Selective Frequency Support Approach for MTDC Systems Integrating Wind Generation

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Abstract—This paper introduces a new control approach for Voltage Source Converter (VSC) stations in a multi-terminal dc (MTDC) grid to provide mutual frequency support among asynchronous ac networks. The developed coordinated control strategy modifies the active power references of each droop-controlled converter considering its adjacent ac system’s operational condition to enable the desired frequency support. Specifically, the proposed controller accurately achieves operator pre-specified frequency deviation ratios between the disturbed ac systems and other areas, thereby providing frequency support to affected grids during the whole frequency event. Therefore, an extra degree of freedom can be achieved in determining the extent of mutual frequency support. The performance of the proposed strategy is tested considering grids with significantly different frequency regulation characteristics. The stability analysis and time-domain validation of the proposed strategy are conducted in Matlab/Simulink.

Index Terms—Multi Terminal HVDC, converter control, P-V droop control, frequency response.

I. INTRODUCTION

Voltage Source Converter (VSC) based Multi Terminal High Voltage DC (MTDC) grids have recently become attractive solutions for the integration of renewable energy resources and interconnection of asynchronous ac grids. Several MTDC projects around the world are already under operation or to be constructed in the near future. China has already commissioned three-terminal (the Nan’ao project), five-terminal (the Zhoushan project) and four-terminal (the Zhangbei project) MTDC systems [1]–[3]. The Zhangbei project was put into operation in 2019 to provide around 4.5 GW of wind power to Beijing. The Atlantic Wind Connection is a prospective MTDC system to be built on the East Coast of the United States to integrate local offshore wind resources [4]. Furthermore, Europe plans to construct a Supergird to interconnect several countries and grid operators and to integrate massive renewable energy sources such as the solar power available in the north of Africa and wind energy from the North Sea [5].

Proper control of the VSCs is vital for the stable functioning of MTDC systems. The existing approaches aiming to control dc systems voltages can be divided into three groups: master-slave, voltage-margin, and voltage-power-droop controls. The master-slave approach relies on a single master converter to regulate the system voltage, and the slave converters operate in an active power control mode. This approach achieves good voltage regulation; however, it has poor reliability as the control of the dc voltage can be lost if the master converter is tripped or reaches its limits [6]. Voltage-margin control, an improved version of the master-slave approach, allows another converter to take over the responsibility to control the dc voltage at a new reference value when the original master converter fails to control it. However, the system might experience stresses during the transition between two voltage references. What is more, the difference between the two reference voltages should be large enough not to cause interaction during normal operation; however, selecting too large a difference might cause voltage limit violation [7], [8].

Voltage-power/power-voltage droop is widely employed in the literature as it enables simultaneous voltage control and sharing of any power mismatch in a dc system between the droop-controlled converters.

Several recent studies including [8]–[10] have proposed new control approaches to achieve enhanced regulation of dc voltage and/or accurate power-sharing between converter stations. With those voltage-power droop controllers, the dc grid disunites ac networks, effectively buffering disturbance propagation from one ac system to the others. This decoupling also results in mutual frequency support between asynchronous ac systems; therefore, each ac system overcomes its disturbance by the local power reserves only.

Extensive research has been conducted on designing control techniques that use frequency information to modify active power exchanges between converter stations, thereby creating artificial coupling of ac systems and enabling reciprocal frequency support between those grids. Frequency droop (FD) technique, originally introduced in [11], has been used in several studies, including [12]–[17], to achieve power reserve sharing.
and frequency provision between MTDC interconnected asynchronous ac systems.

However, the extent of support that each ac system should provide during a disturbance is not clearly defined with conventional droop control. Enhancement of the original FD control was attempted in [14] within the unit commitment (UC) framework. This study concluded that the extent of support between asynchronous ac systems is highly dependent on droop-coefficient selection. [15], [16] suggested the addition of a distress signal to transmit information about the ac side disturbance in MTDC systems, activate the FD loop, and to achieve ratio-based reserve sharing. Based on the simplified mathematical models of the whole system, [15], [16] attempted the design and parameter setting of FD controllers, e.g., droop-coefficient selection. However, those design procedures require prior knowledge of system topology and parameters and do not consider the complete system dynamics (e.g., important dynamics associated with the turbine-governor action of ac generators are usually neglected). Therefore, accurate ratio-based frequency deviations might not be achieved during the entire period of a frequency event, especially during the maximum frequency deviation (nadir) point, as the latter is a complex function of system parameters [18]. Moreover, many of these parameters having a major impact on the frequency dynamics (e.g., system inertia) might experience significant variation in a relatively short period [19], hindering achievement of the desired mutual frequency support during the primary frequency response.

