Abstract: The dynamic performance of voltage source converter-based multi-terminal high-voltage direct current (VSC-MTDC) grid for large-scale renewable energy integration is becoming a concern. This study proposes a system-level dynamic response model of wind farm (WF)-MTDC-main AC systems, and then analyses the dynamic performance based on the singular value decomposition (SVD) technique. In the modelling, an improved virtual synchronous machine control is developed, and the interaction between AC frequency and DC voltage can be naturally described. Using the SVD technique, parameters of the controllers are tuned, thereby making the AC frequency and DC voltage deviations within the limitations. Some oscillation modes of the system are observed and virtual power system stabiliser is proposed to suppress the oscillations. Additionally, the oscillation can be mitigated by emulating capacitance-based inertia response. The efficiency of the proposed model and analysis is verified through the frequency-domain and time-domain results.

1 Introduction

Voltage source converter-based high-voltage multi-terminal direct current (VSC-MTDC) is an effective way to realise large-scale and efficient utilisation of renewable energy sources such as wind power and photovoltaic (PV) power. With the VSC-MTDC technologies, the flexible DC power grid in Zhangbei, China, is under planning and construction, and it will collect ~7 million kW of wind power and other renewable energy into main power grid [1]. However, weak AC systems at the sending and receiving ends of the MTDC system are becoming a concern due to the lack of natural inertia and damping by using the power electronics relative to conventional synchronous generators [2]. The theoretical analysis, experiment, and field testing show that an integration of renewable energy generation through flexible DC grid is facing at the dynamic problems such as subsynchronous oscillations, harmonic instability, and so on. Therefore, a stable and safe operation of renewable energy VSC-MTDC system will be a vital challenge.

In VSC-MTDC interconnected AC/DC systems, VSC stations often use the phase-locked loop (PLL) to maintain their synchronisation with connected AC systems. However, weak inertia and damping at the sending and receiving ends of the system may deteriorate PLL synchronisation performance, even resulting in instability [3]. To improve the dynamic performance, a large number of literatures have proposed a variety of virtual synchronous machine (VSM) control methods for renewable energy distributed integration. The corresponding VSM-VSC small-signal modelling and dynamic analysis were performed in [4]. In addition, the VSM control strategy has been applied to high-voltage modular multi-level converter stations and HVDC interconnected AC systems [5–7]. The theoretical consideration and realistic engineering application of the VSM in terms of AC frequency and DC voltage responses need to be studied in a further step, aiming at a safe operation for high-voltage VSC-MTDC system.

The dynamic behaviour of MTDC-based AC/DC system can be analysed using the state-space eigenvalue analysis, impedance analysis, time-domain simulation, transient energy function, probability analysis, bifurcation theory, and so on. The VSC-MTDC system as a multi-input multi-output (MIMO) system poses a challenge to an application of the state-space eigenvalue analysis, for example, model dimension reduction, and eigenvalue extraction. The frequency-domain impedance analysis is essentially a Nyquist analysis, and it is difficult to apply it to the multi-variable systems. The singular value decomposition (SVD) is an efficient means to describe the dynamic characteristic and controller design of an MIMO system. Dehghani et al. [8] monitor the closeness of voltage collapse in wind power integration in AC systems by tracking minimum singular value and bifurcation points. However, the mentioned studies are limited to the singular value analysis at a single frequency. Khadja and Mohamed [9] used the SVD to optimise phasor measurement unit data in power systems, and then described the dynamic stability of the system. Prieto-Araujo et al. [10, 11] applied the SVD to an MTDC system where the DC voltage droop control parameters based on the SVD analysis of the complete system were tuned. The SVD can also be used to minimise the influence of AC disturbance on dynamic characteristics of the DC power grid [12]. In [13], the influence of different modelling methods on the dynamic characteristics of the AC/DC system via the SVD was evaluated.

