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► **To cite this version:**

Yankai Xing, Elkhatib Kamal, Bogdan Marinescu, Florent Xavier. Robust H_∞ Dynamic Output-feedback Control of Power Oscillation Damped via VSC-HVDC Transmission Systems. 2020 Electrical Power and Energy Conference, Nov 2020, Edmonton, Alberta, Canada. 10.1109/EPEC48502.2020.9320068 . hal-03172343

HAL Id: hal-03172343

<https://hal.science/hal-03172343v1>

Submitted on 17 Mar 2021

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Robust H_∞ Dynamic Output-feedback Control of Power Oscillation Damped via VSC-HVDC Transmission Systems

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Abstract—This paper addresses the problem of a particular case of high-voltage direct current transmission inserted into a meshed AC grid, which has an inter-area oscillation mode with a higher frequency than the normal mode. The classic Power Oscillation Damping (POD) controller failure to deal with this situation and the other changing operation point cases. Moreover, Non-Minimum Phase Zeros (NMPZs) were systematically put into evidence. Combined with the system uncertainties, they present a serious challenge for the control. A same reduced-order model of High-Voltage Direct Current line (HVDC) and adjacent AC area as former research is used for control design in this paper. Based on the reference model, using the LMI optimization method, a Dynamic Output Feedback Controller (DOFC) is proposed to provide modulation of active and reactive power to damp the inter-area oscillations, enhance the damping of the other modes, eliminate some impacts of NMPZs in the system and achieve robustness against variation of the operation point. The linearization and nonlinear models of the system are studied to establish and verify the method. The efficiency and robustness of the proposed controller were tested on the same actual benchmark of 19 generators connected through the mesh AC grid.

Index Terms—Power system oscillations, HVDC, damping controller, inter-area modes, robustness.

I. INTRODUCTION

As mentioned in past research [1] and [2], the inter-area modes which were analyzed and controlled were the ones at around 0.2 Hz in Europe. For HVDC line inserted into a mesh AC grid (such as the recent interconnection reinforcement in Europe) (for example, the France-Spain and France-Italy links), the inter-area control can be controlled by the high-voltage direct current converter. The mode may be at a higher frequency of about 1 Hz. The classic vector POD controller (see, e.g., [3]) is tested in paper [1], [2] as not satisfying to deal with this complex topology with NMPZs in the system.

In addition, in many applications, modeling errors and system uncertainties in plant models are inevitable. For preciseness, a design technique must accommodate these errors and uncertainties to be practically feasible. Thus, robust control has grown, in the last past years, as one of the most important areas in modern control design since the pioneering works [4].

Moreover, the Linear Matrix Inequality (LMI) methodologies, which are computationally simple and numerically reliable for solving convex optimization problems [5], moreover, its effective tools for robust controller design of linear uncertain systems. Recently, some attempts have been made to design robust dynamic output feedback controllers [6], either for norm-bounded uncertainty or polytopic uncertainty.

A large amount of research has been carried out on the development of the dynamic output feedback controllers according to Lyapunov theory via LMI approaches, e.g. [7]. Most of these methods present an iterative algorithm in which a set of LMIs are iteratively repeated until some certain termination criteria are met. In addition, since Linear Parameter Varying (LPV) systems are also an important class of systems from a theoretical and practical point of view, there has been much progress in the field of gain-scheduled H_∞ control of polytopic LPV systems using parameter-dependent Lyapunov method [8], [9]. In addition, a robust controller which is effective under different operating conditions is required.

Based on the same Bode plot-based reduced-order control model, sufficient conditions are derived for robust stabilization in the sense of Lyapunov asymptotic stability and are formulated in the format of LMIs to obtain gains for a H_∞ -type controller (Dynamic Output-feedback Controller (DOFC)) based on the reference model. Investigations with nonlinear model of the system were done to settle and validate the approach. The efficiency and robustness of the proposed controller are tested and compared with each others.

