Adaptive Droop Control for Compromise Between DC Voltage and Frequency in Multi-Terminal HVDC

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ABSTRACT By connecting many wind farms and grids via multi-terminal high-voltage direct current transmission (MT-HVDC), the reserve power of each grid can be shared to balance the power mismatch. Resulting from a shortage of generated power, the frequency nadir and the lowest DC voltage may violate the constraints of continuous operation. Using a trade-off, this paper proposes a new control strategy based on adaptive droop control to make a compromise between DC voltage and grid frequency. By applying the proposed method, the demands from both sides are efficiently met. The proposed method relies on a decentralized approach, avoiding dependence on the communication link. In addition, wind farms are allowable to operate at the optimal power point without using a de-loading strategy. Time-domain simulations are conducted in PSCAD. The improvement in system reliability is proved by comparing with existing methods.

INDEX TERMS Adaptive control, HVDC transmission, power system reliability.

I. INTRODUCTION

High-voltage direct current transmission (HVDC) is a well-known method of transmitting high power (>500 MW) over long distances (hundreds of kilometers). Nowadays, voltage source converters (VSCs) are becoming popular in HVDC plans owing to bi-directional transmission as well as active and reactive power decoupling control. To reduce emissions, numerous VSC-based HVDC projects have been commissioned and planned worldwide to transmit a large amount of power from renewable energy sources (RES) to load centers. At present, almost all existing and planned HVDC transmission systems are point-to-point schemes. As these systems increase in number, keeping the historical development of AC networks in mind, a transition from point-to-point systems to multi-terminal systems is expected, either at the design stage or at the time of new connections [1]. Expanding to multi-terminal HVDC (MT-HVDC) actually increases the geographical distribution of wind power, reducing variability and increasing the predictability of wind power [2]. Moreover, by sharing reserve power among different synchronous grids via MT-HVDC, the net amount for balancing power can be minimized [3]. This is a promising solution that allows the massive integration of renewable energy resources [4].

High penetration of converter-based RES might level down power system inertia, which leads to issues such as low frequency nadir and low transient stability. Frequency support from grid-connected converters has become a topic of interest because of the fast development of renewable energy [5]–[7]. In general, the power sources to balance the generation mismatch may come from DC capacitors, de-loading operation of RES (also known as de-rated or sub-optimal operation), and energy storages [8], [9].

Similar to other converter-based generators, the frequency support from a converter terminal in an MT-HVDC system may also be realized [10]–[13]. In addition, by connecting many AC grids via an MT-HVDC system, the reserve power from other synchronous grids may also be deployed, providing an efficient way to stabilize system frequency. Upon a frequency contingency in a specific grid, the connected HVDC terminal quickly mitigates the mismatch using energy from the DC capacitor, which causes DC voltage variation. Then, this variation of DC voltage is used as a signal to trigger power support from other synchronous grids. This forms a sequence of actions that allows asynchronous grids to share supporting power with each other.
To enable power sharing, it is vital to investigate DC voltage control strategies. An overview of the basic strategies, including master-slave control (DC slack), voltage margin control, and droop control, has been provided [14]. Accordingly, for master-slave control, a master converter is selected and is responsible for controlling the voltage; thus, the master converter should connect to a significantly robust grid. The voltage margin control is the master-slave control, but a second converter can take over the role of DC voltage regulation immediately if the master converter goes off-line or reaches its power limit. For DC voltage droop control, many converters regulate system voltage similarly to power-frequency droop control in AC systems. Because the regulation responsibility is shared among many terminals in the DC grid, the DC voltage droop control is thus preferred due to its high reliability. However, this causes frequency variation in all AC grids since they provide power to the DC system. In DC voltage droop control, the droop gain can determine the sharing percentage among terminals during the transient period, and maintaining that sharing ratio may cause low frequency nadir. Consequently, the grid code for frequency may be violated in a low-inertia power system [15].

