A Method for Analyzing the Voltage Deviation Isolation Performance With an Application in Two-Stage High-Frequency Isolated AC-DC Converters in LVDC Systems

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Abstract—The differences between the power quality at the AC and DC sides, caused by AC-DC converters with constant DC voltage control, commonly exist in low-voltage direct current (LVDC) systems. The voltage deviation isolation (VDI) is one of the typical phenomenons. A method is proposed to analyze the VDI performance and applied in two-stage high-frequency isolated AC-DC converters, which can isolate not only the faults but also the voltage deviation at the AC side and improve the voltage quality at the DC side. First, the voltage deviation isolation ratio (VDIR) is defined to assess VDI. Based on VDIR, the operation characteristics of AC-DC converters with constant DC voltage control are analyzed and the range of VDI is defined. Second, with considering the conditions for stable operation of AC-DC converters, constraints on power transmission limit and static stability limit are used to determine the range of VDI. Third, a simulation model is established and the feasibility and validity of the method are verified. Finally, the main factors affecting the range of VDI are analyzed. Actually, the method proposed is adapted to various types of AC-DC converters with constant DC voltage control.

Index Terms—High-frequency isolated AC-DC converter, power transmission limit, static stability limit, voltage deviation isolation (VDI), voltage deviation isolation ratio (VDIR).

I. INTRODUCTION

As the worldwide demand for low-carbon emission increases, low-voltage direct current (LVDC) systems develop rapidly due to the convenience to access distributed power supply [1]–[3], which brings new challenges to power quality. Some research has done for power quality of LVDC, such as the definition and measurement of indices [4], analysis and control

of LVDC power quality [5]–[8]. For grid-connected LVDC systems, the power quality at the point of common coupling (PCC) also attracts attention [9]. Nevertheless, the existing research usually pays attention to the power quality only at the AC side [10] or DC side. The studies on the differences between the power quality at the AC side and DC side for grid-connected LVDC systems are rare. In grid-connected LVDC systems, AC-DC converters usually adopting constant DC voltage control are used for LVDC systems to connect to the AC grid, which can hold the DC voltage with different AC voltage deviations. It is necessary to research the difference between the power quality at the AC side and DC side of the grid-connected converters, which is helpful to understand the defense of LVDC systems against power quality issues from the AC grid.

When there is a voltage deviation at the AC side, the AC-DC converters may be able to keep the DC voltage at the instruction value. The phenomenon that the voltage deviation at the DC side is different from the AC side is called voltage deviation isolation (VDI) in the paper. It is obvious that the performance of VDI of AC-DC converters is an important factor to improve the power quality at the DC side of LVDC systems. In previous studies, voltage deviation, voltage qualification rate and voltage regulation are common indices to applied in voltage deviation research. Voltage deviation and qualification rate, are the indices without comparison features and not suitable for VDI. Voltage regulation is proposed to describe the difference between the conventional no-load voltage and the voltage at load excluding the correcting effect of stabilizing means if any [11]. However, voltage regulation is not suitable for VDI. For first example, the low AC voltage in rural areas caused by the long lines can be transformed into a normal DC voltage by AC/DC converters. In this case, voltage regulation is obviously not suitable without the change of loads. For second example, when the AC voltage changes because of change of the loads of other lines, and the loads of the line connected to the LVDC systems remain the same, voltage regulation is obviously not suitable. Both cases belong to VDI but can not be described by voltage regulation. Therefore, it is necessary to propose a new index and method to assess and analyze VDI.

As one type of the typical grid-connected AC-DC converters,

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two-stage high-frequency isolated AC-DC converters have advantages of efficiency, energy density and fault isolation [12]. Previous research on high-frequency isolated AC-DC converters mainly focus on topology design, control strategy, new materials [13], performance analysis [12] and et al. In [14], a topology is presented for high-frequency AC-DC converters to improve the efficiency and suppress EMI noise. The control strategies are modified to suppress current harmonic, improve efficiency and eliminate the DC bias flux in [9], [15], [16] respectively. However, there is little research to quantitatively analyze the VDI performance for two-stage high-frequency isolated AC-DC converters.

