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Network State Indicators in Flexibility Evaluation for Operational Planning in Electricity Market

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***Abstract*-- The paper deals with the integration of the Uncertainty Scenario Flexibility Indexes (USFI) in an operation planning problem. For USFI application in this medium term planning process, it is necessary to define a procedure that allows selecting the network states for which flexibility has to be evaluated. The proposed network state selection procedure is based on the use of Network State Indicators (NSI), whose value defines the network states for flexibility assessment. In order to choose the right NSI, a correlation analysis has been performed with some Penalty Functions (PF), chosen as an "indirect" measure of the importance of evaluating flexibility in a given state of the network. The NSI selection procedure includes many steps that have been implemented in home-made software, named *Ne.S.C.A.* (*Network State Correlation Analysis*), written in MatLab7® workspace, with multiple tasks. The results of the application of the procedure to the IEEE-RTS point out that the best NSI for the flexibility evaluation has been represented by the global network load.**

***Index Terms*-- Correlation Analysis, Electricity Market, Flexibility Index, Operational Planning, Penalty Function, State Indicator, Transmission Network.**

I. INTRODUCTION

IN a competitive environment the role of the Independent System Operator (ISO) is to provide a non discriminatory access to the network and its related services to all the market participants, maintaining a good level of reliability [1]-[4]. This task has to be included in the objectives of the transmission planning and operational planning processes, taking into account different constraints and uncertainties associated to competitive environment on basis of the time horizon. In this framework a new attribute for electrical bulk systems in market environment has been introduced in the most recent literature: it is the flexibility, defined as "the ability to adapt the planned development of the transmission system, quickly and at a reasonable cost, to any change, foreseen or not, in the conditions that were considered at the time it was planned" [5]. From this general standard definition, a more specific meaning of flexibility can be extracted, that is the flexibility of the transmission system in respect of generation system changes, which constitute the principal uncertainties associated to market environment, in the short, medium and long period.

In [6]-[9] the authors proposed some mathematically validated Uncertainty Scenario Flexibility Indexes (USFI) for the long term transmission planning of highly developed systems in market environment, as the Italian one. In particular these USFI take into account both structural and operational parameters, calculated for the whole system and for some network areas, and they have been defined through criteria based on both technical and economical information. Besides USFI calculation procedure includes two optimization problems solved with specialized Genetic Algorithm (GA), implemented in MatLab7® workspace, and it is integrated in a planning study by means of an innovative Series Approach [10],[11].

For its definition, transmission flexibility in respect to generation changes represents an attribute that has to be guaranteed also in the power systems operation, especially in a market environment; in other words it should be an attribute to reach with the operational planning process.

In order to apply the flexibility evaluation model in the operational planning, it has been necessary to define a procedure that allows selecting the network states for which flexibility has to be evaluated. This network state selection procedure is required because generation systems uncertainties, in function of which network flexibility has to be evaluated, change with the time horizon of planning. In fact in the long term (planning horizon) they include siting and sizing generation expansion, generation costs, market rules change, whereas in the medium term (operational planning horizon) they regards generations bids and so LMPs, spot wheeling transactions, availability of system facilities. In computational terms, considering the 8760 simulation hours for a year, whereas for the planning process flexibility indexes have to be evaluated referring to all the simulation hours, by means of a probabilistic assessment [8]-[9], for the operational planning process they have to be evaluated referring to a pre-selected set of hours (pre-defined network states). So, even though the flexibility indexes formula can be the same in long and medium period, the data selected for its calculation have to be different. In particular, as in the long term it is possible to refer the flexibility indexes to data evaluated on all the 8760 hours, in the medium term it is necessary to refer the flexibility indexes to specific data, evaluated only in the selected states on the 8760 hours.

The network state selection procedure has been based on

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the use of Network State Indicators (NSI), whose value defines the network states for flexibility assessment. In order to choose the right NSI, a correlation analysis has been performed with some Penalty Functions (PF), chosen as an "indirect" measure of the importance of evaluating flexibility in a given state of the network. The whole correlation analysis and PF-NSI evaluation procedure have been implemented in a software in MatLab7® workspace, and they have been applied to IEEE RTS.

