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A New Quantitative Analysis Method for Overvoltage in Sending End Electric Power System With UHVDC

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ABSTRACT With the development of renewable electric power generation and ultra-high voltage direct current (UHVDC) transmission, the transient overvoltage in the sending end electric power system with UHVDC occurs, but it is lack of quantitative transient voltage assessment index (TVAI) to assess the overvoltage. To deal with the above problems, this paper proposes a new quantitative transient voltage assessment index considering overvoltage and voltage dip in the sending end electric power system with UHVDC, and applies it to analyze different influencing factors of overvoltage and determine the dynamic reactive power compensation capacity. In detail, first, according to the principle of the transient voltage assessment index considering voltage dip and the overvoltage assessment index for the distribution network, a new transient voltage assessment index considering transient overvoltage in the sending end electric power system with UHVDC is proposed with the approximated step function. Then, based on the requirements of the system with UHVDC, the parameters of the proposed transient voltage assessment index are determined. Furthermore, with the absolute and relative sensitivity, the impact of the parameters of voltage dependent current order limiter and current control amplifier on the transient overvoltage is analyzed and compared quantitatively. Finally, the impact of reactive power compensation equipment, such as synchronous condenser, static var compensator, and static var generator, on the transient overvoltage of the system with UHVDC is compared quantitatively, and the reactive compensation capacity needed to maintain transient voltage security and stability is estimated. The two applications show the effectiveness and advantages of the proposed index in the sending end electric power system with UHVDC.

INDEX TERMS Transient overvoltage, transient voltage assessment index, UHVDC system.

NOMENCLATURE

CCA:	current control amplifier
SVC:	static var compensator
SVG:	static var generator
TVA:	transient voltage assessment
TVAI:	transient voltage assessment index
TVDA:	transient voltage dip acceptability
UHVDC:	ultra-high voltage direct current
VDCOL:	voltage dependent current order limiter

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I. INTRODUCTION

Recently, with the development of renewable electric power energy in western China, a lot of ultra-high voltage direct current (UHVDC) projects had been planned to transmit the renewable electric power to the east of China. By the end of 2019, fourteen UHVDC projects have been completed in China, such as Hami to Zhengzhou UHVDC project, Ningdong to Zhejiang UHVDC project, Xinjiang to Anhui UHVDC project, etc., with a total rated capacity of up to 110.2 MW.

However, the hybrid AC/DC power grid, which had facilitated the long-distance transmission of electric power, may lead to the complex dynamic behavior of the power grid [1], [2], increase the complexity of the control and energy management [3], [4], and increase operation risks, such as the risks in transient stability [5], low-frequency oscillation [6], transient overvoltage and so on. Among them, the transient overvoltage of the AC transmission line at rectifier side in the case of fault becomes more and more prominent in the UHVDC system [7]–[9], as the overvoltage may damage equipment and it is a hidden danger to the safety of renewable electric power generation and transmission [10], [11]. Therefore, to provide measures to suppress the overvoltage, it is necessary to evaluate the transient overvoltage of the sending end electric power system with UHVDC accurately.

The transient voltage assessment (TVA) includes two aspects, i.e., the transient voltage dip and transient overvoltage. Currently, there are a lot of TVA methods considering the transient voltage dip. In general, they could be divided into three categories.

(1) The methods assess the transient voltage by comparing the static slip and the fault slip, and the electromagnetic torque and the mechanical torque when the voltage reaches the extreme value [12], [13]. However, due to the large scale of the actual power grid, it is impossible to get the critical cut-off time and electromagnetic torque-slip curve of each motor, and the transient voltage instability of the motor does not necessarily correspond to the transient voltage instability of the system [14]. Therefore, it is difficult to apply this kind of TVAI to the transient voltage stability assessment of the actual power grid.

(2) The methods determine the transient voltage stability with the judgement of whether the voltage in the transient process is lower than a certain threshold for a period of time. For example, [15] proposed a TVAI which is defined as transient voltage dip acceptability (TVDA). Generally, this kind of criterion can only judge the stability of transient voltage qualitatively, and can not analyze quantitatively.

(3) The methods could give out quantitative TVAI combined with the information of voltage dip. For example, [16] proposed a TVAI which includes not only the TVDA in fault, but also the information of voltage recovery after fault. Reference [17] distinguished the concepts of transient voltage stability and TVDA, and proposed the assessment of the margins for transient voltage stability and TVDA, but did not consider the influence of voltage dip degree. Reference [18] proposed a new TVAI, based on three variables of TVDA, transient minimum voltage, and recovery voltage after fault. Furthermore, recognizing the problem of the above proposed TVAI only using the information of voltage dip, [19] proposed a new TVAI using voltage dip information deeply. According to the idea of "different weights to different dip", i.e., the proposed TVAI divides the voltage dip degree into different sections based on the operation requirements of the power grid and assigned with different weights. With the effectiveness of the above proposed TVAI and application in the reactive power assignment [20], the idea of "different weights to different dip" has been expended to transient frequency stability assessment [21], [22], which considers both low frequency and high frequency.

On the other hand, there are few TVA methods considering the transient overvoltage. For example, [23] proposed multiple overvoltage thresholds to ensure the safety of transient voltage, but these thresholds are discrete and could not be used to develop control measures. Reference [24] proposed a method to calculate the transient overvoltage, based on the analysis of the relationship between transient overvoltage and short circuit ratio as well as that between transient overvoltage and blocking capacity, but it may not work when the short circuit ratio is low. Reference [25] proposed the TVAI with the ratio of the short circuit capacity of AC system and the reactive compensation capacity configured in the converter station, but it is hard to compute on-line. Reference [26] proposed a TVAI considering overvoltage for the distribution network, but it is not suitable for high voltage power systems, especially the sending end electric power system with UHVDC.

