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ON THE INDEXES TO QUALIFY AN HVDC CONNECTED TO VERY WEAK AC NETWORKS

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Resumen: Este artículo analiza la estabilidad de voltaje de sistemas ac/dc empleando indicadores estáticos y modales. Los indicadores se normalizan y comparan para diferentes relaciones de cortocircuito, SCR, en varias redes conocidas para un voltaje base común. Se proponen dos nuevos indicadores para proveer mayor información sobre requerimientos de potencia reactiva para la estabilidad de voltaje. El primer indicador propone valores críticos para diferentes SCR´s, mientras que el segundo permite caracterizar dos tipos de sistemas, suaves y no-suaves, para calificar requerimientos de potencia reactiva. El alcance presentado puede emplearse para asesorar estrategias de compensación reactiva y control en aplicaciones HVDC.
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Abstract: This paper develops a voltage stability analysis of ac/dc systems using static and modal indexes. The indexes are normalized and compared for different short circuit ratios, SCR, for several known networks at a common voltage base.
Two new indexes are proposed to provide more information on reactive power requirements for voltage stability. The first index proposes critical values for several SCR´s, whereas the second allows featuring two types of systems, soft and non-soft, to qualify requirements of reactive power. The approach can assist for considering the reactive compensation or control strategies in HVDC applications.

Keywords: HVDC transmission and control, Weak ac systems, Transient analysis, Voltage stability.

1. INTRODUCTION

THE indexes used to qualify a feasible connection between HVDC systems and ac networks go from steady state to dynamic analysis (Canizares et al., 2003; Gao et al., 1992; Gavrilovic, 1991; Hammad y Kühn, 1986; Nayak et al., 1995). The main idea is to establish a distance or diagnosis to voltage instability when HVDC technology is

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included.

One of the shortcomings to use the static indexes is the expected lack of accuracy when specific loads are considered (Taylor, 1994). The dynamic indexes were developed to provide a better explanation of the response of ac/dc systems based on their natural behavior (Gao et al., 1992). Putting together the methodologies about indexes for ac/dc projects, the systems are typically ranked as critical when their short circuit ratios, SCR, are lower or equal than 3.0 (Gavrilovic, 1991; Taylor, 1994; Arrillaga, 1998; Nayak et al., 1994). Based on such values, different strategies or reactive control methods are applied to prevent voltage instabilities (Nayak et al., 1994; Jovcic et al., 1999; Jovcic et al., 2000; Ainsworth et al., 1980; Gonzalez et al., 2006). The strategies could demand robust equipment like synchronous condensers, fixed capacitors or even Flexible AC Transmission Systems, FACTS.

The most outstanding static work to propose limit indexes for critical ac/dc interconnections was presented in (Hammad y Kühn, 1986). Nevertheless, the static and dynamic procedures, still lead to a kind of arbitrary variety of solutions founded on the strategies just mentioned. In the recent works, it has been proposed to establish a systematic methodology to select a better solution going from the less expensive control strategies to expensive solutions like FACTS (Gonzalez et al., 2006).

It is of great concern then, to count on complimentary analysis to compare different networks, with different strengths in which indexes can be treated in a common normalization, to assist for cost-effective solutions of critical ac/dc projects.

In the present paper, in section II, static and modal indexes are reviewed, and from normalization two new simple indexes are proposed. In section III the indexes are computed for several networks with different HVDC installations. In section IV the indexes are analyzed and critical ac/dc considerations related to the voltage stability are judged from complimentary points of view to consider reactive power needs as much in stable state as from the natural dynamics of the studied networks.

2. STATIC AND MODAL INDEXES USED TO QUALIFY ac/dc INTERCONNECTIONS

2.1. Static indexes

Based on the continuation power flow, it is possible to generate static indexes for the voltage stability in planning studies (Ajjarapu y Christy, 1992; Kundur, 1994). The continuation power flow method includes a gradual loading factor increase, λ_{LF}, in its problem equations:

$$\overline{F}(\overline{\delta},\overline{V},\lambda_{LF}) = \overline{0}, \qquad (1)$$

$$\begin{aligned} P_{Li} &= P_{Li0} + \lambda_{LF} * K_P \\ Q_{Li} &= Q_{Li0} + \lambda_{LF} * K_q \end{aligned}, \qquad (2)$$

Where,

F equations of power flow problem

δ angles of buses

V voltage of buses

i number designating the nodes of the electrical network.