In the paper, Section II. describes the network state selection procedure; Section III. includes the mathematical models for the definition of the PF and NSI; Section IV. shows the main results of the application of the correlation analysis to the IEEE RTS [12]; Section V. reports the conclusions.

II. Network State Selection Procedure

The network state selection procedure is based on the use of Network State Indicators (NSI), whose value defines the network states for flexibility assessment. In order to choose the right NSI, a correlation analysis has been performed. In particular their choice method has been developed in four main steps:

1. Selection and clustering of network states with load shedding or generation re-dispatching due to transmission network limits violation;
2. Definition of technical-economical Penalty Functions (PF) to associate to each network state;
3. Definition of technical Network State Indicators (NSI);
4. Correlation analysis between NSI and PF with the aim of choosing the best NSI for flexibility evaluation.

About the first step of the procedure, it deals with the selection and clustering of network states that are 8760 in one year simulation. After an analysis and selection, based on some preliminary simulations and correlations, the only states including a contingency involving the violation of a transmission limit have been selected. Then, considering that the main contingencies that can happen in a power system are faults on transmission lines or faults on generators, on the selected states, two main Clusters have been defined, in function of the type of contingency that involves a violation of a transmission limit:

- Cluster 1 including all the network states with a load shedding or a generation re-dispatching due to a fault on a transmission component;
- Cluster 2 including all the network states with a generation re-dispatching due to a fault on a generation component.

Besides in Cluster 1 it is possible to separate two sub-clusters:

- Cluster 1.A including all the network states with only a load shedding due to a fault on a transmission component;
- Cluster 1.B including all the network states with only a generation re-dispatching due to a fault on a transmission component.

After states selection and clustering, the second step of the procedure has been the definition of some Penalty Functions (PF). Five definitions have been selected, dependent on the type of contingency's consequence and based on some technical and economical parameters, such as:

- additional generation costs for re-dispatching,
- load shedding costs,
- their linear combination,
- lines flowing powers, etc….

PF give an "indirect" measure of the importance of evaluating flexibility in a given state of the network: if a network state is characterized by a high value of a PF, it is necessary to make an assessment of flexibility in that state. Really the PF definition is only a middle step for the definition of the true Network State Indicators (NSI) that are other parameters selected by means of a correlation analysis with the PF: those one with the maximum correlation degree have been selected as a "direct" measure of the importance of evaluating flexibility in a given state of the network.

With this aim six NSI have been defined, dependent on the type of contingency event and based on other parameters, such as network load and generation powers, lines and nodes equivalent distribution power factors, etc…

In the next Section the mathematical models for NSI and PF are reported. No theoretical explanation about their definitions have been reported in the present paper, because PF and NSI are just heuristic, but it is worth to stress that all of them have been formulated on the basis of knowledge of the power systems mathematical models and phenomenology.

III. Mathematical Models

A. Main definitions

The following sets of buses and lines are defined:

- $\mathcal{B} = \{1, 2, \dots, N\}$ as the set of all the buses of the network,
- $\mathcal{G} = \{1, 2, \dots, N_g\}$ as the set of the generation buses;
- $C = \{1, 2, \dots, N_c\}$ as the set of the load buses;
- $T = \{1, 2, \dots, N_t\}$ as the set of transit buses, that means the buses without generation and load;
- $\mathcal{L} = \{1, 2, \dots, L\}$ as the lines set, where a line ℓ is defined by a pair of buses i and j which it connects $\ell = \{i, j\}$, with $i, j \in \mathcal{B}$.

It is possible to associate to each generator $g \in \mathcal{G}$ the following set of 4 values:

$$S_g(g) = \{b, P_g, [P_g^{min}, P_g^{max}]\}$$

where $b \in \mathcal{G}$ is the bus of connection of the generator g, P_g is the power injection at the bus b,$[P_g^{min}, P_g^{max}]$ is the power generation range.

