Flexible controls to reduce DC voltage deviations in multi-terminal DC grids

Guihong Wu | Zhengchun Du | Yangyang Zhao | Guiyuan Li

1 School of Electrical Engineering, Xi’an Jiaotong University, Xi’an, China
2 The State Key Laboratory of HVDC, Electric Power Research Institute, China Southern Power Grid, Guangzhou, China

Abstract
Various disturbances in voltage source converter based high-voltage, multi-terminal DC grids will significantly cause DC voltage deviations when the classical voltage droop control is adopted. The unsatisfactory voltage deviations weaken the voltage regulation ability and increase the risk of instability. Two flexible controls at the top of the classical voltage droop control to reduce voltage deviations are proposed, and the power–voltage (P–V) curves of the classical voltage droop control are translated co-ordinately. Firstly, a global DC voltage oscillation damping control designed based on the Lyapunov theory is proposed for transient voltage deviations. Secondly, a constant weighted voltage control is designed for reducing steady weighted voltage deviations. The steady active power injections keep almost unchanged under proposed controls, consistent with those under only the classical voltage droop control. The stability influence and the power flow impact are carried out to evaluate the proposed controls theoretically. Tests are conducted on a multi-terminal DC grid with five-terminal voltage source converters. Simulation results show the proposed controls’ effectiveness and superiority under various fault conditions, including both the outage of a constant power voltage source converter and a droop voltage source converter.

1 INTRODUCTION
Research on high-voltage, multi-terminal DC (MTDC) grids is becoming more and more popular due to evolving voltage source converter (VSC) high-voltage DC (HVDC) technology [1–6]. Several VSC-HVDC projects have been put into the operation [7], and two VSC-MTDC grids have gone into service in China since 2013 [8,9].

DC voltage control, active power control and power sharing control are essential operational tasks in the VSC-MTDC grid [10]. To ensure the overall grid system stability, DC voltage control has become a priority. Ref. [11] reported that DC voltage oscillations between DC stations could lead to MTDC grid instability. In practice, attempts are made to keep the DC voltages within ±10% [11] for the insulation and protective devices or a stricter limit of ±5% [12,13] for the safe operation. Several DC voltage controls have been suggested, including the master slave methods [14], voltage margining methods [15] and the classical voltage droop (CVD) control [16,17], which is preferred in most literature.

Previous work addressed the issue of the droop coefficients setting for the CVD control. Ref. [1] proposed a basic method for selecting the droop coefficients according to rating powers and acceptable voltage deviations. Ref. [16] suggested continuously adjusting the adaptive droop coefficients based on a function of the available headroom, and ref. [18] proposed a coordinated design of droop coefficients, which is realized based on the model predictive control. In the work of ref. [19], the droop coefficients were selected based on two cascaded control schemes for loss minimization. Ref. [20] proposed a tuning method considering three factors: Desired active power sharing, DC voltage deviation minimization and loss minimization. For the process suggested by ref. [17,21,22], the desired voltage deviations are considered. Then the droop coefficients are optimized for different objects using different methods.
Despite these attempts at DC voltage control, voltage deviations are unavoidable due to the power–voltage (P–V) curve of the CVD control. Once the power sharing task begins, voltage deviations will exist. Therefore, droop setting optimization cannot solve the voltage deviations problem as if DC voltage deviations have to be tolerated in the CVD control for active power sharing.

The unsatisfactory voltage deviations weaken the voltage regulation ability of the system and increase the risk of instability. To further reduce DC voltage deviations, an improved pilot voltage droop based control is proposed in ref. [23]. The control in ref. [23] proposes the average DC voltage concept and improves the steady voltage performance satisfactorily. However, the reduction of transient voltage deviation fails to get noticed. Ref. [12] proposed a local DC voltage oscillation damping control that reduces the transient voltage deviations but may do damage to the global stability of MTDC grid in some cases. Besides, the effectiveness of the local DC voltage oscillation damping control is just evaluated in a simple radial network instead of a typical meshed networks. In addition, the stability influence and the power flow impact have not been sufficiently demonstrated, which are the important concerns from the system operators’ perspective.

To overcome the drawback and keep the active power sharing characteristic, the coordinated translation of the P–V curve comes into play. The translation of the P–V curve in this work means that the P–V curve moves left or right adaptively and coordinately according to an auxiliary voltage-based signal. This idea is considered as a supplement to the conventional droop setting optimization methods for further DC voltage deviation reduction, and few researchers use the coordinated and adaptive translation of multiple P–V curves to solve DC voltage deviation problems, which are caused consequentially by the CVD control in MTDC grids. Different from most previous relevant works that just focus on transient voltage deviations or steady voltage deviations, the present study is carried out as a comprehensive attempt for considering both transient voltage deviations and steady voltage deviations. Two new flexible controls related to the translation of multiple P–V curves are proposed. A global DC voltage oscillation damping (GVOD) control that can reduce transient voltage deviations steadily was designed based on the Lyapunov theory. A constant weighted DC voltage (CWV) control was designed to regulate the weighted voltage. The CWV control reduces the steady voltage deviations with few signals than the method proposed in ref. [23] while the steady active power of droop VSCs can still remain almost unchanged.