P_{Li} , Q_{Li} real and reactive power demand at bus i

P_{Li0} , Q_{Li0} real and reactive power demand of the base case at bus i

K_p, K_q factors that include the rate of change of active and reactive load increase at bus i

With the loading increase, the set of equations yield:

$$\left[J_{\delta,V,\lambda}\right] * \left[d_{\delta,V,\delta}\right] = \overline{0}, \qquad (3)$$

Where

$[J_{\delta,V,\lambda}]$ modified Jacobian matrix including the load parameter λ_{LF}.

$[d_{\delta,V,\lambda}]$ tangent vector of δ, V, λ variations

With the aid of the vector $[d_{\delta,V,\lambda}]$ and the power flow equations, it is possible to calculate, among others, the following voltage indexes for system loading, λ_{LF} steps:

-*dVi*: incremental voltage change at node *i*.

-*dVi/dQt*: incremental voltage change at node *i* by the total incremental change of reactive power.

-*dQt/dVi*: total incremental change of reactive power by the incremental voltage change at

node *i*.
TVI: Tangent Vector Index. Equals *1/abs(dVi)*
dVi/Sum(dVj): incremental voltage change at node *i* by the sum of all incremental voltage changes of load nodes in the network.

Depending on system load conditions and on their mathematical definition, as being direct or inverse to the voltage variable, some indexes would grow or extinguish when no control actions are applied during system loading grow. For ac/dc operation, equivalent responses would be expected on indexes as SCRs diminish, since the rating of the HVDC system tends to reach the strength of the ac system.

2.2. Modal indexes

The voltage stability characteristics are a function of the active and reactive power. For the quasi-steady approach of the power flow, active power can be assumed constant at each operating point, i.e., $\Delta P=0$; only the incremental variations in reactive power and voltage are to be considered. Therefore, the linear polar power flow equation is reduced to (4), (Kundur, 1994; Hitzeroth, 2001), which defines the reduced Jacobian matrix J_R in (5).

$$\Delta V = J_R^{-1}\Delta Q\,, \tag{4}$$

$$J_R = J_{QV} - J_{Q\delta}J_{P\delta}{}^{-1}J_{PV}\,, \tag{5}$$

J_R can be written in modal form, in terms of (6) and then inverted in (7).

$$J_R = \xi\Lambda\eta\,, \tag{6}$$

$$J_R{}^{-1} = \xi\Lambda^{-1}\eta\,, \tag{7}$$

Where
ξ normalized right eigenvector
η normalized left eigenvector
Λ diagonal matrix of eigenvalues.

Here, *i* will denote each eigenvalue. Substituting (7) in (4) gives (8). Rewriting (8) for each eigenvalue *i*, gives (9).

From (9), it can be concluded that the smallest eigenvalue and eigenvectors of J_R, serve as indexes to judge the stability of a system from a point of view of the physical elements associated with the modes of oscillation. When the eigenvalue is small or negative, the related mode is defined to be voltage stability critical (Hitzeroth, 2001; Lee et al., 2000).

$$\Delta V = \xi\Lambda^{-1}\eta\Delta Q\,, \tag{8}$$

$$\Delta V = \sum_i \frac{\xi_i\eta_i}{\lambda_i}\Delta Q\,, \tag{9}$$

The Branch Participation Factor in bus *k* for a specific mode, *d,* is defined in (10). For the critical mode, this index provides information concerning the placement of remedial measures to alleviate the system about voltage stability.

$$P_{k,d} = \xi_{kd}\eta_{dk}\,, \tag{10}$$

The Singular Value Decomposition, SVD, can also be used to get more information on voltage stability problem. The SVD applied to (4) yields (Hitzeroth, 2001; Zurmuehl y Falk, 1984):

$$\Delta V = J_R^{-1}\Delta Q = (U\Sigma V^T)^{-1}\Delta Q\,, \tag{11}$$

Where *U* and *V* are ortho-normal matrices, whereas $\Sigma=diag(\sigma 1, \sigma 2,\ldots, \sigma r)$ is a real matrix, being *r* equal to the number of eigenvalues. Also: $\sigma 1\geq \sigma 2\geq \ldots\geq \sigma 1\geq \sigma r\geq 0$. Since J_R^{-1} is a square matrix, $(\sigma 1, \sigma 2,\ldots, \sigma r)$ are called the set of singular values. The minimum singular value of a square matrix is a measure of the distance of that matrix to a singular one. This is a proper index for voltage stability analysis.