So defined the line set $\mathcal{L} = \{1, 2, \dots, L\}$, where a line ℓ is defined by a pair of buses i and j which it connects $\ell = \{i, j\}$, with $i, j \in \mathcal{B}$, it is possible to associate to each line $\ell \in \mathcal{L}$ the following set of 5 values:

$$S_l(l) = \{P_{ij}, M_{ij}, I_{ij}, R_{ij}, P_{ij}^{max}\}$$

where P_{ij} is the power flow, M_{ij} is the power margin on the line capacity, P_{ij}^{max} is the maximum power capacity, I_{ij} is the current, R_{ij} is the resistance.

For each $l = \{i, j\}$, with $i, j \in \mathcal{B}$, and for each $k \in \mathcal{B}$ it is possible define the distribution factor of the node k to the line $l = \{i,j\}$, named $CINF_{ij}^{k}$ and defined as:

$$CINF_{ij}^{k} = y_{ij} \cdot \left(Z_{ik} - Z_{jk}\right)$$

where:

y_{ij} longitudinal admittance of the line i-j;

Z_{ik} and Zj_k elements i-k and j-k of the node impedance matrix.

P_{ij} are connected to P_k by the distribution factors matrix:

$$[P_{ij}] = [CINF_{ij}^{\ k}][P_k]$$

For each $l = \{i, j\}$, with $i, j \in \mathcal{B}$ it is possible to compute the power losses P_{ij}^{losses}, in first approximation, given by:

$$P_{ij}^{\ losses} = R_{ij} P_{ij}^{\ 2}$$

For each $k \in \mathcal{G}$ it is possible to associate a scalar value $C_{gk}(P_k)$ that is the generation cost related to the power P_k defined with a three-terms formula :

$$C^{g}_{\ k}(P_k) = a_k P_k^2 + b_k P_k + c_k$$

where a_k, b_k *and* c_k are three scalar terms defined for each generator type.

Besides, for each $k \in \mathcal{G}$ it is possible to associate a scalar value $\Delta C_{gk}(\Delta P_k)$ that is the additional generation cost related to the deviation of generation power ΔP_k due to a re-dispatching in the network.

For each node $k \in C$ it is possible to associate a scalar value $C^{sh}_{\ k}(\Delta P_k)$ that is the load shedding cost associated to shed load ΔP_k,:

$$C^{sh}_{\ k}(\Delta P_k) = c^{sh}_{\ k} \cdot \Delta P_k,$$

where $c^{sh}_{\ k}$ is the per-unit load shedding cost.

B. Mathematical Models for Penalty Functions (PF)

Taking into account the definitions in III.A, it is possible to define five Penalty Functions (PF).

1) $$PF_1 = \alpha_G \sum_{k\ \in G} \Delta C_k^g + \alpha_C \sum_{k \in C} C_k^{sh}$$

where α_G and α_C are two scalar network-dependent coefficients.

In other terms PF_1 is the weighted mean of the additional generation costs due to the re-dispatching in the buses $k \in \mathcal{G}$ and of the load shedding costs associated to shed loads ΔP_k with $k \in C$.

This PF is defined for all the samples of the Cluster 1 and Cluster 2.

2) $$PF_2 = \sum_{k\ \in G} \Delta C_k^g$$

In other terms PF_2 is the sum of the additional generation costs due to the re-dispatching in all the buses $k \in \mathcal{G}$ caused by violation of a transmission limit.

This PF is defined for all the samples of the Cluster 1.B and Cluster 2.

3) $$PF_3 = \sum_{k \in C} C_k^{sh}$$

In other terms PF_3 is the sum of the load shedding costs associated to shed load ΔP_k with $k \in C$.

This PF is defined for all the samples of the Cluster 1.A.

4) $$PF_4 = \sum_{i,j \in B} | P_{ij} |$$

In other terms PF_4 is the sum of the absolute values of the flowing powers on the single line of the transmission network.

