Dynamic Performance and Resource Mix Modification in Competitive Environments

S. Ríos M., R. Raineri B., M. Roca O.

Abstract — **Within the competitive framework in which the electricity industry operates, there is a need for tools to assess, both the actual and the short term operating conditions. This paper develops and applies a metric represented by a global index in order to justify resource mix modifications, based on a quantitative assessment of the dynamic performance of the power system. The proposed metric includes a set of indices to assess both the system steady-state operating condition and the three main dynamic aspects of system stability: transient or angular, frequency and voltage stability. These indices are weighted according to the security and quality levels required by regulator policies. Based on the global index value, control actions on the system are established and economically evaluated according to the benefit and cost produced in improving its dynamic performance. The metric is applied to one of the Chilean Interconnected Systems through five different operating scenarios.**

Index Terms— **Dynamic Security Analysis, Power System Stability, Severity Index, Global Dynamic Index.**

I. INTRODUCTION

The full or partial collapses being experienced in large interconnected power systems belonging to several developed countries (USA, UK, Italy, etc.), during the last years and particularly during 2003 has raised again some deep questioning about the tools and methodologies available for assessing both the system operating dynamic performance and the ability in predicting its dynamic evolution, when some disturbances occur.

It appears that the methodologies based on simple contingency analysis, where a large number of them can be quickly examined and despite positive results (regarding contingency impact) are obtained, this seems not to be enough for detecting further system dynamic operating complexities.

In this context a good example is obtained from August 14th Blackout in USA and Canada [1], where the traditional methodological approach is described and it has the following common features when it is compared with previous blackouts:

- Failure to ensure operation within secure limits
- Failure to identify emergency conditions and communicate that status to neighboring systems
- Inadequate operator training
- Inadequate regional-scale visibility over the power system

Within this complex environment in which the power generation and transmission sector operates, there is a need to develop metrics to provide specific quantitative information needed to implement the appropriate measures to keep the system security and reliability. Due to the existence of a broad range of measures used to assess the dynamic performance of power system, it is necessary to choose a set of the most representative ones, in order to have a quantitative and global overview of the dynamic performance of the system to different disturbances.

An important achievement in the process of dynamic security analysis is presented in paper [2], where a set of severity indices based on the concepts of coherency, the transient energy conversion between kinetic and potential energy, and three dot products of system variables are defined and applied to four different power systems. However, the indices fail to include the pre-disturbance state, in other words, to establish how much stressed was the power system before the disturbance occur. Since power systems correspond to nor-linear mathematical system, the dynamic response is very much dependent upon the initial pre-disturbance state. In addition, the authors recognized that individual indices fails to detect some unstable cases although the authors mention that the composite index is able to detect them. In paper [3] exactly the same indices are considered but the values of the weighting factors are upgraded via statistical methods, assigning more weight to those indices which deliver a more accurate assessment of the contingency ranking.

In this paper a measure to assess the dynamic performance of a power system utilizing a reduced set of indices is proposed. These indices are individually weighted and considered as vector components of a global index or metric. These indices are structured in three parts corresponding to i) the pre-disturbance assessment of the power system (e.g. the robustness and the degree of stress of the operating conditions), ii) the state during the fault and iii) the post-disturbance state. The indices are also focused on three key stability aspects following the lines proposed by Kundur in [4] and Vittal in [5]: transient or rotor angle stability, frequency stability and voltage stability. The final goal of the metric is to provide, to all the agents that participate in the Generation and Transmission sectors, with a fast measure of a global index capable of contributing to a better understanding of the key aspects that must be considered when deciding and evaluating the requirements on the dynamic operation of the electric system, in order to satisfy the minimum-quality standards previously defined according to the contracted quality of service, mandated by the agents willingness to pay.

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The established metric in addition to provide the operator a more complete picture on the system dynamic performance it is also a valuable tool to explore a different methodological approach to assess one or more sequence of disturbance events, as it normally happens in all the major blackouts where the initiating disturbance seems not to cause a problem or affect the power system but together with a second and also not harmful disturbance is all what is needed in some cases, to take the system to an emergency or collapse state.

When the metric is applied to a real power system (SING), a change in the resource mix is implemented and economically evaluated to improve the main dynamic deficiencies discovered, when the power system is exposed to external disturbances. The economic evaluation of each resource mix modification is assessed considering the benefits and the costs of each of them to reach an improvement of the system where the benefit exceeds its cost, as a Pareto improvement.

II. DEFINITION OF THE METRIC

The first step to define the metric is the characterization of the system components (lines, transformers, etc.) and its steady-state operating scenarios. A key aspect is the identification of the system adequacy under normal and (N-1) security criteria conditions, in order to find those elements that may take the system to a situation of instability. Appendix I shows details of some robustness indices used in this classification.