Further property of SVD is that for a square, symmetric and positive definite matrix, the eigenvalue decomposition and SVD are equivalent, whereas the SVD of a real matrix is always real (Zurmuehl y Falk, 1984).

2.3. Other indexes proposed

For a variety of analysis in electrical power systems, it is necessary to use per-unit based procedures to allow comparisons of common phenomena for networks of different size. The indexes studied so far can be normalized and studied in a common picture for different power systems. This is what will be done in the next section.

For the nature of events affecting the voltage stability, important amounts of reactive power are transferred inside electrical systems. So, any normalized index or sensitivity should be naturally scaled on a basis of the net incremental reactive power, *dQt*. In this way, the indexes normalized could be stated as times *dQt* defining here the **dQt* or "NORMQ" indexes (12). A special name ending with the words "NORMQ" is given to each index under it:

$$(-dV_i) * dQt$$
DVNORMQ,

$$(-dV_i / dQt) * dQt$$
DVQNORMQ,

$$(-dQt / dV_i) * dQt$$
DQVNORMQ,

$$TVI * dQt \qquad (12)$$
TVINORMQ,

$$(dV_i / SumdV_j) * dQt$$
DVSUMNORMQ,

$$eig\_\min * dQt$$
MODALNORMQ,

$$\sigma\_\min * dQt$$
SVDNORMQ,

The eigenvalues and singular values provide information on the dynamic nature of a power system. For the voltage stability phenomena, the dynamics of the reactive power responses of any kind of the compensation equipment, are very important to avoid regimens of collapse. From this point of view, indexes relating the net incremental reactive power and the present minimum eigenvalue or minimum singular value, can expose the dynamic reactive power interchanged when the system is submitted to the most compromising conditions on voltage. These indexes are the defined in (13). A special name is given to each index under it:

$$dQt / eig\_\min$$
SOFTMODAL,

$$dQt / \sigma\_\min \qquad (13)$$
SOFTSVD,

3. SYSTEMS TO BE STUDIED

The standard IEEE-14, IEEE-39, IEEE-118 buses and the standard 16 generators - 68 busbars system are studied in terms of voltage stability behavior. Firstly, a program based on the continuation power flow method and a modal analysis is run for the base case to identify the weaker nodes of each network, according to their participation factors and following a gradual increase on active and reactive power on load buses. HVDC applications in different schemes and control modes are connected to those weaker nodes, to surround the more critical situations for the voltage stability. SCRs of 15, 8, 5, 4, 3.5, 3.0, 2.5 2.0 and 1.5 were considered. For the 16 generators (68 buses) system, when an HVDC was connected to its weaker node, only convergence for SCR values greater than 3.0 was reached.

For each case, the indexes exposed in section II were quantified and then normalized to achieve common basis comparisons between different networks and then get qualifications of the different indexes. Because of the objective of normalization, for each SCR the inverter ac voltage is set to 1.05 p.u. modifying shunt capacitor compensation in the node of interest. Also, with this methodology, it will be possible to know more about the status of the system in terms of conditions near to instabilities. In this way of thought, indexes are calculated for the first step of the loading factor λ_{LF} where the normalization is achieved.

Only as a reference, to inform about the size of the studied networks, the inverter side active power *Pinv* and reactive power *Qinv*, for SCR of 2.0 will be indicated.

For all the cases, ten indexes were studied and compared in a normalized way, i.e. as per unit values, having as the base the maximum value drawn for each index along the SCRs: *–dVi, -dVi/dQt, -dQt/dVi, TVI, dVi/SumdVj, eig_min, σ_min, Bus Participation Factor,* DVNORMQ, DVQNORMQ, DQVNORMQ, TVINORMQ, DVSUMNORMQ, MODALNORMQ, SVDNORMQ, the Bus Participation Factor and the SOFTMODAL.

The subscript *i* in the indexes, makes reference to the weakest node.