[20] and [21] proposed an adaptive modification of the droop gains based on the local frequency error to provide a more reasonable allocation of the unbalanced power between ac systems. [20] uses the conventional cascaded control structure of VSCs, whereas [21] is based on the virtual synchronous generator concept. However, similar to the previous strategies, and verified by the results presented in [20], [21], the latter approaches do not have a mechanism to achieve precise frequency deviation ratios between ac grids. The main deficiency of the frequency-droop control strategies, including adaptive droop approaches, is their inability to accurately achieve desired ratio of frequency deviations of ac systems. This deficiency results from the lack of a mechanism (e.g., integral action) in frequency droop approaches for nullifying the error in ratio-based difference of the frequency deviations. By adaptively modifying the droop gains, this error could be minimized (but not nullified) at the expense of larger variation of the dc voltages, the latter being caused by a more aggressive response of the proportional droop controller. Relatively large variation of droop gains might even cause a violation of the dc voltage limits. A unified control structure proposed in [22] applied an integral action on the local frequency error. As this action tries to nullify the frequency error in each grid at the expense of other ac systems, it might eventually result in controller fighting due to the limited spare active power reserves available in the interconnected system. Frequency consensus (FC) based algorithms proposed in [23]–[25], on the other hand, limited the mutual frequency support in enforcing only equal frequency deviations during the grid disturbances. The above-discussed control strategies for the VSCs of MTDC systems can be broadly generalized into three groups as follows. The first group of controllers does not artificially couple the MTDC interconnected ac systems, therefore each ac system overcomes its disturbance with its own power reserves. The second group of controllers, on the other hand, artificially couples the ac systems but does not define the extent of the mutual support. The third group aims equalizing the consequences of the disturbances on each ac system. However, the last group does not provide a selectivity between the systems actually under the disturbance and the systems assisting to overcome that disturbance. Therefore, the existing control strategies do not achieve fair and precise mutual frequency support.

This paper proposes a control approach to accurately achieve the desired extent of mutual frequency support between MTDC interconnected asynchronous ac grids while considering the operational states of those grids. Specifically, each of the affected grids would receive frequency support from healthy systems based on the predefined ratios of frequency deviations between supporting ac systems and the affected ac grid. Therefore, the relative effect of the disturbance on the participating grids can be pre-defined, providing more fair allocation of the available power reserves. The developed detection technique continuously identifies the affected area, and the support algorithm is modified accordingly to accomplish the above-mentioned control objective. Thus, compared to the existing approaches, the proposed controller adds an extra degree of freedom for controlling the amount of mutual frequency support between MTDC interconnected asynchronous ac systems.

Eigenvalue analysis is conducted to evaluate the effect of the proposed frequency control structure on the system stability. Moreover, ac systems dominated by generating units with different characteristics have been used in Matlab/ Simulink time-domain simulations when evaluating the effectiveness of the proposed controller.

II. STUDY SYSTEM AND ITS MODELING

A. System Under Study

A typical structure of MTDC system is shown in Fig. 1, which is a part of the CIGRE benchmark test system and is considered in this study. Converters #2 and #3 normally operate
in the inverter mode to deliver active power to the second and third areas, respectively. The other three converters normally operate in the rectifier mode, with the converters #4 and #5 supplying the wind power to the dc grid. The generation of Areas 1 and 3 is assumed to be dominated by thermal units, whereas the generation of Area 2 is assumed to be dominated by gas-fired power plants. The selection of systems with different frequency response characteristics is meant to make it more challenging for achieving precise mutual frequency support. The dc system nominal voltage is ±400 kV, while the rest of the system parameters can be found in the Appendix.

B. Modeling of the System

The current work focuses on the relatively slow dynamics associated with the frequency changes of ac systems. Therefore, lumped parameter pi-section approximation is used for the modeling of dc transmission cables. The dynamics associated with higher frequency transients (e.g., switching transients) can be captured by using more-advanced line models.

Considering that at each converter station the capacitances of the cables and that of the converters are in parallel, the equivalent capacitance $C_{eq,i}$ is calculated as per

$$C_{eq,i} = C_{i,SC} + \sum_{j=1, j \neq i}^{n} \frac{C_{i,j}}{2} \tag{1}$$

where $C_{i,j}$ is the capacitance of the dc cable connecting $i$th and $j$th nodes, $C_{eq,i}$ is the aggregated capacitance at $i$th station, $C_{i,SC}$ is the capacitance of the $i$th converter capacitor bank, and $n$ is the number of the nodes connected to that station. The equivalent capacitance of the intermediate nodes (e.g., at Bus Bb-B4 in Fig. 1) is also given by (1) with the converter capacitance set to zero. Afterwards, the dc voltage at the $i$th node is calculated by

$$V_{dc,i} = \frac{1}{C_{eq,i} \Delta t} \left( I_{i,inj} + \sum_{j=1, j \neq i}^{n} \frac{V_{dc,j} - V_{dc,i}}{2(R_{dc,ij} + L_{dc,ij} \Delta t)} \right) \tag{2}$$

where $L_{dc,ij}$ and $R_{dc,ij}$ are the inductance and the resistance of the dc cable between $i$th and $j$th nodes, respectively. The current injected from ac to dc system, $I_{i,inj}$, is determined based on the power balance equation given by

$$I_{i,inj} = \frac{P_{dc,i}}{V_{dc,i}} \approx \frac{P_{SC,i}}{V_{dc,i}} \tag{3}$$

where $P_{SC,i}$ is the active power transferred from ac to dc side of the $i$th converter.

An aggregated representation of the ac generators together with frequency-dependent loads is used for the modeling of ac systems [26], therefore the frequency dynamics of the $i$th ac grid can be expressed as follows

$$f_i - f_{nom,i} = \frac{P_{m,i} - P_{L,i} - P_{SC,i}}{2H_i \Delta t + D_i} \tag{4}$$

where $f_i$ and $f_{nom,i}$ are the measured and nominal frequencies of the system, $P_{m,i}$ and $P_{L,i}$ are the mechanical power provided to the generator and the load demand at the system, $H_i$ and $D_i$ are the equivalent inertia and load damping constant, respectively.