Adaptive droop control is a control method that updates droop coefficients based on the current situation. It has been adopted to address several technical issues, such as optimizing cost [16] or power flow accuracy [17], [18]. Adaptive droop control has also been adopted to improve transient responses. To deal with contingencies, most of the existing methods follow the communication-free approach where droop coefficients are calculated locally without dependence on updating from a higher level. Because of latency or losing communication links, relying on communication links may become too late to take actions. The relationship between the maximum allowed support power and maximum allowed DC voltage deviation is established by fuzzy logic [19]. This method can be implemented on the local control level where only local measurements are needed. In a similar approach to limit power deviation and DC voltage deviation, [20]–[22] proposed new techniques to set up the link between those two signals for the adaptive laws. However, limiting the maximum allowed support power does not ensure a frequency nadir within the frequency standard since the inertia constants, droop gains, dead bands, and ramp rates of generators in that grid substantially affect the frequency nadir [23]. In [24]–[26], droop gain is adaptively changed by the margin to frequency limit, which protects the supporting grid’s frequency from violating the frequency standard. However, the condition of DC voltage is neglected in these papers, which may pose instability to the system.

This paper proposes a method to efficiently re-distribute supporting power during the transient time and maintain both frequency and DC voltage within their limits predefined by the operators of AC and DC grids. While the existing methods considered either frequency or DC voltage, the proposed method has a novel approach to practically establish a relationship between the two variables. The adaptive law established by this method can update the droop coefficient to search for an operating point where the requirements of both sides’ operators can be fulfilled. Adaptive droop control is adopted at the local level (decentralized approach) to avoid dependence on the communication link. This paper also points out the unstable possibility of the frequency margin approach. Therefore, the proposed method provides the exit paths returning to the scheduled droop gain to avoid instability during the transient time and maintain the scheduled sharing ratio at the steady state. The proposed method is then validated through simulation and compared with existing methods.

II. MT-HVDC SYSTEM DESCRIPTION

The system under study consists of a DC grid, onshore AC grids, offshore wind farms, and the VSCs, as shown in Fig. 11.1 The wind farm side converters (WFCs) act as power sources that inputs power into the DC grid, and the grid side converters (GSCs) act as loads converting DC to AC. In this HVDC scheme, the WFCs inject all available power of wind farms into the DC grid, i.e., they operate at the maximum power point (MPP). Wind power fluctuation causes the DC voltage variation; thus, the GSCs share the responsibility to regulate DC voltage via droop control. Fig. 2(a) shows the P-Vdc characteristic of a WFC. Theoretically, wind farms can provide support power via de-loading control. However, considering the uncertainty of wind power, in this paper, wind farms do not provide any contribution in regulating DC voltage.

A. VOLTAGE SOURCE CONVERTERS (VSCS)

For the control of a VSC, a synchronous dq-frame is employed as shown in Fig. 3. Three-phase voltage \(v_{abc}\) and current \(i_{abc}\) measured at the point of coupling are transformed to \(dq\)-axis with the synchronized angle from a phase-locked-loop (PLL) block. The alignment between \(a\)-phase and \(q\)-axis is performed to keep the value on \(d\)-axis positive, and the value on \(q\)-axis approximates to zero.

The active power that a GSC injects into the connected AC grid is expressed as:

\[
P_{ac} = \frac{3}{2} \left( v_d i_d + v_q i_q \right) \approx \frac{3}{2} v_d i_d \tag{1}
\]
FIGURE 2. Control mode of terminals in a HVDC system: (a) Constant power control for WFC, (b) DC voltage droop control for GSC, (c) Frequency droop control for GSC, (d) Adaptive DC voltage droop control for GSC.

FIGURE 3. Control of a GSC.

The current reference $i_d^*$ is expressed as:

$$i_d^* = P_{ac}^* + \frac{\Delta P_{support}}{2V_d}$$  \hspace{1cm} (2)

where $\Delta P_{support}$ is the supporting amount to the DC voltage ($\Delta P_V$) or to the grid frequency ($\Delta P_f$).

DC voltage variation within a limited range is required for the normal operation of the converters. Hence, the GSCs are equipped with DC voltage droop control to shoulder a certain amount of unbalanced power following a contingency. The support amount for DC voltage $\Delta P_V$ is expressed as follows:

$$\Delta P_V = K_V (V_{dc} - V_{dc}^*)$$  \hspace{1cm} (3)

where $K_V$ is DC droop gain of the GSC. Fig. 2(b) illustrates the P-Vdc characteristic described in (3).

The connected AC grid may require GSCs to provide frequency support. A control loop that combines both virtual inertia and droop control is adopted:

$$\Delta P_f = k_f D (f^* - f) - k_f \frac{df}{dt}$$  \hspace{1cm} (4)

where $k_f D$ and $k_f$ are the frequency droop gain and the virtual inertia, respectively. Fig. 2(c) illustrates the P-f characteristic of the frequency droop control.

