Quantitative Analysis on Relationship between VDCOL Controller Parameters and Voltage Stability Factor in Multi-infeed DC Transmission System

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Abstract. Based on the incremental power flow equation, the influence of VDCOL controller parameters on voltage stability factor VSF was studied by sensitivity analysis method, and the mathematical relationship between the two was obtained for the first time. Based on the analytical relationship, the quantitative relationship between VDCOL control parameters and voltage stability factor VSF was made clear, which lays a mathematical and theoretical foundation for the controller parameters tuning. Taking CIGRE standard DC system parameters as typical parameters, the relation curve between VDCOL control parameters and VSF was obtained. Combined with the relation curve, the influence of VDCOL parameters on the system voltage stability was further expounded, and some useful conclusions were obtained. The simulation analysis shows that the method and conclusions obtained in this paper are correct and effective, and have important theoretical guidance and practical significance on the design and operation of the system.

Introduction

Compared with the traditional AC transmission mode, HVDC transmission system has many unique advantages[1,2]. With the development of technology, more and more transmission projects begin to adopt DC transmission. In China, East China Power Grid and Southern Power Grid have formed a typical pattern of multi-infeed DC (MIDC) system transmission. In these power grids, the electrical distance of each DC drop point is very close. The interaction between AC and DC system, and each DC subsystems is very strong. The system fault will not only greatly reduce the local voltage of commutation bus, but also obviously affect the nearby voltage of commutation bus, which may lead to the commutation failure of several inverter stations in succession or at the same time. After fault removal, the fast power recovery of each DC subsystem will adversely affect the system voltage, and slow down the recovery of the power transmission. Therefore, the reasonable determination of DC system control mode and the optimization among DC system controllers are of great significance to the security and stability of the whole system and the improvement of performance.

The voltage-dependent current order limit (VDCOL) can change the DC instruction current according to the system voltage level and reduce the reactive-power demand for the converter from AC system during the fault or recovery period, which is beneficial to the stability and recovery of the system voltage. Compared with the method of improving DC system control, the system operation performance can be obviously improved by simply adjusting the control parameters of VDCOL. Therefore, it is of great practical significance to study thoroughly the influence of VDCOL control on the system voltage stability. The influence of VDCOL controller parameters on voltage and power recovery of AC and DC system under large disturbance was studied in reference [3,4]. It was clearly pointed out that the recovery performance of DC system can be effectively improved by VDCOL controller as faulty. In reference [5], the variation of optimal parameters of VDCOL controller with
the strength of AC system was discussed. The simulation results showed that the optimal VDCOL control curve tends to shift to right with the decrease of system strength. In reference [6], the conventional VDCOL characteristic curve was improved to reduce the reactive-power consumption of converter stations during system recovery period, thus effectively improving the transient stability of multi-infeed DC system. A dynamic adaptive VDCOL controller based on the bus voltage level was proposed in reference [7]. The high voltage threshold of the controller varies with the bus voltage, and the DC current can be controlled reasonably under different conditions. The simulation results showed that the new VDCOL controller had improved the voltage stability of the system. The structure of VDCOL controller was improved in reference [8-10], so that the improved VDCOL can delay the current instruction during fault recovery, and obviously improve the recovery performance of multi-infeed DC system.

Most of the relevant references[3-5] studied the influence of VDCOL controller parameters on the system stability by simulation analysis, and the result was only a qualitative conclusion. In order to provide mathematical basis for the VDCOL controller design and control strategy formulation, it is necessary to go deep into the influence of VDCOL controller on the system characteristics and to obtain a quantitative relationship. In this paper, based on the power flow equation, the relationship between the parameters of VDCOL controller and the voltage stability factor (VSF) is established, and the influence of VDCOL on the system voltage stability is revealed.

VDCOL and System Model

Operating Principle and Characteristics of VDCOL Controller

When the system voltage is low, if the DC power (or current) is still maintained at the rated value, a large number of reactive-power demand generated by the converter station for the AC system will further deteriorate the system voltage, and even make the DC system unable to work normally. Therefore, it is necessary to introduce VDCOL controller into DC control system in order to limit the DC current when the voltage is low. According to the different detection voltage, VDCOL can be divided into two types of: a) VDCOL dependent on DC voltage (DC-VDCOL) and b) VDCOL dependent on AC voltage (AC-VDCOL). The AC-VDCOL can quickly respond to the fluctuation of AC voltage but have little effect in DC fault. The DC-VDCOL can achieve better performance not only in DC fault but also in AC fault. Therefore, the DC-VDCOL controller is used in most of the long-distance DC transmission projects at present. The schematic diagram and characteristic curve are shown in figures 1 and 2.