The remainder of this paper is organized as follows. Section 2 describes the system modeling, including VSC modeling and MTDC grid modeling. The weighted voltage and the proposed flexible controls are described and analysed in Section 3. Section 4 presents the stability analysis and power flow impact analysis to evaluate the proposed controls theoretically. The simulations of a meshed five-terminal VSC-MTDC grid system are carried out using PSCAD/EMTDC software in Section 5. Conclusions are drawn in Section 6.

2 | SYSTEM MODELING

To illustrate the effectiveness of proposed flexible controls, the system modeling, including VSC modeling and MTDC grid modeling, will be presented firstly in this Section.

The typical layout of a generic VSC-MTDC grid, shown in Figure 1, contains two types of VSCs. Several VSCs using constant active power control are installed on the source side for integrating renewable source energy as much as possible; other VSCs installed on the grid side usually adopt the CVD control to participate in the active power sharing and absorb all energy safely.

2.1 | Voltage-source converter modeling

The circuit of a VSC is shown in Figure 2. A VSC usually connects to an AC grid through the resistance $R_s$ and inductance $L_s$. Based on Kirchhoff’s voltage law, its decoupled current equations in the d–q rotating frame is given as [3,24]

$$\begin{align*}
I_{n} \frac{di^{d}_n}{dt} &= u^{d}_n - v^{d}_n - \omega L_s i^{q}_n - R_s i^{d}_n \\
I_{n} \frac{di^{q}_n}{dt} &= u^{q}_n - v^{q}_n + \omega L_s i^{d}_n - R_s i^{q}_n
\end{align*}$$

(1)
where the scripts d (q), s (c) and ref represent the d-axis (q-axis), the point near the network (the converter valve) and the reference of signals, respectively [3].

Ignoring the losses caused by the switch valves and the converter resistance, there will be

\[ P_{dc} \approx P_c \approx P_s = u_{ds}i_{ds} + u_{qs}i_{qs} \]  \( (2) \)

The primary controllers [3], shown in Figure 3, are designed for power control. The gain tuning of the primary controllers could be determined by frequency responses of closed-loop transfer functions or optimized by other technologies [25]. Both the active power and the reactive power will track their set references by adjusting the current references of the inner controllers. The inner controllers control the currents and produce voltage references for PWM, which is usually considered ideal.

### 2.2 Multi-terminal DC grid modeling

Each VSC in a MTDC grid will connect to other VSCs through several DC lines. The classical pi-equivalent model [26], including the resistance \( R_{line,ij} \), the inductance \( L_{line,ij} \) and the capacitance \( C_{line,ij} \), is implemented for the DC line. The line capacitance \( C_{line,ij} \) and the large capacitance \( C_{dc,i} \), which is usually installed in each VSC, will form the equivalent capacitance \( C_{VSC,i} \) [18]

\[ C_{VSC,i} = C_{dc,i} + \sum_{\sigma_{ij}=1} \sigma_{ij} C_{line,ij} \]  \( (3) \)

where \( \sigma_{ij} \) represents the service flag. If \( \sigma_{ij} = 1 \), the DC line between the \( i^{th} \) DC terminal and \( j^{th} \) DC terminal will be in service, otherwise \( \sigma_{ij} = 0 \).

Considering the dynamic of both the equivalent capacitance \( C_{VSC,i} \) and the line inductance \( L_{line,ij} \), the whole model of a MTDC grid will be presented as

\[
\begin{align*}
\frac{dU_{dc,i}}{dt} &= \frac{P_{dc}}{U_i} - \sum_{\sigma_{ij}=1} \sigma_{ij} L_{line,ij} \\
\frac{dI_{line,ij}}{dt} &= \frac{U_{dc,i}}{2} - \frac{U_{dc,j}}{2} - R_{line,ij}I_{line,ij}
\end{align*}
\]

\( \text{where } U_{dc,i} \text{ is the DC voltage at the } i^{th} \text{ (or } j^{th} \text{) DC terminal.} \)

The dynamics of VSC controllers are usually considered to be faster than the DC voltage dynamics of the connected MTDC grid [21]. Otherwise, the controllers could not regulate the DC voltages of MTDC grids.

### 3 CONTROL SCHEMES

The whole picture of the control scheme, including primary controllers, CVD controllers and proposed flexible controls, is provided in Figure 4. The CVD control is employed widely to regulate DC voltages by producing the active power reference for primary controllers. When there are voltage deviations, CVD controllers will adjust the active power reference according to the predefined droop coefficient \( k_{\text{droop}} \), which can be seen from the steady \( P-V \) curve in Figure 5 (\( P_s \), \( U_{dc} \) and \( k_{\text{droop}} \) represent the active power injection, DC voltage and the droop coefficients, respectively).