B. ONSHORE AC GRID MODEL

An onshore grid is simulated as parallel synchronous generators equipped with turbines and governors connected to a constant power load. For frequency dynamic study, the aggregated inertia of a grid is an important parameter. As reported in [27], [28], by increasing RES penetration and retiring conventional power plants, the effective rotational inertia that resists frequency deviations will be decreased. Hence, in the simulation model, the inertia constant of a grid can be chosen regarding the penetration ratio.

C. SEQUENCE OF ACTIONS

To understand the sequence of actions in power sharing, a general MT-HVDC system with $m$ terminals of WFC and $n$ terminals of GSC is investigated. The power mismatch in the whole system may come from a frequency disturbance (e.g., generator unit outage, sudden change of load power) or wind power variation (e.g., power fluctuation, partly/total outage of a wind farm). In this study, the low frequency and low DC voltage are mainly concentrated because the excess power produced can be cut down effectively. Meanwhile, the shortage of generated power causes the majority of instability cases and imposes many mechanical constraints.

For a frequency disturbance that occurs in Grid $i$, the under-frequency situation can be expressed according to the following swing equation:

$$\frac{2H_i}{f_0} \frac{df}{dt} = P_{gen} - P_{load} = (P_{SG_i} + P_{GSC_i}) - P_{L_i}$$  \hspace{1cm} (5)

where $P_{SG_i}$ indicates the total generation from synchronous generators in Grid $i$; $P_{GSC_i}$ indicates the generation from connected HVDC terminal; $P_{L_i}$ indicates the load amount.

With the decrease of $P_{SG_i}$ due to generator unit outage or increase of $P_{L_i}$ due to a sudden increase in load, the rate of change of frequency (RoCoF) becomes negative, indicating that Grid $i$'s frequency has started to decrease. The frequency drop triggers the connected converter GSC$_i$ to switch from DC voltage droop to frequency supporting. As described in equation (4) and Fig. 2(b), GSC$_i$ withdraws more power from the DC grid to support the AC grid.

DC voltage dynamics when GSC$_i$ raises the support for Grid $i$ is approximated as follows:

$$CV_{dc} \frac{dV_{dc}}{dt} = \sum_{k=1}^{m} P_{WFC_k} - \sum_{j=1}^{n} P_{GSC_j}$$
A shortage of wind power causes low DC voltage. All connected grids can share the shortage power via DC droop control, as expressed above. As before, a low frequency nadir may appear in all supporting grids.

To put it simply, maintaining higher DC voltage requires lowering the frequencies of supporting grids. However, protecting the grids from UFLS may cause the DC voltage to drop too low. Thus, instead of being a fixed value, adaptive control methods have been adopted to provide better performance.

D. THE CONSTRAINTS OF THE SYSTEM

Constraints of the system that should be considered are frequency nadir (AC side) and lowest DC voltage (DC side). During normal operation, the frequency might be maintained above the shedding threshold $f_{limit}$, which is predefined by the AC grid operator. On the DC side, the lowest DC voltage constraint $V_{limit}$ is considered due to the modulation limit of the connected converters [30], [31].

In this study, AC grids have a nominal frequency value of 60Hz, and the UFLS is triggered if the frequency drops lower than 59.5Hz. On the ±250kV DC system, the constraint for DC voltage is set at 5% of the nominal pole-to-pole value of 500kV. During the operation time, GSCs with droop control are expected to maintain their DC voltages and grid frequencies within these constraints.

III. ADAPTIVE DROOP STRATEGIES

Adaptive droop control is a control strategy where the droop gain is adaptively adjusted to perform better with the system’s dynamics. Fig. 2(d) illustrates the DC voltage adaptive droop method in [19] is preferred due to its flexibility in setting the adjustment rule.

A. LIMITING DC VOLTAGE AND POWER DEVIATION

By considering maximum allowed power deviation and maximum allowed DC voltage deviation, the control strategies proposed in [19], [20] are expected to maintain both DC voltage and power deviation within the limit. The fuzzy-based method in [19] is preferred due to its flexibility in setting the adjustment rule.