This paper is organised as follows. Section II introduces the problem formulation, main difficulties and modeling. LMI-based design of robust dynamic output feedback controller is given in section III, section IV shows validation of nominal cases and robust tests. Finally, Section V concludes the paper.

II. MAIN DIFFICULTIES AND MODELING

A. Main difficulties

Firstly, highly meshed grid present inter-area modes at higher frequencies which are less spread and at high frequencies. It should be noted for the regulators to not disturb the

TABLE I
THE LINEARIZED MODEL

No.	Mode	Damping ξ (%)	Freq. (Hz)	Mode shape (participation mag (%))		Residue	
				+	-	ABS MAG	Phase
1	-1.62+j8.19	19.5	1.30	GE_914 (100)	GE_913 (32.4)	0.0157	35.0
2	-0.24+j5.53	4.5	0.88	GE_911 (100)	GE_917 (68.8)	0.0181	83.4
3	-0.53+j5.29	10.1	0.84	GE_917 (100)	GE_918 (55.1)	0.0129	-56.2
4	-0.40+j4.79	8.3	0.76	GE_918 (44.3)	GE_912 (100)	0.0038	-33.3
5	-0.33+j3.29	10.1	0.52	GE_915 (100)	GE_918 (17.7)	0.0121	104.5
6	-18.83+j7.21	93.3	1.14	GE_921, GE_922 (100)	GE_923, GE_924 (74.1)	0.0034	14.5
7	-1.54+j6.55	22.9	1.04	GE_914 (100)	GE_911 (68.3)	0.0125	151.5
8	-19.32+j6.47	94.8	1.03	GE_921 (100)	GE_922 (37.6)	0.0117	118.9
9	-20.33+j4.86	97.2	0.77	GE_921, GE_922 (84.5)	GE_927 (100)	0.0026	-168.1
10	-18.72+j3.35	98.4	0.53	GE_913 (33.4)	GE_912 (100)	0.0072	136.1

other dynamics like local modes or electric coupling modes in close frequency. A reduced model called *control model* of full linearized model should be improved to carefully capture the all dynamics in this range. Secondly, it is well know that NMPZs brings much more difficulties for a controller. The existence of the NMPZs depends on the topology of the power grid [1]. This may cause the controller to fail to improve the damping of the mode. In previous work [1], this phenomenon has been verified on the results. Also, modeling errors and system uncertainties in plant models are inevitable. This is the third task to be solved in this paper.

B. Test system

The past research used test system is recalled here. It contains 19 generators and one HVDC line. After eigen-analysis, the modes which we concerned are list in Table I. To capture the dynamics mentioned above in frequencies close to the modes to be damped, and to maintain consistency with former research, the same control model is used to design the controllers. (see [1], [2])

C. Control model

To design the mentioned controller based on the state-represent model and focus on the interested dynamics, the simple reduced control model is not sufficient. To capture the dynamics mentioned above in frequencies close to the modes to be damped, two strategies are possible. First consists in starting from a full model of the power system and *reduce* it at a reasonable scale (about 10 state variables) for control by preserving dynamics of interest. This is very difficult for large-scale system and led us to a second approach based on *aggregation* of a transfer model around the modes of interest (see details in our former work [2]). Another significant control aspect is selection of the input signal for the designed controller. According [10], to rate the candidates input signals, residues of the corresponding open-loop transfer functions are systematically computed. The terminal difference of angles, $\Delta\theta = \theta_1 - \theta_2$, has the high *residue* is selected as control signal to provide power modulation as illustrated in Fig. 2.

