Abstract — This paper presents a detailed case study of small-signal stability analysis for the Cigré DC-grid test system. The presented investigations are intended for identifying critical modes of interaction between different parts of the electrical system and the controllers in multi-terminal HVDC (MTDC) schemes. Oscillatory and critical modes of the system are investigated by modal analysis, including participation factor analysis and studies of the parameters sensitivity. The potentially unstable modes are investigated by calculating the participation factors of the system, which identify the influencing components. The sensitivity of the eigenvalues to the control parameters is also presented in order to reach an improved control design for MTDC with sufficient damping and enhanced dynamic response. Time-domain simulation results are further presented in order to verify the transient performance of the control system.

Keywords — DC power systems, Offshore Grids, Multi-terminal HVDC, Small-signal Stability, System Interactions

I. INTRODUCTION

HVDC transmission based on Voltage Source Converters (VSCs) is becoming the preferred solution for grid connection of large-scale offshore wind farms at long distances from shore. Further developments of offshore wind power together with future VSC-based HVDC interconnections between existing AC grids are expected to result in multi-terminal HVDC (MTDC) grids. Plans for such MTDC grids have especially been considered relevant in the North Sea region, due to the foreseen requirements for electric power transmission infrastructure associated with existing plans for offshore power generation as well as electrification of oil installations. There will also be significant benefits of more interconnections between the countries surrounding the North Sea [1], [2]. Similar plans for offshore HVDC grids are also considered for integration of offshore wind power from Northern Africa in the Mediterranean region, and for integration of offshore wind power along the east coast of the US [3, 4]. Thus, there are indications that MTDC will be a potential attractive solution for the grid integration of offshore resources in the near future [5]. In the longer term, meshed VSC-based HVDC grids have also been envisioned for future large scale overlay grids covering mainland Europe. However, until now, the only operative VSC-based MTDC grid is a three-terminal grid recently commissioned in China [6].

Although there are remaining challenges with design of protection systems and interruption of fault currents in HVDC grids, construction of such large systems is considered technically feasible with available cables and VSC technology. Many studies of modelling, control and operation of multi-terminal VSC-based HVDC system have therefore been published during the last few years, in parallel with technology developments of DC circuit breakers and protection systems for meshed DC grids [7]. Since there is not yet any practical validation of large-scale multi-terminal HVDC grids, these studies have been based on simulations of various system configurations with a wide range of system parameters. Therefore, the B4 working groups of Cigré have recently proposed a DC-grid test system which is intended as a common reference that can allow for easier comparison of results from various types of investigations [8].

From the general characteristics of VSC-based HVDC converter stations and previous interconnection studies, it is clear that the controllability of multi-terminal HVDC grids can benefit the overall power system [9]. The utilization of this control capability can however influence the stability properties of the system [10]. Eigenvalue analysis of a linearized small-signal system model can, therefore, be an important tool for studying the interactions between the system configurations and the converter control systems. This paper will present and discuss the results of small-signal stability analysis of this Cigré DC grid test system modelled in DlgSILENT Power Factory [11]. The oscillatory and critical modes of the system are identified, and participation factor analysis are presented to reveal which states that are influencing these modes [12]. Parameter sensitivity analysis is also presented to identify how important physical system
parameters and controller settings of the HVDC converters can be modified to improve the overall system stability. Stability improvements obtained on basis of the small-signal analysis are verified by time-domain simulations of the complete Cigré DC grid test system.

II. SYSTEM MODELING AND CONTROL

The investigated MTDC system is implemented by three-phase VSCs, which are all modelled by conventional averaged models represented as a voltage source on the AC-side and a current source on the DC-side [13]. The converters are assumed to have a filter inductor modelled as a series RL circuit, but any filter capacitor or tuned harmonic filters are neglected in the following investigations. An overview of the configuration of one converter unit and the corresponding control structure is shown in Fig. 1. The control system of VSCs, used in this study, is described in this section.