This PF is defined for all the samples of the Cluster 1 and Cluster 2.

5) $$PF_5 = \beta_L \sum_{i,j \in B} | P_{ij} | + \beta_C \sum_{k \in C} \Delta P_k^{sh}$$

where β_L and β_C are two scalar network-dependent coefficients.

In other terms PF_5 is the weighted mean of the absolute values of the flowing powers on the single lines of the transmission network and of the sum of the shed loads.

This PF is defined for all the samples of the Cluster 1.A.

C. Mathematical models for Network State Indicators (NSI)

Taking into account the definitions in IV.A, it is possible to define six NSI.

1) $$NSI_1 = \sum_{k \in C} P_k^L$$

In other terms NSI_1 is the sum of all the loads (network load). This indicator can be evaluated in all the samples of the Cluster 1 and Cluster 2.

2) $$NSI_2 = \begin{cases} \sum_{k \in B} \left(P_k^L - P_k^G\right) & if \left(P_k^L - P_k^G\right) \geq 0 \\ 0 \quad if \left(P_k^L - P_k^G\right) \leq 0 \end{cases}$$

In other terms NSI_2 is the sum, extended to all the buses, of the differences between generation and load powers in the single buses, only if positive. In the other cases NSI_2 is equal to zero.

This indicator can be evaluated in all the samples of the two clusters.

3) $$NSI_3 = \begin{cases} \sum_{k \in B} \sum_{ij \in B} CINF_{ij}^k \\ \sum_{k \in G} \sum_{ij \in B} CINF_{ij}^k \, with \ \mathrm{G} \subset B \\ \sum_{k \in G_{rd}} \sum_{ij \in B} CINF_{ij}^k \, with \ G_{rd} \subset G \subset B \end{cases}$$

In other terms NSI_3 is a multiple indicator defined as the sum of the distribution factors of all the lines in respect of:

- all the buses of the network;
- all the generation buses of the network;
- all the generation buses of the network where there is a re-dispatching due to a transmission deficit ($g \in \mathcal{G}_{rd}$).

This indicator can be evaluated in of the Cluster 1 and Cluster 2.

4) $$NSI_4 = N_{Lf} \sum_{l \in Lf} | CINF_l^k |$$
$$CINF_l = \sum_{k \in G_{rd}} CINF_{ij}^k \, with \quad l = \{i, j\} ij \in B \quad G_{rd} \subset G$$

In other terms NSI_4 is given by the product of the number of lines with a fault and the sum extended to the same lines, of the absolute value of the global distribution factors $CINF_l$ of

the single line in respect to the buses where there is a re-dispatching ($g \in \mathcal{G}_{rd}$).
This indicator can be evaluated in all the samples of the Cluster 1.

5) $$NSI_5 = N_{Gf} \sum_{g \in Gf} | CINF_g^k | \; with \;\; g \in G_f \subset G \quad k \in G_{rd} \subset G$$

In other terms NSI_5 is given by the product of the number of generators with a fault with the sum extended to the same generators ($g \in G_f$), of the absolute value of the bus-equivalent distribution factors $CINF_g$ of the single generation bus in respect to the buses where there is a re-dispatching ($g \in \mathcal{G}_{rd}$).
This indicator can be evaluated in all the samples of the Cluster 2.

6) $$NSI_6 = N_{Gf} \sum_{g \in Gf} | CINF_{ij}^g | \; with \; g \in G_{gf} \subset G \, , l = \{i, j\} \, \text{with } i \; or \; j \equiv g$$

In other terms NSI_5 is given by the product of the number of generators with a fault with the sum, extended to the same generators ($g \in \mathcal{G}_f$), of the absolute values of the distribution factors of the single generation buses in respect to the all the lines connected to the same bus.
This indicator can be evaluated in all the samples of the Cluster 2.