With the above background, a method is proposed to analyze the VDI performance and applied in two-stage high-frequency isolated AC-DC converters in LVDC systems. In section II, the voltage deviation isolation ratio (VDIR) is defined to assess VDI. With considering the operation characteristics of AC-DC converters with constant DC voltage control, the definition of the range of VDI is presented. In section III, based on the conditions for stable operation of AC-DC converters, constraints on the power transmission limit and the static stability limit are considered to determine the range of VDI. The formulas to analytically compute steady-state points rather than to simulate or numerically calculate are given. In section IV, the results of theoretical analysis are testified by the comparison with simulation results. In section V, the main factors affecting the range of VDI are analyzed with the control variable method. The paper is concluded in section VI.

II. VDIR AND THE RANGE OF VDI

A. Voltage Deviation Isolation Ratio

Differences between voltage deviations at both ends of the power conversion module are common, which is called VDI in the paper. To assess VDI, VDIR is defined as:

$$\text{VDIR} = (1 - \frac{\Delta U_2}{\Delta U_1}) \times 100\% \quad (1)$$

Where ΔU_1 and ΔU_2 are voltage deviations at both ends of the power conversion module respectively shown in Fig. 1. When $\Delta U_1 = 0$, calculating VDIR is meaningless. VDIR represents the percentage reduction of ΔU_2 relative to ΔU_1 . Therefore, it is noted that ΔU_1 should remain the same when a VDIR is compared with another.

VDIR for grid-connected AC-DC converters is as (2):

$$\text{VDIR} = (1 - \frac{\Delta U_{DC}}{\Delta U_{AC}}) \times 100\% \quad (2)$$

Where ΔU_{DC} and ΔU_{AC} are voltage deviations based on DC instruction voltage and AC rated voltage respectively. VDIR is the percentage reduction of ΔU_{DC} relative to ΔU_{AC} .

B. Range of VDI

Without consideration of the output limit and deviation

Fig. 1. Voltage deviations at both ends of the power conversion module.

Fig. 2. Schematic diagram of the range of VDI.

of proportional-integral (PI) controller, there are only two operating states for AC-DC converters with constant DC voltage control: Run at the instruction DC voltage so that $\text{VDIR} = 100\%$ or $\Delta U_{AC} = 0\%$, or run at an unstable state.

The range of ΔU_{AC} where AC-DC converters can run at the instruction DC voltage is defined as the range of VDI, as shown in Fig. 2.

III. DETERMINATION OF THE RANGE OF VDI FOR TWO-STAGE HIGH-FREQUENCY ISOLATED AC-DC CONVERTERS

The topology and control strategy of the two-stage high-frequency isolated AC-DC converter in LVDC systems are shown in Fig. 3. To simplify the analysis, the AC grid is regarded as an AC source in series with an inductor, and only the resistive load is considered at the DC side.

In topology part, u_{sabc} are the phase AC grid source voltages. N is the neutral point. u_{abc} and i_{abc} are the phase voltages and currents at the PCC respectively. u_{sabc} are the phase output voltages of the arms of the AC-DC converter. u_{dc} and i_{dc} are the voltage and current at the DC side of the front stage of the AC-DC converter respectively. u_{dc1} and i_{dc1} are the voltage and current at the DC side of the back stage of the AC-DC converter. L_s is the equivalent inductance of the AC grid. L is the inductance of the filter at the AC side. C and C_1 are capacitors at the DC side of the front and back stages of the AC-DC converter. L_{hf} and R_{hf} are the inductance and equivalent resistance in series with the two-stage high-frequency isolated transformer respectively. k is the rated voltage ratio of the two-stage high-frequency isolated transformer. R_L is the resistance load.