D. Classic POD and its limitations

The structure of the classic IEEE HVDC POD controller [3] contains a gain K , a wash-out filter and n phase lead-lag

blocks. It is defined by the transfer function given by (1). In this case, $K = 2.5614$, $T_1 = 0.4746$, $T_2 = 0.0688$, $T_w = 1$ and $n = 2$. Its tuning of parameters of our test system are detailed in [1].

$$H_{POD}(s) = K \left(\frac{T_w s}{1 + T_w s} \right) \left(\frac{1 + T_1 s}{1 + T_2 s} \right)^n \quad (1)$$

When a target damping of 10% was fixed for mode 2, the tuning methodology mentioned above yields: $K = 2.5614$, $T_1 = 0.4746$, $T_2 = 0.0688$, $T_w = 1$ and $n = 2$. However, the real damping of this mode is only about 6% as reported in Table II. Further more, it can be observed that the damping of mode 4 is decreased by this controller. Moreover, the classic IEEE damping controller design synthesis [3] is simple but tends to lack of robustness. Its phase compensation is settled down for a specific grid situation which may not be suitable for changed phase of residue of the mode.

III. ROBUST H_∞ DYNAMIC OUTPUT-FEEDBACK CONTROL BASED ON REFERENCE MODEL

To overcome these difficulties mentioned above, and from experiences of solving convex optimization problems via LMIs [11]- [19], the Robust H_∞ Dynamic Output-feedback Controller (DOFC) Based on Reference Model strategy is proposed.

A. Selection of reference model

The reference model is chosen as having the desired output, that is horizontally shifting the poles to left until getting the desired damping (over 10%). In this case, the state space of the reference model can be given as the following:

$$\begin{aligned} \dot{x}_r(t) &= A_r x_r(t) + B_r u_r(t) \\ y_r &= C_r x_r(t) \end{aligned} \quad (2)$$

The selection of reference model is significant for the effectiveness of this controller. In general, this reference model is chosen as having the desired output, that is horizontally shifting the poles to left until getting the desired damping (over 10%). More addition, in order to eliminate the impact of unstable zeros, unstable zeros in reference model are placed to left plane but closed to virtual axis (decrease the control difficulty). In the meanwhile, the other stable zeros keep the

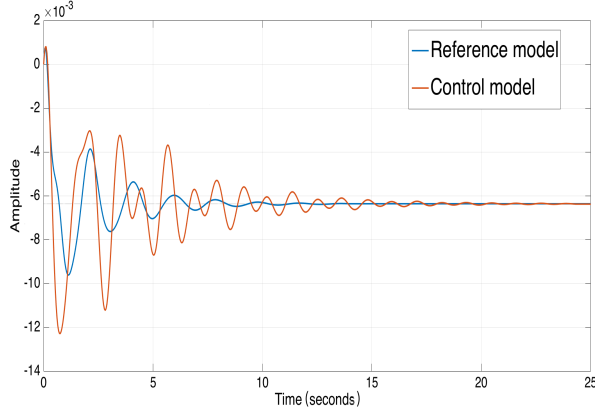


Fig. 1. Step response of reference model.

original position. The step response of the reference model compared with open-loop is shown in Figure 1.

Now, consider linear time-invariant continuous system is given by:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) \end{aligned} \quad (3)$$

where $x(t) \in \mathbb{R}^{n \times 1}$, $y(t) \in \mathbb{R}^{g \times 1}$ and $u(t) \in \mathbb{R}^{m \times 1}$ are the state vector, output vector and the control input, respectively, $C \in \mathbb{R}^{g \times n}$ is the system output matrix, $A \in \mathbb{R}^{n \times n}$ and $B \in \mathbb{R}^{n \times m}$, are the system and input matrix, respectively.

The structure of Robust H_∞ Dynamic Output-feedback Controller (DOFC) Based on Reference Model strategy is given in Fig. 2.

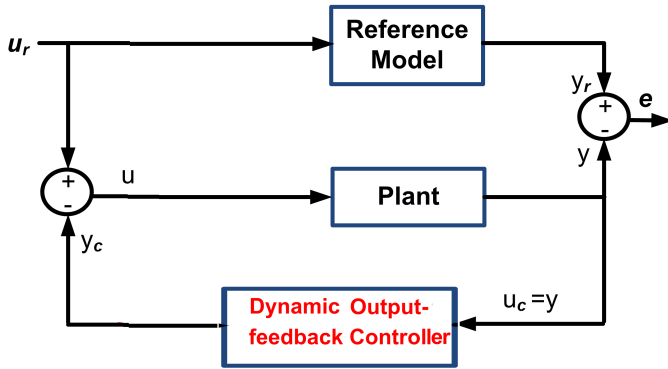


Fig. 2. Controller structure.