The mechanical power $P_{m,i}$ is provided by the corresponding turbine-governor model. IEEEG1 turbine-governor model, which is depicted in Fig. 2, is used in this study to represent steam power plants as recommended by [27]. The parameters of the model are taken from [28]. The gas-fired plants are represented with the GAST turbine-governor model of Fig. 3 with the parameters acquired from [29].

Type-4 variable speed wind turbines with Permanent Magnet Synchronous Generators (PMSG-WT) are considered in this study with the dynamics of the $i$th turbine given by

$$\begin{align*}
&\begin{cases}
  w_{r,i} - w_{r,nom,i} = \frac{1}{2H_{WT,i} \Delta t} (P_{m,i} - P_{r,i}) \\
  P_{m,i} = \frac{1}{2} \pi \rho R^2 v_{wind}^3 C_p(\beta, \lambda_i) \\
  P_{r,i} = P_{MPPT,i} - \Delta P_{del,WT,i}
\end{cases}
\end{align*} \tag{5}$$

where $P_{m,i}$ and $P_{r,i}$ are the mechanical and electrical power injections, respectively, $w_{r,i}$ is the turbine speed, $\rho$ is the air density, $R$ is the turbine radius, $v_{wind}$ is the wind speed, $C_p$ is the power coefficient, which is a function of the tip speed ratio $\lambda = w_{r,i}/v_{wind}$ and pitch angle $\beta_i$, $H_{WT,i}$ is the combined inertia of the generator and turbine blades, $P_{MPPT,i}$ is the power acquired from Maximum Power Point Tracking (MPPT) algorithm as per (6). Please notice that the turbines are operating at off-MPPT point by $\Delta P_{del,WT,i}$ reduced power as the unloaded
operation enables WTs to provide sustainable frequency support capability [30], [31].

\[
P_{MPPT,i} = w_{T,i}^m k_{MPPT} \\
\Delta P_{del.WT,i} = P_{del.WT,max,i} - P_{del.WT,i}
\]

(6)

10% maximum deloading level for WTs \((P_{del.WT,max} = 0.9P_{MPPT})\) is considered in this study [32]. \(P_{del.WT,i}\) is the actual deloading power, which is a function of frequency deviations and is generated by the centralized controller as will be explained later.

From the WPP owners’ perspective the above-described suboptimal operation of wind turbines might not be desired. However, organizations like European Network of Transmission System Operators (ENTSO-E) have already put requirement on WPPs to participate in frequency support even at the cost of operating the turbines below the available capacity during normal conditions [33], [34]. The participation of wind farms in frequency regulation might also be viewed as an ancillary service with additional financial benefits provided for that service [33], and this participation can also improve the system flexibility [35]. The main advantage of the proposed controller, on the other hand, is its capability to precisely execute any extent of desired mutual frequency support considering the operational state of the participating areas. Therefore, even if WPPs do not participate in the frequency support, the proposed scheme will properly allocate the power reserves among MTDC interconnected ac systems. Thus, the detailed investigation of the dynamic response of individual wind turbine during frequency support interval is out of scope of the current study.

III. CONTROL OF THE MTDC CONVERTERS

A. Inner Current and Voltage-Power Droop Control Loops

The conventional vector current control is used in the inner control level for all VSCs of Fig. 1, enabling decoupled control of the active and reactive power injections [10]. The active and reactive current references are provided by the outer control loops. For the converters interfaced to ac systems (converters 1, 2 and 3), the outer loop comprises of the power-voltage droop control structure for determining the reference active current component according to

\[
I_{d,ref,i} = (V_{dc,ref,i} + K_{pd,i}(P_{ref,i} - P_i) - V_{dc,i})G_{PI,dc,i}(s)
\]

(7)

where \(V_{dc,ref,i}\) and \(V_{dc,i}\) are the reference and measured dc voltages, \(P_{ref,i}\) and \(P_i\) are the reference and measured converter active power injections, \(G_{PI,dc,i}(s)\) is the representation of the PI controller responsible for dc voltage regulation. The controller implementation according to equation (7) allows converters to simultaneously regulate the dc system voltage by sharing the system power unbalance proportional to their power droop gains \(K_{pd,i}\). However, the penalizing term \(K_{pd,i}(P_{ref,i} - P_i)\) inevitably causes the dc system voltage to deviate from its desired value \(V_{dc,ref,i}\) in the off-nominal operation. Therefore, the centralized voltage regulation approach presented in [25] is employed in this study, where an identical voltage correction term \(\Delta V_{avg}\) is added to the initial voltage reference \(V_{dc,ref,i,0}\) of the \(i_{th}\) droop-controlled converter as per (8)

\[
\begin{align*}
V_{dc,ref,i} &= V_{dc,ref,i,0} + \Delta V_{avg} \\
\Delta V_{avg} &= (V_{dc,nom} - V_{dc,avg}) \left( k_p AVS + \frac{k_i AVS}{s} \right) \\
V_{dc,avg} &= \frac{1}{n} \sum_{i=1}^{n} V_{dc,i}
\end{align*}
\]

where the average dc system voltage \(V_{dc,avg}\) is regulated to system nominal voltage \(V_{dc,nom}\) shortly after power unbalances occur in the system. High-speed fiber optic links embedded within sub-sea cables are used as communication media in the current study.