![Figure 1. Schematic diagram of VDCOL.](image1)

![Figure 2. Limit characteristic of VDCOL.](image2)
In figure 1, $R_v$ is a composite resistor to determine the VDCOL starting voltage is the DC voltage on which point of the DC line. The parameter $I_{\text{max}}$ in figure 2 is the maximum allowable current, $I_{\text{min}}$ is the minimum allowable current, $U_H$ is the VDCOL limited starting voltage, and $U_L$ is the minimum current limited starting voltage. Among these parameters, the control characteristics of VDCOL can be changed by adjusting $U_H$, $U_L$ and $I_{\text{min}}$, so as to improve the performance of the system, as shown in figure 2. In order to further analyze the influence of the VDCOL controller on the system voltage stability, it is necessary to clarify the relationship between VDCOL output instruction current $I_{\text{ord}}$ and AC voltage.

For inverter, we have

\[
\begin{align*}
U_{\text{doi}} &= \frac{3\sqrt{6}}{\pi} N_b K_i U_i \\
U_{di} &= U_{\text{doi}} \cos \gamma - N_b \frac{3}{\pi} X_{ci} I_d
\end{align*}
\]

(1)

where $U_{\text{doi}}$ is the ideal no-load DC voltage of the inverter; $U_{di}$ is the DC voltage of the inverter; $U_i$ is the phase voltage of the AC converer bus for inverter; $I_d$ is the DC current; $\gamma$ is the inverter arc extinction angle; $K_i$ is the transformer ratio of the inverter; $N_b$ is the number of six-pulse converter bridges in the converer station; $X_{ci}$ is the commutation reactance of a single converer bridge.

The linear equation for the characteristic curve of A-B section in Fig. 2 is given as:

\[
I_{\text{MAX}}^* = \frac{I_{\text{max}} - I_{\text{min}}}{U_H - U_L} (U_{\text{DC}*} - U_H) + I_{\text{max}}
\]

(2)

where $U_{\text{DC}*}$ is expressed as:

\[
U_{\text{DC}*} = U_{\text{do}}^* + I_{d*} R_v^*.
\]

(3)

Because of $I_{d*} = I_{\text{ord*}}$, $I_{\text{MAX}*} = I_{\text{ord*}}$, combined equations (1)-(3), the relationship between instruction current $I_{\text{ord}}$ of control characteristic A-B section of VDCOL and AC voltage $U_i$ can be obtained as follows:

\[
I_{\text{ord}} = k U_i + b
\]

(4)

here we have

\[
\begin{align*}
k &= \frac{3\sqrt{6}}{\pi R_v} N_b K_i \cos \gamma \\
b &= \frac{(U_H I_{\min} - U_L I_{\max}) U_{\text{do}}}{(I_{\text{max}} - I_{\text{min}}) R_v} \\
R_v &= \frac{U_H - U_L}{I_{\text{max}} - I_{\text{min}}} R_{db} + \frac{3}{\pi} N_b X_{ci} - R_v
\end{align*}
\]

(5)

where $U_{\text{do}}$ and $R_{db}$ are respectively the reference voltage and the reference resistance of the DC system.

It can be seen that the relationship between the output instruction current $I_{\text{ord}}$ and AC voltage of VDCOL controller within the whole range is
\[
\begin{align*}
I_{\text{ord}} &= I_{\text{max}}I_{db} = I_{dN} \quad (U_{DC^+} > U_H) \\
I_{\text{ord}} &= kU_i + b \quad (U_L < U_{DC^+} < U_H) \\
I_{\text{ord}} &= I_{\text{min}}I_{db} \quad (U_{DC^+} < U_L)
\end{align*}
\]

where \( I_{db} \) is reference current of DC system; \( I_{dN} \) is rated DC current.

