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

Evaluation of Some Indices for Voltage Stability Assessment

S. Massucco – *IEEE M.*, S. Grillo – *IEEE St. M.*, A. Pitto*– *IEEE St. M.*, and F. Silvestro – *IEEE M.*
University of Genova

**reference author*: apitto@epsl.die.unige.it

***Abstract*—The liberalization of the electricity markets causes power systems to work closer and closer to their limits. The on-line assessment of system security becomes a topic of paramount importance in control centers. In this context fast indices to quickly assess system security are fundamental in an on-line DSA session. This paper considers three voltage stability indices recently proposed in literature and carries out some comparisons. In the first part the authors briefly describe the theoretical background of each index. The second part is devoted to two comparisons: at first, the three indices are compared by using an IEEE test system. Secondly, the FVSI (Fast Voltage Stability Index) and the VCI (Voltage Collapse Index) are compared by adopting a model of the Italian HV transmission grid. The comparisons will show the peculiar information provided by each of the considered indices and will assess the performance of these indices also on a realistic power system. Final remarks are reported and discussed.**

***Index Terms*— Voltage Stability Assessment, Voltage collapse, Fast indices, Steady-state Voltage Stability**

I. Introduction

Deregulation has forced electric utilities to make better use of the available transmission facilities of their power system. This has resulted in increased power transfers, reduced transmission margins and diminished voltage security margins.

Several voltage instability incidents have been reported, in the recent past, all over the globe. These are the results of a system operation with very little voltage stability margin under normal conditions. Thus, lot of work is being carried out to better understand voltage stability, to detect it faster and to evolve a strategy to mitigate it once its likelihood is observed.

To this purpose, it is essential to estimate the maximum permissible loading of the system using information about the current operation point. The maximum loading of a system is not a fixed quantity but depends on various factors, such as network topology, availability of reactive power reserves and their location etc. Determining the maximum permissible loading, within the voltage stability limit, has become a very important issue in power system operation and planning studies. The conventional P-V or VQ curves are usually used as a tool for assessing voltage stability and hence for finding the maximum loading at the verge of voltage collapse. These curves are generated by running a large number of load flow cases using conventional methods. While such procedures can be automated, they are time-consuming and do not readily provide information useful in gaining insight into the cause of stability problems.

To overcome the above disadvantages several techniques have been proposed in the literature, such as bifurcation theory, energy methods, eigenvalue and singular value methods [1][2], multiple load flow solutions method, etc.

They are computationally intensive, which makes them less viable for fast computation during a sequence of discontinuities like generators hitting field current or reactive limits, tap changer limits, switchable shunt capacitor susceptance limits etc. In a dynamic voltage stability computation regime, it is necessary to consider all these discontinuities into the analysis. Moreover, above all in the present deregulated context, a quick computation is necessary to take adequate corrective actions in time to save the system from an impending voltage collapse. Nowadays, these requirements (i.e. speed, and analysis of discontinuities) are fulfilled, for example, by the QSS method [3], which is used also for on-line DSA applications.

The present paper describes the application of three voltage stability indices (recently proposed in literature) to an IEEE test system and to a large realistic power system. Section II briefly presents the mathematical formulation of the indices. Section III describes the simulation tools used for the analyses. Section IV shows the results of a first indices comparison carried out on an IEEE test system for validation purposes. Section V presents the results of a second voltage stability indices comparison carried out on a model of a realistic power system (the Italian HV transmission grid): such an application can provide a contribution to the realization of effective voltage stability tools to support control center operators. Section VI presents some considerations about the performance of the analyzed indices. At last some conclusions are drawn in Section VII.

S. Massucco, S. Grillo, A. Pitto, F. Silvestro are with UGDIE – Electrical Engineering Department, University of Genova, Italy. Email: massucco@die.unige.it, sgrillo@epsl.die.unige.it, apitto@die.unige.it, fsilvestro@die.unige.it.

II. Theoretical Background of the Indices

A. *VII (Voltage Instability Index)*

The mathematical formulation of this index [4] has been

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first carried out on a simple two-bus test system, composed by a line, a load and a simplified generator. The voltage at the load bus will collapse when the Jacobian matrix determinant becomes zero.

The generalization to a N-bus system is performed by considering the complete admittance matrix Y (with its inverse Z and partitioned as $[Y_{LL}\ \ Y_{LG};\ Y_{GL}\ \ Y_{GG}]$) which links the voltages and the currents at generator (G) and load (L) buses.