As shown in Fig. 4, input signals of the fuzzy block are voltage deviation ($\Delta V_{dc} = V_{dc} - V_{dc}^*$) and power deviation ($\Delta P_{ac} = P_{ac} - P_{ac}^*$). And DC droop coefficient is the output variable. With the predefined allowed voltage deviation and allowed power deviation, the membership functions are built for the two input variables, as shown in Fig. 5. The logic behind the updating rule is shown in Table 1.

It shows the relationship between input variables and output variable such that: as $\Delta V_{dc}$ decreases from zero (Z) to negative-large (NL), the droop coefficient increases to recover the DC voltage; and as $\Delta P_{ac}$ decreases from...
Z to NL, the droop coefficient decreases to avoid violating the frequency nadir constraint.

The defuzzification process using center of gravity is applied according to the output membership function shown in Fig. 6 to achieve the adaptive droop coefficient.

Since the physical constraints of generation units (such as droop gain, ramp rate, dead band) and inertia of the system cause strong effects on the frequency control performance, limiting power deviation may not ensure frequency nadir from dropping lower than 59.5 Hz, which is defined as the UFLS threshold. Moreover, because this is the primary control, $\Delta V_{dc}$ and $\Delta P_{ac}$ are different from zero at the steady state. Therefore, the droop gains will not be returned to the initial values, according to Table 1.

### TABLE 1. Rules for droop coefficient adjustment.

| Droop coefficient | Voltage deviation $\Delta V_{dc}$ | Power deviation $\Delta P_{ac}$ |
|-------------------|----------------------------------|---------------------------------|
|                   | NL | NS | Z | PS | PL |
| Power deviation   | NL | M  | LM | L  | M  | M  |
|                   | NS | HM | M  | LM | M  | M  |
|                   | Z  | H  | HM | M  | HM | H  |
| PS                | M  | M  | M  | M  | PL |
| PL                | M  | M  | M  | M  | M  | M  |

**B. FREQUENCY MARGIN**

The idea of adaptive droop control using the frequency margin has been realized in [24], [25]. The frequency of an AC grid is continuously detected by measuring [24] or estimated from collecting the parameters of the on-line generators in the system [25]. The margin showing the distance from frequency at the moment to the predefined frequency limit is then calculated as follows:

$$M_f = 1 - \frac{|\Delta f|}{\Delta f_{max}}$$

(11)

It can be seen that as the frequency approaches the predefined limit, the frequency margin $M_f$ decreases to zero. To prevent frequency from exceeding the limit, the adaptive rule is defined as follow:

$$K'_V = \beta_f M_f K^o_V$$

(12)

where $\beta_f$ is a sensitivity coefficient that indicates the slope of adaptive droop characteristic.

By using this rule, the method aims to increase the support amount to the DC grid when the margin is still significant and reduce the support amount to zero when the frequency reaches its limit. Frequency is thus efficiently protected from violating the AC side constraint. However, it is foreseen that $K'_V$ always jumps to the maximum value at the beginning of the disturbance and decreases to zero as $\Delta f$ approaches $\Delta f_{max}$. This makes the support power unnecessarily high initially, and thus, the frequency drops rapidly toward $f_{limit}$. The GSCs may then refuse to support the DC voltage to protect the grid frequency, leaving the DC voltage unregulated. This may cause instability if the exit of frequency margin control is not available.

**IV. PROPOSED METHOD**

As discussed above, following a shortage of generated power (e.g., outage of a synchronous generator, sudden drop of wind power generation), the reserve power from each connected grid in the MT-HVDC system will share a certain amount to balance the mismatch. Since the sharing mechanism is implemented via DC voltage droop control, the variations will appear at both DC and AC sides, where the DC voltage and...
AC grid frequency constraints may be violated. While the existing approaches on adaptive control only consider either DC voltage or AC frequency, this paper proposes a method that considers both variables to ensure continuous system operation without triggering protection schemes. Fig. 7 shows the structure of the proposed control method, where DC voltage and frequency along with their derivatives are the input signals. With the predefined limits for DC voltage variation \( V_{\text{limit}} \) and frequency nadir \( f_{\text{limit}} \), the proposed method practically sets up the relationship between the two variables directly. The droop gain of each GSC is then updated to search for an operating point that can satisfy the constraints from both DC voltage and frequency.

