Impact of AC-line-emulation controllers of VSC-HVDC links on inter-area-oscillation damping

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***Abstract*— This paper presents a fundamental study on the impact of AC-line-emulation controllers of High Voltage Direct Current links based on Voltage Source Converters (VSC-HVDC) on inter-area-oscillation damping. The analysis has been carried out using eigenvalue and frequency-domain methods. The results presented in the paper show that an AC-line-emulation controller in a VSC-HVDC link can have either a positive or negative impact on the damping ratio of inter-area modes, depending on the value of the filter time constant of the controller. The study concludes that the filter time constant must be high enough to avoid negative interactions of this control alternative on power oscillations and the paper provides guidelines for the design of this parameter.**

Keywords— HVDC transmission, VSC-HVDC, AC-line emulation control, power oscillation damping, power system stability.

I. Introduction

High Voltage Direct Current links based on Voltage Source Converters (VSC-HVDC) are already being considered to increase the transmission capacity of the power system [1]. Most traditional option to control the active power through a VSC-HVDC link is to control it to a constant value. The active-power set point can be changed according to Transmission System Operator (TSO) preferences. However, recent VSC-HVDC installations operate the link as an emulated Alternating Current (AC) line [2-5]. This means that the power flow transmitted by the HVDC link must be made proportional to the angle difference between the terminal AC buses. In addition, gain of the controller hast to be equal to the inverse of the reactance of the emulated AC line. This control scheme allows handling a VSC-HVDC link embedded in an AC system easily, since, in case of disturbances, for example, power-flows will be distributed automatically between the VSC-HVDC link and parallel AC lines, according to the impedances of the AC lines and the emulated reactance of the VSC-HVDC link. Examples of VSC-HVDC systems in operation with AC-line-emulation control are Mackinac back-to-back interconnector (USA) [2], [3] and INELFE Spain-France interconnector through the Catalonian Pyrenees [4], [5]. Furthermore, new INELFE VSC-HVDC interconnector between Spain and France through the Gulf of Bizkaia, already commissioned, will be also operated as an emulated AC line [6].

It is essential for TSOs to understand the impact of VSC-HVDC systems on power system stability. Furthermore, a main concern in Europe are inter-area oscillations in the Continental European power system, which are strongly affected by power flows through HVAC and HVDC interconnectors and control strategies in VSC-HVDC systems. An example of the relevance of this aspect is the event on 1st December 2016, in which poorly damped inter-area oscillations of 0.15 Hz where observed in the Continental European system. Oscillations were damped by reducing the power exchange from Spain to France [7].

Control strategies in a VSC-HVDC links can have two components: steady-state controllers (i.e. constant power or AC-line-emulation controllers) and support controllers (e.g. supplementary controllers for power oscillation damping, transient stability improvement or frequency support, among others). In supplementary support controllers a set point is added to the steady-state set point of active- or reactive-power injections of the VSCs, depending on the application. Supplementary controllers in VSC-HVDC systems for power-oscillation damping have proved to be an effective solution to damp inter-area oscillations [8-12]. Nevertheless, current VSC-HVDC installations do not have these type of controllers implemented yet. Regarding steady-state controllers, the work in [13] analysed the impact of the operating point of a VSC-HVDC link operated in constant power mode on inter-area oscillations, concluding that active-power operating point of the link and the bandwidth of the outer controllers of the converters have an impact on the damping ratio of inter-area oscillations. Furthermore, the AC-line-emulation control of a VSC-HVDC link might affect the damping of inter-area oscillations depending on several parameters. However, no study on the impact of AC-line-emulation-control of VSC-HVDC links on power oscillations has been reported so far.

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The study reported in this paper focuses on the investigation of the impact of AC-line-emulation controllers in VSC-HVDC links on the inter-area-oscillation damping. The performance of this control alternative has been investigated by means of eigenvalue and frequency domain methods using a generic two-machine system that exhibits a slow inter-area mode where a point-to-point VSC-HVDC system has been embedded.