D. Mathematical models implementation

A home-made software named *Ne.S.C.A.* (*Network State Correlation Analysis*), implemented in MatLab7® workspace, has been realized with multiple tasks:

- *Pre-processing activities*, such as automatic selection and clustering of the samples on the 8760 simulation hours a year, according to the definition reported in Section II.;
- *Calculation activities,* such as the calculation of the Penalty Functions and of the Network State Indicators according to the mathematical models reported in Sections III.B and III.C;
- *Correlation activities* between PF and NSI in order to find out the best NSI for the assessment of the flexibility.

The dedicated software can work from the output of any simulation program that allows getting all the data necessary for the three above-said steps.

IV. IEEE RTS APPLICATION

A. Test Systems Description

The test network chosen for the application of the procedure for the best NSI selection has been the IEEE RTS, shown in Figure 1.

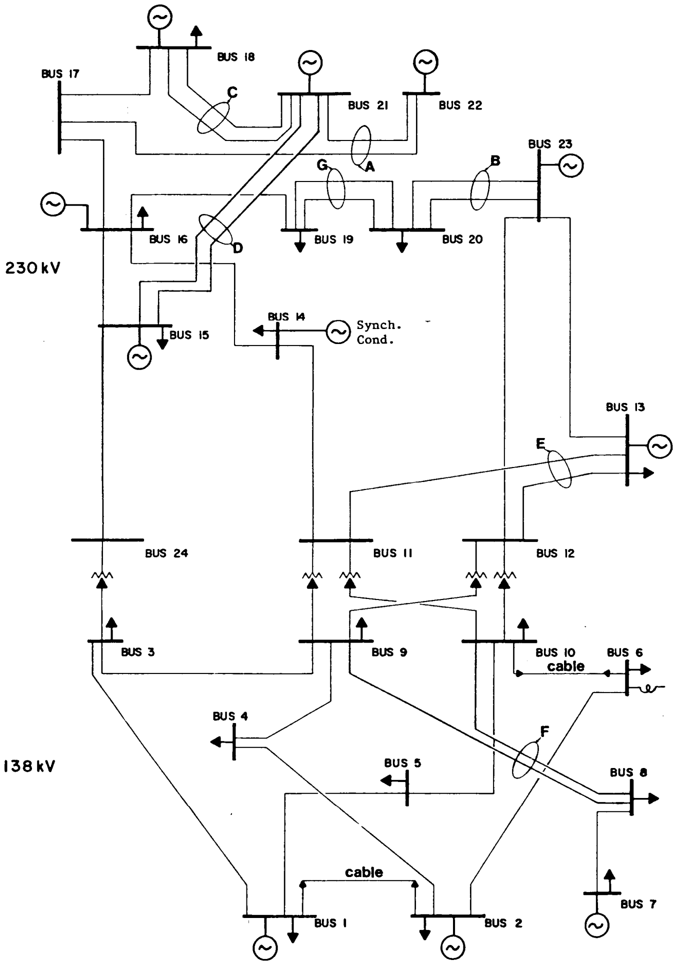

Fig. 1. IEEE RTS layout.

The main figures of the network are:

- generation system including 32 units, with size from 12 MW to 400 MW;
- transmission system including 24 generation/load and interconnection buses, linked by means of 33 lines/cables and 5 transformers on two voltage levels (138 kV e 230 kV);
- annual peak load equal to 3.650 MW.

For more details about electrical and availability data of the bulk system, see the reference paper [12].

From these standard configurations, with a same topography and generation/load buses asset, other operational configurations have been generated with growing values of Electric Energy Not Supplied (EENS) in order to apply the whole procedure.

The control variables for building the different network configurations have been:

- the maximum power capacity of the single lines of the network, that has been reduced, as shown in Table I;
- the failure rate of the single lines of the network, that has been increased.

