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Proposal of indexes for fast voltage stability evaluation of ac/dc transmission systems

Propuesta de indicadores para una rápida evaluación de la estabilidad de tensión de sistemas de transmisión ca/cd

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Abstract

This paper develops voltage stability analysis of ac/dc systems using static and modal indexes. New indexes treatment is proposed to provide more information on requirements for specific network strengths in terms of voltage stability constituting a means to prevent potential issues of high voltage dc transmission system (HVdc), connected to weak ac nodes. The indexes are per unitized and compared for different short circuit ratios (SCR), in a modified IEEE 14 buses network, with a HVdc system connected to its weakest bus. The approach can assist as much for planning as for on-line monitoring of voltage stability in power systems including ac/dc nodes.

------ *Keywords:* Voltage stability, HVdc systems, weak networks, stability indexes, SCR

Resumen

En este artículo se desarrolla un análisis de estabilidad de tensión de sistemas ca/cd empleando indicadores estáticos y modales. Se propone un tratamiento novedoso para indicadores de estabilidad de tensión, con el fin de obtener una mayor información sobre los requerimientos en redes de variadas fortalezas, en términos de la estabilidad de tensión. El nuevo tratamiento se ofrece como un medio para prevenir potenciales problemas en redes de transmisión de

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corriente directa, High Voltage dc Transmission Systems (HVdc), conectados a nodos débiles. Los indicadores son convertidos a por unidad y comparados en diferentes relaciones de corto circuito, Short Circuit Ratios (SCR), en una red modificada tipo IEEE de 14 barras, la cual posee un sistema HVdc conectado en su barra más débil. Los alcances pueden servir tanto para planeamiento como para monitoreo en tiempo real de la estabilidad de tensión en sistemas eléctricos de potencia incluyendo nodos ca/cd.

------ *Palabras clave:* Estabilidad de tensión, sistemas HVdc, redes débiles, indicadores de estabilidad, SCR

Introduction

Ac/dc interactions between high voltage dc transmission systems (HVdc) connected to weak ac networks have been a matter of special interest for years. This is an important field since HVdc applications are at present being widespread all around the world. However, there are situations of operation for weak ac/dc interfaces that may lead the system to a voltage collapse or black-out. There are reports of high black-outs in the world as a consequence of ac/dc interactions [1].

Indexes to evaluate voltage stability problems for ac/dc networks could predict or give information to avoid voltage instabilities. Nevertheless, due to the magnitude of modern electrical networks and ruled by market requirements, it is a need to count on fast, effective and reliable indexes for voltage stability assessment, for on-line monitoring or during planning stages.

The classical indexes for assessing voltage stability can be of the steady or dynamic principle [2-6]. Dynamic indexes were developed to compliment a better explanation of the response of ac/dc systems based natural behaviors [2]. Static indexes can lead to a lack of accuracy when special loads are considered [1].

For ac/dc systems, the criticality about voltage stability is identified when the short circuit ratio in the interface busbar, SCR, is lower or equal than 3.0 [1, 4]. Based on such values, different strategies or reactive control methods are applied to prevent voltage instabilities [7-12]. Static, Modal and Dynamic indexes are proposed in [1-3, 6, 13-15]. In [16] novel indexes for voltage stability assessment are proposed using Artificial Neural Networks with Back Propagation technique, in that reference, the indexes are encouraged for future application in on-line monitoring. The static and dynamic procedures require the whole simulation to be run before qualifying the potential problems on voltage stability, or the distance to voltage collapse. This consumes time of computation depending on the network size and on the actual level of load.

In a typical voltage stability study, the indexes are obtained as a function of a loading factor. Near the instability limit, some indexes increase or decrease, but some change more rigorously than others. If this behavior is tracked by an operator or analyst, the indexes that are not so sensible could tend to damp or avoid the analyst to achieve potential quick repairing actions. According to the latter, there is a need to count on complimentary analysis to compare different indexes in a common normalization, as to identify common excursions of voltage stability problems, in which indexes could clearly show the imminence of collapses. In this manner, it could be possible to assess for fast, effective and reliable identification of potential voltage stability problems and make the first moves to find solutions in the network. The normalization, or per unitizing procedure for indexes, has not been used to date in assessing for the voltage stability conditions of electrical networks. In this paper, voltage stability indexes are firstly reviewed; from per unitization new simple static and modal indexes analysis is then proposed with the goal of obtaining a reliable and fast identification of voltage stability conditions.

