An on-line power/voltage stability index for multi-infeed HVDC systems

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Abstract High-voltage direct current (HVDC) transmission is playing an increasingly important role in modern power systems, and the resulted power/voltage stability issue has raised widespread concern. This paper presents an on-line power/voltage stability index (PVSI) for multi-infeed HVDC (MIDC) systems. Different from the existing indices which are developed mainly for off-line and static analysis, the proposed PVSI can be applied in real time. Effects of system changes on stability assessment such as change of system states and control strategies are considered. Thus, helpful guidance can be provided for on-line HVDC stability and controls. The PVSI is originally

deduced for single-infeed HVDC systems in an “AC way” by analyzing the power and voltage stability of both pure AC systems and HVDC systems. Moreover, its on-line application in practical MIDC systems is realized by building an equivalent single-infeed model, and utilizing nowadays measurement and communication infrastructures such as wide-area measurement system (WAMS). The effectiveness of the PVSI is verified through simulations in real-time digital simulator (RTDS).

Keywords Multi-infeed high-voltage direct current (HVDC) system, Power stability, Voltage stability, Stability index, Practical on-line application

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1 Introduction

High-voltage direct current (HVDC) transmission is getting more and more attention and applications due to its advantage in long-distance bulk power transmission and fast modulation [1, 2]. In the planning of offshore wind farms, HVDC transmissions are widely applied for grid connection [3, 4], and China Southern Power Grid (CSG) is building a large-scale multi-infeed HVDC (MIDC) network with a total installed generation capacity of more than 243 GW [1]. Line-commutated converter HVDC (LCC-HVDC) is used in most HVDC projects in the CSG.

Due to the increasing scale and complexity of MIDC systems nowadays, the power and voltage stability problems brought by HVDCs is becoming prominent. Thus, the corresponding on-line assessment and control methods are important to be discussed.

Power stability refers to the ability of an AC/DC system to increase DC power by an increase in DC current [5], and voltage stability is the ability of an AC/DC system to

maintain its voltage when subjected to a given disturbance [6]. In previous researches, the two problems have been clearly illustrated in single-infeed HVDC systems [7]. However, HVDCs will interact with each other when fed into an AC system in a close proximity [8, 9], and the problems therefore become quite complex in MIDC systems.

To address this issue, indices such as multi-infeed short circuit ratio (MSCR), multi-infeed interactive short circuit ratio (MISCR) and multi-infeed effective short circuit ratio (MIESCR) are proposed by CIRGE [9], while these indices are defined with empirical estimation instead of analytical deduction. Reference [10] does a prominent work and proposes the equivalent effective short circuit ratio (EESCR), which considers the MIDC system as an equivalent single-infeed system when addressing the interested bus. The EESCR successfully resolves the ambiguity of the empirical indices, while operation data should be obtained. Moreover, this index is mainly derived for the steady operation of the system, and has not been rigorously discussed and verified for transient. Reference [11] proposes a concept named generalized short circuit ratio (gSCR) to generalize SCR to MIDC system. The gSCR is mathematically deduced with the help of the Jacobian matrix of MIDC system, and shows better accuracy than conventional MISCR and MIESCR [12]. Reference [13] further elaborates on gSCR and illustrates the concept of critical gSCR and boundary gSCR, which prominently enriches gSCR's physical meaning. Nevertheless, the SCR-based indices are used mainly for HVDC planning and selection for locations, as stated in [12–15]. Some advanced indices such as EESCR is capable for on-line application, while they require more data than conventional SCR [13]. And it is still difficult to clearly consider the impact of nonlinear and time-varying control of the system during transient.

