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Optimising DC Voltage Droop Settings for AC/DC System Interactions

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***Abstract*—In this paper, a methodology is presented to optimise the DC voltage droop settings in a Multi-terminal Voltage Source Converter High Voltage Direct Current (VSC HVDC) system with respect to the AC system stability. Implementing a DC voltage droop control allows to have multiple converters assisting the system in case of a converter outage. However, the abrupt power set-point changes create additional stress in the AC system, especially when multiple converters are connected to the same interconnected AC system. This paper presents a methodology to determine optimised converter droop settings in order not to compromise the AC system stability, thereby taking into account the adverse effect the droop control actions have on the interconnected AC system. Developing a disturbance model of the interconnected AC/DC system the principal directions indicate the gain and directionality of the disturbances; from this optimal droop settings are derived to minimise the disturbance gain.**

***Index Terms*—HVDC transmission, HVDC converters, VSC HVDC, Voltage Droop.**

I. INTRODUCTION

In recent years, the interest for Voltage Source Converter High Voltage Direct Current (VSC HVDC) in a Multi-terminal configuration has increased significantly. This interest can partly be explained by the expected massive integration of offshore wind power in the transmission system, as well as due to the preliminary plans to construct overlay supergrids in Europe and in other parts of the world. The VSC HVDC technology seems to be favoured over both AC technology and the Line Commutated Converter (LCC) HVDC technology, due to economic benefits, legislative issues (e.g. permitting) and the technical limitations of the aforementioned technologies [1] (e.g. cable charging with AC cables or a cumbersome multi-terminal operation with LCC HVDC).

Whereas current day schemes have been conceived as point-to-point connections, the VSC HVDC technology has good prospects for an operation in multi-terminal DC grids. In such multi-terminal configurations, the DC voltage at the different buses in the system plays a crucial role when it comes to the system control. To some extent, the DC voltage can be attributed the same role as the frequency in AC systems, in the sense that its value reflects the unbalance that can exist between ‘production’ and ‘consumption’, i.e. the power that is injected and withdrawn by the VSC converters. Any increase or decrease of the DC voltage results from the discharging of the cable capacitances and the DC capacitors in the converter stations. Making the analogy with the frequency in an AC grid, the DC voltage is considered as one of the most vital parameters in a DC system.

In existing two-terminal systems one converter controls the DC voltage and the other one controls the active power over the link. Straightforwardly applying this control concept to a multi-terminal set-up would result in all but one converters controlling their active power injections and one ’slack converter’ controlling the DC voltage at its terminal.

Since the DC voltage plays a crucial role in the system control, it is of interest to spread the DC voltage control amongst different converters. A truly distributed control can be obtained by using a so-called voltage droop control [2]–[5]. The main advantage of such a distributed voltage controller is that all controlling converters react upon a change in the DC voltage, similarly to the way a synchronous generator reacts on frequency changes. The main difference with AC frequency control is the time scale of the DC voltage variations, which is a couple of orders of magnitude smaller than its AC frequency counterpart. This makes the control of the DC voltage more challenging, especially when one takes into account the fact that the DC voltage at the different buses varies as a result of the power flows through the lines.

Similarly, when different HVDC links are connected to the same AC network, the maximum power that can be injected by each link is limited by the AC system stability, as was first demonstrated in [6]. In [7]–[9], it has been shown that a coordinated control of these HVDC links can improve the dynamic stability of the AC system and increase the transfer capacity. The problem complexity increases significantly when DC grids are considered. Contrary to point-to-point DC connections, a converter outage does not only impact one DC link. When implementing a distributed DC voltage control, all converters change their set-points as a result of a power mismatch caused by a converter outage. When parallel paths exist in both the AC and DC side, a converter outage will also influence the power flows in the AC network. The overall control action after a converter outage might cause loop flows

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between the AC and DC layer or cause instability problems. At the moment of the converter outage, the affected AC system does not only suffer from the loss of the power injected by the converter, but additionally faces set-point changes of the other converters connected to this AC system.

Different methods have been presented to optimise the DC grid control settings. In [10] the voltages in the system have been optimised to minimise the system losses. In [11], adaptive droop coefficients were proposed to share the power distribution according to the available headroom of each converter station. In [5], the settings of the DC droops have been optimised with respect to the DC grid dynamics using a singular value decomposition (SVD).

Although significant research has been carried out on the DC voltage droop control itself, the effect of the controller gains on the AC system has not received too much attention so far. In [12], the voltage droop control was integrated in an AC/DC power flow algorithm to study the effect of the droop control schemes on both the AC and DC power flows. It was shown that the overall control actions of the voltage droop control scheme have a major influence on the power flows in both networks after a contingency, thereby pointing out the need for a coordinated control of all droop controlled converters. In [13], the impact of the voltage drops on the power flows in the DC grid was studied. Recently, [14] introduced a general small-signal stability model for multi-terminal VSC HVDC systems to study the effect of gains of the VSC controllers. However, no voltage droop control was considered.

