence of contingencies and power plant dispatches in mode damping factors and security regions can be observed.

SAGE system presents 628 state variables and 129 scenarios were evaluated in these tests. The QR method [52, 53] was monitoring all oscillation modes and DPSE method [54] was monitoring only 8 modes.

The processing time was around 5 minutes for DNM by QR method [52, 53] and 2 minutes for DNM by DPSE method [54], using a processor Intel (R) Core (TM) i7-3537U CPU @ 2.00 GHz.

A comparison between the DNM results obtained through both eigensolutions can be made, which is presented in figure 6.14.

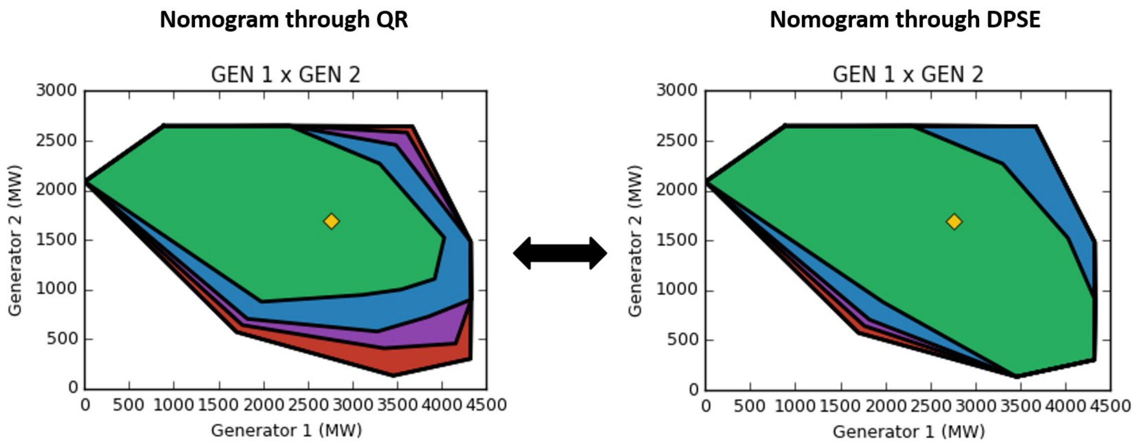


Figure 6.14: Comparison of nomograms obtained through QR and DPSE methods.

The results obtained through QR [52, 53] and DPSE [54] are different, because all modes are calculated in DNM by QR (full eigensolution), but only a mode set is determined in DNM by DPSE (partial eigensolution).

DNM by DPSE is faster than DNM by QR, but it loses some information about mode damping factor when monitoring only a set of oscillation modes. In this case, the inter-area oscillation modes should be chosen for monitoring, due to their importance to power systems.

The DNM by QR method should not be used for evaluating large-scale power system. The processing time would be very large, so its use would not be feasible. In this case, DNM by DPSE method is recommended.

Small-signal stability margins and corrective measures for power systems can be determined through using the damping nomogram method, in order to improve their planning and operation.

These corrective measures can be related to power plant redispatches and control system tuning, as represented in figures 6.15 and 6.16.

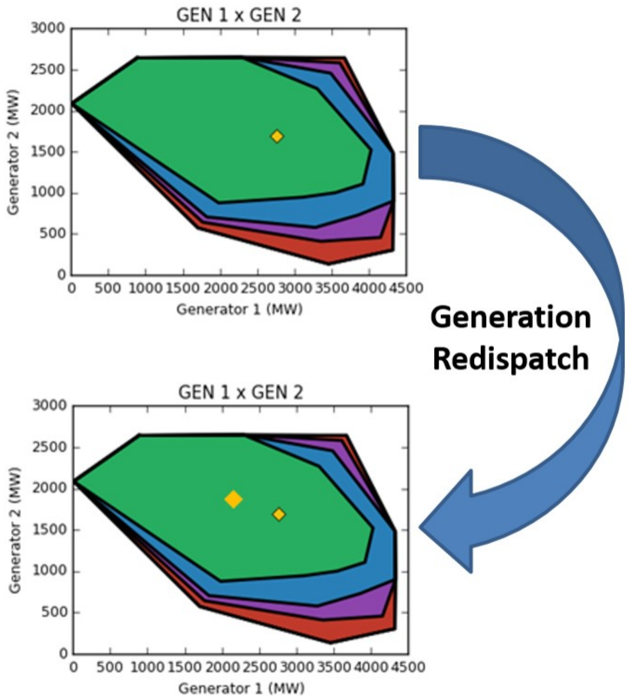


Figure 6.15: Corrective measure through power plant redispatch.

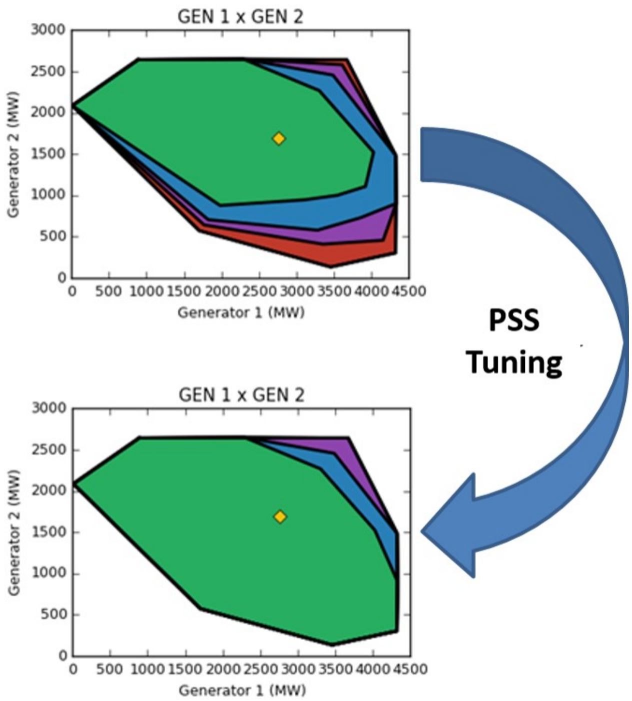


Figure 6.16: Corrective measure through PSS tuning.

Power plant redispatches could be made, in order to change the system operating point to a better scenario, as presented in 6.15, where the small yellow dot is the initial scenario and big yellow dot is the new operating point.

A control system tuning could also be made, in order to improve system security levels, as presented in 6.16, where the secure regions (green and blue) of the nomogram become bigger after a PSS tuning.

## 6.2 Two Areas System Results

On-line monitoring of oscillation (OLMO), generation sensitivity calculation and CSBGRES method were tested in Two area system (appendix B), containing about 11 buses and 4 machines [4, 57].

Figure 6.17 presents the single-line diagram of Two areas system, showing interconnections between two electrical areas. The area 1 has the power plants of buses 1 and 2, while, area 2 has the power plants of buses 3 and 4.

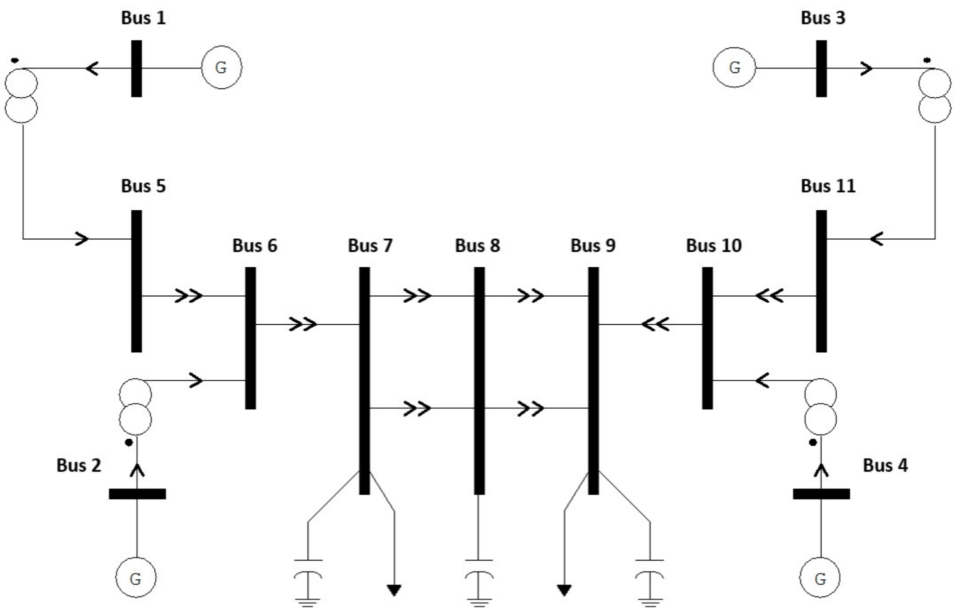


Figure 6.17: Two areas system single-line diagram.

The system was presenting a base case with the following characteristics:

• Power plant dispatch and terminal voltage at bus 1 = 700 MW and 1.03 pu;

• Power plant dispatch and terminal voltage at bus 2 = 450 MW and 1.05 pu;

• Power plant dispatch and terminal voltage at bus 3 = 533 MW and 1.03 pu;

• Power plant dispatch and terminal voltage at bus 4 = 150 MW and 1.01 pu;

• Load at bus 7 = 600 MW;

• Load at bus 9 = 1167 MW.

The electromechanical oscillation mode $-0.2493 + j3.9152$ was monitored, which presents damping factor of 6.35% and frequency of 3.9152 rad/s.

OLMO was executed and several events were applied in electrical grid, aiming to test the on-line monitoring of oscillations tool.

These events are described following:

1°) Modification in load at bus 9 to 1150 MW and dispatch at bus 3 to 515 MW, applied at 15.643 hours;

2°) Modification in dispatch at bus 1 to 690 MW and bus 3 to 523 MW, applied at 15.656 hours;

3°) Modification in dispatch at bus 1 to 680 MW and bus 3 to 532 MW, applied at 15.679 hours;

4°) Modification in terminal voltage at bus 2 to 1.03 pu and bus 4 to 1.03 pu, applied at 15.710 hours;

5°) Modification in load at bus 7 to 610 MW, dispatch at bus 1 to 690 MW and bus 3 to 533 MW, applied at 15.760 hours;

6°) Modification in load at bus 7 to 620 MW and dispatch at bus 3 to 543 MW, applied at 15.796 hours;

7°) Modification in terminal voltage at bus 1 to 1.04 pu and bus 3 to 1.04 pu, applied at 15.841 hours;

8°) Modification in load at bus 7 to 610 MW and dispatch at bus 3 to 533 MW, applied at 15.903 hours;

9°) Modification in load at bus 7 to 600 MW and dispatch at bus 3 to 523 MW, applied at 15.965 hours.

Figure 6.18 presents the mode frequency results obtained through the OLMO.

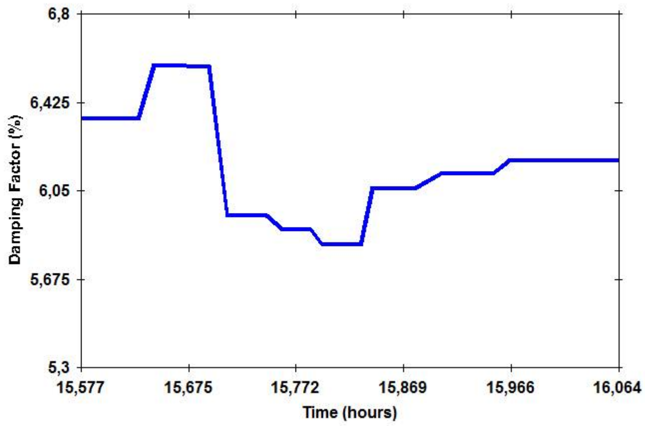


Figure 6.18: Mode damping factor timeline for Two areas system.

Figure 6.19 presents the mode damping factor results obtained through the OLMO.

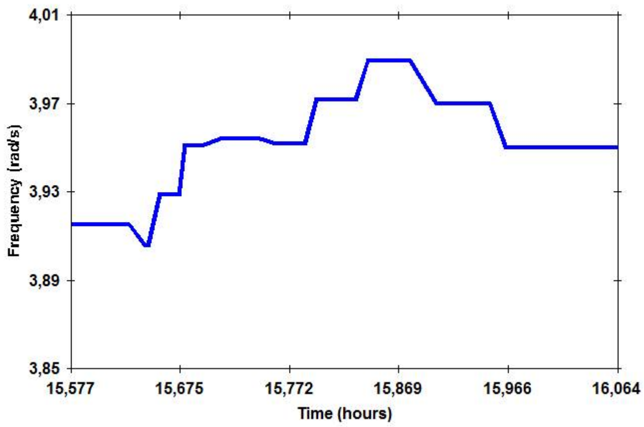


Figure 6.19: Mode frequency timeline for Two areas system.

The mode dynamic behavior can be observed in the results of the on-line monitoring of oscillations. If a problem is seen during OLMO, corrective measures should be used to improve system operation, through increasing mode damping factor.

Generation sensitivities were calculated for mode $-0.2493 + j3.9152$ and the results are presented in figure 6.20 and table 6.1.

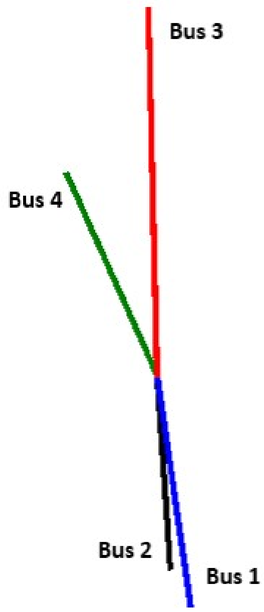


Figure 6.20: Normalized generation sensitivity phasors for Two areas system.

Table 6.1: Normalized generation sensitivity list for Two areas system.

| Generator | Module | Phase |
|---|---|---|
| Bus 3 | 1.0000 | 91.3540 |
| Bus 1 | 0.6340 | -81.8740 |
| Bus 4 | 0.6002 | 114.0800 |
| Bus 2 | 0.5273 | -86.1590 |

Two areas system presents 28 state variables in this test. The processing time for generation sensitivity calculation was around 1 second, using a processor Intel (R) Core (TM) i7-3537U CPU @ 2.00 GHz.

The CSBGRES method was used, in order to obtain a system security margins, through determining a minimum redispatch for all power plants capable of decreasing the mode damping factor from 6.35% to 5%.

Figure 6.21 and table 6.2 present the CSBGRES results for this case.

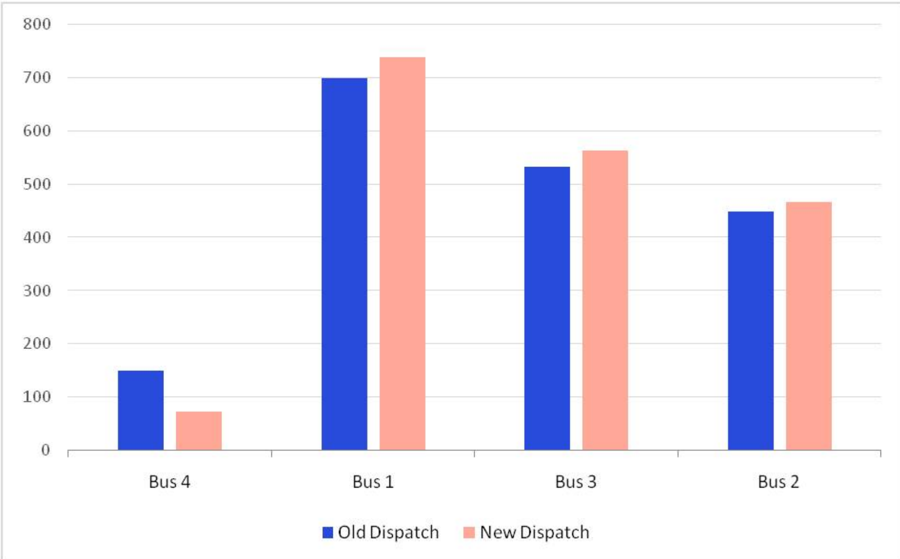


Figure 6.21: CSBGRES histogram (MW) to reach 5% of damping factor in Two areas system.

Table 6.2: CSBGRES redispatches (MW) to reach 5% of damping factor in Two areas system.

| Generator | Old dispatch | New dispatch | Variation |
|---|---|---|---|
| Bus 4 | 150.0000 | 73.9690 | -76.0310 |
| Bus 1 | 700.0000 | 738.9400 | 38.9400 |
| Bus 3 | 532.8000 | 563.9000 | 31.1000 |
| Bus 2 | 450.0000 | 467.6300 | 17.6300 |

Then, CSBGRES method was used, in order to obtain a corrective measure for the system, through determining a minimum redispatch for all power plants capable of increasing the mode damping factor from 6.35% to 8%.

Figure 6.22 and table 6.3 present the CSBGRES results for this other case.

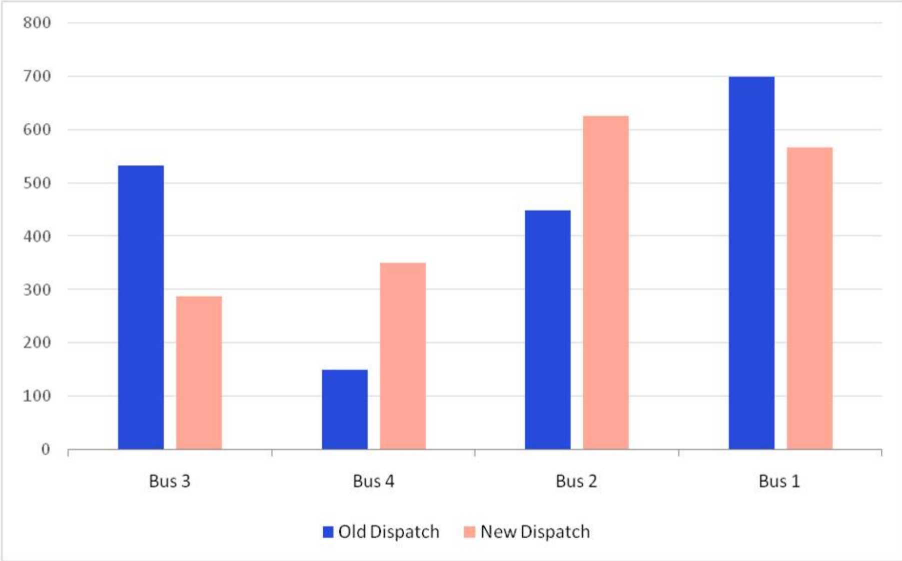


Figure 6.22: CSBGRES histogram (MW) to reach 8% of damping factor in Two areas system.

Table 6.3: CSBGRES redispatches (MW) to reach 8% of damping factor in Two areas system.

| Generator | Old dispatch | New dispatch | Variation |
|---|---|---|---|
| Bus 3 | 532.8000 | 288.3500 | -244.4500 |
| Bus 4 | 150.0000 | 350.0000 | 200.0000 |
| Bus 2 | 450.0000 | 625.8600 | 175.8600 |
| Bus 1 | 700.0000 | 566.4600 | -133.5400 |

The first CSBGRES application consists of determining security margins, obtaining the maximum power plant redispatches that can be used before the system presents oscillation problems.

In this case, the damping factor was decreased to 5% and mode $-0.1926 + j3.8090$ was obtained in 3 iterations, which presents 5.0495% of damping factor.

The second CSBGRES application consists of determining corrective measures, obtaining the minimum power plant redispatches that must be used to improve system dynamic behavior.

In this case, the damping factor was increased to 8% and mode $-0.2986 + j3.7527$ was obtained in 9 iterations, which presents 7.9311% of damping factor.

The CSBGRES results were tested and validated. The obtained modes does not have exact desired damping factor, because method tolerance is 0.1% and is used in damping factor converge verification.

The processing time for these CSBGRES applications to reach damping factors of 5% and of 8% were, respectively, around 1 second and around 2 seconds, using a processor Intel (R) Core (TM) i7-3537U CPU @ 2.00 GHz.

## 6.3 Brazilian Power System Results

Generation sensitivity calculation and CSBGRES method were tested in Brazilian power system (appendix C), using planning study data base of 2020 [58].

Figure 6.23 presents the single-line diagram of Brazilian power system [59].