In another point of view, power and voltage stability are discussed free from the framework of SCR. Reference [16] focuses on the power stability phenomenon with the help of maximum power curves (MPCs), and [6] focuses on the voltage stability phenomenon by expanding the concept of voltage sensitivity factor (VSF) [17]. These works discover the close relationship between power and voltage stability of MIDC systems with sensitivity methods, and further depict the power/voltage stability margin of the system. However, these analyses are based on an ideal dual-infeed system with the entire AC part replaced by an ideal AC source. To make the techniques more practical, discussions on a limited types of practical AC components are particularly made in [18–20], but none of the literatures propose

a general way for a power system with practical topology, a quantity of HVDCs, and various AC components. Although the reduction of a practical system to a simple equivalent source has been proposed for pure AC systems [21–23], the methodologies cannot be utilized for sensitivity method used above, for the sensitivity relations will be reduced in the reduction procedures. Moreover, the methods are used merely for a particular operating point of MIDC under particular fixed controls, and are dependent on system states. During system dynamics, both the controls and states are time-varying, and some of the needed states cannot be obtained even by wide-area measurement system (WAMS), e.g. overlap angle of each converter.

To address the underlying interrelationships of indices for MIDC systems, [24] organizes and develops a taxonomy. The indices are discussed respectively for application on stability and interaction analysis, and are sorted as nodal approach and modal approach. Some new indices such as nodal DC power/current interaction factor (NPIF/NCIF) are proposed.

Though discussions are widely made, the basic nature of power/voltage phenomenon can still be dealt with some simple tools. References [25, 26] employ the concept of voltage stability index (VSI), and [27] employs the P - V curves for voltage related problems. In this paper, similar techniques are utilized and further developed.

In this paper, an on-line power/voltage stability index (PVSI) is proposed. The PVSI is developed from the common ground of power and voltage stability phenomenon in both AC/DC systems and pure AC systems, so both AC states and techniques for pure AC systems can be utilized for the PVSI. Compared to the existing power/voltage analysis techniques, the proposed PVSI can be applied to MIDC systems in real time. Effect of system states, changed parameters and controls is evaluated in real time with the help of WAMS. The PVSI can provide guidance for HVDC controls during system dynamics, and has no difficulty when applied to any practical systems, even if various HVDCs and AC components exist.

The rest of this paper is organized as follows: Section 2 compares the power/voltage stability in AC and AC/DC systems, and deduces the PVSI for single-infeed HVDCs in an “AC way”. Section 3 generalizes the PVSI to practical MIDC systems by building an equivalent single-infeed circuit, compares the PVSI with other indices, and illustrates its application in large-scale systems. In Section 4, the distinct features of the PVSI are verified by real-time digital simulator (RTDS) in comparison with two existing indices. Conclusions of this work are drawn in Section 5.

2 PVSI for single-infeed HVDC systems

2.1 Power and voltage stability phenomenon

The derivation of the proposed PVSI is based on the similarities of the stability phenomenon in both AC and HVDC systems. The CIGRE single-infeed HVDC benchmark in Fig. 1 is used for illustration [28], compared with a simple AC system in Fig. 2.

The power stability of an HVDC addresses on its ability to maintain the transferred DC power. When an HVDC is operated under constant power-constant extinction angle (CP-CEA) control, a general way to increase the DC power is to increase the DC current at the rectifier side. However, an increase in DC current does not necessarily guarantee an increased DC power. The HVDC system is power unstable when DC power does not increase according to DC current. The relationship between DC current and DC power is depicted in Fig. 3. In this figure, point A is a stable operating point, point B is an unstable operating point, and point C is the critical point, which indicates the maximum available power (MAP) of an HVDC system. The P - I curve is also called the maximum power curve (MPC) of HVDC.

A higher DC current can lead to more reactive power consumption of an inverter, thus results in a lower AC voltage at the point of common coupling (PCC) [29]. From this point of view, one can replace the DC current in the horizontal axis in Fig. 3 by AC voltage. The resulted figure is shown in Fig. 4, and the characteristics of the three points hold the same. Points A and B in Fig. 4 are with the same DC power, but different voltages and different DC currents. The high voltage point (point A) is of low current, which corresponds to the point A in Fig. 3, and is a stable operating point. In a similar way, we can conclude that point B in Fig. 4 is an unstable point, and point C is the critical point.

Figure 4 also depicts the nose curve in pure AC systems, which is mentioned as P - V curves in some literatures [7, 27]. When referred to a pure AC system, the characteristics of points A, B and C are similar to that of HVDC. This suggests the possibility to analyze the power/voltage stability of HVDCs in an “AC way”.