In view of the above analysis, this paper proposes a novel self-synchronous control method for VSM which is applicable to VSC-MTDC systems, and then analyses dynamic characteristics of the system using the SVD technique. The main contributions in this paper are threefold. First, the traditional VSM control strategy is improved, and a virtual power system stabiliser (PSS) controller is introduced, thereby offering more damping to a stable operation of the MTDC system. Second, the dynamic characteristics of DC voltage and AC frequency of the MTDC/AC multi-variable system are analysed using the SVD to reveal an oscillation mechanism of the AC/DC system. Using the virtual PSS, the oscillations over a wide frequency range are suppressed. Third, the proposed modelling and analysis method are validated by the frequency-domain and time-domain simulation results.

This paper is organised as follows. Section 2 proposes a self-synchronous control method for VSC stations. A dynamic response model of AC frequency and DC voltage for a VSC-MTDC/AC system is developed in Section 3. The SVD-based dynamic analysis method is presented in Section 4. The modelling and analysis method is validated in Section 5. Conclusions are drawn in Section 6.
Assumed that the VSC-MTDC has an arbitrary grid topology, while loads through the AC grid. In order to simplify the analysis, it is introduced with the VSM control, respectively, where voltage droop control in this paper is combined with the VSM

\[ \Delta \omega_n = \frac{1}{T_{\text{pss}}} (\Delta v_n - \Delta v_{\text{ref}}) \]

2. System description

A multi-terminal VSC-HVDC for an integration of large-scale wind and PV power is schematically shown in Fig. 1. Assuming that there are \( m \) wind farms (WFs) connected individually to the sending end VSC converters where the local AC systems exist. The PV power station is directly connected into the DC network through the DC/DC converter. In this case, the VSC-MTDC collects and integrates the renewable energy to the main AC system. On the main AC system side, the \( N_{\text{dc}} \) receiving end VSCs and conventional synchronous generator supply power to the loads through the AC grid. In order to simplify the analysis, it is assumed that the VSC-MTDC has an arbitrary grid topology, while the main AC system is an isolated system, not divided into subsystems interconnected by tie lines.

In this section, the VSM control is used to emulate the swing motion of conventional synchronous machine, thereby leading to an active power–AC frequency regulation function. The DC voltage droop control in this paper is combined with the VSM active power–frequency control, as shown in Fig. 2, which can be expressed in the time domain as follows:

\[ J_{\text{dc}} \frac{d \Delta v_n}{dt} = P_{\text{ref}} - P_n - K_{\text{dc}} (\Delta v_n - \Delta v_{\text{ref}}) \]

where \( J_{\text{dc}} \) and \( K_{\text{dc}} \) are virtual inertia constant and damping introduced with the VSM control, respectively, \( K_{\text{dc}} \) is the droop gain of DC voltage control loop. By adjusting the value of \( K_{\text{dc}} \), the DC voltage droop control can be converted to constant power control or constant voltage control. By setting appropriate DC voltage droop and VSM damping gains, active power through the VSC can be controlled to obtain the self-synchronisation. Therefore, the angle position of the VSM control is given by

\[ \frac{d \delta}{dt} = \Delta \omega_n - \omega_n \]

It is noted that the active power through the VSC is regarded with the positive direction flowing from the DC side to AC side of the VSC. In this paper, the VSC is the inverter with VSM control acting as a generator, otherwise it becomes the rectifier with VSM control acting as a motor.