In this paper we analyse the effect of a converter outage in a multi-terminal DC system by taking the directionality in the disturbance models into account to optimise the voltage droop settings. The analysis performed is complementary to the one from [5]: Like [5], the method developed in this paper uses SVD, but unlike [5] where the DC system dynamics are studied, the focus in this paper is entirely on the AC system dynamics. A disturbance on the DC side gives rise to, among others, transients and power oscillations in the AC system. The aim is to minimise the overall impact on the AC side of different disturbances on the DC side. Optimising the voltage droop gains may significantly reduce this adverse effect. The contribution of this paper is a method which makes it possible to derive optimal power sharing and hence relative droops settings to minimise the adverse effect.

The paper is structured as follows: Section II discusses the voltage droop control and how the control affects the power distribution after a contingency. Section III introduces the multi-input multi-output system (MIMO) analysis, comprising of the SVD and the study of converter outages as perceived from the AC system side. Finally, Section IV discusses the simulation results.

II. DC Voltage Droop Control

This section discusses the DC voltage droop control and the effect of the control actions on the AC system power injections. The main focus of this work is on the adverse effect of a converter outage on the AC system stability. With a local DC voltage used for droop control, the relation between the active DC power P_{dc} and the voltage U_{dc} at converter i can be written as

$$P_{dc_i} = P_{dc,0_i} - \frac{1}{k_{dc_i}}(U_{dc_i} - U_{dc,0_i}), \tag{1}$$

with $P_{dc,0_i}$ and $U_{dc,0_i}$ the DC power and voltage reference values and k_{dc_i} the converter droop constant at converter i. If a converter will be taken out of service the power in this converter is brought down to zero in short time. The other converters in the multi-terminal DC system share the power change in order to keep the DC voltage and thereby the DC power balance. From the AC system point of view these control actions can be seen as abrupt power changes since the time constants of the DC system are much smaller than the ones considered in AC system stability problems. The power change depends on the DC voltage droop settings of each converter except for the disconnected converter which has a fixed change depending on the pre-fault value. If a converter will be taken out of service the power in this converter is brought down to zero in short time. The other converters in the multi-terminal DC system share the power change in order to keep the DC voltage and thereby the DC power balance. From the AC system point of view these control actions can be seen as abrupt power changes since the time constants of the DC system are much smaller than the ones considered in AC system stability problems. The power change depends on the DC voltage droop settings of each converter except for the disconnected converter which has a fixed change depending on the pre-fault value.

Assuming that the entire power imbalance has to be redistributed amongst the different converters, the power sharing can be written as a function of the voltage droop constants in the DC grid.

Neglecting the change in DC system losses, an outage of converter i having the steady-state power injection of p_i gives rise to the power change in the converters which can be described as follows

$$\Delta P_{DCi} = -p_i, \tag{2}$$

$$\Delta P_{DCj} = p_i g'_j, \tag{3}$$

where g'_j is the modified gain for converter j

$$g'_j = \frac{g_j}{\sum\limits_{\substack{k=1\\k\neq i}}^{m} g_k}, \tag{4}$$

thereby taking the DC grid out of the analysis by assuming that the changes of the system bus voltages are similar for all buses. Meanwhile, it is assumed that no converter current limits are hit as a result of the voltage droop control.

III. MIMO System Analysis

A converter outage and the subsequent power changes of the voltage droop controlled converters can be regarded as a change of different system inputs and hence a disturbance in a certain direction, depending on the droop settings. Consequentially this disturbance impacts different system variables or a combination thereof. Depending on the droop settings each converter outage can be seen as a disturbance in a certain direction. Different disturbances, or disturbance directions, excite the AC system modes to different extent [15], [16].

It is known that MIMO control systems pose complexity in issues as gain, phase and directions which are strongly interrelated. In MIMO systems, the magnitude of the output signal depends not only on the magnitude of disturbances, but also on the relative phase displacement between the disturbance signals i.e. the disturbance directions. Thus, the DC voltage droop gains have an impact of the adverse effect in the AC system due to a converter outage.

One way of looking at the directionality and system gain is to linearise the system around the operating point and perform SVD. SVD is associated with the principal directions and gains. SVD is the general case of eigenvalue and eigenvector decomposition, hence, also valid for non-squared matrices.

Disturbances on the DC side, e.g. converter outage, may be modelled by a disturbance model $G_d(s)$ having the active power change into the AC system as the input signal vector and the speed deviation of the generators as outputs. Thus, modelling the AC/DC system by

$$G_d(s) = C(sI - A)^{-1}B + D, \tag{5}$$

with matrices A, B, C and D defining the state-space representation of the linearised system. The disturbance response highly depends on the DC voltage droop settings since these settings, in combination with the converter outage i, decide the direction d_i of the disturbance.