It is worth noting that the existing quantitative TVAI of high voltage power systems can only consider the voltage dip, but not the transient overvoltage in the power system with UHVDC, i.e., there is no quantifiable TVAI considering overvoltage in the sending end electric power system with UHVDC.

Recognizing the above problems, this paper presents a transient voltage assessment index (TVAI) considering transient overvoltage in the sending end electric power system with UHVDC, combining our two previously proposed indexes, i.e., the index considering transient voltage dip in [19], and the index considering the overvoltage of the distribution network in [26]. Furthermore, in this paper, according to the regulations of the high voltage power system and UHVDC system, the parameters are determined, the influencing factors are analyzed, and the dynamic reactive power compensation capacity is determined. The contributions of this paper are as follows:

(1) For the sending end electric power system with UHVDC, a new quantitative transient voltage assessment index (TVAI) considering transient voltage dip and transient overvoltage is proposed, and the related parameters are determined according to operation requirements of high voltage power systems with UHVDC, rather than the distribution network. Also, the proposed TVAI can be applied to evaluate the degree of transient overvoltage in the sending end electric power system with UHVDC.

(2) Based on the proposed index and sensitivity, the impact of control parameters in DC on the transient overvoltage, which appeared in the sending end electric power system with UHVDC, is quantitatively analyzed and compared, which can provide suggestions for suppressing transient overvoltage with parameter tuning.

(3) Based on the proposed index and sensitivity, the reactive power compensation capacity of the UHVDC system is determined, which can provide suggestions for electric power system planning.

The remainders of the paper are organized as follows. Section II proposed the TVAI considering transient voltage dip and overvoltage, based on the modification to the TVAI considering voltage dip, with the approximated step function. Section III introduces the voltage requirements of UHVDC system, and then determines the parameters of the proposed TVAI. Section IV analyzes the influence of the parameters of voltage dependent current order limiter (VDCOL) and current control amplifier (CCA) on the transient overvoltage based on the proposed index and related sensitivity. Section V analyzes the influence of synchronous condenser, static var compensator (SVC), and static var generator (SVG) on the transient overvoltage, and estimates the dynamic reactive power compensation capacity. Finally, Section VI presents the conclusions and remarks.

II. TRANSIENT VOLTAGE ASSESSMENT INDEX

This section firstly introduces the transient voltage stability index considering voltage dip in [19]. And then, it proposes the TVAI considering transient overvoltage, based on the modification with the approximated step function in [26].

A. TVAI OF VOLTAGE DIP

According to the idea of "different weights to different dips" shown in Fig.1, combined with the operation requirements of the depth and corresponding acceptable time of voltage dip, the TVAI of voltage dip can be the sum of different voltage dips integration with different weight, which can be expressed mathematically as follows:

$$F_1 = \sum_{i=0}^{n}\sum_{j=1}^{m} K_j g_j(V[t_i])\,|V[t_i] - V_{\mathrm{N}}|\,\Delta t$$

$$\text{where, } g_j(V[t_i]) = \begin{cases} 1 & \left(V_{cr.j+1} \le V[t_i] \le V_{cr.j}\right) \\ 0 & \left(V[t_i] < V_{cr.j+1} \text{ or } V[t_i] > V_{cr.j}\right) \end{cases} \quad (1)$$

where K_i is the upper limit voltage of weight K_i; t_{mi} (t'_{mi}) is the time point when the voltage is lower (higher) than $V[t_i]$ in the process of voltage dip (recovery); $V[t_i]$ is the weight coefficient; $V[t_i]$ is the voltage at time t_i; V_N is the rated voltage of the power grid; Δt is the step length of calculation; and $g_j(V[t_i])$ is a piecewise function which is equal to 1 when $V[t_i]$ is greater than $V_{cr.j+1}$ and less than $V_{cr.j}$, and when $V[t_i]$ is greater than $V_{cr.j}$ or less than $V_{cr.j+1}$, it is equal to 0.

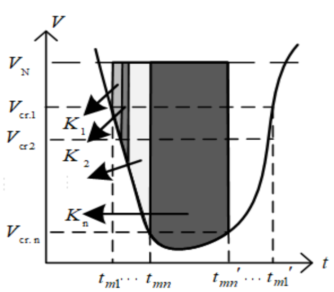

FIGURE 1. TVAI of voltage dip.

The deeper the dip is, the shorter the maximum acceptable duration and the greater the corresponding weight coefficient will be.

The steps to determine the parameter of TVAI considering voltage dip are as follows. Firstly, according to the requirements of the power system for voltage dip, the voltage curve is divided into several sections. Secondly, the corresponding weight of each section is calculated according to the operation requirements of the depth and corresponding acceptable time of voltage dip. Finally, the TVAI of voltage dip is obtained according to the weighted sum of (1).

Furthermore, as stated in [19], if $F_1 \ge 1$, the transient voltage of the system will be unstable; if $F_1 < 1$, the transient voltage of the system will be stable.

Clearly, the above index (1) could not be used to consider the transient overvoltage. Therefore, it is urgent to modify this index to account for both transient voltage dip and transient overvoltage.

B. TVAI OF OVERVOLTAGE

Currently, several overvoltage thresholds have been set up to limit the transient overvoltage [23]. Thus, in order to consider the transient overvoltage, the TVAI shall meet the following requirements: if the overvoltage threshold is not exceeded, the index value shall be determined by (1); if the overvoltage threshold is exceeded, the overvoltage index shall suddenly increase, indicating that the transient voltage is no longer safe.