Specifically, the contributions of this paper are the following:

- A fundamental analysis of the impact of AC-line-emulation controllers on power oscillations. To the best of the authors' knowledge, no previous publications have addressed such problem and this paper presents such study for the first time.
- Results in the paper show that filter time constant of the AC-line-emulation controller in VSC-HVDC should be high enough to avoid negative impact on the damping ratio of power oscillations.
- The paper provides guidelines for the design of the time constant of this control alternative.

The rest of the paper is organised as follows. Section II describes the fundamentals of VSC-HVDC links and the AC-emulation controller, as well as the test system used for the study. Sections III and IV present the small-signal stability results, using simplified models for the generators and using detailed models for the generators, respectively. Finally, Section V presents the conclusions of the study.

II. AC-LINE-EMULATION CONTROL OF A VSC-HVDC LINK

Fig. 1 shows a simple model of a two-machine system with an embedded VSC-HVDC link (1000 MW, ±320 kV (DC voltage)). The data of the AC system and the VSC-HVDC link are provided in the Appendix.

Station VSC1 controls its active-power injection ($P_{s,1}$) into the AC side, while station VSC2 controls its DC voltage ($V_{dc,2}$). Both VSC stations control their reactive-power injections ($Q_{s,1}$ and $Q_{s,2}$) to zero. Each VSC is connected to a 400 kV grid through a 400/330kV transformer.

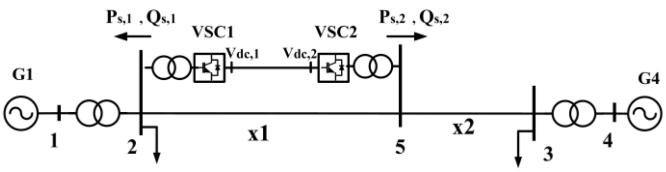

Fig. 1: VSC-HVDC link.

For AC-line-emulation control, the active-power set point of VSC1 is given by [5]:

$$P_{s,1}^{ref} = P_{s,1}^{0} - \frac{K}{1+sT}\left(\delta_{s,1} - \delta_{s,2}\right) \tag{1}$$

where $P_{s,1}^{0}$ is a constant set point, $\delta_{s,i}$ is the angle of the voltage measured at the connection point station VSC i ($i = 1,2$), K is the controller gain and T is the time constant of the filter of the controller. K must be made equal to the inverse of the equivalent reactance of the emulated AC line:

$$K = \frac{1}{x_{hvdc,eq}} \tag{2}$$

Notice that $P_{s,1}^{0} = 0$ is used to emulate the behaviour of an AC line with (1). Nevertheless, due to the flexible control in VSC-HVDC links, a constant set-point value, as an additional capability, could also be added ($P_{s,1}^{0} \neq 0$ in (1)).

Gain K must be designed to distribute the power flows among the VSC-HVDC link and the parallel AC lines, according to the preferences of the TSO.

Since the AC-line-emulation control is a steady-state controller, a question that arises is whether the time constant T can interact with electromechanical oscillations and whether it has positive or negative impact on inter-area oscillations.

Therefore, the purpose of this study is to analyse:

- The impact of value of the filter time constant (T) on the damping of the inter-area oscillation.
- The impact of the modelling details of the synchronous machines on the results.
- The impact of the location of the VSC-HVDC link with respect to the generators on the results. The analysis of this point will be conducted by using different values of x_1 and x_2 in Fig. 1.

The purpose of analysing the impact of modelling of synchronous machines is to give useful insight regarding the damping contribution of AC-line-emulation controller. Simplified classical models of generators and commonly-used 6th-order models of synchronous machines with their controllers will be used. It should be noted that common practice is the use of the latter type of generator models.