A. Singular Value Decomposition

Let us consider a matrix $\Lambda \in C^{l\times m}$, then Λ can be decomposed into its SVD [17]. There exists $\Sigma \in R^{l\times m}$ and unitary matrices $U \in C^{l\times l}$ and $V \in C^{m\times m}$ such that

$$\Lambda = U\Sigma V^H, \tag{6}$$

with Σ a rectangular diagonal matrix with the singular values $\sigma_1 \dots \sigma_q$, as diagonal elements in descending order, with $q = \min\{l, m\}$. The columns of $U = [u_1 \dots u_l]$ and $V = [v_1 \dots v_m]$ contain respectively the left- and right-singular vectors and are orthonormal set, hence they are orthogonal and of unit length. V^H denotes the conjugate transpose of the matrix V.

The matrix Λ can be rewritten as

$$\Lambda = \sum_{k=1}^{r} \sigma_k u_k v_k^H, \tag{7}$$

where $r = \text{rank}(\Lambda) \leq min\{l, m\}$, since $\sigma_k = 0\ \forall k > r$.

B. SVD of the Transfer Function

Let us substitute Λ in (6) by $G_d(s)$, the linearised transfer function is given by

$$G_d(s) = \sum_{k=1}^{r} \sigma_k(s) u_k(s) v_k(s)^H, \tag{8}$$

and the frequency response at a particular frequency is given by evaluating $G_d(s)$ at $s = \jmath\omega$. The maximum $\overline{\sigma}(G_d(\jmath\omega))$ and minimum $\underline{\sigma}(G_d(\jmath\omega))$ system gains, are given by [17]

$$\underline{\sigma}(G_d(\jmath\omega)) \leq \frac{||G_d(\jmath\omega)d||_2}{||d||_2} \leq \overline{\sigma}(G_d(\jmath\omega)), \tag{9}$$

with

$$G_d(\jmath\omega)\overline{v} = \overline{\sigma}\,\overline{u}, \tag{10}$$

$$G_d(\jmath\omega)\underline{v} = \underline{\sigma}\,\underline{u}, \tag{11}$$

d is any input direction, not in the null space of G_d, and $||\cdot||_2$ the Euclidian norm. The vector $\overline{v}$ corresponds to the input direction with largest amplification, and $\overline{u}$ is the corresponding output direction in which the inputs are most effective. The least effective input direction is associated with $\underline{v}$ corresponding to the output $\underline{u}$. With $q = \min\{l, m\}$, the maximum and minimum system gains, respectively $\overline{\sigma}$ and $\underline{\sigma}$, are given by

$$\overline{\sigma} = \sigma_1 \tag{12}$$

$$\underline{\sigma} = \begin{cases} \sigma_q & l \geq m \\ 0 & l < m \end{cases} \tag{13}$$

In power systems the relative magnitude and phase of the elements of the largest singular value, at each frequency of oscillation, shows the groups of generators that are oscillating against each other [18], also the most effective input direction to excite this mode is shown. with one mode being dominant over the others at frequency ω_1, (8) can be approximated as

$$G_d(\jmath\omega_1) \approx \overline{u}\,\overline{\sigma}\,\overline{v}^H \tag{14}$$

C. Converter Outage Analysis

As the relation between the converter gains is of concern, the entire subset of gains has to be scaled to achieve an acceptable dynamic response [5]. In this analysis, we disregard the intermediate dynamics and we model the outage as if the converter powers change abruptly at the same time. Therefore, only the relative values of the converter gains are of concern for this analysis. Hence, with the power sharing after an outage of converter i as in (4), an additional equation is defined such that

$$\sum_{k=1}^{m} g_k = 1. \tag{15}$$

The disturbance caused by the outage of converter i can be expressed mathematically as

$$\Delta P_{d_i} = p_i d_i, \tag{16}$$

with

$$d_i = [g'_1, \dots, g'_{i-1}, -1, g'_{i+1}, \dots, g'_m]^T, \tag{17}$$

being the disturbance direction, p_i the power in converter i before the outage and ΔP_{d_i} the vector of power changes in all the converters.

The disturbance direction d_i for each converter outage i can be rewritten as linear combinations of the input directions V

$$d_i = V\alpha_{d_i} \tag{18}$$

with the coefficient vector $\alpha_{d_i} = [\alpha_{d_{i1}} ... \alpha_{d_{im}}]^T$.