The VII indicator at load bus *j* is:

$$indicator_j = \left|1+\frac{\dot{V}_{0j}}{\dot{V}_j}\right| = \left|\frac{\dot{S}_j^{'}}{V_j^2 \cdot \dot{Y}_{jj}^{'}}\right| = \frac{S_j^{'}}{V_j^2 \cdot Y_{jj}^{'}} \qquad (1)$$

where

$$\dot{S}_j^{'} = \left(\sum_{i\in L}\frac{\dot{Z}_{ji}\,\dot{S}_i}{\dot{Z}_{jj}\,\dot{V}_i}\right)\dot{V}_j = \dot{S}_j + \left(\sum_{\substack{i\in L\\ i\neq j}}\frac{\dot{Z}_{ji}\,\dot{S}_i}{\dot{Z}_{jj}\,\dot{V}_i}\right)\dot{V}_j$$

and

$$\dot{V}_{0j} = -\sum_{k\in G} A_{jk}\,V_k \qquad \dot{Y}_{jj}^{'} = 1/\dot{Z}_{jj}$$

with $A = -Z_{LL}\cdot Y_{LG}, \quad Z_{LL} = Y_{LL}^{-1}$.

When the index of one of the load buses becomes equal to 1, system voltage collapse occurs. Thus, for the overall system the indicator is the maximum of the indicators of all the load buses of the system.

If one considers a time domain simulator, at each time step the power balance equations are satisfied. Thus, the VII index which is uniquely derived from these equations holds valid also in dynamic simulations, as well as the other two implemented indices.

B. VCI (Voltage Collapse Index)

This index, deduced from [5], derives from a simple observation: when the load apparent power changes, load voltage and current change as well to satisfy the relationship:

$$\dot{S}_i = \dot{V}_i\,\dot{I}_i^{*} \qquad (2)$$

Also after a network configuration change, voltage and current change. Applying the Taylor's theorem to (2) and neglecting the high order terms, [5] obtains:

$$\Delta S_i = V_i\,\Delta I_i + I_i\,\Delta V_i \qquad (3)$$

When the load of a bus increases, the load current increases and the load voltage decreases. However, when the load of a bus approaches the critical value or the voltage collapse point, the increment of load at the bus may not increase the load apparent power S_i due to a rapid reduction of voltage.

After dividing (3) by $V_i\,\Delta I_i$ the voltage stability limit is given by:

$$0 \le 1+\left(\frac{I_i}{V_i}\right)\left(\frac{\Delta V_i}{\Delta I_i}\right) \qquad (4)$$

Thus, the measure of the distance from the voltage collapse point is given by the right hand side of (4).

The voltage stability index proposed is given by:

$$VCI_i = \left[1+\left(\frac{I_i}{V_i}\right)\left(\frac{\Delta V_i}{\Delta I_i}\right)\right]^{\alpha} \qquad (5)$$

where $\alpha > 1$ is used to linearize the trend of the index itself especially near the collapse point. At a power system level, the VCI of the weakest bus can be considered the system VCI.

C. FVSI (Fast Voltage Stability Index)

This index, [6], is deduced from the analysis of a two-bus power system model. Fig. 1 shows the scheme.

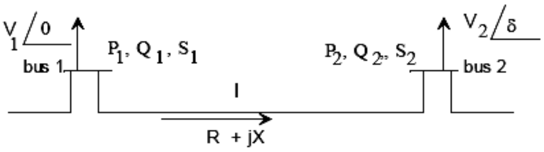

Fig. 1. Two-bus model for FVSI formulation

The voltage at the receiving end (bus 2) is written as a function of the line parameters, the reactive flow at the receiving end and the voltage at the sending end:

$$V_2 = \frac{\left(\frac{R}{X}\sin\delta+\cos\delta\right)V_1}{2} \pm \frac{\sqrt{\left[\left(\frac{R}{X}\sin\delta+\cos\delta\right)V_1\right]^2 - 4\left(X+\frac{R^2}{X}\right)Q_2}}{2} \qquad (6)$$

The expression has real roots only if

$$\frac{4\,Z^2 Q_2\,X}{V_1^2\,(R\sin\delta + X\cos\delta)^2} \le 1 \qquad (7)$$

By assuming that $\delta \approx 0,\ R\sin\delta \approx 0$, $X\cos\delta \approx X$, one can define the fast voltage stability index for line *i-j*

$$FVSI_{ij} = \frac{4\,Z^2\,Q_j}{V_i^2\,X} \qquad (8)$$

When the FVSI of one line approaches unity it means that the line is approaching its stability limits. The FVSI of all the lines must be lower than 1 to assure the stability of the power system.

III. Simulation Tools

The abovementioned indices have been applied to both test and realistic power systems. A Voltage Stability tool has been developed within MATLAB environment which allows the use of two loadflow programs:

- Power System Toolbox (PST), [7], a toolbox fully integrated in MATLAB.
- An engineering-level loadflow program called FLOWAC, [8], which is adequate to simulate large realistic power systems, like the Italian HV grid.

Fig. 2 shows the interaction of the voltage stability tool with the simulation programs.