Almost identical values for the pairs *–dVi* and *-dVi/dQt*; *-dQt/dVi* and *TVI*; *eig_min* and *σ min* are obtained. It is clear because of their definition and also for the pair *eig_min* and *σ_min* since the Jacobian matrices are symmetrical in the studied cases (e.g., no phase shifting devices are included).

Some basic HVDC parameters common for many of the simulations are shown in Table 1. Other data are exposed in each case.

TABLE 1. Data for HVDC between nodes 14 (Inverter) and 13 for the ieee 14-bus System.

Characteristics	Value
Extinction angle (gamma)	18 degrees
Converter transformers ratios	0.5 – 0.6
dc line resistor (RL)	0.0189 p.u.
Commutation resistance (rectifier – inverter)	0.0113 p.u.
Number of six-pulse bridges	2

3.1. IEEE-14 buses

Buses 9, 10 and 14 were identified as weak nodes and then three HVDC installations are studied and compared when stressing these nodes using *Kp=Kq=1.0* in the continuation power flow. Node 14 was identified as the weakest according to modal analysis:

HVDC between nodes 14 (inverter) and 13: with the rectifier in Constant Current Control (CC) and the inverter in Constant Extinction Angle (CEA) control mode for each SCR. The SCR=2.0 corresponds to Pinv=93.29 MW and Qinv=33.89 MVAr.. The transmission line between nodes 13 and 14 was replaced by the HVDC.

HVDC in node 14 (inverter): in constant power control mode for each SCR. The SCR=2.0 corresponds to Pinv=173.4 MW and Qinv=104 MVAr. The transmission line between nodes 13 and 14 was kept.

HVDC in node 14 (inverter): in CC-CEA control mode for each SCR. The rectifier side belongs to another ac network. The SCR=2.0 corresponds to Pinv=173.4 MW while Qinv=68.48 MVAr for the selected control. The transmission line between nodes 13 and 14 was also kept.

The system with the three proposed HVDC installations is shown in Fig. 1. The traces related to this case are named according with the installations proposed, as follows: *ieee14-1*, *ieee14-2* and *ieee14-3*.

In Figs. 2 to 11 the indexes are depicted and comparisons with the other cases are possible.

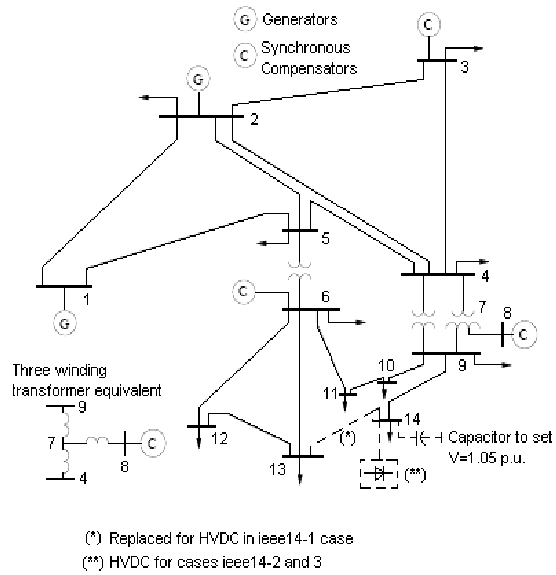

Fig. 1. IEEE-14 bus system with the proposed HVDC installations

3.2. IEEE-39 buses

Bus 12 was identified as the weakest node and then one HVDC in constant power control mode is studied when stressing all the PQ nodes using *Kp=Kq=1.0* in the continuation power flow.

SCR=2.0 corresponds to *Pinv*=7242 MW and *Qinv*=4345 MVAr. It can be noticed that this system is of a higher power capacity than the14 busbar system.

In Figs. 2 to 11 the indexes are traced and compared with the other cases. The traces related to this case are named *ieee39*.

3.3. IEEE-118 buses

Bus 21 was identified as the weakest node and then one HVDC in constant power control mode is studied when stressing all the PQ nodes using *Kp=Kq=1.0* in the continuation power flow.

SCR=2.0 corresponds to *Pinv*=358 MW and *Qinv*=214.8 MVAr. This system is of higher capacity than the 14 busbar system.

See Figs. 2 to 11 where the indexes are traced and compared with the other cases. The traces related to this case are named *ieee118*.