It will be concluded that the methodology using per unit voltage stability indexes will offer new alternatives for decision making while complementing the classical indexes. The advantages of having complimentary indexes and analysis will increase the reliability in HVdc applications, allowing the power systems comprising dc links to grow even more and with enhanced monitoring conditions, even for special systems that get weak under unexpected disturbances or changes in their configurations. It is important to highlight that nowadays, conventional and big Ultra HVdc projects are under construction, increasing the interest in more stable networks interacting in ac/dc nodes.

Voltage stability indexes

In [13], based on the continuation power flow, static and modal indexes for the voltage stability in planning studies were developed using well known Continuation power flow method [14, 15]. The continuation power flow method includes a gradual loading factor increase, λ_{LF}, in its problem equations (1) to (3):

$$\bar{F}(\bar{\delta},\bar{V},\lambda_{LF}) = \bar{0} \tag{1}$$

$$P_{Li} = P_{Li0} + \lambda_{LF} * K_p \tag{2}$$

$$Q_{Li} = Q_{Li0} + \lambda_{LF} * K_q \tag{3}$$

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 to the modified Jacobian matrix [14] including the load parameter λ_{LF}. In this way, a tangent vector of δ, V, λ variations is developed in order to calculate the following voltage indexes for system loading, λ_{LF} steps:

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

dVi/Sum(dVj): incremental voltage change at node *i* by the sum of all incremental voltage changes of load nodes in the network. This index is known as Voltage Sensitivity Factor [15].

Other indexes could be developed, but the behavior under normalization of the last ones will be of special attention in this work.

Depending on system load conditions and on their analytical 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 increment. For ac/dc operation, equivalent responses would be expected on indexes as the strength of the ac bus decreases while the rating of the HVdc system approaches the strength of the ac system.

For the quasi-steady approach of the power flow, active power can be assumed constant at each operating point, i.e., only the incremental evolution in reactive power and voltage are to be considered. Therefore, the linear polar power flow equation is reduced to (4), [15, 17].

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

Now, the reduced Jacobian matrix J_R can be defined in (5).

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

Where the subscripts *P, Q, V, δ* address the relationship of the same variables under the Jacobian matrix.

J_R can be written in modal form, in terms of (6).

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

J_R is then inverted in (7).

$$J_R^{-1} = \xi \Lambda^{-1} \eta \quad (7)$$

Where,

ξ: normalized right eigenvector

η: normalized left eigenvector

Λ: diagonal matrix of eigenvalues.

Here, *i* will denote each eigenvalue. Substituting (7) in (4) leads to (8).

$$\Delta V = \xi \Lambda^{-1} \eta \Delta Q \quad (8)$$

Rewriting (8) for each eigenvalue *i*, gives (9).

$$\Delta V = \sum_i \frac{\xi_i \eta_i}{\lambda_i} \Delta Q \quad (9)$$

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 [15, 17, 18].

The Bus Participation Factor, FPB, 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.

$$P_{k,d} = \xi_{kd} \eta_{dk} \quad (10)$$

The indexes studied can be per unitized for studies in a common basis. The proposed per unitizing procedure is simple: the registry of index values, dependant of load increase in terms of lambda, are divided by the highest value of the index.

Methodology

System to be studied

The IEEE 14 Bus Test Case represents a portion of the American Electric Power System in the Midwestern US as of February, 1962. It consists of five synchronous machines, three of which are synchronous compensators used only for reactive power support. There are 11 loads in the system, totaling 259 MW and 81.3 Mvar.

A modified IEEE-14 network will be studied in terms of voltage stability behavior. Firstly, a program based on the continuation power flow method and a modal analysis is executed for the base case to identify the weaker nodes of the network, according to their participation factors and following a gradual increase on active and reactive power on load buses. Node 14 was identified as the weakest according to modal analysis. A HVdc system is connected to bus 14, in the more critical situations for the voltage stability.

The Short Circuit Ratio, SCR, has typically served as qualifier for potential issues in voltage stability. The SCR is defined in (11).

$$SCR = \frac{MVA_{sh}}{P_{cd}} \quad (11)$$

Where,

MVA_{sh} : Short circuit three phase MVA

P_{cd}: cd power of the HVdc

An SCR lower than 3.0 would normally lead to voltage instabilities issues [4].

In this work, SCR of 10, 3 and 2.5 were studied. For each case, the indexes were quantified and then per unitized for common comparisons.

Four indexes were studied and compared in per unit, having as the base the maximum value traced for each index along the SCR: *-Vi/dQt pu, dVi/SumdVj pu, eig_min pu* and Bus Participation Factor, *FPB pu*.