Using a SVD of the linearised system G_d from (5), and substituting G_d and d_i using respectively (6) and (18), the system response or gain for disturbance d_i can be rewritten as

$$||G_d d_i||_2 = ||U \Sigma \alpha_{d_i}||_2. \quad (19)$$

Since the left-singular vectors, the columns in U, are orthogonal $u_i^H u_j = \delta_{ij}$. Hence, (19) can be rewritten as

$$||G_d d_i||_2 = ||\Sigma \alpha_{d_i}||_2 = \sqrt{\sum_{k=1}^{r} \sigma_k^2 \alpha_k^2}. \quad (20)$$

Alternatively, one can only take the largest singular value into account. The disturbance gain for a disturbance d_i, based on (9) and (14), is then approximated by

$$||G_d d_i||_2 \approx ||\overline{\sigma}_d \, \overline{u} \, \overline{v}^H d_i||_2 = \overline{\sigma}_d \; ||\overline{v}^H d_i||_2. \quad (21)$$

Substituting d_i from (18), and taking into account the orthogonality of the right-singular vectors, $v_i^H v_j = \delta_{ij}$ and the expression simplifies to

$$\overline{\sigma}_d \; ||\overline{v}^H d_i||_2 = \overline{\sigma}_d ||\overline{\alpha}_d||_2. \quad (22)$$

To be noted is that the disturbance gain is not divided by $||d_i||_2$ as in (9). The disturbance direction d_i is defined as in (16)–(17) and element i is normalised and equal to -1 for an outage of converter i i.e., $d_i(i) = -1$. Thus, it is the output magnitude caused by d_i and not the relative output magnitude that is of interest. The Euclidian norm of d_i varies depending on g but as (15) is fulfilled (16) solves the power mismatch. Eq. (21) can be interpreted as the projection of d_i onto $\overline{v}$ that is amplified. Similarly, the more general expressions (19) – (20) can be interpreted as the projections of the disturbance d_i on the input directions V.

To minimise the impact, these directions should be considered when setting the voltage droop gains g in the converters.

The abrupt power changes in the different converters are modelled as step functions. In the Laplace s-domain the step or heaviside function is $1/s$, thus, it has a wide frequency spectrum. This means that a converter outage can excite all modes to some extent and that modes with a higher frequency are more attenuated than the ones with a low frequency.

The frequencies where the gain peaks should be considered when minimising the adverse effect of a converter outage. A singular value plot provides a means to generalise this information by generating a plot of the frequency dependence of singular values of the transfer matrix evaluated at different frequencies. The peaks occur at the frequencies of the modes in the system, thus, indicate the frequencies at which the system is likely to exhibit dynamic stability problem as the modes get excited by the disturbance.

The aim in this study is to minimise the disturbance gain for the lowest damped mode or, put differently, to reduce the excitation of these modes during an outage. The total gain, including all possible converter outages, can be expressed by using (21) as

$$\beta_{tot} = \sqrt{\sum_{\forall i} ||G_d d_i||_2^2}. \quad (23)$$

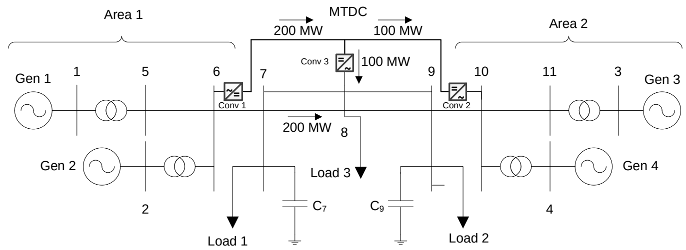


Fig. 1. Two-area four-machine system with an multi-terminal DC system.

TABLE I
MODES OF THE TEST SYSTEM

Eigenvalue	Damping	Frequency	Mode shape
−0.1028 ± j 3.3220	3.09%	0.529 Hz	G1,G2—G3,G4
−0.5052 ± j 6.1779	8.15%	0.983 Hz	G3—G4
−0.5143 ± j 5.8197	8.81%	0.926 Hz	G1—G2

We want to minimise the gain for all converter outages with respect to the DC voltage droop gains. This can be formulated as

$$min \quad \beta_{tot} \quad (24)$$

$$\text{s.t.} \quad \sum_{k=1}^{m} g_k = 1 \quad \text{and} \quad g_k \geq 0. \quad (25)$$

and by solving this problem the adverse effect is minimised.

IV. Simulation Results

To verify the developed methodology simulations are performed in two test systems and in each test system a three terminal DC system is installed.

A. Test system 1 – Two-area system

This test system is the Two-area system [19] where an multi-terminal DC system is connected to Buses 6, 8 and 10 transferring 200 MW and a load supported by the MTDC is connected to Bus 8, shown in Fig. 1. The reason for choosing this relatively simple test system as an example is that it allows to verify the proposed method against results that can be expected from a system with two clear areas. Linearising the system one inter-area mode and two local modes are found. Table I contains the eigenvalues and as can be seen the modes are positively damped.

The singular value frequency response of the dynamic system is plotted in Fig. 2. The gain for the inter-area mode is much higher than for the local modes, therefore the DC voltage droop gains need to be optimised to minimise the disturbance gain for the inter-area mode. The system i.e., G_d is evaluated at $f = 0.529\ Hz$ and (21) gives the disturbance gain for different directions d_i. It can be noted that the difference between the largest and smallest direction $\overline{\sigma}$ and $\underline{\sigma}$ is rather large, in particular for the frequency of inter-area oscillation.