B. Frequency Control of the Converters Interfacing AC Systems With the Proposed Approach

With the above-described control of MTDC converters, however, the ac grids connected through such systems would not provide frequency support to each other in case of a disturbance, leaving the total impact on the disturbed grid only. The existing mutual frequency support algorithms, on the other hand, aim to equalize the extent at which all the grids are affected in case of a disturbance in one of those grids.

The previous studies, however, did not consider which grid is under the disturbance, so they do not provide any selectivity during the frequency event. Accordingly, the system operators had no mechanism to redefine the relative amount of the frequency support provided by each area based on the latter’s state (e.g. area under disturbance or area supporting the disturbed network). To overcome this issue, detection of the affected grid and modification of the FC algorithm are suggested in this paper. The proposed controller for the \(i_{th}\) converter station is shown in Fig. 4 and is elaborated below.

1) Algorithm for Detecting the Affected Grid: Proper detection of the grid where the disturbance actually happened is of prime importance for providing selectivity in mutual frequency support. It is worth noting that conventionally the frequency event is detected continuously based on the deviation of the frequency from the specified dead-band limits [14]. However, with any frequency support algorithm (FD, FC, etc.), the frequencies of all interconnected systems would likely exceed the dead-band limits as a result of the provided frequency support by each of the participating grids. This situation hinders from the identification of the area causing the disturbance. To overcome this issue, a method is developed to continuously identify the affected ac system.

If the disturbance occurring in the \(i_{th}\) area causes an active power shortage, the frequency support sharing algorithm would try to increase the active power flowing from MTDC system to that area (positive \(\Delta P_i\) in Fig. 4). Therefore, independent of the operation mode of the \(i_{th}\) converter (inverter vs rectifier mode), the converter would experience a positive change in the power deviation \(\Delta P_{i,F S}\) in Fig. 4).

Meanwhile, the actual frequency deviation of that area \(\Delta f_i\), defined as a difference of the nominal and measured frequencies as per (9), would also be a positive quantity due to the decreased
In contrary, the converter of the healthy \( j_{th} \) grid trying to provide frequency support to the affected \( i_{th} \) system would decrease its power reference (negative \( \Delta P_j \)) and would experience frequency decline (positive \( \Delta f_j \)) due to the extra power it injects to the dc grid. Following the discussed logic, the trend of the power and frequency deviations during possible system disturbances is summarized in the below table. The considered disturbances are the ac power shortage or surplus (e.g., due to the ac generator/load connection or disconnection) and increase or decrease of the power injected to the dc grid by the converters except the droop-controlled ones (e.g., wind power increase or decrease).

| Disturbance       | \( \Delta P_{affect} \) | \( \Delta f_{affect} \) | \( \Delta P_{support} \) | \( \Delta f_{support} \) |
|-------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| ac power shortage | pos.                    | pos.                    | neg.                    | pos.                    |
| ac power surplus  | neg.                    | neg.                    | pos.                    | neg.                    |
| dc power increase | pos.                    | neg.                    | pos.                    | neg.                    |
| dc power decrease | neg.                    | pos.                    | neg.                    | pos.                    |

As it can be clearly observed from the above table, if any of the ac grids causes the system disturbance, the product of its power deviation \( \Delta P_{affect} \) and frequency deviation \( \Delta f_{affect} \) would be a positive quantity. Opposite trend can be identified for the supporting healthy grids with the identical product being a negative quantity. In case if none of the ac grids are affected, and the frequency deviations are due to an external cause (e.g., change in the power injected by the WPP), all of the ac converters observe a negative product of the discussed quantities. Therefore, the sign of the \( \Delta P_i \Delta f_i \) product serves as an indicator for the operational condition of the \( i_{th} \) ac grid. Shown in Fig. 4, once the frequencies exceed the minimum deadband and the discussed product is positive, the disturbance is detected at the \( i_{th} \) system.

In case of the disturbed area the binary variable \( \gamma_i \) is positive, which is later used to modify the weight factors in the frequency support algorithm. The frequency deviation deadband has an aim to disable the supplementary operational loop during undesirable minor transients and is set to \( \pm 0.05 \) Hz in this study.

2) Adaptive Modification of the Weight Factors With the Proposed Approach: After an identification of the affected area, an accurate ratio-based frequency support sharing can be achieved. To this end, the original power reference of the \( i_{th} \) out of \( m \) droop-controlled converters \( P_{ref,i,0} \) is modified as per (10)

\[
P_{ref,i} = P_{ref,i,0} + \Delta P_{i,FS}
\]

\[
\Delta P_{i,FS} = \left( \sum_{k=1,k\neq i}^{m} \frac{\Delta f_{k,weighted}}{m-1} - \Delta f_{i,weighted} \right) G_{P_{1,FS}}
\]

Due to the integral action of the controller \( G_{P_{1,FS}} = k_{P,FS} + k_{I,FS}/s \), the weighed frequency deviation of the \( i_{th} \) area \( \Delta f_{i,weighted} \), which is given by (11), would be accurately regulated to the same quantity of the other participating grids.

\[
\Delta f_{i,weighted} = \Delta f_{i} w_i
\]

\[
w_i = \frac{w_{i,0} + AF_i}{100\%}; \gamma_i = 1
\]

\[
w_i = w_{i,0}; \gamma_i = 0
\]

In (11), the original weight factor \( w_{i,0} \) is determined based on the relative strictness of the frequency regulation in each of the participating ac grids. For example, if the MTDC interconnected ac grids have similar grid codes on frequency regulation, then identical original weight factors could be set for all participating grids. In the proposed strategy, based on the disturbance index \( \gamma_i \), the original weight factor of the affected area \( w_{i,0} \) is multiplied by the assistance factor \( AF_i \).