A. Current Controller

The current-control establishes the core of the VSC controller. A Synchronous Reference Frame (SRF) decoupled vector control scheme is used, in which the d-axis of the SRF is aligned with the voltage vector (v_f) at the grid side of the filter inductor by a Phase Locked Loop [14]. The controller is designed to regulate the decoupled dq components of the ac-side currents by providing the voltage reference for the pulse-width modulation (PWM) switching strategy of the converter. Neglecting the PWM switching transients, the dynamic behaviour of the output three phase currents i_{abc} is described by the space-vector equation according to (1) [10].

\[
v_{f_{abc}} - v_{c_{abc}} = R_{i_{abc}} I_{abc} + L \frac{d}{dt} i_{abc}
\]  

(1)

In this equation i_c, v_c and v_f are the space-vector representations of three phases converter current, converter voltage, and output voltage, at the point of common coupling (PCC), for each converter station. The VSC terminal voltage is controlled by the modulation vector in terms of its dq-frame component. The complex space-vector representation of the modulation index (m_{dq}) is calculated from the control command (u_c) produced by the current controller, according to:

\[
\begin{bmatrix}
  m_d \\
  m_q
\end{bmatrix} = \frac{2}{U_{dc}} \begin{bmatrix}
  u_{c_d} \\
  u_{c_q}
\end{bmatrix}
\]

(2)

This effectively decouples the performance of the ac side control of the converter from variations in the dc link voltage. Then, the converter voltage (v_c) is resulted in the converter model, by using the control signals. Finally, the output current is resulted from the circuit model of the RL filter \( \frac{1}{R+L} \) based on the equivalent circuit parameters expressed in (1). The schematic of the decoupling current controller together with the converter and filter inductor model is indicated in Fig. 2. The time-domain equation of the d- and q-axis current components assuming an operating point with an angular frequency \( \omega \) is given by (3).

\[
L \frac{d}{dt} \begin{bmatrix}
  i_d \\
  i_q
\end{bmatrix} = \begin{bmatrix}
  v_d \\
  v_q
\end{bmatrix} - \begin{bmatrix}
  v_{d_c} \\
  v_{q_c}
\end{bmatrix} - R \begin{bmatrix}
  i_d \\
  i_q
\end{bmatrix} + aoL \begin{bmatrix}
  0 \\
  1
\end{bmatrix} \begin{bmatrix}
  i_d \\
  i_q
\end{bmatrix} + \begin{bmatrix}
  0 \\
  -1
\end{bmatrix} \begin{bmatrix}
  i_q \\
  -i_d
\end{bmatrix}
\]

(3)

The controller uses a proportional-integral (PI) compensator as follows:

\[
\begin{bmatrix}
  u_{r_d} \\
  u_{r_q}
\end{bmatrix} = aoL \begin{bmatrix}
  0 & 1 \\
  -1 & 0
\end{bmatrix} \begin{bmatrix}
  i_d \\
  i_q
\end{bmatrix} - k_{r_d} e_{r_d} - k_{r_q} e_{r_q}
\]

(4)

The current controller scheme enables decoupled control of active and reactive power by controlling the d-axis and q-axis current components, respectively. In this case, the q-axis component of voltage is settled to zero as long as the control system is synchronized to the grid voltage by the PLL. Therefore, the active power generated or absorbed by the converter is determined by the d-axis voltage and d-axis current of the converter \( (P = v_{d_f} i_{d_f}) \), while the reactive power is given by the d-axis voltage and the q-axis current \( (Q = -v_{d_f} i_{q_f}) \). The reference currents \( (i_{r_d}, i_{r_q}) \) are resulting from the outer loop control which is described in the next section, and determines the dynamic behaviour of the current components generated by the converter. The Controller parameters used in this study are given in Appendix.

B. Outer Control Loops and Droop Control

The outer-loop of the control system for VSC-HVDC converters is associated with the active and reactive power flow, as well as the DC voltage control. The outer-loop provides the current references for the current controllers \( (i_{r_d}, i_{r_q}) \). The d-axis reference current \( (i_{r_d}) \) is usually produced by a power controller or a DC voltage controller. The q-axis reference current \( (i_{r_q}) \) is usually produced by a reactive power controller or AC voltage controller. For operation in an islanded system, the d- and q-axis current components can also be given by voltage controllers for regulating the d- and q-axis components \( (v_{d_f}) \) and \( (v_{q_f}) \) of the output voltage. The operator of the system can select among these control functions depending on the application and the operating conditions of the converter. For generality, all the control functions can be included in the control system of a converter terminal, and an interface block can be used for selecting which control loops provide the reference currents as