The proposed adaptive law is shown in the flow chart in Fig. 8. Starting by measuring the frequency \( f \) and DC voltage \( V \), the conditions \( f_{\text{limit}} - f > 0 \) and \( V_{\text{limit}} - V > 0 \) are first checked. If these conditions are true, the two curves are outside the limits, implying that the disturbance is too severe, and further protection schemes are unavoidable. The best solution is to return the droop gain to the initial value (\( K_V^{\text{dc}} \)). Conversely, the RoCoF \( \frac{df}{dt} \) and rate of change of DC voltage \( \frac{dV}{dt} \) are compared with the threshold values \( \varepsilon_f \) and \( \varepsilon_V \) to detect a disturbance in the system.

When \( \frac{df}{dt} < -\varepsilon_f \) and \( \frac{dV}{dt} < -\varepsilon_V \), there is a shortage of generating power in the system, and the negative signs show the slopes of the curves when approaching their limits. If the frequency and DC voltage are still above their limits (\( f_{\text{limit}} - f < 0 \) and \( V_{\text{limit}} - V < 0 \)), the margin time to reach the limits of the two curves can be defined as follows:

\[
\Delta t_f = \frac{f_{\text{limit}} - f}{df/dt}, \quad \Delta t_V = \frac{V_{\text{limit}} - V}{dV/dt}
\]  

The margin time factors are the estimated values showing that if the current droop gain is maintained constant, the time for the frequency reaching \( f_{\text{limit}} \) is \( \Delta t_f \). Similarly, the time for the DC voltage reaching \( V_{\text{limit}} \) is \( \Delta t_V \). Fig. 9 illustrates the estimated time to reach the limit of frequency and DC voltage. By comparing \( \Delta t_f \) with \( \Delta t_V \), we can quickly detect which curve will reach its limit faster.

The \( \alpha \) factor is defined as follows:

\[
\alpha = \Delta t_f - \Delta t_V
\]  

The \( \alpha \) factor shows the comparison in time approaching the limit between DC voltage and frequency. \( \alpha > 0 \) indicates that if we keep the droop coefficient unchanged, \( V_{\text{dc}} \) will approach its limit earlier than \( f \). The available headroom in the AC grid represented by frequency shows that the AC grid still has the ability to support more power to the DC system. Thus, \( V_{\text{dc}} \) becomes the priority, and droop gain needs to be increased to allocate more power to the DC side.

The opposite situation can be seen when \( \alpha < 0; f \) will approach its limit earlier than \( V \) if droop gain is kept constant. Hence, supporting \( f \) is the priority at this moment.

To keep the lowest point of \( V_{\text{dc}} \) and frequency curve within limits, an updating rule using the \( \alpha \) factor for the compromise between DC voltage and frequency can be defined as follows:

\[
K_V' = K_V^0 [1 + \beta \cdot \tanh (\alpha)]
\]  

where \( K_V' \) is the adaptive droop coefficient. The \( \tanh(\alpha) \) function is chosen to scale down the comparison factor \( \alpha \) into \(-1\) to \(+1\).

According to (15), the range of adaptive droop coefficient will be from \( K_V^0(1 - \beta) \) to \( K_V^0(1 + \beta) \). \( \beta \) is selected by considering the available spinning reserve in the grid. In addition, small-signal stability analysis may also be conducted to ensure the damping of the system.

It can be seen that when \( \alpha > 0, K_V' > K_V^0 \) indicates the increase of support for \( V \). By contrast, when \( \alpha < 0, K_V' < K_V^0 \) indicates the decrease of support for \( V \).

In case \( f_{\text{limit}} - f > 0 \) and \( V_{\text{limit}} - V < 0 \), the adaptive coefficient will be set to the minimum value, which is \( K_V^0(1 - \beta) \) with the objective of protecting frequency.

In case \( f_{\text{limit}} - f < 0 \) and \( V_{\text{limit}} - V > 0 \), the adaptive coefficient will be set to the maximum value, which is \( K_V^0(1 + \beta) \) with the objective of protecting DC voltage.

In case \( \frac{df}{dt} < \varepsilon_f \), this condition may indicate a frequency nadir or steady state. If it is a frequency nadir, the previous adaptive value will be held to continue waiting for more support from the ramping process of the governing system. On the other hand, if it is the steady state, the droop gain is returned to the initial value.

To remove noise amplification caused by the derivatives, the input signals should be filtered before being used. Moreover, due to the decentralized approach, the local measurement with a high sampling frequency is possible for the accuracy of the measurement.