Consider the class of linear time-invariant continuous-time control system and reference system given in (3) and (2), respectively. The dynamic output feedback controller is given by.

$$\dot{x}_c(t) = A_c x_c(t) + B_c u_c(t), \quad y_c = C_c x_c(t) \quad (4)$$

where A_c , B_c and C_c are controller matrices to be designed. Applying the reference model (2) and the dynamic output feedback controller (4) to the system (3). From Fig. 2, it can be seen that:

$$\begin{aligned} u &= u_r - u_c = u_r - y_c = u_r - C_c x_c \\ u_c &= y = Cx \end{aligned} \quad (5)$$

From (3), (2) and (4), the augmented of the control system is given by:

$$\dot{X}(t) = \bar{A}X(t) + \bar{B}u_r, \quad Y(t) = \bar{C}X(t) \quad (6)$$

$$\begin{aligned} \text{where } \bar{A} &= \begin{bmatrix} A & 0 & -BC_c \\ 0 & A_r & 0 \\ B_c C & 0 & A_c \end{bmatrix}, \bar{B} = \begin{bmatrix} B \\ B_r \\ 0 \end{bmatrix}, \\ \bar{C} &= \begin{bmatrix} -C \\ C_r \\ 0 \end{bmatrix}^T, X(t) = \begin{bmatrix} x \\ x_r \\ x_c \end{bmatrix}^T \end{aligned}$$

B. Stability Analysis of the Proposed Robust H_∞ DOFC design

The main results for the global asymptotic stability of the system (6) are given Theorem 2:

Theorem 2: The system (6) is robustly stabilizable with the dynamic output-feedback controller given in (4), if there exist positive definite symmetric matrices $Q, Z \in \mathbb{R}^{(n+n_r) \times (n+n_r)}$ and full matrices $\hat{A}, \hat{B}, \hat{C} \in \mathbb{R}^{(n+n_r) \times (n+n_r)}$ and scalar γ , such that the following LMI is satisfied,

$$\min \gamma \quad (7)$$

subject to

$$\begin{bmatrix} \phi_1 + \phi_1^T & \hat{A}^T + \begin{bmatrix} A & 0 \\ 0 & A_r \end{bmatrix} & Z \begin{bmatrix} B \\ B_r \end{bmatrix} + \hat{B} & Q \begin{bmatrix} -C^T \\ C_r^T \\ -C^T \\ C_r^T \\ 0 \\ -\gamma I \end{bmatrix} \\ * & \phi_2 + \phi_2^T & * & * \\ * & * & -\gamma I & * \\ * & * & 0 & -\gamma I \end{bmatrix} \leq 0 \quad (8)$$

$$\begin{bmatrix} Q & I \\ I & Z \end{bmatrix} \geq 0 \quad (9)$$

where

$$\begin{aligned} \phi_1 &= \begin{bmatrix} A & 0 \\ 0 & A_r \end{bmatrix} Q + \begin{bmatrix} -B\hat{C} \\ 0 \end{bmatrix}, \phi_2 = Z \begin{bmatrix} A & 0 \\ 0 & A_r \end{bmatrix} + \begin{bmatrix} B\hat{B}C \\ 0 \end{bmatrix}^T, \\ N &= (I - ZQ)M^{-T}, \\ \bar{A} &= \hat{A} - Z \begin{bmatrix} A & 0 \\ 0 & A_r \end{bmatrix} Q - N \begin{bmatrix} B_c C \\ 0 \end{bmatrix}^T Q - Z \begin{bmatrix} BC_c \\ 0 \end{bmatrix} M^T \\ A_c &= N^{-1} \bar{A} M^{-T}, C_c = \hat{C} M^{-T}, B_c = N^{-1} \hat{B}, \end{aligned}$$