---

Fig. 1. Control system for VSC-HVDC converter connected to an AC grid

Fig. 2. Current controller and converter model
The droop control can be used in multi-converter systems, as the upper control level, for allowing the converters to participate sufficiently in the voltage and frequency regulation of the grid. In the distributed control approach for MTDC system, one converter has the main responsibility for the DC voltage regulation and others use power control with droop functions in the outer-loop to contribute to the DC voltage control [16]. The droop characteristic shown in Fig. 3 is assumed to be a linear relation between the dc voltage and the power such as: \[ P_{\text{ref}} = P^i + R_{\nu,dc}(U_{\text{dc}} - U_{\text{dc}}^i). \] Where, \( P^i \) is the power set-point of an individual converter, \( U_{\text{dc}}^i \) is the set-point of the DC voltage, and \( R_{\nu,dc} \) is the droop gain. The droop gain represents the characteristic of the voltage deviation in portion to the power deviation such as:

\[
R_{\nu,dc} = \frac{P_{N,i}}{\rho_p U_N}
\]

Where, \( P_{N,i} \) is the rated power capacity of each converter, \( U_N \) is the rated operating DC voltage and \( \rho_p \) is slope of the droop curve. The impact of the variation of \( R_{\nu,dc} \) on the stability of the system is investigated in Section IV-D. In a similar way, a droop gain \( K_f \) is introduced for the frequency droop scheme which is set to a constant value [17].

C. Small Signall stability and Participation Factors

Modal analysis is associated with calculation of the eigenvalues and eigenvectors of the linearized dynamic model of the system composed by the controllers and the electrical circuits. The small-signal stability properties of system can be investigated by studying the eigenvalues of the linearized state space model of the system on the form \( \Delta X = A \Delta X + B.U \). Assume a system with \( n \) state variables and \( n \) eigenvalues, whereof some eigenvalues are complex conjugate pairs expressed as: \( \lambda_{i,j+1} = \sigma_i \pm j\omega_i, \ i \in n \). Then for the right eigenvector \( \Phi_i \), the contribution of a state variable in an oscillating mode can be calculated as:

\[
\Delta x_i(t) = \sum_j c_j \Phi_j e^{\lambda_j t}
\]

Where, \( c_i \) is the excitation of the mode \( i \) in the initial step, and \( \Delta x_i(t) \) is the deviation of the state variable. The right eigenvectors \( \Phi_i \), and in a similar way left eigenvectors \( \Psi_i \), play the main role in identification of mode activities.

The elements of the right eigenvectors, called observability vector, represents the mode shape of the eigenvalue \( \lambda_i \) and shows the activity of the state variable while a specific mode is considered. The left eigenvectors observe the activity of a state variable in the mode \( i \). The combination of these two factors results in a comprehensive factor called “participation factors”, which give an appropriate indicative identification of the dynamic behaviour of the system [12]. The participation factors are important for power system stabilizer design. The eigenvalues and the participation factors are calculated in Section IV, in order to study the influences of the controllers on the general oscillation pattern of the system. To study the sensitivity of modes to the system states, the location of selected poles is identified while changing the control parameters and system components.

III. REPRESENTATION OF CIGRE DC GRID TEST SYSTEM

As discussed in the previous section, several control strategies are presented for MTDC, and among them DC voltage droop as a general approach for managing both power and voltage regulation. However, none of them are implemented and tested on a real large-scale VSC-based MTDC system. Researches in this topic have had the problem of lack of a benchmark for control and stability studies. The multi-terminal DC grid test system, proposed by the B4.57 group of Cigre [8], is considered in this paper as a relevant case study for control and stability studies of such future systems. This test system is based on a meshed topology of a DC grid consisting of several VSCs and DC-DC converters.