In this system there are three converters so there are three possible converter outages. For each converter outage we may vary the DC voltage droop gains and plot the disturbance gain. The disturbance gain can be plotted for different distribution

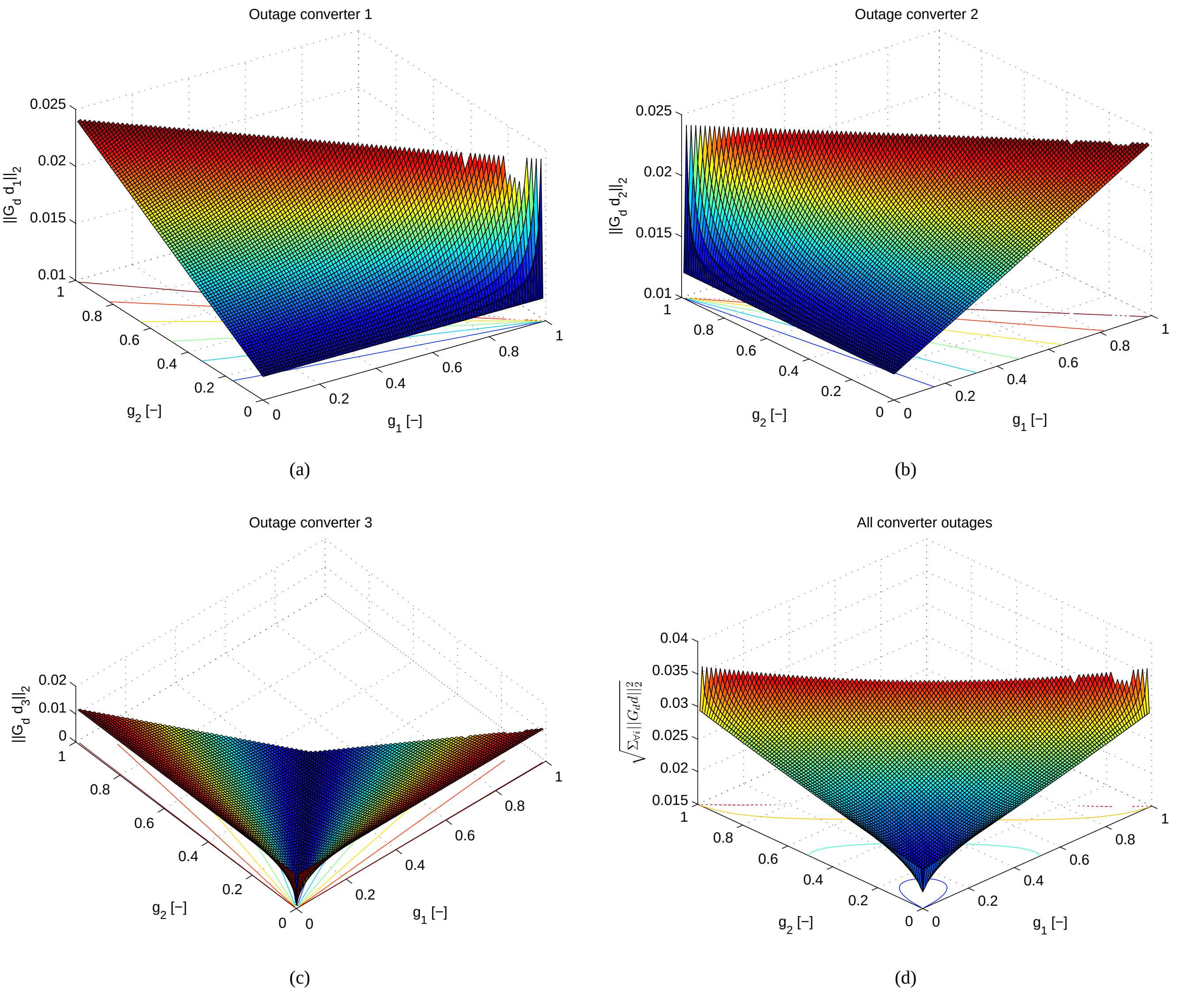


Fig. 3. System gains for the Two-area system: Outage in (a) converter 1, (b) converter 2, (c) converter 3 and (d) total system gain

of the DC voltage droop settings. g_1 and g_2 are along the x-axis and y-axis, g_3 is a function of g_1 and g_2 as follows

$$g_1 = 0 \longrightarrow 1 \tag{26}$$

$$g_2 = 0 \longrightarrow 1 - g_1 \tag{27}$$

$$g_3 = 1 - g_1 - g_2. \tag{28}$$

Fig. 3a shows the disturbance gain for an outage of converter 1. Clearly, the DC voltage droop gain g_1 has no impact on the disturbance gain since the corresponding converter is out of service. In the direction of g_2 the disturbance gain increases. Intuitively, a higher disturbance is expected when the power mismatch is solved by converter 2 instead of converter 3 and this is also the result. This is explained by considering the power flow change in the AC system. Solving the power deficit in converter 3, due to outage in converter 1, only changes the power transfer on the AC lines between Buses 6 and 8. Instead solving the power deficit in converter 2 also increases the power transfer in the AC lines between Buses 8 and 10, thus between the two areas. Moreover, this means a larger power flow change in the system, which creates larger voltage angle deviation at the buses, thereby exciting the inter-area mode in the system to a larger extent.