The analysis has been carried out using eigenvalue and frequency domain methods with a Matlab-based tool for small-signal analysis of power systems (SSST) [14]. SSST is a matlab version of SMAS3, which is a Fortran-based tool for the same application [15]. The models for VSC-HVDC systems follow the guidelines provided in [16] and [17] for electromechanical simulation (type-6 models). Linearised models for the VSC-HVDC were included in SSST. A full description and validation of the model can be found in [18] and [19].

III. ANALYSIS OF INTER-AREA-OSCILLATION DAMPING WITH CLASSICAL MODELS OF THE GENERATORS

First of all, generators G1 and G4 of Fig. 1 are represented using classical models, without controllers and with zero damping constant. In principle, with classical generator models, a purely active-power modulation proportional to the angle difference between AC terminals is expected to produce a purely synchronising effect, without any damping effect (i.e. it will change the frequency of a mode, but not its real part). However, P modulation in a VSC-HVDC link presents dynamics associated to the controllers of the VSC stations and also the time constant of the filter of the AC-line-emulation supplementary controller, which may have an impact on the damping. Understanding the importance of this time constant is one of the mains motivations of the study reported in this paper.

The value of $P_{s,1}^{0}$ in (1) is set to zero and the impact of parameter T on inter-area mode is analysed, evaluating different values for K (i.e. of $x_{hvdc,eq}$). For the analysis of this section, it has been assumed that $x_1 = x_2 = 0.25$ p.u (base values: 400 kV and 100 MVA). Notice that different equivalent reactances of the VSC-HVDC link produce different operating points. For example, if $x_{hvdc,eq} = x_1$, the steady-state active power through the VSC-HVDC and its parallel AC line will be almost the same. However, if $x_{hvdc,eq} < x_1$, the former will carry more active power than the latter. In the base case (i.e. if $K = 0$), the inter-area mode of the system of Fig. 1 obtained from the linearised model of the system is:

$$\lambda = \pm j1.4741,\ \zeta = 0\%,\ f = 0.23\ Hz \quad (3)$$

The evolution of the inter-area mode and its damping ratio versus T, obtained from Small-signal analysis (SSA) are shown in Fig. 2. For three values of $x_{hvdc,eq}$, the initial eigenvalue (for $T = 0.02\ s$) is marked in the upper plot of Fig. 2 with a cross (×), while the final eigenvalue (for $T = 100\ s$) is marked with a circle (o).

The inter-area mode moves to the lower right hand side of the complex plane as T increases (for small values of T). If the time constant T is very large, the AC-line-emulation controller has no longer any effect and the electromechanical mode will be only affected by the operating point. In this case study, the inter-area mode converges to $\zeta = 0\%$ for large values of T.

A positive damping is obtained for a small value of T (see Fig. 3, with the damping ratio of the inter-area mode versus T, for $T = 0 - 2$ s). The damping ratio decreases as T increases and it reaches a minimum (and negative) value for a certain T. That minimum takes place at $T = 0.8 - 1.6$ s in the case study, depending on the value of $x_{hvdc,eq}$. If T increases further, the damping ratio increases up to values close to the original one.

The rate of change of the damping ratio as a function of T depends strongly on the gain value $x_{hvdc,eq}$ (i.e. on the gain value K). As K/T increases (decreases), the rate of change of the damping ratio also increases (decreases). Therefore, the AC-line-emulation controller of the VSC-HVDC can have a negative or positive impact on the damping of the inter-area mode, depending on the value of the filter time constant T. Furthermore, the AC-line-emulation controller does not produce a pure synchronising effect on the inter-area mode due to the low-pass filter $1/(1 + sT)$.