The last parameter is pre-set by the system operator for the \( i_{th} \) ac system participating into mutual frequency support. \( AF_i \) determines the relative extent to which all other ac grids participate in providing frequency support in response to any disturbance happening in the \( i_{th} \) ac system. Specifically, by means of the power rerouting in dc grid, the proposed controller enables the supporting ac systems to experience the frequency...
deviation of $AF_i$ percent of that of the $i_{th}$ ac systems frequency deviation when the disturbance is caused by the latter system. Varying AF from 0% to 100% would allow the operators to precisely change the extent of mutual frequency support between asynchronous ac systems from 0% to 100%. That being said, with $AF_i = 0\%$, the $i_{th}$ ac system would get no support from other grids in case if it experiences a disturbance. With an increase of $AF_i$, the frequency support provided to the $i_{th}$ grid would increase accordingly. Selection of the particular value for the AFs would be under the discretion of system operators. Thus, the proposed approach provides an added degree of freedom that allows system operators to accurately determine the extent of mutual frequency support.

C. Coordinated Frequency Support Strategy From WPPs

To achieve frequency support from WPP during the main ac system disturbance, an ancillary frequency controller is implemented. The amount of the additional power is determined as a function of the onshore frequency deviations to reflect the severity of the ac disturbance and to extract the appropriate amount of extra power.

The weighted average sum of the ac system frequencies is first calculated and then supplied to the controller to determine the total additional wind power $P_{del,WPP,total}$ injected to the dc grid as per

$$\begin{align*}
P_{WPP,total} &= (\sum_{i=1}^{m} v_i \Delta f_i) G_{PD} \\
\sum_{i=1}^{m} v_i &= 1
\end{align*}$$

(12)

where the $v_i$ is the weight determining the extent each ac grid would have contribution on the frequency support provided by WPP, $m$ is the total number of ac grids connected to the droop-controlled converters, $G_{PD}$ is the transfer function of the proportional-derivative controller. Please notice that similar weighted frequency based control approach have been previously presented in [12] to reflect onshore frequency changes on the frequency of offshore wind farms. The maximum power headroom $P_{del,WPP,max,i}$ at each WPP, which is the sum of headrooms of all WTs belonging to that plant, is then used for determining the relevant portion of the power that the $i_{th}$ WPP should supply.

$$P_{del,WPP,max,i} = \frac{1}{k} P_{WPP,total} \frac{P_{del,WPP,max,i}}{\sum_{i=1}^{n} P_{del,WPP,max,i}}$$

(13)

with $n$ being a total number of the participating WPPs, $k$ is the number of WTs in that plant. Following system disturbance, the WPP frequency support controller is being activated if any of the ac frequencies exceed pre-specified dead-band. As mentioned earlier, the functioning of the proposed algorithm is not dependent on the frequency support provided by the WPPs. However, as it will be seen in the results section, the implemented controller enhances the distribution of the active power provided by the WPPs for frequency response.

IV. Modal Analysis

The effect of the parameter variation of the proposed controller on the stability of the system of Fig. 1 is investigated in this section. After developing the system model based on differential-algebraic equations described in Section II, the linearization around an operating point is performed using the Simulink linearization toolbox, resulting in the system model of the form

$$\Delta \dot{x} = A \Delta x + B \Delta u$$

(14)

where $\Delta x$ and $\Delta u$ represent the state and input vectors, $A$ and $B$ represent the state and input matrix, respectively. Afterwards, the system eigenvalues are acquired from the state matrix $A$ under varying parameters as discussed later.

The acquired modes are used to investigate the effect of the parameter variation on the movement of the eigenvalues. Furthermore, the participation factor analysis was conducted to illustrate the relative significance of a specific state to the mode of interest. Therefore, the right ($V_i$) and left ($W_i$) eigenvectors are calculated so that they satisfy the following

$$A \ast V_i = \lambda_i \ast V_i$$

(15)

$$W_i \ast A = \lambda_i \ast W_i$$

(16)

where $\lambda_i$ is the $i_{th}$ eigenvalue. The participation factor matrix is then constructed based on the definition of [36], [37] as per

$$P_{h,i} = \frac{|V_{i,k}| |W_{k,i}|}{\sum_{k=1}^{n} |V_{i,k}| |W_{k,i}|}$$

(17)

The participation factor $P_{h,i}$ indicates the relative participation of the $k_{th}$ state variable on the $i_{th}$ eigenvalue, which can be helpful, especially for understanding the root cause of the dominant poles. The above definition of participation factor resolves the issue of imaginary parts of the participation factor that would result from direct element-wise multiplication of right and left eigenvectors when complex eigenvalues are present in the system.