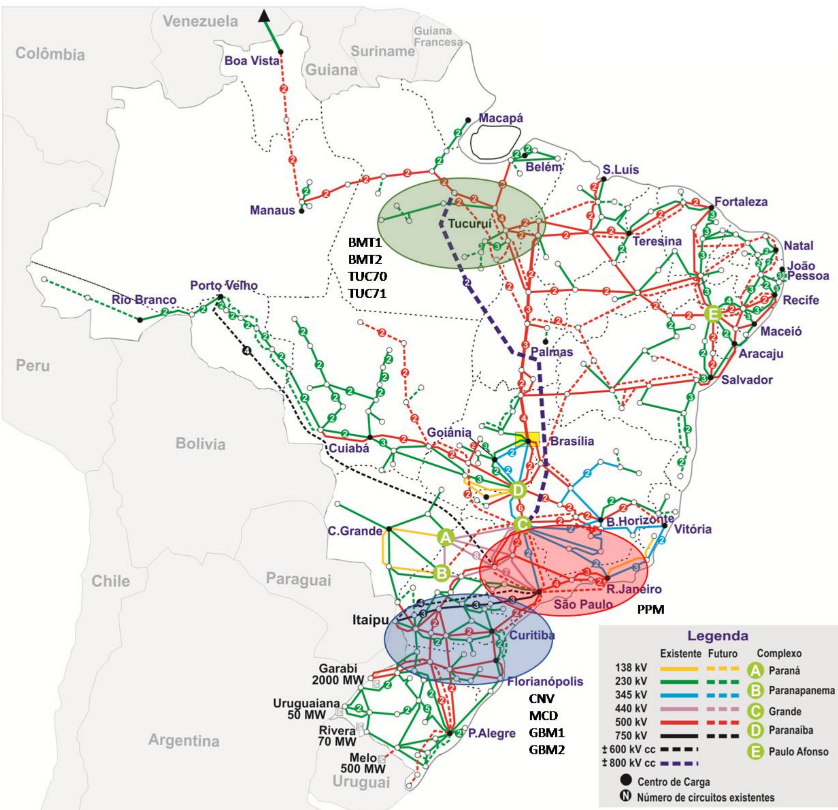


Figure 6.23: Brazilian power system single-line diagram.

Campos Novos (CNV), Machadinho (MCD), Governador Bento Munhoz (GBM1 and GBM2), Porto Primavera (PPM), Tucuruí (TUC70 and TUC71) and Belo Monte (BMT1 and BMT2) power plants are highlighted in figure 6.23, because they will be used to test the CSBGRES method.

The electromechanical oscillation mode $-0.0527 + j2.5482$, with 2% of damping factor, was obtained through using QR method [52, 53]. This mode represents the natural oscillation between North and South regions of Brazilian system.

CSBGRES method will be used to increase damping factor of this mode, but, first, the generation sensitivities must be utilized to select the better power plants for redispatch. The main results are presented in figure 6.24 and table 6.4.

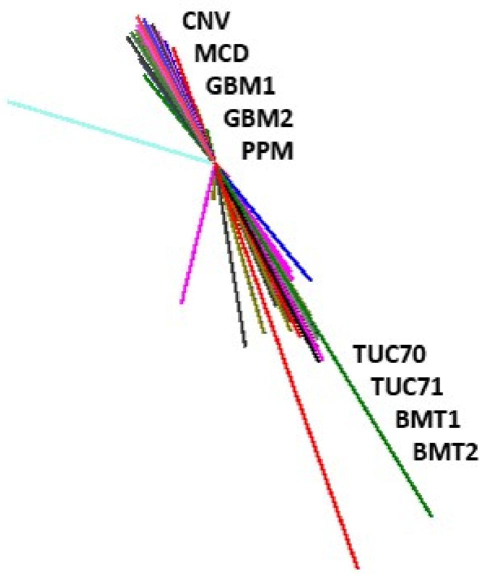


Figure 6.24: Normalized generation sensitivity phasors for Brazilian power system.

Table 6.4: Normalized generation sensitivity list for
Brazilian power system.

| **Generator** | **Module** | **Phase** |
|---|---|---|
| TUC71 | 0.4577 | -60.6150 |
| TUC70 | 0.4516 | -60.6970 |
| BMT1 | 0.4490 | -62.9370 |
| BMT2 | 0.4249 | -62.9080 |
| CNV | 0.3593 | 116.4900 |
| MCD | 0.3464 | 118.7500 |
| GBM1 | 0.3455 | 122.1100 |
| PPM | 0.3438 | 119.3800 |
| GBM2 | 0.3384 | 121.8600 |

CNV, MCD, GBM1, GBM2, PPM, TUC70, TUC71, BMT1 and BMT2 are highlighted in the results, again, because they are the largest power plants with the highest generation sensitivities.

These machines were selected to be used in CSBGRES method, through evaluating their generation sensitivities in comparison with the other plants.

Brazilian power system presents 7868 state variables in this test. The processing time for generation sensitivity calculation was around 18 minutes, using a processor Intel (R) Core (TM) i7-3537U CPU @ 2.00 GHz.

The CSBGRES method was used, in order to obtain a corrective measure for the system, through determining a minimum redispatch for selected power plants capable of increasing the mode damping factor from 2% to 5%.

Figure 6.25 and table 6.5 present the CSBGRES results for redispatch the power plants of interest in this case.

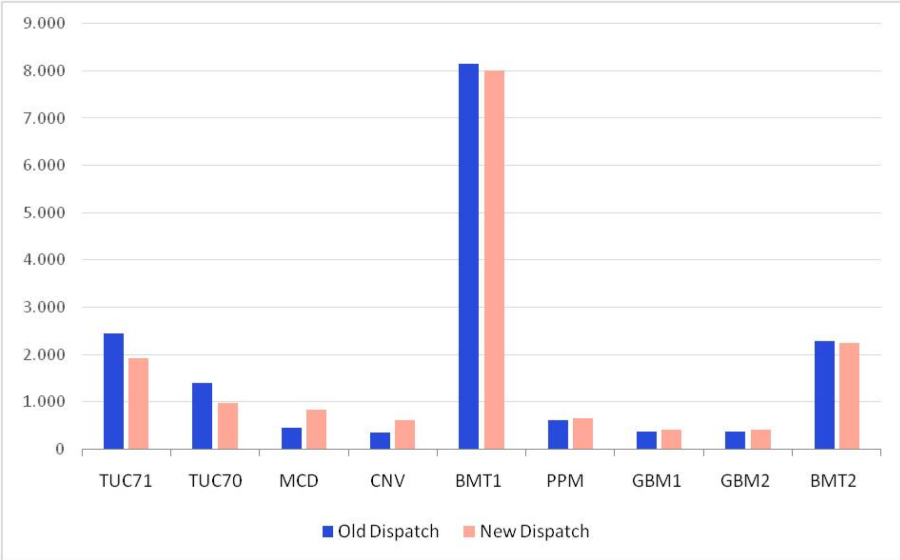


Figure 6.25: CSBGRES histogram (MW) to reach 5% of damping factor in Brazilian power system.

Table 6.5: CSBGRES redispatches (MW) to reach 5% of damping factor in Brazilian power system.

| Generator | Old dispatch | New dispatch | Variation |
|---|---|---|---|
| TUC71 | 2460.0000 | 1930.7000 | -529.3000 |
| TUC70 | 1406.0000 | 987.1400 | -418.8600 |
| MCD | 468.5000 | 837.0000 | 368.5000 |
| CNV | 364.2000 | 622.0000 | 257.8000 |
| BMT1 | 8151.0000 | 8014.5000 | -136.5000 |
| PPM | 616.0000 | 672.0000 | 56.0000 |
| GBM1 | 376.6500 | 419.0000 | 42.3500 |
| GBM2 | 376.6500 | 419.0000 | 42.3500 |
| BMT2 | 2299.0000 | 2260.5000 | -38.5000 |

Loss variation was -356.16 MW and was considered in the redispatches of selected power plants. The system losses decreased, because the new dispacthes are relieving the North-South interconnection.

The CSBGRES results show redispatches needed to achieve the damping factor of 5% for the North-South oscillation mode. The mode $-0.1351+j2.6886$ was obtained in 16 iterations, which presents 5.0186% of damping factor.

The processing time for the CSBGRES execution was around 1 minute, using a processor Intel (R) Core (TM) i7-3537U CPU @ 2.00 GHz.

## 6.4 Nordic 44 System Results

Generation sensitivity calculation, CSBGRES method and OLMO were tested, again, in a Nordic equivalent system, called Nordic 44 (appendix D), containing about 44 buses and 18 machines [60].

Figure 6.26 presents the single-line diagram of Nordic 44 system [60], showing interconnections between Norway, Sweden and Finland.

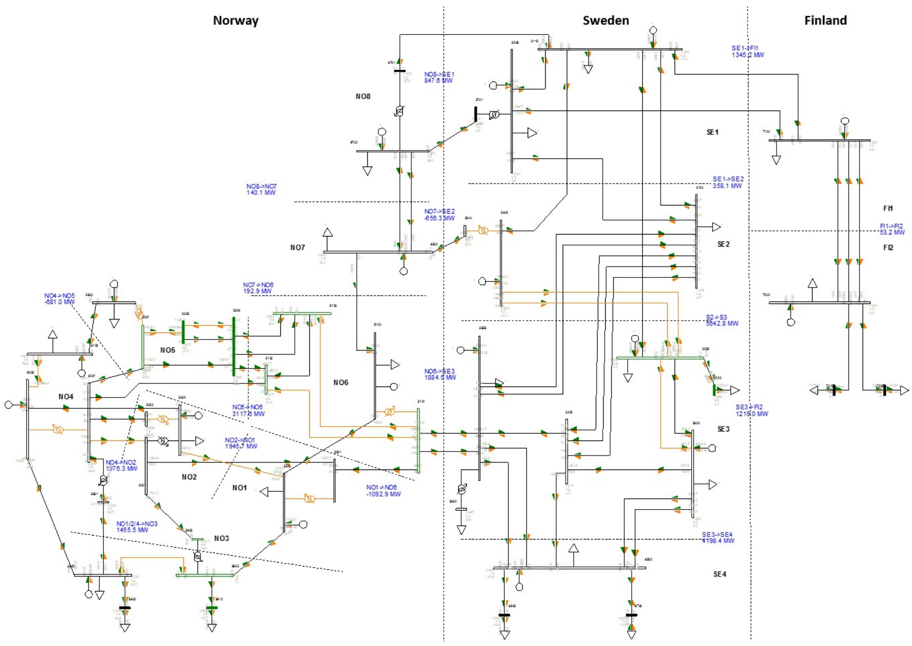


Figure 6.26: Nordic 44 system single-line diagram.

The generation sensitivities were calculated for the inter-area oscillation mode $-0.1021+j2.0400$, which is the lower damped mode of the system. These results are presented in figure 6.27 and table 6.6.

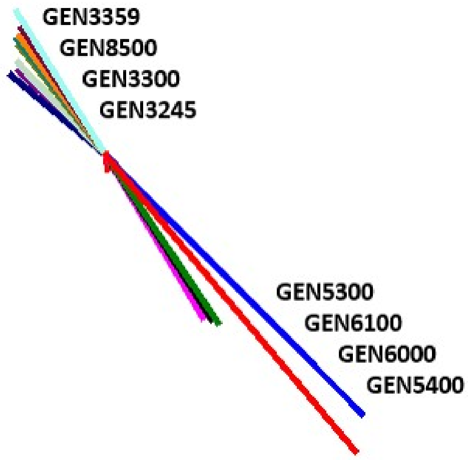


Figure 6.27: Normalized generation sensitivity phasors for Nordic 44 system.

Table 6.6: Normalized generation sensitivity list for Nordic 44 system.

| Generator | Module | Phase |
|---|---|---|
| GEN5300 | 1.0000 | -49.9100 |
| GEN6100 | 0.9383 | -45.2760 |
| GEN6000 | 0.5193 | -56.2070 |
| GEN5400 | 0.5035 | -57.3040 |
| GEN5600 | 0.4871 | -59.1980 |
| GEN3359 | 0.4369 | 121.8500 |
| GEN8500 | 0.3930 | 123.6100 |
| GEN3300 | 0.3791 | 126.0500 |
| GEN3245 | 0.3769 | 127.4300 |
| GEN6500 | 0.3595 | 128.5700 |
| GEN3000 | 0.3546 | 127.0900 |
| GEN6700 | 0.3290 | 133.4300 |
| GEN7000 | 0.3206 | 139.8100 |
| GEN3115 | 0.3189 | 133.9300 |
| GEN3249 | 0.3136 | 135.7000 |
| GEN7100 | 0.2993 | 137.6200 |
| GEN5100 | 0.1595 | 126.5700 |
| GEN5500 | 0.0354 | -83.7440 |

These results show the mode displacement trend in complex plane in function of power plant dispatches.

Nordic 44 system presents 224 state variables in this test. The processing time for generation sensitivity calculation was around 3 seconds, using a processor Intel (R) Core (TM) i7-3537U CPU @ 2.00 GHz.

The CSBGRES method was used, in order to obtain a corrective measure for the system, through determining a minimum redispatch for all power plants capable of increasing the mode damping factor from 5% to 8%.

Figure 6.28 and table 6.7 present the CSBGRES results for redispatch all system power plants in this case.

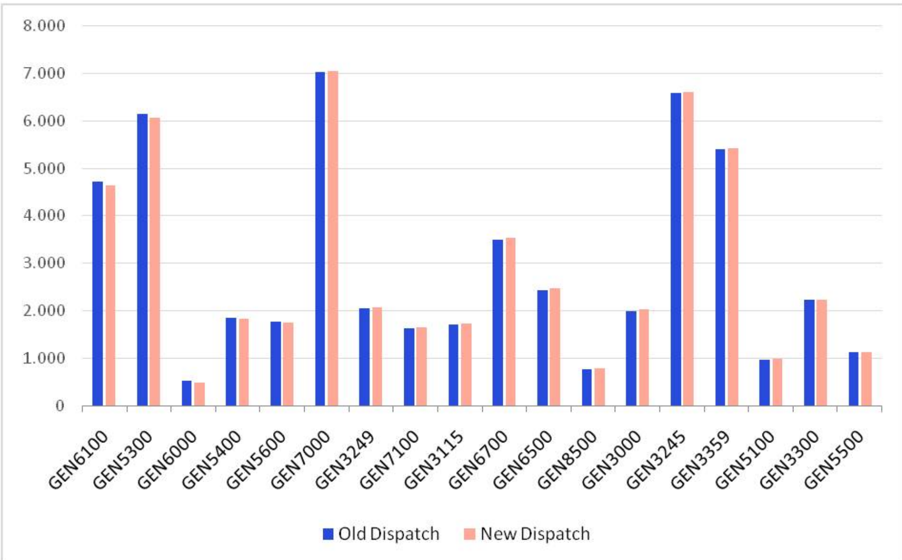


Figure 6.28: CSBGRES histogram (MW) to reach 8% of damping factor in Nordic 44 system.

Table 6.7: CSBGRES redispatches (MW) to reach 8% of damping factor in Nordic 44 system.

| Generator | Old dispatch | New dispatch | Variation |
|---|---|---|---|
| GEN6100 | 4730.0000 | 4638.0000 | -92.0000 |
| GEN5300 | 6151.0000 | 6062.0000 | -89.0000 |
| GEN6000 | 523.0000 | 483.2200 | -39.7800 |
| GEN5400 | 1858.0000 | 1819.9000 | -38.1000 |
| GEN5600 | 1774.0000 | 1738.7000 | -35.3000 |
| GEN7000 | 7038.0000 | 7063.8000 | 25.8000 |
| GEN3249 | 2048.0000 | 2073.1000 | 25.1000 |
| GEN7100 | 1620.0000 | 1645.0000 | 25.0000 |
| GEN3115 | 1700.0000 | 1724.7000 | 24.7000 |
| GEN6700 | 3506.0000 | 3530.5000 | 24.5000 |
| GEN6500 | 2442.0000 | 2466.1000 | 24.1000 |
| GEN8500 | 754.0000 | 777.3700 | 23.3700 |
| GEN3000 | 2000.0000 | 2022.9000 | 22.9000 |
| GEN3245 | 6599.0000 | 6621.8000 | 22.8000 |
| GEN3359 | 5400.0000 | 5422.7000 | 22.7000 |
| GEN5100 | 972.0000 | 980.2500 | 8.2500 |
| GEN3300 | 2223.9000 | 2232.0000 | 8.1000 |
| GEN5500 | 1132.0000 | 1128.0000 | -4.0000 |

The CSBGRES results show redispatches needed to achieve the damping factor of 8% for the inter-area oscillation mode. The mode $-0.1690 + j2.1233$ was obtained in 7 iterations, which presents 7.9359% of damping factor.

The processing time for the CSBGRES execution was around 4 seconds, using a processor Intel (R) Core (TM) i7-3537U CPU @ 2.00 GHz.

Then, the on-line monitoring of oscillations tool was tested in the Nordic 44 system. The CSBGRES method was used to keep the system modes with, at least, 5% of minimum damping factor, during the OLMO execution.

The inter-area oscillation modes $-0.3750 + j3.7519$, with 10% of damping factor, and $-0.1021 + j2.0400$, with 5% of damping factor, obtained in first operating point, were monitored in the OLMO.

Real Nordic electrical system measurement data were utilized to create several operation scenarios for Nordic 44 system.

These scenarios were being sent to software PacDyn [8], during the OLMO execution, in a regular time interval, to simulate a system real-time operation.

Figure 6.29 presents mode damping factor timelines obtained through OLMO.

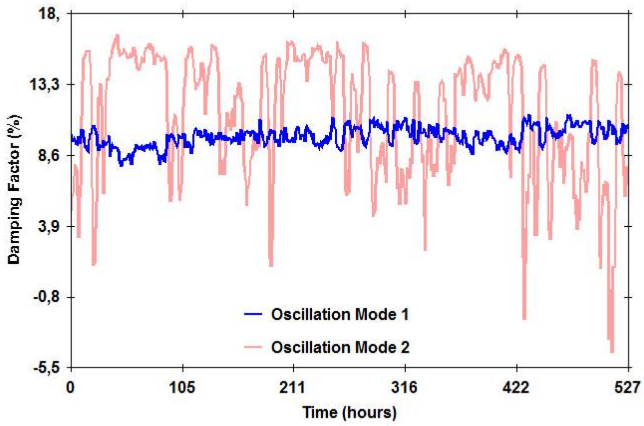


Figure 6.29: Mode damping factor timelines for Nordic 44 system.

Figure 6.30 presents mode frequency timelines obtained through OLMO.

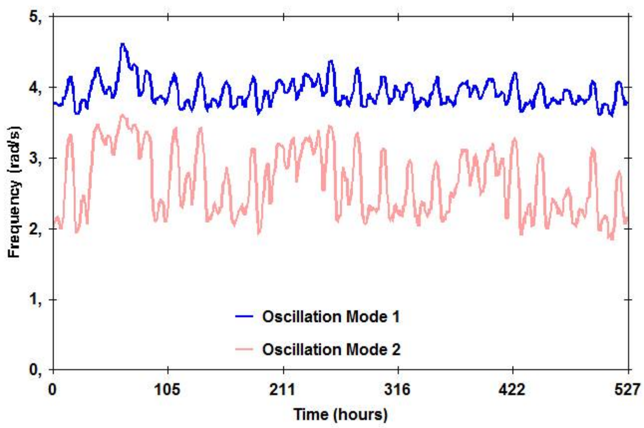


Figure 6.30: Mode frequency timelines for Nordic 44 system.

System oscillation mode 2 presented undesired damping factors (lower than the desired value of 5%) in some operating points.

The CSBGRES method can be used to solve this oscillation problem, determining a minimum redispatch for the power system, so mode 2 can present 5% of damping factor in the critical scenarios.

Figure 6.31 presents mode damping factor timelines obtained through OLMO.

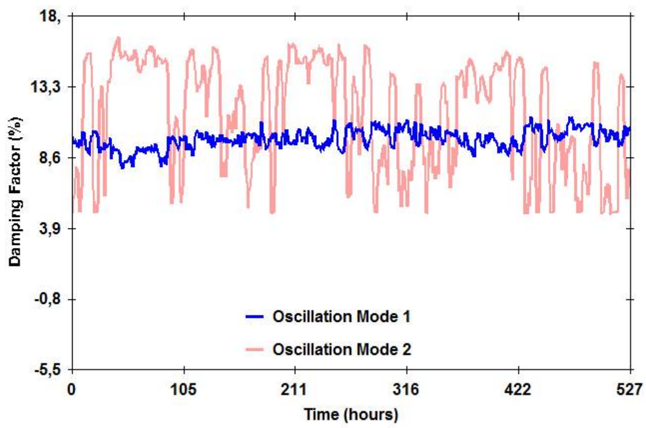


Figure 6.31: Mode damping factor timelines for Nordic 44 system, using CSBGRES method.

Figure 6.32 presents mode frequency timelines obtained through OLMO.

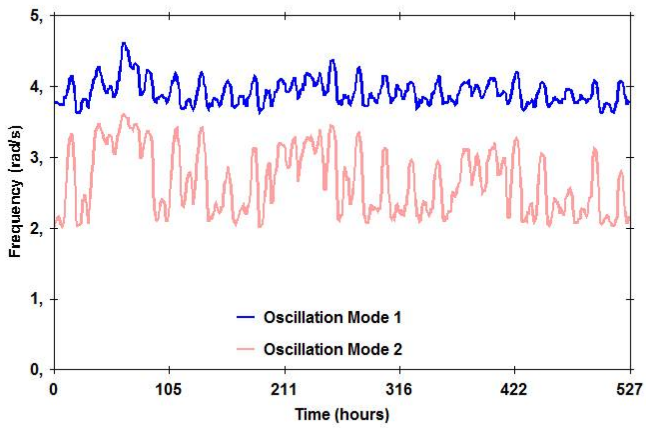


Figure 6.32: Mode frequency timelines for Nordic 44 system, using CSBGRES method.