TABLE I
GLOBAL NETWORK PEAK LOAD [MW] AND POWER LINES CAPACITY [MW] FOR DIFFERENT NETWORK CONFIGURATIONS

Network Configuration	Global Network Peak Load [MW]	Global Power Lines Capacity [MW]
RTS_1	3.650,0	1.150,0
RTS_2	3.650,0	1.041,6
RTS_3	3.650,0	934,0
RTS_4	3.650,0	771,8
RTS_5	3.650,0	711,8
RTS_6	3.650,0	711,6
RTS_7	3.650,0	652,1

In this way seven different operational configurations have been selected with different values of Electric Energy Not Supplied (EENS), as summarized in Table II and in Figures 2 and 3.

In particular the different configurations present:

- constant EENS due to generation deficit with all the network components in service (no fault);
- constant EENS due to generation deficit with network separation in zones for a transmission deficit;
- growing EENS due to transmission deficit for lines overloading.

TABLE II
COMPONENTS OF EENS IN MWH AND IN %
FOR DIFFERENT RTS CONFIGURATIONS

RTS Configuration	EENS for Transmission Deficit [MWh]		EENS for Generation. Deficit [MWh]	Total EENS [MWh]	EENS % for Transmission Deficit	EENS % for Generation Deficit
	Line Overload	Generation Deficit due to network separation in zones				
RTS_1	91,5	1.284,00	1.534,8	3.121,6	44,06%	49,17%
RTS_2	103,2	2.230,20	1.285,0	3.907,7	59,71%	32,88%
RTS_3	358,5	2.230,20	1.285,0	4.162,6	62,18%	30,87%
RTS_4	858,2	2.230,20	1.285,0	4.662,7	66,24%	27,56%
RTS_5	4.427,3	2.230,20	1.285,0	8.231,8	80,88%	15,61%
RTS_6	15.217,3	2.230,20	1.285,0	19.021,8	91,72%	6,76%
RTS_7	123.382,4	2.230,20	1.285,0	127.186,9	98,76%	1,01%

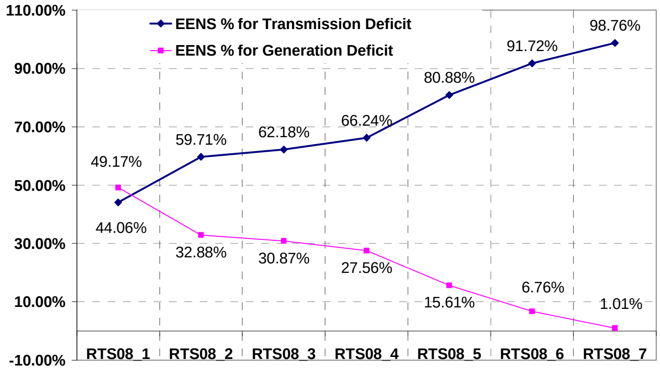

Fig. 2. EENS components for generation and transmission deficit in % on the total value.

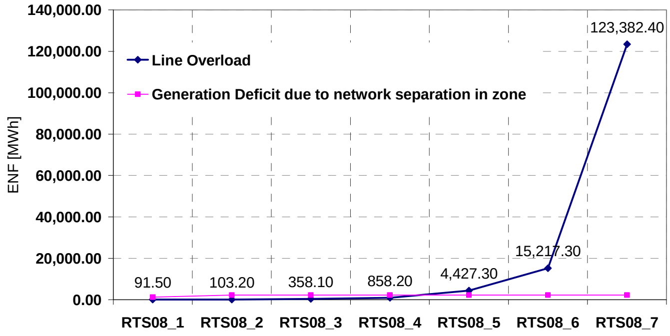

Fig. 3. EENS components for transmission deficit in MW.

B. *Main results*

For the seven IEEE RTS configurations, PF and NSI have been evaluated after the selection and clustering of the samples in 8760 simulation hours, by means of *Ne.S.C.A.* Software.