A. Global Index

To make a simple interpretation of the results obtained from the proposed metric, a single index that represents the system's global dynamic performance is defined. This global index is based on the weighted summation of the results delivered by each individual index:

$$M_{\text{GLOBAL}} = \sum_{i=1}^{4} \sum_{j=1}^{3} \omega_{ij} \cdot m_{ij} \qquad (1)$$

Where,

ω_{ij} = weighting factors
m_{ij} = metric's components (defined next)
i = 1,…,4 (types of analyses)
j = 1,…,3 (nº of index for each type of analysis)

In addition, weighting factor ω_{ij} is formed in the following manner:

$$\omega_{ij} = \alpha_i \cdot \theta_j \qquad (2)$$

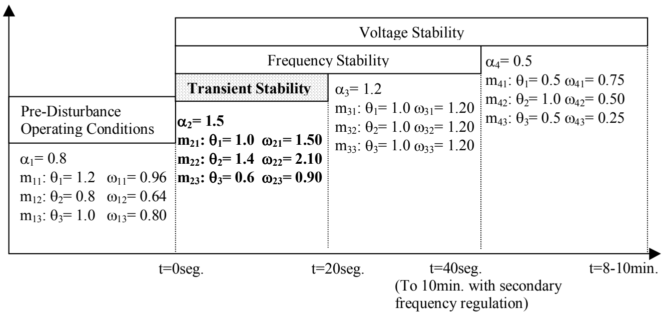
Where,

α_i = weighting factor that defines the relevance of the type of analysis within the metric,
θ_j = weighting factor that defines the relevance of one index within a specific type of analysis

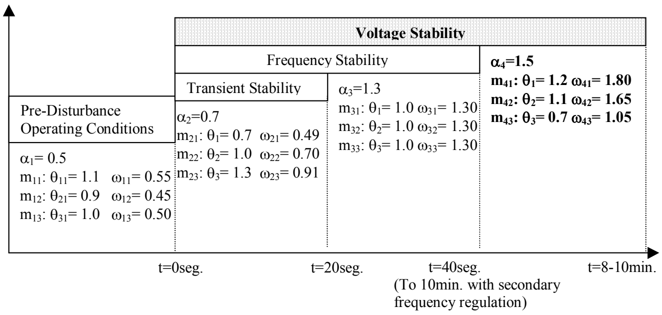
For each power system operating scenario, the magnitudes of factors "α_i" and "θ_j" are chosen such as their average value gives 1.

It is a well known fact that every interconnected power system is unique in its nature regarding several aspects such as: network topology and adequacy, generation resource mix, load composition and variation, etc. For example, large longitudinal interconnected power systems normally suffer of angular stability, also called transient stability. By taking into account this fact, the corresponding weighting factors ω_{ij} should give a greater value to the "angular stability" instead of the other types of stability indices. In general, the weighting factors ω_{ij} should be assigned according to the own deficiencies of the power system, deficiencies that can be previously established by an adequacy analysis of it.

Additionally, the weighting factor α_i allows assigning a time dependent relevance to the dynamic analysis. For example, if more weighting is applied to the rotor angle stability, indirectly more relevance is given to the fast dynamic phenomena (Case A in Figure 1). On the other hand, if more relevance is required for the slow dynamic phenomena, it is enough to increase the factor corresponding to the voltage stability analysis (Case B in Figure 1). Two cases of weighting the metric components to illustrate the above mentioned concept are included in Figure 1.



Case A



Case B

Fig 1. Example of weighting factors assignation

The advantage of grouping the individual indices to form a global index M_{GLOBAL} is the simplicity to interpret and to perform a close follow up of the dynamic performance of the system. However, it is important to note the disadvantages of grouping the indices since any problem found in a specific index will be hidden.

The tuning of the weighting factors can be performed through a learning process based on the power system dynamic characteristics and operating experience, or alternatively based on long term Regulator operating policies.

B. Metric's Components (m_{ij})

Firstly, with the proposed metric the dynamic performance of the system, under a normal or base load operating condition, is assessed. The aim of this analysis is to check if the system complies with the minimum standard of security and dynamic performance required when dealing with small load variations. Secondly, three indices are also used to evaluate rotor angle and transient voltage stability in case of a three-phase short-circuit occurring at the busbar that exhibits the lowest robustness. Thirdly, three indices to evaluate the frequency stability in case of an outage of the main generating unit are included. Fourthly, the system voltage stability is evaluated using static analysis tools (power flows, PV curves and modal analysis). The mathematical description of the indices proposed for each type of analysis is shown next.

1) Analysis of Pre-Disturbance Operating Conditions (m_{1j})

To assess how far or near the base load scenario is from limit values associated to steady-state operating conditions the following indices and variables are evaluated:

m_{11}) Eigenvalues ($\sigma+j\omega$) and their respective damping ratios ($\varsigma = -\sigma/\sqrt{\sigma^2+\omega^2}$) of the system's characteristic matrix, calculated from a small signal analysis.

m_{12}) The main busbar voltage magnitudes are verified against the allowed voltage band (e.g. ±5% of rated voltage).

m_{13}) The pre-disturbance or steady-state generation rotor angles are checked with respect to the reference angle in order that their difference belongs to a specified range.