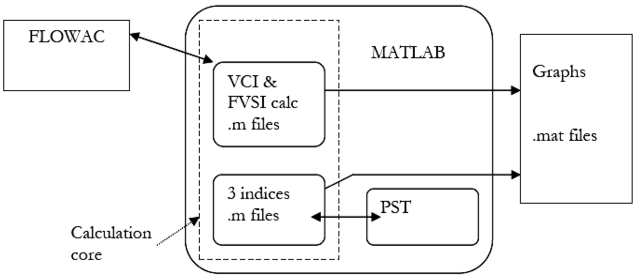

Fig. 2. Interaction of the voltage stability tool with simulation programs

This tool has been applied both to IEEE test systems and to models of realistic HV power systems, as it will be illustrated in the next sections.

IV. Indices Validation on an IEEE Test System

The application of the load ramp by means of PST to test power systems in PST format is carried out by multiplying the base case load of a specific load/s by a factor λ. In order to simulate generators response, the program multiplies the output active powers at the generator PV nodes by the same factor (this is a classical way to simulate the generator response widely used in literature [5]). The maximum active powers of the generators are considered: if they are not provided, they are estimated from the initial active power injected by each generator. Loads are considered constant power loads and the generator reactive capability is taken into account. In particular $Q_{max} = 0.5 * P_{max}$ where P_{max} is the maximum admissible active power.

This section shows some results concerning the use of the Voltage Stability tool presented in Section III on an IEEE test system and the comparison of the three voltage stability indices introduced in Section II. The test system considered for the first comparison is the 3-machine 9-bus IEEE test system. Fig. 3 shows the network. In the present simulations, parameter α for VCI has been set to 3 (which allows to linearize the relevant index).

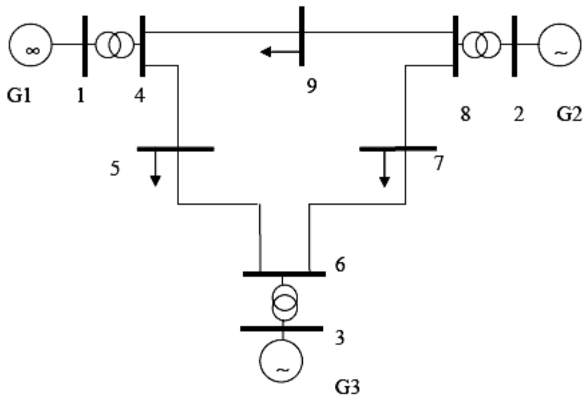

Fig. 3. IEEE 3-machine 9-bus test system

The goal of the following simulations is to compare the information coming from the voltage stability analyses performed with the three indices in case of a load increase on the test system.

A. *Load increase at node 5 (reinforced reactive limits)*

This paragraph analyses the results obtained from the simulation of a load increase at node 5 in the 3-machine 9-bus system. In this case the reactive capability limits of machines 2 and 3 are supposed to be illimited. The load increase is performed by multiplying the base load by a load increase factor λ. The load increase is compensated by multiplying the base case generated powers of the machines by the same factor. The simulation is carried on until loadflow equations no longer converge. Fig. 4 shows the V I I curves for the three load buses of the network.

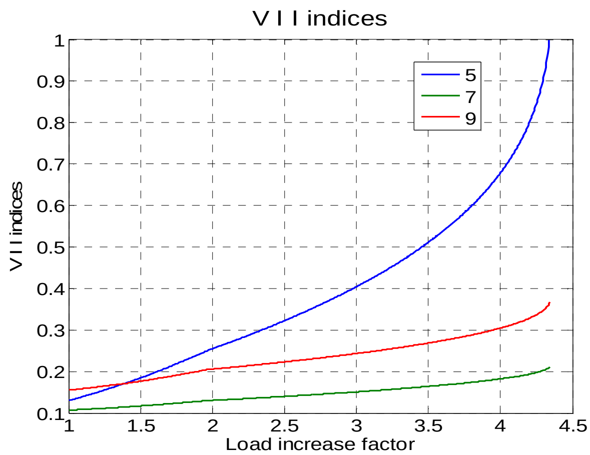

Fig. 4. V I I indices for the three load buses – reinforced reactive limits

Fig. 4 shows that the most critical node is node 5 (where the load increase takes place). Also the VCI confirms this conclusion as it can be noticed from Fig. 5. The maximum load increase which is admissible at node 5 corresponds to a load increase factor equal to 4.35.