Obviously, the step function could meet the above requirements, as it could engage the property that when it is less than the threshold value, the value of the step function is 0; when it is greater than or equal to the threshold value, the value of the step function reaches a certain value. However, the step function is not differentiable or even continuous. Therefore, the following continuous and smooth approximated step function $f(V_{[t_i]})$ [26] is used to approximate the step function. The characteristic of the approximated step function is shown in Fig. 2.

$$F_{2[t_i]} = f(V_{[t_i]}) = \frac{k}{1 + e^{-\frac{(V_{[t_i]} - V_N - a)c}{b}}} \quad (2)$$

where k, a, b, and c are constants. k is the weight coefficient which reflects the maximum value of $F_{2[t_i]}$; a reflects the position where the step occurs; and b and c reflect the steepness of the step. The smaller b is, the steeper the step will be while the larger c is, the steeper the step will be. And $F_{2[t_i]}$ is the value of F_2 at time t_i, $F_2 = \sum_{i=1}^{n} F_{2[t_i]}$. That is, the TVAI of overvoltage can be the sum of the approximated step function values at each time point of the voltage curve.

As shown in Fig. 2, for the above approximated step function (2), when the transient voltage does not exceed the overvoltage threshold $V_N + a$, the value of $F_{2[t_i]}$is near zero, while once the voltage exceeds the threshold $V_N + a$, the value of $F_{2[t_i]}$ rises rapidly, reaching the stable value k, which is far greater than the TVAI of voltage dip, indicating that the transient voltage is unsafe.

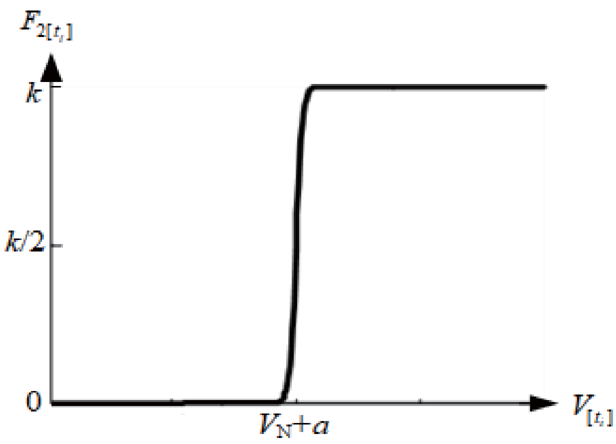

FIGURE 2. The characteristic of $F_{2[t_i]}$.

Combining (1) and (2), the TVAI which can evaluate the safety (overvoltage) and stability (voltage dip) of the transient voltage at the same time can be obtained as follows.

$$F = F_1 + F_2 = \sum_{i=0}^{n}\sum_{j=1}^{m} K_j g_j(V[t_i])\,|V[t_i] - V_N|\,\Delta t + \sum_{i=1}^{n} \frac{k}{1+e^{-\frac{(V[t_i]-V_N-a)c}{b}}} \quad \text{where,}$$
$$g_j(V[t_i]) = \begin{cases} 1 & (V_{cr.j+1} \le V[t_i] \le V_{cr.j}) \\ 0 & (V[t_i] < V_{cr.j+1} \text{ or } V[t_i] > V_{cr.j}) \end{cases} \tag{3}$$

In the case of voltage dips, the transient voltage must be less than the overvoltage threshold $V_N + a$, so the transient voltage safety index (F_2) does not work, and TVAI is determined by the transient voltage stability index (F_1), reflecting the influence of voltage dip accumulation.

In the case of voltage exceeding the overvoltage threshold V_N+a, F_2 will increase rapidly, far greater than F_1, indicating that the transient voltage is not safe. At this time, the TVAI is mainly determined by the transient voltage safety index (F_2), and F_1 still works but the value is far less than F_2, so the influence of F_1 is not significant.

III. PARAMETERS OF TVAI IN UHVDC SYSTEM

This section determines the parameters of TVAI, according to the operation standards of the power system and the voltage requirements of UHVDC system.

A. PARAMETERS OF VOLTAGE DIP

The operation of UHVDC system requires the voltage to be maintained at a certain level. The commutation failure will occur when converter bus voltage drops to 0.80p.u. [27], and furthermore, the medium and long term of the converter bus voltage should be maintained or recovered to more than 0.9p.u. after the fault disturbance [28]. Therefore, the voltage dip range can be divided into two intervals, i.e., 0.9p.u. ~1p.u. and 0.8p.u. ~0.9p.u..

Furthermore, according to the code [28], the load bus voltage should recover to more than 0.80p.u. within 10s after the fault, and according to the code [29], the voltage of pivot buses shall not be lower than 0.75p.u. for more than 1s, and the voltage of pivot buses of 220kV and above voltage levels shall not be lower than 0.9p.u. after the transient process. Therefore, the criterion of (0.80p.u., 10s) and (0.90p.u., 60s) should be considered for the load bus, and the criterion of (0.80p.u., 10s), (0.90p.u., 60s) and (0.75p.u., 1s) should be considered for the pivot network bus.

According to the method proposed in [19], weight coefficient can be obtained step by step, as shown in (4).

$$\begin{aligned} K_1\,(V_N - V_{cr.1})\,T_{cr.1} &= 1 \\ K_2\,(V_N - V_{cr.2})\,T_{cr.2} &= 1 \\ &\vdots \\ K_n\,(V_N - V_{cr.n})\,T_{cr.n} &= 1 \end{aligned} \tag{4}$$

where $T_{cr.i}$ is the maximum allowed duration when voltage is lower than $V_{cr.i}$.

The weight coefficient obtained according to (4) is shown in Table 1.

TABLE 1. Two-element notation and weight coefficient (V_N = 1.0p.u.).