Fig. 3b displays the disturbance gain for converter outage 2. In this case it is also expected that the disturbance gain is lower if converter 3 solves the power mismatch. As can be seen in the figure the result is similar to the previous case.

The last case is when converter 3 has an outage and in this case the DC voltage gain g_3 has no impact on the disturbance gain. The disturbance gain is low if the power is equally distributed between converters 1 and 2 as shown in Fig. 3c. In Fig. 3d the total disturbance gain is shown as given in (23). It shows the better option is to have higher DC voltage droop gain in converter 3. The minimum gain is achieved when $g_1 = 0$, $g_2 = 0$ and $g_3 = 1$.

To verify the result time simulations have been performed using Power System Analysis Toolbox (PSAT), a Matlab toolbox for electric power system analysis and simulation [20],

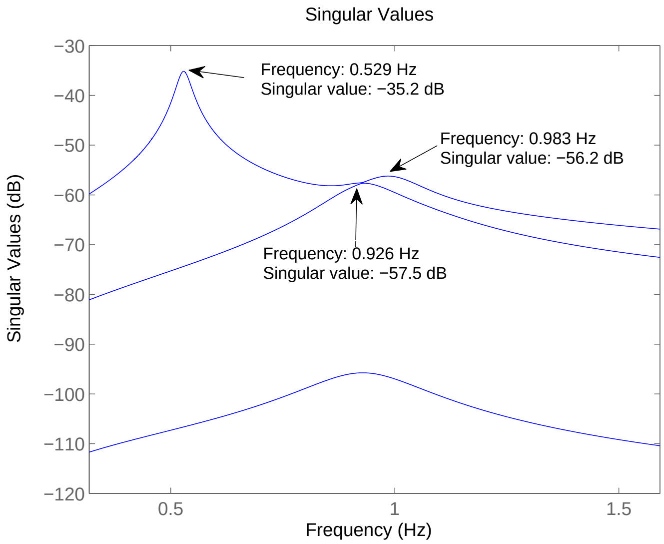


Fig. 2. SVD plot for the Two-area test system

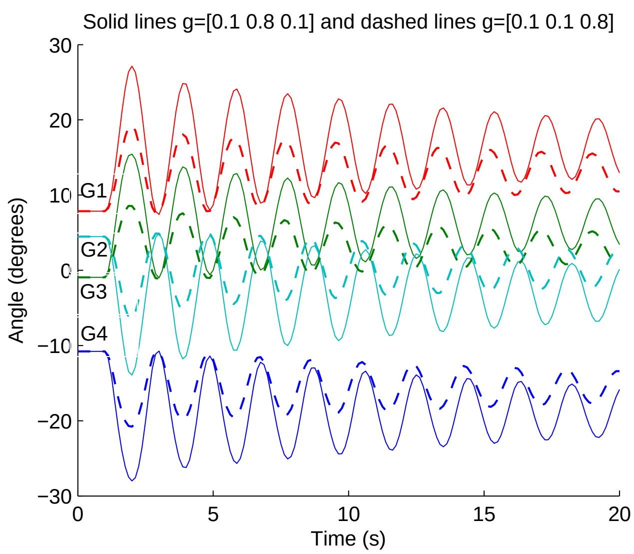


Fig. 4. Time simulations for an outage of converter 1

and the result for an outage of converter 1 is shown in Fig. 4. It can be seen in the figure that the deviation of the generator angles is lower in the case of more power sharing in converter 3 and it means the inter-area mode is excited to less extent with this droop setting. Clearly, it is better to have higher gain in converter 3 to lower the impact of a converter outage.

B. Test system 2 – IEEE 39 bus system

Test system 2 is the New England, IEEE 39 bus 10 machine, system presented in [21]. An overview of the system is shown in Fig. 5.