The subscript *i* in the indexes, makes reference to the weakest node, i.e., node 14.

It is useful to point out that the studies are static only, e.g., no commutation failures due to voltage decrease were supposed for the weaker cases (SCR lower than 3.0). The analysis is primarily on transmission constraints and its influences on voltage stability when a HVdc system demands important amounts of reactive power, also with such objective, reactive power limits of generators were not included either. Due to the latter, the HVdc system is represented as a generator injecting an active power according to the SCR in bus 14 and withdrawing a reactive power of 60% the active value.

The three-phase short circuit current in 345 kV bus 14 is 600 A, which yields an MVA short-circuit power according to (12).

$$MVA_{sh} = \sqrt{3} * 345 * 600 = 358.53 \quad (12)$$

For instance, for the SCR=10, the active power injected in the inverter node by the HVdc systems is obtained as follows in (13):

$$P_{cd} = \frac{MVA_{sh}}{SCR} = \frac{358.53}{10} = 35.85\ MW \quad (13)$$

The reactive power demanded by the HVdc in the inverter side will be in (14):

$$Q = 0.6 * 35.85 = 21.51\ Mvar \quad (14)$$

Table 1 shows the different values for each SCR. The system with the proposed HVdc is shown in figure 1. No convergence was possible for the SCR=2 case.

Table 1 HVdc P and Q data for each SCR and output of the studies

MW	Mvar	SCR	Lambda	Vnose	Vini
35.85	21.51	10	9.01	0.56	1.0227
71.70	43.02	5	9.41	0.53	1.0000
119.51	71.70	3	8.96	0.54	0.9500
143.41	86.05	2.5	8.05	0.55	0.9100
179.26	107.56	2	-	-	-

Results and discussion

Figure 2 shows the P-V curves for each SCR. The load factor lambda is applied to increase the demand in the HVdc inverter side busbar. For example, the maximum power is for a lambda of approximately 9.41 for the case with SCR=5.0. The reactive power required by the HVdc is determinant in this behavior.

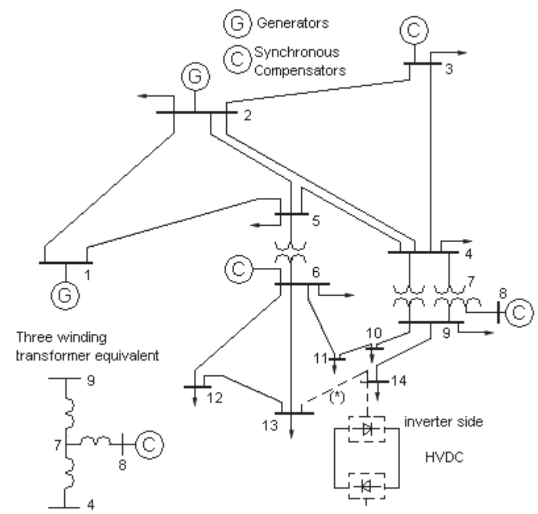

Figure 1 IEEE-14 bus system with the proposed HVdc installation

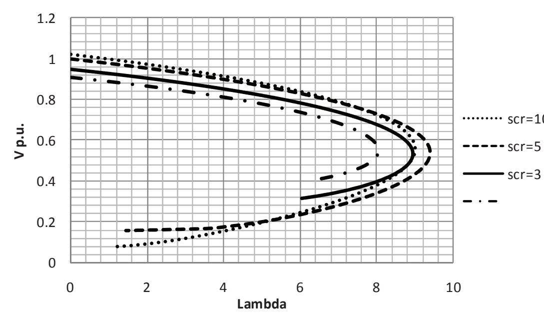

Figure 2 P-V curves for different ac/dc SCR

It is useful to point out that the studies are static only, e.g., no commutation failures due to voltage decrease were supposed for the weaker cases (SCR lower than 3.0). The analysis is primarily on transmission constraints and its influences on voltage stability when an HVdc system demands important amounts of reactive power, with such objective, reactive power limits of generators were not included either.

For this particular case, the maximum active and reactive power withdrawn from the network are obtained after having assigned a *Kp* and *Kq* equal to the base load in bus 14, i.e., 14.9 MW and 5 Mvar respectively. Those maximum powers reached are (15) and (16):

$$P_{L14} = P_{L140} + \lambda_{LF} * K_p = P_{L140}(1+\lambda_{LF}) = 0.149(1+9.41) = 1.551 \equiv 155.1\ MW \quad (15)$$

$$Q_{L14} = Q_{L140} + \lambda_{LF} * K_q = Q_{L140}(1+\lambda_{LF}) = 0.05(1+9.41) = 0.5205 \equiv 52.05\ MW \quad (16)$$

Figures 3 to 6 present the indexes for each SCR as a function of lambda. It is clear that the indexes behave very similar as load increases, except for the case of the index *dVi/sum(dVj),* figure 5, that starts from clearly different values in the base cases.