2) Rotor Angle Stability and Transient Busbar Voltage(m_{2j})

The rotor angle and transient voltage stability is calculated applying a disturbance such as a three-phase short-circuit in a system busbar. This busbar can be chosen depending upon the evaluation of the robustness index presented in Appendix I or according to the level of importance it has for the system. Specifically, the indices obtained in this analysis are:

m_{21}) Maximum amplitude value of the first rotor angle swing.

m_{22}) Magnitude of the rotor angle variation in order to verify the damping of each of the rotor angle signals. If this variation is below a specific range within the first 15 seconds after the disturbance, the signal is considered dampened.

m_{23}) Magnitude and rate of busbar voltage transient signal response when affected by a three-phase short-circuit. These values are measured through the evaluation of the maximum and minimum values reached by the voltage, and the voltage damping measured through its derivative's performance.

3) Frequency Stability (m_{3j})

The dynamic performance of the primary frequency regulation of the system is analyzed during a period of 20 seconds for the outage of the system's largest generating unit. This analysis excludes the study of secondary frequency regulation. The indices used are:

m_{31}) Minimum frequency excursion value.

m_{32}) Performance index for the frequency signal. The ISE index (Integrated Squared Error) is used to evaluate the system's frequency signal response, and it is defined as:

$$\mathrm{ISE} = \int_0^{T_0} e_f^{\,2}(t)\, dt \qquad (3)$$

Where,

T_0 = time in which $|df/dt| < \varepsilon$, measured from the moment when the frequency has reached its minimum value (maximum integration time)

e_f (t) = error defined by the initial or pre-disturbance frequency value minus the instantaneous frequency

m_{33}) Final frequency error after that primary frequency regulation has ended (final frequency value 20 seconds after the failure).

4) Voltage Stability (m_{4j})

A first approach to analyze this problem is based on static tools such as power flows or modal analysis. To assess the performance of the system in relation to voltage stability, the following three indices are used [4],[6]:

m_{41}) Load buses loading margin through the construction of the PV curve for each busbar.

m_{42}) Modal analysis through the calculation of singular values of the Reduced Jacobian matrix. The smaller singular value of this matrix allows to predict how near the system is to the voltage instability.

m_{43}) Level of use of reactive power by each generator. With this measure the dependence of voltage stability on the system reactive power reserves can to be illustrated.

C. Aspects related to the application of the Metric

The first step in the application of the proposed metric was to characterize the main elements of the system to map the zones where a failure produces the biggest damage in the system. The steady-state robustness busbar index, described in Appendix I, was applied to classify the whole set of system busbars.

As a practical application of this metric, this section proposes an evaluation scheme based on score (S) levels that indicate the performance level of the system. This scheme can be used with multiple rating or grading steps for each index. This method, on one side it allows the regulator to supervise the dynamic performance of the system; and on the other side it can help the agents to anticipate or prevent dynamic operation problems through the implementation of better control actions on the system. The proposed evaluation scheme considers three rating steps that are defined by 2, 1 or 0 [7]. A three-level rating system is used to associate to each index value an operational state of the system (normal, alert or emergency) as defined by Fink & Carlsen [8].

A score of 2 (good) in any index means that for the condition evaluated, the operational limits are fulfilled according to the level of security required by the system under study. This fact is related to a *normal* operating condition.

However, for a score of 1 (regular) the system is less secure in this index, so it could be found in a level of alert in this variable. To prevent the system's performance to continue worsening, here becomes necessary implementing control actions to improve the rating of this index and therefore to move to a normal state.

Finally, a score of 0 (poor) indicates that the system shows serious stability deficiencies under that operating condition, therefore, if no fast control actions are implemented to improve this rating, the system can evolve to a state of collapse. This rating is associated to the state of *emergency*.

The number of steps used to disaggregate the rating must be designed according to the degree of security and fine-tuning that each system requires. An evaluation scheme with more steps (e.g. 1 to 10) can better anticipate or prevent a specific problem in a particular index, and that helps to timely execute a corrective control action. Nevertheless, it is important to note that having a higher number of rating steps also requires to more accurate measurement and control equipment, increasing the metric's implementation costs. Also, the metric's application complexity increases with more rating steps.

III. CONTROL ACTIONS AND ASSOCIATED COSTS

Knowing the main operating problems of the electrical system it is possible to define the control actions required to achieve a secure or "normal" state of operation. Such actions are classified according to both their associated costs and required time for implementing control action, namely as short and long term control actions.

Short-term actions allow to quickly improving the qualification of a specific index using or reassigning the existing resources of the system. Some examples of these actions are increase in spinning reserve, dispatch of additional units or resource mix modification, and operation changes of either capacitors or transformer taps.

On the other hand, long–term actions consist on the installation of new elements (or updating current elements) in order to reinforce the current system's security. These actions require a longer time of implementation, and demand considerable investments for their execution. Some of these actions are, for example, line, generators and capacitors installations, or updating machine voltage or speed regulators with poor dynamic performance.

Each transition to a more secure operating state can be valued according to the profitability it gives to the system as a whole, starting from an insecure operating state to a more secure one.

From the economic viewpoint, security improvement must be made according to the real benefit (B) that the system perceives by having a more secure system versus the costs (C) of the control actions required to take the system to this state. If the benefit of executing the control actions is higher than the cost required for their implementation, the transition from an insecure state to a secure one has a positive effect on social welfare. The social value that defines a "Pareto superior" [9] improvement of the system in economic terms can be formulated in the following manner[1]:

$$\text{SOCIAL VALUE} = (B_{\text{SECURE STATE}} - B_{\text{INSECURE STATE}}) - C_{\text{ACTIONS}} \qquad (4)$$

For example, the benefit of being in a more secure state can be associated to the reduction of the customers' outage probability and its impact on reducing the cost of failure. On the other hand, the costs of control actions are associated to the operating and investment costs required to take the system from an insecure state to a more secure state.