Fig. 2 gives a block diagram of a virtual automatic voltage regulator (AVR) where \( E_{\text{av}} \) denotes the VSC-VSM control internal voltage. The virtual AVR is typically used to increase or decrease the amplitude of \( E_{\text{av}} \), and thus, the reactive power can be regulated. In this paper, additional angular frequency control is proposed, whose function is similar to the PSS. The virtual PSS provides some damping to suppress DC voltage and angular frequency oscillations, and also offers additional output voltage for AVR. Taking into account the VSC AC-side voltage RMS reference value and its actual value, the virtual AVR and PSS are represented in the frequency domain as follows:

\[ E_{\text{av}} = \left( k_{\text{pu}} + \frac{k_{\text{pu}}}{s} \right) \left( u_n^{\text{ref}} - u_n + \Delta u_{\text{pss}} + \Delta u_{\text{vss}} \right) + E_o \]

where \( k_{\text{pu}} \) and \( k_{\text{pu}} \) are PI controller parameters, \( k_{\text{pss}} \) is the virtual PSS gain, \( T_{\text{av}} \) and \( T_{\text{pss}} \) are the time constants of phase compensation. For simplification, the reactive power reference is set to zero, and dynamic performance of reactive power control is ignored. In this paper, the upper score indicates a per-unit value, and for simplifying notation, the upper score hereafter is ignored. The VSC-VSM loop provides the voltage phase and amplitude references for the VSC inner-outer loop control which presents the DQ-reference frame decoupling control. Such control loop generates the nearest level modulation signal to drive the VSC.

3. Dynamics response modelling of VSC-MTDC/AC systems

The dynamics of the complete WF-MTDC–AC system can be modelled by dividing it into multiple regions individually covering converter station, WF or PV, local system as well as main AC system. Fig. 3 shows a schematic diagram of multiple regions in which each region can be represented by AC frequencies or DC voltages. The dynamic control of multiple-region division is similar to primary frequency control of conventional interconnected subsystems connected by tie lines. In this context, multiple areas interact through active power transmission along the tie line, which is presented in this paper with the WF-VSC AC line, VSC–VSC DC line, and VSC-conventional power plant AC connection, as denoted by the double arrows in Fig. 3. Increasing or decreasing exchanged active power will result in a complex interaction between the DC voltages and AC frequencies. In order to study the dynamic characteristics of interaction between different regions, low-order DC voltage–AC frequency response model of WF-MTDC–AC system is developed in the following.

3.1 DC voltage response model

Although the energy storage capacity of a capacitor in the DC grid is limited, the VSC converter station can be used to temporarily support primary DC voltage response. As illustrated in Fig. 1 that the VSC DC side may be modelled with an equivalent capacitance and equivalent resistance, and the latter takes into account the VSC switching and resistance losses, \( P_{\text{loss}} = \frac{u_n^2}{R_{\text{loss}}} \). The DC voltage dynamics of the equivalent capacitance can be expressed as

\[ C_{\text{eq}} \frac{d u_n}{dt} = \sum_{k=1}^{N_{\text{dc}}} P_k - P_{\text{ref}} - \frac{u_n^2}{R_{\text{loss}}} \]

where \( C_{\text{eq}} \) denotes the VSC and transmission line capacitances, and \( N_{\text{dc}} \) is a set of transmission line ends connected to the nth converter. Herein, a virtual inertia is defined as the ratio of the energy storage with respect to rated active power \( P_{\text{Sref}} \), therefore,

\[ \frac{C_{\text{eq}}}{P_{\text{Sref}}} \]
H_{eqp} = 0.5C_{eqp}\frac{\partial^2\phi_{dc}}{\partial \phi_{dc}^2} P_{scn}. Substituting it for that in (5) and linearisation of the equation lead to

\[2H_{eqp}\frac{\partial \phi_{dc}}{\partial \phi_{dc}} \frac{d\Delta u_{dcn}}{dt} = \sum_{i=1}^{m} \Delta P_{in} - \Delta P_{en} - D_{eqp}\Delta u_{dcn}\]

(6)

where \(D_{eqp} = 2\Delta u_{dcn}(P_{loss})\). Depending on a small deviation around the operating point, (6) can be written in a transfer function form as

\[\Delta u_{dcn} = \frac{1}{2H_{eqp} + D_{eqp}} \left(\sum_{i=1}^{m} \Delta P_{in} - \Delta P_{en}\right)\]