Fig. 1 Single-infeed HVDC system

Fig. 2 Simple AC system for voltage stability analysis

Fig. 3 P - I relationship for HVDC power stability

Fig. 4 P - V relationship for HVDC and AC voltage stability

As an “AC way”, the P - V curve is used to illustrate influences that a load has on bus voltage in pure AC system, and relatively sensitive buses can thus be found with the curve [27]. Critical operating point of the bus lies in point C in Fig. 4, which is the same as HVDC.

The P - V curve offers a perceptual tool indicating the voltage stability of a system, but numerical results can hardly be obtained. Moreover, the curves are defined in steady state. To have a better assessment of power/voltage stability in a quantified way and to help with on-line control, an index should be analytically proposed. This motivates the proposal of PVSI.

2.2 PVSI for single-infeed HVDC systems

In this section, the PVSI for single-infeed HVDC system will be derived in an “AC way”. The system in Fig. 1 will be taken for illustration.

To make the HVDC system more similar to the AC system in Fig. 2, an equivalent system is formed in Fig. 5, and the shunt capacitors are considered in the Thevenin equivalent source. Techniques for AC voltage stability analysis in Fig. 2 can thus be modified and applied.

Fig. 5 Equivalent single-infeed HVDC system

In Fig. 5, $\dot{S}$ is the complex power exchanged between the inverter and the system, with the arrow indicating its reference direction; φ is the power factor of $\dot{S}$; $\dot{V}$ is the voltage phasor at the PCC; $Z\angle\theta$ is the equivalent impedance of the Thevenin equivalent AC circuit; $\dot{E}$ is the equivalent voltage source of the Thevenin circuit.

The power flow equation for the system shown in Fig. 5 can be expressed as:

$$\begin{cases} S \cos \varphi = \frac{V}{Z} (E \cos(\theta - \varphi) - V \cos \varphi) \\ S \sin \varphi = \frac{V}{Z} (E \sin(\theta - \varphi) - V \sin \varphi) \end{cases} \quad (1)$$

With (1), the authors of this paper obtain a quadratic equation on V^2 in [30]:

$$(V^2)^2 + (2ZS \cos(\theta - \varphi) - E^2)V^2 + Z^2S^2 = 0 \quad (2)$$

Solve (2) and we can obtain:

$$V = \left[\frac{E^2}{2} - ZS \cos(\theta - \varphi) \pm \left(\frac{E^4}{4} - Z^2S^2 \sin^2(\theta - \varphi) - E^2ZS \cos(\theta - \varphi) \right)^{\frac{1}{2}} \right]^{\frac{1}{2}} \quad (3)$$

Note that the voltage amplitude should be positive, so the negative solution is discarded.

The system operates exactly at a critical state (point C in Figs. 3 and 4) when (1) has a unique solution [30], namely (3) has a unique solution. The stability margin of the system is thus expressed as (4), and a PVSI can be defined for the system in Fig. 5 as (5).

$$\frac{2SZ(1 + \cos(\theta - \varphi))}{E^2} = 1 \quad (4)$$

$$PVSI = \frac{2SZ(1 + \cos(\theta - \varphi))}{E^2} \quad (5)$$

This index represents the power/voltage stability of the HVDC system. When $0 < PVSI < 1$, the system is operating within the stability margin, and the DC power is less than its MAP. When $PVSI = 1$, the system is operating at the margin, and the DC power is equal to the MAP. When $PVSI > 1$, no stable operating point can be obtained.

It should be noted that the PVSI in this section is deduced for the system in Fig. 5. To deal with such simple system, some other indices can also be used, such as the

VSI in [25, 26]. The VSI is originally proposed for radial distribution network, which can be equivalently represented by Fig. 2. The domain of VSI is $[0, +\infty)$ for system's stable operation, while the PVSI is delicately designed so that its domain is $[0, 1]$. In this way, the upper bound of PVSI is clearly determined. Moreover, the PVSI can be generalized for practical meshed MDC system, as will be elaborated in Section 3.