IV. APPLICATION EXAMPLE

The proposed metric was applied to assess the dynamic performance of the SING Chilean power system (Sistema Interconectado del Norte Grande), located in the north of Chile. This system at present has an installed capacity of 3,634 MW (73 generating units with several very old ones which normally are not dispatched) and an annual peak demand of 1,360 MW. Figure 2 shows a diagram of the system, while Table I shows the main features of this electrical system.

The system modeled has 192 busbars, of which 58 are load busbars. To validate the system modeled and the parameters used in the computer simulation, the actual system's frequency response measurement records for the case of outage of the largest unit were used in order to compare the real response with the simulated one. Very close agreement between both responses was obtained.

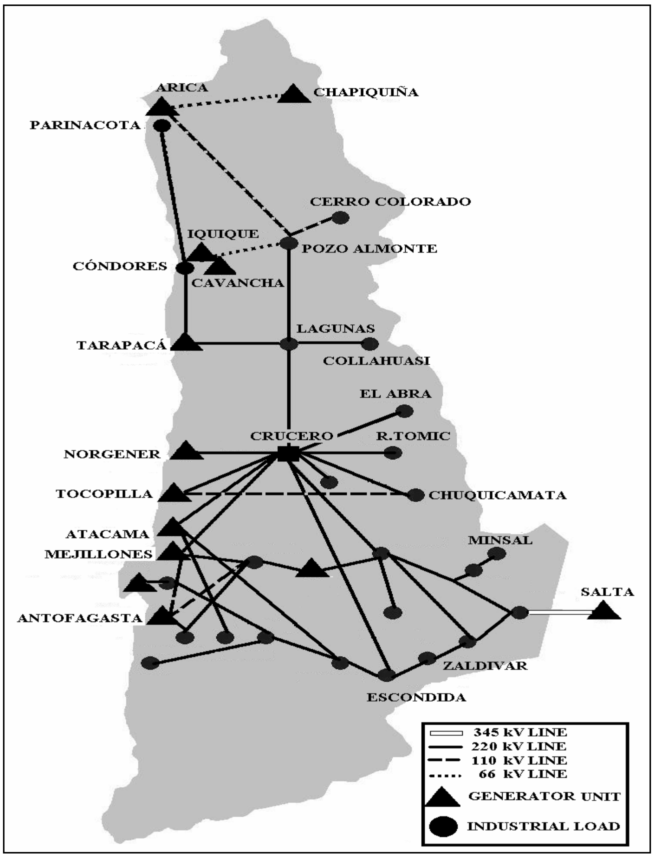


Fig. 2. SING Diagram

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[1] Here it is analyzed a solution where the resource mix modification is one where the benefits exceed the costs. However, there is no guarantee that the resource mix modification that is proposed up front an unstable situation of the electric system is the one that maximizes the difference between benefits and costs. It is looked for a Pareto Superior resource mix, but not necessarily for a Pareto Optimum resource mix, because that analysis is beyond the scope of this paper.

TABLE I.
SING`S MAIN CHARACTERISTICS

• Almost all the generation comes from thermal plants due to the lack of hydrological resources.
• Electricity demand is mostly industrial, with very large mining customers, which explains nearly 90% of the System Total Demand.
• Large demand growth, and very large growth of the installed power between 1993 and 2002 that almost threefold the peak demand level (see Figure 3).
• Interaction of different generation technologies (natural gas combined cycle power plants, coal-fired steam power plants and diesel power generators), each one with its own dynamic performance.
• There are large thermal power plants (643 MW, 400 MW) compared to the system total demand, which forces the system operator to restricts the output of these large and new power units to add more security to the system (each of this generation units is restricted, due to (N-1) criterion, to a maximum output of 240 MW)
• Generator governor droops are set between 6.5 and 12% of its own base. This droops are too large compared to international standards (4-6%). This explains the rather large frequency deviations observed under normal steady state operating conditions.

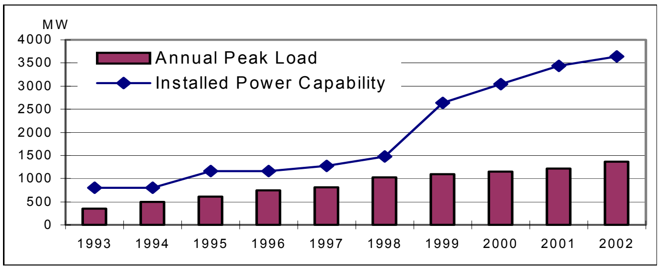

Fig. 3. Peak Demand and Installed Power in SING from 1993 until 2002.