System Model

The multi-infeed DC system structure used in this paper is shown in figure 3. The inverter stations of each DC subsystem connect to the same AC system. The converter buses are connected to each other by coupling impedance, and rectifier sides of the DC systems are independent of each other. At the same time, there are AC loads at each converter buses\(^{[11,12]}\).

\[\text{Figure 3. Model of multi-infeed HVDC system.}\]

Solution of VSF for Multi-infeed DC System

As a static analysis method of voltage stability, the voltage stability index and the sensitivity information for the system state and control variables can be given by the sensitivity analysis method. It is helpful to deeply understand the influence of system components, control modes and faults etc on voltage stability. It is often used to detect voltage stability, design and optimize various control devices for voltage stability. In reference [13,14], a sensitivity index, voltage stability factor (VSF), is introduced to measure the stability of system voltage. It represents the sensitivity of node voltage to injected reactive-power disturbance, its definition is

\[
\text{VSF} = \frac{\Delta U}{\Delta Q_r}
\]

(7)

When the VSF is positive, the system voltage is statically stable, the smaller the VSF value, the better the voltage stability; when the VSF is negative, the system voltage is unstable.

For the multi-infeed DC system as shown in Fig. 3, a reactive-power disturbance is injected into “i” of the converter bus. By means of Taylor expansion and linearization at the stable operation point of the AC power flow equation of the multi-infeed system before being disturbed, the incremental power flow equation of the system before and after being disturbed can be obtained as

\[
\begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix} \approx J \begin{bmatrix}
\Delta \theta \\
\Delta U
\end{bmatrix}
\]

(8)

Where \( J \) is a Jacobian matrix of order \( 2n \times 2n \). It can be seen that the power flow equation of the system in incremental form is formally consistent with its modified equation.

In order to reflect the influence of VDCOL controller on bus voltage, the power variation of DC system cannot be neglected in equation (8). At the same time, in order to reflect the influence of
VDCOL on system voltage as accurately as possible, the changes of AC system and the power changes of load injecting into node should also be considered. For node \( j \), the variation of injection power before and after being disturbed is as follows:

\[
\Delta P_{ij} = \Delta P_{j-d} + \Delta P_{j-i} + \Delta P_{j-l} \quad (j = 1, \ldots, n)
\]
\[
\Delta Q_{ij} = \Delta Q_{j-d} + \Delta Q_{j-i} + \Delta Q_{j-l} \quad (j = 1, \ldots, n, j \neq i)
\]

(9)

Where the subscript \( d \) represents converter stations; \( i \) represents equivalent current source of AC system; \( l \) represents AC load. The reactive-power variation injected into disturbance node \( i \) also includes reactive-power disturbance \( \Delta Q_R \).

\[
\Delta Q_i = \Delta Q_{i-d} + \Delta Q_{i-i} + \Delta Q_{i-l} + \Delta Q_R
\]

(10)

1) Variation of power injected from converter station

In general, the rectifier of DC transmission system is controlled by constant current, and the inverter is controlled by constant extinction angle. In this way of control, we have

\[
\begin{align*}
I_d &= I_{ord} \\
\gamma &= \gamma_{ord}
\end{align*}
\]

(11)

Where \( \gamma_{ord} \) is extinction angle instruction.

At this time, the external characteristic equation of the inverter station can be expressed as

\[
\begin{align*}
P_{di} &= \frac{U_{di} I_d}{3} \\
Q_{di} &= -\frac{I_d}{3} \sqrt{U_{do}^2 - U_{di}^2}
\end{align*}
\]

(12)

where \( P_{di} \) and \( Q_{di} \) are respectively one-phase active-power and reactive-power injected into converter bus of AC system by inverter station. When the system is disturbed to different extent, the operating point of VDCOL will be in different regions of the characteristic curve. According to formulas (1), (4)-(6), (11) and (12), the relationship between \( \Delta P_{di} \), \( \Delta Q_{di} \) and \( \Delta U_i \) in different cases can be obtained.