A diagram with an overview of this grid is shown in Fig. 4. As seen from the figure, the Cigre DC grid test system consists of offshore- and onshore-side grids with two DC voltage levels and connection to the AC grids on onshore-side which are considered as reduced order synchronous machine equivalents. In the diagram, dashed lines represent cables in offshore-side and the solid lines are overhead lines in onshore-side of the DC grid. There are two different voltage levels in different parts of the grid, which are linked at one point by a DC-DC converter. The voltage level in onshore (right-side) is ±400 kV and in the offshore-side (left-side); the area C and D (upper part) operate in ±400 kV, and area E and F (lower part) have voltage level ±200 kV. In addition to the DC-DC
converter used to adapt the DC voltage levels, there is also one
DC-DC converter station for controlling the power flow
between two areas.

In Fig. 4, the buses connected to different type of converter
stations are labelled with prefixes. The term “Ba” is used for
onshore AC buses with voltage 380 kV. The term “Bo” is for
offshore AC buses with voltage 145 kV. Symmetrical
monopole DC buses with voltage ± 200 kV are indicated with
“Bm” and bipole DC buses, which have voltage rating ±400
kV, with “Bb.” Consequently, the symmetrical monopole
converter stations with single VSC are shown with “Cm”, bi-
pole converter stations with two VSCs with “Cb” and DC-DC
converters are mentioned with “Cd”. Symmetrical monopole
converter stations consist of one VSC at ± 200 kV DC
operating voltage whereas bipole converter stations consist of
two VSC at ±400 kV.

The onshore area A consists of two busses Ba-A0 and Ba-
A1. Bus Ba-A1 is connected to two VSCs, a symmetrical
monopole and bi-pole converter. Bus Ba-A0 is the reference
for the load angle. The area A transfers active power to the DC
system. Onshore AC area B has three busses Ba-B1, Ba-B2,
Ba-B3 which are connected to the VSCs, and the bus Ba-Bo is
a slack bus. Offshore buses C, D and F are connected to
offshore wind farms, and bus E is supplying offshore loads on
an oil and gas platform. The offshore load is considered as a
constant power load (CPL) and the wind farms as power
sources. The ac slack busses are modelled as voltage source
with impedance ratio (R/X) of 0.1 and maximum short circuit
power is 10 GVA. The secondary frequency bias setting is
with impedance ratio (R/X) of 0.1 and maximum short circuit
sources. The ac slack busses are modelled as voltage source
constant power load (CPL) and the wind farms as power

A. Time Domain Simulation

The time-domain simulations in DiGILENT Power Factory
software can be conducted with two different approaches; by RMS
simulation with simplified transient models or by detailed
ElectroMagnetic Transient (EMT) models. Electromagnetic
dynamics of electrical networks are neglected in the RMS
simulation, and AC voltages and currents are represented only
by their phasor magnitude and phase angle. For stability
analysis of the control design, the RMS simulation mode is
more suitable as it uses less computation times [11]. Examples
of EMT simulations of point-to-point connection within the
Cigré DC test grid system are presented in [18]. Here, the time
domain simulations are given only in RMS, in order to save
the calculation time.

Prior to the transient simulation, the power flow is carried
out, and the results of power flow are used for the design of
the droop control. The controllers use different control
strategies such as active power control, reactive power control,
frequency control, and DC voltage droop control as discussed
previously. Referring to Fig. 4, converters Cb-B1 and Cb-B2
are introduced to supply a controlled active and reactive power
to the AC grid. Converters Cm-A1 and Cm-B2 regulate the
DC voltage and reactive power. Converter Cm-B3 controls the
active power and AC voltage, since it is connected to a weak
AC grid and needs to participate to voltage regulation.

Converter Cm-F1 is introduced as a slack bus, and Cm-E1
supplies an offshore load, which is considered as a constant
power load (CPL). Converter Cb-C2 is controlling the power
supplied from the offshore wind farm to the DC grid. The
converter Cb-A1 is functioning to provide the reactive power
service. Converters Cb-B1, Cb-B2, Cb-B3, Cb-C2 are
equipped with the frequency and voltage droop, and therefore,
participate in frequency and DC voltage regulation together.
The AC cable between buses Bo-C1 and Bo-C2 is overloaded
at the initial step, because of the reactive power transfer
between the two converter stations. Consequently, these two
buses have overvoltage problem which is solved by using the
reactive power-AC voltage (Q-V) droop.