In control strategy part, s_j ($j = a, b, c, g, 1$) are the switching functions representing the switching state of the power electronic devices of the front stage. When the switch of the upper/lower arm is conducted, s_j ($j = a, b, c$) is equal to 1/-1. When the switch corresponding to s_j ($j = g, 1$) is or not conducted, s_j ($j = g, 1$) is equal to 1/-1. ω and ω_{hf} are the rated frequency of AC grid and high-frequency isolated transformer respectively. θ_{pll} is the output of PLL. θ is the phase difference between u_{abc} and u_{sabc} . u_{dq} , i_{dq} and s_{dq} are u_{abc} , i_{abc} and s_{abc} in dq coordinate. i_{dref}

Fig. 3. The topology and control strategy of the two-stage high-frequency isolated AC-DC converter connected to AC grid.

u_{dcref} and k_{ref} are the instruction values for i_{dq} , u_{dc} and the ratio of u_{dc1} and u_{dc} . k_{pj} and k_{ij} ($j = u, d, q, hf, pll$) are the parameters of the PI controllers. x_j ($j = u, d, q, hf, pll$) are the integral outputs.

The conditions for two-stage high-frequency isolated AC-DC converters to run stably at the instruction DC voltage are as follow:

- Power for maintaining DC voltage at instruction value can be transmitted by grid-connected AC-DC converters.
- The system is statically stable.

Therefore, there are two constraints to determine the range of VDI. One is the constraint on power transmission limit, the other is the constraint on static stability limit.

A. Constraint on Power Transmission Limit

The active power from the AC grid to the AC-DC converter is represented with P_c . Usually unit power factor control is adopted by grid-connected AC-DC converters. According to Kirchhoff laws, (3) and (4) can be given as follows and their graphs are given in Fig. 4.

$$U_c^2 = f_c(U_{PCC}^2) = U_{PCC}^2 + \left(\frac{P_c}{3U_{PCC}}\omega L\right)^2 \quad (3)$$

$$U_s^2 = f_s(U_{PCC}^2) = U_{PCC}^2 + \left(\frac{P_c}{3U_{PCC}}\omega L_s\right)^2 \quad (4)$$

Where U_s , U_{PCC} and U_c are steady-state root mean square of u_{sabc} , u_{abc} and u_{cabc} .

Based on (3) and (4), (5) and (6) can be given as follows:

$$U_c^2 \geq \frac{2P_c\omega L}{3} \quad (5)$$

$$U_s^2 \geq \frac{2P_c\omega L_s}{3} \quad (6)$$

Fig. 4. Graphs of $U_c^2 = f_c(U_{PCC}^2)$ and $U_s^2 = f_s(U_{PCC}^2)$.

When $U_{PCC}^2 = \frac{P_c\omega L}{3}$ or $\frac{P_c\omega L_s}{3}$, the equality in (5) or (6) holds.

With the modulation ratio $M \leq 1$, (7) can be given as follows:

$$U_c^2 \leq \frac{U_{dc}^2}{8} \quad (7)$$

Where U_{dc} is steady-state value of u_{dc} .

Substitute (3) into (7), (8) can be given as follows:

$$x_1 \leq U_{PCC} \leq x_2 \quad x_{1,2} = \sqrt{\frac{U_{dc}^2}{16} \mp \sqrt{\frac{U_{dc}^4}{256} - \frac{P_c^2 \omega^2 L_s^2}{9}}} \quad (8)$$

Substitute (8) into (4) and combine with (6).