3 On-line power/voltage stability assessment in large-scale MDC systems

The PVSI proposed in Section 2 is based on an ideal single-infeed HVDC system, which is far from practical ones. This section firstly discusses the theoretical generalization of PVSI to large-scale MDC systems, and secondly compares the PVSI with some existing indices. At last, the procedures to practically apply the PVSI in large-scale system are illustrated.

3.1 Generalization of PVSI for large-scale practical MDC systems

In this section, the PVSI will be generalized for large-scale systems. A large-scale MDC system has a topology different from the ideal system in Fig. 5, and the PVSI cannot be directly applied. Moreover, the performance of AC components will have effect on the power/voltage stability, so as the mutual interactions between converters.

A typical large-scale MDC system can be represented by Fig. 6. The system consists of generators ($G_1, G_2, \dots, G_n$) under different controls, loads ($LD_1, LD_2, \dots, LD_n$) with various characteristics, HVDCs connecting two buses in the system, HVDCs connecting with other asynchronous systems, and AC transmission lines that connect all the

Fig. 6 Schematic diagram of practical MDC system

components. Moreover, the types of HVDCs vary. This paper address only on the stability of LCC-HVDC, while other types of HVDC can have influence on it.

To generalize the PVSI, an equivalent circuit in the form of Fig. 5 is to be formed. Note that the interested converter should be a real converter instead of an equivalent one, so the rest of the system is to be reduced into the equivalent impedance and source, as will be illustrated in the followings.

For the practical system in Fig. 6, the network equation can be expressed as:

$$\mathbf{I} = \mathbf{YV} \quad (6)$$

where $\mathbf{I}$, $\mathbf{Y}$, $\mathbf{V}$ denote the injecting current matrix, admittance matrix, and bus voltage matrix of the system, respectively.

Considering PCCs, load buses, tie buses and generator buses respectively, (6) can be expressed as:

$$\begin{bmatrix} \mathbf{I}_{LD} \\ \mathbf{I}_{PCC} \\ \mathbf{0} \\ \mathbf{I}_G \end{bmatrix} = \mathbf{Y}_{net} \begin{bmatrix} \mathbf{V}_{LD} \\ \mathbf{V}_{PCC} \\ \mathbf{V}_T \\ \mathbf{V}_G \end{bmatrix} \quad (7)$$

where $\mathbf{Y}_{net}$ is the admittance matrix of the network; $\mathbf{I}_{LD}$, $\mathbf{I}_{PCC}$ and $\mathbf{I}_G$ represent the currents of load buses, PCCs and generator buses, respectively; $\mathbf{V}_{LD}$, $\mathbf{V}_{PCC}$, $\mathbf{V}_T$ and $\mathbf{V}_G$ represent the voltages of load buses, PCCs, tie buses and generator buses, respectively. When the generators are considered in the classical model [7], each generator is represented by an ideal internal voltage source $\dot{E}'_G$ in series with a reactance X'_d . Equation (7) is thus expanded as:

$$\begin{bmatrix} \mathbf{I}_{LD} \\ \mathbf{I}_{PCC} \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{I}_G \end{bmatrix} = \begin{bmatrix} \mathbf{Y} & \mathbf{Y}_{12} \\ \mathbf{Y}_{21} & \mathbf{Y}_{22} \end{bmatrix} \begin{bmatrix} \mathbf{V}_{LD} \\ \mathbf{V}_{PCC} \\ \mathbf{V}_T \\ \mathbf{V}_G \\ \mathbf{E}'_G \end{bmatrix} \quad (8)$$

where $\mathbf{Y}$ is the admittance matrix of the network considering the internal reactance of generators; $\mathbf{Y}_{12}$, $\mathbf{Y}_{21}$ and $\mathbf{Y}_{22}$ are new submatrices introduced by the reactance; $\mathbf{E}'_G$ is the internal voltage of generators.