3.4. 68 buses

This system is a simplified version of the New England/New York transmission network (Rogers, 2000). Bus 40 was identified as the weakest node and then one HVDC in constant power control mode, installed in that node, is studied when stressing all the PQ nodes using *Kp=Kq=1.0* in the continuation power flow.

SCR=2.0 corresponds to *Pinv*=1308 MW and *Qinv*=785.24 MVAr. This system has the second highest power capacity compared to the 14 busbar system.

As it will be found, this system is very special, helping to establish important features. The indexes are traced and compared with the other cases in Figs. 2 to 11. The traces related to this case are named *system68*.

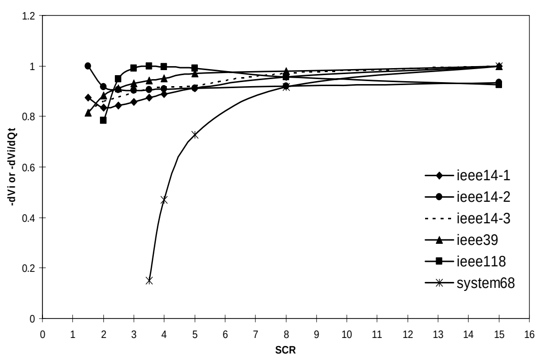

Fig. 2. Normalized –dVi or –dVi/dQt indexes for the studied cases

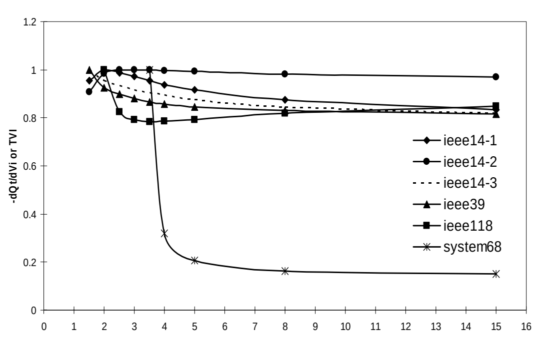

Fig. 3. Normalized –dQt/dVi or TVI indexes

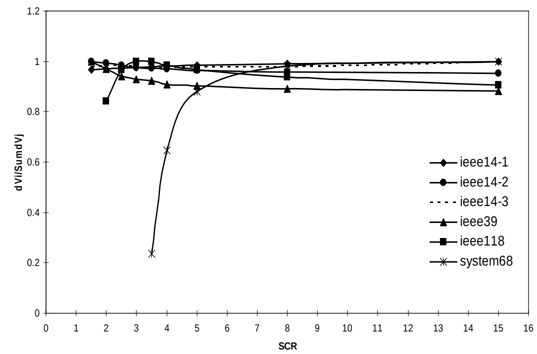

Fig. 4. Normalized dVi/SumdVj indexes

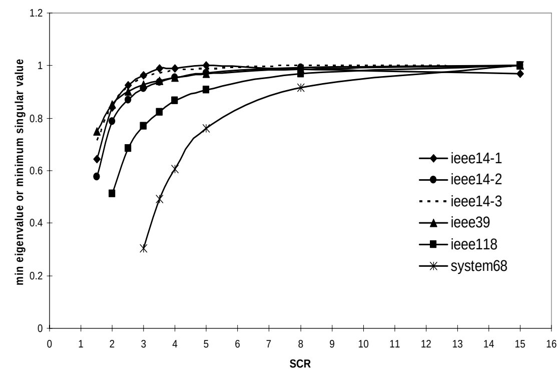

Fig. 5. Normalized Minimum eigenvalue or singular value indexes for the studied cases