V. SIMULATION

Fig. 10 illustrates a typical MT-HVDC system on ±250 kV connecting 2 WFCs and 4 GSCs. The onshore grids’ parameters are shown in Table 2. The load size is the total consuming power of a grid. The total rated power and operating point of the synchronous generators in each grid are also provided,
and the difference between them is the spinning reserve of a grid. With the high RES penetration of each grid (transmitting wind power from connected HVDC terminal), the lower inertia constant (on the base of total generators rate) is relatively suggested [27], [28].

Table 3 provides the rated power and operating point of the converters. The DC capacitance of each terminal is designed corresponding to the stored energy of 40 kJ/MVA.

The simulation system shown in Fig. 10, along with the control methods, is built in PSCAD to validate the following test cases.

A. TEST CASE 1: OUTAGE OF A GENERATOR UNIT IN GRID1

In this case, the two WFs produce a total of 1105 MW inputting into the DC system. At 25s, Grid1 has an 80 MW generation outage, equivalent to 15% power shortage. As shown in Fig. 11, frequency drop triggers the GSC1
switching to frequency supporting mode, which withdraws more power from the DC side, causing a decrease of DC voltage. As a part of the sequence of actions, GSC2, GSC3, and GSC4 lower their output power and exploit their connected grids’ reserve power to support DC voltage, with the DC droop gains being 4, 6, and 2 MW/kV, respectively. For the traditional fixed droop, these values are maintained throughout the simulation time. Meanwhile, for the adaptive droop methods, these are the initial values and the droop coefficients are adaptively updated. By modeling the load as constant power, 80 MW of the mismatched electric power from the outage unit is compensated by the remaining generators in Grid1 and GSC1.

By keeping the fixed droop gains, it can be seen in Fig. 13(b) that the frequency of Grid2 reaches its nadir at 59.26 Hz violating the allowable limit of 59.5 Hz. Meanwhile, according to Fig. 14(b) and Fig. 15(b), Grid3 and Grid4 still can share more power when the frequency nadirs stop at 59.59 Hz and 59.54 Hz, respectively.

In the fuzzy-based method, by limiting the deviation power, less support is required at Grid2. Fig. 13(b) shows that the frequency nadir is enhanced to 59.43 Hz compared to 59.26 Hz from the fixed droop method. Instead, more support is allocated at Grid3 and Grid4, as shown in Fig. 14 and Fig. 15, respectively. However, limiting the deviation power is not enough to ensure that Grid2’s frequency remains within the limit, as in an AC grid, factors such as inertia constant and ramp rate also significantly affect frequency nadir.

The frequency margin method is successful in protecting the frequency in all grids above 59.5 Hz. However, since the DC voltage is not taken into consideration, Fig. 16 shows that the DC voltage drops lower than 475 kV and violates the requirement from the DC network. The main reason is the inefficiency in distributing the support power during this time.
The efficiency in the compromise between DC voltage and frequency can be seen in the proposed method. It can be seen that both DC voltage and frequency of each terminal are maintained within limits. By applying the proposed method, the supporting power is flexibly distributed between the GSCs to adapt to the present priority. When Grid2 frequency approaches the limit, supporting power from Grid2 is reduced for nadir protection. Meanwhile, more power is exploited from Grid3 and Grid4, where there is still available headroom. Consequently, according to Fig. 13(b), Fig. 14(b), and Fig. 15(b), the frequency nadir of Grid2, Grid3, and Grid4 ends up at 59.5 Hz, 59.51 Hz, and 59.51 Hz, respectively. In addition, DC voltage could be lowered during the transient time to reduce the stress on supporting grids, providing that the Vdc constraint is not violated (Fig. 16).

Because the proposed method changes the priority in supporting frequently, the output electrical power of the GSCs oscillates significantly compared to the other two methods (Fig. 13(a), Fig. 14(a), and Fig. 15(a)). It can be seen that the rapid power adjustment characteristic of power electronic devices has been efficiently exploited to provide better performance. Meanwhile, no any sudden oscillation in the frequencies is observed, so the proposed method does not cause a significant effect on the system stability in this case. If a severe contingency occurs and the constraints are violated, the proposed method provides an exit path to return to the initial droop gain, as discussed in Section IV. The further protection schemes of the system are applied (e.g., load shedding) to maintain the system stability.

Moreover, at the steady state, the proposed method allows the droop gains to turn back to scheduled values (initial values), implying that the shared amount of each grid is the same for the proposed method and the traditional method. For example, Fig. 13(a) clearly shows that after 60s, power values of GSC2 applying the fuzzy and frequency margin method are different from the proposed and fixed droop method.