(7)

On the other hand, it is common practice to use lumped-parameter PI model to describe the dynamics of DC transmission lines. Herein, the capacitance of transmission lines are added to \(C_{eqp}\). The dynamics of cascaded resistance–inductance (\(r_1, r_2\) in Fig. 1) are replaced by \(m, n\) can be expressed as follows:

\[L_{rn} \frac{du_{rn}}{dt} = u_{dcn} - u_{dcn} - i_{rn} R_{rn}\]

(8)

where the self-flux is defined as a function of DC voltage deviations, \(\Delta \phi_n = \int \Delta u_{dcn}\) and \(\Delta \phi_n = \int \Delta u_{dcn}\). Around the operating points, (8) is expressed in the per-unit form as

\[\frac{d\Delta P_{pmn}}{dt} = -\frac{R_{rn}}{L_{rn}} \Delta P_{pmn} + \frac{v_{dcn}^2}{L_{rn} P_{pmn}} (\Delta u_{dcn} - \Delta u_{dcn})\]

(9)

Equation (9) is written in the frequency domain as

\[\Delta P_{pmn} = G_{pmn}(s)(\Delta \phi_n - \Delta \phi_n)\]

\[= \frac{\Delta u_{dcn}}{(s + R_{rn})P_{pmn}} (\Delta u_{dcn} - \Delta u_{dcn})\]

(10)

3.2 AC frequency response model

Proceeding a similar way of deriving (6), inertia constant of the VSM is defined as \(H_{sc} = 0.5J_{sc} \omega_0^2 / P_{scn}\), and then inserting it into (1) yields

\[2H_{sc} \frac{\partial \omega_{scn}}{\partial \omega_{scn}} \frac{d\Delta \omega_{scn}}{dt} = -k_{scn}\Delta \omega_{scn} + k_{dcn}\Delta u_{dcn}\]

\[+ \Delta P_{VSCn} - \Delta P_{en}\]

(11)

where the power–frequency damping coefficient in a per-unit is \(k_{scn} = K_{scn}\omega_0 / P_{scn}\) and the per-unit DC voltage droop gain is \(k_{dcn} = K_{dcn}\omega_0 / P_{scn}\). \(P_{VSCn}\) is the active power reference, and it can be obtained from secondary DC voltage and AC frequency control. In this paper, the WFs are assumed to participate in primary frequency control at the sending AC systems of the MTDC. The frequency dynamics of the sending AC system can be described as referred to [14]. In addition, following a generation-load mismatch in main AC systems, primary frequency control is often provided by conventional turbine-governing systems. The corresponding AC frequency dynamics of main AC system is described in [15]. Now, it is a key step to calculate transmitted power between different frequency areas, for example, \(\Delta P_{en}\) in Fig. 3, and application of small-signal modelling in a per-unit form yields

\[\Delta P_{en} = \left(a_{in} + \frac{\omega_0}{s}\right) (\Delta \omega_{scn} - \Delta \omega_{pss})\]

(12)

where

\[a_{in} = \frac{\alpha_{in}k_{pss}\omega_0}{E_{in}}\]

\[a_{in} = \frac{\alpha_{in}(\omega_0k_{pss} + v_0E_{v0})}{E_{in}}\]

(13)

4 Dynamics evaluation of MTDC/AC system using the SVD method

To describe the dynamic response behaviour of WF-MTDC participating in primary frequency regulation, a state-space equation of Fig. 3 can be obtained

\[x(t) = Ax(t) + Bu(t)\]

(14)

where \(x(t)\) is the state variable and \(u(t)\) the disturbance.

\[x = \left[\begin{array}{c} m \in 1, \cdots, M_k \\
\Delta \omega_{WFk}, \Delta \omega_{VSCk}, \Delta \omega_{pss}, \cdots, \\
l \in \{1, \cdots, N_k\}, \Delta \omega_{scn}, \Delta \omega_{dcn}, \Delta \omega_{ls}, \Delta \omega_{pr}\]
\end{array}\right]