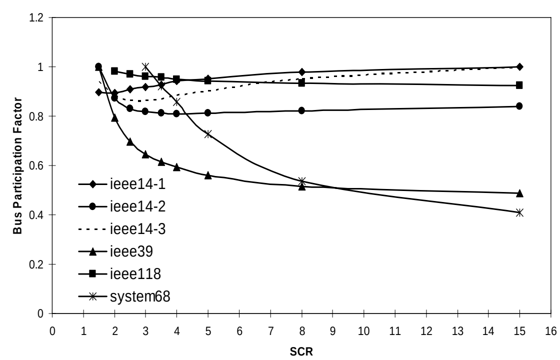

Fig. 6. Normalized Bus Participation Factor indexes

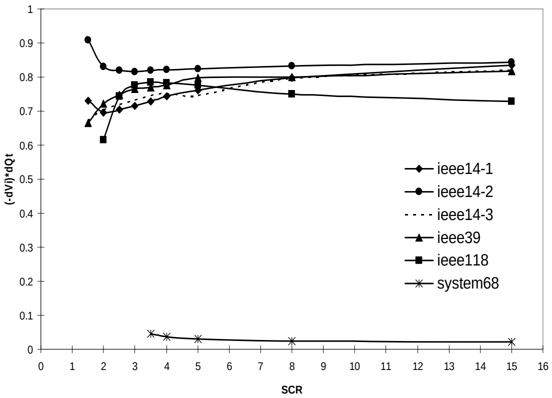

Fig. 7. DVNORMQ indexes

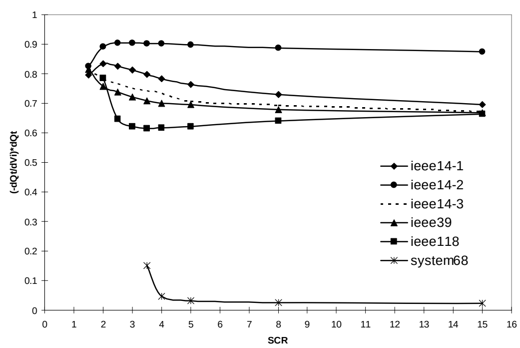

Fig. 8. DQVNORMQ indexes

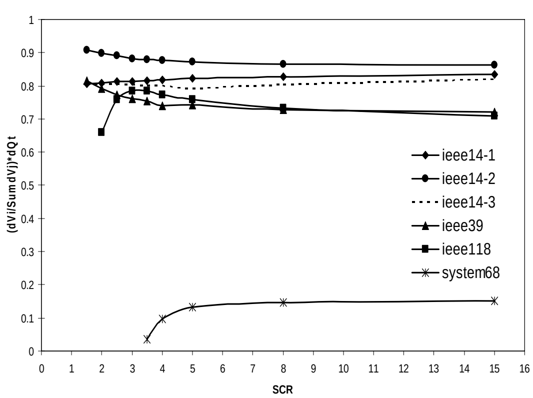

Fig. 9. DVSUMNORMQ indexes

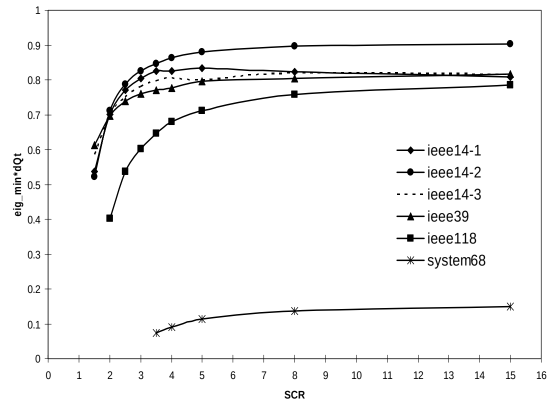

Fig. 10. MODALNORMQ indexes

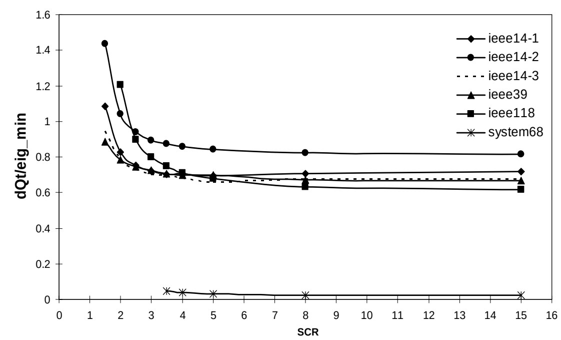

Fig.11. SOFTMODAL index for the studied cases

4. RESULTS ANALYSIS

For the ieee14-1, ieee14-2, ieee14-3 and ieee39 cases, the normalized indexes *–dVi* or *-dVi/dQt* presented in Fig. 2 softly decrease as SCR decreases. This can be explained e.g., by the power – voltage characteristics of a capacitive compensated bus, like it is the present case for low SCR´s while keeping a voltage objective of 1.05 p.u. Near SCR of 2.0, ieee14-1 and ieee14-2 have a critical point in which they start to increase back, describing the nose point in e.g., a power – voltage characteristic. In Fig. 2, case ieee118, tend to increase as SCR decreases but around a SCR of 3.0 starts to decrease with a high slope. For the system68 case, these normalized indexes present stronger slopes when SCR goes below 8.0.