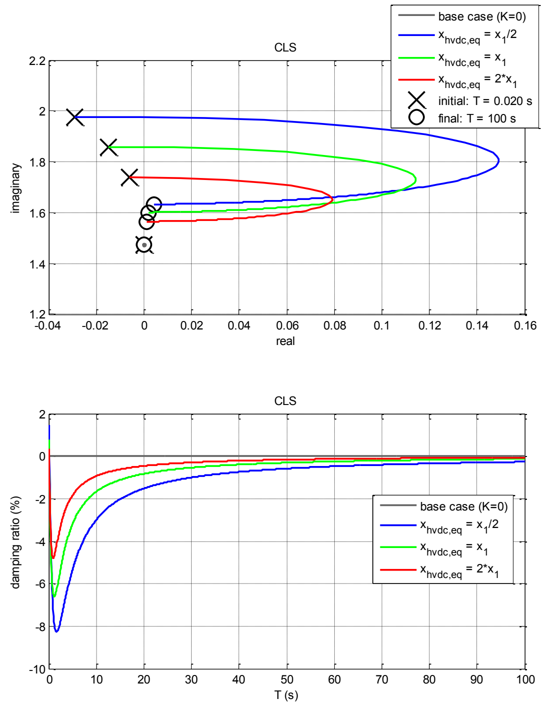

Fig. 2: SSA with a classical model for the generators.

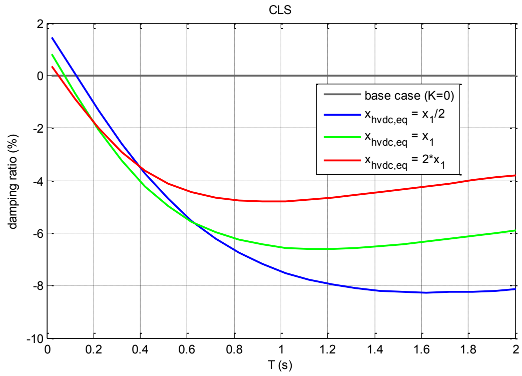

Fig. 3: SSA with a classical model for the generators. (detail).

IV. Analysis of Inter-Area-Oscillation Damping with Detailed Models of the Generators

Generators G1 and G4 of Fig. 1 have also been represented using detailed 6th-order models for the synchronous generators (two axes), including their governors, excitation systems and power-system stabilisers. As before, the constant set-point $P^0_{s,1}$ in (1) was set to zero and the impact of the filter time constant T on the damping of the inter-area mode was analysed. In the base case ($K = 0$), the inter-area mode of the system of Fig. 1 is:

$$\lambda = -0.1362 \pm j1.4306,\ \zeta = 9.48\%,\ f = 0.23\ Hz \quad (4)$$

Three cases will now be compared, in order to illustrate the impact of the location of the VSC-HVDC link of Fig. 1 on the results:

- Case 1: $x_1 = x_2 = 0.25$ p.u
- Case 2: $x_1 = 0.1$ p.u and $x_2 = 0.4$ p.u
- Case 3: $x_1 = 0.4$ p.u and $x_2 = 0.1$ p.u

A. Case 1

The effect of the filter time constant (T) on the inter-area mode is shown in Fig. 4. The damping ratio of the inter-area mode versus T, for low values of T, is shown in Fig. 5. Results show a similar pattern as the one when simplified generator models were used (Section III), although numerical values are different.

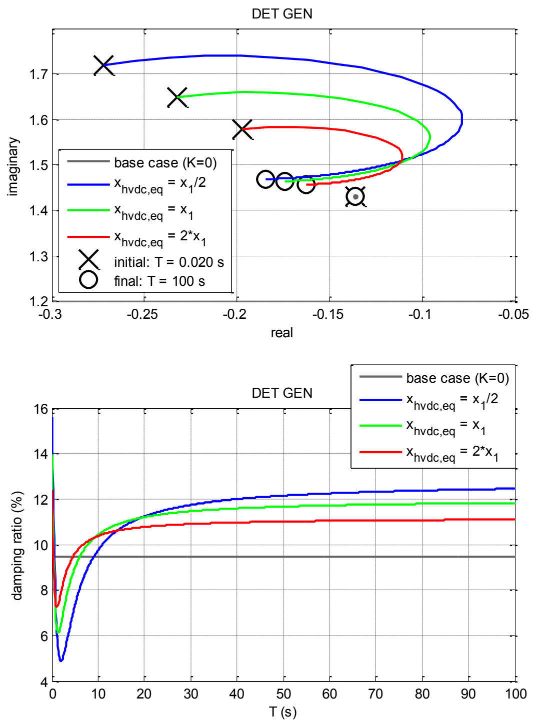

Fig. 4: SSA with detailed model for the generators. Case 1.