To reduce DC voltage deviations caused by disturbances in the CVD control, two flexible controls are proposed in this paper, the GVOD control and the CWV control. Their control schemes are presented in Figure 6.

The weighted voltage \( U_{dc,\text{avg}} \) is a key indicator of both the GVOD control and CWV control. The GVOD control and CWV control will co-ordinately adjust the active power injection of each droop VSC with the scheme...
shown in Figure 6, using the weighted voltage of

$$U_{dc\text{avg}} = \sum_{i \in \Omega_{\text{droop}}} \alpha_i U_{dc}^i.$$  \hspace{1cm} (5)

where $\Omega_{\text{droop}}$ represents the group of all droop VSCs, $U_{dc}^i$ is the DC voltage of the $i$th droop VSC, $\alpha_i \in [0,1]$ is the weighted coefficient, and there will be

$$\sum_{i \in \Omega_{\text{droop}}} \alpha_i = 1.$$  \hspace{1cm} (6)

Note that the weighted voltage is calculated based on only the droop VSCs instead of all VSCs, which requires few signals than the method proposed in ref. [23]. Two factors should be considered in the weighted coefficient selection process. Firstly, the weighted coefficient of the VSCs with strong active power adjust ability could be larger so that the oscillation suppression provided by the GVOD control would be much significant. Secondly, the weighted coefficient of the VSCs with higher importance in the voltage regulation could be larger so that the steady voltage deviations of those VSCs would be smaller.

With the flexible controls shown in Figure 6, the general active power injection of each droop VSC with two flexible controls both can be calculated from

$$P_{ref,s} = P_0^s + \Delta P_{ref,dc}^s + \Delta P_{ref,TV}^s,$$  \hspace{1cm} (7)

where

$$\Delta P_{ref,dc}^s = k_{\text{CVD}} \Delta U_{dc}^s = k_{\text{CVD}} (U_{dc}^{s,0} - U_{dc}^s).$$  \hspace{1cm} (8)

and $\Delta P_{ref,TV}^s$ is the translation value (TV) produced by flexible controls, the GVOD control or the CWV control. Figure 7 shows the schematic diagram for the $P$–$V$ curve translation determined by the flexible controls.

3.1 | The global DC voltage oscillation damping control

Ref. [12] proposed a local voltage oscillation damping control to improve voltage performance. However, it cannot ensure the global stability of the whole MTDC grid. Therefore, a GVOD control is proposed based on Lyapunov theory. Unlike the local voltage oscillation damping control, the proposed GVOD control can enhance the voltage performance and ensure the global stability of the whole MTDC grid.

A compensator between $U_{dc}^{s,0}$ and $U_{dc}^s$ is included to produce the translation value $\Delta P_{ref,GVOD}^s$ for all droop VSCs, which is given as

$$\Delta P_{ref,GVOD}^s = k_{GVOD} (U_{dc}^{s,0} - U_{dc}^s).$$  \hspace{1cm} (9)

where $k_{GVOD}$ is the proportion coefficient of GVOD controllers.

The suggested compensator includes a low pass filter and a washout filter. The former filter is used to eliminate noise from measurements, and the later filter is used to avoid modifying the steady power injections established by the CVD control. The time constants $T_f$ and $T_w$ are tuned based on the principle proposed in ref. [12].

The transient DC voltage deviations will be reduced without damaging the global stability of the whole MTDC grid if the proportion coefficient $k_{GVOD}$ is tuned according to the principle introduced in the next section. The stability influence will be also deduced in detail in the next section.

3.2 | The constant weighted voltage control

Different from the GVOD control, the object of the CWV control is to keep the weighted DC voltage from deviating from its rated value. The control scheme is given in Figure 6(b).

A compensator between $U_{dc}^{s,0}$ and $U_{dc}^s$ is included to produce the translation value $\Delta P_{ref,CWV}^s$ for all droop VSCs, and a PI regulator is applied to eliminate the weighted DC voltage deviation $\Delta U_{dc,CWV}^{s,0}$. The translation value for each droop VSC is given as

$$\Delta P_{ref,CWV}^s = k_{CWV} \left( k_p \Delta U_{dc,CWV}^s + \frac{1}{T} \int \Delta U_{dc,CWV}^s dt \right).$$  \hspace{1cm} (10)
where $k_{CWV}$ is the proportion coefficient of CWV controllers, $k_p$ and $T$ are the proportion coefficient and the integration time coefficient of the PI regulator, respectively. The PI parameters can be tuned based on the closed-loop function method proposed in ref. [25].