A comparison between original and CSBGRES results for mode 2, during the OLMO execution, is presented in 6.33.

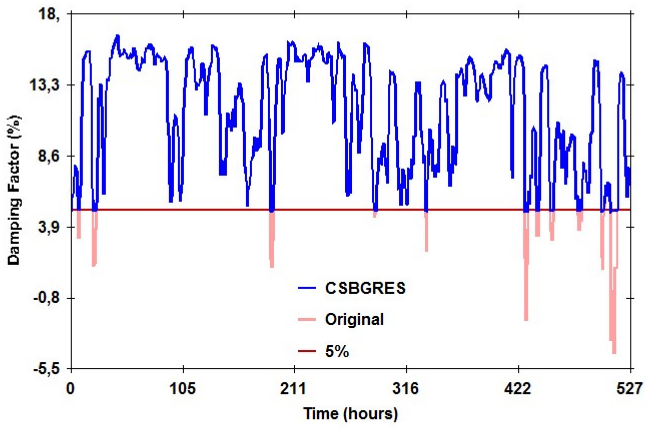


Figure 6.33: OLMO results with and without utilization of CSBGRES method.

Power plant redispatches determined through CSBGRES method was able to solve the problem observed in the OLMO, keeping the system oscillation modes with, at least, 5% of damping factor, during all the monitoring.

The worst scenario obtained in the OLMO presented -4.5% of damping factor for oscillation mode 2. The CSBGRES results for this operating point can be observed in figure 6.34 and table 6.8.

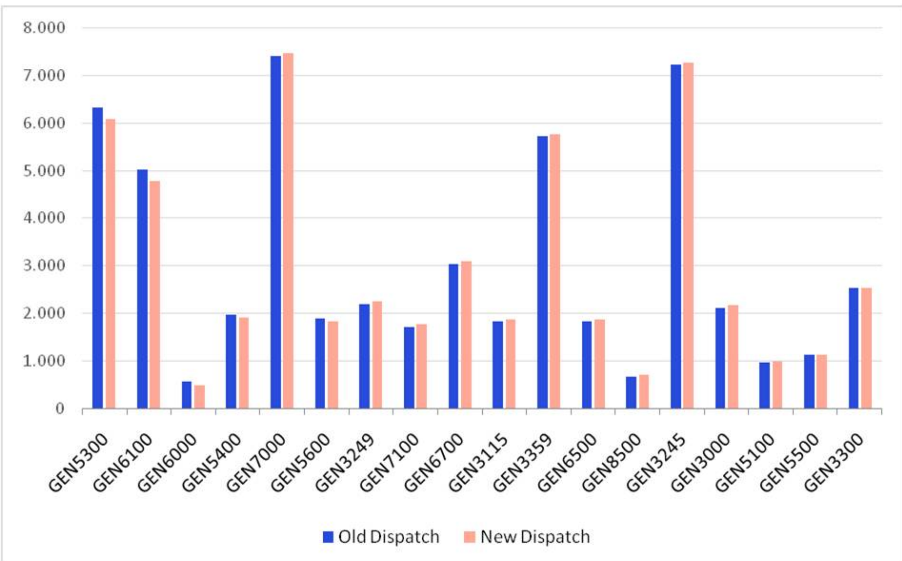


Figure 6.34: CSBGRES histogram (MW) to reach 5% of damping factor in Nordic 44 system in worst scenario.

Table 6.8: CSBGRES redispatches (MW) to reach 5% of damping factor in Nordic 44 system in worst scenario.

| Generator | Old dispatch | New dispatch | Variation |
|---|---|---|---|
| GEN5300 | 6326.0000 | 6081.2000 | -244.8000 |
| GEN6100 | 5022.3000 | 4785.4000 | -236.9000 |
| GEN6000 | 555.3200 | 486.1900 | -69.1300 |
| GEN5400 | 1972.8000 | 1907.9000 | -64.9000 |
| GEN7000 | 7416.8000 | 7472.7000 | 55.9000 |
| GEN5600 | 1883.6000 | 1828.1000 | -55.5000 |
| GEN3249 | 2196.6000 | 2249.9000 | 53.3000 |
| GEN7100 | 1707.2000 | 1760.2000 | 53.0000 |
| GEN6700 | 3034.0000 | 3086.7000 | 52.7000 |
| GEN3115 | 1823.4000 | 1875.9000 | 52.5000 |
| GEN3359 | 5722.1000 | 5774.3000 | 52.2000 |
| GEN6500 | 1827.3000 | 1878.7000 | 51.4000 |
| GEN8500 | 661.0000 | 711.5100 | 50.5100 |
| GEN3245 | 7229.0000 | 7278.3000 | 49.3000 |
| GEN3000 | 2119.3000 | 2168.1000 | 48.8000 |
| GEN5100 | 961.8400 | 993.8700 | 32.0300 |
| GEN5500 | 1120.2000 | 1129.2000 | 9.0000 |
| GEN3300 | 2537.7000 | 2537.7000 | 0.0000 |

Small redispatches were capable of modifying considerably the damping factor of the mode of interest. The largest dispatch variation obtained through CSBGRES method was, approximately, 250 MW for power plant GEN5300.

This plant was dispatching 6000 MW. Thus, 250 MW is a reasonable and feasible value for the redispatch of this specific machine.

The CSBGRES results show redispatches needed to achieve the damping factor of 5% for the mode 2. The mode $-0.1005 + j2.0300$ was obtained in 19 iterations, which presents 4.9436% of damping factor.

The processing time for this CSBGRES execution was around 7 seconds, using a processor Intel (R) Core (TM) i7-3537U CPU @ 2.00 GHz.

## 6.5 Final Considerations

SAGE system was used to test the damping nomogram method, which was able to determine the small-signal security regions.

Two areas system was utilized to test the on-line monitoring of oscillations, generation sensitivity calculation and CSBGRES method.

Brazilian power system was used to test the generation sensitivity calculation and CSBGRES method in a large-scale power system.

Nordic 44 system was utilized to test the generation sensitivity calculation and CSBGRES method during an OLMO execution.

The results obtained in this chapter evidence benefits brought by the methods developed in this thesis for power system analysis.

# Chapter 7

# Conclusion

This chapter will review the main topics covered by this thesis, which are related to power systems security assessment, focusing on SSA. Conclusions will be made, in order to show the benefits brought by the application of the methods proposed in this work for power system analyses.

## 7.1 Considerations

Power flow, fault and electromechanical stability analyses should be done for power system planning and operation and were described in chapter 1.

The research motivations and thesis contributions were presented. This work focused on SSA and development of CSBGRES method.

The thesis structure with chapter descriptions and lists of produced papers were also presented, finishing chapter 1.

Power system electromechanical stability was described in chapter 2. The transient and small-signal stability analyses were reviewed.

Then, modal analysis principles were presented, including the concepts of eigenvalues, eigenvectors, participation factors, mode shapes, controlability, observability and transfer functions residues.

Control system design was discussed, including a methodology for control tuning based on Nyquist diagrams, finishing chapter 2.

Power system security assessment state of art was described in chapter 3, including a VSA, TSA and SSA literature review.

Critical contingencies and several scenarios should be evaluated in the determination of power system security margins.

Chapter 3 is finished with a discussion about SDSA results, which can be observed through security indexes or nomograms.

The main concepts of voltage, transient and small-signal security assessment were described in chapter 4, focusing on SSA.

Damping nomogram method (DNM), root-locus method (RLM) and on-line monitoring of oscillations (OLMO) were proposed for SSA execution.

The computational implementations of DNM and OLMO in software PacDyn [8], from CEPEL, were presented, finishing chapter 4.

Hopf bifurcation analysis and the closest security boundary in control parameter space algorithm were reviewed in chapter 5.

A generation sensitivity calculation was developed. These sensitivities show mode displacement trend in complex plane in function of power plant dispatches.

The CSBGRES method was presented, which can be used to obtain minimum redispatch considering a damping factor criteria, finishing chapter 5.

In chapter 6, four systems were used to test the proposed methods: SAGE system, Two areas system, Brazilian power system and Nordic 44 system.

The results obtained in these tests evidence the benefits brought by the methods developed in this thesis for power system analysis.

## 7.2 Conclusions

The damping nomogram method (DNM), root-locus method (RLM) and on-line monitoring of oscillations (OLMO) were developed in this work for small-signal security assessment (SSA) of power systems.

A numerical generation sensitivity calculation and the CSBGRES method were developed and presented in this thesis.

This method can be used for determining minimum redispatch for power systems, considering a desired damping factor for oscillation modes.

The main innovations and contributions of this thesis are:

- Damping nomogram method development, which can be used to determine small-signal security regions;

- On-line monitoring of oscillations development, which can be utilized to monitor small-signal stability;

- Numerical generation sensitivity calculation, which can be used to select power plants for being utilized in the CSBGRES method;

- CSBGRES method development, which can be used to determine a minimum redispatch for electrical power systems capable of making a oscillation mode presents a desired damping factor.

Small-signal stability margins and security levels can be determined through using the methods proposed in this work, which facilitate the determination of corrective measures to improve power system dynamic behavior.

Corrective measures can be related to control system tuning or power plant redispatch. This last can be obtained through using the CSBGRES method, which was developed in this thesis.

Concluding, the methods and methodologies proposed in this work and implemented in software PacDyn [8] contribute greatly to small-signal security assessment of power systems, enabling a better planning and operation.

## 7.3 Future Works

The following future works can be proposed:

• Improvement of the methods proposed in this work, through using parallel processing and other techniques, in order to increase algorithm efficiency;

• Development of CSBGRES method extension, in order to consider loading limits for the equipment of power systems;

• Development of methods based on CSBGRES algorithm, considering variation of other power flow parameters, such as terminal voltages or bus loads.

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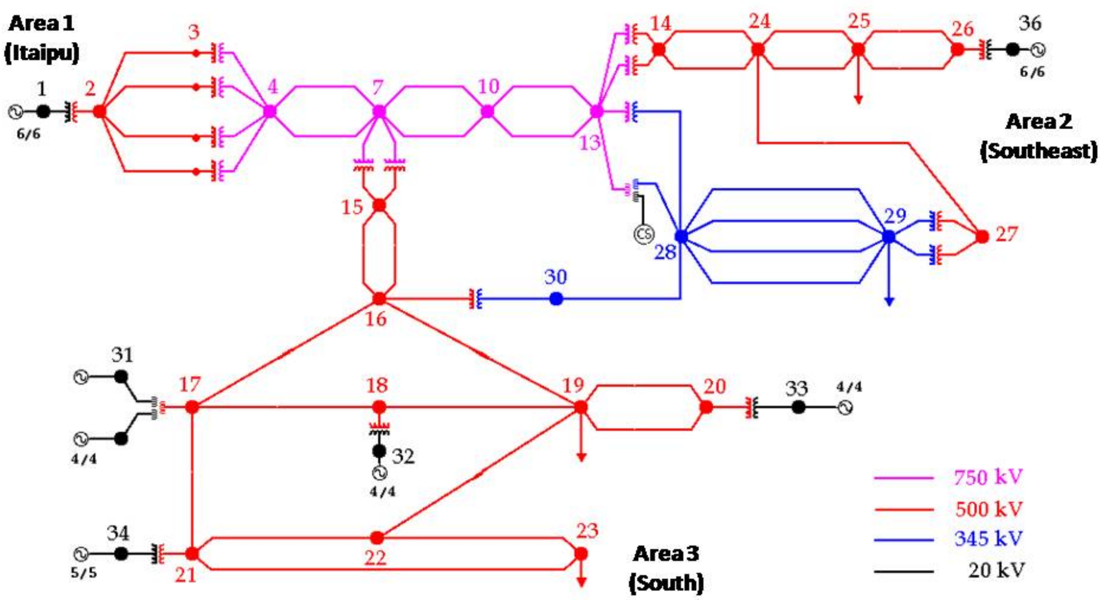
# Appendix A

# SAGE System



# A.1 Power Flow Data File

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99999
DCTE
BASE   100. DASE   100. TEPA    .01 EXST     .4 TETP     5. TBPA     5.
TLPP     1. TEPR    .01 QLST     .4 TLPR     1. TLPQ     2. TSBZ    .01
TSBA     5. ASTP    .05 VSTP     5. TLVC     .5 TLTC    .01 TSFR  .1E-7
ZMAX   500. TLPV     .5 VDVM   200. VDVN    40. TUDC   .001 TADC    .01
PGER    30. TPST     .2 VFLD    70. ZMIN   .001 HIST    470 LFIT     10
ACIT    200 LFCV      1 DCIT     10 VSIT     10 LPIT     50 LFLP     10
PDIT     10 LCRT     96 LPRT     60 CSTP     5. ASDC     1.
ICIT   9000 DMAX      5 FDIV     2. ICMN     .1 VART     5. TSTP     33
ICMV     .5 APAS    90. CPAR    70. VAVT     2. VAVF     5. VMVF    15.
VPVT     2. VPVF     5. VPMF    10. VSVF    20. VINF     1. VSUP     1.
TLSI     0. NDIR    10. STTR     1. TRPT   100. STIR    10. BFPO     1.
99999
DBAR
    1 L2G1EST01A       1 992  0.457.816.99-727.441.6                       1 992
    2 L1G1EST01B       1 992.019 460.17.13-727.441.6                       1 992
    3 L1G1EST01C       1 992.019 460.17.13-727.441.6                       1 992
    4 L1G1EST01D       1 992.019 460.17.13-727.441.6                       1 992
    5 L1G1EST01E       1 992.019 460.17.13-727.441.6                       1 992
    6 L2G1EST01F       1 992  0.457.716.98-727.441.6                       1 992
    7 L1G2EST02A       11086-3.8   0.42.67   0.   0.                       11086
    8 L G2EST03A       11086-3.9                                           11086
    9 L G2EST03B       11086-3.9                                           11086
   10 L G2EST03C       11086-3.9                                           11086
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   14 L G3EST10A       11063-23.                                           11062
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   16 L G2EST14A       11069-38.                                           11069
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   18 L G2EST16A       11071-11.                                           31070
   19 L G2EST17A       110332.43                 -757.197.6       31032
   20 L G2EST18A       110322.41                                           31031
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   34 L1G1EST31B       110314.41 80.5-5.08-379.210.2                       31031
   35 L1G1EST31C       110274.41 80.5-12.4-377.210.8                       31027
   36 L1G1EST31D       110254.41 80.5-18.3-325.183.7                       31025
   37 L1G1EST32A       110167.35 212.-58.8-334.186.1                       31016
   38 L1G1EST32B       110287.29 212.-32.3-189.118.2                       31028
   39 L1G1EST32C       110317.28 212.-24.3-281.154.1                       31031
   40 L1G1EST32D       11027 7.3 212.-34.9-146.105.8                       31027
   41 L1G1EST33A       110294.47 223.-81.7-369.209.2                       31029
   42 L1G1EST33B       110254.49 223.-89.6-415.246.5                       31002
   43 L1G1EST33C       110204.52 223.-101.-380.218.9                       31020
   44 L1G1EST33D       110254.49 223.-89.6-145.119.3                       31040
   45 L1G1EST34A       110448.22  67.-19.8-316.183.8                       31044
   46 L1G1EST34B       110448.22  67.-19.8-316.183.8                       31044
   47 L1G1EST34C       110408.23  67.-25.8-231.152.7                       31040
   48 L1G1EST34D       110448.22  67.-19.8-316.183.8                       31044
   49 L1G1EST34E       110448.22  67.-19.8-316.183.8                       31044
   50 L1G1EST35A       1 967-33.   0.-235.-290.290.1                       1 967
   51 L1G1EST36A       11060-45. 283.-31.7-250. 250.                       21060
   52 L1G1EST36B       11062-45. 283.-19.7-250. 250.                       21062
   53 L1G1EST36C       11060-45. 283.-33.4-250. 250.                       21060
   54 L1G1EST36D       11062-45. 283.-19.7-250. 250.                       21062
   55 L1G1EST36E       11060-45. 283.-33.6-250. 250.                       21060
   56 L1G1EST36F       11060-45. 283.-34.5-250. 250.                       21070
   64 L G3C2E07ASC1A   11038-20.                                           11038
   65 L G3C2E07ASC1B   11040-5.7                                           11039
   66 L G3C2E07ASC2B   11040-5.7                                           11040
   67 L G3C2E10ASC1B   11029-13.                                           11029
   68 L G3C2E10ASC2B   11030-13.                                           11030
   72 L G3C2E07ASC2A   11038-20.                                           11038
80000 L 00C2S05TR31     1027-33.                                           11027
80001 L 00C4S07TR31     10332.52                                           31032
80002 L 00C4S07TR32     10332.52                                           31032
99999
DLIN
    1         7 1          1.701      .9125                       805.805.  805.
    2         7 1          1.701      .9125                       805.805.  805.
    3         7 1          1.701      .9125                       805.805.  805.
    4         7 1          1.701      .9125                       805.805.  805.
    5         7 1          1.701      .9125                       805.805.  805.
    6         7 1          1.701      .9125                       805.805.  805.
    7         8 1    .0052   .0511.033                            23042304  2304
    7         9 2    .0051   .05 10.87                            23042304  2304
    7        10 3     .005   .0510.688                            23042304  2304
```