The right-most eigenvalues of the combined system experiencing relatively larger movement during the variation of the proposed controller’s parameters are shown in Figs. 5–7. Specifically, the proportional and integral gain variation effect is depicted in Figs. 5 and 6, respectively, whereas Fig. 7 demonstrates the effect of the variation of the AFs of the proposed controller. In all three figures four pair of oscillatory eigenvalues ($\lambda_1 - \lambda_4$) have been identified as the ones with relatively more movement during the variation of the considered parameters of interest. Another fast moving eigenvalue ($\lambda_5$) was located in the stable region for the considered variation and had no imaginary component. The black arrows indicate the direction of the eigenvalue movement as the parameter is varied in the specified range. Please notice that the numbering of eigenvalues shown in Figs. 5–7 is for convenience only and is not according to the order they appear in after they are extracted from the state matrix. Fig. 8 presents the section of the results of participation factor analysis that associates the critical oscillatory modes to the states of the system. Only the states making a major contribution to the considered modes are depicted in Fig. 8. It can be seen that the major contributing states are those associated with the dc voltage-droop controller (Vdc-cont), the turbine governors of the three areas (G-TG, combined participation of
Fig. 5. The effect of the change of the proportional gain $k_{P,FS}$ on system eigenvalues.

Fig. 6. The effect of the change of the integral gain $k_{I,FS}$ on system eigenvalues.

Fig. 7. The effect of the change of AF on system eigenvalues.

Fig. 8. The percent participation of the color coded states to the critical oscillatory eigenvalues $\lambda_1 - \lambda_4$.  

all relevant states), generator speeds of three areas (G-w), the dc side currents (Idc, combined participation of all relevant states) and the states associated with the proposed controller (FS). Specifically, the states associated with the proposed controller have relatively greater participation on modes $\lambda_1$ and $\lambda_2$, and lesser participation on the other two modes. Following a closer look is given to the Figs. 5–7. In Fig. 5, the proportional gain is varied in the range from 2 pu to 150 pu, by the step of 0.1–1 pu depending on the section of interest to accurately capture the trajectories of interest. During low values of the proportional gains, the eigenvalues with lowest damping are $\lambda_1$ and $\lambda_2$. With an increase of the parameter, the $\lambda_1$ and $\lambda_2$ start moving to the left hand side of the complex plane and increase the damping of the system, verifying the results of the participation factor analysis. At an inflection point that happens at the gains of 18 pu, the eigenvalues $\lambda_1$ and $\lambda_2$ start moving downwards with a greater speed. However, the eigenvalues $\lambda_3$ and $\lambda_4$ demonstrate an opposite trend, as the imaginary part of those eigenvalues is increased with an increase of the proportional gain. Specifically, the eigenvalue $\lambda_3$ experiences an inflection point at a gain of 23 pu and starts fast upward movement. For a large range of the parameter variation the system eigenvalues are well within the left hand plain. However, the proportional gain of 20 pu is selected in this study to ensure the maximum damping. Furthermore, Fig. 6 demonstrates the effect of the variation of the integral gain in the range of 1 pu–1400 pu, by the step of 1–16 pu depending on the section of interest. Opposite to the previous case, the $\lambda_3$ and $\lambda_4$ are the ones with lower damping during the initial values of integral gains. The increase of the gain causes a decrease of the imaginary parts of $\lambda_3$ and $\lambda_4$ and increase of the respective parameter for $\lambda_1$ and $\lambda_2$. At the gain of around 80 pu, an inflection point occurs, and the modes $\lambda_1$ and $\lambda_2$ start upper-right movement towards the unstable region, implying an upper limit for the selection of the integral gains. Finally,
the Fig. 7 presents the effect of the change of AF on system eigenvalue movement. The whole range of the AF variation, from 0–1 pu (0–100%) is considered by increasing the AF by the steps of 0.1 pu. The increase of the AF results in an increased system damping as suggested by the trajectories of $\lambda_1$ and $\lambda_2$. Although the other two oscillatory modes experience an increase in their imaginary components, even for the largest values of AF those modes remain better damped than $\lambda_1$ and $\lambda_2$. The modal analysis results imply the effectiveness of the proposed controller to enhance the damping and the stability of the system.

V. SIMULATION RESULTS AND EVALUATION

The effectiveness of the proposed algorithm is evaluated using time-domain simulation conducted in Matlab/ Simulink environment. Several operational cases are considered for the comprehensive evaluation. Identical frequency regulation grid codes are considered for the ac networks for the clarity of illustration.

P-V droop-controlled converters VSC1 and VSC3 work in the inverter mode and transfer power from dc grid to the respective ac systems. The third droop-controlled converter VSC2, together with the VSC4 and VSC5 interfaced to the WPPs, operate in the rectifier mode and inject power to the dc system. The positive direction of the current is from the ac side of the VSC to the dc side.