When $x_1^2 \geq \frac{P_c \omega L_s}{3}$, as shown in Fig. 4(a), $U_{smin} = \sqrt{f_s(x_1^2)}$,

$x_1^2 < \frac{P_c \omega L_s}{3}$, as shown in Fig. 4(b), $U_{smin} = \sqrt{\frac{2P_c \omega L_s}{3}}$

The range of U_s with consideration on constraint on the power transmission limit is as follows:

$$U_{smin} \leq U_s \leq U_{smax} \quad \begin{cases} U_{smin} = \begin{cases} \sqrt{f_s(x_1^2)} & x_1^2 \geq \frac{P_c \omega L_s}{3} \\ \sqrt{\frac{2P_c \omega L_s}{3}} & x_1^2 < \frac{P_c \omega L_s}{3} \end{cases} \\ U_{smax} = \sqrt{f_s(x_2^2)} \end{cases} \quad (9)$$

Based on (9), the range of VDI only with consideration on constraint on the power transmission limit can be given as follows:

$$[\Delta U_{v1}, \Delta U_{v2}] = \frac{[v_1, v_2] - U_{sn}}{U_{sn}} \times 100\% \quad (10)$$

$$\begin{cases} v_1 = \begin{cases} x_1 & x_1^2 \geq \frac{P_c \omega L_s}{3} \\ \sqrt{\frac{P_c \omega L_s}{3}} & x_1^2 < \frac{P_c \omega L_s}{3} \end{cases} \\ v_2 = x_2 \end{cases}$$

Where U_{sn} is the rated voltage of the AC grid.

When over modulation or space vector pulse width modulation (SVPWM) is considered, (7) is modified as follows:

$$U_c^2 \leq \frac{2U_{dc}^2}{\pi^2} \quad (11)$$

Substitute (3) into (11), (12) can be given as follows:

$$x_1 \leq U_{PCC} \leq x_2 \quad x_{1,2} = \sqrt{\frac{U_{dc}^2}{\pi^2} \mp \sqrt{\frac{U_{dc}^4}{\pi^4} - \frac{P_c^2 \omega^2 L_s^2}{9}}} \quad (12)$$

Similarly, the range of U_s and VDI with consideration on constraint on the power transmission limit can be obtained.

B. Constraint on Static Stability Limit

Based on Fig. 3, The equations of the main circuit of the front stage of the AC-DC converter are given as follows:

$$\begin{cases} (L + L_s) \frac{di_j}{dt} = u_{sj} - \frac{s_j u_{dc}}{2} \quad j = a, b, c \\ C \frac{du_{dc}}{dt} = \frac{1}{2} \sum_{j=a,b,c} s_j i_j - i_{dc} \end{cases} \quad (13)$$

The transformation matrix is shown as (14).

$$\begin{bmatrix} d \\ q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \theta_{pll} & \cos(\theta_{pll} - \frac{2\pi}{3}) & \cos(\theta_{pll} + \frac{2\pi}{3}) \\ \sin \theta_{pll} & \sin(\theta_{pll} - \frac{2\pi}{3}) & \sin(\theta_{pll} + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (14)$$

$$\theta_{pll} = \omega t + \theta \quad (15)$$

Transform (13) into dq coordinate.

$$\begin{cases} (L + L_s) \frac{di_d}{dt} = u_{sd} - \frac{s_d u_{dc}}{2} - (L + L_s) \frac{d\theta_{pll}}{dt} i_q \\ (L + L_s) \frac{di_q}{dt} = u_{sq} - \frac{s_q u_{dc}}{2} + (L + L_s) \frac{d\theta_{pll}}{dt} i_d \\ C \frac{du_{dc}}{dt} = \frac{3(s_d i_d + s_q i_q)}{4} - i_{dc} \end{cases} \quad (16)$$

Where u_{sdq} are the u_{sabc} in dq coordinate.