Power/voltage instability can occur at either PCCs or load buses, so both types of buses are regarded as generalized load buses. For convenience, buses with zero current injection are regarded as special load buses. Then (8) can be further expressed as:

$$\begin{bmatrix} \mathbf{I}_L \\ \mathbf{I}_G \end{bmatrix} = \begin{bmatrix} \mathbf{Y} & \mathbf{Y}_{12} \\ \mathbf{Y}_{21} & \mathbf{Y}_{22} \end{bmatrix} \begin{bmatrix} \mathbf{V}_L \\ \mathbf{E}'_G \end{bmatrix} \quad (9)$$

where the current of generalized load $\mathbf{I}_L = [\mathbf{I}_{LD}^T, \mathbf{I}_{PCC}^T, \mathbf{0}^T, \mathbf{0}^T]^T$; $\mathbf{V}_L = [\mathbf{V}_{LD}^T, \mathbf{V}_{PCC}^T, \mathbf{V}_T^T, \mathbf{V}_G^T]^T$.

With (9), a practical large-scale system in Fig. 6 can be considered in the form of Fig. 7, where various generalized loads are supported by generators through a passive network, i.e. transmission lines of the power system. The loads also interact with each other through the network.

The voltage phasor at buses in the passive network can be expressed as:

$$\mathbf{V}_L = \mathbf{M}\mathbf{E}'_G + \mathbf{Z}\mathbf{I}_L \quad (10)$$

$$\mathbf{Z} = \mathbf{Y}^{-1} \quad (11)$$

$$\mathbf{M} = -\mathbf{Z}\mathbf{Y}_{12} \quad (12)$$

In (10), effect of generators and generalized loads are accounted for by $\mathbf{M}\mathbf{E}'_G$ and $\mathbf{Z}\mathbf{I}_L$, respectively.

For a specific generalized load bus j in a network with n AC buses, we can obtain:

$$\dot{V}_{Lj} = Q_j + \sum_{i=1}^n \dot{I}_{Li} Z_{ji} \angle \theta_{ji} \quad (13)$$

where Q_j is an element of $\mathbf{Q}$, $\mathbf{Q} = \mathbf{M}\mathbf{E}'_G$, which is a column vector.

Equation (13) can be further expressed as:

$$\dot{V}_{Lj} = \left(Q_j + \sum_{i=1, i \neq j}^n \dot{I}_{Li} Z_{ji} \angle \theta_{ji} \right) + \dot{I}_{Lj} Z_{jj} \angle \theta_{jj} \quad (14)$$

When the status of the generalized load bus is described in (14), an equivalenced single-infeed HVDC system can be obtained for PVSI. Assume the equivalent voltage source as (15), and then the other parameters of the system can be obtained, which is shown in Fig. 8. The arrows in the figure indicate the reference directions of branch current.

$$\dot{E}_{eq,j} = Q_j + \sum_{i=1, i \neq j}^n \dot{I}_{Li} Z_{ji} \angle \theta_{ji} \quad (15)$$

Substituting the parameters in (15) and Fig. 8 into (5), the PVSI can be generalized into MIDC systems. For a specified bus j in an MIDC system, we can obtain:

Fig. 7 Equivalent system described by (9)

Fig. 8 Equivalent single-infeed HVDC system

$$PVSI_j = \frac{2S_j Z_{ij} (1 + \cos(\theta_{ij} - \varphi_j))}{|-A_j + \sum_{i=1, i \neq j}^n \dot{I}_{Li} Z_{ji} \angle \theta_{ji}|^2} \quad (16)$$

where A_j is an element of $\mathbf{A}$, $\mathbf{A} = \mathbf{Z}\mathbf{Y}_{12}\mathbf{E}'_G$, which is a column vector.

The power/voltage stability margin for MISC system can be obtained by substituting the parameters into (4) as well, which is expressed as:

$$\frac{2S_j Z_{ij} (1 + \cos(\theta_{ij} - \varphi_j))}{|-A_j + \sum_{i=1, i \neq j}^n \dot{I}_{Li} Z_{ji} \angle \theta_{ji}|^2} = 1 \quad (17)$$

3.2 Connections and differences of existing indices

Except for the PVSI, there are three types of indices that are widely used for similar purpose: SCR-based indices [9–14], MPC-based indices [5, 16] and VSF-based indices [6, 17]. It is necessary to make a comparison and distinguish the advantages of the PVSI from the others.