Bus type	Two-element notation	Weight coefficient
Load bus	(0.9,60)	0.1667
	(0.80,10)	0.5000
Pivot bus	(0.9,60)	0.1667
	(0.80,10)	0.5000
	(0.75,1)	4.000

B. PARAMETERS OF OVERVOLTAGE

To the overvoltage, there are following rules in operation.

(1) According to regulation [30], under normal and fault conditions, the voltage of the buses of 220kV and above voltage levels shall not exceed 1.1p.u..

(2) For the UHVDC system, the regulation [31] shows that, in order to ensure safety of the converter valve, the AC side of DC system should withstand the power frequency temporary overvoltage which is 1.3 times of the operating voltage before fault.

Therefore, the transient overvoltage index should include two parts, one should allow 0.3p.u. voltage deviation, and the other should allow 0.1p.u. voltage deviation.

Considering the margin, the parameter a in Eq. (2) could be 0.25 and 0.06 respectively. By adjusting b and c, the transient overvoltage index (F_2) can approximate the step function. In detail, the value of F_2 should be very close to the maximum value when the voltage is 1.1p.u. and 1.3p.u. respectively. In addition, to reflect the influence of overvoltage degree on the index, weight k is taken as 100 and 10 respectively, which ensures the rapid increase of TVAI in case of overvoltage. The parameters of the TVAI of overvoltage are shown in Table 2.

TABLE 2. Parameters applicable to different voltage limits.

Voltage	a	b	c	k
$\geq$ 1.3p.u.	0.25	0.20	15	100
1.1p.u. $\leq V <$ 1.3p.u.	0.06	0.20	35	10

Therefore, the proposed TVAI of the UHVDC system is as follows.

$$F = F_1 + F_2 = \sum_{i=0}^{n}\sum_{j=1}^{m} \mathrm{K}_j g_j(V[t_i])\,|V[t_i] - V_\mathrm{N}|\,\Delta t_i + \sum_{i=1}^{n}\left(\frac{10}{1+e^{-\frac{(V[t_i]-V_N-0.06)35}{0.20}}} + \frac{100}{1+e^{-\frac{(V[t_i]-V_N-0.25)15}{0.20}}}\right)$$

$$\text{where, } \left\{ g_j(V[t_i]) = \begin{cases} 1 & (V_{j+1} \leq V[t_i] \leq V_j) \\ 0 & (V[t_i] < V_{j+1} \text{ or } V[t_i] > V_j) \end{cases} \right. \tag{5}$$

Note: due to different grid codes of the high voltage power system and distribution network, the parameters of F_2 in this paper are different from those in [26].

Note: although there are different grid codes in different countries, the calculation method of parameters of the TVAI is the same as that mentioned in the above subsection. However, the parameters may be different.

IV. APPLICATION 1: IMPACT OF PARAMETERS IN UHVDC SYSTEM

Based on the proposed TVAI, this section analyzes the impact of the parameters of VDCOL and CCA in DC control on the transient overvoltage for a system with UHVDC.

A. SIMULATION SYSTEM AND MAIN CONTROLLERS IN UHVDC

The system used in simulation is a UHVDC system with voltage level of ±800kV, and the transmission capacity being 8 GW [32], as shown in Fig. 3. The transfer electric power mainly comes from renewable electric power generation. It consists of 4 hydropower plants and 2 photovoltaic power stations. The electric power is transferred out through the HL rectifier station.

For the UHVDC system in Fig. 3, the main controllers that affect the transient overvoltage, i.e., the voltage dependent current order limiter (VDCOL) controller and current control amplifier (CCA) controller are shown in Fig. 4. In case of a commutation failure, the DC system will absorb reactive power from AC system firstly, which would make the voltage of the sending AC power grid dip rapidly. When the VDCOL detects the voltage dip at the sending end, it outputs a DC current setting value (I_ord, as shown in Fig. 4). Then the CCA controller will increase the trigger angle of the rectifier according to I_ord, thus the DC current (I_D) will decrease to

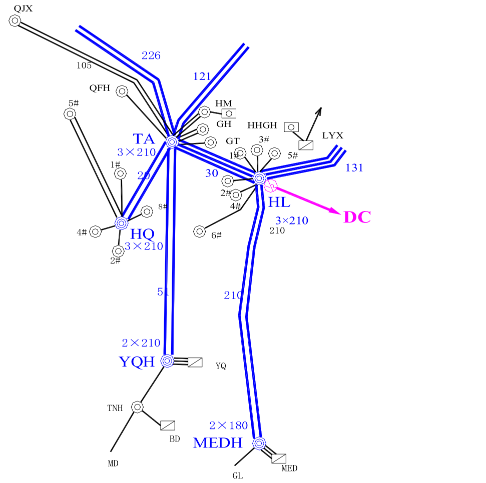

FIGURE 3. Geographical diagram of the near area of rectifier station.

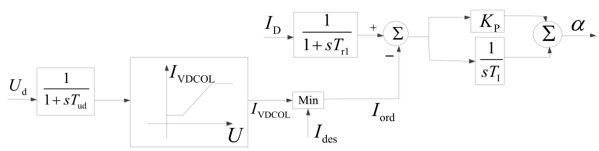

FIGURE 4. Control block diagram of VDCOL and CCA.

TABLE 3. Adjustable parameters of VDCOL and CCA.

Link	Parameter	Value
VDCOL	Measuring time constant (T_ud)	0.03
	Upper voltage limit (U_dhigh)	0.48
	Lower voltage limit (U_dlow)	0.28
	Minimum current limit (I_omin)	0.5
CCA	Proportion coefficient (K_p)	0.025
	Integral time constant (T_I)	3.6

the setting value. Then, the reactive power is produced by DC system, resulting in voltage rise of the sending AC power grid, thus the transient overvoltage appears.