Proof. Bound real lemma [20] if there are exists a $(n+n_r)$ -dimensional controller making $\|P\|_\infty \leq \gamma$ if and only if there exists symmetry matrix $W \in \mathbb{R}^{2(n+n_r) \times 2(n+n_r)}$ satisfying

IV. VALIDATION TESTS

$$\begin{bmatrix} \bar{A}^T W + W \bar{A} & W \bar{B} & \bar{C}^T \\ \bar{B}^T W & -\gamma I & 0 \\ \bar{C} & 0 & -\gamma I \end{bmatrix} \leq 0, \quad W \geq 0 \quad (10)$$

Inequality (10) is a BMI when the controller is unknown. Here we will use the variables substitution method proposed in [21] to linearize it. Partition W and W^{-1} as

$$W = \begin{bmatrix} Z & N \\ N^T & \star \end{bmatrix}, W^{-1} = \begin{bmatrix} Q & M \\ M^T & \star \end{bmatrix} \quad (11)$$

where Q and Z are $(n+n_r) \times (n+n_r)$ symmetry matrices, M and N are $(n+n_r) \times (n+n_r)$ full matrices, \star stands for unknown matrix. Set

$$\Pi_1 = \begin{bmatrix} Q & I \\ M^T & 0 \end{bmatrix}, \Pi_2 = \begin{bmatrix} I & Z \\ 0 & N^T \end{bmatrix} \quad (12)$$

From $WW^{-1} = I$, we can infer

$$\Pi_2 W \bar{A} = \Pi_2 \bar{A} \Pi_1 \quad (13)$$

So that,

$$\begin{aligned} \Pi_2 \bar{A} \Pi_1 &= \begin{bmatrix} I & 0 \\ Z & N \end{bmatrix} \begin{bmatrix} A & 0 & -BC_c \\ C & A_r & 0 \\ B_c C & 0 & A_c \end{bmatrix} \begin{bmatrix} Q & I \\ M^T & 0 \end{bmatrix} \\ &= \begin{bmatrix} A & 0 \\ 0 & A_r \end{bmatrix} Q + \begin{bmatrix} -BB_c \\ 0 \end{bmatrix} M^T \begin{bmatrix} A & 0 \\ 0 & A_r \end{bmatrix} \\ &\quad Q_1 \quad \quad \quad Q_2 \end{aligned} \quad (14)$$

$$\Pi_1^T W \bar{B} = \Pi_2^T \bar{B} \Pi_1 = \begin{bmatrix} I & 0 \\ Z & N \end{bmatrix} \begin{bmatrix} B \\ B_r \\ 0 \end{bmatrix} = \begin{bmatrix} B \\ B_r \\ Z \begin{bmatrix} B \\ B_r \end{bmatrix} \end{bmatrix} \quad (15)$$

then,

$$\Pi_1^T \bar{C} = \begin{bmatrix} -C & C_r & C \end{bmatrix} \begin{bmatrix} Q & I \\ M^T & 0 \end{bmatrix}^T \begin{bmatrix} Q \begin{bmatrix} -C^T \\ C_r^T \\ -C_r^T \\ C_r^T \end{bmatrix} \end{bmatrix} \quad (16)$$

where,

$$\begin{aligned} Q_1 &= Z \begin{bmatrix} A & 0 \\ 0 & A_r \end{bmatrix} Q + N \begin{bmatrix} B_c & C & 0 \end{bmatrix} Q + Z \begin{bmatrix} -BC_c \\ 0 \end{bmatrix} M^T + \\ &N A_c M^T, Q_2 = Z \begin{bmatrix} A & 0 \\ 0 & A_r \end{bmatrix} + N \begin{bmatrix} B_c & C & 0 \end{bmatrix} \end{aligned} \quad (17)$$

Thus,

$$\begin{aligned} \hat{A} &= Z \begin{bmatrix} A & 0 \\ 0 & A_r \end{bmatrix} Q + N \begin{bmatrix} B_c & C & 0 \end{bmatrix} Q + Z \begin{bmatrix} -BC_c \\ 0 \end{bmatrix} M^T \\ &+ N A_c M^T, \hat{B} = N B_k, \hat{C} = C_k M^T \end{aligned} \quad (18)$$

Therefore, (10) are equivalent to (8) and (9) in the Theorem 2.