Note that an approximation is recommended for constructing the required closed-loop function. For the physical insights, if the DC lines are regarded as ideal, the capacitance $C_{VSC,i}$ at each VSC will operate in parallel. Therefore, an approximation is used to get the transfer function easily. The MTDC grid will be treated as a component installed with an equivalent capacitance $C_{VSC}$. The weighted voltage $U_{dc}^{avg}$ is treated as the voltage of the equivalent capacitance. The dynamic of the equivalent capacitance $C_{VSC}$ is determined by all active power injections, which can be given as:

$$C_{VSC} \frac{dU_{dc}^{avg}}{dt} = \frac{p_0 + \Delta P^{CVD} + \Delta P^{ref,CWV}}{U_{avg}^{ref,dc,0}}. \quad (11)$$

where

$$p_0 \approx \sum_{i \in \Omega_{VSC}} p_{s,i} = \text{cons tan t}$$

$$\Delta U_{dc}^{avg} = U_{avg}^{ref,dc} - U_{dc}^{avg}$$

$$\Delta P^{CVD} \approx - \sum_{i \in \Omega_{loop}} k_{CVD} \Delta U_{avg}^{dc}$$

$$\Delta P^{ref,CWV} = \sum_{i \in \Omega_{loop}} k_{CWV} \left( k_p \Delta U_{avg}^{dc} + \frac{1}{T} \int \Delta U_{avg}^{dc} \, dt \right)$$

Therefore the closed-loop transfer function is expressed as

$$\frac{U_{dc}^{avg}}{U_{avg}^{ref,dc}} \approx \frac{-k_{CVD}^{\Omega} + k_p k_{CWV}^{\Omega}}{C_{VSC} U_{avg}^{ref,dc,0}} T s + 1$$

$$\approx \frac{\left( -k_{CVD}^{\Omega} + k_p k_{CWV}^{\Omega} \right) T s + 1}{C_{VSC} U_{avg}^{ref,dc,0} T s^2 + \left( -k_{CVD}^{\Omega} + k_p k_{CWV}^{\Omega} \right) T s + 1}. \quad (13)$$

where

$$k_{CVD}^{\Omega} = \sum_{i \in \Omega_{VSC}} k_{CVD}^{i}$$

$$k_{CWV}^{\Omega} = \sum_{i \in \Omega_{loop}} k_{CWV}^{i} \quad (14)$$

Evaluating the transfer function in $s = j \omega$ and analyzing the frequency response of the transfer function, the PI parameters can be tuned with the bode plot.

Note that the steady active power injections will keep almost unchanged under the CWV control when compared with those under the CVD control as if the proportion coefficient $k_{CWV}$ is tuned according to the principle introduced in the next section.

4 | STABILITY ANALYSIS AND POWER FLOW IMPACT ANALYSIS

The MTDC is used for the integration of renewable energy or the interconnection between different AC systems. The impact of proposed controls on the stability of the system and the impact on the DC power flow are the major concerns from the system operators’ perspective.

The Lyapunov theory based stability analysis and DC power flow analysis will be carried out in this section to evaluate the proposed controls theoretically. The coordinated principles of selecting the major coefficients $k_{CVD}$ and $k_{CWV}$ are both explained as well.

4.1 | Stability analysis

4.1.1 | The global DC voltage oscillation damping control

The GVOD control focuses on the transient voltage deviation reduction and has a significant influence on the MTDC grid’s stability. To maintain the global stability of the whole MTDC grid, Lyapunov theory was used in the control design.

This methodology has been widely used to derive suitable flexible controls for transient stability improvements [27,28]. In Lyapunov theory, a control Lyapunov function (CLF) $E(x,u)$ is used to evaluate the stability of a control system. That is, for any state $x$, we can find a control vector $u(x)$ such that the nonlinear system $x = f(x) + g(x)u$ can be brought back to its original state by applying a control vector $u(x)$. The time derivative of the CLF, which can be derived from the following equation, consists of the controlled part $E(x,u)_{\text{ctrl}}$ and the uncontrolled part $E(x,u)_{\text{unctrl}}$.

$$\dot{E}(x,u) = L_x E(x,u) = \nabla E(x,u) f(x) + \nabla E(x,u) g(x) u$$

$$= \dot{E}(x,u)_{\text{ctrl}} + \dot{E}(x,u)_{\text{unctrl}}.$$ \quad (15)

The original uncontrolled system is stable if

$$\dot{E}(x,u)_{\text{unctrl}} \leq 0. \quad (16)$$

To make a CLF, one needs to find the control vector $u(x)$ such that $E(x,u)$ is negative definite or at least negative semi definite.