The singular value plot is shown in Fig. 6 which peaks at $f = 0.64\ Hz$ for the eigenvalue at $-0.0743 \pm j\,4.0151$, as it is the mode having lowest damping. Therefore, the system is considered at this frequency, thus, G_d is evaluated at this frequency when searching for the DC droop settings. It is clear

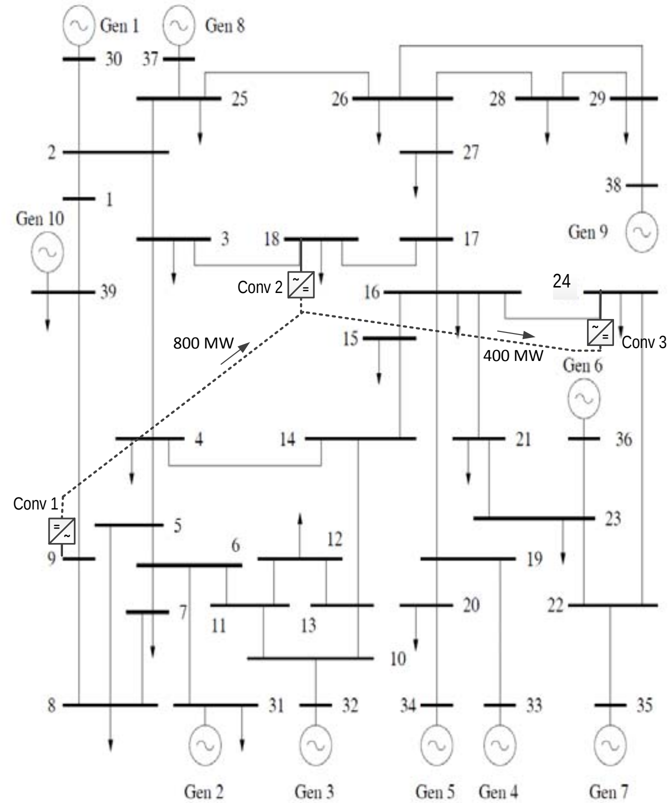


Fig. 5. New England, IEEE 39 bus system and a three terminal DC system.

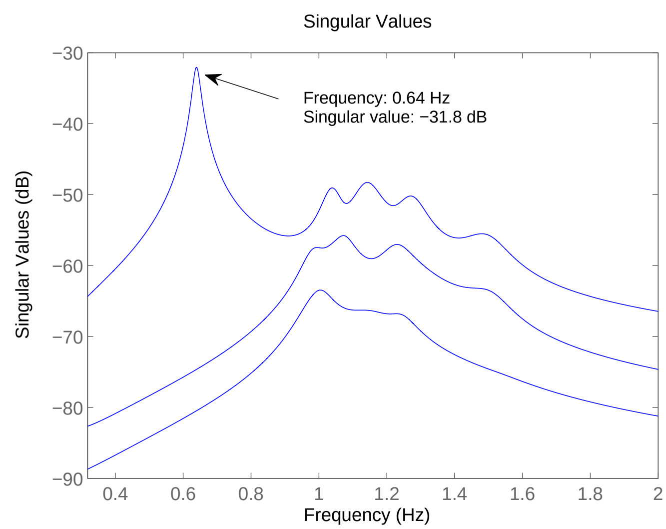
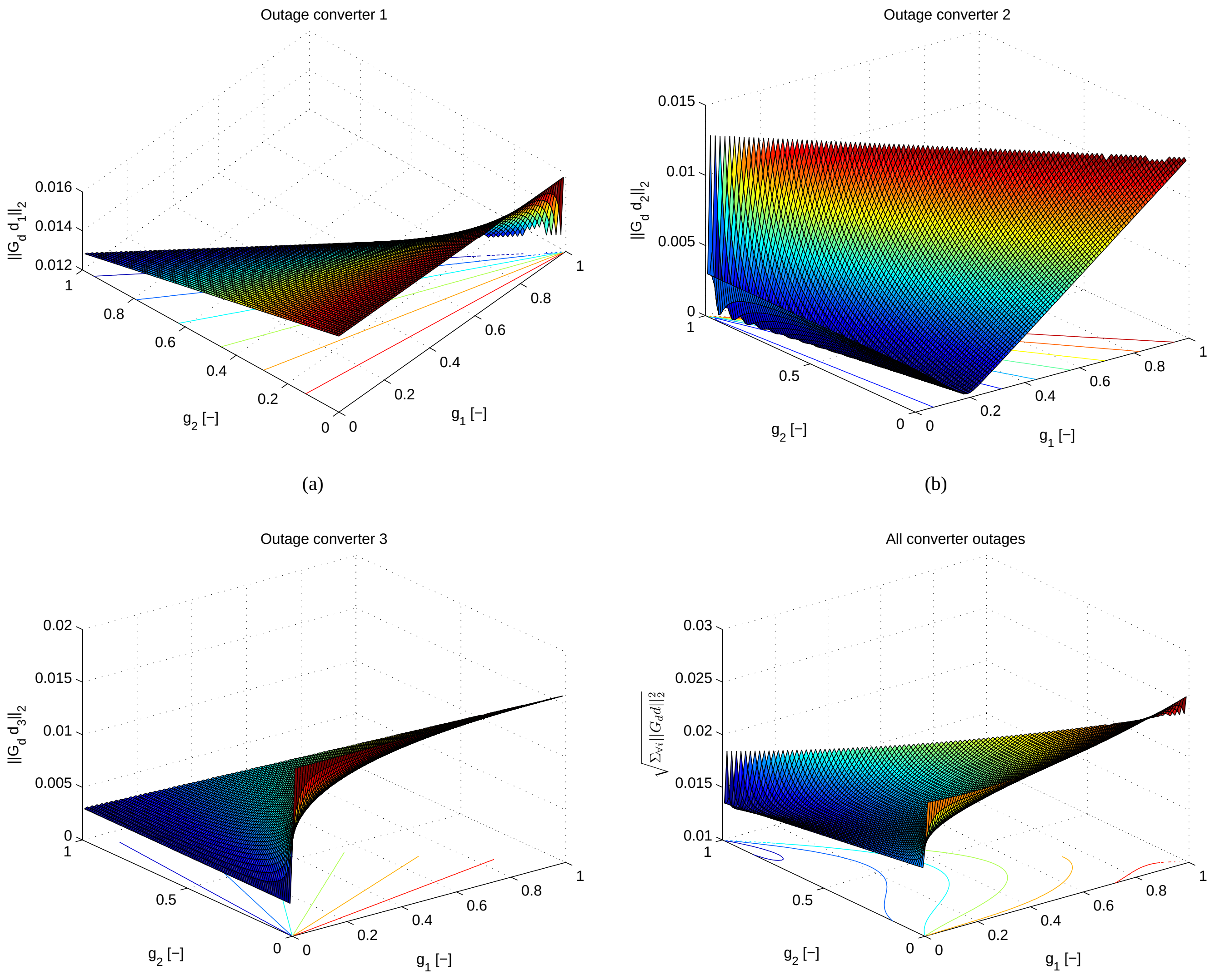