The main results of the correlation analysis between PF and NSI have been summarized in Table III where the correlation degree is defined as the mean value on the seven tests:

TABLE III
CORRELATION ANALYSIS RESULTS

Correlation Degree		PF_1 (Cl.1-2)	PF_2 (Cl. 1B-2)	PF_3 (Cl. 1A)	PF_4 (Cl. 1-2)	PF_4 (Cl. 1A)
Network state Indicators (NSI)	NSI_1 (Cl.1-2)	0.36	0.61	0.53	0.82	0.05
	NSI_2 (Cl. 1-2)	0.41	0.57	0.63	0.64	0.05
	NSI_3 (Cl. 1-2)	0.12	0.03	0.05	0.01	0.01
	NSI_4 (Cl. 1)	0.00	0.11	0.12	0.00	0.01

	NSI_5 (Cl. 2)	0.00	0.12	---	0.00	---
	NSI_6 (Cl. 2)	0.00	0.12	---	0.00	---

From the analysis of these results, it is possible to point out that:

- NSI_1 (global network load) has the maximum correlation degree with all the PF, with the exception of PF_5. The maximum values (about 82%) is with PF_4 that is the sum of the flowing powers on the network lines;
- NSI_2 (differences between generation and load powers in the single buses) has a medium value of correlation degree (about 50%) with all the PF, with the exception of PF_5.
- NSI_3 (based on the global power factors) has a very low correlation degree with all the PF, that means that an NSI based on global power factors is not a good indicator;
- NS_4, NS_5 and NS_6 (all based on power factors linked to the only lines or generators with fault) have very low correlation degrees with all the PF. An explanation could be that these indicators include local information whereas the PF include global system information.

V. CONCLUSIONS

A procedure, based on the use of Network State Indicators (NSI), has been proposed for selecting the accurate cases for flexibility assessment in the operational planning process. In order to choose the right NSI, a correlation analysis with some Penalty Functions (PF) has been performed. The whole correlation analysis and PF-NSI evaluation procedure have been implemented in a software in MatLab7® workspace, and they have been applied to IEEE RTS. This application allows pointing out that the best NSI, for the flexibility evaluation, is represented by the global network load.

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VII. BIOGRAPHIES

Alfonso Capasso has joined the University of Rome "La Sapienza" since 1968, where he has been Assistant Professor since 1970, Associate Professor since 1973 and Professor in Electric Power Systems since 1980. From 1997 to 2000 he was also President of the Italian University Research Group in Electrical Power Systems. His main interests are in computer applications to electric power systems, power quality and railway electrification. He has been involved, as a part-time consultant, in many Railway electrification studies; presently he is engaged in the design activities of the new Italian High-Speed Lines Bologna- Florence and Turin-Milan, under construction. He is a member of AEI (Italian Electrical Association), CEI Committee 110 (EMC), CIFI (Italian Railway Engineers Association) and Senior Member of IEEE.

Maria Carmen Falvo was born in 1979. She received her Master Degree with honors and her PhD in Electrical Engineering, in 2002 and in 2007, from the University of Rome "Sapienza". At present she is with the University of Rome "Sapienza" as Assistant Professor at Department of Electrical Engineering. Her main research interests include transmission network planning in electricity market, power systems for metro-transit and railway transport. She is a member of AEI (Italian Electric Association) from 2001 and of IEEE-PES from 2004.

Regina Lamedica has joined the University of Rome "La Sapienza" where she has been Assistant Professor in Electric Power Systems since 1978, Associate Professor since 1987 and Full Professor in Electric Power Systems for Transportation since 2000. Her main interests are in computer applications to electrified transportation systems and to power systems analysis. She is a member of IEE-PES, CIFI (Italian Railway Engineers Association) and AEI (Italian Electrical Association).

Sergio Scalcino was born in Rome 1945. He received the Master Degree in 1968 and post graduated with a course of one year in Automatic Controls in 1972, from the University of Rome "La Sapienza". He worked in University of Rome in 1969. After he joined in Enel in 1970 where he was mainly involved in studies on generation and transmission network and on reliability. He retired in 2002 and work now as consultant for the dept. of Electrical Engineering of the University of Rome "La Sapienza".