B. TEST CASE 2: FLUCTUATION AND SUDDEN LOSS OF WIND FARMS POWER

The power fluctuation of WFs shown in Fig. 17 is applied to check the stability of the proposed method in a total duration of 120s. In this case, the power fluctuation is less than 10%, which is the typical fluctuation rate required by the operators’ standards [32]. In addition, at 60s, a partial outage of 20% happens in WF1.

In this case, the disturbance directly affects the DC system. Thus, all four connected onshore AC systems can take part in the supporting process. Fig. 17 shows that the wind power injected into the DC system constantly fluctuates, which results in a fluctuation of the power of GSCs and the frequencies of onshore grids. Before the partial outage at 60s, the system operates near the nominal value, and the difference between the methods is insignificant. The loss of wind power causes a sudden drop in DC voltage which is shown in Fig. 18. The performances of the control methods are compared in Fig. 19-Fig. 22.

The frequency margin method is advantageous in protecting the frequencies of grids from dropping lower than 59.5 Hz. Fig. 18 shows that DC voltage is regulated at the highest value before 61.6s owing to the large frequency margin at the beginning. This causes the frequencies to decrease...
very fast to 59.5 Hz while the governing system cannot ramp up fast enough. Hence, it leads to a lack of supporting power in the later time, when all four grids stop the DC voltage support to protect their frequencies. Finally, the DC voltage ends up at 471.4 kV at 64.4s.

For the fuzzy-based method, as discussed previously, DC voltage deviation could be well maintained. However, the frequency of Grid2 (Fig. 20) and Grid4 (Fig. 22) are not maintained above the frequency limit, while Grid1 and Grid3 can still provide more support to the DC system (Fig. 19 and Fig. 21).

The proposed method efficiently allocates the power at each GSCs to extract the maximum allowable supporting power from the AC grids and maintain the DC voltage in the acceptable range. It can be seen that the predefined constraints of operators on both AC and DC sides are satisfied.

These two test cases indicate that searching for priority in the proposed method can result in better performance. The adaptive law can provide a compromise between the two variables for continuous operation without violating both sides’ constraints.

C. TEST CASE 3: SEVERE CONTINGENCY

In this test case, WF2 is completely tripped out of the system at 30s, causing a loss of more than 600 MW. This is a severe disturbance that is impossible to maintain in the system within the predefined limits. This test case aims to evaluate the stability of the control methods.
For the frequency margin method, the system becomes unstable because after reaching 59.5 Hz, all grids refuse to regulate the DC voltage. This problem has been predicted by considering previous test cases.

The fixed droop method shows robustness when it can maintain the whole system stable. By using the fuzzy-based method, the system is also stable due to the defined rules shown in Table 1. It can be seen that when voltage deviation and power deviation are both negative large (NL), the adjusting rule of adaptive droop coefficient is medium (M) which means returning to the initial value. Fuzzy logic is well known for its flexibility in designing to achieve a specific target. Hence, when the fuzzy rules are changed for a different target, the system will be unstable if the unappropriated rule is chosen (e.g., low (L) is chosen).

After the disturbance, the proposed method provides the support to catch the drop of DC voltage as shown in Fig. 23. However, because of the severity of the disturbance, the proposed adaptive control follows the path to exit the adjustment and returns to the initial droop gain.

VI. CONCLUSION
In this paper, the trade-off process between DC voltage and frequency was clearly explained and visualized. An adaptive droop control was proposed for the compromise between the two variables. By applying the proposed method, supporting stress on the AC grids and DC capacitor bank could be reduced, but the lowest points of the curves were still satisfied with the operator’s standards. The simulation demonstrated the efficiency of the proposed method in securing the standards of both sides.

The proposed method exhibited the advantage in control topology where only local information of each GSC is required, thus avoiding dependence on the communication link. The simulation proved the efficiency in re-distributing the supporting power at each terminal. Thus, grids with available headroom could shoulder more sharing power and reduce the stress on the grids approaching the limit. On the DC side, voltage was allowed to be lower within the limit to extract more energy. At the steady state, droop gains always converge to scheduled values to match the setting of the sharing ratio from the operator. The proposed method has shown a promising approach to increase operational reliability. The other adaptive laws based on this approach may be investigated to improve the performance.

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