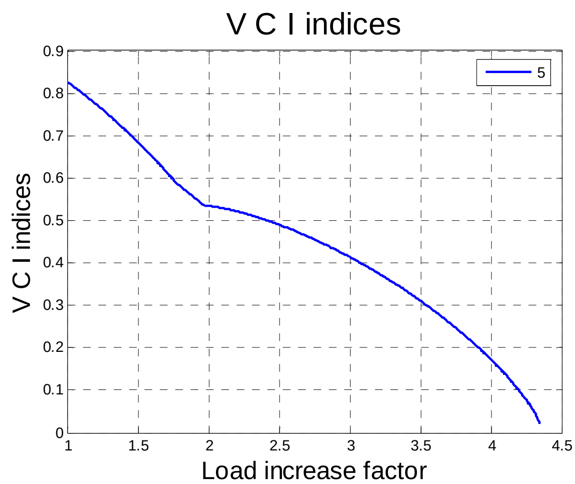

Fig. 5. V C I index for node 5 as a function of the load increase factor – reinforced reactive limits

The change in the VCI curve slope is due to the fact that machines 2 and 3 reach their maximum admissible output active powers around a load increase factor equal to 2.

The FVSI curves in Fig. 6 indicate that the lines with the highest index are the lines which connect nodes 5 and 4, 5 and 6 (which are also the lines with the highest reactive flows in the last converging loadflow).

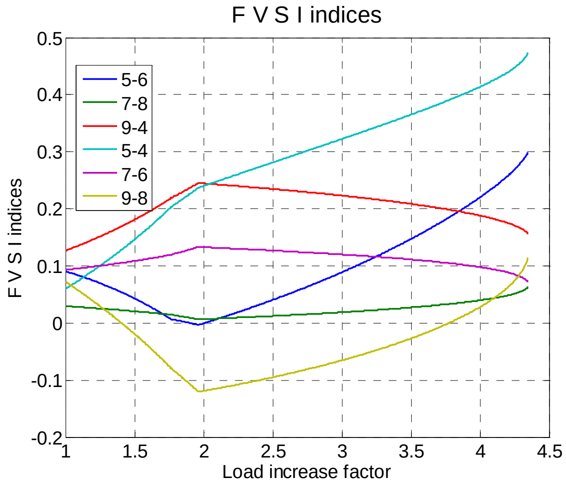

Fig. 6. FVSI for the lines with the highest index values at the end of the simulation, as a function of the load increase factor – reinforced reactive limits

In particular the maximum active power limits deeply influence the power flows along the grid, thus also the trend of the FVSI curves. The two lines which have the highest FVSI values are the lines which connect bus 5 to the grid.

B. *Load increase at node 5 (limited reactive capability)*

In this scenario the reactive capability limits of machines 2 and 3 are set respectively to ±1 p.u. and to ±1.5 p.u. The same load increase at node 5 is performed and no capacitor banks are switched during the load increase. Fig. 7 summarizes the graphical results for the three indices.

The first generator which hits the overexcitation limit is generator 2 (with an upper limit equal to 1 p.u.). This event causes a temporary decrease of the VII indices for the three load buses (top diagram around λ=3.4) and an increase of the slope of the FVSI curves (thus a higher criticality) for the lines which connect buses 7-6 and 9-4: at λ=3.4 the reactive saturation of generator 2 determines a relatively fast decrease of voltages at nodes 9 and 7 and consequently an increasing criticality for lines 9-4 and 7-6.

The voltage stability margin is lower than in the previous scenario: in fact VII curves approach 1 at a load increase factor equal to 3.96. The comparison between the first scenario (reinforced reactive limits) and the present scenario can be easily derived from the VCI diagram: the dashed curve represents the VCI curve for node 5 in case of reinforced reactive limits, while the curve for the present scenario is the solid one.