An approximation was adopted in the process to make a CLF. In general, the active power modulation process is enough faster than the voltage regulation process so that the active power on the DC side $P^{dc}$ will be equal to $P^{ref}$. This means...
that the dynamic of the active power modulation process can be neglected. The approximation is acceptable, and the voltage improvement is validated in the time-domain simulation. The approximate system is given as

\[
C_{\text{VSC,i}} \frac{dU_{\text{dc}}^i}{dt} = \frac{p_{\text{dc}}^i}{U_{\text{dc}}^i} - \sum_{j=1}^{n} \sigma_{ij} I_{\text{line},ij} = \frac{p_{\text{dc}}^i}{U_{\text{dc}}^i} - \sum_{j=1}^{n} \sigma_{ij} I_{\text{line},ij}
\]

\[
= P_{\text{dc}}^i + \Delta P_{\text{dc}}^\text{GVOD} + \Delta P_{\text{dc}}^\text{CVD} - \sum_{j=1}^{n} \sigma_{ij} I_{\text{line},ij}
\]

\[
\frac{dI_{\text{line},ij}}{dt} = \frac{U_{\text{dc}}^i P_{\text{dc}}^i}{2} - \frac{U_{\text{dc}}^i}{2} - R_{\text{line},ij} I_{\text{line},ij}
\]

(17)

\( \Delta P_{\text{dc}}^\text{GVOD} \) is controllable in the approximate system. Note that, \( \Delta P_{\text{dc}}^\text{CVD} \) is equal to zero for the VSCs which adopt the constant power control.

The system energy is usually treated mathematically by the CLF [27,29]. Therefore, \( E(x,u) \) can be written as:

\[
E(x,u) = \sum_{i=1}^{n} \frac{1}{2} C_{\text{VSC,i}} (U_{\text{dc}}^i)^2 + \sum_{j=1}^{n} \frac{1}{2} \sigma_{ij} I_{\text{line},ij}^2.
\]

(18)

Thus

\[
\dot{E}(x,u)_{\text{ctrl}} = \nabla E(x,u) \dot{g}(x,u) = \sum_{i \in \Omega_{\text{droop}}} C_{\text{VSC,i}} U_{\text{dc}}^i \frac{1}{C_{\text{VSC,i}}} U_{\text{dc}}^i \Delta P_{P_{\text{dc}}^i}^\text{GVOD}
\]

\[
= \sum_{i \in \Omega_{\text{droop}}} \Delta P_{P_{\text{dc}}^i}^\text{GVOD}
\]

\[
= \sum_{i \in \Omega_{\text{droop}}} k_{P_{\text{dc}}^i}^\text{GVOD} (U_{\text{avg}}^i - U_{dc}^i).
\]

(19)

A constructive proof is given as follows. If the proportion coefficient of the GVOD controllers and the weighted coefficients verify the following Equation (20),

\[
k_{P_{\text{dc}}^i}^\text{GVOD} \frac{\alpha_1}{\alpha_2} = \frac{\alpha_2}{\alpha_3} = \cdots = \frac{\alpha_j}{\alpha_j}.
\]

(20)

The follow equation will be true:

\[
\dot{E}(x,u)_{\text{ctrl}} = 0.
\]

(21)

Therefore, the time derivative of the CLF can be given as:

\[
\dot{E}(x,u) = \dot{E}(x,u)_{\text{unctrl}} + \dot{E}(x,u)_{\text{ctrl}} \leq 0.
\]

(22)

This means that the GVOD control can simultaneously improve voltage performance and guarantee the global stability of the MTDC grid. Note that the ratio between the proportion coefficient of the GVOD controllers and weighted coefficients could be further optimized based on the control effect or various optimization technologies.

4.1.2 | The constant weighted voltage control

The above methodology may not be suitable for the CWV control design because of the difficulty of building a workable CLF. The stability impact of the CWV control will be tested by the time domain simulation only.

4.2 | Power flow impact analysis

The proposed flexible controls will affect the DC power flow of the MTDC grid in the steady state as well as during the transient period.

4.2.1 | The global DC voltage oscillation damping control

The GVOD control changes the DC power flow during the transient period to improve the voltage performance. The droop VSC stations near the disturbance sources will adjust their active power injections much more significantly. The suppression impact on the transient voltage deviation will be enhanced with bigger coefficients. Note that overlarge coefficients \( k_{P_{\text{dc}}^i}^{\text{CWV}} \) may lead to the over-modulation and the active power constraints of droop VSC stations may be violated in some cases.

The washout filter added in the GVOD control avoids the adjustment in the steady state. As a result, the steady active power injections established by the CVD control will not be modified by the GVOD control.