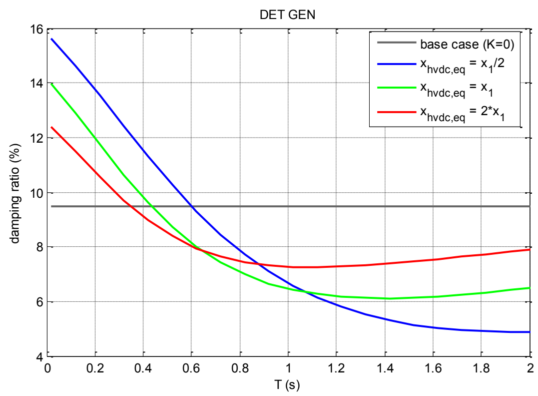

Fig. 5: SSA with detailed model for the generators. Case 1 (detail).

When T is small, the damping ratio of the inter-area mode is greater than the one obtained in the base case (no AC-line emulation) (see Fig. 5). Initially, the damping ratio of the inter-area mode deteriorates rapidly, although it remains above the base case if $T < 0.35$ s, for all the values of $x_{hvdc,eq}$ considered. Nevertheless, as shown in Fig. 4, this damping ratio soon bottoms ot and, eventually, goes back above the one of the base case ($T > 10$ s). A quantitative analysis of Fig. 4 and Fig. 5 shows, clearly, the influence of the value of $K = 1/x_{hvdc,eq}$. It is also worth pointing out that the three ranges of the filter time constant that drive the behaviour of the damping of the inter-area oscillation ([0, 0.35 s), [0, 10 s) and [10 s, ∞)), might have different numerical values, depending on the bandwidth of the inner and outer controllers of a certain VSC-HVDC link.

Notice that the damping ratio of the inter-area mode converges to different values depending on $x_{hvdc,eq}$: although a very large value of T implies that the AC-line-emulation controller itself will not produce any effect on the dynamics, the steady-state operating point will change and, therefore, the inter-area mode can also change. Typically, the more loaded is an AC line, the less damped is the inter-area mode. Therefore, lower values of the equivalent impedance of the VSC-HVDC link, which deload parallel AC lines, produce higher damping ratios for large values of T, as shown in Fig. 4.

B. Case 2

In this case, $x_1 = 0.1$ p.u and $x_2 = 0.4$ p.u in Fig. 1, which means that the VSC-HVDC link is close to generator G1, and far to generator G4. The question now is whether the VSC-HVDC link can have a significant effect on the inter-area mode being far from one of the areas involved.

The effect of the time constant T on the inter-area mode is shown in Fig. 6 and the details for small values of T are showed in Fig. 7. The inter-area mode in Case 2 follows a similar pattern as in Case 1 when T changes. However, the numerical values are remarkably different. In Case 2, the damping ratio obtained for intermediate values of T (0.8-10 s) are higher than in Case 1, and the minimum damping ratios obtained in Case 2 are very close to the one obtained in the base case (9.48 %). For $T > 6$ s, the damping ratio obtained for all the values of $x_{hvdc,eq}$ analysed is greater than the one obtained in the base case.

Therefore, the conclusion is that when the VSC-HVDC link is far from the machines involved in the inter-area mode, low impact on the damping ratio of that mode is expected.