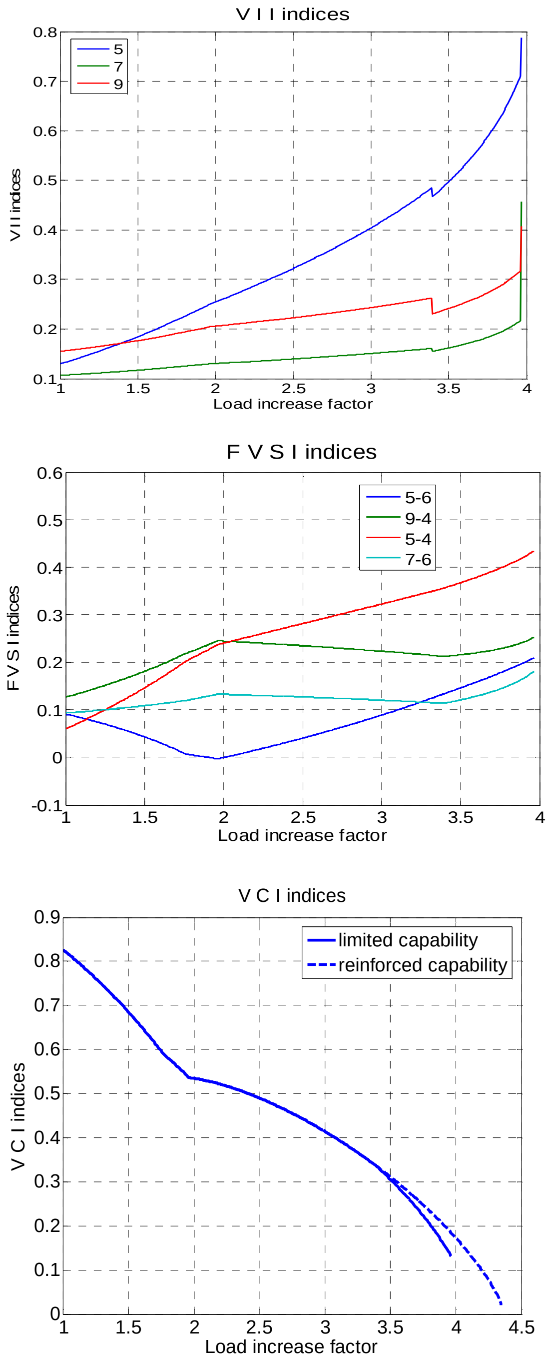

Fig. 7. VS indicators in case of limited reactive capability of the generators: a) VII curves for the three load buses; b) FVSI curves for the power system lines with the highest index values at the end of the simulation; c) VCI at node 5: a comparison between reinforced (dashed line) and limited (solid line) reactive capability

C. *Three machine test system: shunt switching*

In this scenario the reactive capability limits of machines 2 and 3 are set to the previous realistic values, and when the load increase factor is equal to 150% a shunt capacitor bank (rated 17 MVAr) is switched on in order to support voltage at the node where the load increase takes place.

Fig. 8 illustrates the trends of the VII indices.

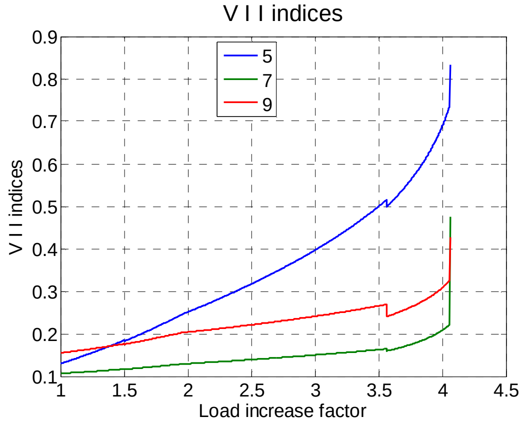

Fig. 8. V I I indices for the three load buses– shunt switching

Fig. 9 shows the FVSI curves for the lines with the highest final index values.

The insertion of the shunt at bus 5 reduces the FVSI values of lines 5-4 and 5-6 (thus, their criticality) because after the manoeuvre less imported reactive power is needed at bus 5.

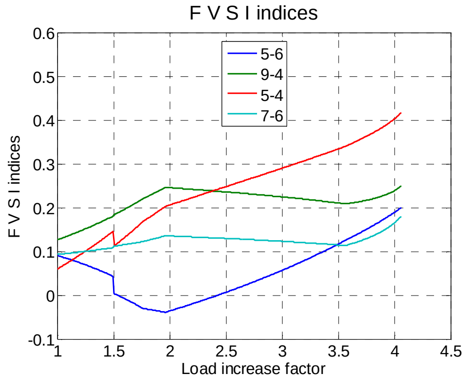

Fig. 9. FVSI indices for the lines with the highest final index values – shunt switching

At last Fig. 10 shows the VCI for node 5 in case of reinforced reactive limits (ideal case) and in case of realistic reactive limits and shunt switching.

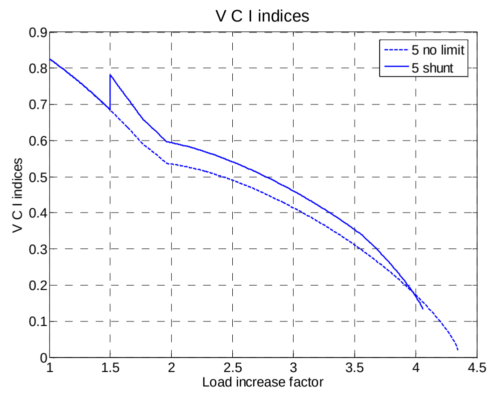

Fig. 10. VCI at node 5: comparison between the case of reinforced reactive limits of generators (dashed line) and the case of limited reactive limits and shunt switching (solid line)

The benefit of the shunt insertion is clearly visible in the VCI curve where the index value jumps from 0.68 to 0.78. It can be noticed that the new voltage stability margin corresponds to a load increase factor equal to 4.06 (vs 4.35 in the ideal case): the new margin is higher than the margin obtained without the shunt insertion (λ_{limit} = 3.96).

V. Simulations on a Large Power System

In order to carry out load ramps on realistic power systems the Voltage Stability tool adopts the engineering-level loadflow program mentioned in Section III. In this case the load ramp can be applied to the loads of a specific area of the grid. The load ramp is carried out by adopting a power factor equal to 0.7 like in [9] in order to consider a heavy load stress. Loads are still considered constant power loads.