The original motivations of the indices vary from each other, and are listed in Table 1. The motivations reflect the initial physical meaning and usage of the indices. Note that this does not restrict their application, and all of the indices can be applied freely according the demand of researchers.

Figure 9 shows some commonly used SCR-based indices. Among them, recently proposed tools such as EESCR and gSCR provide rigorous and analytical views of MISC systems [10–13]. The EESCR is a rigorous extension of ESCR from single-infeed HVDC system to MISC system, and the gSCR is an extension of SCR. Critical buses can be indicated by indices as critical-EESCR (CEESCR) and critical gSCR (CgSCR). The boundary gSCR (BgSCR) is another application of gSCR to MISC systems. Moreover,

Fig. 9 Taxonomy of SCR-based indices

the gSCR is capable to indicate the critical direction of power change in MISC.

To study the power stability of MISC, [16] utilizes the concept of MPC, and derives various power stability indices for MISC system. The indices aim at determining the MAP of the system, and are respectively used for different HVDC control modes.

The VSF-based indices evaluate the system stability by finding out the point where voltage collapses. An index for voltage stability is first proposed in [17] for single infeed HVDC system, and expanded for MISC system in [6].

Some of the above indices can be sorted as modal indices and nodal indices, on the basis of their analytical methods and interrelationship [24], while these indices mostly utilize or address the sensitivity relationship between states of the system. This requires detailed and precise model of all the components and controls of the system, which is hard to obtain in practical application.

The PVSI is deduced in a different way. It forms an equivalent Thevenin circuit for AC network with the help of data from supervisory control and data acquisition (SCADA) system and WAMS, and utilizes this circuit to evaluate the stability of each bus, respectively. The equivalent circuit is applicable for the PVSI, but not applicable for most of the other indices. This is because the sensitivity relations are reduced when forming the circuit. Moreover, the time-varying characteristics of the system are taken into account by the PVSI, such as voltage dependent current order limiter (VDCOL) of HVDCs [29], while most other indices are deduced for a fixed model with fixed controls, and cannot cope with the change of the system.

This paper mainly addresses on the on-line application of the PVSI, while the PVSI is also applicable in planning

Table 1 Motivations of existing indices

Index	Motivation
SCR	Indicate the relative strength between AC and DC systems
MPC	Study power-related phenomenon of ideal HVDC system
VSF	Study voltage-related phenomenon of ideal HVDC system
PVSI	Indicate power/voltage stability practically in real time and provide guidance for MISC control

Table 2 Names and corresponding stability margins of indices

Index name	Stability criterion
λ_{MPC}	$\lambda_{MPC,i} > 0$
$\det(\mathbf{J}_{IR})$	$\det(\mathbf{J}_{IR}) > 0$
PVSI	$PVSI_i < 1$

The value of the three indices are calculated when the system in Fig. 11 is operating at the nominal operating point, and are listed in Table 3. Different indications are given by the indices. Index $\det(\mathbf{J}_{IR})$ indicates that the system is voltage unstable, index λ_{MPC} indicates that inverter 1 is power unstable, while index PVSI indicates that the system is stable.

The correctness of the indications can be verified through time-domain simulations in RTDS. Note that VDCOL is not considered in the two existing indices [6, 16], and will not be tested in this case.

A small disturbance occurred to the system at the time $t = 0.5$ s, which is modelled as 1% power order increase for inverter 1. As is shown in Fig. 12, the MIDC system maintains power and voltage stable, which verifies the indication given by PVSI.

When the power order of an HVDC has a larger increase, the system in Fig. 11 will move to another operating point, which can be an unstable one. PVSI is still effective during the dynamics. In the following simulation, the power order of inverter 1 is increases by 8% at $t = 0.5$ s, and the response of the system is shown in Fig. 13.