The equations of the control circuit of the front stage are as follows:

$$\begin{cases} \frac{dx_u}{dt} = u_{dref} - u_{dc} \\ \frac{dx_{ij}}{dt} = i_{jref} - i_j \quad j = d, q \end{cases} \quad (17)$$

$$\begin{cases} i_{dref} = k_{pu}(u_{dref} - u_{dc}) + k_{iu} x_u \\ i_{qref} = 0 \\ s_d = u_d - \omega L i_q - k_{pd}(i_{dref} - i_d) - k_{id} x_{id} \\ s_q = u_q + \omega L i_d - k_{pq}(i_{qref} - i_q) - k_{iq} x_{iq} \end{cases} \quad (18)$$

The equation of phase-locked loop (PLL) is as follows:

$$\begin{cases} \frac{d\theta}{dt} = -\omega - k_{pll} u_q - k_{ipll} x_{pll} \\ \frac{dx_{pll}}{dt} = u_q \end{cases} \quad (19)$$

Based on Fig. 3, the equations of the main circuit of the back stage of the AC-DC converter are given as follows:

$$\begin{cases} L_{hf} \frac{di_{hf}}{dt} = s_g u_{dc} - \frac{s_{g1} u_{dc1}}{k} - R_{hf} i_{hf} \\ C_1 \frac{du_{dc1}}{dt} = \frac{s_{g1} i_{hf}}{k} - \frac{u_{dc1}}{R_L} \end{cases} \quad (20)$$

$$i_{hf} = s_g i_{dc} \quad (21)$$

The transformation matrix is shown as (22).

$$\begin{bmatrix} d \\ q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \omega_{hf} t & \cos(\omega_{hf} t - \frac{2\pi}{3}) & \cos(\omega_{hf} t + \frac{2\pi}{3}) \\ \sin \omega_{hf} t & \sin(\omega_{hf} t - \frac{2\pi}{3}) & \sin(\omega_{hf} t + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (22)$$

Extend (20) to the equations in three phases and transform them into dq coordinate.

$$\begin{cases} L_{hf} \frac{di_{hfd}}{dt} = s_{gd} u_{dc} - \frac{s_{gld} u_{dc1}}{k} - \omega_{hf} L_{hf} i_{hfd} - R_{hf} i_{hfd} \\ L_{hf} \frac{di_{hfq}}{dt} = s_{gq} u_{dc} - \frac{s_{glq} u_{dc1}}{k} + \omega_{hf} L_{hf} i_{hfd} - R_{hf} i_{hfq} \\ C_1 \frac{du_{dc1}}{dt} = \frac{s_{gld} i_{hfd} + s_{glq} i_{hfq}}{2k} - \frac{u_{dc1}}{R_L} \end{cases} \quad (23)$$

Where s_{gdq} , s_{gldq} and i_{hfdq} are s_g , s_{gl} and i_{hf} in dq coordinate.

The equations of the control circuit of the back stage are follows:

$$\frac{dx_{hf}}{dt} = k_{ref} - \frac{u_{dc1}}{u_{dc}} \quad (24)$$

$$\begin{cases} s_g = \frac{4}{\pi} \sin \omega_{hf} t \\ s_{gl} = \frac{4}{\pi} \sin \left\{ \omega_{hf} t - [k_{phf} (k_{ref} - \frac{u_{dc1}}{u_{dc}}) + k_{ihf} x_{hf}] \pi \right\} \end{cases} \quad (25)$$

Transform (25) into dq coordinate.

$$\begin{cases} s_{gd} = 0 & s_{gq} = \frac{4}{\pi} \\ s_{gld} = -\frac{4}{\pi} \sin [k_{phf} (k_{ref} - \frac{u_{dc1}}{u_{dc}}) + k_{ihf} x_{hf}] \pi \\ s_{glq} = \frac{4}{\pi} \cos [k_{phf} (k_{ref} - \frac{u_{dc1}}{u_{dc}}) + k_{ihf} x_{hf}] \pi \end{cases} \quad (26)$$

Based on the above equations, select $\mathbf{X}$ as state variables and the state-space average model of the two-stage high-frequency isolated AC-DC converter can be obtained.

$$\mathbf{X} = [i_d, i_q, u_{dc}, x_u, x_{id}, x_{iq}, \theta, x_{pll}, i_{hfd}, i_{hfq}, u_{dc1}, x_{hf}]^T \quad (27)$$