(15)

\[w(t) = [m \in 1, \cdots, M_k, \Delta P_L]^T\]

(16)

In this paper, secondary control commands are set to be constant, that is, \(\Delta P_{VSC} = 0\). This is because that the secondary control-related dynamics are slower than that of the primary control responses. Using the SVD technique, a complex value matrix of dimension \(l \times m\) can be decomposed into

\[A = UV^\dagger\]

(17)

where \(\Sigma\) is the \(l \times m\) singular value matrix which has \(\sigma_1, \sigma_2, \cdots, \sigma_r\) as its diagonal entries that present a descending order (\(r = \min(l, m)\), non-diagonal entries are zero), \(U\) and \(V\) are left and right singular value vectors, respectively, \(U = [u_1, \cdots, u_l]\) and \(V = [v_1, \cdots, v_m]\), and \(V^\dagger\) is a conjugate transpose matrix of \(V\).

Now the SVD is applied to a multi-variable transfer function matrix \(G_k(j\omega)_m\), and the latter can be obtained by converting (14) in the frequency domain as

\[G_k(s) = \frac{B}{s I - A}\]

(18)

Then this matrix can be expanded in a further step as

\[G_k(s) = U(s) \Sigma V^H(s)\]

(19)

The curve of maximum singular values approximates the maximum gain (equivalent to \(L_2\) norm) of the multi-output variables with respect to the multi-inputs in the frequency domain. According to the singular value curve, dynamic performance of the transfer function matrix can be presented with its amplitude, resonance peak, and other indicators. In addition, the sensitivity analysis of singular value can be used to find a direct relationship between the oscillation frequencies and transfer function parameters such as controller and electrical parameters.

5 SVD dynamic analysis and simulation verification

In order to analyse dynamic behaviour of the proposed response model using the SVD method, a five-terminal VSC-HVDC meshed grid with rated DC voltage of ±500 kV is employed. As shown in
be maintained within the allowable deviation range. In this paper, the fluctuations are assumed to be within ±10% with respect to the rated power of the system. Following such disturbances, the AC frequencies and DC voltages of the AC/DC system are controlled within ±5%. This can be achieved with the regulation from the VSC-VSM controls, WF frequency controllers, as well as SG speed regulator that are based on available inertia and damping in such AC/DC systems.

The singular value of the MIMO system reflects the maximum output-input gain [17], and it can be controlled over a wide frequency range by adjusting the controller parameters. In this section, the VSM damping coefficients and the DC voltage droop coefficients are tuned. Table 1 gives three sets of the parameters, and the singular value curves of this system in such cases are shown in Fig. 5. During the steady state and low-frequency range, the singular values using the second and third sets of the parameters are within the allowable limitations. However, over the high-frequency range, the singular value peaks at the frequencies $f_1 = f_2 = 119.16 \text{ Hz}$, $f_3 = f_4 = 47.74 \text{ Hz}$, $f_5 = f_6 = 32.42 \text{ Hz}$ significantly exceed the constricted values. This implies that if frequencies of wind or PV power fluctuations appear at the same points, then oscillations even instability of the system may occur. This can also be verified with eigenvalue analysis of the state-space equations where some eigenvalues are located at the right-hand side of the plate. With the sensitivity analysis, the peak values of singular values cannot be eliminated by adjusting the droop and damping coefficients.