The joint action of VDCOL and CCA controller will affect the transient overvoltage. Thus, the parameters in the above two controllers should be investigated. The parameters in VDCOL controller that can affect the transient overvoltage are: the measuring time constant (T_ud), the upper voltage limit (U_dhigh), the lower voltage limit (U_dlow), the minimum current limit (I_omin), the maximum current limit (I_olim), etc.. The parameters in CCA controller are: the filtering time constant (T_r1), the proportion coefficient (K_p), the integration time constant (T_I), etc.. Furthermore, according to the actual parameter limitation and the adjustability of the parameters, the following parameters shown in Table 3 are considered to investigate the impact on transient overvoltage with the proposed TVAI.

Furthermore, in simulations, the fault is set as the commutation failure of the inverter station.

B. INFLUENCE OF PARAMETERS OF VDCOL

1) MEASURING TIME CONSTANT

With the setting fault, the transient voltage response of the system with respect to the measuring time constant (T_{ud}) being 0.03, 0.04, 0.05, and 0.06 could be obtained, as shown in Fig. 5. Also, the corresponding TVAI and maximum overvoltage amplitude could be obtained as shown in Table 4.

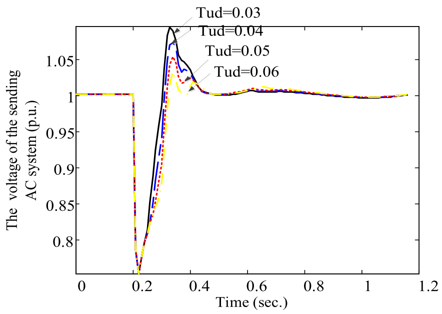

FIGURE 5. Voltage curve for different measuring time constants.

TABLE 4. Maximum voltage and TVAI with different T_{ud}.

T_{ud}	TVAI	Maximum voltage
0.03	15.1932	1.0957
0.04	0.0096	1.0734
0.05	0.0077	1.0548
0.06	0.0082	1.0339

Fig. 5 and Table 4 show that, when T_{ud} is 0.03, the amplitude of transient overvoltage is the largest, which is close to the overvoltage threshold 1.1, so the TVAI is greater than 1. As T_{ud} increases, the amplitude of transient overvoltage decreases, which is gradually far away from the overvoltage threshold 1.1, and TVAI is also less than 1. In this situation, TVAI is mainly determined by voltage dip, and the impact of transient overvoltage is not significant.

Therefore, in a certain range, increasing the measuring time constant of VDCOL can reduce the transient overvoltage.

2) UPPER VOLTAGE LIMIT

With the setting fault, the transient voltage response of the system with respect to the upper limit of voltage (U_{dhigh}) being 0.48, 0.58, and 0.68 could be obtained, as shown in Fig. 6. Also, the corresponding TVAI and maximum overvoltage amplitude could be obtained, as shown in Table 5.

Fig. 6 and Table 5 show that the larger U_{dhigh} of VDCOL at the rectifier side is, the longer the duration of transient overvoltage will be, leading to a larger TVAI and a worse transient voltage security. But the amplitude of transient overvoltage does not change obviously.

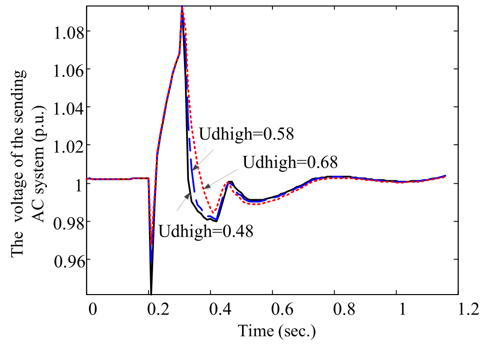

FIGURE 6. Voltage curve for different upper voltage limits.

TABLE 5. Maximum voltage and TVAI with different U_{dhigh}.

U_{dhigh}	TVAI	Maximum voltage
0.48	6.4165	1.0933
0.58	6.9138	1.0935
0.68	7.1757	1.0936

Therefore, in a certain range, reducing the upper voltage limit of VDCOL can suppress the transient overvoltage.

3) LOWER VOLTAGE LIMIT

With the setting fault, the transient voltage response of the system with respect to the lower voltage limit (U_{dlow}) being 0.28, 0.38, and 0.48 could be obtained, as shown in Fig. 7. Also, the corresponding TVAI and maximum overvoltage amplitude could be obtained, as shown in Table 6.

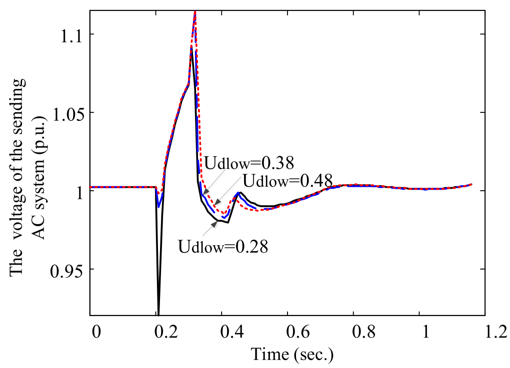

FIGURE 7. Voltage curve for different lower voltage limits.

Fig. 7 and Table 6 show that, the larger U_{dlow} of VDCOL at the rectifier side is, the larger transient overvoltage amplitude will be, leading to a greater TVAI. When U_{dlow} is 0.28, the maximum voltage is close to the overvoltage threshold 1.1. Therefore, TVAI is greater than 1, indicating that the voltage is unsafe. When U_{dlow} increases to 0.38 and 0.48, the maximum voltage has exceeded the voltage threshold 1.1, so the TVAI increases rapidly.