4.2.2 | The constant weighted voltage control

The CWV control is designed to reduce the steady weighted voltage deviations. When the operators active the CWV control in all droop VSC stations, each droop VSC station responds to both the voltage deviation in its terminal and the weighted voltage deviation of the whole MTDC grid. The steady active power injection in the CVD control and CWV control can be given as

\[
P_{P_{\text{dc}}^i}^{\text{CVD}} = P_{P_{\text{dc}}^i}^0 + k_{P_{\text{dc}}^i}^{\text{CVD}} (U_{\text{dc}}^i - U_{\text{avg}}^i),
\]

(23)

\[
P_{P_{\text{dc}}^i}^{\text{CWV}} = P_{P_{\text{dc}}^i}^0 + k_{P_{\text{dc}}^i}^{\text{CWV}} (U_{\text{dc}}^i - U_{\text{avg}}^i) + \Delta P_{P_{\text{dc}}^i}^{\text{ref,CWV}}
\]

\[
+ k_{P_{\text{dc}}^i}^{\text{CWV}} [(U_{\text{avg}}^i - U_{\text{avg}}^i)^2 U_{\text{avg}}^i] dt + \frac{1}{T} \int (U_{\text{avg}}^i - U_{\text{avg}}^i) dt
\]

(24)
The translation value $P_{i, \text{ref}, \text{CWV}}^\text{ref}$ will simultaneously determine the weighted voltage change $U_{\text{avg}}^{\text{dc}}$ and the VSC voltage change $U_i^{\text{dc}}$. In the same MTDC grid, $U_{\text{avg}}^{\text{dc}}$ increases or decreases under disturbances, and $U_i^{\text{dc}}$ will change in the same direction accordingly. Generally, the following will be true in the steady state:

$$U_i^{\text{dc,CWV}} - U_i^{\text{dc,CVD}} \approx U_{\text{avg}}^{\text{dc,CWV}} - U_{\text{avg}}^{\text{dc,CVD}}. \quad (25)$$

If the coefficients $k_i^{\text{CWV}}$ are set as proportional to the droop coefficients $k_i^{\text{CVD}}$, which means that

$$k_i^{\text{CWV}} = \frac{k_i^{\text{CWV}}}{k_i^{\text{CVD}}} = \cdots = \frac{k_i^{\text{CWV}}}{k_i^{\text{CVD}}}. \quad (26)$$

the sum of the droop value $\Delta P_i^{\text{ref,dc}}$ and the translation value $\Delta U_i^{\text{ref,dc}}$ will remain almost unchanged. As a result, the following will be true in the steady state:

$$P_i^{\text{ref,CWV}} \approx P_i^{\text{ref,CVD}}. \quad (27)$$

This means that if the coefficients $k_i^{\text{CWV}}$ are set according to the above principle (26), the CWV control can reduce the steady weighted voltage deviation without bringing obvious changes to the steady active power injections when compared with those under the CVD control. Note that the ratio between the proportion coefficients of CWV controllers and the droop coefficients of CVD controllers could be further optimized based on the control effect or various optimization technologies.

### 4.3 Comparison of the two controls

There are some similarities and differences between the two flexible controls. The GVOD control reduces the transient voltage deviation steadily while the CWV control focuses on steady voltage deviation reduction. When the flexible controls realize their control objects, the steady active power injections of droop VSCs under different flexible controls will have very little change. This means that the flexible controls will not influence the steady active power injections determined by the CVD control.

The stability of the GVOD control can be supported by the Lyapunov theory while the stability of the CWV control is verified through the simulations. The simulations also show that both two flexible controls can still work to regulate the DC voltage whatever the fault VSC is a droop VSC or not.

The GVOD control is recommended when the MTDC grid is connected to strong AC grids because the control object is characterized by the fast active power modulation during the fast transient period. The CWV control is appropriate for solving the problems caused by steady voltage deviations, such as the active power transfer limitation for the renewable power generation or interconnected AC grids.

### 5 SIMULATION

The study system was designed based on the topology proposed in ref. [1]. The study meshed MTDC grid consists of five-terminal VSCs, which are shown in Figure 8.

Table 1 shows the circuit parameters, and Table 2 presents the initial operating conditions. The droop coefficients are reset considering the initial operating condition and the available headroom of each VSC. The weighted coefficients $\alpha$ are set as

**TABLE 1** The circuit parameters

| Parameters | Value | Parameters | Value |
|------------|-------|------------|-------|
| Converter resistance ($\Omega$) | 0.200 | Dc line resistance ($\Omega$ km$^{-1}$) | 0.015 |
| Converter inductance (H) | 0.072 | Dc line capacity ($\mu$F km$^{-1}$) | 0.260 |
| Parallel DC side capacitor ($\mu$F) | 400.0 | Dc line inductance ($\mu$H km$^{-1}$) | 0.298 |

**TABLE 2** The initial operating conditions

| Control mode | VSC1 | VSC2 | VSC3 | VSC4 | VSC5 |
|--------------|------|------|------|------|------|
| $P_i^{\text{CVD}}$ (MW kV$^{-1}$) | 15.00 | 12.50 | 10.00 | 0.00 |
| $P_i^0$ (MW) | 480.00 | 400.00 | 450.00 | 148.75 | 400.00 |
| $U_i^{\text{dc,0}}$ (kV) | 400.00 | 400.00 | 400.00 | 400.00 | 400.00 |
| $P_i/U_i^{\text{dc}}$ (MW) | 475.62 | 400.00 | 447.62 | 143.949 | 400.00 |
| $U_i^{\text{dc}}$ (kV) | 399.71 | 405.57 | 399.76 | 400.47 | 405.66 |
1/3 for simplicity, and the coefficients $k^{GVOD}$ and $k^{CWV}$ are set as 10 and 100, respectively. The PI parameters for the outer controller and the inner controller of the VSCs are tuned by means of the frequency response of closed loop transfer functions [25].