A. *Metric's Evaluation Characteristics*

Appendix II shows the metric evaluation scheme applied to the SING, including the corresponding ranges and rating scores for each index. Each type of analysis has associated three components that rate both the most important characteristics of each type of stability and the pre-disturbance state. The frequency and voltage indices were calibrated according to the requirements established in the Chilean system's electricity regulation standards [10]. For other variables that are still not regulated in the Chilean legislation, such as the case of both machine's damping ratio and rotor angle values, the corresponding ranges were obtained from the Argentinean regulation [11]-[12], where there is a specific regulation on dynamic issues. Finally, for indices that are not directly available in electricity regulations, such as the case of ISE, the ranges used are similar to the ones theoretically presented in the literature [4].

Five different cases of study were analyzed to give examples of the metric's applications. They are detailed in Table II next. The first case corresponds to a Maximum Demand scenario (2002) where the dispatched generation units are each restricted to a maximum output of 240 MW. The second case is identical to case 1 but generation unit output is not restricted. The third case represents a future demand scenario (2007), which present a expected growth of 47% with respect to the 2002 peak demand. The fourth case corresponds to a real case scenario, which represents a fault occurring in the largest power plant of the system (Salta power plant). Finally, the fifth case is like the previous one but including control actions such as to modify the resource mix to improve the system frequency performance.

The outage of the largest unit in the system (Salta Power Plant, located in Argentine) and a three-phase short-circuit (6 cycles) on the most important busbar of the system (Crucero 220 kV busbar) were simulated for each scenario. Crucero busbar interconnects the main generating sources with the major loads, so it fulfils a strategic function within the system (see Figure 2).

TABLE II.
CASE STUDIES

CASE	LOAD	GENERATION
1) Maximum real demand 2002.	1,360 MW	1420 MW (13 units: 5 combined cycle,4 TG-TV and 1 open cycle, and 4 coal-fired thermal units)
2) Maximum real demand 2002 without generation restriction in units.	1,326 MW	1,393 MW (10 units: 5 combined cycle power plants, all TG-TV)
3) Maximum projected demand for 2007 with generation restrictions.	1,993 MW	2086 MW (16 units: 5 combined cycle, all TG-TV, and 6 coal-fired thermal units)
4) Real operating case, with outage of the largest unit in the system (231 MW).	1,170 MW	1,213 MW (11 units: 4 combined cycle, 3 TG-TV and 1 open cycle, and 4 coal-fired thermal units
5) Case 4 applying the dispatch of three new thermal plants and increasing the spinning reserve of dispatched units as a control action.	1,186 MW	1,219 MW (14 units: 4 combined cycle, 3 TG-TV and 1 open cycle, and 7 coal-fired thermal units)

B. *Application Results*

Before the metric is applied, a classification of the system's most important busbars and lines, according to the size of loads and the robustness index presented in Appendix I, must be performed in order to select the set of busbars and lines where the disturbances will be applied. Table III shows these results, and for the generators it includes the critical eigenvalues calculated from individual tests on each generating unit connected to an infinite busbar.

TABLE III.
SING'S BUSBAR AND LINES RANKING

<table>
<tr><th colspan="5">BUSBARS</th></tr>
<tr><th colspan="2">Load (%total)</th><th colspan="3">Robustness Index</th></tr>
<tr><td>1</td><td>Chuquicamata (21.23%)</td><td>1</td><td colspan="2">Crucero (4.4)</td></tr>
<tr><td>2</td><td>Escondida (12.49%)</td><td>2</td><td colspan="2">Collahuasi (5.4)</td></tr>
<tr><td>3</td><td>R. Tomic (7.97%)</td><td>3</td><td colspan="2">El Abra (8.8)</td></tr>
<tr><td>4</td><td>El Abra (7.71%)</td><td>4</td><td colspan="2">R. Tomic (9.5)</td></tr>
<tr><td>5</td><td>Collahuasi (7.53%)</td><td>5</td><td colspan="2">Escondida (10.0)</td></tr>
<tr><td>6</td><td>Zaldivar (5.58%)</td><td>6</td><td colspan="2">Chuquicamata (11.5)</td></tr>
<tr><th colspan="5">LINES</th></tr>
<tr><th></th><th>Name</th><th colspan="3">Load Index (%)</th></tr>
<tr><td>1</td><td>Chacaya -Crucero 220kV</td><td colspan="3">74.1%</td></tr>
<tr><td>2</td><td>Lagunas – Crucero 220 kV</td><td colspan="3">54.9%</td></tr>
<tr><td>3</td><td>Crucero- Laberinto 220kV</td><td colspan="3">45.5%</td></tr>
<tr><td>4</td><td>Tocopilla - Crucero 220kV</td><td colspan="3">44.4%</td></tr>
<tr><td>5</td><td>Domeyko – Escondida 220 kV</td><td colspan="3">43.6%</td></tr>
<tr><th colspan="5">GENERATORS</th></tr>
<tr><th>Name</th><th>Size (MW)</th><th>Eigenvalue</th><th>Damping</th><th>Freq.</th></tr>
<tr><td>Salta</td><td>643</td><td>-0.633+j6.61</td><td>9.54</td><td>1.05</td></tr>
<tr><td>U-16 Tocopilla</td><td>400</td><td>-0.548+j6.28</td><td>8.68</td><td>1</td></tr>
<tr><td>CC1 Nopel</td><td>389</td><td>-0.644+j5.66</td><td>11.3</td><td>0.901</td></tr>
<tr><td>CC2 Nopel</td><td>381</td><td>-0.677+j5.49</td><td>12.2</td><td>0.874</td></tr>
<tr><td>CTM3 Mejillones</td><td>251</td><td>-1.108+j19.35</td><td>5.72</td><td>3.08</td></tr>
</table>