```
    7        11 4     .005   .0510.538                         23042304  2304
    8        12 1          .6276       1.05                    23102310  2310
    9        12 1          .6276       1.05                    23102310  2310
   10        12 1          .6276       1.05                    23102310  2310
   11        12 1          .6276       1.05                    23102310  2310
   12        64 1     .076  1.84 927.8                         42004200  4200
   12        72 2     .076  1.85 929.1                         42004200  4200
   13        64 1          -.749                               99989998  9998
   13        65 1          -.778                               99989998  9998
   13        66 1          -.778                               99989998  9998
   13        72 1          -.749                               99989998  9998
   14        67 1          -.915                               99989998  9998
   14        68 1          -.915                               99989998  9998
   15     80000 1           -.11        1.                     21002100  2100
   16        15 1             .7      1.042.87961.169        1623102310352310
   16        15 2             .7      1.042.87961.169        1623102310352310
   16        26 1 T  .0826  1.04   32.                         25322532  2532
   16        26 2 T  .0826  1.04   32.                         25322532  2532
   17        13 1             .7      1.042.87961.169        1723102310352310
   17        13 2             .7      1.042.87961.169        1723102310352310
   17        18 1 T    .01   .05 1.135                         24542454  2454
   17        18 2 T    .01   .05 1.135                         24542454  2454
   18        19 1     .154  1.94236.97                         32733273  3273
   18        21 1     .191 2.414294.92                         32733273  3273
   19        20 1     .056  .69785.746                         24562456  2456
   19        23 1     .172  2.17265.16                         25322532  2532
   19     80001 1     .016  .097            1.                 10001000  1000
   19     80002 1     .016  .101            1.                 10001000  1000
   20        21 1    .0624 .784896.592                         24562456  2456
   21        22 1      .01  .12615.428                         23372337  2337
   21        22 2      .01   .13 15.16                         23372337  2337
   21        24 1     .162 2.048250.17                         32733273  3273
   23        24 1     .102 1.268155.24                         25322532  2532
   23        25 1     .282 3.852 493.7                         25322532  2532
   24        25 1     .225 3.033381.46                         25322532  2532
   26        27 1    .0284  .352 10.83                         25322532  2532
   26        27 2    .0284  .352 10.83                         25322532  2532
   26        29 1    .0223   .2814.462                         25322532  2532
   27        28 1     .007  .088 2.707                         25322532  2532
   27        28 2     .007  .088 2.707                         25322532  2532
   30        15 1           .899      1.028.85921.102        3021002100232100
   30        31 1 T  .0812    .8  7.56                         20302030  2030
   30        31 2 T  .0812    .8  7.56                         20302030  2030
   30        31 3 T  .0812    .8  7.56                         20302030  2030
   30        31 4 T  .0812    .8  7.56                         20302030  2030
   30        32 1      1.6    9.  300.                         20302030  2030
   30     80000 1          1.033           1..85931.115      3021002100232100
   31        29 1           1.44       1.04                    784.784.  784.
   31        29 2           1.44       1.04                    784.784.  784.
   32        18 1           .899      1.066                    784.784.  784.
   33     80001 1     .034 4.359            1.                 10001000  1000
   34     80001 1     .034 4.365            1.                 350.500.  350.
   35     80002 1     .034  4.34            1.                 10001000  1000
   36     80002 1     .034 4.323            1.                 350.500.  350.
   37        20 1            4.2      1.013                    347.347.  347.
   38        20 1            4.2      1.013                    347.347.  347.
   39        20 1            4.2      1.013                    347.347.  347.
   40        20 1            4.2      1.013                    347.347.  347.
   41        22 1           4.32      1.034                    461.461.  461.
   42        22 1           4.32      1.034                    461.461.  461.
   43        22 1           4.32      1.034                    461.461.  461.
   44        22 1           4.32      1.034                    461.461.  461.
   45        23 1    .08255.6814      1.057                    385.385.  385.
   46        23 1    .08255.6814      1.057                    385.385.  385.
   47        23 1    .08255.6814      1.057                    385.385.  385.
   48        23 1    .08255.6814      1.057                    385.385.  385.
   49        23 1    .08255.6814      1.057                    385.385.  385.
   50     80000 1          2.483            1.                 297.326.  297.
   51        28 1          1.701            1.                 805.805.  805.
   52        28 1          1.701            1.                 805.805.  805.
   53        28 1          1.701            1.                 805.805.  805.
   54        28 1          1.701            1.                 805.805.  805.
   55        28 1          1.701            1.                 805.805.  805.
   56        28 1          1.701            1.                 805.805.  805.
   65        14 1     .064  1.53  760.                         42004200  4200
   66        14 2     .063  1.53 755.7                         42004200  4200
   67        15 1     .072  1.75 877.5                         42004200  4200
   68        15 2     .072  1.75  873.                         42004200  4200
99999
DBSH
   13           F 0000 0000    13  -330. C
 1       2   2  -165.
FBAN
   14           F 0000 0000    14  -100. C
 1       1   1  -100.
FBAN
   23           F 0000 0000    23  -150. C
 1       1   1  -150.
FBAN
   24           F 0000 0000    24  -100. C
 1       1   1  -100.
FBAN
   30           F 0000 0000    30  883.2 C
 1       4   4  220.8
FBAN
```

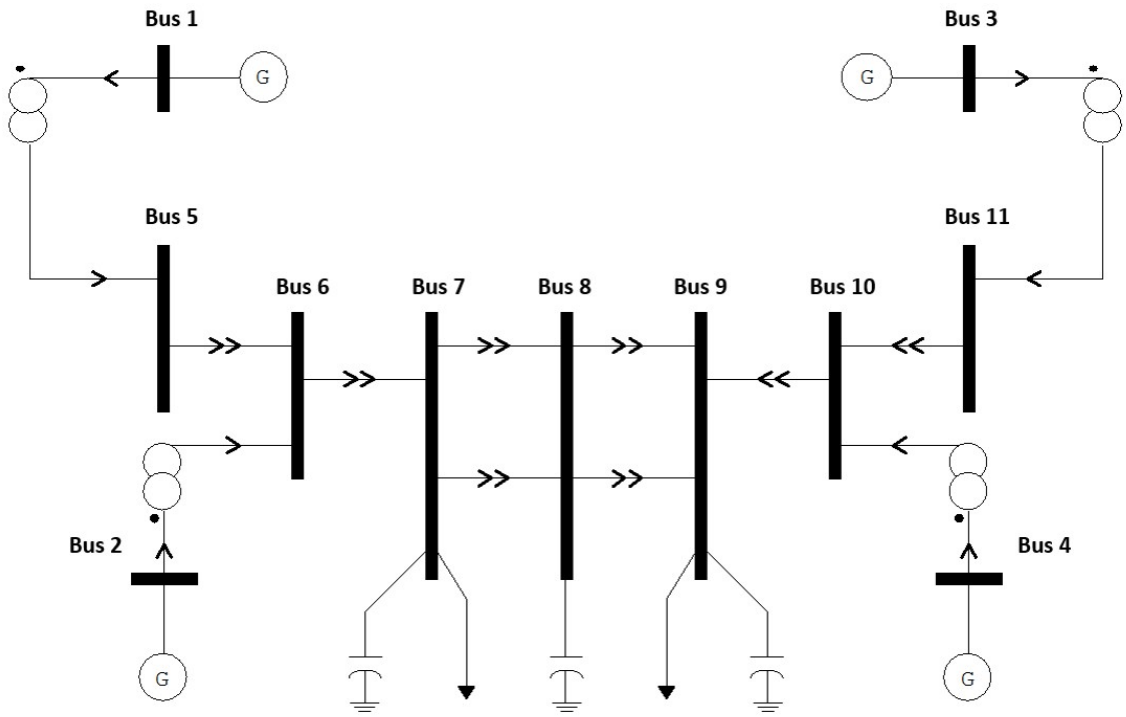
```
99999
DSHL
   12       64 1  -330. -150.  L  L
   12       72 2  -330. -150.  L  L
   18       19 1  -100.        L
   18       21 1  -100.        L
   19       23 1        -150.     L
   21       24 1        -100.     L
   23       25 1        -150.     L
   24       25 1        -150.     L
   65       14 1  -330. -330.  L  L
   66       14 2  -330. -330.  L  L
   67       15 1        -165.     L
   68       15 2        -165.     L
99999
DGER
    1       0. 723.55 16.67  100.
    2       0. 723.55 16.67  100.
    3       0. 723.55 16.67  100.
    4       0. 723.55 16.67  100.
    5       0. 723.55 16.67  100.
    6       0. 723.55 16.67  100.
   33       0.   355. 3.046  100.
   34       0.   355. 3.046  100.
   35       0.   355. 3.046  100.
   36       0.   355. 3.046  100.
   37       0.   315. 2.703  100.
   38       0.   315. 2.703  100.
   39       0.   315. 2.703  100.
   40       0.   315. 2.703  100.
   41       0.   419. 3.596  100.
   42       0. 415.44 3.565  100.
   43       0.   419. 3.596  100.
   44       0.   419. 3.596  100.
   45       0.  294.8  2.53  100.
   46       0.  294.8  2.53  100.
   47       0.  294.8  2.53  100.
   48       0.  294.8  2.53  100.
   49   -9999.  294.8  2.53  100.
   50       0.     0.    0.  100.
   51       0. 440.94 8.317  100.
   52       0. 441.74 8.332  100.
   53       0. 440.82 8.315  100.
   54       0. 441.74 8.332  100.
   55       0. 440.81 8.314  100.
   56       0. 444.82  8.39  100.
99999
DCAR
barr     7 E barr    19 E barr    27 E barr    31 A  25  25  25  25   60.
barr    21 E barr    24 E barr    25 E barr    29 A  25  25  24  24   60.
barr    23                                        A  24  24  25  25   60.
barr    30                                        A   0   0   0   0   60.
99999
DGLT
 0    .5   1.5    .5   1.5
99999
DARE
  1        0.     ÁREA 1 - S101                        -.1E8   .1E8
  2        0.     ÁREA 2 - S101                        -.1E8   .1E8
  3        0.     ÁREA 3 - S101                        -.1E8   .1E8
99999
DGBT
G3  750.
G2  500.
G4  345.
G1   20.
00    1.
99999
FIM
```

## A.2 Dynamic Data File

```
TITU
SNAPSHOT DO CASO BASE: EXTGCASOBASE
ULOG
4
EXTGCASOBASE.OUT
DOPC IMPR CONT
IMPR L FILE L CONT L 80CO L
999999
DCTE
TETE 1.e-04
TEMD 1.e-04
TABS 1.e-07
TEPQ    .01
999999
ULOG
2
sage.sav
ULOG
8
EXTGCASOBASE.PLT
ARQV REST
01
ULOG
3
BDEMO.BLT
ARQM
ULOG
3
DadosIndiv.CDU
ARQM
DMAQ
    1   60          1    901    907u   947u   977u
    2   61          1    901    908u   948u   978u
    3   62          1    901    909u   949u   979u
    4   63          1    901    910u   950u   980u
    5   64          1    901    911u   951u   981u
    6   65          1    901    912u   952u   982u
   51   10          1    901    901u   941u   971u
   52   11          1    901    902u   942u   972u
   53   12          1    901    903u   943u   973u
   54   13          1    901    904u   944u   974u
   55   14          1    901    905u   945u   975u
   56   15          1    901    906u   946u   976u
   33   20          1    807    810u   850u   880u
   34   21          1    807    811u   851u   881u
   35   22          1    807   2810u  2850u  2880u
   36   23          1    807   2811u  2851u  2881u
   37   50          1    702    704u   744u   774u
   38   51          1    702    705u   745u   775u
   39   52          1    702    706u   746u   776u
   40   53          1    702    707u   747u   777u
   41   40          1    700    700u   740u   770u
   42   41          1    700    701u   741u   771u
   43   42          1    700    702u   742u   772u
   44   43          1    700    703u   743u   773u
   45   30          1    808    812u   852u   882u
   46   31          1    808    813u   853u   883u
   47   32          1    808    814u   854u   884u
   48   33          1    808    815u   855u   885u
   49   34          1    808    816u   856u   886u
999999
DSIM
   15.00  .003     1
EXSI
FIM
```

# Appendix B

# Two Areas System



# B.1 Power Flow Data File

```
TITU
Two Area Test System Modificado
DCTE
BASE   100. DASE  1000. TEPA  .1E-7 EXST     4. TETP     5. TBPA     5.
TLPP     1. TEPR  .1E-7 QLST     4. TLPR     1. TLPQ     2. TSBZ    .01
TSBA     5. ASTP    .05 VSTP     5. TLVC     .5 TLTC    .01 TSFR  .1E-7
ZMAX   500. TLPV     .5 VDVM   200. VDVN    40. TUDC   .001 TADC    .01
PGER    30. TPST     2. VFLD    70. ZMIN   .001 HIST    470 LFIT     10
ACIT     30 LFCV      1 DCIT     10 VSIT     10 LPIT     50 LFLP     10
PDIT     10 LCRT     30 LPRT     60 CSTP   500. ASDC     1.
ICIT     30 DMAX      5 FDIV     2. ICMN    .05 VART     5. TSTP     32
ICMV     .5 APAS    90. CPAR    70. VAVT     2. VAVF     5. VMVF    15.
VPVT     2. VPVF     5. VPMF    10. VSVF    20. VINF     1. VSUP     1.
TLSI     0. NDIR    20. STTR     5. TRPT   100. STIR     1. BFPO     1.
99999
DBAR
    1 L1  Barra1        103032.7 700.82.96-999999999                       11000
    2 L1  Barra2        105020.7 450.214.6-999999999                       11000
    3 L2  Barra3        1030 -7.532.891.49-999999999                       21000
    4 L1  Barra4        1010-18. 150.47.65-999999999                       21000
    5 L   Barra5        102326.3                                           11000
    6 L   Barra6        101816.6                                           11000
    7 L   Barra7        100710.3                            600. 100. 200.  11000
    8 L   Barra8         983-6.5                                       50.  11000
    9 L   Barra9         995-23.                           1167. 100. 250.  21000
   10 L   Barra10       1002-19.                                           21000
   11 L   Barra11       1019-12.                                           21000
99999
DLIN
    1         5 1         1.6666         1.
    2         6 1         1.6666         1.
    3        11 1         1.6666         1.
    4        10 1         1.6666         1.
    5         6 1      .25   2.5  4.35
    6         7 1       .1    1.  1.75
    7         8 1      1.1   11. 19.25
    7         8 2      1.1   11. 19.25
    8         9 1      1.1   11. 19.25
    8         9 2      1.1   11. 19.25
    9        10 1       .1    1.  1.75
   10        11 1      .25   2.5  4.37
99999
DARE
  1        0.     *  AREA 1                          *
  2        0.     *  AREA 2                          *
99999
FIM
```

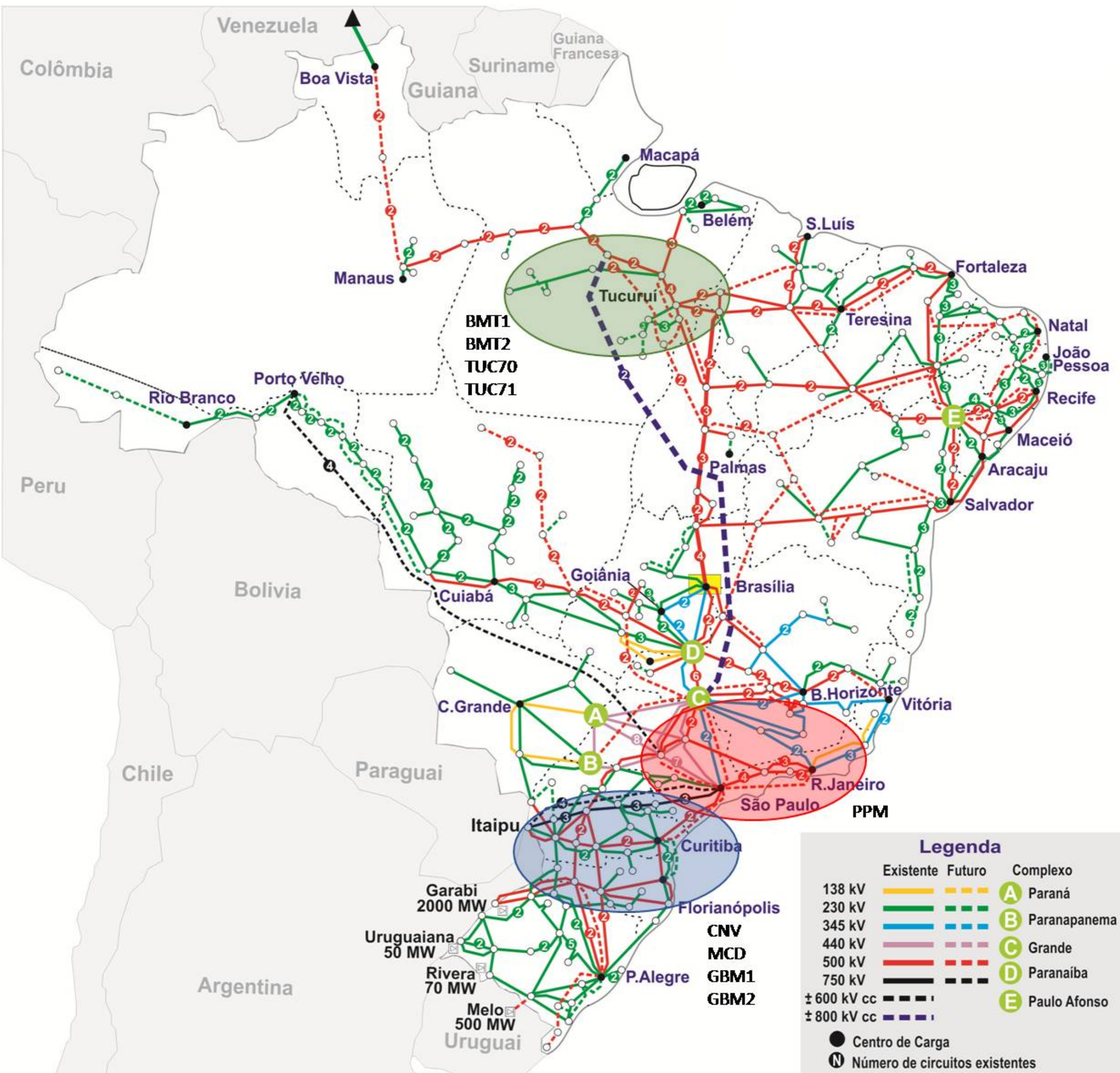
# B.2 Dynamic Data File

```
TITU
** Two areas system **
ULOG
2
2areas.sav
ULOG
8
2areas.plt
DOPC IMPR CONT FILE
IMPR   FILE
999999
DCTE
TEPQ    .01
TEMD  1.E-7
TETE  1.E-7
TABS  1.E-7
999999
ARQV REST
01
DMDG MD03
0001   0001   180  170  030  055  025  020  8.0  0.4 0.03 0.05
0001   .25    6.5  0.0 1200
0002   0001   180  170  030  055  025  020  8.0  0.4 0.03 0.05
0002   .25    6.5  0.0  900
0003   0001   180  170  030  055  025  020  8.0  0.4 0.03 0.05
0003   .25  6.175  0.0  900
0004   0001   180  170  030  055  025  020  8.0  0.4 0.03 0.05
0004   .25  6.175  0.0  350
999999
DCST
0001   2 0.015    9.6      0.9
999999
DCDU IMPR
  0001 AVRMAQ1
DEFPAR #Tr                 0.01
DEFPAR #Ka                400.0
DEFPAR #Lmin                 -4
DEFPAR #Lmax                  4
   1 IMPORT VOLT          ET
   2 ENTRAD               VREF
   3 IMPORT VSAD          VPSS
   4 LEDLAG        ET     X4     1.0          1.0   #Tr
   5 SOMA         +VREF   X5
                  -X4     X5
                   VPSS   X5
   6 GANHO         X5     X6     #Ka
   7 LIMITA        X6     EFD                             LMIN   LMAX
   8 EXPORT EFD    EFD
DEFVAL        LMIN   #Lmin
DEFVAL        LMAX   #Lmax
FIMCDU
  0002 AVRMAQ2
DEFPAR #Tr                 0.01
DEFPAR #Ka                400.0
DEFPAR #Lmin                 -4
DEFPAR #Lmax                  4
   1 IMPORT VOLT          ET
   2 ENTRAD               VREF
   3 IMPORT VSAD          VPSS
   4 LEDLAG        ET     X4     1.0          1.0   #Tr
   5 SOMA         +VREF   X5
                  -X4     X5
                   VPSS   X5
   6 GANHO         X5     X6     #Ka
   7 LIMITA        X6     EFD                             LMIN   LMAX
   8 EXPORT EFD    EFD
DEFVAL        LMIN   #Lmin
DEFVAL        LMAX   #Lmax
FIMCDU
  0003 AVRMAQ3
DEFPAR #Tr                 0.01
DEFPAR #Ka                400.0
DEFPAR #Lmin                 -4
DEFPAR #Lmax                  4
   1 IMPORT VOLT          ET
   2 ENTRAD               VREF
   3 IMPORT VSAD          VPSS
   4 LEDLAG        ET     X4     1.0          1.0   #Tr
   5 SOMA         +VREF   X5
                  -X4     X5
                   VPSS   X5
   6 GANHO         X5     X6     #Ka
   7 LIMITA        X6     EFD                             LMIN   LMAX
   8 EXPORT EFD    EFD
DEFVAL        LMIN   #Lmin
DEFVAL        LMAX   #Lmax
FIMCDU
  0004 AVRMAQ4
DEFPAR #Tr                 0.01
DEFPAR #Ka                400.0
DEFPAR #Lmin                 -4
DEFPAR #Lmax                  4
   1 IMPORT VOLT          ET
   2 ENTRAD               VREF
   3 IMPORT VSAD          VPSS
```

```
   4 LEDLAG        ET     X4     1.0          1.0    #Tr
   5 SOMA         +VREF   X5
                  -X4     X5
                   VPSS   X5
   6 GANHO         X5     X6     #Ka
   7 LIMITA        X6     EFD                                 LMIN   LMAX
   8 EXPORT EFD    EFD
DEFVAL        LMIN   #Lmin
DEFVAL        LMAX   #Lmax
FIMCDU
  0005 PSS1
DEFPAR #Kstab              20.0
DEFPAR #Tw                 10.0
DEFPAR #T1                 0.05
DEFPAR #T2                 0.02
DEFPAR #T3                  3.0
DEFPAR #T4                  5.4
   1 IMPORT WMAQ          W
   2 GANHO         W      X2     #Kstab
   3 WSHOUT        X2     X3     #Tw   1.0    #Tw
   4 LEDLAG        X3     X4     1.0   #T1    1.0    #T2
   5 LEDLAG        X4     VPSS   1.0   #T3    1.0    #T4
   6 EXPORT VSAD   VPSS
FIMCDU
  0006 PSS2
DEFPAR #Kstab              20.0
DEFPAR #Tw                 10.0
DEFPAR #T1                 0.05
DEFPAR #T2                 0.02
DEFPAR #T3                  3.0
DEFPAR #T4                  5.4
   1 IMPORT WMAQ          W
   2 GANHO         W      X2     #Kstab
   3 WSHOUT        X2     X3     #Tw   1.0    #Tw
   4 LEDLAG        X3     X4     1.0   #T1    1.0    #T2
   5 LEDLAG        X4     VPSS   1.0   #T3    1.0    #T4
   6 EXPORT VSAD   VPSS
FIMCDU
  0007 PSS3
DEFPAR #Kstab              20.0
DEFPAR #Tw                 10.0
DEFPAR #T1                 0.05
DEFPAR #T2                 0.02
DEFPAR #T3                  3.0
DEFPAR #T4                  5.4
   1 IMPORT WMAQ          W
   2 GANHO         W      X2     #Kstab
   3 WSHOUT        X2     X3     #Tw   1.0    #Tw
   4 LEDLAG        X3     X4     1.0   #T1    1.0    #T2
   5 LEDLAG        X4     VPSS   1.0   #T3    1.0    #T4
   6 EXPORT VSAD   VPSS
FIMCDU
  0008 PSS4
DEFPAR #Kstab              20.0
DEFPAR #Tw                 10.0
DEFPAR #T1                 0.05
DEFPAR #T2                 0.02
DEFPAR #T3                  3.0
DEFPAR #T4                  5.4
   1 IMPORT WMAQ          W
   2 GANHO         W      X2     #Kstab
   3 WSHOUT        X2     X3     #Tw   1.0    #Tw
   4 LEDLAG        X3     X4     1.0   #T1    1.0    #T2
   5 LEDLAG        X4     VPSS   1.0   #T3    1.0    #T4
   6 EXPORT VSAD   VPSS
FIMCDU
999999
DMAQ
    1   10          1      1      1u
    2   10          1      2      2u
    3   10          1      3      3u
    4   10          1      4      4u
999999
DEVT IMPR
TCDU      1.0     1                     .005                    2
TCDU      1.0     3                    -.005                    2
999999
DPLT IMPR
VOLT        1
VOLT        2
VOLT        3
VOLT        4
PELE        1          10
PELE        2          10
PELE        3          10
PELE        4          10
DELT        1          10
DELT        2          10
DELT        3          10
DELT        4          10
999999
DSIM
    10.0  .001     5     1   1
EXSI
FIM
```

# Appendix C

# Brazilian Power System



# C.1 Power Flow Data File