A. System Response During AC Side Disturbances

In this scenario, the effect of the proposed controller for frequency response sharing is evaluated during the ac side disturbances. Figs. 9–11 demonstrate the system response during subsequent load increases in the area 3 and area 2. The AF for the affected grids is set to 50% in this scenario, aiming to achieve twice more effort from the disturbed grid(s) compared to the supporting grid(s). When the load in area 3 is increased by 0.4 pu at time $t = 5$ s, the power unbalance in area 3 causes the frequency decrease in that area. Due to the provided active power support, the other two ac systems also experience a decline in their frequencies (positive frequency deviation shown in Fig. 9(a)). As the frequency deviations of all ac systems exceed the specified threshold ($\eta_{min}$–$\eta_{max}$) in Fig. 9(a), detection of the area causing the disturbance would not be possible by observing the frequency change only. Therefore, the proposed controller of Fig. 4 utilizes the power deviation $\Delta P$ to continuously detect the area under the disturbance. As can be seen from Fig. 9(b), after the disturbance at $t = 5$ s, only the affected area 3 experiences positive power deviation $\Delta P_3$. As the product of the frequency deviation $\Delta f_3$ and $\Delta P_3$ is positive, the disturbance is detected in area 3 (Fig. 9(c)). Please notice that the disturbance state $\gamma$ in the other two areas remains zero. The detection of the affected grid modifies the respective frequency contribution factor of area 3 (equation (11)) to achieve desired ratio-based frequency regulation. Fig. 10 depicts the frequency trajectories of the three ac systems in response to the system disturbances. When the load
in area 3 is increased, both area 1 and area 2 become supporting grids by injecting extra power to the dc grid. At this situation, as the first two areas have identical operational status and grid codes, the proposed algorithm achieves uniform frequency regulation between those areas. As such, the frequency deviations at the nadir points are $\Delta f_{1,nadir} = \Delta f_{2,nadir} = 0.4$ Hz, and frequency deviations at the quasi-steady-state conditions are $\Delta f_{1,qss} = \Delta f_{2,qss} = 0.21$ Hz. As per the ratio pre-specified by the system operators, the affected area experiences twice the frequency deviation of the supporting areas with $\Delta f_{3,nadir} = 0.8$ Hz and $\Delta f_{3,qss} = 0.42$ Hz, ensuring the selective participation of the ac grids into frequency response precisely determined by the desired ratios.

Furthermore, gas turbine dominated area 2 experiences 0.4 pu load increase at time $t = 35$ s. As can be seen from Fig. 9(b), the $\Delta P_2$ becomes a positive quantity, and, because of having identical sign with the frequency deviation $\Delta f_2$ in Fig. 9(a), the disturbance in area 2 is also detected (Fig. 9(c)). After detection of the state of the area 2, the respective weight factor is modified according to its predefined AF. The desired ratio-based frequency support is precisely achieved throughout the disturbance period as seen in Fig. 10. The dc system voltages and converter power injections for the considered two disturbances are depicted in Fig. 11, where shown in Fig. 11(a) the dc system average voltage is adjusted around nominal value as a result of the action of the voltage regulation loop. The wind warm active power increase during the frequency events in main ac systems can be observed from the respective power trajectories in Fig. 11(b).

B. Comparison With Other Methods

The proposed strategy is compared with several recently-reported control approaches as follows: with power-voltage (P-V) droop control of [10], with the conventional FD algorithm (C-FD) presented in [17], with Adaptive Droop Control (ADC) reported in [20], with Adaptive Virtual Synchronous Generator (A-VSG) method of [21], and with the FC algorithm of [25]. The results of the comparison for the five considered cases are shown in Figs. 12–16. In all considered scenarios of this subsection 0.4 pu demand increase is initiated in area 2 at time $t = 45$ s.

When using P-V droop controllers, including the one proposed in [10], asynchronous ac grids interconnected through MTDC systems do not provide any mutual frequency support. Assuming that in this case it is desired by the system operators to achieve no frequency support between ac systems, the AF of the affected grid with the proposed strategy is set to zero to allow a fair comparison. As can be seen from the dotted frequency trajectories of Fig. 12(a), area 1 and area 3 do not assist area 2 in overcoming the disturbance. Meanwhile, the WPPs inject more power to dc grid during the frequency event, and the P-V droop controllers distribute this additional power between all three areas. This distribution of P-V controller results in an unnecessary allocation of power to area 1 and area 3, which causes an increase of the frequencies of those areas. The solid frequency trajectories of Fig. 12(a) demonstrate the response of the system with the proposed strategy. With the AF set to zero, the proposed controller quickly regulates the summation of the weighted frequency deviation of area 1 and area 3 to zero (Fig. 4). Therefore, the frequencies of both area 1 and area 3 are controlled to their nominal values, not allowing any unnecessary power being allocated to those areas. This control action results in redirection of all additional power to the affected area 2 and increase of its frequency profile compared to the case when P-V control is used. In particular, the frequency nadir is improved by 0.13 Hz and quasi steady-state (QSS) frequency is improved by 0.05 Hz. This improvement verifies the advantage of the proposed controller considering the specific operation objective when no mutual frequency support is required.

The strategies of [17], [20], [21], [25], on the other hand, would try to equalize the frequency deviations of asynchronous ac systems given an equal droop gain settings for [17], [20], [21] methods or equal weight factors for [25] approach. Therefore, the AF of the affected area is set 100% to achieve full support between asynchronous ac systems when compared to those methods. It can be observed from Fig. 13(a) that with C-FD approaches the relative frequency deviations are poorly defined.
with the supporting grids’ frequencies ($f_{1.C-FD}$ and $f_{3.C-FD}$) being much higher than the identical parameter of the affected grid ($f_{2.C-FD}$). With the proposed strategies, on the other hand, equal frequency deviations is achieved for all three areas as per the system operator requirement. As a result, the proposed strategy increases the frequency nadir by 0.355 Hz and QSS frequency by 0.39 Hz.