The offshore load at bus Bo-E1 is consuming 100 MW and
wind farm at bus Bo-F1 is producing 500 MW. There are also
three loads connected at buses Ba-B1, Ba-B2 and Ba-B3. The
RMS voltages of the onshore- and the offshore-sides, the DC
voltages and the frequencies on the buses are shown in Fig. 5.
In Fig. 5(a); the bus Ba-A1 has the lowest AC voltage
deviation, as the converter Cb-A1, connected to this bus, is
operating in voltage control mode. The set-point of the AC
voltage is 1.0 pu, and for the DC voltage 1.01 pu. However,
the bus Ba-B1 has voltage above 1 pu, as it is controlled to
provide the requested power without voltage regulation. In the
offshore side, the buses Bo-C1 and Bo-C2 have transient
overvoltage as shown in Fig. 5 (b), since the AC cable is
producing reactive power which increases the bus voltages.
The converter Cb-C2 is working as a rectifier and the reactive
power droop provides the AC voltage regulation. In this case,
we do not use the direct AC voltage control, and the reactive
power droop is regulating the voltage.

In this case, the initialization transient of the simulation is
used in order to assess the dynamic properties of the control
system. It should also be noted that the transient over-voltages,
seen in Fig. 5(b), are because of the initial conditions of the
grid (at t=0s), and the time response of the reactive power
droop on the converter station Cb-C2. The droop scheme is
not fast but is advantageous as it does not need the
communication systems in for operation of the control loops.

The DC voltages of different converter stations are shown in
Fig. 5 (c), for the onshore and offshore areas. The dc voltage
of converter Cb-A1 is kept on the voltage set-point of this
converter (1.01 p.u.) since it is operating as DC voltage
controller for the bi-pole DC system. In case of the converter
Cm-A1, voltage deviation is observed due to the dominant
effect of the AC system. It is because of the connection to a
weak AC grid (bus Ba-A1), but anyway the system remains
stable, and the DC voltage is settled in 1 pu as expected. The
reactive power control on converter Cb-C2 provides stable
voltages on this section (bus Bo-C2). The frequency droop is
not used for normal operation of the system. The frequencies
of the AC buses are acceptable without any large deviation,
as seen in Fig. 5 (d). However, the frequency of the area A is a
bit low as the converter Cb-A1 is feeding power into the DC
grid with high power rating and fixed set-point without
frequency droop.
The DC voltage of Cm-B3 is slightly lower than others, because the converter is injecting power into the AC system, and the resistance in the DC grid causes a voltage droop. However, this negative effect could be attenuated by using the droop control on the cost of reduced power flow.

The simulation is repeated for the case that the reactive power droop on converter Cb-C2, and Cm-B3 are switched off and the AC voltage controller is used instead. In this case, the AC cable is also producing reactive power. Hence, the voltages of these two offshore busses are rising and the DC links face over-voltages as shown in Fig. 6. The main problem is caused by the uncontrolled voltage on the critical bus Bo-C1. However, it affects the total DC grid after few cycles.

As a next step of investigation, we eliminate the DC voltage droop on the converter Cb-B1, and a normal PI controller is used instead. The bus voltages of the onshore side (Area A and B) are presented in Fig. 7. The RMS voltages have unstable oscillations in this case because the control of the system is missing the dynamic power set-point. The droop control can effectively give the set-point of the controller, based on the state of the system, but when the voltage droop is deactivated, the initial set-point is used by the controller which cannot always provide stability of the system. In the next section, the behaviour of the converters is scrutinized with modal analysis to further identify the causes of the identified instability effects.

B. Modal Analysis

The stability of the DC network is analysed with small signal stability tools as described before. The oscillatory modes of the system are the main target of the stability analysis as long as no unstable real poles are identified. The eigenvalue calculation is done for different control modes, such as active and reactive power droop, DC voltage droop, and AC voltage controller. This is needed in order to investigate the influence of the droop control on the dynamic stability of the system. The pole locations selected modes in the studied system are indicated in Fig. 8, where the modes are classified according to their dominating participation factors as identified with various colours and markers. Fig. 8 (a) illustrates the oscillating modes for stable system. In the case that the voltage droop control for converter Cb-B1 is eliminated (as shown in Fig. 7), the pattern of the unstable system is given in Fig. 8 (b).