In this section, the DOFC based on reference model strategy depicted in section III are validated in the case of the problem of damping inter-area oscillations via power modulation of a VSC-HVDC link integrated in a power AC grid in two cases linearized and nonlinear systems. For all tests, the response to the short-circuit at the node connected to generator 918 (which is closed to most participated generator 911 of mode 2) is studied which excites the modes of interest. (Table I).

Notice that, to evaluate the effective of the controllers, some key point should be mentioned: The several swing in the beginning mainly contains the dynamic performance of controllers; the oscillation in the end before settling down can be seen as interested mode in the system (1Hz).

A. Validation on the linearized system

In this subsection, the controller is tested on the linear approximation of the system in Matlab. The step response of the difference of angles $\Delta\theta$ in nominal case is shown in Figure 3.

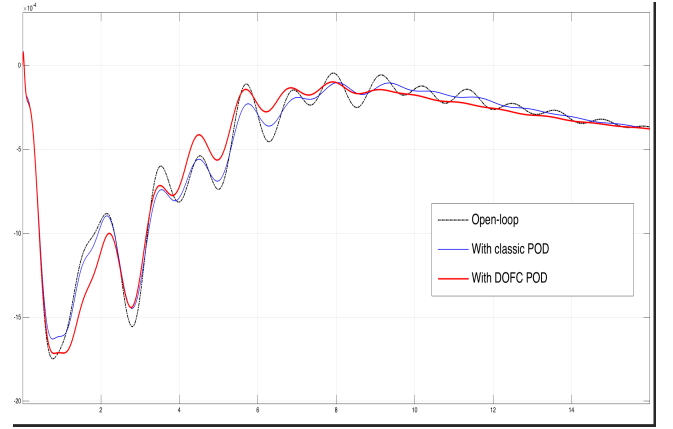


Fig. 3. Comparison of linearized model.

From this linearized system closed-loop results, it can be seen that, for the modes damping, the DOFC POD gives a good performance compared to classic POD strategy.

B. Validation on the nonlinear system

The controllers are now tested on the nonlinear model of the system in Eurostag. Not only nominal case is considered but also robust cases as given in the following tests. The non-linear system closed-loop responses shown in Fig.4. The linearization after applying PODs is done to calculate the damping shown in Table II.

1) *Nominal case:* Comparison between controllers of nominal case is shown in Figure 4.

From Fig. 4, it can be seen that, for at the least damped mode, the DOFC POD performs the best in the swings in the end of the curve where the mode is the most observable. Notice that, several swings in the beginning are due to the dynamic transient of the system. From Table II, the DOFC POD improve each modes over 10%. The classic POD improves a little the mode 2, but disturbs mode 4.

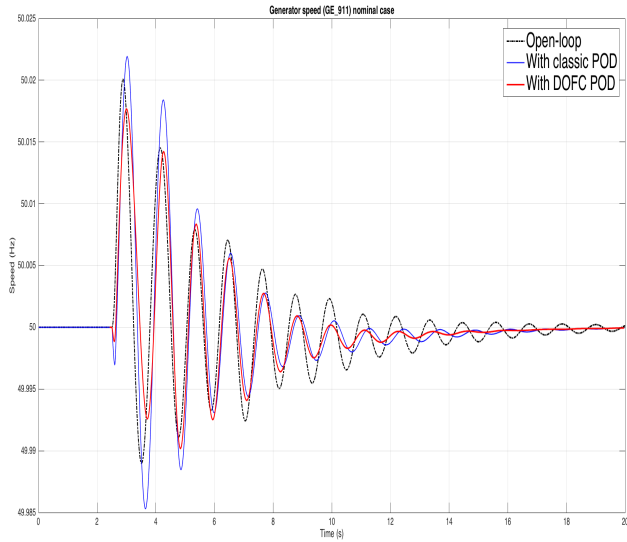


Fig. 4. Nominal case.