```
TITU
SIN 2020
DBAR
( EPE - Banco de Dados - 2020 (aproximadamente, 8000 barras)
99999
DLIN
( EPE - Banco de Dados - 2020 (aproximadamente, 11000 linhas de transmissao)
99999
DCSC
  736      539 1          -1.76  -.59 -.637X  -.637   736
  758      539 1          -1.76  -.59 -.637X  -.637   758
 5000     3895 1          -1.76  -.59 -.637X  -.637  5000
 4431     3895 1          -1.76  -.59 -.637X  -.637  4431
99999
DBSH
( EPE - Banco de Dados - 2020
99999
DSHL
( EPE - Banco de Dados - 2020
99999
DCER
  341   10  2   332     2. -214.-100. 150. P L
  421   10  1   421     5. 5.202 -88. 97.4 P L
  425   10  1   425   1.5 58.73-175.189.6 P L
  444   10  1 11244     1. 24.07   0.209.1 P L
  476   10  1   276     1. 160.9-114. 225. P L
  581   10  1   585     .8 -290.-250. 250. P L
  702   90  1   624     2. 20.03   0.  20. P L
  716   90  1   216     1. 3.049 -45.  90. P L
 2610   90  1  2634     1. -104.-300. 300. P L
 2974   90  1  2628     1. -127.-120. 150. P L
 3329   10  1  3329     1. 7.167-54.563.96 P L
 3330   10  1  3322     1. 55.42 -20.  55. P L
 3628   10  1  3628     3. 7.146 -25.  29. P L
 3630   10  1  3909     2. -3.66 -56. 88.5 P L
 3631   10  1  3785     2.   -4. -55.90.31 P L
 3632   10  1  3909     2. -3.66 -56. 88.5 P L
 3718   90  1  3717     1. -98.2-300. 300. P L
 4301   90  1  4300     1. 276.4-150. 300. P L
 4324   90  1  4322     1. -31.2-150. 300. P L
 4688   10  1  4688     1. 13.24 -80.  20. P L
 7726   90  1  7741     1. -55.7-100. 300. P L
 9504   10  1  9535     2. 3.644 -50. 100. P L
 9505   10  1  9538     2.  39.1 -20.  55. P L
 9539   90  1  3288     2. -133.-130.  75. P L
 9540   90  1  9530     2. 103.4-100. 100. P L
10013   90  1 10009     1.  -44.-200. 200. P L
10014   90  1 10010     1. -180.-200. 200. P L
10015   90  1 10011     1. -67.2-200. 200. P L
10016   90  1 10017     1. 111.5-100. 100. P L
11562   90  1 11560     1. -17.3-100. 200. P L
12331   90  1 11246     1.  67.2 -75. 150. P L
12332   90  1 12546     1. 20.82 -75. 150. P L
12333   90  1   289     1. 242.6-150. 250. P L
12334   90  1   555     1. -27.3-100. 200. P L
12335   90  1   526     1. -130.-150. 250. P L
12336   90  1   287     1. -20.1 -20.  30. P L
13018   90  1 13018     1. -101.-150. 300. P L
14901   90  1 14901     1. 52.46-150. 300. P L
26453   90  1  1485     1. -230.-200. 300. P L
27950   90  1  1481     1. -21.4 -84. 100. P L
29051   90  1  2154     1. 12.74 -90. 100. P L
38859   90  1  7758     1. 40.28 -50.  50. P L
38860   10  1  7755     2. 76.36-100. 100. P L
38860   90  1  7755     2. 96.84-100. 100. P L
38868   90  1  4285     1. -82.6-200. 300. P L
39001   90  1 39311     1. -43.8-150. 150. P L
40660   10  1 40660     1.    0.   0. 280. P L
41176   90  1  4594     1. -181.-200. 200. P L
52213   90  1 52207     1. -126.-120. 150. P L
99999
DCTR
( EPE - Banco de Dados - 2020
99999
DARE
   1        0.     CHESF - SISTEMA SUL
   2        0.     CHESF - SISTEMA LESTE
   3        0.     CHESF - SISTEMA NORTE
   4        0.     CHESF - SISTEMA OESTE
   5        0.     CHESF - SISTEMA CENTRO
   6        0.     CHESF - SISTEMA SUDOESTE
   7        0.     ELETRONORTE
   8        0.     NORTE-SUL
   9        0.     ALUMAR (MARANHAO)
  10        0.     TUCURUI-MACAPA-MANAUS
  12        0.     CELTINS
  13        0.     CEB
  14        0.     PCH-GOIAS
  15        0.     CDSA
  17        0.     CELG - D
  18        0.     CELG - D (GOIÂNIA)
  19        0.     CELG - G&T
  20        0.     ELETRONORTE-CENTRO-OESTE
  21        0.     CEMAT
  22        0.     CEMAT
  23        0.     CEMIG - GERACAO E CONTROLE DE TENSAO
  24        0.     CEMIG - SISTEMA DE TRANSMISSAO
  25        0.     CEMIG - REGIAO CENTRO
  26        0.     CEMIG - REGIAO LESTE
  27        0.     CEMIG - REGIAO SUDESTE
  28        0.     CEMIG - REGIAO DO TRIANGULO MINEIRO
  29        0.     CEMIG - REGIAO OESTE
  30        0.     CEMIG - REGIAO NORTE
```

```
  31        0.     CEMIG - REGIAO SUL
  32        0.     CEMIG - BARRAS DE TERCIARIO
  33        0.     CFLCL - MINAS
  35        0.     AES-TIETE
  36        0.     CESP
  37        0.     DUKE-GP
  38        0.     EMAE
  39        0.     CPFL - SANTA CRUZ
  40        0.     CPFL - SUDESTE
  41        0.     CPFL - NOROESTE
  42        0.     CPFL - NORDESTE
  43        0.     CPFL PIRATININGA - BAIXADA
  44        0.     CPFL PIRATININGA - OESTE
  45        0.     CTEEP - SISTEMA DE 440KV E 500KV
  46        0.     CTEEP - 138KV DA REGIÃO OESTE
  47        0.     CTEEP - SISTEMA DE 88KV
  48        0.     CTEEP - 138KV DO LITORAL E C. BONITO
  49        0.     CTEEP - 138KV DA REGIÃO DO PARDO
  50        0.     CTEEP - SISTEMA DE 345KV E 230KV
  51        0.     REDE ENERGIA
  52        0.     ELEKTRO - CENTRO
  53        0.     ELEKTRO - LESTE
  54        0.     ELEKTRO - NOROESTE
  55        0.     ELEKTRO - SUL
  56        0.     BANDEIRANTE
  58        0.     ELETROPAULO
  59        0.     CPFL JAGUARIUNA
  60        0.     CONSUMIDORES LIVRES (RB) - SE/CO
  61        0.     FURNAS - ITAIPU 50 Hz
  62        0.     FURNAS - GERACAO E CONTROLE
  63        0.     FURNAS - TRANSMISSAO RJ ES MG SP
  64        0.     FURNAS - TRANSMISSAO GO DF MT
  65        0.     FURNAS- BARRAS TERCIARIAS E FIC
  68        0.     LIGHT
  69        0.     AMPLA-REGIAO SUL FLUMINENSE
  70        0.     AMPLA-REGIAO NORTE FLUMINENSE
  71        0.     AMPLA-REGIAO NITEROI
  73        0.     CENF
  74        0.     ESCELSA
  75        0.     TELES PIRES
  76        0.     BELO MONTE
  77        0.     MADEIRA
  78        0.     ACRE E RONDONIA
  79        0.     ICG - SE/CO
  80        0.     TRANSMISSORAS SUDESTE-COESTE
  81        0.     GERADORES HIDR SUDESTE-COESTE
  82        0.     GERADORES TERM SUDESTE-COESTE
  83        0.     A.E.S.
  84        0.     CEEE
  85        0.     CEEE DISTRIBUIDORA
  86        0.     ENERSUL
  87        0.     RGE
  88        0.     CELESC - AREA LESTE
  89        0.     CELESC - OESTE + SUL
  90        0.     ELETROSUL 230KV - SE/CO
  91        0.     COPEL - G&T
  92        0.     COPEL - D
  93        0.     ELETROSUL 525KV
  94        0.     ELETROSUL 230KV - SUL
  95        0.     CPFL
  96        0.     GERASUL
  97        0.     OUTRAS EMPRESAS DE GERACAO SUL
  98        0.     CONSUMIDORES LIVRES (RB) - SUL
 101        0.     CEPISA
 102        0.     COELCE
 103        0.     COSERN
 104        0.     SAELPA
 105        0.     CELPE
 106        0.     CEAL
 107        0.     ENERGIPE
 108        0.     COELBA
 109        0.     CEMAR
 110        0.     CELPA
 111        0.     CELB
 112        0.     CONSUMIDORES LIVRES (RB) - Norte
 113        0.     MANAUS
 114        0.     AMAPA
 115        0.     RORAIMA
 116        0.     TAPAJÓS
 117        0.     CONSUMIDORES LIVRES (RB) - Nordeste
 118        0.     ÉOLICAS NORDESTE
99999
DELO
( EPE - Banco de Dados - 2020 (aproximadamente, 40 elos de corrente continua)
99999
DCBA
( EPE - Banco de Dados - 2020
99999
DCLI
( EPE - Banco de Dados - 2020
99999
DCNV
( EPE - Banco de Dados - 2020
99999
DCCV
( EPE - Banco de Dados - 2020
99999
DGBT
( EPE - Banco de Dados - 2020
99999
FIM
```

## C.2 Dynamic Data File