Time domain simulations, considering the outage of a constant power VSC and the outage of a droop VSC, are carried out using the PSCAD/EMTP software. Four different control groups, named 1) without flexible controls, 2) with the GVOD control, 3) with the CWV control and 4) with both the GVOD control and the CWV control, are compared to show the effectiveness and superiority of the proposed flexible controls.

### 5.1 Outage of a constant power voltage source converter

The outage of a constant power VSC is one of the typical serious fault conditions representing the cases where the wind farms are unavailable. Assume that the constant power VSC2 is lost at $t = 3$ s in the simulation. The faulty converter VSC2 is close to VSC1 but relatively far from VSC3. Figure 9 shows the active power injection of VSC1 and VSC3. It is clearly seen that $P_{s,1}$ increases much more quickly in the first 0.1s to support the DC voltage of VSC1 as long as there are proposed controls. The behaviour of $P_{s,3}$ is similar. However, when only the GVOD control is active, $P_{s,3}$ will slow down its increment speed to guarantee MTDC grids’ stability. Note that the steady active powers keep almost the same whatever the flexible controls are active or not.

The voltage of VSC1, which is most affected by the outage of VSC2, is showed in Figure 10. Clearly, the transient DC voltage deviation of VSC1 is decreased under the flexible controls. The max DC voltage deviations of VSC1 in the first 0.1s with four control groups are 12.46, 10.02, 4.59 and 3.53 kV, respectively. The transient voltage deviation reduction and the steady DC voltage deviation reduction of VSC1 are 8.93 and 10.5 kV, respectively. The response of VSC3 is also shown in Figure 10, which is consistent with that of VSC1. Table 3 presents more details about the voltage deviations of all VSCs after the outage of VSC2, including max transient voltages in 0.1 s, steady voltages, max transient voltage deviations, and steady voltage deviations.

### 5.2 Outage of a droop voltage source converter

The outage of the droop VSC is another typical serious fault condition, which may happen when its connected AC grid is unavailable. Note that a correction method will be added in the GVOD control. When the fault happens in a droop VSC, the voltage of the fault VSC will be removed in the calculation of the weighted voltage $U_{dc}^{avg}$.

In this simulation, we assumed that at $t = 3$ s, the droop VSC1 is lost. Figure 11 shows the active power injections of the remaining droop VSCs under four different control groups. When the GVOD control is active, $P_{s,3}$ (in red and blue line) decreases much more significantly in the first 0.1s than that (in black and green line) without GVOD control. $P_{s,4}$ behaves in the opposite way to avoid increasing the net injection power continuously and guarantee the stability of the MTDC grids. When the CWV control is active, the adjustment $P_{s,3}$ and $P_{s,4}$ (in green and blue line) will be dependent on the deviation of the weight voltage $U_{dc}^{avg}$. Note that the steady active powers keep almost same whatever the flexible controls are active or not.

The voltage of VSC3, which is most affected by the outage of VSC1, is showed in Figure 12. The maximum DC voltage deviations of VSC3 in the first 0.1 s with four control groups are 20.04, 16.03, 9.59 and 7.71 kV, respectively. The transient voltage deviation reduction and the steady DC voltage deviation reduction of VSC3 are 8.31 and 33.0 kV, respectively. The response of VSC 4 is also shown in Figure 12, which is consistent with that of VSC 3. Different from the outage of VSC2, when the droop VSC1 is lost, there are only two remaining droop VSCs, VSC3 and VSC4. Apart from the power unbalance, the ability to regulate the DC voltage will be weakened as well. The DC voltage fluctuations are much more significant in the first 0.1 s, and the duration of the transient periods increases from 300 to 500 ms.
More details about the voltage deviations of all VSCs after the outage of VSC1 are listed in the Table 4, including max transient voltages in 0.1 s, steady voltages, max transient voltages deviations and steady voltage deviations.

### 5.3 Interaction analysis

Although the two flexible controls are employed in different time scales, they interact with each other when they are active together. The GVOD control works during the first 0.1 s to reduce the transient voltage deviations. Figure 13 presents the influence of the CWV control on the GVOD control. If the CWV control is active, the transient voltage deviations will be reduced a few by the CWV control, so the max translation value of VSC1 produced by the GVOD control decreases from 244 to 190 MW.