TABLE 6. Maximum voltage and TVAI with different U_{dlow}.

U_{dlow}	TVAI	Maximum voltage
0.28	5.3153	1.0928
0.38	99.7321	1.1148
0.48	99.7624	1.1151

Therefore, in a certain range, reducing the lower voltage limit of VDCOL can suppress the transient overvoltage.

4) MINIMUM CURRENT LIMIT

With the setting fault, the transient voltage response of the system with respect to the minimum current limit (I_{omin}) being 0.5, 0.75, and 1.0 could be obtained, as shown in Fig. 8. The TVAI and maximum overvoltage amplitude are measured as shown in Table 7.

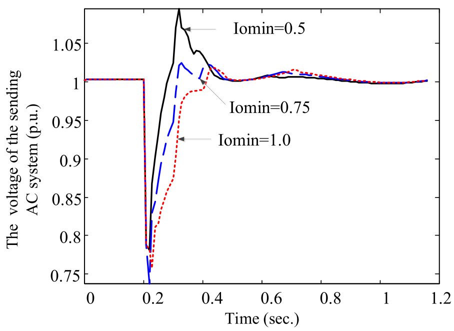

FIGURE 8. Voltage curve for different minimum current limits.

TABLE 7. Maximum voltage and TVAI with different I_{omin}.

I_{omin}	TVAI	Maximum voltage
0.5	7.4499	1.0937
0.75	0.0146	1.0239
1.0	0.0078	1.0177

Fig. 8 and Table 7 show that, the larger I_{omin} is, the smaller transient overvoltage amplitude will be, leading to the smaller TVAI. When I_{omin} is 0.5, the TVAI is greater than 1 because the maximum voltage is close to the overvoltage threshold 1.1. When I_{omin} is 0.75 and 1.0, maximum voltage does not exceed overvoltage threshold, and TVAI is less than 1.

Therefore, in a certain range, increasing the minimum current limit of VDCOL can suppress transient overvoltage.

C. INFLUENCE OF PARAMETERS OF CCA

1) INTEGRAL TIME CONSTANT

With the setting fault, the transient voltage response of the system with respect to the integral time constant (T_I) being 0.025, 0.0375, 0.05, and 1.0 could be obtained, as shown in Fig. 9. The TVAI and maximum overvoltage amplitude are measured as shown in Table 8.

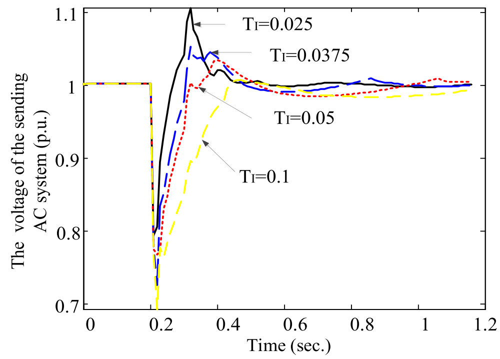

FIGURE 9. Voltage curve for different integral time constants.

TABLE 8. Maximum voltage and TVAI with different T_I.

T_I	TVAI	Maximum voltage
0.025	94.4821	1.1071
0.0375	0.0142	1.0531
0.05	0.0062	1.0354
0.1	0.1126	1.0077

Fig. 9 and Table 8 show that when T_I is 0.025, the amplitude of transient overvoltage is the largest, and the maximum voltage is greater than the overvoltage threshold 1.1, so the TVAI is greater than 1. As T_I increases, the amplitude of transient overvoltage decreases, and the TVAI is less than 1.

Therefore, in a certain range, increasing the integral time constant can suppress transient overvoltage. However, it should also be noted that increasing the integral time constant may lead to decreasing the recovery speed of transient voltage.

2) PROPORTION COEFFICIENT

With the setting fault, the transient voltage response of the system with respect to the proportion coefficient (K_P) being 1.8, 2.7, and 3.6 could be obtained, as shown in Fig. 10. The TVAI and maximum overvoltage amplitude are measured as shown in Table 9.

Fig. 10 and Table 9 show that when K_P increases, the amplitude of transient overvoltage increases slightly, and the TVAI increases. When K_P is 1.8, 2.7, and 3.6 respectively, the highest voltage is close to the overvoltage threshold, so the TVAIs are greater than 1.

Therefore, in a certain range, increasing the proportion coefficient can suppress transient overvoltage.

D. COMPARISON WITH SENSITIVITIES

The previous subsections analyze the influence of each parameter on transient overvoltage. This subsection will compare the influence with the viewpoint of sensitivities. The absolute sensitivity and relative sensitivity are used, which

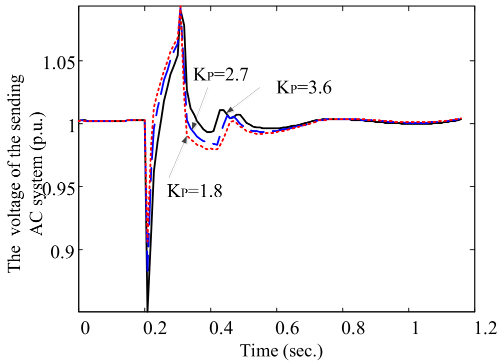

FIGURE 10. Voltage curve for different proportion coefficients.

TABLE 9. Maximum voltage and TVAI with different K_P.

K_P	TVAI	Maximum voltage
1.8	1.8714	1.0901
2.7	4.7430	1.0925
3.6	5.3154	1.0928

are defined as (6) and (7) respectively.

$$h = \frac{F - F_0}{x - x_0} \tag{6}$$

$$\tilde{h} = \frac{h * x_0}{F_0} \tag{7}$$

where x is control parameter; x_0 is the initial value of control parameter; and F_0 is the TVAI corresponding to the initial value of control parameter.