Shown in Figs. 14(a) and 15(a), the controllers of [20] and [21] have both demonstrated an improved performance in achieving full mutual frequency support compared to the C-FD approach. However, the proposed strategy still outperforms those approaches in achieving full mutual frequency support. Specifically, when compared to the ADC approach, the proposed approach achieves 0.125 Hz and 0.25 Hz improvement at the nadir and QSS points, respectively. The A-VSG approaches achieve further improvement compared to ADC approach by falling behind the proposed strategy by only 0.085 Hz and 0.19 Hz at the frequency nadir and QSS frequency, respectively. The droop approaches also cause significant deviation of the
dc voltages (Figs. 13(b), 14(b) and 15(b)). This deviation is highly dependent on the selected droop gains and extent of the disturbance. Selection of higher droop gains might result in further improvement of their frequency support objectives which would come at the cost of larger voltage deviations. Finally, Fig. 16 demonstrates that for this case the proposed strategy acts like FC algorithm: it ensures identical frequency deviations for all interconnected areas independent of which grid is causing the disturbance. The results presented in Figs. 13–16 reveal operation of the proposed strategy at only one operation mode (full mutual frequency support) as the studies used for comparison are limited to those modes only. The main advantage of the proposed controller, on the other hand, is the capability to precisely achieve any extent of mutual frequency support considering the operational state of the participating area.

C. System Response During Changes in the Wind Speed

The performance of the proposed strategy was also tested in the situation when the disturbance is not caused by any of the participating ac grids. As such, the wind speed is varied from 12 m/s to 11 m/s and from 11 m/s to 13 m/s at times $t = 5$ s and $t = 35$ s, respectively.

As depicted in Fig. 17(a) and (b), all of the ac systems demonstrate similar trend in terms of frequency deviations $\Delta f$ and power mismatches $\Delta P$. Therefore, no disturbance is detected in those three areas (Fig. 17(c)), and the proposed controller redirects the active power to share the burden on all three ac areas equally by achieving identical frequency deviations as shown in Fig. 18. The dc voltages and active power injections for this scenario are depicted in Fig. 19(a) and (b), respectively.

D. System Response With No Frequency Support From WPPs

As mentioned in Section III, the proposed strategy achieves proper allocation of the power reserves between asynchronous ac systems even if there is no extra support from WPPs. The simulation scenario is therefore conducted to compare a case
when WPPs provide the frequency support with a case when WPPs do not provide any extra support during the frequency event. For the latter case, the WPPs operate at MPPT mode during the normal condition (e.g., \( \Delta P_{\text{del},W,T} = 0 \)). The previous scenario of a 0.4 pu load increase in area 3 is repeated here. The assistance factor of the affected area is pre-set to 50%. As can be seen from Fig. 20, for both cases the proposed controller achieves twice the frequency deviation of the affected area compared to the identical parameter of the healthy grids (area 1 and area 2 in this case). Therefore, accurate allocation of the power reserves between asynchronous ac grids based on the operator’s pre-specified ratios is achieved throughout the frequency event. It can also be noticed that the extraction of additional power from WPP results in less frequency deviation in all three grids, which, however, is at the cost of operation WPPs at off-MPPT during normal conditions.

Apart from WPPs frequency response controller, other strategies can also be seamlessly integrated with the proposed approach to provide extra power support during frequency events and so to enhance the frequency response of the interconnected system. Such methods include but are not limited to the extraction of additional power from converter capacitors [38] or storage devices [39], and modulation of the converters’ reactive power output as in [40]. The development of a strategy combining different techniques for boosting the frequency response will be a subject matter of our future research.

VI. CONCLUSION

The mutual frequency response of the asynchronous ac systems interconnected through Voltage Source Converter based Multi Terminal High Voltage Direct Current grids was the subject matter of this paper. The proposed coordinated control structure was shown to enhance the frequency support between ac systems by redistributing the active power between converter stations. In particular, the proposed controller achieved frequency deviations based on pre-defined ratios considering the operational condition of the participating ac grids, allowing system operators to determine the extent of the assistance that the healthy grids provide to the system under the disturbance. The stability of the implemented controller was evaluated by conducting a modal analysis, revealing that the increase of the Assistant Factor improves overall system damping. The time-domain simulations proved the effectiveness of the proposed controller and demonstrated its ability to provide an extra degree of freedom in mutual frequency support.
APPENDIX

TABLE I
PARAMETERS OF THE STUDY SYSTEM IN FIG. 1 AND ITS CONTROLLERS

| Parameter | Value |
|-----------|-------|
| \( V_{dc, nom} \) | ± 400 kV |
| \( I_{nom} \) | 50 Hz |
| \( S_{base} \) | 1000 MVA |
| \( V_{bus} \) | 380 kV |
| \( V_{ripple} \) | 220 kV |
| \( V_{ripple} \) | 145 kV |
| \( H_{area1} \) | 3 s |
| \( H_{area2} \) | 2490 s |
| \( K_{Base} \) | 1 pu |
| \( K_{Real} \) | 20 pu |
| \( K_{Im} \) | 0.3 pu |

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