```
TITU
SIN 2020
DOPC IMPR CONT
IMPR L CONT L 80CO L FILE L
999999
ULOG
8
SIN2020.PLT
ULOG
2
NNE-EXP-PES-CRITICO.SAV
ARQV REST
2
ULOG
3
USINAS-EXISTENTES-EPE.BLT
ARQM
ULOG
3
USINAS-EXISTENTES-EPE.CDU
ARQM
ULOG
3
USINAS-FUTURAS-EPE.BLT
ARQM
ULOG
3
USINAS-FUTURAS-EPE.CDU
ARQM
ULOG
3
Madeira-EPE.CDU
ARQM
ULOG
3
Madeira-EPE.BLT
ARQM
ULOG
3
BeloMonte-EPE.CDU
ARQM
ULOG
3
BeloMonte-EPE.BLT
ARQM
ULOG
3
TelesPires-EPE.CDU
ARQM
ULOG
3
TelesPires-EPE.BLT
ARQM
ULOG
3
Tapajós-EPE.CDU
ARQM
ULOG
3
Tapajós-EPE.BLT
ARQM
DMAQ
 3581   10 100 100   1    100    100u   140u   170u      3581 ANGRA-1--1GR
 3582   10 100 100   1    101    101u   141u   171u      3582 ANGRA-2--1GR
 3586   10 100 100   4    103    103u   143u   173u      3586 LCBARRET-4GR
 3596   10 100 100   2    105    105u   145u             3596 FUNIL----2GR
 3587   10 100 100   4    107    106u   146u             3587 FURNAS---4GR
 3592   10 100 100   3    109    108u   148u   178u      3592 ITUMBIAR-3GR
 3588   10 100 100   4    111    110u   150u   180u      3588 MARIMBON-4GR
 3595   10 100 100   2    128    128u   159u   189u      3595 MANSO----2GR
 3589   10 100 100   3    113    111u   151u   181u      3589 M.MOR.A--3GR
 3590   10 100 100   2    114    112u   152u   182u      3590 M.MOR.B--2GR
 3591   10 100 100   2    116    113u   153u             3591 P.COLOMB-2GR
 3597   10 100 100   2    118    114u   154u             3597 SCRUZ-19-2GR
 3598   10 100 100   2    120    115u   155u             3598 SCRUZ-13-2GR
 3601   10 100 100   2    121    132u   161u   172u      3601 SCRUZ-16-2GR
 3593   10 100 100   2    122    116u   156u   186u      3593 CORUMBA--2GR
 3594   10 100 100   3    124    117u   157u   187u      3594 S.MESA---3GR
 3626   10 100 100   1    130    120u                    3626 B.GERAL1-1CS
 3629   10 100 100   1    132    121u                    3629 VITORIA2-1CS
 3623   10 100 100   1    134    126u                    3623 GRAJAU-1-1CS
 3624   10 100 100   1    134    130u                    3624 GRAJAU-2-1CS
 3625   10 100 100   1    132    123u                    3625 VITORIA1-1CS
 3622   10 100 100   4    138    127u                    3622 IBIUNA---4CS
 3621   10 100 100   1    140    125u                    3621 T.PRETO--1CS
 4057   10  69  73   3    200    200u   240u   270u      4057 NPECANHA-3GR
 4057   20  31  27   2    201    201u   241u   271u      4057 NPECANHA-2GR
 4060   10  33  38   1    202    202u   242u   272u      4060 FONTES---1GR
 4060   20  67  62   2    203    203u   243u   273u      4060 FONTES---2GR
 4062   10 100 100   1    205    205u   245u   275u      4062 P.PASSOS-1GR
```

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 4066 | 10 | 29 | 29 | 2 | 206 | 206u | 246u | | 4066 | I.POMBOS-2GR |
| 4066 | 20 | 16 | 17 | 1 | 207 | 207u | 247u | | 4066 | I.POMBOS-1GR |
| 4066 | 30 | 27 | 30 | 1 | 208 | 208u | 248u | | 4066 | I.POMBOS-1GR |
| 4066 | 40 | 28 | 24 | 1 | 209 | 209u | 249u | | 4066 | I.POMBOS-1GR |
| 4385 | 10 | 100 | 100 | 2 | 210 | 210u | 250u | | 4385 | CTE-CSN--2GR |
| 1426 | 10 | 100 | 100 | 2 | 300 | 300u | 340u | 370u | 1426 | EMBORCAC-2GR |
| 1430 | 10 | 100 | 100 | 2 | 302 | 302u | 342u | 372u | 1430 | JAGUARA--2GR |
| 1435 | 10 | 100 | 100 | 2 | 303 | 303u | 343u | 373u | 1435 | N.PONTE--2GR |
| 1445 | 10 | 100 | 100 | 3 | 304 | 304u | 344u | 374u | 1445 | S.SIMAO--3GR |
| 1446 | 10 | 100 | 100 | 5 | 305 | 305u | 345u | 375u | 1446 | T.MARIAS-5GR |
| 1448 | 10 | 100 | 100 | 2 | 306 | 306u | 346u | 376u | 1448 | V.GRANDE-2GR |
| 1428 | 10 | 100 | 100 | 2 | 314 | 314u | 354u | 384u | 1428 | GUILMAN--2GR |
| 1433 | 10 | 100 | 100 | 3 | 315 | 315u | 355u | 385u | 1433 | MIRANDA--3GR |
| 1429 | 10 | 100 | 100 | 3 | 316 | 316u | 356u | 386u | 1429 | IGARAPAV-3GR |
| 4664 | 10 | 100 | 100 | 1 | 308 | 308u | | | 4664 | MESQUITA-1CS |
| 4678 | 10 | 100 | 100 | 1 | 308 | 309u | | | 4678 | NEVES-1--1CS |
| 4680 | 10 | 100 | 100 | 1 | 308 | 310u | | | 4680 | NEVES-2--1CS |
| 1449 | 10 | 100 | 100 | 1 | 312 | 312u | | | 1449 | IGARAPE--1GR |
| 1436 | 10 | 100 | 100 | 1 | 317 | 317u | 357u | | 1436 | PESTRELA-1GR |
| 1427 | 10 | 100 | 100 | 2 | 318 | 318u | 358u | 388u | 1427 | FUNILGRD-2GR |
| 1440 | 10 | 100 | 100 | 3 | 319 | 319u | 359u | 389u | 1440 | QUEIMADO-3GR |
| 1431 | 10 | 100 | 100 | 3 | 320 | 320u | 360u | 390u | 1431 | IRAPE----3GR |
| 1421 | 10 | 100 | 100 | 2 | 321 | 321u | 361u | 391u | 1421 | AIMORES--2GR |
| 1452 | 10 | 100 | 100 | 2 | 322 | 322u | 362u | 392u | 1452 | BAGUARI--2GR |
| 3382 | 10 | 22 | 32 | 1 | 400 | 400u | 440u | | 3382 | HBORD-88-1GR |
| 3382 | 20 | 40 | 34 | 1 | 401 | 401u | 441u | | 3382 | HBORD-88-1GR |
| 3382 | 30 | 38 | 34 | 1 | 402 | 402u | 442u | | 3382 | HBORD-88-1GR |
| 3385 | 10 | 23 | 15 | 1 | 402 | 403u | 443u | | 3385 | HBORD230-1GR |
| 3385 | 20 | 51 | 57 | 2 | 403 | 404u | 444u | | 3385 | HBORD230-2GR |
| 3385 | 30 | 26 | 28 | 1 | 404 | 405u | 445u | | 3385 | HBORD230-1GR |
| 3386 | 10 | 100 | 100 | 2 | 407 | | | | 3386 | PIR-13.8-2GR |
| 3387 | 10 | 100 | 100 | 2 | 408 | | | | 3387 | PIR-14.4-2GR |
| 3394 | 10 | 100 | 100 | 2 | 406 | 406u | 446u | 476u | 3394 | N.PIRAT1-2GR |
| 3395 | 10 | 100 | 100 | 2 | 406 | 407u | 447u | 477u | 3395 | N.PIRAT2-2GR |
| 1001 | 10 | 100 | 100 | 5 | 500 | 500u | 540u | 570u | 1001 | A.VERMEL-5GR |
| 2041 | 10 | 100 | 100 | 13 | 501 | 501u | 541u | 571u | 2041 | I.SOLTE-13GR |
| 2042 | 10 | 80 | 80 | 4 | 502 | 502u | 542u | | 2042 | JUPIA----4GR |
| 2042 | 20 | 20 | 20 | 1 | 502 | 503u | 543u | 573u | 2042 | JUPIA----1GR |
| 2043 | 10 | 100 | 100 | 1 | 502 | 504u | 544u | 574u | 2043 | JUPIA138-1GR |
| 3011 | 10 | 100 | 100 | 2 | 506 | 505u | 545u | 575u | 3011 | JURUMIRI-2GR |
| 3016 | 10 | 100 | 100 | 2 | 507 | 506u | 546u | 576u | 3016 | CAPIVARA-2GR |
| 3021 | 10 | 100 | 100 | 2 | 508 | 507u | 547u | 577u | 3021 | CANOAS-1-2GR |
| 3020 | 10 | 100 | 100 | 2 | 509 | 508u | 548u | 578u | 3020 | CANOAS-2-2GR |
| 2045 | 10 | 100 | 100 | 6 | 510 | 509u | 549u | 579u | 2045 | P.PRIMA--6GR |
| 3019 | 10 | 100 | 100 | 2 | 511 | 510u | 550u | 580u | 3019 | ROSANA-1-2GR |
| 32900 | 10 | 100 | 100 | 1 | 511 | 527u | 565u | 590u | 32900 | ROSANA-2-1GR |
| 3013 | 10 | 100 | 100 | 2 | 512 | 511u | 551u | | 3013 | S.GRANDE-2GR |
| 3017 | 10 | 100 | 100 | 3 | 513 | 512u | 552u | 582u | 3017 | TAQUARUC-3GR |
| 3012 | 10 | 100 | 100 | 4 | 514 | 513u | 553u | | 3012 | CHAVANTE-4GR |
| 1009 | 10 | 100 | 100 | 2 | 515 | 514u | 554u | | 1009 | BARIRI-A-2GR |
| 21502 | 10 | 100 | 100 | 1 | 515 | 529u | 569u | | 21502 | BARIRI-B-1GR |
| 1006 | 10 | 100 | 100 | 4 | 516 | 515u | 555u | | 1006 | B.BONITA-4GR |
| 1003 | 10 | 100 | 100 | 3 | 517 | 516u | 556u | | 1003 | IBITINGA-3GR |
| 1002 | 10 | 100 | 100 | 3 | 518 | 517u | 557u | 585u | 1002 | N.AVANHA-3GR |
| 1004 | 10 | 100 | 100 | 3 | 519 | 518u | 558u | | 1004 | PROMISSA-3GR |
| 2044 | 10 | 100 | 100 | 3 | 520 | 519u | 559u | 587u | 2044 | T.IRMAOS-3GR |
| 1007 | 10 | 100 | 100 | 1 | 521 | 520u | 560u | | 1007 | CACONDE--1GR |
| 1008 | 10 | 100 | 100 | 2 | 522 | 521u | 561u | | 1008 | E.CUNHA--2GR |
| 1005 | 10 | 100 | 100 | 1 | 523 | 522u | 562u | | 1005 | LIMOEIRO-1GR |
| 2056 | 10 | 100 | 100 | 1 | 525 | 523u | 563u | | 2056 | JAGUARI--1GR |
| 2058 | 10 | 100 | 100 | 1 | 526 | 524u | 564u | 589u | 2058 | PARAIBUN-1GR |
| 2644 | 10 | 100 | 100 | 1 | 532 | 525u | | | 2644 | EMBU-GUA-1CS |
| 2652 | 10 | 100 | 100 | 1 | 533 | 526u | | | 2652 | S.ANGELO-1CS |
| 1081 | 10 | 100 | 100 | 2 | 600 | 600u | 640u | | 1081 | C.DOUR11-2GR |
| 1082 | 10 | 100 | 100 | 1 | 601 | 601u | 641u | | 1082 | C.DOUR13-1GR |
| 1083 | 10 | 100 | 100 | 1 | 602 | 602u | 642u | 672u | 1083 | C.DOU13A-1GR |
| 1084 | 10 | 100 | 100 | 2 | 603 | 603u | 643u | 673u | 1084 | C.DOU13N-2GR |
| 1085 | 10 | 100 | 100 | 2 | 604 | 604u | 644u | 674u | 1085 | C.DOU13K-2GR |
| 6979 | 10 | 50 | 50 | 1 | 700 | 700u | 740u | 770u | 6979 | GBMun1e2-1GR |
| 6979 | 20 | 50 | 50 | 1 | 9700 | 9700u | 9740u | 9770u | 6979 | GBMun3e4-1GR |
| 6982 | 10 | 100 | 100 | 2 | 701 | 702u | 742u | | 6982 | GPSouza--2GR |
| 7190 | 10 | 100 | 100 | 2 | 702 | 706u | 746u | 776u | 7190 | GJRicha--2GR |
| 7195 | 10 | 100 | 100 | 2 | 702 | 704u | 744u | 774u | 7195 | GNBraga--2GR |
| 6604 | 10 | 100 | 100 | 2 | 703 | 708u | 748u | 778u | 6604 | AraucarG-2GR |
| 6605 | 10 | 100 | 100 | 1 | 704 | 709u | 749u | 779u | 6605 | AraucarV-1GR |
| 7193 | 10 | 100 | 100 | 1 | 705 | 710u | 750u | 780u | 7193 | StaClara-1GR |
| 6969 | 10 | 100 | 100 | 1 | 706 | 711u | 751u | 781u | 6969 | Fundao---1GR |
| 8951 | 10 | 100 | 100 | 2 | 810 | | | | 8951 | Charquea-2GR |
| 8975 | 10 | 100 | 100 | 3 | 808 | 812u | 852u | 882u | 8975 | Ita------3GR |
| 8954 | 10 | 100 | 100 | 2 | 800 | 800u | 840u | | 8954 | JLacA1e2-2GR |
| 8955 | 10 | 100 | 100 | 2 | 801 | 801u | 841u | | 8955 | JLacA3e4-2GR |
| 8956 | 10 | 100 | 100 | 2 | 802 | 802u | 842u | 872u | 8956 | JLacB5e6-2GR |
| 8957 | 10 | 100 | 100 | 1 | 803 | 803u | 843u | 873u | 8957 | JLacerC7-1GR |
| 8718 | 10 | 100 | 100 | 2 | 815 | 815u | 855u | 885u | 8718 | Machadin-2GR |
| 8960 | 10 | 100 | 100 | 1 | 804 | 804u | 844u | 874u | 8960 | PFundo---1GR |
| 8972 | 10 | 100 | 100 | 2 | 805 | 806u | 846u | 876u | 8972 | SOsor1a4-2GR |
| 8973 | 10 | 100 | 100 | 1 | 806 | 808u | 848u | 878u | 8973 | SOsor5e6-1GR |
| 8974 | 10 | 100 | 100 | 2 | 807 | 810u | 850u | 880u | 8974 | SSantiag-2GR |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 8706 | 10 | 100 | 100 | 1 | 811 | 816u | 856u | | 8706 | WArjona1-1GR |
| 8707 | 10 | 100 | 100 | 1 | 811 | 817u | 857u | | 8707 | WArjona2-1GR |
| 8708 | 10 | 100 | 100 | 1 | 812 | 818u | 858u | | 8708 | WArjona3-1GR |
| 8710 | 10 | 100 | 100 | 1 | 812 | 819u | 859u | | 8710 | WArjona4-1GR |
| 8704 | 10 | 100 | 100 | 1 | 811 | 820u | 860u | | 8704 | WArjona5-1GR |
| 8750 | 10 | 100 | 100 | 1 | 818 | 823u | 862u | 887u | 8750 | Monjolin-1GR |
| 8801 | 10 | 100 | 100 | 1 | 824 | 824u | 863u | 888u | 8801 | SPilao---1GR |
| 4482 | 10 | 100 | 100 | 3 | 814 | 814u | 854u | 884u | 4482 | CBRAVA---3GR |
| 4486 | 10 | 100 | 100 | 2 | 817 | 822u | 861u | 886u | 4486 | SSALVADO-2GR |
| 3637 | 10 | 100 | 100 | 9 | 900 | 900u | 940u | | 3637 | ITAIPU50-9GR |
| 3584 | 10 | 100 | 100 | 9 | 901 | 901u | 941u | 971u | 3584 | ITAIPU60-9GR |
| 9141 | 10 | 100 | 100 | 2 | 1000 | 1000u | 1040u | 1070u | 9141 | Itauba---2GR |
| 9151 | 10 | 100 | 100 | 3 | 1001 | 1002u | 1042u | 1072u | 9151 | Jacui----3GR |
| 8918 | 10 | 100 | 100 | 2 | 1005 | 1010u | 1050u | 1080u | 8918 | UruguaiG-2GR |
| 8920 | 10 | 100 | 100 | 1 | 1006 | 1011u | 1051u | 1081u | 8920 | UruguaiV-1GR |
| 9432 | 10 | 100 | 100 | 2 | 1002 | 1004u | | | 9432 | PMediciA-2GR |
| 9440 | 10 | 100 | 100 | 2 | 1003 | 1006u | | | 9440 | PMediciB-2GR |
| 9251 | 10 | 100 | 100 | 1 | 1004 | 1008u | 1048u | 1078u | 9251 | PReal----1GR |
| 9091 | 10 | 100 | 100 | 1 | 1007 | 1009u | 1049u | 1079u | 9091 | DFrancis-1GR |
| 9327 | 10 | 100 | 100 | 1 | 1008 | 1013u | 1043u | 1073u | 9327 | SaoJose--1GR |
| 7730 | 10 | 100 | 100 | 1 | 1009 | 1014u | 1044u | 1074u | 7730 | PSJoao---1GR |
| 6716 | 10 | 100 | 100 | 2 | 1010 | 1015u | 1045u | 1075u | 6716 | Maua-----2GR |
| 35000 | 10 | 45 | 45 | 1 | 1100 | 1100u | 1140u | 1170u | 35000 | MASCAREN-1GR |
| 35000 | 20 | 55 | 55 | 1 | 1101 | 1101u | 1141u | 1171u | 35000 | MASCAREN-1GR |
| 35001 | 10 | 100 | 100 | 2 | 1102 | 1102u | 1142u | 1172u | 35001 | SUICA----2GR |
| 35002 | 10 | 100 | 100 | 2 | 1103 | 1103u | 1143u | 1173u | 35002 | RBONITO--2GR |
| 1 | 10 | 100 | 100 | 3 | 1200 | 1200u | 1240u | | 1 | PAFO-1G1-3GR |
| 4 | 10 | 100 | 100 | 1 | 1201 | 1202u | 1242u | | 4 | PAFO-2G1-1GR |
| 5 | 10 | 100 | 100 | 1 | 1201 | 1203u | 1243u | | 5 | PAFO-2G2-1GR |
| 6 | 10 | 100 | 100 | 1 | 1201 | 1204u | 1244u | | 6 | PAFO-2G3-1GR |
| 7 | 10 | 100 | 100 | 1 | 1202 | 1205u | 1245u | | 7 | PAFO-2G4-1GR |
| 8 | 10 | 100 | 100 | 1 | 1202 | 1206u | 1246u | | 8 | PAFO-2G5-1GR |
| 9 | 10 | 100 | 100 | 1 | 1202 | 1207u | 1247u | | 9 | PAFO-2G6-1GR |
| 10 | 10 | 100 | 100 | 2 | 1203 | 1208u | 1248u | | 10 | PAFO-3G1-2GR |
| 11 | 10 | 100 | 100 | 2 | 1203 | 1210u | 1250u | | 11 | PAFO-3G2-2GR |
| 14 | 10 | 100 | 100 | 6 | 1204 | 1211u | 1251u | 1271u | 14 | PAFO-4G1-6GR |
| 28 | 10 | 100 | 100 | 2 | 1205 | 1213u | 1253u | | 28 | ASALESG1-2GR |
| 29 | 10 | 100 | 100 | 2 | 1205 | 1215u | 1255u | | 29 | ASALESG2-2GR |
| 33 | 10 | 100 | 100 | 3 | 1206 | 1217u | 1257u | 1272u | 33 | LGONZAG1-3GR |
| 34 | 10 | 100 | 100 | 3 | 1207 | 1219u | 1259u | 1273u | 34 | LGONZAG2-3GR |
| 89 | 10 | 100 | 100 | 6 | 1208 | 1221u | 1261u | 1274u | 89 | XINGO----6GR |
| 841 | 10 | 100 | 100 | 1 | 1212 | 1231u | | | 841 | RCD-SIE--1CS |
| 941 | 10 | 100 | 100 | 1 | 1213 | 1232u | | | 941 | RCD-ALS--1CS |
| 428 | 10 | 100 | 100 | 1 | 1212 | 1233u | | | 428 | TERESINA-1CS |
| 44 | 10 | 100 | 100 | 2 | 1210 | 1226u | 1266u | | 44 | BOAESP-1-2GR |
| 46 | 10 | 100 | 100 | 2 | 1211 | 1228u | 1268u | 1277u | 46 | BOAESP-2-2GR |
| 81 | 10 | 100 | 100 | 5 | 1214 | 1235u | 1269u | 1278u | 81 | CAMACARI-5GR |
| 874 | 10 | 100 | 100 | 2 | 1213 | 1234u | | | 874 | CAMACARI-2CS |
| 21 | 10 | 100 | 100 | 6 | 1209 | 1223u | 1263u | 1275u | 21 | SOBRADIN-6GR |
| 485 | 10 | 100 | 100 | 1 | 1215 | 1237u | | | 485 | BJLAPA---1CS |
| 483 | 10 | 100 | 100 | 1 | 1216 | 1238u | | | 483 | IRECE----1CS |
| 938 | 10 | 100 | 100 | 2 | 1308 | 1308u | | | 938 | PDUTRA---2CS |
| 939 | 10 | 100 | 100 | 3 | 1310 | 1310u | | | 939 | IMPERATR-3CS |
| 199 | 10 | 100 | 100 | 1 | 1306 | 1307u | | | 199 | MARABA---1CS |
| 50 | 10 | 100 | 100 | 5 | 1300 | 1300u | 1340u | 1370u | 50 | TUCURUI1-5GR |
| 52 | 10 | 100 | 100 | 3 | 1301 | 1301u | 1341u | 1371u | 52 | TUCURUI2-3GR |
| 54 | 10 | 100 | 100 | 4 | 1303 | 1303u | 1342u | 1372u | 54 | TUCURUI3-4GR |
| 70 | 10 | 100 | 100 | 4 | 1304 | 1305u | 1343u | 1373u | 70 | TUCURUI5-4GR |
| 71 | 10 | 100 | 100 | 7 | 1304 | 1311u | 1344u | 1374u | 71 | TUCURUI6-7GR |
| 898 | 10 | 100 | 100 | 2 | 1306 | 1306u | | | 898 | VCONDE---2CS |
| 813 | 10 | 100 | 100 | 1 | 98 | | | | 813 | ALU_BINF-1GR |
| 26400 | 10 | 100 | 100 | 2 | 1403 | 1403u | 1443u | 1473u | 26400 | JUBA-1---2GR |
| 26401 | 10 | 100 | 100 | 2 | 1403 | 1406u | 1446u | 1476u | 26401 | JUBA-2---2GR |
| 26405 | 10 | 100 | 100 | 2 | 1404 | 1404u | 1444u | 1474u | 26405 | JAURU----2GR |
| 26404 | 10 | 100 | 100 | 3 | 1405 | 1405u | 1445u | 1475u | 26404 | GUAPORE--3GR |
| 167 | 10 | 100 | 100 | 5 | 1500 | 1500u | 1540u | 1570u | 167 | LAJEADO--5GR |
| 4383 | 10 | 75 | 75 | 6 | 1600 | 1600u | 1640u | | 4383 | UTBLSOBR-6GR |
| 4383 | 20 | 25 | 25 | 2 | 1601 | 1601u | 1641u | | 4383 | UTBLSOBR-2GR |
| 4394 | 10 | 100 | 100 | 12 | 1700 | 1700u | 1740u | | 4394 | UTEMLAGO12GR |
| 4396 | 10 | 100 | 100 | 8 | 1701 | 1701u | 1741u | | 4396 | UTEMLAGO-8GR |
| 433 | 10 | 100 | 100 | 2 | 1803 | 1800u | 1840u | 1870u | 433 | UTEJSPER-2GR |
| 4391 | 10 | 57 | 57 | 2 | 1900 | 1900u | 1940u | 1970u | 4391 | UTLBRZG1-2GR |
| 4391 | 20 | 43 | 43 | 1 | 1902 | 1902u | 1942u | 1972u | 4391 | UTLBRZ18-1GR |
| 4402 | 10 | 67 | 67 | 2 | 1900 | 1903u | 1943u | 1973u | 4402 | UTLBRZG2-2GR |
| 4402 | 20 | 33 | 33 | 1 | 1901 | 1905u | 1945u | 1975u | 4402 | UTLBRZ28-1GR |
| 4400 | 10 | 67 | 67 | 2 | 1900 | 1906u | 1946u | 1976u | 4400 | UTLBRZG3-2GR |
| 4400 | 20 | 33 | 33 | 1 | 1901 | 1908u | 1948u | 1978u | 4400 | UTLBRZ38-1GR |
| 4051 | 10 | 100 | 100 | 3 | 2000 | 2000u | 2040u | 2070u | 4051 | N.FLU-G1-3GR |
| 4049 | 10 | 100 | 100 | 1 | 2001 | 2001u | 2041u | 2071u | 4049 | N.FLU-V1-1GR |
| 95 | 10 | 100 | 100 | 3 | 2100 | 2100u | 2140u | 2170u | 95 | ITAPEBI--3GR |
| 26406 | 10 | 100 | 100 | 1 | 2200 | 2200u | 2240u | 2270u | 26406 | ITIQ-M1--1GR |
| 26412 | 10 | 100 | 100 | 1 | 2201 | 2201u | 2241u | 2271u | 26412 | ITIQ-M2--1GR |
| 170 | 10 | 100 | 100 | 1 | 2300 | 2300u | 2340u | 2370u | 170 | UTETBAHI-1GR |
| 3600 | 10 | 100 | 100 | 2 | 2400 | 2400u | 2440u | 2470u | 3600 | SIMPLICI-2GR |
| 4494 | 10 | 100 | 100 | 1 | 2500 | 2500u | 2540u | 2570u | 4494 | PIRAJU---1GR |
| 8717 | 10 | 100 | 100 | 1 | 2600 | 2600u | 2640u | 2670u | 8717 | STIARAJU-1GR |
| 4397 | 10 | 100 | 100 | 1 | 2601 | 2601u | 2641u | 2671u | 4397 | UTACHAVG-1GR |
| 4423 | 10 | 100 | 100 | 1 | 2602 | 2602u | 2642u | 2672u | 4423 | UTACHAVV-1GR |

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 4392   10 100 100   2   2603   2603u         2673u      4392 UTCPRESA-2GR
 4393   10 100 100   2   2603   2604u         2674u      4393 UTCPRESB-2GR
 4374   10 100 100   1   2605   2605u  2645u             4374 UTEROCHG-1GR
 4384   10 100 100   1   2606   2606u  2646u             4384 UTEROCHV-1GR
  339   10 100 100   4   2700   2700u  2740u  2770u       339 TERMOCEG-4GR
  327   10 100 100   2   2900   2900u  2940u  2970u       327 TERMFTZG-2GR
  330   10 100 100   1   2901   2901u  2941u  2971u       330 TERMFTZV-1GR
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  160   10 100 100   2   3100   3100u  3140u  3170u       160 TERMOPEG-2GR
  161   10 100 100   1   3101   3101u  3141u  3171u       161 TERMOPEV-1GR
 7303   10 100 100   2   3200   3200u  3240u  3270u      7303 BGRANDE--2GR
   48   10 100 100   2   3300   3300u  3340u  3370u        48 P.CAVALO-2GR
 4483   10 100 100   2   3301   3301u                    4483 OURINHOS-2GR
 1437   10 100 100   1   3302   3302u  3342u  3372u      1437 PICADA---1GR
26407   10 100 100   2   3400   3400u  3440u  3470u     26407 P.PEDRA--2GR
 7309   10 100 100   1   3500   3500u  3540u  3570u      7309 MCLARO---1GR
 7311   10 100 100   2   3501   3501u  3541u  3571u      7311 CALVES---2GR
 7313   10 100 100   1   3502   3502u  3542u  3572u      7313 14JULHO--1GR
 4386   10 100 100   1   3600   3600u  3640u  3670u      4386 JFORA-A--1GR
 4387   10 100 100   1   3600   3601u  3641u  3671u      4387 JFORA-B--1GR
 1442   10 100 100   2   3700   3700u  3740u  3770u      1442 STACLARA-2GR
 1423   10 100 100   2   3800   3800u  3840u  3870u      1423 R.NEVES--2GR
 3599   10 100 100   3   3900   3900u  3940u  3970u      3599 PEIXEANG-3GR
 1424   10 100 100   2   4000   4000u  4040u  4070u      1424 AMADORA1-2GR
 1425   10 100 100   2   4001   4001u  4041u  4071u      1425 AMADORA2-2GR
 7301   10 100 100   2   4100   4100u  4140u  4170u      7301 CNOVOS---2GR
 4371   10 100 100   1   4300   4300u  4340u  4370u      4371 CORUMBA4-1GR
23310   10 100 100   2   4400   4400u  4440u  4470u     23310 ESPORA---2GR
 9512   10 100 100   3   4702   4702u  4742u  4772u      9512 UTETN2-G-3GR
 9514   10 100 100   1   4703   4703u  4743u  4773u      9514 UTETN2-V-1GR
 9511   10 100 100   4   4704   4704u  4744u             9511 UTETN1---4GR
 9501   10 100 100   4   4705   4705u  4745u  4775u      9501 UHESAMUE-4GR
 9518   10 100 100   3   4706   4706u  4746u999991u      9518 UHEROND2-3GR
  413   10 100 100   1   4803   4803u  4843u              413 UTEMANAU-1GR
  412   10 100 100   1   4802   4802u  4842u              412 UTEPFERR-1GR
16402   10 100 100   2   4800   4800u  4840u            16402 UTEPOTI1-2GR
16403   10 100 100   3   4801   4801u  4841u            16403 UTEPOTI3-3GR
  108   10 100 100   8   4805   4805u  4845u              108 UTEMURIC-8GR
  109   10 100 100  60   4804   4804u                     109 UTEAREMB60GR
  128   10 100 100  60   4807   4810u  4850u              128 UTEGLOBI60GR
  129   10 100 100  60   4807   4811u  4851u              129 UTEGLOII60GR
  801   10 100 100   1   4808   4812u  4852u  4872u       801 PITAQUI--1GR
 3583   10 100 100   2   4900   4900u  4940u  4970u      3583 R.BAIXO--2GR
 4540   10  50  50   1   5000   5000u         5070u      4540 CSA-G1---1GR
 4540   20  50  50   1   5000   5002u         5072u      4540 CSA-G2---1GR
 4539   10 100 100   1   5001   5001u         5071u      4539 CSA-V----1GR
 4405   10  50  50   5   5100   5100u  5140u             4405 VIANA-A--5GR
 4405   20  50  50   5   5100   5101u  5141u             4405 VIANA-B--5GR
( 4406   10 100 100   32   5101   5102u  5142u  5172u      4406 UTELINHA24GR
 4364   10 100 100   4   5300   5300u  5340u  5370u      4364 DARDANE1-4GR
 4360   10 100 100   1   5301   5301u  5341u  5371u      4360 DARDANE2-1GR
   80   10 100 100   8   5400   5400u  5440u  5470u        80 ESTREITO-8GR
 8712   10 100 100   1   5500   5500u  5540u  5570u      8712 CANDIOT3-1GR
 7305   10 100 100   2   5600   5600u  5640u  5670u      7305 FCHAPECO-2GR
 4343   10 100 100   1   5720   5720u  5760u  5780u      4343 CACU-----1GR
 4344   10 100 100   1   5721   5721u  5761u  5781u      4344 SALTO----1GR
 4342   10 100 100   1   5722   5722u  5762u  5782u      4342 B.COQUEI-1GR
 4331   10 100 100   1   5723   5723u  5763u  5783u      4331 S.R.VERD-1GR
 4341   10 100 100   1   5724   5724u  5764u  5784u      4341 FRCLARO--1GR
 4336   10 100 100   1   5800   5800u  5840u  5870u      4336 SERRAFAC-1GR
 5194   10  50  50   4   6000   6000u  6040u  6070u      5194 SANTO-MD-4GR
 5194   20  50  50   4   6000   6001u  6041u  6071u      5194 SANTO-MD-4GR
 5193   10 100 100   4   6000   6002u  6042u  6072u      5193 SANTO-LE-4GR
 5213   10 100 100   8   6000   6003u  6043u  6073u      5213 SANTO-LE-8GR
 5192   10 100 100   8   6000   6004u  6044u  6074u      5192 SANTO-ME-8GR
 5212   10 100 100  16   6000   6005u  6045u  6075u      5212 SANTO-ME16GR
 5191   10 100 100  25   6100   6100u  6140u  6170u      5191 JIRAU-MD25GR
 5190   10 100 100  18   6101   6101u  6141u  6171u      5190 JIRAU-ME18GR
13003   10 100 100   2   4810   4815u  4855u  4875u     13003 MARANIVG-2GR
13007   10 100 100   1   1315  40041u 40042u 40052u     13007 MARANIVV-1GR
13008   10 100 100   2   4810   4816u  4856u  4876u     13008 MARANV-G-2GR
13009   10 100 100   1   1315   4413u  4433u  4453u     13009 MARANV-V-1GR
13016   10 100 100   2   1311   1315u  8345u  8375u     13016 MARAN3-G-2GR
(13029   10 100 100    1   4810   4817u  4857u  4877u     13029 N.VENEC2-1GR
  104   10 100 100  23   4809   4818u  4858u  4878u       104 UTEPERN323GR
  101   10 100 100  16   6020   6021u  6022u              101 UTESUAP216GR
11001   10 100 100   2   4808   4813u  4853u  4873u     11001 PPECEM1--2GR
11010   10 100 100   1   4808   4814u  4854u  4874u     11010 PPECEM2--1GR
 8735   10 100 100   2   6400   6400u  6440u  6470u      8735 UHSROQUE-2GR
 6609   10 100 100   2   6500   6500u  6540u  6570u      6609 BIGUACU -2GR
 4398   10  65  65   2   2687   2687u  2667u  2697u      4398 BAIXFLUG-2GR
 4398   20  35  35   1   2688   2688u  2668u  2698u      4398 BAIXFLUV-1GR
  307   10 100 100  23   6324   6324u  6424u              307 UTE1JAGA23GR
11015   10 100 100  23   6329   6329u  6429u            11015 UTE1JAGB23GR
11016   10 100 100   9   6330   6330u  6430u            11016 UTE2JAGA-9GR
11017   10 100 100   9   6326   6326u  6426u            11017 UTE2JAGB-9GR
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  130   10 100 100  20   7803   7804u  7814u            130 TERMOPAR20GR
  137   10 100 100  20   7803   7803u  7813u            137 TERMONE 20GR
  135   10 100 100   8   7802   7802u  7812u  7872u     135 MARACAT1-8GR
  102   10 100 100   3   7805   7805u  7815u            102 MARACAT2-3GR
40201   10 100 100   1   5501    136u   166u   347u   40201 ANTA-----1GR
10020   10 100 100   2   7000   7000u  7040u          10020 C.NUNES1-2GR
10021   10 100 100   1   7001   7001u  7041u          10021 C.NUNES2-1GR
10411   10 100 100   1   7104   7104u  7144u          10411 BALBINA1-1GR
10412   10 100 100   1   7104  40061u 40032u          10412 BALBINA2-1GR
10413   10 100 100   1   7104  40033u 40034u          10413 BALBINA3-1GR
10414   10 100 100   1   7104  40035u 40036u          10414 BALBINA4-1GR
10415   10 100 100   1   7104  40037u 40038u          10415 BALBINA5-1GR
10471   10 100 100  19   7112   7112u  7152u          10471 PIE-JRQ-19GR
10447   10 100 100  19   7113   7113u  7153u          10447 PIE-TBQ-19GR
10436   10 100 100   4   7107   7109u  7149u          10436 PIE_MANA-4GR
10391   10 100 100   4   7108   7110u  7150u          10391 PIE-GERA-4GR
10406   10 100 100   2   7109   7111u  7151u          10406 CROCHA_E-2GR
 4941   10  78  78  14   8101  80501u 80502u 80503u    4941 BM------14GR
 4941   20  22  22   4   8102  80513u 80514u 80515u    4941 BM-IMPIS-4GR
  195   10 100 100   6   8103  80551u 80552u 80553u     195 BM-SECUN-6GR
 7227   10 100 100   1   4005   2803u  2804u           7227 UHTELBOR-1GR
 8730   10 100 100   2   4030   2821u  2822u           8730 UHGARIBA-2GR
 4373   10 100 100   1   1511   2827u  2828u           4373 UH-CORUM-1GR
 4583   10 100 100   2   8896   8896u  8887u  8892U    4583 COLIDER--2GR
 4589   10 100 100   4   8883   8883u  8888u  8891U    4589 T.PIRES -4GR
 4581   10 100 100   3   8881   8881u  8886u  8899U    4581 SINOP   -3GR
 4585   10 100 100   4   8885   8885u  8890u  8893U    4585 SMANOEL -4GR
 4587   10 100 100   1   8884   8884u  8889u           4587 F.APIAC -1GR
10082   10 100 100   3   6081   4271u  4272u          10082 F.GOMES -3GR
10084   10 100 100   3   6080   4261u  4262u  4263u   10084 S.A.JARI-3GR
10171   10 100 100   3   8304   8312U  8322U  8332U   10171 CACH. CA-3GR
41970   10 100 100   4   8305   8313U  8323U980522U   41970 SANT.ADI-4GR
38079   10 100 100   1   8307   8315U  8325U  8335U   38079 ITAOCAR1-1GR
 4334   10 100 100   2   8308   8316U  8326U  8336U    4334 DAVINOPO-2GR
50205   10 100 100   1   8311   8319U  8329U  8339U   50205 COMISSIO-1GR
50207   10 100 100   1   8312   8320U  8330U  8340U   50207 F.PIQUIR-1GR
 8716   10 100 100   1   5013   2859u  2860u           8716 CANOAS2 -1GR
  357   10  91  91   2   1512   2849u  2850u            357 FAFEN-1 -2GR
  357   20   9   9   1   1518   2851u  2852u            357 FAFEN-2 -1GR
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  50      60 1         1231.9
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1109    1110 1         2691.0
1113    1114 1         2691.0
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2105    2106 1           80.00
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3105    3106 1         2497.0
3109    3110 1         2987.0
3113    3114 1         2987.0
4101    4102 1         2497.0
4105    4106 1         2497.0
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0003        1
0004        1
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1002        1
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3002        2
3003        2
3004        2
4001        2
4002        2
999999
DCNV
   1          5. 163.         01   0193u
   2        100.       17.    02
   3          5. 163.         01   0194u
   4        100.       17.    02
   5          5. 163.         01   0195u
   6        100.       17.    02
   7          5. 163.         01   0196u
   8        100.       17.    02
1201                         101   9301u
1202                         102
1203                         101   9303u
1204                         102
1205                        9009u
1206                        9010u
1207                        9011u
1208                        9012u
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2201                       9321 U
2202                       9322 U
2203                       9323 U
2204                       9324 U
3201                         301
3202                         302
3203                         301
3204                         302
3205                         303
3206                         304
3207                         303
3208                         304
4201                        4201
4202                        4202
4203                        4201
4204                        4202
8011                        1393u
8012                        1394u
8021                        1395u
8022                        1396u
8031                        1397u
8032                        1398u
999999
DFCM
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   4        14.1 0.016
   6        14.1 0.016
   8        14.1 0.016
1202 0.8         0.016
1204 0.8         0.016
1206 0.8         0.016
1208 0.8         0.016
2202 0.8          .016
2204 0.8          .016
3202 0.8         0.016
3204 0.8         0.016
3206 0.8         0.016
3208 0.8         0.016
4202 0.8         0.016
4204 0.8         0.016
999999
ULOG
1
DCER-2020.DAT
DLOC
1296   CIRCAC   58511594 1  585
1497   CIRCAC  953441967 1
999999
DCNE IMPR
9000     9300u
9315     9315U
999999
DCSC
 4431    3895  1    199u
  539     736  1   1391u
 5000    3895  1   2890u
  539     758  1   2891u
999999
ULOG
1
DPLT.DAT
DCAR
AREA   1   A AREA 118                              100  0   0  100
999999
DSIM
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EXSI
DSIM
    20.0  .001    11
EXSI
FIM
```
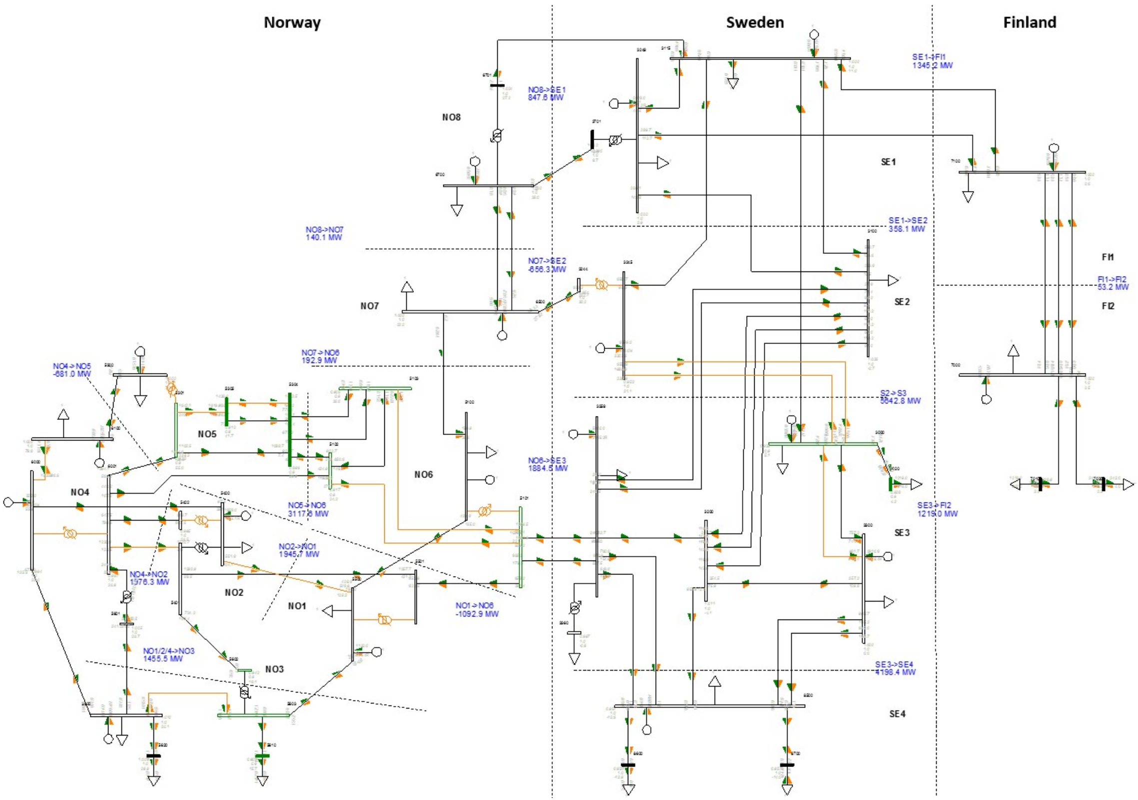