With the above simulation results, the absolute sensitivity and relative sensitivity of each parameter can be obtained, as shown in Table 10.

TABLE 10. Sensitivity of each parameter (absolute value).

Control parameter	Absolute sensitivity	Relative sensitivity
Integral time constant of CCA	1258.26	0.33
Measuring time constant of VDCOL	506.17	1.00
Lower voltage limit of VDCOL	472.24	24.88
Minimum current limit of VDCOL	14.88	1.00
Upper voltage limit of VDCOL	3.80	0.28
Proportion coefficient of CCA	1.91	1.84

Table 10 show that, in terms of absolute sensitivity, the parameters with high sensitivity for TVAI are: the integral time constant of CCA, the measuring time constant of VDCOL, and the lower voltage limit of VDCOL. According to the voltage response presented in subsection B&C, the impact of these three parameters on suppressing transient overvoltage is quite obvious, so attention should be paid to these parameters when restraining overvoltage. From the perspective of relative sensitivity, the parameter with the highest sensitivity is the lower voltage limit of VDCOL. Therefore, the lower voltage limit of VDCOL should also be noted when adjusting the parameters to suppress overvoltage.

It should be noted that the parameters of CCA can not only improve the transient characteristics of DC system, but also affect the dynamic performance, so the dynamic stability performance of the whole system is also needed to be taken into account when adjusting the parameters of CCA [33].

V. APPLICATION 2: REACTIVE COMPENSATION PLANNING

As pointed previously, the transient overvoltage could be suppressed by adjusting the control parameters in DC, but this method is limited, so more convenient methods are needed. One is to use the reactive power compensate equipment at the sending end of UHVDC system.

In this section, the impact of different reactive power compensation equipment, such as synchronous condenser, SVC, and SVG, on the transient overvoltage is compared, with the system presented in Section IV. And the reactive compensation capacity to maintain the safety and stability of transient voltage is estimated based on sensitivity, which provides guidance for electric power system planning.

A. COMPARISON OF REACTIVE POWER COMPENSATION EQUIPMENT

In the simulations, the fault is set as DC bipolar block, and the compensation mode of the synchronous condenser, SVC, and SVG is local compensation, and the compensation capacity is 1500MVar.

With the setting fault, the transient voltage response of the bus at the sending end of UHVDC system (i.e. the 750kV bus) with respect to different reactive power compensation equipment could be obtained, as shown in Fig. 11. Also, the corresponding TVAI and maximum overvoltage amplitude are measured, as shown in Table 11.

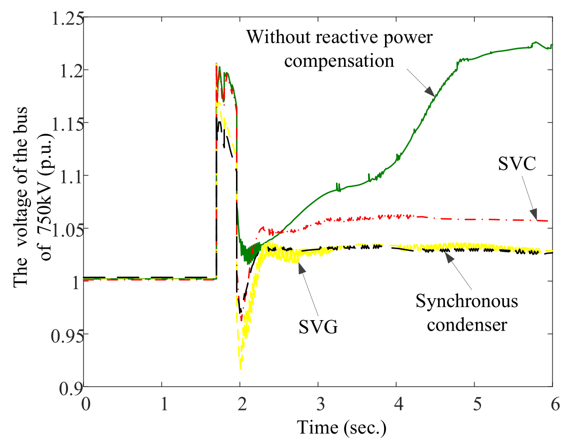

FIGURE 11. Voltage response with different reactive power compensation equipment.

Fig. 11 shows that in the case of DC bipolar block, if there is no reactive power compensation equipment, the voltage of 750kV bus will exceed the overvoltage threshold 1.1p.u., and continue to rise. If the reactive power compensation equipment is installed, the voltage of 750kV bus will be lower, and the final voltage will be lower than 1.1p.u..

TABLE 11. Maximum voltage and TVAI with different reactive power compensation equipment.

Reactive power compensation equipment	TVAI	Maximum voltage
Without reactive power compensation equipment	4904.2557	1.2262
Synchronous condenser	300.3504	1.1601
SVG	297.3395	1.2029
SVC	1752.2034	1.2052

Table 11 shows that in terms of TVAI, compared with SVC, the TVAI is smaller when there is synchronous condenser or SVG, indicating that the effects of synchronous condenser and SVG on suppressing transient overvoltage are better. In terms of the maximum voltage, the maximum voltage is significantly lower than other cases after installing synchronous condenser, which shows that synchronous condenser is the best equipment to suppress transient overvoltage.

Thus, the synchronous condenser is the best reactive power compensation equipment for 750kV bus.

B. REACTIVE COMPENSATION CAPACITY

As shown in Table 11, when the reactive compensation capacity is 1500MVar, the TVAI is still greater than 1, and the transient voltage is unsafe. Thus, to maintain the transient voltage security and stability, the reactive compensation capacity should be increased.

Considering that the effect of SVC, whose dynamic performance is poor, and the performance on suppressing the transient overvoltage is also not as good as that of synchronous condenser and SVG, thus, in the following examples, only the synchronous condenser and SVG are considered.

With reactive compensation capacity of 1501MVar, the TVAI and maximum overvoltage amplitude are obtained, as shown in Table 12.

TABLE 12. Maximum voltage and TVAI with reactive compensation capacity of 1501MVar.