TABLE IV.
RESULTS FROM THE APPLICATION OF THE METRIC IN 5 DIFFERENT CASES OF STUDY

	METRIC	α_i	θ_j	ω_{ij}	CASE 1		CASE 2		CASE 3		CASE 4		CASE 5	
	Analysis of Pre-Disturbance Operating Conditions				**Measured Value**	**S**	**Measured Value**	**S**	**Measured Value**	**S**	**Measured Value**	**S**	**Measured Value**	**S**
m_{11}	Critic Eigenvalue and Damping Ratio (ς)	1.1	1.1	1.21	-0.84+j13.3 $\varsigma = 6.31\%$	1	-0.65+j12.9 $\varsigma = 5.05\%$	1	-0.8+j14.3 $\varsigma = 5.61\%$	1	-0.28+j4.67 $\varsigma = 6.18\%$	1	-0.52+j7.41 $\varsigma = 6.96\%$	1
m_{12}	Voltage Ranks in Steady State (p.u.)	1.1	0.9	0.99	0.975-1.041	1	0.962-1.042	1	0.941-1.044	0	0.98-1.04	1	0.98-1.017	2
m_{13}	Maximum Rotor Angle Difference in Steady State(º)	1.1	1.0	1.1	34.7	1	32.8	1	34.557	1	33.2	1	30.6	1
	Rotor Angle Stability and Transient Voltage													
m_{21}	Maximum rotor angle amplitude during the first swing after the disturbance. (º)	0.8	1.0	0.80	46.74	2	52.93	2	49.93	2	47.58	2	40.23	2
m_{22}	Time when the rotor angle signal derivative for all the generators is below the range ±1. (sec.)	0.8	1.0	0.80	19.39	1	> 20seg.	0	18.62	1	16.45	1	12.5	2
m_{23}	Maximum and minimum voltage values and time when the voltage signal derivative is below the range ±0.1 p.u.	0.8	1.0	0.80	Vmin=0.917 Vmax=1.09 t >20seg.	0	Vmin=0.86 Vmax=1.13 t >20seg.	0	Vmin=0.95 Vmax=1.077 t >20seg.	0	Vmin=0.929 Vmax=1.142 t=4.01seg.	1	Vmin=0.969 Vmax=1.087 t=3.33seg.	2
	Frequency Stability													
m_{31}	Minimal Frequency	1.2	1.1	1.32	48.55	0	43.19	0	48.5	0	48.544	0	49.01	2
m_{32}	Frequency Performance Index (ISE)	1.2	1.1	1.32	31.858	1	773.31	0	50.18	0	30.1876	1	8.797	2
m_{33}	Frequency Error (Hz.)	1.2	0.8	0.96	0.19	2	6.81	0	0.41	1	0.309	1	0.466	1
	Voltage Stability													
m_{41}	Minimum Loading Margin (%)	0.9	1.0	0.90	84.15	1	27.13	0	25.09	0	81.04	1	102.96	2
m_{42}	Minimum Singular Value	0.9	1.0	0.90	0.0738	1	0.0055	0	0.0098	0	0.0679	1	0.1532	2
m_{43}	Minimum Reactive Power Reserve (%)	0.9	1.0	0.90	61.93	2	49.55	1	30.65	1	65.58	2	75.46	2
	Total Score				**12.54**		**5.80**		**6.57**		**12.38**		**20.73**	
	Maximum Score				**24**		**24**		**24**		**24**		**24**	
	Global Index (M_{GLOBAL})				**52.3%**		**24.2%**		**27.4%**		**51.6%**		**86.4%**	
	STATE OF THE SYSTEM				**ALERT**		**EMERGENCY**		**EMERGENCY**		**ALERT**		**NORMAL**	

Table IV shows the results obtained from the application of the metric to the 5 cases of study, displaying the corresponding measured value and its associated score according to the evaluation ranges described in Appendix II. In addition, the weighting factors for each index are presented. These factors were on purpose chosen in order to assign a higher relevance to both, the frequency stability (because the power system shows the highest deficiencies in this regard) and to analysis of pre-disturbance operating conditions.

Finally, the Global Index (M_{GLOBAL}) is presented for each case of study. For this specific power system, it has been established that the system is:

- In a "normal" state when M_{GLOBAL} is in the range between 100% and 70% of the maximum score (=24) and there exist no more than one 0 score;
- In an "alert" state when M_{GLOBAL} is between 70% and 50% of the maximum score (=24) and there exist no more than two 0 scores; and
- In a state of "emergency" when M_{GLOBAL} is less than 50% of the maximum score (=24) or there are three or more 0 scores.

The results of Case 1 show serious problems in all stability aspects, indicating that for a peak demand scenario, the system can show a deficient dynamic performance. Case 2 show that the system dynamic performance worsens considerably mainly due to the reduced number of generators and due to the small amount of spinning reserve. In Case 3 the problems related to the frequency and voltage stability are emphasized mainly due to the lack of both spinning reserves and reactive reserves in the system.