Fig. 6. SVD plot for the IEEE 39 bus system

from the figure that the system has high directionality as there is a large difference in the singular values for the selected mode.

The disturbance gain for converter outage 1 is plotted in Fig. 7a, self-explaining gain g_1 has no affect. The affecting gains are g_2 and g_3 where the relation between them is of importance. Seen in the figure, the disturbance gain decreases as g_2 increases, therefore lower system gain comes with more power sharing in converter 2 than in converter 3. Fig. 7b shows



(a) (b) (c) (d)

Fig. 7. System gains for the IEEE 39 bus system : Outage in (a) converter 1, (b) converter 2, (c) converter 3 and (d) total system gain

the disturbance gain in the case of an outage of converter 2. The output magnitude increases as g_1 increases, thus, g_3 has lower impact on the AC system. In this case power sharing should take place in converter 3 if the mode of interest in the AC system should be less excited. The disturbance gain for an outage of converter 3 is plotted in Fig. 7c. The system gain increases with g_1, thus the opposite as g_2 increases. Using (23) the total gain can be calculated and is shown in Fig. 7d. Clearly, lowering the overall impact, as in (23), the power sharing should take place in converter 2. The system gain increases as g_1 and g_3 increase, but increases more in the direction of g_1 than g_3.

A time simulation is shown in Fig. 8 for an outage of converter 2 where some of the generator angles, which are representative for the system's behaviour, are plotted. It can be seen that the excitation of the lowest damped mode is significantly reduced by proper voltage droop settings based on the proposed methodology.

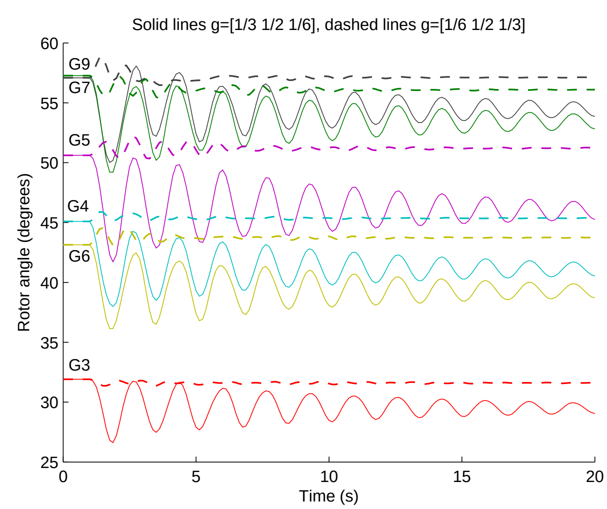


Fig. 8. Time simulations for an outage of converter 2

V. Conclusion

In this paper, a methodology has been presented to assess the impact of converter outages in a DC grid on the AC grid stability by analysing the input directions that will cause the smallest effect on the system outputs due to disturbances on the DC side. The contribution of this paper is a method which derives the voltage droop settings to minimise the adverse effect of a disturbance on the DC side. The method is based on SVD and MIMO system analysis. Simulation results show the validity of the proposed approach.

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