To the contrary, the influence of the GVOD control on the CWV control is insignificant. Figure 14 shows the translation value of VSC1 produced by the CWV control. The bias between two curves is very little. This can be explained that the GVOD control does not influence to the deviation of the weighted voltage, which can be seen in Figure 15.

### 6 CONCLUSION

Two new flexible controls for DC voltage control in MTDC grids have been proposed to reduce voltage deviations,
TABLE 4 Voltage deviations after an outage of a droop VSC

| Converter          | VSC1    | VSC2    | VSC3    | VSC4    | VSC5    |
|--------------------|---------|---------|---------|---------|---------|
| Initial voltage (kV) | 399.71  | 405.57  | 399.76  | 400.47  | 405.66  |
| Max transient voltages (kV) | CVD     | 419.86  | 425.95  | 419.80  | 418.77  | 423.54 |
|                    | GVOD    | 417.70  | 423.10  | 415.79  | 415.92  | 420.62 |
|                    | CWV     | 411.54  | 417.35  | 409.35  | 404.41  | 414.15 |
|                    | GVOD&CWV| 411.55  | 416.85  | 407.47  | 404.23  | 412.60 |
| Steady voltages (kV) | CVD     | 434.35  | 439.81  | 433.22  | 432.84  | 438.59 |
|                    | GVOD    | 434.44  | 439.90  | 433.07  | 432.91  | 438.51 |
|                    | CWV     | 401.42  | 407.44  | 400.07  | 399.76  | 406.00 |
|                    | GVOD&CWV| 401.59  | 407.35  | 400.16  | 399.92  | 406.00 |
| Transient voltages deviations (kV) | CVD     | 20.15   | 20.38   | 20.04   | 18.30   | 17.88  |
|                    | GVOD    | 17.99   | 17.53   | 16.03   | 15.45   | 14.96  |
|                    | CWV     | 11.83   | 11.78   | 9.59    | 3.94    | 8.49   |
|                    | GVOD&CWV| 11.84   | 11.28   | 7.71    | 3.76    | 6.94   |
| Steady voltage deviations (kV) | CVD     | 3.64    | 3.42    | 3.46    | 3.27    | 3.93   |
|                    | GVOD    | 3.73    | 3.33    | 3.31    | 3.44    | 3.85   |
|                    | CWV     | 1.71    | 1.87    | 0.31    | −0.71   | 0.34   |
|                    | GVOD&CWV| 1.88    | 1.78    | 0.40    | −0.55   | 0.34   |

FIGURE 13 The influence of the constant weighted voltage control on the global DC voltage oscillation damping control

including the transient voltage deviations and the steady voltage deviations.

Different severe faults, including the outage of a constant power VSC and the outage of a droop VSC, were tested under four flexible control groups. The transient and steady voltage deviations were reduced significantly by the proposed controls. The power flow impact was carried out, and the steady active power injections kept almost the same whatever the flexible controls are active or not. The interactions between two flexible controls were investigated as well.

The voltage performances in simulations showed the effectiveness and superiority in reducing DC voltage deviations. The simulation results also indicated that the transient voltage deviations would be reduced slightly by the CWV control, and so the max translation value produced by the GVOD control would decrease. To the contrary, the influence of the GVOD control on the CWV control is insignificant.

It would be interesting to consider the dynamic behaviours of the connected AC grids in system modeling. The interaction analysis between the proposed flexible control and other supplementary control for AC grids, such as oscillation suppression and frequency support, could be carried out. Further research could also be conducted to optimize relevant control parameters further.
FIGURE 15  Weighted voltage after the outage of VSC2

ACKNOWLEDGEMENTS
This work was supported by the National Key Research and Development Program of China under Grant 2016YFB0900600.

ORCID
Guibang Wu  https://orcid.org/0000-0001-7482-8394

REFERENCES
1. Xiao, L., et al.: Improved analytical model for the study of steady state performance of droop-controlled VSC-MTDC systems. IEEE Trans. Power Syst. 32, 2083–2093 (2017)
2. Stamatiou, G., Bongiorno, M.: Power-dependent droop-based control strategy for multi-terminal HVDC transmission grids. IET Generation, Transmission & Distribution 11(2), 383–391 (2017)
3. Wu, G., et al.: VSC-MTDC operation adjustments for damping inter-area oscillations. IEEE Trans. Power Syst. 34, 1373–1382 (2019)
4. Fu, J., et al.: Flexible controls to reduce DC voltage deviations in MTDC grids. IET Gener. Transm Distrib. 15, 1830–1840 (2021)

How to cite this article: Wu G, Du Z, Zhao Y, Li G. Flexible controls to reduce DC voltage deviations in MTDC grids. IET Gener. Transm Distrib. 2021;15:1830–1840. https://doi.org/10.1049/gtd2.12138