Set the derivative of the state variable to 0 and obtain (28) and (29) by ignoring the power of R_{hf} . The steady-state point of the model can be approximately obtained by analytic expressions rather than simulation and numerical calculation.

$$\begin{cases} u_{sd} = \sqrt{\frac{U_s^2}{2} + \frac{\omega L_s k_{ref}^2 u_{dref}^2}{3R_L}} + \sqrt{\frac{U_s^2}{2} - \frac{\omega L_s k_{ref}^2 u_{dref}^2}{3R_L}} \\ u_{sq} = \begin{cases} \sqrt{2U_s^2 - u_{sd}^2} & P_c < 0 \\ -\sqrt{2U_s^2 - u_{sd}^2} & P_c \geq 0 \end{cases} \\ i_d = \frac{2k_{ref}^2 u_{dref}^2}{3R_L u_{sd}} & i_q = i_{qref} & u_{dc} = u_{dref} & x_u = \frac{i_d}{k_{iu}} \\ x_{id} = \frac{(u_{dc} - 2)u_{sd}}{u_{dc} k_{id}} & x_{iq} = \frac{2Lu_{sq} + \omega L_s u_{dc} i_d}{L_s u_{dc} k_{iq}} \\ \theta = -\arctan(\frac{u_{sq}}{u_{sd}}) & x_{pll} = \frac{\omega}{k_{ipll}} \end{cases} \quad (28)$$

Fig. 5. Determination of the range of VDI with both constraints on power transmission limit and static stability limit.

$$\begin{cases} u_{dc1} = k_{ref} u_{dref} & x_{hf} = \frac{1}{\pi k_{ihf}} \arcsin(\frac{\pi^2 \omega_{hf} L_{hf} k_{ref}^2}{8R_L}) \\ s_{gld} = -\frac{4}{\pi} \sin k_{ihf} x_{hf} \pi & s_{glq} = \frac{4}{\pi} \cos k_{ihf} x_{hf} \pi \\ i_{hfd} = \frac{2u_{dc1}^2}{R_L s_{glq} u_{dc}} & i_{hfq} = \frac{2ku_{dc1}}{R_L s_{gld}} - \frac{s_{glq} i_{hfq}}{s_{gld}} \end{cases} \quad (29)$$

Where $\langle \cdot \rangle$ represent the steady-state value of $\langle \cdot \rangle$.

Through linearizing the model at the steady-state point, the small signal model is obtained [17], as follows:

$$\frac{d\Delta \mathbf{X}}{dt} = \mathbf{A} \Delta \mathbf{X} + \mathbf{B} \Delta \mathbf{Y} \quad (30)$$

The constraint on the static stability limit of high-frequency isolated AC-DC converter is as follow:

$$\max \{ \text{real}[\lambda(\mathbf{A})] \} < 0 \quad (31)$$

Where $\text{real}[\lambda(\mathbf{A})]$ represents the real parts of the eigenvalues of matrix $\mathbf{A}$.

C. Determination of Range of VDI

The range of VDI can be determined as shown in Fig. 5. Based on (10), the range of abscissa is $[\Delta U_{v1}, \Delta U_{v2}]$. According to (31), $[\Delta U_{VDImin}, \Delta U_{VDImax}]$ can be determined.

The flow chart of the proposed method for determination of the range of VDI for two-stage high-frequency isolated AC-DC converters with constant DC voltage control was given in Fig. 6. Actually, the method is available for other types of AC-DC converters with constant DC voltage control in LVDC systems.

IV. SIMULATION TEST

A. Parameters of Simulation Model

A simulation model of the two-stage high-frequency isolated AC-DC converter is established based on Fig. 3. The parameters of the simulation model are shown in Table I.

B. Calculation Results

According to the proposed method, the ranges of U_s and

Fig. 6. Method for determination of the range of VDI for two-stage high-frequency isolated AC-DC converters with constant DC voltage control.