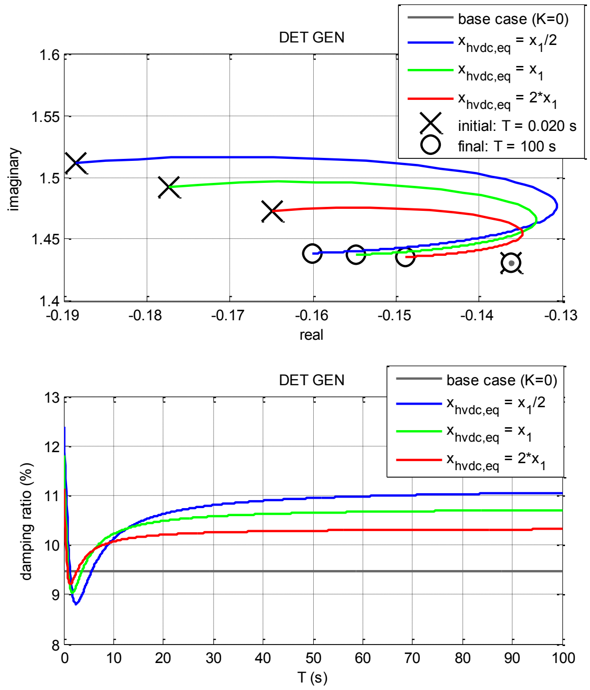

Fig. 6: SSA with detailed model for the generators. Case 2.

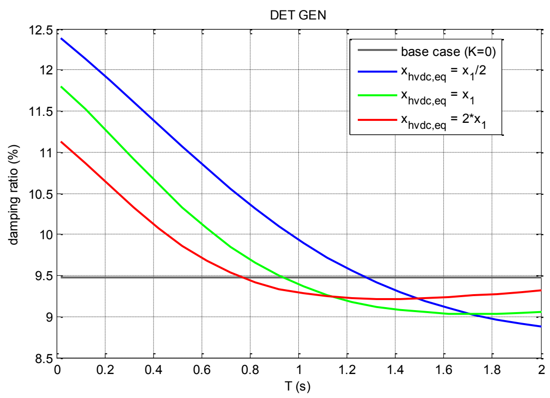

Fig. 7: SSA with detailed model for the generators. Case 2 (detail).

C. Case 3

In this case, $x_1 = 0.4$ p.u and $x_2 = 0.1$ p.u in Fig. 1, which means that stations VSC1 and VSC2 of the HVDC link are close to machines G1 and G4, respectively.

Fig. 8 shows the inter-area mode locus as T changes, and Fig. 9 shows the damping ratio versus T for $T = 0.02 - 2$ s.

The inter-area mode follows as similar pattern as in cases 1 and 2, but now the impact of T is much more noticeable. For example, for $x_{hvdc,eq} = x_1/2$, a damping ratio of 20% is obtained for $T = 0.20$ s, but the damping ratio ratio obtained for $T = 1 - 15$ s is lower than the one obtained in the base case (9.48 %). Moreover, the system is unstable if $T = 0.8 - 3$ s and $x_{hvdc,eq} = x_1/2$. For large values of T, the damping ratio is greater than the one obtained in the base case. Specifically, for $T > 17$ s, the damping ratio obtained for all values of $x_{hvdc,eq}$ considered is greater than the damping ratio of the base case. Therefore, if the VSC-HVDC link is close to the machines involved in the inter-area mode, it will have an important impact on the inter-area mode. If T is either very small, or very large, the impact will be positive. However, for intermediate values of T, the impact will be negative.