a) VDCOL not started

\[
\begin{align*}
\Delta P_{di} &= \frac{\sqrt{6}}{\pi} N_i K_I I_{max} I_{di} \cos \gamma_{ord} \Delta U_i \\
\Delta Q_{di} &\approx \frac{\sqrt{6}}{\pi} N_i K_I I_{max} I_{di} \left( U_{di} \cos \gamma_{ord} - U_{do} \right) \left[ \Delta U_i \right]_{(1)}
\end{align*}
\]

(13)

Where subscript \( (1) \) represents the steady-state value of the system before disturbed.

b) Operating point of VDCOL is located in Section A-B

\[
\begin{align*}
\Delta P_{di} &\approx \frac{N_i}{\pi} \left( \sqrt{6} K_I \cos \gamma_{ord} - kX_{ci} \right) I_d + \frac{k U_{di}}{3} v_{ice} \Delta U_i \\
\Delta Q_{di} &\approx -\frac{N_i I_d}{\pi} \left[ \sqrt{6} K_I U_{do} - U_{di} \left( \sqrt{6} K_I \cos \gamma_{ord} - kX_{ci} \right) \right] - \frac{k}{3} \sqrt{U_{do}^2 - U_{di}^2} v_{ice} \Delta U_i
\end{align*}
\]

(14)

Where \( I_d \) as shown in Formula (4). Formula (14) only applies to the case when the analytical parameter \( U_H \) unchanged. For the case of parameter \( U_H \) changes, according to the formulas (1), (4),
(5), (11) and (12), the injection power of the inverter station corresponding to the operation point after disturbed is subtracted from the initial injection power before disturbed. Assumed \(U_i = U_i^{(1)} + \Delta U_i\), the relationship between \(\Delta P_{di}\), \(\Delta Q_{di}\) and \(\Delta U_i\) can be obtained as:

\[
\begin{align*}
\Delta P_{di} &= f_1(\Delta U_i) \\
\Delta Q_{di} &= f_2(\Delta U_i)
\end{align*}
\]

Formula (15) is the nonlinear function of \(\Delta U_i\), whose form is no longer listed because of limited length.

c) Operating point of VDCOL is located in the section with minimum current limited

According to the formulas (1), (6), (11) and (12), using the same method as formula (15), the relationship between \(\Delta P_{di}\), \(\Delta Q_{di}\) and \(\Delta U_i\) can be obtained at this time as:

\[
\begin{align*}
\Delta P_{di} &= f_3(\Delta U_i) \\
\Delta Q_{di} &= f_4(\Delta U_i)
\end{align*}
\]

The \(\Delta P_{di}\) in formula (16) is the linear function of \(\Delta U_i\), \(\Delta Q_{di}\) is the nonlinear function of \(\Delta U_i\).

(2) Power variation injected by equivalent current source in AC system

The series impedance branch of voltage source in AC system is equivalent to the parallel impedance form of current source. The system power variation injected by equivalent current source can be obtained by linearization method of Taylor expansion.

\[
\begin{align*}
\Delta P_{j,\text{eq}} &\approx \frac{U_j^{(1)}}{|Z_j|} E_j \sin(\theta_j^{(1)} + \delta_j - \xi_j) \Delta \theta_j + \frac{E_j}{|Z_j|} \cos(\theta_j^{(1)} + \delta_j - \xi_j) \Delta U_j \approx a_{j,\text{eq}} \Delta \theta_j + a_{j,\text{eq}} \Delta U_j \\
\Delta Q_{j,\text{eq}} &\approx \frac{U_j^{(1)}}{|Z_j|} E_j \cos(\theta_j^{(1)} + \delta_j - \xi_j) \Delta \theta_j + \frac{E_j}{|Z_j|} \sin(\theta_j^{(1)} + \delta_j - \xi_j) \Delta U_j \approx b_{j,\text{eq}} \Delta \theta_j + b_{j,\text{eq}} \Delta U_j
\end{align*}
\]

Where \(Z_j = |Z_j| \angle \delta_j\).