TABLE I
PARAMETERS OF THE SIMULATION MODEL

Parameter	Value	Parameter	Value
U_{sn}	220 V	u_{deref}	700 V
ω	100π rad/s	k_{pu}	10
L_s	30 μH	k_{iu}	1000
L	600 μH	i_{qref}	0 A
C	6300 μF	$k_{pd/q}$	5
C_1	3300 μF	$k_{id/q}$	100
ω_{hf}	$2\pi \times 10^4$ rad/s	k_{ppl}	578
R_{hf}	0.001 Ω	k_{ipll}	10285
L_{hf}	25 μH	k_{ref}	0.75/0.7
k	0.75/0.7	k_{phf}	0.01
R_L	5.625 Ω	k_{ihf}	10

TABLE II
RANGES OF U_s AND VDI ONLY WITH CONSIDERATION ON CONSTRAINT ON POWER TRANSMISSION LIMIT

Modulation Ratio	U_{smin}	U_{smax}	ΔU_{v1}	ΔU_{v2}
$0 < M \leq 1$	28.3 V	246.2 V	-88.4%	+11.9%
$0 < M \leq \frac{4}{\pi}$	25.4 V	314.5 V	-90.9%	+42.9%

VDI only with consideration on constraint on the power transmission limit are given in Table II. The range of VDI is shown in Fig. 7. If over modulation or SVPWM is considered, the range of VDI is $[-51.9\%, +42.9\%]$, else the range of VDI is $[-51.9\%, +11.9\%]$.

C. Simulation Results

To testify the correctness of the calculation results, three scenarios are selected as shown in Table III.

In scenario 1, $-88.4\% < \Delta U_{AC} = -60\% < -51.9\%$, which satisfies the constraint on the power transmission limit but not the static stability limit. The simulation results are shown in Fig. 8. u_{dc1} oscillates around instruction voltage when i_{abc} and s_{abc} also oscillate, which means the converter can transmit the

Fig. 7. Range of VDI for the two-stage high-frequency isolated AC-DC converter.

TABLE III
THREE SCENARIOS TO SIMULATE

Number	1	2	3
U_s	88.1 V	132.0 V	264.0 V
ΔU_{AC}	-60%	-40%	+20%

Fig. 8. Waveforms of the currents at the AC side, voltage at the DC side and modulation signals in scenario 1.

power in need but not keep stable.

In scenario 2, $-51.9\% < \Delta U_{AC} = -40\% < +11.9\%$, which satisfies the constraint on the power transmission limit and the static stability limit with $M \leq 1$. The simulation results are shown in Fig. 9. s_{abc} are between -1 and 1. u_{dc1} is stabilized at the instruction voltage which means the converter can stably transmitted the power in need without over modulation.

In scenario 3, $+11.9\% < \Delta U_{AC} = +20\% < +42.9\%$, which satisfies the constraint on the power transmission limit and the static stability limit with $M > 1$. The simulation results are shown in Fig. 10. u_{dc1} is stabilized at the instruction voltage and

Fig. 9. Waveforms of the currents at the AC side, voltage at the DC side and modulation signals in scenario 2.

Fig. 10. Waveforms of the currents at the AC side, voltage at the DC side and modulation signals in scenario 3.

S_{abc} are out of the range from -1 to 1 . Due to over modulation, i_{abc} have more harmonics in scenario 3 than in scenario 2.

The simulation results in three scenarios are in accord with the theoretical analysis so that the feasibility and validity of the proposed method are verified.

V. ANALYSIS OF INFLUENCE FACTORS OF RANGE OF VDI

Several factors are selected to research their influences on the range of VDI, including parameters of PI controllers, the impedance of AC grid, transmitted power and DC output voltage. The factors probably affecting the range of VDI are analyzed based on the AC-DC converter given in section IV.

Fig. 11. Ranges of VDI with different k_{pu}/k_{iu} .