# Appendix D

# Nordic 44 System



# D.1 Power Flow Data File

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  3100,'            ', 420.0000,1,  22,   1,   1,1.02520,   0.0345,1.10000,0.90000,1.10000,0.90000
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  3244,'            ', 300.0000,1,  22,   1,   1,0.94693,  32.3216,1.10000,0.90000,1.10000,0.90000
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  3249,'            ', 420.0000,2,  21,   1,   1,1.00000,   8.1348,1.10000,0.90000,1.10000,0.90000
  3300,'            ', 420.0000,3,  23,   1,   1,1.00000,   0.0000,1.10000,0.90000,1.10000,0.90000
  3359,'            ', 420.0000,2,  23,   1,   1,1.00000,   1.5693,1.10000,0.90000,1.10000,0.90000
  3360,'            ', 135.0000,1,  23,   1,   1,0.99657,   2.0240,1.10000,0.90000,1.10000,0.90000
  3701,'            ', 300.0000,1,  21,   1,   1,0.99020,  12.8634,1.10000,0.90000,1.10000,0.90000
  5100,'            ', 300.0000,2,  16,   1,   1,0.96635,  16.2245,1.10000,0.90000,1.10000,0.90000
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  5301,'            ', 420.0000,1,  15,   1,   1,0.92864,  60.4580,1.10000,0.90000,1.10000,0.90000
  5304,'            ', 420.0000,1,  15,   1,   1,0.88780,  44.8952,1.10000,0.90000,1.10000,0.90000
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  5601,'            ', 300.0000,1,  13,   1,   1,1.00428,  41.9598,1.10000,0.90000,1.10000,0.90000
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  6001,'            ', 420.0000,1,  14,   1,   1,0.98625,  42.1113,1.10000,0.90000,1.10000,0.90000
  6100,'            ', 300.0000,2,  14,   1,   1,1.00000,  85.7523,1.10000,0.90000,1.10000,0.90000
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  7100,'            ', 420.0000,2,  31,   1,   1,1.00000,   7.1215,1.10000,0.90000,1.10000,0.90000
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  3359,  8500,'1 ', 1.20000E-2, 2.70000E-1,   0.10000, 1500.00, 2000.00, 2500.00,  0.00000,  0.00000,  0.00000,
0.00000,1,1,   0.00,   1,1.0000
  3359,  8500,'2 ', 2.50000E-2, 3.20000E-1,   0.09000, 1100.00, 1300.00, 1400.00,  0.00000,  0.00000,  0.00000,
0.00000,1,1,   0.00,   1,1.0000
  3701,  6700,'1 ', 2.50000E-1, 2.00000E+0,   0.03000,  300.00,  400.00,  500.00,  0.00000,  0.00000,  0.00000,
0.00000,1,2,   0.00,   1,1.0000
  5100,  5500,'1 ', 2.70000E-2, 2.60000E-1,   0.04400,  700.00,  800.00,  900.00,  0.00000,  0.00000,  0.00000,
0.00000,1,2,   0.00,   1,1.0000
  5100,  6500,'1 ', 8.00000E-2, 9.00000E-1,   0.06000,  800.00,  900.00,  950.00,  0.00000,  0.00000,  0.00000,
0.00000,1,1,   0.00,   1,1.0000
  5101,  5102,'1 ', 8.00000E-3, 1.00000E-1,   0.09000, 1700.00, 1800.00, 1900.00,  0.00000,  0.00000,  0.00000,
0.00000,1,2,   0.00,   1,1.0000
  5101,  5103,'1 ', 1.00000E-2, 1.40000E-1,   0.04000, 1350.00, 1600.00, 1800.00,  0.00000,  0.00000,  0.00000,
0.00000,1,2,   0.00,   1,1.0000
  5101,  5501,'1 ', 1.00000E-2, 1.50000E-1,   0.55000, 2000.00, 2200.00, 2500.00,  0.02230, -0.97440, -0.02160,
0.97440,1,2,   0.00,   1,1.0000
  5102,  5103,'1 ', 4.00000E-3, 7.00000E-2,   0.03000, 2000.00, 2200.00, 2400.00,  0.00000,  0.00000,  0.00000,
0.00000,1,1,   0.00,   1,1.0000
  5102,  5304,'1 ', 1.70000E-2, 2.40000E-1,   0.07000, 1500.00, 1800.00, 2000.00,  0.00000,  0.00000,  0.00000,
0.00000,1,2,   0.00,   1,1.0000
  5102,  6001,'1 ', 3.00000E-2, 4.60000E-1,   0.13000, 1450.00, 1700.00, 2000.00,  0.00020,  0.00010,  0.00020, -
0.00010,1,2,   0.00,   1,1.0000
  5103,  5304,'1 ', 2.00000E-2, 2.50000E-1,   0.07000, 1000.00, 1200.00, 1400.00,  0.00000,  0.00000,  0.00000,
0.00000,1,2,   0.00,   1,1.0000
  5103,  5304,'2 ', 1.30000E-2, 2.00000E-1,   0.06000, 1500.00, 1800.00, 2000.00,  0.00000,  0.00000,  0.00000,
0.00000,1,2,   0.00,   1,1.0000
```