(3) Power variation injected by AC load

The AC load is based on the static load model described in reference [15-17]. Because the frequency of AC system is constant, the terms related to frequency change in the model can be ignored. According to the linearization method of Taylor expansion and considering the direction of power, the system power variation injected by load can be obtained as:

\[
\begin{align*}
\Delta P_j &\approx -\frac{P_0}{U_0} (2K_{pc} + K_{pi} + n_{pu1}K_{pi} + n_{pu2}K_{pi}) \Delta U \approx a_{j,\text{p}} \Delta U \\
\Delta Q_j &\approx -\frac{Q_0}{U_0} (2K_{qc} + K_{qi} + n_{qu1}K_{qi} + n_{qu2}K_{qi}) \Delta U \approx b_{j,\text{q}} \Delta U
\end{align*}
\]

The meaning of each variable in the formula (18) is detailed in references [15-17].

From the formulas (9), (10), (13), (14), (17) and (18), we can see that \(\Delta P_j\) and \(\Delta Q_j\) are linear functions of \(\Delta \theta_j\) and \(\Delta U_j\). Substitute them into formula (8) and transfer the items, we have
$$\left[ \begin{array}{c} \Delta \theta \\ \Delta U \end{array} \right] \approx J^{-1}_R \left[ \begin{array}{c} \vdots \\ 0 \\ \Delta Q_R \\ 0 \\ \vdots \end{array} \right]$$  

(19)

Where $J_R$ is modified Jacobian matrix.

From Formula (19), the voltage stability factor can be written as:

$$V SF_i = \frac{\Delta U_i}{\Delta Q_R} \approx J^{-1}_{R(n+i,n+i)}$$  

(20)

That is to say, the voltage stability factor $V SF_j$ of node $i$ is equal to the element in column $n+i$ and row $n+i$ of matrix $J^{-1}_R$. Formula (20) includes the influence of DC system, AC system parameters, reactive-power compensation device and load on voltage stability. Similarly known, the diagonal elements $J^{-1}_{R(n+j,n+j)}$ $(1 \leq j \leq n)$ of the matrix $J^{-1}_R$ are the voltage stability factors of the corresponding nodes $j$, that can be expressed as

$$V SF_j \approx J^{-1}_{R(n+j,n+j)} (1 \leq j \leq n)$$  

(21)

For the nonlinear functions shown in the formula (15), (16), which can still be substituted into the formula (8). For the determined $\Delta Q_R$, all the remaining state variables $\Delta \theta_j$ and $\Delta U_j$ can be obtained from equation (8), so that VSF of any node can be obtained.

**Influence of VDCOL Control Parameters on VSF**

In order to further clarify the influence of VDCOL controller on voltage stability, taking single-infeed DC system as an example. According to the analysis method in section 2, the relationship between VDCOL control parameters and VSF can be obtained as

$$V SF \approx \frac{a_i}{a_i \Delta \theta - i} (J_{22} - b_d - b_{U - i} - b_{i - 1} - b_{i - 1} - b_{i - 1} - b_{i - 1} - b_{i - 1} - b_{i - 1})$$  

(22)

Where the parameters $a_d$ and $b_d$ as shown in formula (14), the control parameters of VDCOL are included, and the remaining parameters in the formula are independent of VDCOL. In formula (14), when $U_{DC} = U_H$, we have

$$U_{d_i} = \frac{U_{H}U_{db} - I_{max}R_{v}^*U_{db}}{U_{H}U_{db}}$$

$$U_{d_{oi}} = \frac{\left( \frac{3}{\pi} N_b X_{ci}I_{db} - R_{v}U_{db} \right) I_{max} + U_{H}U_{db}}{\cos \gamma_{ord}}$$  

(23)

By substituting the parameters of DC transmission system under CIGRE standard[18,19] as typical parameters into the formula (22), the relationship curve between the control parameters of VDCOL and VSF can be obtained as shown in Fig. 4. VDCOL control parameters of CIGRE standard DC system are initially set as follows: $U_H = 0.9$, $U_L = 0.4$, $I_{min} = 0.55$. 