The normalized indexes depicted in Fig. 3, i.e. *–dQt/dVi* or *TVI* are more sensitive with the equivalent behaviors near SCR of 3.0 for the ieee14-1, ieee14-2, ieee14-3, ieee39 and ieee118 cases, whereas in the system68 case the critical change of slope is near a SCR of 5.0.

The case of the normalized *dVi/SumdVj* index in Fig. 4, appears to be a little smoother than the indexes *–dVi* or *-dVi/dQt*, for all the cases excepting system68. This index has to be carefully analyzed to avoid misinterpretations like hiding system effects.

In Fig. 5, the minimum eigenvalue or minimum singular value indexes are very straight indexes to qualify the evolution of the network as it is gradually stressed. For ieee14 and ieee39 cases, the voltage issues could be expected for values of SCR below 4.0 where there is a change of slope, whereas for the ieee118 case the voltage issues could start below 5.0. The system68 case continues to be special, diagnosing voltage problems for SCRs under 8.0.

The Bus Participation Factor index, Fig. 6, could be very suggestive in explaining how nodes of interest could evolve during network stressing, i.e., node 14 in ieee14 cases is sustained along SCRs whereas node 40 in system68 quickly increases as critical SCRs are reached. This can help to explain the severity of system 68 in the traces shown so far.

In general, for the three ieee14 cases the indexes follow similar trajectories before reaching critical SCRs, but being the case of constant power control mode the more prone to cause voltage instabilities.

The "NORMQ" indexes allow to "decouple" back the indexes and show them in a new normalized "subspace" of reactive power requirements. In Fig. 7 to 10, it can be found an advantage gained in such subspace: in general all "NORMQ" indexes point out the triggering of instabilities for approximately the same SCR, i.e., under 5.0. This result could be the base of a new standardization related to voltage stability methodologies.

According to Fig. 11, the SOFTMODAL index (equivalent to SOFTSVD in this case) can be assigned two types of behavior according to ieee118 and system68 cases, which appear to be two extreme cases according to what will be explained next. In the first case, the dynamics related to reactive power needs are predictable as little changes in the SCRs produce equivalent changes in the reactive power. This could be seen as a *moderately* or *soft dynamic* case in terms of reactive power requirements. For the second case, system68 is almost unpredictable where it is reaching instabilities, this index behaves almost constant for all the SCRs. But this feature could be very useful since it can explain stable dynamic behavior limits more accurate than it could be the case of a point in the relatively extended knee of the ieee118 case.

As it was defined for the ieee118 case, the system68 case could be seen as a *non-soft dynamic* case because of its sudden step to instability. Finally, from the latter considerations, the assistance of the reactive power compensators, should be chosen accordingly taking into account the SOFTMODAL indexes, e.g., for *soft dynamic* cases, dynamic compensators like synchronous condenser or FACTS devices could be more appropriate than fixed compensators (e.g., capacitors banks) as it would be for the case of *non-soft* dynamic cases. In the same direction, control strategies of HVDC systems could be expected to be more successful for the *soft dynamic* cases.

5. CONCLUSIONS

The voltage stability analysis of ac/dc systems can be achieved with normalized static and modal indexes. The analyses done in this work have shown that specific ac/dc networks expose differences in their limits of SCRs in terms of voltage instabilities relationships for classic indexes.

Two simple new indexes have been proposed with the objective of providing more information on reactive power requirements and voltage behavior. The first index, called "NORMQ" help to establish or "normalize in Q basis" the triggering of instabilities for approximately the same SCR within the networks considered. This result could be the base of a standardization related to voltage stability methodologies. The second proposed index allows featuring two types of systems, *soft and non-soft dynamical systems* in which the index serve to qualify a requirement of reactive power according to the nature of systems. The latter, can serve to consider fixed or dynamic reactive compensation or control strategies for HVDC applications as a function of their strength.

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