The participation factor analysis used to plot the results in Fig. 8 makes it possible to identify which states are related to a specific mode. For example, for the unstable system in Fig. 8 (b), the unstable complex conjugate modes are associated with the voltage controller, which is classified as outer loop control. However, based on this classification, it is also found that the fast oscillatory modes in the system, marked by green * in the figure, are related to the capacitors connected to the DC side of the converters. Low frequency modes are related to the PLLs of the converters, and far poles (the modes with high real value) are associated with the measurement filters in the controllers. The very slow oscillatory modes are related to outer loop control, which can be droop control or PI voltage control.
controllers, as discussed before. However, identification of the control components which are contributing to the critical modes is a systematic way to design proper controllers in multi-converter system. The participation factors are therefore a convenient index for observing how the controllers and system states participate in unstable and oscillatory modes of the system.

A similar analysis is also performed for the case when the reactive power droop on converter Cb-C2 is deactivated. In this case, the unstable mode $\lambda = 33.728 \pm 0.0$ appears in the right-hand of the complex pane, as indicated by the instability observed in the time-domain results from Fig. 6. The participation factors for $\lambda = 33.728 \pm 0.0$ are calculated for this case, and plotted in Fig. 9 (a). In this case, the AC voltage controller has the most contribution of participation; however, AC voltage measurement filter and PLL are also associated with this mode.

Another unstable mode is considered when the reactive droop on the monopole converter Cm-B3 is eliminated. In this case, the power balance on the bus Ba-B3 is not maintained, and the unstable mode $\lambda = 9.337 \pm 0.0$ appears in the eigenvalues of the linearized system. The participation of control parameters to this mode are indicated in Fig. 9 (b). Again the voltage controller and the measurement filter have the highest participation.

The next unstable case occurs when the voltage droop is eliminated from the outer loop control of converter Cb-B1. The oscillating unstable mode $\lambda = 1.974 \pm 31.19$ occurs in this case, which is seen also from time-domain simulation in Fig. 7. The dominant participation factors of this mode are shown in Fig. 9 (c). The DC voltage controllers (C.Vdc) of the converters Cm-B2, and Cb-A1, which are connected on the DC side of this converter, participate in this mode. However, the converters own PLL and measurement filters are associated with this mode as well. This study illustrates the potential interaction of the controllers in a multi-converter system. Consequently, the controllers should be designed taking into account the impacts of the system and the controllers of other converters. Similar modal analysis of point to point and four terminal configurations as sub-systems within the Cigré DC grid test system are presented in [18], to indicate how the stability is influenced when expanding a system towards a large-scale DC grid.

C. Transient Stability

In this section transient events are introduced to observe the stability of the test system in time-domain simulations. To impose perturbations to the system, the generated power of the wind farm connected at bus Bo-D1 is increased by 20% at instant $t=1$ s, and at $t=2$ s the reference power of Cb-C1 is changed to 0.8 p.u whereas initial power setting is 0.625 p.u. At instant $t=3$ s, the generated power by the wind farm connected to bus Bo-C2 is reduced by 20%. The onshore AC voltages resulting from this sequence of perturbations are presented in Fig. 10 (a). The simulation also shows the initialization transient starting from $t=0$, and therefore there are oscillations before the instant $t=1$ s. However, these oscillations are damped properly, and the system is in steady-state while applying the disturbance.

The complex frequency of voltage oscillation of the Area B is $\lambda = -10.73 \pm 108.17$. Based on the participation factor analysis, the voltage controllers of Cb-B2 and Cb-B1 have the highest contributions to this mode, as shown in Fig. 11(a). The DC voltages resulting from the sequence of perturbations are presented in Fig. 10 (b). The oscillating mode of the voltage of converter Cb-A1 is $\lambda = -4.08 \pm 132.74$. The DC link capacitor has significant influence on this oscillation, and the state variable of dc voltage controller is associated with this mode. The complex oscillating mode of DC voltage on converter Cb-B1 is $\lambda = -86.102 \pm 35.641$. With the participation factor analysis shown in Fig. 11(b), it is

![Fig. 8. Eigenvalue pattern with classification for (a) stable operation, (b) unstable operation without DC voltage droop on Cb-B1](image1)

![Fig. 9. Participation of control parameters to the unstable modes (a): for $\lambda = 33.728 \pm 0.0$, (b): $\lambda = 9.337 \pm 0.0$, (c): $\lambda = 1.974 \pm 31.19$.](image2)
identified that measurement filters on system A (converter Cb-A1), have the high participation of contribution to this mode.