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In figure 4, curve 1 shows the influences of $U_L$ on VSF, meanwhile $U_H = 0.9$, $I_{\text{min}} = 0.55$. Curve 2 shows the influences of $I_{\text{min}}$ on VSF, meanwhile $U_H = 0.9$, $U_L = 0.4$. The point A on curve 1 and point A on curve 2 correspond to the same control parameters. As shown in figure 4: 1) With the increase of $U_L$, VSF gradually decreases. This shows that the increase of $U_L$ can improve the voltage stability of the system. At the same time, the larger $U_L$ is, the more obvious its influence on the voltage stability is; 2) With the increase of $I_{\text{min}}$, VSF gradually increases. This shows that the increase of $I_{\text{min}}$ can deteriorate the voltage stability of the system. At the same time, the larger $I_{\text{min}}$ is, the more obvious its influence on the voltage stability is; 3) The absolute slope values at point A and $A'$ are close to each other, and the variation ranges of VSF are basically the same in the range of $U_L$ and $I_{\text{min}}$. These results show that near the initial value of VDCOL control parameters, the influences of $U_L$ and $I_{\text{min}}$ on VSF are basically the same.

The relation curve between $U_H$ and VSF can be obtained based on formula (15), as shown in figure 5. In figure 5, curve 1 corresponding $U_L = 0.4$, $I_{\text{min}} = 0.55$, and curve 2 corresponding $U_L = 0.5$, $I_{\text{min}} = 0.55$. As shown in figure 5: 1) With the increase of $U_H$, VSF gradually decreases. This shows that the increase of $U_H$ can improve the voltage stability of the system, but with the increase of $U_H$, the effect on improving voltage stability is less obvious. 2) For the same value $U_H$, the larger $U_L$ is, the smaller VSF is, and the more stable the system voltage is. At the same time, the larger $U_L$ is, the more obvious the influence of the change of $U_H$ on voltage stability is.

The above analysis is about the influence of AB section of VDCOL control characteristic on voltage stability. The influence of the section with minimum current limited on voltage stability can be obtained based on formula (16), as shown in figure 6.
The influence of section with VDCOL minimum current limited on voltage stability is only related to parameter $I_{\text{min}}$, while the other parameters do not affect the characteristics of section with minimum current limited. As can be seen from figure 6, with the increase of $I_{\text{min}}$, $VSF$ gradually increases and the voltage stability of the system becomes weaker. At the same time, the influences of different $I_{\text{min}}$ on voltage stability are almost the same.

**Simulation Results**

Based on the VDCOL initial set value of DC transmission system under CIGRE standard, $U_H$, $U_L$ and $I_{\text{min}}$ are changed respectively, and a reactance is put into the converter bus at the inverter side when $t = 3.0s$. The simulation results are shown in figures 7-9.
In figures 7-9, Curve 1, 2 and 3 respectively represent the voltages of converter bus corresponding the different conditions as: $U_H$ equals to 0.9, 0.8, 0.7; $U_L$ equals to 0.4, 0.5, 0.6; $I_{\min}$ equals to 0.55, 0.45, 0.35. As can be seen from figures 7-9: 1) With the decrease of $U_H$, the voltage stability of the system becomes weaker, at the same time, the smaller $U_H$ is, the more obvious the influence of the change of $U_H$ on voltage stability is; 2) With the increase of $U_L$, the voltage stability of the system becomes stronger, at the same time, the larger $U_L$ is, the more obvious the influence of the change of $U_L$ on voltage stability is; 3) With the decrease of $I_{\min}$, the voltage stability of the system becomes stronger, at the same time, the smaller $I_{\min}$ is, the less the influence of the change of $I_{\min}$ on voltage stability is. Simulation results show that the conclusions of theoretical analysis about influence of VDCOL control parameters on voltage stability of the system is correct and effective.

**Conclusion**

The VDCOL controller can adjust the DC current instruction according to the voltage level of the system, which has a significant influence on the operation characteristics of the AC and DC system, so setting VDCOL control parameters reasonably and accurately can effectively improve the performance of the system.

1) Based on the incremental power flow equation, the relationship between VDCOL control parameters and voltage stability factor VSF is thoroughly analyzed, and the mathematical relationship between the two is obtained for the first time. Based on the analytical expression obtained already, the quantitative relationship between VDCOL control parameters and voltage stability factor VSF is defined, which lays a mathematical foundation for the tuning of controller parameters.

2) Taking the parameters of DC system under CIGRE standard as typical parameters, the relationship curves between the VDCOL control parameters and VSF are given.

3) The influence of VDCOL parameters on voltage stability of the system is further elaborated based on obtained curves.

4) The simulation results show that the method and conclusions in this paper are correct and effective, which provides a theoretical basis for system design and operation, and has important practical value.

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