```
  5300,  6100,'1 ', 2.10000E-2, 2.20000E-1,   0.01000,  800.00,  900.00,  950.00,  0.00000,  0.00000,  0.00000,
0.00000,1,2,   0.00,   1,1.0000
  5301,  5304,'1 ', 1.00000E-2, 2.00000E-1,   0.06000, 1250.00, 1500.00, 1700.00,  0.00000,  0.00000,  0.00000,
0.00000,1,1,   0.00,   1,1.0000
  5301,  5305,'1 ', 7.00000E-3, 1.20000E-1,   0.03100, 1250.00, 1500.00, 1700.00,  0.00000,  0.00000,  0.00000,
0.00000,1,1,   0.00,   1,1.0000
  5301,  6001,'1 ', 1.30000E-2, 2.00000E-1,   0.05000, 1800.00, 2000.00, 2150.00,  0.00000,  0.00000,  0.00000,
0.00000,1,2,   0.00,   1,1.0000
  5304,  5305,'1 ', 1.00000E-2, 1.50000E-1,   0.05000, 1950.00, 2200.00, 2400.00,  0.00000,  0.00000,  0.00000,
0.00000,1,2,   0.00,   1,1.0000
  5304,  5305,'2 ', 1.30000E-2, 1.70000E-2,   0.04000, 1350.00, 1400.00, 1500.00,  0.00000,  0.00000,  0.00000,
0.00000,1,2,   0.00,   1,1.0000
  5400,  5500,'1 ', 9.00000E-3, 9.40000E-1,   0.05000,  400.00,  550.00,  650.00,  0.00000,  0.00000,  0.00000,
0.00000,1,1,   0.00,   1,1.0000
  5400,  6000,'1 ', 3.30000E-2, 3.60000E-1,   0.02500,  800.00,  900.00,  950.00,  0.00000,  0.00000,  0.00000,
0.00000,1,2,   0.00,   1,1.0000
  5401,  5501,'1 ', 1.75000E-2, 2.70000E-1,   0.08000, 1500.00, 1800.00, 2000.00,  0.00000,  0.00000,  0.00000,
0.00000,1,1,   0.00,   1,1.0000
  5401,  5602,'1 ', 1.60000E-2, 2.55000E-1,   0.09000, 2200.00, 2400.00, 2600.00,  0.00000,  0.00000,  0.00000,
0.00000,1,1,   0.00,   1,1.0000
  5401,  6001,'1 ', 6.40000E-3, 1.00000E-1,   0.02800, 1250.00, 1500.00, 1700.00, -0.00020, -0.00050,  0.00020,
0.00050,1,2,   0.00,   1,1.0000
  5402,  6001,'1 ', 7.00000E-4, 1.00000E-2,   0.00300, 1500.00, 1700.00, 1900.00,  0.00000,  0.00000,  0.00000,
0.00000,1,2,   0.00,   1,1.0000
  5500,  5603,'1 ', 5.00000E-2, 6.00000E-1,   0.05000,  800.00,  900.00,  950.00,  0.00030,  0.00130, -0.00030, -
0.00130,1,1,   0.00,   1,1.0000
  5600,  5601,'1 ', 3.00000E-2, 3.40000E-1,   0.02000,  800.00,  900.00,  950.00,  0.00000,  0.00000,  0.00000,
0.00000,1,2,   0.00,   1,1.0000
  5600,  5603,'1 ', 2.00000E-2, 2.20000E-1,   0.02000,  900.00, 1050.00, 1200.00,  0.00000,  0.00000,  0.00000,
0.00000,1,1,   0.00,   1,1.0000
  5600,  5620,'1 ', 0.00000E+0, 1.00000E-2,   0.00000,    0.00,    0.00,    0.00,  0.00000,  0.00000,  0.00000,
0.00000,1,1,   0.00,   1,1.0000
  5600,  6000,'1 ', 2.00000E-2, 2.00000E-1,   0.07000, 1350.00, 1500.00, 1650.00,  0.00000,  0.00000,  0.00000,
0.00000,1,1,   0.00,   1,1.0000
  5603,  5610,'1 ', 0.00000E+0, 1.00000E-2,   0.00000,    0.00,    0.00,    0.00,  0.00000,  0.00000,  0.00000,
0.00000,1,1,   0.00,   1,1.0000
  6000,  6100,'1 ', 3.40000E-2, 4.20000E-1,   0.03000,  800.00,  900.00,  950.00,  0.00000,  0.00000,  0.00000,
0.00000,1,1,   0.00,   1,1.0000
  6500,  6700,'1 ', 1.70000E-1, 1.80000E+0,   0.10000,  800.00,  900.00,  950.00,  0.00000,  0.00000,  0.00000,
0.00000,1,1,   0.00,   1,1.0000
  6500,  6700,'2 ', 1.00000E-1, 1.30000E+0,   0.12000, 1000.00, 1200.00, 1300.00,  0.00000,  0.00000,  0.00000,
0.00000,1,1,   0.00,   1,1.0000
  7000,  7010,'1 ', 0.00000E+0, 1.00000E-2,   0.00000,    0.00,    0.00,    0.00,  0.00000,  0.00000,  0.00000,
0.00000,1,1,   0.00,   1,1.0000
  7000,  7020,'1 ', 0.00000E+0, 1.00000E-2,   0.00000,    0.00,    0.00,    0.00,  0.00000,  0.00000,  0.00000,
0.00000,1,1,   0.00,   1,1.0000
  7000,  7100,'1 ', 4.00000E-2, 1.20000E-1,   0.13000, 1040.00, 1200.00, 1500.00,  0.00000,  0.00000,  0.00000,
0.00000,1,2,   0.00,   1,1.0000
  7000,  7100,'2 ', 4.00000E-2, 1.20000E-1,   0.13000, 1040.00, 1200.00, 1500.00,  0.00000,  0.00000,  0.00000,
0.00000,1,2,   0.00,   1,1.0000
  7000,  7100,'3 ', 4.00000E-2, 1.40000E-1,   0.13000, 1200.00, 1500.00, 1700.00,  0.00000,  0.00000,  0.00000,
0.00000,1,2,   0.00,   1,1.0000
  8500,  8600,'1 ', 0.00000E+0, 1.00000E-2,   0.00000,    0.00,    0.00,    0.00,  0.00000,  0.00000,  0.00000,
0.00000,1,1,   0.00,   1,1.0000
  8500,  8700,'1 ', 0.00000E+0, 1.00000E-2,   0.00000,    0.00,    0.00,    0.00,  0.00000,  0.00000,  0.00000,
0.00000,1,1,   0.00,   1,1.0000
0 / END OF BRANCH DATA, BEGIN TRANSFORMER DATA
  3244,  3245,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'            ',1,   1,1.0000,   0,1.0000,   0,1.0000,
0,1.0000,'            '
 5.00000E-3, 2.00000E-2,  1000.00
1.00000,   0.000,   0.000,   500.00,   500.00,     0.00, 1,   3245, 1.40000, 0.60000, 1.01000, 0.99000, 127, 0,
0.00000, 0.00000,  0.000
1.00000,   0.000
  3701,  3249,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'            ',1,   1,1.0000,   0,1.0000,   0,1.0000,
0,1.0000,'            '
 2.00000E-2, 5.00000E-1,  1000.00
1.00000,   0.000,   0.000,   300.00,   350.00,     0.00, 1,   3701, 1.40000, 0.60000, 1.01000, 0.99000, 127, 0,
0.00000, 0.00000,  0.000
1.00000,   0.000
  3359,  3360,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'            ',1,   1,1.0000,   0,1.0000,   0,1.0000,
0,1.0000,'            '
 5.00000E-3, 2.00000E-2,  1000.00
0.99980,   0.000,   0.000,  1000.00,  9000.00,  9000.00, 1,   3360, 1.40000, 0.60000, 1.01000, 0.99000, 127, 0,
0.00000, 0.00000,  0.000
1.00000,   0.000
  5101,  5100,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'            ',1,   1,1.0000,   0,1.0000,   0,1.0000,
0,1.0000,'            '
 8.00000E-4, 3.05000E-2,  1000.00
1.00635,   0.000,   0.000,  1000.00,  9000.00,  9000.00, 1,   5101, 1.40000, 0.60000, 1.01000, 0.99000, 127, 0,
0.00000, 0.00000,  0.000
1.00000,   0.000
  5300,  5301,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'            ',1,   1,1.0000,   0,1.0000,   0,1.0000,
0,1.0000,'            '
 1.60000E-3, 6.10000E-2,  1000.00
1.00000,   0.000,   0.000,  2000.00,  9000.00,  9000.00, 1,   5301, 1.40000, 0.60000, 1.01000, 0.99000, 127, 0,
0.00000, 0.00000,  0.000
1.00000,   0.000
  5400,  5401,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'            ',1,   1,1.0000,   0,1.0000,   0,1.0000,
0,1.0000,'            '
 3.20000E-3, 1.20000E-1,  1000.00
1.00635,   0.000,   0.000,  1000.00,  9000.00,  9000.00, 1,   5401, 1.40000, 0.60000, 1.01000, 0.99000, 127, 0,
0.00000, 0.00000,  0.000
1.00000,   0.000
  5400,  5402,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'            ',1,   1,1.0000,   0,1.0000,   0,1.0000,
0,1.0000,'            '
```

```
 4.00000E-4, 1.50000E-2,  1000.00
1.00000,   0.000,   0.000,  1000.00,  9000.00,  9000.00, 1,   5402, 1.40000, 0.60000, 1.01000, 0.99000, 127, 0,
0.00000, 0.00000,  0.000
1.00000,   0.000
  5500,  5501,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'            ',1,   1,1.0000,   0,1.0000,   0,1.0000,
0,1.0000,'            '
 4.00000E-4, 1.50000E-2,  1000.00
1.01260,   0.000,   0.000,  1000.00,  9000.00,  9000.00, 1,   5501, 1.40000, 0.60000, 1.01000, 0.99000, 127, 0,
0.00000, 0.00000,  0.000
1.00000,   0.000
  5601,  6001,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'            ',1,   1,1.0000,   0,1.0000,   0,1.0000,
0,1.0000,'            '
 2.00000E-4, 7.60000E-3,  1000.00
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0.00000, 0.00000,  0.000
1.00000,   0.000
  5603,  5602,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'            ',1,   1,1.0000,   0,1.0000,   0,1.0000,
0,1.0000,'            '
 8.00000E-4, 3.05000E-2,  1000.00
0.96825,   0.000,   0.000,  1000.00,  9000.00,  9000.00, 1,   5602, 1.40000, 0.60000, 1.01000, 0.99000, 127, 0,
0.00000, 0.00000,  0.000
1.00000,   0.000
  6000,  6001,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'            ',1,   1,1.0000,   0,1.0000,   0,1.0000,
0,1.0000,'            '
 4.00000E-4, 1.50000E-2,  1000.00
1.00625,   0.000,   0.000,  1000.00,  9000.00,  9000.00, 1,   6001, 1.40000, 0.60000, 1.01000, 0.99000, 127, 0,
0.00000, 0.00000,  0.000
1.00000,   0.000
  6700,  6701,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'            ',1,   1,1.0000,   0,1.0000,   0,1.0000,
0,1.0000,'            '
 5.00000E-3, 2.00000E-2,  1000.00
1.01250,   0.000,   0.000,  1000.00,  9000.00,  9000.00, 1,   6701, 1.40000, 0.60000, 1.01000, 0.99000, 127, 0,
0.00000, 0.00000,  0.000
1.00000,   0.000
0 / END OF TRANSFORMER DATA, BEGIN AREA DATA
  11,     0,     0.000,    10.000,'NO1         '
  12,     0,     0.000,    10.000,'NO2         '
  13,     0,     0.000,    10.000,'NO3         '
  14,     0,     0.000,    10.000,'NO4         '
  15,     0,     0.000,    10.000,'NO5         '
  16,     0,     0.000,    10.000,'NO6         '
  17,     0,     0.000,    10.000,'NO7         '
  18,     0,     0.000,    10.000,'NO8         '
  21,     0,     0.000,    10.000,'SE1         '
  22,     0,     0.000,    10.000,'SE2         '
  23,     0,     0.000,    10.000,'SE3         '
  24,     0,     0.000,    10.000,'SE4         '
  31,     0,     0.000,    10.000,'FI1         '
  32,     0,     0.000,    10.000,'FI2         '
0 / END OF AREA DATA, BEGIN TWO-TERMINAL DC DATA
0 / END OF TWO-TERMINAL DC DATA, BEGIN VSC DC LINE DATA
0 / END OF VSC DC LINE DATA, BEGIN IMPEDANCE CORRECTION DATA
0 / END OF IMPEDANCE CORRECTION DATA, BEGIN MULTI-TERMINAL DC DATA
0 / END OF MULTI-TERMINAL DC DATA, BEGIN MULTI-SECTION LINE DATA
0 / END OF MULTI-SECTION LINE DATA, BEGIN ZONE DATA
0 / END OF ZONE DATA, BEGIN INTER-AREA TRANSFER DATA
0 / END OF INTER-AREA TRANSFER DATA, BEGIN OWNER DATA
0 / END OF OWNER DATA, BEGIN FACTS DEVICE DATA
0 / END OF FACTS DEVICE DATA, BEGIN SWITCHED SHUNT DATA
0 / END OF SWITCHED SHUNT DATA, BEGIN GNE DATA
0 / END OF GNE DATA, BEGIN INDUCTION MACHINE DATA
0 / END OF INDUCTION MACHINE DATA
Q
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## D.2 Dynamic Data File

```
/
/ Nordic 44 system
/
   3000 'GENROU' 1     5.0000       0.50000E-01   1.0000       0.50000E-01
          5.9700       0.0000       2.2200       2.1300       0.36000
         0.46800      0.22500      0.16875      0.10890      0.37795    /
   /3000 'STAB2A' 1     1.0000       2.0000       0.0000       2.0000
   /      0.55000       1.0000      0.10000E-01  0.30000E-01/
   3000 'IEEET2' 1     0.0000       729.00      0.40000E-01   5.3200
         -4.0500       1.0000      0.44000      0.66700E-01   2.0000
         0.44000       6.5000      0.54000E-01   8.0000      0.20200    /
   3000 'IEESGO' 1    0.10000E-01   0.0000      0.15000      0.30000
          8.0000      0.40000       0.0000      0.70000      0.43000
          1.0000       0.0000    /
   3115 'GENSAL' 1     7.5700      0.45000E-01  0.10000       4.7410
          0.0000      0.94600      0.56500      0.29000      0.23000
         0.11077      0.10239      0.27420    /
   /3115 'STAB2A' 1     1.0000       4.5000      0.87000       2.0000
   /      0.87000E-01   1.0000      0.10000E-01  0.40000E-01/
   3115 'SCRX'   1    0.25385       13.000       31.000      0.50000E-01
          0.0000       4.0000       0.0000       0.0000    /
   3115 'HYGOV'  1    0.60000E-01  0.40000       5.0000      0.50000E-01
         0.20000      0.10000       1.0000       0.0000       1.0000
          1.0577      0.50000      0.10000    /
   3245 'GENSAL' 1     5.0000      0.60000E-01  0.10000       3.3000
          0.0000      0.75000      0.50000      0.25000      0.15385
         0.11538      0.10239      0.27420    /
   3245 'SCRX'   1    0.25385       13.000       31.000      0.50000E-01
          0.0000       4.0000       0.0000       0.0000    /
   3245 'HYGOV'  1    0.60000E-01  0.40000       5.0000      0.50000E-01
         0.20000      0.10000       1.0000       0.0000       1.0000
          1.0100      0.50000      0.10000    /
   3249 'GENSAL' 1     10.130      0.60000E-01  0.10000       4.5430
          0.0000       1.0360      0.63000      0.28000      0.21000
         0.11538      0.10239      0.27420    /
   3249 'SCRX'   1    0.25385       13.000       31.000      0.50000E-01
          0.0000       4.0000       0.0000       0.0000    /
   3249 'HYGOV'  1    0.60000E-01  0.40000       5.0000      0.50000E-01
         0.20000      0.10000       1.0000       0.0000       1.0000
          1.1000      0.50000      0.10000    /
   3300 'GENROU' 1     10.800      0.50000E-01   1.0000      0.50000E-01
          6.0000       0.0000       2.4200       2.0000      0.23000
         0.41080      0.16000      0.14812      0.10890      0.37795    /
   /3300 'STAB2A' 1     1.0000       4.5000       0.0000       2.0000
   /      0.55000       1.0000      0.10000E-01  0.30000E-01/
   3300 'SCRX'   1     0.0000      0.40000E-01   10.000      0.40000E-01
          0.0000       5.0000       0.0000       0.0000    /
   3300 'IEESGO' 1    0.10000E-01   0.0000      0.15000      0.30000
          8.0000      0.40000       0.0000      0.70000      0.43000
          1.0000       0.0000    /
   3359 'GENROU' 1     4.7500      0.50000E-01   1.0000      0.50000E-01
          4.8200       0.0000       2.1300       2.0300      0.31000
         0.40300      0.19370      0.14531      0.10890      0.37795    /
   /3359 'STAB2A' 1     1.0000       4.5000       0.0000       2.0000
   /      0.68000       1.0000      0.10000E-01  0.30000E-01/
   3359 'SCRX'   1    0.20000       10.000       165.00      0.40000E-01
          0.0000       5.0000       0.0000       0.0000    /
   3359 'IEESGO' 1    0.10000E-01   0.0000      0.15000      0.30000
          8.0000      0.40000       0.0000      0.70000      0.43000
          1.0000       0.0000    /
   5100 'GENSAL' 1     4.9629      0.50000E-01  0.15000       3.9871
          0.0000       1.1332      0.68315      0.24302      0.15135
         0.13405      0.10000      0.30000    /
   5100 'SEXS'   1    0.50000E-01   100.00       200.00      0.50000
          0.0000       4.0000    /
   5100 'HYGOV'  1    0.60000E-01  0.40000       5.0000      0.50000E-01
         0.20000      0.20000       1.0000       0.0000       1.0000
          1.1000      0.50000      0.10000    /
   5300 'GENSAL' 1     6.4000      0.50000E-01  0.15000       3.5000
          0.0000       1.1400      0.84000      0.34000      0.26000
         0.20000      0.10000      0.30000    /
   /5300 'STAB2A' 1     1.0000       4.5000       0.0000       2.0000
   /      0.55000       1.0000      0.10000E-01  0.30000E-01/
   5300 'STAB1' 1     25.00       5.0000      4.200       0.03
         4.200      0.03      0.10000E-00/
   5300 'SCRX'   1    0.25385       13.000       61.000      0.50000E-01
          0.0000       4.0000       0.0000       0.0000    /
   5300 'HYGOV'  1    0.60000E-01  0.40000       5.0000      0.50000E-01
         0.20000      0.20000       1.0000       0.0000       1.0000
          1.1000      0.50000      0.10000    /
   5400 'GENSAL' 1     6.5000      0.50000E-01  0.15000       4.1000
          0.0000       1.0200      0.63000      0.25000      0.16000
         0.13000      0.10000      0.30000    /
   5400 'SEXS'   1    0.50000E-01   100.00       200.00      0.50000
          0.0000       4.0000    /
   5400 'HYGOV'  1    0.60000E-01  0.40000       5.0000      0.50000E-01
         0.20000      0.20000       1.0000       0.0000       1.0000
          1.1000      0.50000      0.10000    /
   5500 'GENSAL' 1     7.1980      0.50000E-01  0.15000       3.0000
          0.0000       1.2364      0.65567      0.37415      0.22825
         0.16194      0.10000      0.30000    /
   5500 'SEXS'   1    0.50000E-01   100.00       200.00      0.50000
          0.0000       4.0000    /
   5500 'HYGOV'  1    0.60000E-01  0.40000       5.0000      0.50000E-01
         0.20000      0.20000       1.0000       0.0000       1.0000
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       1.1000      0.50000      0.10000    /
5600 'GENSAL' 1     7.8500      0.50000E-01  0.15000       3.5000
       0.0000      1.0000      0.51325      0.38000      0.28000
      0.21000      0.10000      0.30000    /
5600 'STAB1' 1     26.97       3.0000      7.881      0.03
      7.881      0.03      0.10000E-00/
5600 'SCRX'  1    0.25385       13.000       61.000      0.50000E-01
       0.0000      4.0000       0.0000       0.0000    /
5600 'HYGOV'  1    0.60000E-01  0.30000       5.0000      0.50000E-01
      0.20000      0.20000       1.0000       0.0000       1.0000
       1.1000      0.50000      0.10000    /
6000 'GENSAL' 1     9.7000      0.50000E-01  0.15000       3.5000
       0.0000      1.2800      0.94000      0.37000      0.28000
      0.20000      0.10000      0.30000    /
6000 'SEXS'  1     1.0000      0.10000       20.000      0.10000
      -4.0000      4.0000    /
6000 'HYGOV'  1    0.60000E-01  0.30000       5.0000      0.50000E-01
      0.20000      0.20000       1.0000       0.0000       1.0000
       1.1000      0.50000      0.10000    /
6100 'GENSAL' 1     9.9000      0.50000E-01  0.15000       3.0000
       0.0000      1.2000      0.73000      0.37000      0.18000
      0.15000      0.10000      0.30000    /
/6100 'STAB2A' 1     1.0000       4.5000       0.0000       2.0000
/      0.55000       1.0000      0.10000E-01  0.30000E-01/
6100 'SCRX'  1    0.25385       13.000       61.000      0.50000E-01
       0.0000      4.0000       0.0000       0.0000    /
6100 'HYGOV'  1    0.60000E-01  0.40000       5.0000      0.50000E-01
      0.20000      0.20000       1.0000       0.0000       1.0000
       1.1000      0.50000      0.10000    /
6500 'GENSAL' 1     5.4855      0.50000E-01  0.15000       3.5580
       0.0000      1.0679      0.64200      0.23865      0.15802
      0.13514      0.10000      0.30000    /
6500 'SEXS'  1    0.50000E-01   100.00       200.00      0.50000
       0.0000      4.0000    /
6500 'HYGOV'  1    0.60000E-01  0.40000       5.0000      0.50000E-01
      0.20000      0.20000       1.0000       0.0000       1.0000
       1.1000      0.50000      0.10000    /
6700 'GENSAL' 1     5.2400      0.50000E-01  0.15000       3.5920
       0.0000      1.1044      0.66186      0.25484      0.17062
      0.14737      0.10000      0.30000    /
/6700 'STAB2A' 1     1.0000       4.5000       0.0000       2.0000
/      0.55000       1.0000      0.10000E-01  0.30000E-01/
6700 'STAB1' 1     5.442       3.0000      6.962      0.03
      6.962      0.03      0.10000E-00/
6700 'SCRX'  1    0.25385       13.000       61.000      0.50000E-01
       0.0000      4.0000       0.0000       0.0000    /
6700 'HYGOV'  1    0.60000E-01  0.40000       5.0000      0.50000E-01
      0.20000      0.20000       1.0000       0.0000       1.0000
       1.1000      0.50000      0.10000    /
7000 'GENROU' 1     10.000      0.50000E-01   1.0000      0.50000E-01
       5.5000      0.0000       2.2200       2.1300      0.36000
      0.46800      0.22500      0.16875      0.10890      0.37795    /
/7000 'STAB2A' 1     1.0000       1.0000       0.0000       2.0000
/      0.55000       1.0000      0.10000E-01  0.30000E-01/
7000 'STAB1' 1     5.192       5.0000      13.50      0.03
      13.50      0.03      0.10000E-00/
7000 'IEEET2' 1     0.0000       800.00      0.40000E-01   5.3200
      -4.0500      1.0000      0.44000      0.66700E-01   2.0000
      0.44000      6.5000      0.54000E-01   8.0000      0.20200    /
7000 'IEESGO' 1    0.10000E-01   0.0000      0.15000      0.30000
       8.0000      0.40000       0.0000      0.70000      0.43000
       1.0000      0.0000    /
7100 'GENSAL' 1     5.0000      0.60000E-01  0.10000       3.2000
       0.0000      0.75000      0.50000      0.25000      0.15385
      0.11538      0.10239      0.27420    /
/7100 'STAB2A' 1     1.0000       4.5000       0.0000       2.0000
/      0.55000       1.0000      0.10000E-01  0.30000E-01/
7100 'SCRX'  1    0.25385       13.000       61.000      0.50000E-01
       0.0000      4.0000       0.0000       0.0000    /
7100 'HYGOV'  1    0.60000E-01  0.40000       5.0000      0.50000E-01
      0.20000      0.10000       1.0000       0.0000       1.0000
       1.0100      0.50000      0.10000    /
8500 'GENROU' 1     10.000      0.50000E-01   1.0000      0.50000E-01
       7.0000      0.0000       2.4200       2.0000      0.23000
      0.41080      0.17062      0.14812      0.10890      0.37795    /
/8500 'STAB2A' 1     1.0000       4.5000       0.0000       2.0000
/      0.55000       1.0000      0.10000E-01  0.30000E-01/
8500 'SCRX'  1     0.0000      0.40000E-01   10.000      0.40000E-01
       0.0000      5.0000       0.0000       0.0000    /
8500 'IEESGO' 1    0.10000E-01   0.0000      0.15000      0.30000
       8.0000      0.40000       0.0000      0.70000      0.43000
       1.0000      0.0000    /
```