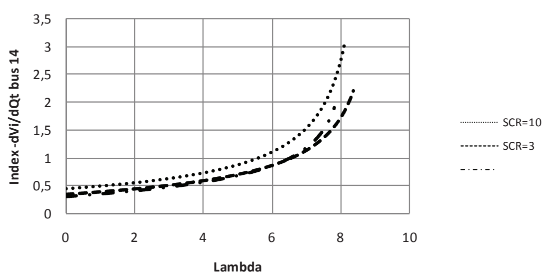

Figure 3 *–dVi/dQt* index for different SCR

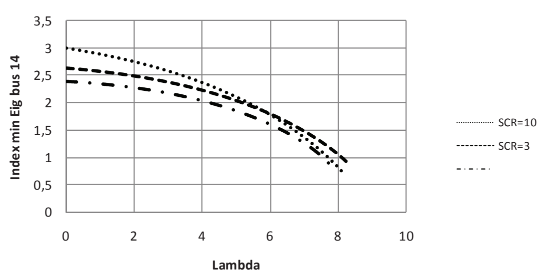

Figure 4 *min Eig* index for different SCR

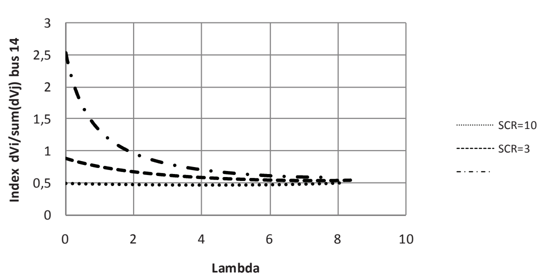

Figure 5 *dVi/sum(dVj)* index for different SCR

Then, the indexes were per unitized for comparisons between them. Plotted in the same frames, figures 7 to 9 show the per–unitized indexes for each SCR as a function of lambda. Though modal indexes are obtained supposing zero active power changes, they were added in the same graphs only for a contrast in tendency. It can be seen that it is difficult to assess for voltage stability issues since some indexes grow in the meantime when some others have opposite tendencies.

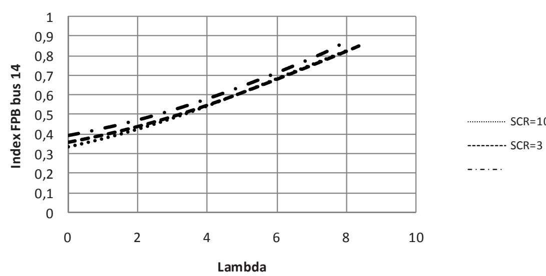

Figure 6 *FPB* index for different SCR

Figures 10 to 13 depict comparisons for each index and SCR. The behavior of the *dVi/sum(dVj)* index, figure 12, is really noticeable in a wide range, in contrast with the evolution of the other indexes as the system is gradually stressed. The behavior of this per unitized index would be useful to rapidly predict, detect or diagnose the likelihood of a weak ac/dc system going to a voltage collapse. This cannot be comparatively reproduced using the other normalized indexes as they evolve in the same manner as the system load is stressed; they even cross to each other in some cases, what could make harder the screening of stability problems.

The *dVi/sum(dVj)* index widely differentiates the different situations on SCR, allowing for a fast identification and diagnosis of voltage stability problems between the different stages of network strength. This is more suitable when it is complimented with the behavior of the same non per unitized index, when all situations of network strength tend to converge to the same value in the vicinities of the point of collapse. This enhances the reliability in the interpretation during the assessment of voltage stability conditions.