If the power system under study is connected to the power systems of other countries (like in the case of the Italian HV transmission grid), the generators of the foreign equivalents do not respond to the load ramp, while the generators of the grid under study increase their power between two subsequent load increase steps k and k-1, to balance the load increase DP_{LOAD}, according to (9).

$$P_{Gi}^{(k)} = P_{Gi}^{(k-1)} + P_{MAX\ i}\left(DP_{LOAD} \Big/ \sum_i P_{MAX\ i} \right) \qquad (9)$$

Also this program takes into account the reactive capability of the generating units and it estimates the actual maximum reactive power of the units by using (10).

$$Q_{\max} = 0.5 * P_{\max} \qquad (10)$$

In case some machines reach their maximum admissible active powers, the power request not provided by these machines is redistributed among the other machines.

The realistic grid under study consists in a loadflow model of the Italian HV (220/400 kV) transmission grid referring to year 2003 (with the relevant foreign equivalents). The overall model includes about 1400 electrical nodes, 300 generating units and 1070 HV lines. Fig. 11 shows an overview of the 400 kV Italian transmission grid.

In this section the voltage stability tool is used to calculate the FVSI and VCI in case of different load increments with different stress directions. Table I summarizes the considered stress directions. For the VCI, parameter α has been set to 2 (which allows to obtain a well linearized trend).

Table I
Description of the Presented Simulations

Simulation ID	Stress direction
Sim 1	Uniform load increment in the HV grid
Sim 2	Load increment in Florence area
Sim 3	Load increment in Naples area

In all the simulations the generating units of the Italian HV grid respond to the load increment in a way proportional to their maximum active power limits.

Fig. 11. Overview of the Italian 400 kV transmission grid

A. Sim 1: uniform load increment

In this case a uniform load increment is applied to all the 132/150 kV load nodes of the national grid. It's worth remembering that the load increment is carried out with a power factor equal to 0.7 (which implies a high reactive stress for the grid).

Fig. 12 shows the VCI for the most critical node of the grid which is identified at the station of Rosara in the Center of Italy. The loadability margin estimated by the index is 3304 MW.

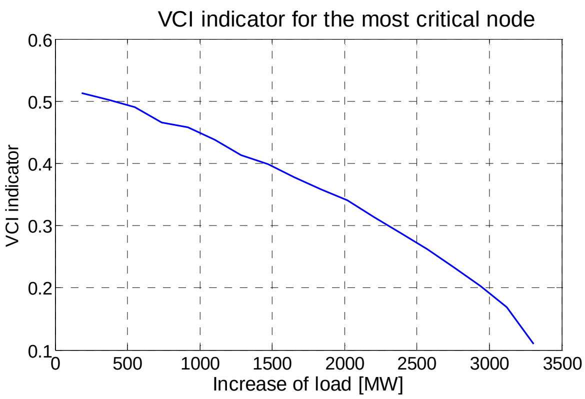

Fig. 12. VCI curve for the most critical node (Rosara) for a uniform load stress

Fig. 13 shows the FVSI as a function of the load increase for the most critical lines (i.e. the lines with the highest FVSI values in the last converging loadflow).

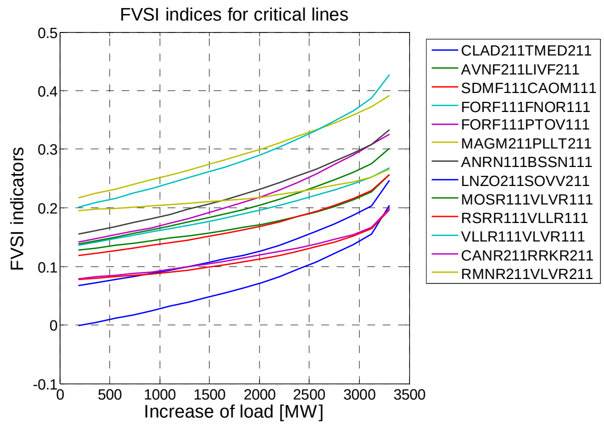

Fig. 13. FVSI curves for the most critical lines

Fig. 13 indicates that the most critical line is the line from Villavalle to Villanova with FVSI =0.43 in the last converging loadflow. Among the most critical lines there are also other lines in the Center of Italy, for example the 400 kV line Fano-Forlì (see Fig. 14), the 220 kV lines Villavalle-Roma Nord and Candia-Rosara.

Fig. 14. Grid area around the critical node (uniform load stress)

The FVSI is able to detect the critical zone by monitoring the reactive power flowing along the lines and the voltage at the terminals of the lines.

The indication of the critical node provided by the VCI is integrated by the information about the most stressed corridors given by the FVSI.