D. Sensitivity Analysis

To analyse the sensitivity of the system, we check the trajectory of the eigenvalues when the system parameters or control design are changed. First, we change the capacitors of the DC links between onshore area A and the offshore areas. The initial value of this capacitor is equal to 200 μF. The pole location of the system is indicated in Fig. 12. When we increase the capacitance, the modes are moving towards the real axis in the complex plane. The size of this capacitor influences the stability of the grid as expected. From this study, it is observed that the DC grid remains stable by 70% variations from the initial value of the capacitance. This observation is important respect to the system design which should ensure the overall stability of the system.

In the next step, the influence of the control system on the dynamic stability of the grid is studied. Based on the time-domain results from Fig. 7 and the eigenvalue locations in Fig. 8, it has been observed that the DC voltage droop can have significant influence on the stability of the dc grid. Hence, we change the droop gain for DC voltage droop control of converter Cb-B1, as shown in Fig. 13. When we increase the droop gain (Rv,dc), one specific mode is moving toward the imaginary axis. However, the other modes of the system are only slightly changed, indicating that the contribution of the DC droop on the other modes is negligible. The results show that the droop gain Rv,dc = 40 is the border of stability in this case, and after that the system will be in the risk of instability. However, the frequency of the oscillations is reduced while increasing the droop gain. It means that low frequency oscillations can be seen when the gain is equal to 40. On the other hand, the larger droop gains provide better damping. Taking to account these two points, the droop gain Rv,dc = 30 can be considered as a trade-off for providing a sufficient damping of the system while ensuring stability. This kind of analysis should be done when we are adding an individual converter to a multi-converter system and makes it possible to develop a large system step by step by control design for each converter.

V. CONCLUSION

This paper has presented a case study of stability analysis of multi-terminal VSC-HVDC system based on the Cigré DC grid test system. The presented simulation results include both time domain simulations and small signal stability analysis of the characteristic eigenvalues of the test system. The system components, contributing to the oscillating modes, have been identified by use of participation factor analysis. Together with investigations of the parameter sensitivity of the system eigenvalues, these results indicate the critical parameters in the system components as well as in the converter control systems that can lead to instability or oscillatory responses in the dynamic characteristics of large scale MTDC systems.

The presented stimulation results indicate that potential overload in the interconnected offshore parts of the grid can be
controlled properly by using a droop scheme. Furthermore, modal analysis proves the influence of the AC voltage controller on the stability of MTDC. Based on the location of eigenvalues and participation factors, the ideal AC voltage controller should be replaced by a reactive power droop control. The sensitivity analysis shows that the DC link capacitor has a significant effect on the damping of the oscillating modes. However, the asymptotic stability of the system is in this case ensured even by using reduced capacitance. The impact of the droop gain has been also studied. The maximum gain for stable operation is identified, which gives the border of stability, provided by the DC voltage droop. This analysis can be used as a basis for further studies of future MTDC systems. It is needed in order to identify and avoid potential poorly damped oscillations or stability problems due to interactions between converter control loops and the particular system configuration. By the case studies in this paper it is shown how it is possible to reach a proper control design for such multi-converter systems.

APPENDIX

The control parameters for the inner-loop and the outer-loop controllers are given in Table I.

<table>
<thead>
<tr>
<th>Control system</th>
<th>Control parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current controller</td>
<td>$k_{pu} = 0.3, k_{qa} = 100 \text{ [s]}$</td>
</tr>
<tr>
<td>Voltage Controller</td>
<td>$k_{pv} = 6, k_{qv} = 4 \text{ [s]}$</td>
</tr>
</tbody>
</table>

REFERENCES