### Table 1 \ AC frequency/DC voltage damping and droop coefficients

| Case  | VSM damping coefficients | DC voltage droop coefficients |
|-------|--------------------------|------------------------------|
| 1     | 20.2 24.3 62.99 60.59    | 16.3 18.4 3.2 5.6            |
| 2     | 4.28 5.42 17.5 15.2      | 2.33 2.68 0.5 1.1            |
| 3     | 4.28 5.42 17.5 15.2      | 16.3 18.4 3.2 5.6            |

### Fig. 4 Schematic diagram of a five-terminal VSC-HVDC and AC system for wind and PV power integration

The virtual PSS is added to the VSM control, and provides virtual damping to oscillations as mentioned above. As shown in Fig. 6, with an increase in the PSS gain, more damping is obtained for most modes of the system. When increasing the PSS gains, the synchronising torque coefficient between the VSM-VSC and AC systems is increased, thereby improving the dynamic stability of the system. It is of interest that for the natural frequency $f_9$, the damping becomes negative when the gain is $<75$, even that no PSS means negative damping.

As shown in Fig. 7, when $K_{pss}$ is chosen as 150, the singular peak values at frequencies 47.74 and 32.42 Hz are damped. This can be verified through the time-domain simulation of the system when it is subjected to sudden increase in PV power generation, for example. As shown in Figs. 7 and Fig. 8 when $K_{pss}$ equals to 75, the DC voltage and AC frequency responses show the oscillations with a period of 0.0028 s. The latter is consistent with the oscillation period of 120 Hz as predicted in Fig. 7. On the other hand, when $K_{pss}$ is increased to 225, the oscillations are damped. As shown in Fig. 8, however, during the transition, there is a sudden change of the responses, and then the medium–high-frequency oscillations of the AC/DC system can be suppressed.

### 5.2 Virtual PSS-based oscillation suppression

When subjected to a fluctuation from the wind power, PV power, or loads, the DC voltage and AC frequency of the system need to

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J. Eng., 2019, Vol. 2019 Iss. 16, pp. 893-898
5.3 Inertia-based dynamic performance improvement

The PV power station is connected to one terminal of the DC grid through the cascaded DC/DC converters. Since the DC/DC converters herein present weak inertia, with the sensitivity analysis of singular value, it is known that the capacitance setting at the DC/DC converter will affect the singular peak values at the oscillation frequencies as noted above. By increasing the capacitance value, the singular peak values over middle–high-frequency range are reduced within the limitations as shown in Fig. 9.

Figs. 10a and b show the oscillation frequencies and damping ratios of 22 modes of the system, respectively. For most of the modes, the natural frequencies decrease as the capacitance value of the DC/DC converter is set larger. The frequencies of modes 1, 2, 5, 6, 9, and 10 are changed, and this is the same case for the damping ratios. According to the sensitivity analysis, such modes are related to the states of DC grid, which presents high natural frequencies with low damping ratios. These results are consistent with those of fast-changing dynamics of the DC grid.

Following a sudden drop of wind power input at WF 1, the AC frequencies and DC voltages have also a drop as shown in Fig. 11. The oscillations are suppressed in a further step with an increase in the capacitance by ten times, and this is clearly illustrated by the zoom-in figure. Therefore, the dynamic performance of DC voltage is improved by adding the capacitor-based inertia constant. Other than the capacitance increase, it is still a challenge to obtain more damping for high-frequency modes in the MTDC systems.

6 Conclusion

The system-level dynamic response model and corresponding SVD analysis of renewable energy-MTDC–AC systems are developed and validated. It is instructive to use the proposed model to analyse the dynamic interaction between DC and AC systems. The SVD analysis reveals that transmitted active power flowing from AC to DC or vice versa, similar to tie-line power between the interconnected AC systems, influences the DC voltage and AC frequency response performances. Based on the SVD, the periodic oscillations over middle–high-frequency range are observed, and they are readily suppressed by tuning virtual PSS gains, thereby leading to less oscillation. In addition, by adding more capacitance-based inertia can improve the dynamic performance of the system.

7 Acknowledgments

The authors gratefully acknowledge the financial support in part by the National Natural Science Foundation of China (no. 51707183), in part by Key Front Science Project of the Chinese Academy of Sciences (no. QYZDY-SSW-JSC025), and in part by the...
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