B. Sim 2: localized load increase in the area of Florence

In this case a localized load increase is applied to the area of Florence. All the Italian generators intervene by increasing their active power injections in a way proportional to their maximum active power. Fig. 15 indicates the VCI curve related to the most critical node which is identified at the station of Ravenna. The loadability margin calculated by subsequent loadflows is 2168 MW.

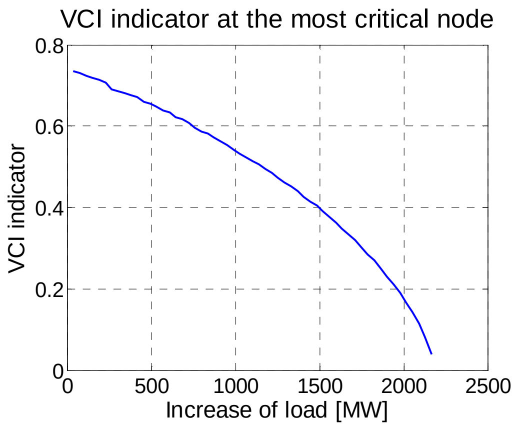

Fig. 15. VCI curve for the most critical node – load stress localized in the area of Florence

Fig. 16 shows the FVSI curves for the most critical lines. It can be noticed that the stress direction assumed for this case determines a high increase of the power import towards the area of Florence, in particular from the North. In fact, the list of the most critical lines contains a lot of lines connecting Florence area with Venice, Turin and Milan areas.

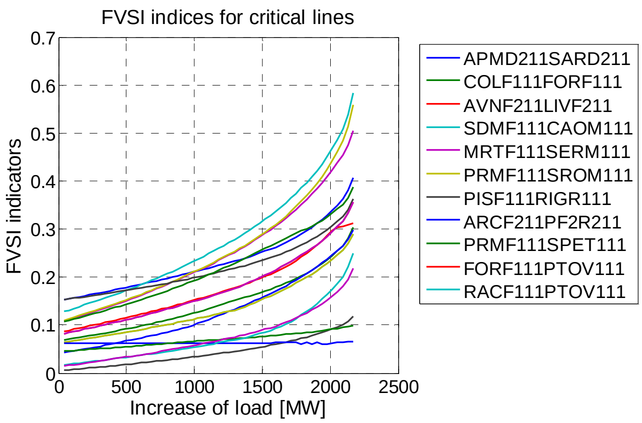

Fig. 16. FVSI curves for the most critical lines – load increment localized in Florence area

Table II indicates the critical lines with their FVSI values sorted in a decreasing order.

TABLE II
LIST OF THE CRITICAL LINES WITH THE RELEVANT FVSI VALUES

Line ID	FVSI
SDMF111-CAOM111	0.5839
PRMF111-SROM111	0.5595
MRTF111-SERM111	0.5053
APMD211-SARD211	0.4067
PRMF111-SPET111	0.3878
PISF111-RIGR111	0.3624
FORF111-PTOV111	0.3555
AVNF211-LIVF211	0.3125
COLF111-FORF111	0.3044
ARCF211-PF2R211	0.2983
RACF111-PTOV111	0.289

The first three lines (S.Damaso-Caorso, S. Rocco Po-Parma and Martignone-Sermide) connect HV stations of Milan and Florence areas. In the list there are also lines connecting Florence area with Venice area (the 400 kV lines Forlì-Portotolle and Ravenna-Portotolle), with Turin area (the 400 kV line La Spezia-Parma) and with Rome area (the 220 kV lines connecting Arezzo with Pietrafitta and P. Speranza with Rignano).

C. Sim 3: localized load increase in the area of Naples

In this case loads of Naples area are increased with a constant power factor. Fig. 17 shows the histogram of the VCI values of the most critical load nodes in Naples area in the last converging loadflow. The most critical node is identified at the station of Andria.

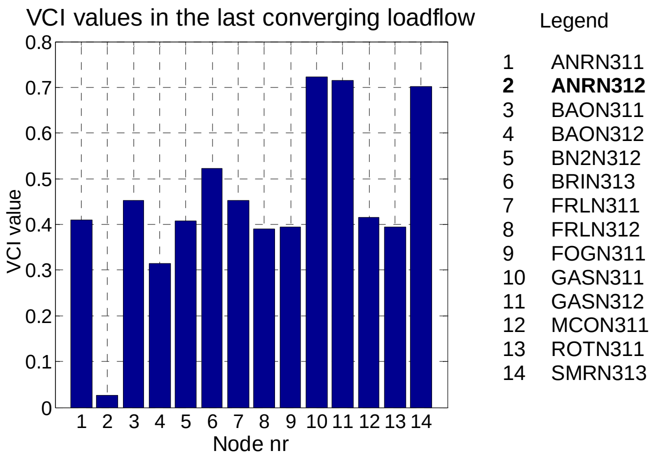

Fig. 17. Histogram of VCI values in the last converging loadflow – load increment localized in Naples area

Fig. 18 shows the FVSI indicators for the most critical lines in the last converging loadflow.