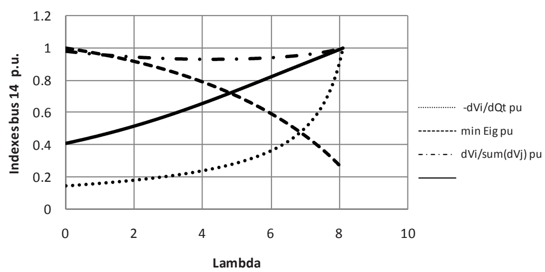

Figure 7 p.u. indexes for SCR=10

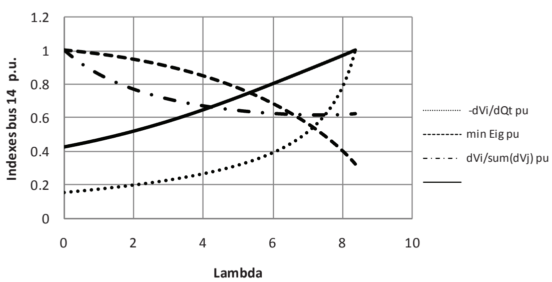

Figure 8 p.u. indexes for SCR=3

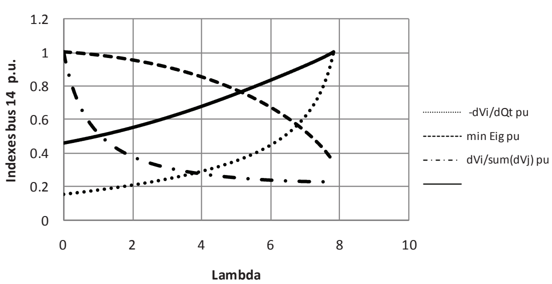

Figure 9 p.u. indexes for SCR=2.5

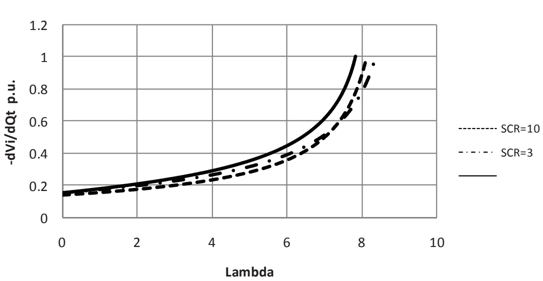

Figure 10 p.u. *–dVi/dQt* index for different SCR

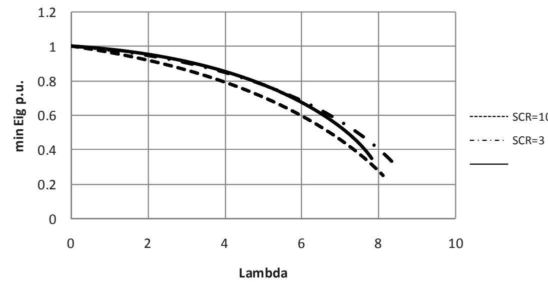

Figure 11 p.u. *min Eig* for different SCR

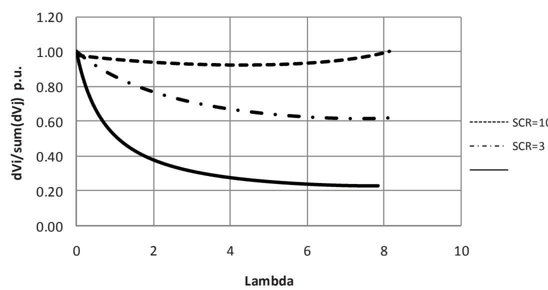

Figure 12 p.u. *–dVi/sum(dVj)* for different SCR

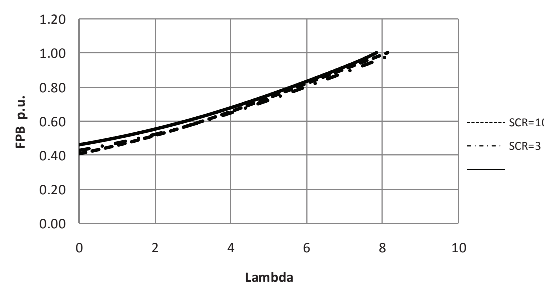

Figure 13 p.u. *FPB* for different SCR

Conclusions

The effects of HVdc systems on voltage stability have been a matter of great concern during years, especially nowadays when the largest projects with this technology are being built around the world. Several indexes have been proposed to evaluate interactions in ac/dc nodes.

In this work, per unit indexes are introduced, and it has been achieved voltage stability analysis of ac/dc systems using per unit static and modal indexes. It was found that the classical indexes could not be enough to straightforwardly identify a network prone to voltage instability.

The complimentary analysis of classical and per unitized indexes can produce an effective detection. Particularly, the index *dVi/sum(dVj)* in its classical form or per unitized, showed to be very sensitive for the exposure and screening of voltage stability tendencies. With the indexes proposed, the analysts and power system operators would be able to rapidly judge the likelyhood of having voltage stability problems in an ac/dc system with situations of weaknesses in inverter buses when the HVdc power is increased.

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