Reactive power compensation equipment	TVAI	Maximum voltage
Synchronous condenser	300.2467	1.160067
SVG	297.2397	1.202880

According to the simulation results in Table 11 & 12, the sensitivity of the reactive compensation capacity of the synchronous condenser and SVG to TVAI and the sensitivity to the maximum voltage can be obtained, as shown in Table 13. Furthermore, with the above sensitivity, the additional reactive compensation capacity required for TVAI equal to 1 or maximum voltage equal to 1.1 is shown in Table 13.

TABLE 13. Sensitivity and additional reactive compensation capacity.

Reactive power compensation equipment	TVAI sensitivity	Additional capacity (MVar)	Maximum voltage sensitivity (*10^{-5})	Additional capacity (MVar)
Synchronous condenser	0.1037	2887	1.41	4271
SVG	0.0998	2969	2.18	4720

Table 13 shows that, according to the sensitivity to TVAI, the reactive compensation capacity of the synchronous condenser needs to be increased by 2887MVar, that is, in order to ensure the stability and safety of the transient voltage, the total reactive compensation capacity of the synchronous condenser should be increased to 4387Mvar. And the reactive compensation capacity of SVG needs to be increased by 2969MVar, i.e., the total reactive compensation capacity of SVG should be increased to 4457MVar.

Similarly, according to the sensitivity to the maximum voltage, the reactive compensation capacity of the synchronous condenser needs to be increased by 4271MVar, that is, the total reactive compensation capacity of the synchronous condenser needs to be increased to 5771MVar. And the reactive compensation capacity of SVG needs to be increased by 4720MVar, i.e., the total reactive compensation capacity of SVG needs to be increased to 6220MVar.

To verify the effectiveness of applying sensitivity to estimate reactive compensation capacity, the transient voltage response of the 750kV bus with respect to the reactive compensation capacity of the synchronous condenser being 4387MVar and 5771MVar and the reactive compensation capacity of SVG being 4457MVar and 6220MVar could be obtained, as shown in Fig. 12. The TVAI and maximum overvoltage amplitude are obtained, as shown in Table 14.

Note: in Fig. 12 and Table 14, V_{Max} sensitivity means maximum voltage sensitivity.

Fig. 12 and Table 14 show that when the reactive compensation capacity is configured according to the sensitivity,

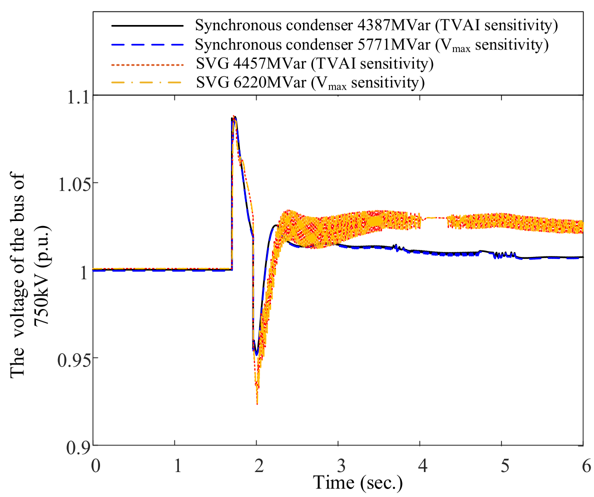

FIGURE 12. Voltage curve for increasing reactive compensation capacity according to sensitivity.

TABLE 14. Maximum voltage and TVAI with increasing reactive compensation capacity according to sensitivity.

Reactive power compensation equipment	Sensitivity	TVAI	Maximum voltage
Synchronous condenser 4387MVar	TVAI sensitivity	0.9151	1.0877
Synchronous condenser 5771MVar	V_{Max} sensitivity	0.644	1.0867
SVG 4457MVar	TVAI sensitivity	0.7402	1.0883
SVG 6220MVar	V_{Max} sensitivity	0.738	1.0883

the maximum voltage could be less than 1.1p.u., and TVAI is less than 1, which shows that it is effective to estimate the reactive compensation capacity by TVAI sensitivity and maximum voltage sensitivity. Compared with TVAI sensitivity, it needs more compensation capacity for the maximum voltage sensitivity, but the TVAI and the maximum voltage after compensation are almost the same. Therefore, TVAI sensitivity is better than the maximum voltage sensitivity in estimating reactive compensation capacity, i.e., the proposed TVAI can estimate reactive compensation capacity more accurately, as it engages more information.

Note: in the above examples, with local compensation, the required reactive compensation capacity is huge, and other schemes are needed. However, from the perspective of quantitative evaluation, it is feasible to apply the proposed TVAI to electric power system planning, and the proposed TVAI is better than the maximum voltage.

VI. CONCLUSION

To the transient overvoltage in the sending end electric power system with UHVDC, this paper proposes a quantitative transient voltage assessment index considering the voltage dip and transient overvoltage, and determines the parameters according to the regulations for the high voltage power system and UHVDC system.

With the proposed index, the influence of parameters of VDCOL and CCA on transient overvoltage in the sending end electric power system with UHVDC is discussed. The simulation results show that the transient overvoltage can be suppressed by increasing the measuring time constant, the minimum current limit in VDCOL, and the integral time constant in CCA, or by reducing the upper and lower voltage limits in VDCOL and the proportion coefficient in CCA. Among them, the lower voltage limit in VDCOL is the most sensitive. So, to suppress the overvoltage, the lower voltage limit in VDCOL should be considered firstly.

Furthermore, the influence of the synchronous condenser, SVC, and SVG on transient overvoltage of the sending end electric power system with UHVDC is also discussed and the reactive power compensation capacity is estimated. The simulation results show that the synchronous condenser is the best compensation equipment, as the TVAI and the maximum voltage are the smallest under the same conditions. And it is effective to apply the proposed TVAI to estimate reactive compensation capacity, which could provide guidance for electric power system planning.

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