Fig. 12. Ranges of VDI with different k_{pdq}/k_{idq} .

Fig. 13. Ranges of VDI with different k_{phf}/k_{ihf} .

A. Ranges of VDI With Different Parameters of PI Controllers

Ranges of VDI with different k_{pu}/k_{iu} , k_{pdq}/k_{idq} and k_{phf}/k_{ihf} are shown in Fig. 11, Fig. 12 and Fig. 13 respectively.

In Fig. 11 and Fig. 12, as the parameters of PI controllers increase, the range of VDI $[\Delta U_{v1}, \Delta U_{v2}]$ with only consideration on power transmitted limit remains the same, ΔU_{VDImin} increases and the range of VDI $[\Delta U_{VDImin}, \Delta U_{VDImax}]$ shrinks. It is because the parameters of PI controllers only affect the static stability limit but not the power transmitted limit and the larger the parameters are, the worse the static stability is. In Fig. 13, the phenomenon is similar but not obvious, which means the range of VDI of the high-frequency isolated AC-DC converters is

Fig. 14. Ranges of VDI with different L_s . Fig. 15. Ranges of VDI with different P_c .

more sensitive to k_{pu}/k_{iu} , k_{pdq}/k_{idq} than k_{phf}/k_{ihf} .

B. Ranges of VDI With Different Equivalent Impedances of AC GRID

Ranges of VDI with different equivalent impedances of the AC grid are shown in Fig. 14. As L_s increase, ΔU_{v1} increases, ΔU_{VDmin} increases and the range of VDI shrinks. It is because the increase of L_s , which reduce the strength of the AC grid, can reduce the power transmission limit and deteriorates the static stability.

C. Ranges of VDI With Different Transmitted Power

Ranges of VDI with different transmitted power of the AC grid are shown in Fig. 15. As P_c increases, ΔU_{v1} increases and the range of VDI shrinks because of the increase of ΔU_{VDmin} caused by the worse static stability.

D. Ranges of VDI With Different DC Output Voltages

According to Fig. 3, u_{dc1} is changed by setting different k_{ref} and the transmitted power P_c remains the same by adjusting R_L . Range of VDI with different k_{ref} is shown in Fig. 16.

As the k_{ref} increases, u_{dc1} increases but range of VDI barely changes. The reason is that it is u_{dc} directly involved in the modulation of u_{cabc} but not u_{dc1} . Because P_c and u_{dc} remain the same, the front stage of the AC-DC converter stays at the same

Fig. 16. Ranges of VDI with different k_{ref} .

condition. The k_{ref} varies by only $\pm 20\%$ so that the back stage can maintain normal operation. Therefore, the range of VDI is barely affected by DC output voltage.

VI. CONCLUSION

In this paper, VDIR and the range of VDI are defined to assess the VDI performance and applied in the two-stage high-frequency AC-DC converters with constant DC voltage control in LVDC systems. A method is proposed to analyze the range of VDI based on the power transmission limit and the static stability limit. The main conclusions are as follows:

(a) The method proposed is useful to determine the range of VDI for two-stage high-frequency AC-DC converters with constant DC voltage control in LVDC systems. Actually, the method is available for various types of grid-connected AC-DC converters in LVDC systems.

(b) The findings from the analysis of the influence factors of the range of VDI are shown as follows.

For two-stage high-frequency AC-DC converters in LVDC systems, the lower and upper bounds of the range of VDI are determined by constraints on static stability limit and power transmission limit.

As parameters of PI controllers, the impedance of AC grid or transmitted power increase, the range of VDI shrinks with the increase of the lower bound. And the range of VDI is barely affected by DC output voltage when the transmitted power remains the same.

In the next research stage, other control strategies will be considered in the analysis of VDI, which can bring more interesting findings. And the isolation ratio proposed in the paper is not only suitable for voltage deviation, but also can be applied for harmonic, voltage dip and other power quality problems, which may be the future research direction.

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