C. Application of Control Actions and Economic Assessment for Case 4

The metric components in Case 4 indicate the existence of problems in all the stability analysis, as a result of this the final value of M_{GLOBAL} = 51.6%. This value indicates that the system is in a state of "alert". Also, in the case of an outage of the largest generating unit, frequency stability shows the most severe problems, mainly caused by the weak response in the primary frequency regulation. The depth of the frequency drop causes a load shedding of 313.7 MW[2], equivalent to 27% of the total demand. If this loss of load (LOL) is valued at the failure cost (335 US$/MW/hr) a social loss of 105,089.5 US$/hr is obtained. To overcome this problem, a control action was established to increase the amount of spinning reserve in the system. This action consists on dispatching three additional and more expensive units and decreasing the power dispatched by each unit in order to increase the spinning reserve. Case 5 shows the application of these control actions.

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[2] The first step in the SING's load shedding is 49 Hz. When the frequency reaches 48.5 Hz, the fifth operating step that corresponds to 48.6 Hz. has been reached.

In this new scenario, the minimum frequency reaches 49.01 Hz, going just above the first load shedding frequency step (49 Hz.), and avoiding the shed of load. The cost of the action is valued according to the increase produced in the total system's generation cost, that reaches 1,585.1 US$/hr. On the other hand, the benefit is quantified according to the non-supplied power reduction once the failure is applied, that is multiplied by the respective failure cost ($C_{failure}$) and the real probability of having the failure occurring ($P_{failure}$):

$$B_{expected} = (LOL_{without\ action} - LOL_{with\ action})*C_{failure}*\ P_{failure} \quad (5)$$

In this case, $LOL_{without\ action}$ = 313.7 MW, $LOL_{with\ action}$ = 0 MW and the power plant failure probability is 2.0%[3]. Therefore, the expected benefit is:

$$B_{expected} = (313.7 - 0)*335*0.02 = 2{,}101.79 \text{ US\$/hr} \quad (6)$$

The profit of the control action or redispatch decision, that corresponds to the differential between the expected benefit and the cost of the action is positive, so both technically and economically it is viable to increase the spinning reserve to improve the security of the system. In addition, when applying this redispatch action, M_{GLOBAL} increases to 86,4%, taking the system to a "normal" state. This justifies that the application of the power system redispatch decision also globally improves the system's security.

V. CONCLUSIONS

In this work a metric to evaluate the dynamic performance of a power system is proposed, based on the three most important stability aspects: voltage stability, rotor angle stability and frequency stability. This metric is formed by a set of indices that captures quantitatively both the pre-disturbance operating state together with the during and post disturbance states, where the later two states capture the main dynamic problems of the system.

The most important indices have been grouped in a single global index, which facilitates a quick assessment of both system security and the required either control actions or redispatch decisions to improve the individual indices on which the metric is based.

The deregulation of the electrical industry and the addition of new markets for basic power dispatch and ancillary services, makes necessary from an economic viewpoint to value each action to improve the system's security. This work presents indications to economically evaluate the feasibility of applying control actions, putting emphasis on their benefits and associated costs.

Finally, it is important to underline the general approach to the metric definition, in order to adjust its metric components (indices) at the quality and security level that the system requires and wills to pay for. This metric is particularly useful in monitoring and keeping a record of security and quality of service, for large, complex and fast-growth power systems.

VI. APPENDICES

1) Appendix I: Indices used for the Characterization of the Main Components of the System

For selecting a set of critical busbars in the system, an index that evaluates their robustness comparing the level of total current injection at each busbar (applied in a peak demand scenario) with its corresponding short-circuit current is used. The index is defined as:

$$I_R = \frac{\text{Three-phase Short-circuit Current } \left[\text{Amp}\right]}{\text{Current Injection in Busbar [Amp]}} \quad (7)$$

Another possible busbar classification criterion is the ordering of the load busbars according to the magnitude of the loads they feed, and measured as a percentage of the total load in the system.

For the case of transmission lines, the index used considers the load percentage of the line referred to its operating limits, which is defined as the peak capacity minus a predetermined security margin over the corresponding operating limit. This operating limit shouldn't reach their thermal capacity under (N-1) security criteria.

$$I_L = \frac{\text{Peak Load Transfered Power [MVA]}}{\text{Operation Limit [MVA]}} \quad (8)$$

Finally, generators units and associated voltage and speed regulators are classified according to both, their size and the dynamic response (e.g. eigenvalues characteristics) obtained during tests, assuming they are connected individually to an infinite busbar. These tests allow to identify either wrong technical parameters or deficient (oscillatory or low damped) responses in the generators.