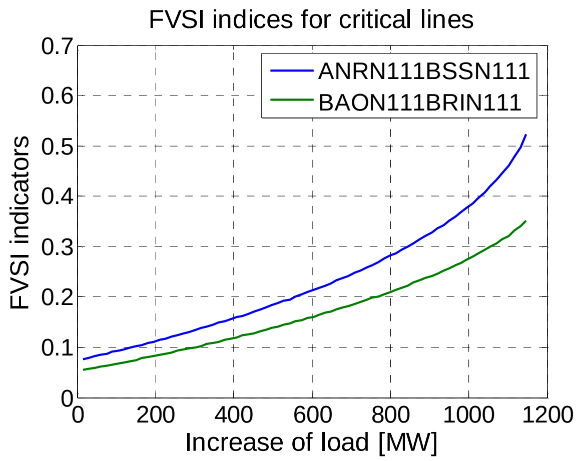

Fig. 18. FVSI curves for the most critical lines – load increment localized in Naples area

The lines with the highest FVSI values refer to two 400 kV lines in the South of Italy (Andria-Brindisi Sud and Bari–Brindisi). This is in line with the results of security assessment studies carried out on the Italian HV grid, which demonstrate the weakness of the zone around Brindisi PP both for transient stability and for voltage stability issues.

VI. Final remarks

The three indices presented in this paper allow to detect the voltage collapse point by monitoring different quantities (the load currents and voltages, the reactive flows on the lines, etc.). They can provide a deeper insight into voltage instability problems of the grid under study: for example in localized load increments the FVSI can provide useful information about the most stressed corridors. In fact localized load increments create high active power flows over long distances along the grid which in turn determine higher reactive losses and depressed voltage profiles, which are monitored by the FVSI.

The VCI provides indications on the load buses affected by voltage stability problems, it requires only local measurements and allows to evaluate the distance from voltage collapse point thanks to its quite linear trend.

The indications of the most critical load buses (provided by the VCI) and of the most stressed corridors (provided by the FVSI) can help operators identify specific grid areas which need a more careful monitoring and possibly the adoption of adequate control actions.

VII. Conclusion

The paper presents a tool for the calculation of some voltage stability indicators in order to detect the weak areas prone to voltage collapse in case of load increments. The tool allows to choose the load stress direction, i.e. the specific load or load area where to apply the load increment.

After a validation of the tool on a IEEE test system, the tool is used to identify the voltage collapse point and the weak grid areas in large realistic power systems. The application of the tool to the loadflow model of the Italian HV transmission grid demonstrates that the two indicators, FVSI and VCI, provide complementary information to a voltage stability study: in particular the role of the FVSI is of paramount importance in case of localized stresses.

The integration of the information coming from these two indicators may help operators better understand the system state and identify specific areas where to execute adequate control actions.

VIII. Acknowledgment

The authors wish to thank Dott. Ing. Diego Cirio, CESI RICERCA, Milan, for his fruitful comments.

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X. Biographies

Samuele Grillo was born in Alessandria, Italy, in 1980. He received the "Laurea" degree in electronic engineering in 2004 and the PhD degree in electrical engineering in 2008, both from the University of Genoa. His research interests regard optimization, automatic control, neural networks and machine learning and their application to power systems.

Stefano Massucco received the Doctor degree in electrical engineering at the University of Genoa, Italy, in 1979. From 1979 to 1987, he had been working at the Electrical Engineering Department of Genoa University, at CREL - the Electrical Research Center of ENEL (Italian Electricity Board) in Milano, Italy, and at ANSALDO S.p.A. in Genoa, Italy. He has been Associate Professor of Power Systems at the University of Pavia and since 1993 at the Electrical Engineering Department, University of Genoa, as Full Professor since 2000. His research interests are in power systems and distributed generation modelling, control, and management. Member of CIGRE Working Group 601 of Study Committee C4 for “Review of on-line Dynamic Security Assessment Tools and Techniques”.

Andrea Pitto was born in Genoa on March 2, 1981. He received his Doctor degree in Electrical Engineering at the University of Genoa, Italy, in 2005. He also received the PhD degree in Electrical Engineering at the same university in 2009. He is currently a research assistant at the Electrical Engineering Department of the University of Genoa. His area of interest includes probabilistic and deterministic approaches to power system security assessment, DG modelling, control and interface with distribution networks, application of bifurcation theory techniques to power systems analysis.

Federico Silvestro received the degree in electrical engineering from the University of Genoa in 1998 and a Ph.D. in power systems in 2002, with a dissertation on artificial intelligence applications to power systems. He is now under contract as Research Assistant at the Electric Engineering Department, University of Genoa, where he is working in power system simulators, security assessment, knowledge based systems applied to power systems.