The power/voltage instability develops gradually after the disturbance. Corresponding to the analysis in Section 2.1, in this process, the value of the DC power order exceeds the MAP at the nose point. The DC current tries to gain extra DC power by moving towards the high current point (point A), but as a result, the AC voltage moves towards the low voltage point (point C), where an increased current does not result in an increased power. The power order thus cannot be satisfied, and the system collapses at last.

During the whole dynamics in the simulation, the values of the two existing indices are plotted in Fig. 14, together with the proposed PVSI. The PVSI accurately depicts the

Table 3 Values of three indices

No. of HVDC	$\det(\mathbf{J}_{IR})$	λ_{MPC}	PVSI
1	-0.71	-0.52	0.70
2	-0.71	0.78	0.74

Fig. 12 System response to small disturbance **Fig. 13** System response to larger power order increase

status of the system when it is losing power/voltage stability, while the two existing indices fail to do so.

Moreover, the two existing indices can hardly be calculated in practice, for they require system states that are unobtainable in real time, e.g. extinction angle and overlap angle of remote converters, while the PVSI can be calculated with the procedures described in Fig. 10.

4.2 Case 2

In this case, simulations will be carried out in the practical meshed network shown in Fig. 15, and HVDC control such as VDCOL is considered.

Fig. 14 Values of three indices during dynamics

VDCOL is usually activated when the voltage is below a certain limit, to help with the power/voltage stability of a system. However, there is no best way to obtain the value of the limit: a higher limit can result in a too sensitive VDCOL and further oscillations or unwanted power loss, while a lower limit will lead to an insensitive VDCOL that cannot help to stabilize the system efficiently. Thus, in this case, the VDCOL is activated when $PVSI = 1$, which implies the system is operating at a critical point.

The test system is a benchmark proposed by CIGRE for MIDC analysis [31]. The two PCCs of inverters are bus 15 and bus 17, respectively. The AC network has a rated voltage of 400 kV. All the generators are with IEEE type 1 excitation controller and IEEE type 1 governor. The load at each bus is modelled by 70% constant impedance and 30% constant power. The HVDCs are operated under CP-CEA controls.

The benchmark is far more complex than the system used in case 1. The expansion of indices such as $\det(J_R)$ and λ_{MPC} in such systems has not been given by any research. In the meanwhile, the PVSI proposed can still be applied to such a complex system easily.

When the system load increases to a certain critical state, a slight oscillation will arise. A 20 Mvar load increase at bus 13 is then conducted at the time $t = 1.5$ s, and the resulted dynamics have a longer duration than those in case 1, as are shown in Fig. 16. The mechanism of the dynamics is much more complex, with various

Fig. 15 CIGRE benchmark for meshed MIDC network

components such as generators, loads and converters contributing to the final collapse. The PVSI accurately depicts the power/voltage stability of the two interested buses.

During the whole process, we have $PVSI_{15} > PVSI_{17}$, therefore the power/voltage stability problem of bus 15 is more severe than that of bus 17. When the VDCOL of bus 15 is enabled in time according to $PVSI_{15}$ (at $t = 6.4$ s), the power/voltage collapse can be avoided, and the system will return to an oscillation similar to the initial state, as is shown in Fig. 17 (a 20 Mvar load increase is conducted at $t = 0.5$ s).

This case reveals that even in a practical MIDC system with complex topology and various components, the PVSI can still dynamically depicts the system's stability, identify the weak buses, and provides helpful guidance for on-line HVDC controls.

5 Conclusion

In this paper, the PVSI for MIDC systems is proposed and verified. Compared to the existing indices, the PVSI has the following distinct features:

- 1) The PVSI considers the system states and parameters in a more appropriate way, including time-varying characteristics such as VDCOL control and load power change, and is capable for practical large-scale MIDC systems.
- 2) The PVSI can be utilized in real time and provide guidance for on-line HVDC controls. Utilizing

Fig. 16 Instable dynamics of system

Fig. 17 Stable dynamics of system

infrastructures such as SCADA and WAMS, feasible application procedures are given in this paper.

In future works, the authors will further test the PVSI with more practical data, such as data of the CSG, to ensure the credibility of the index. Original controls utilizing the PVSI are also to be designed.

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