B. Appendix II: Evaluation Metric applied to SING

TABLE B1
ANALYSIS OF PRE-DISTURBANCE OPERATING CONDITIONS

m_{11}	*Small Signal Dynamic Analysis: Eigenvalues and Damping Ratio for the System's Characteristic Matrix*	*Score*
	• Under normal operating conditions, the system's critical damping ratio is higher than 10%	2
	• Under normal operating conditions, the system's critical damping ratio is higher than 5%	1
	• Under normal operating conditions, the system's critical damping ratio is less than 5%	0
m_{12}	*Voltage Busbars Operating Ranges in Steady State Condition*	*Score*
	• The voltages of main busbars (>110 kV in SING's case) are within the 0.98-1.02 p.u. range	2
	• The voltages of main busbars (>110 kV in SING's case) are within the 0.95-1.05 p.u. range	1
	• The voltages of main busbars (>110 kV in SING's case) are beyond the 0.95-1.05 p.u. range	0
m_{13}	*Generator Rotor Angle in Steady State Conditions*	*Score*
	• The greatest angle difference between a generator and the average of the angles of all the generators is less than 30°, under a steady state evaluation	2
	• The greatest angle difference between a generator and the average of the angles of all the generators is less than 60°, under a steady state evaluation	1
	• The greatest angle difference between a generator and the average of the angles of all the generators is higher than 60°, under a steady state evaluation	0

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[3] Source: CDEC-SING (Chilean ISO)

TABLE B2

ROTOR ANGLE STABILITY AND TRANSIENT VOLTAGE ANALYSIS

In case of a three-phase short-circuit in the most important busbar in the system, the following indices will be evaluated:		
m_{21}	*Maximum Amplitude of the First Rotor Angle Swing in the Generators*	*Score*
	• When a short-circuit happens, the rotor angles of all generators have a first swing maximum amplitude of less than 60° (compared to the average angles of all the system's generators)	2
	• When a short-circuit happens, the rotor angles of all generators have a first swing maximum amplitude of less than 120° (compared to the average angles of all the system's generators)	1
	• When a short-circuit happens, the rotor angles of all generators have a first swing maximum amplitude of more than 120° (compared to the average angles of all the system's generators)	0
m_{22}	*Generator Rotor Angle Damping*	*Score*
	• The rotor angle variations in all generators (measured as the derivative of the angle signal) are below the ± 1 range within the first 15 seconds after the disturbance	2
	• The rotor angle variations in all generators (measured as the derivative of the angle signal) are below the ± 1 range within the first 20 seconds after the disturbance	1
	• The rotor angle variations in all generators (measured as the derivative of the angle signal) are above the ± 1 range within the first 20 seconds after the disturbance	0
m_{23}	*Dynamic Performance of the Voltage in the busbar affected by the short-circuit*	*Score*
	• The swings happening during the post-failure stage are within the range of 0.9-1.1 p.u. and the voltage variation in the post-failure stage (measured as the voltage derivative with respect to time) is below the ± 0.1 range within the first 4 seconds after the disturbance	2
	• The swings happening during the post-failure stage are within the range of 0.7-1.2 p.u. and the voltage variation in the post-failure stage (measured as the voltage derivative with respect to time) is below the ± 0.1 range within the first 10 seconds after the disturbance	1
	• The swings happening during the post-failure stage are above the range of 0.7-1.2 p.u. or the voltage variation in the post-failure stage (measured as the voltage derivative with respect to time) is above the ± 0.1 range within the first 10 seconds after the disturbance	0

TABLE B3

FREQUENCY STABILITY ANALYSIS

In case of an unscheduled outage of the largest dispatched generating unit, the following indices will be evaluated:		
m_{31}	*Minimum Frequency produced by the disturbance*	*Score*
	• The minimum frequency was higher than 49 Hz . (1st load shedding step)	2
	• The minimum frequency was higher than 48.7 Hz . (4th load shedding step)	1
	• The minimum frequency was lower than 48.7 Hz	0
m_{32}	*Calculation of the Performance Index of the ISE (Integral Square Error) Frequency Signal with a value of* $\varepsilon = 0.01$	*Score*
	• The ISE performance index is less than 25	2
	• The ISE performance index is less than 50	1
	• The ISE performance index is higher than 50	0
m_{33}	*Frequency Error 40 seconds after the failure (evaluation of the frequency primary regulation)*	*Score*
	• Error less than 0.3 Hz	2
	• Error less than 0.7 Hz	1
	• Error higher than 0.7 Hz	0

TABLE B4

VOLTAGE STABILITY ANALYSIS

m_{41}	*Loading Margin of Load Busbars: Capacity of demand increase in the busbar up to the point of collapse defined by the PV curve.*	*Score*
	• The minimum loading margin of the main 5 load busbars in the system is higher than 100% of the demand in the respective busbar	2
	• The minimum loading margin of the main 5 load busbars in the system is higher than 50% of the demand in the respective busbar	1
	• The minimum loading margin of the main 5 load busbars in the system is lower than 50% of the demand in the respective busbar	0
m_{42}	*Modal Analysis: calculation of the lowest singular value of the Reduced Jacobian Matrix for the power flow*	*Score*
	• The lowest singular value of the system is higher than 0.1	2
	• The lowest singular value of the system is higher than 0.05	1
	• The lowest singular value of the system is less than 0.05	0
m_{43}	*Evaluation of the Reactive Power Reserve in the Generators*	*Score*
	• All the generators operating in the system have a reactive power reserve of more than 50% of their limit defined by the PQ curve	2
	• All the generators operating in the system have a reactive power reserve of more than 10% of their limit defined by the PQ curve	1
	• There is one generator operating with a reactive power reserve margin of less than 10% of its total capacity	0

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