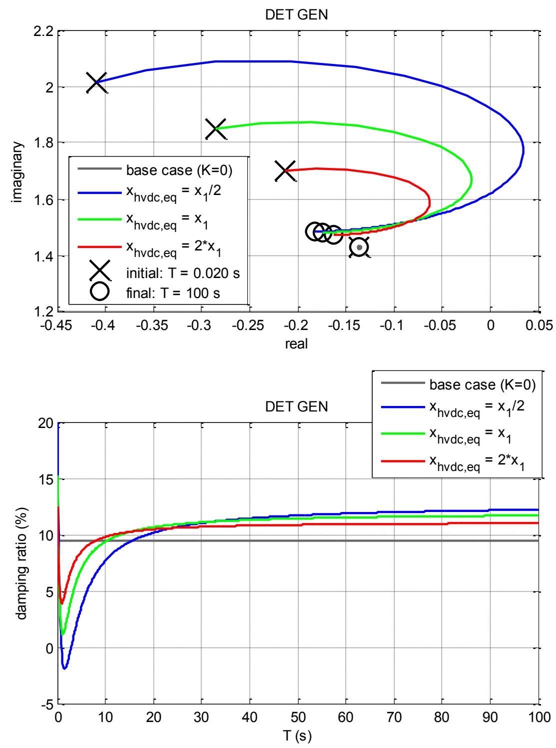

Fig. 8: SSA with detailed model for the generators. Case 3.

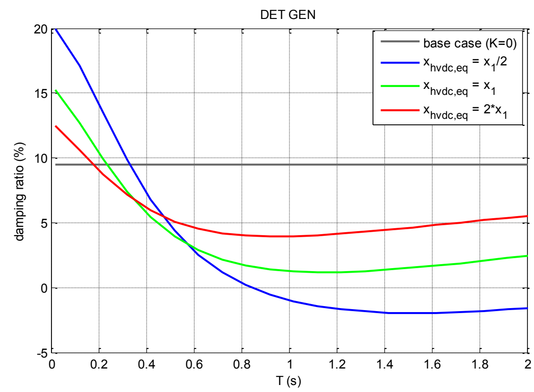

Fig. 9: SSA with detailed model for the generators. Case 3 (detail).

V. Conclusions

The following conclusions have been drawn from the results presented in this paper:

- The filter time constant (T) of the AC-line-emulation controller of a VSC-HVDC link may have a relevant impact on inter-area-oscillation damping. The impact can be either positive or negative, depending on the values of the time constant (T) and the gain ($K = 1/x_{hvdc,eq}$).

- For small values of T, the controller will increase the damping ratio of the inter-area oscillation.
- For intermediate values of T the controller will reduce the damping ratio of the inter-area mode.
- For large values of T, the controller will not have negative impact on the damping ratio of the inter-area mode.
- Since the AC-line-emulation control is a steady-state controller, a large T could be chosen to avoid negative interactions. However, as already mentioned, that value should be designed taking into account the highest value of K to be used. In the case study of this paper, reasonable designs of T are 20 s or greater.

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APPENDIX

TABLE I: DATA OF THE AC BRANCHES.

Branch	Impedance (system p.u) (base values 400kV, 100MVA)
Traf. 1-2	j0.01
Traf. 3-4	j0.01
Line 2-5 (x1)	j0.10
Line 3-5 (x2)	j0.40

TABLE II: OPERATING POINT OF THE GENERATORS.

Generator	PG (MW)	Vt (p.u)
1	1350	1.0
4	3900	1.0

TABLE III: LOAD DATA.

Load	PL (MW)	QL (MVAr)
2	1250	0
3	4000	0

TABLE IV: VSC-HVDC LINK DATA.

Parameter	Value
Power Rating	1000 MVA
DC-voltage rating	$\pm$320 kV
AC-voltage rating	330 kV
Configuration	Symmetrical monopole
Connection impedance (reactor + 400/330 kV transformer)	0+j0.17 p.u.
DC-voltage PI's parameters (K_P, K_I)	2 p.u, 0.12 p.u/s
Time constant of the inner current controllers	5 ms
DC-line series resistance	2.05 Ω
DC-line series inductance	140.1 mH
Equivalent capacitor at the DC side of each VSC station	195 μF