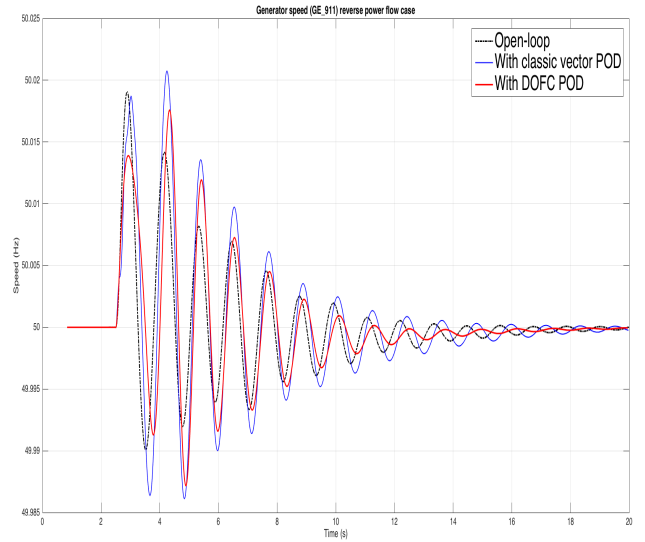


Fig. 5. Reverse power flow case.

TABLE II
COMPARISON OF DAMPING

No.	ξ without POD (%)	ξ with classic POD (%)	ξ with DOFC POD (%)
1	19.5	30.5	23.3
2	4.5	6.1	12.6
3	10.1	12.0	10.8
4	8.3	8.1	10.6
5	10.1	12.4	14.1

2) *Robust cases:* In order to analyze system uncertainties, the changing operation point situations are studied in this part.

The uncertainty analysis is proceeding in several cases listed here:

- 1) Inverse the power flow direction and the value of the active power on HVDC lines (from $+800MW$ to $-200MW$);
- 2) Increase the load on the nodes connected the most participating generator in the critical mode 2 (increase 30%);
- 3) Tripping the generators closed to the most participation machine;
- 4) Tripping lines closed to the most participating generator to the critical mode 2.

Comparisons between controllers of robust cases are shown in Figure 5, 6, 7, 8.

For reverse power flow case, the performance of DOFC POD is good in the beginning. Closed loop with classic POD is even worse than open-loop.

For increased load case and tripping generator cases, it is obviously, the most advantage controller is DOFC POD.

In tripping lines case, The classic POD has the same performance with DOFC POD for damping the modes but

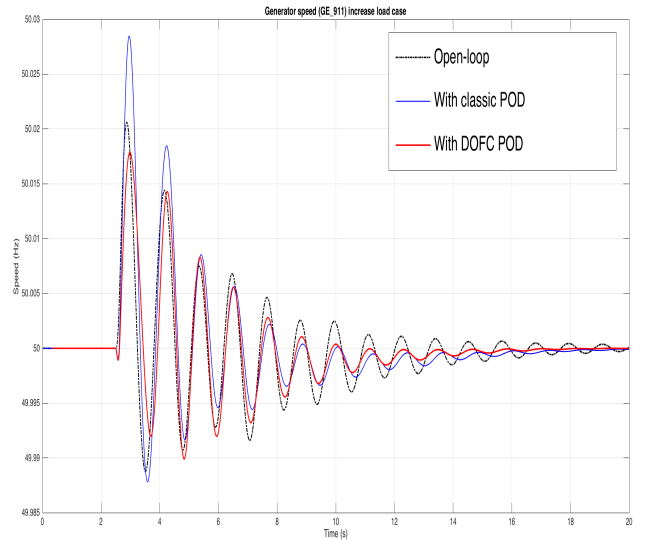


Fig. 6. Increase load case.

worse dynamic response in the beginning.

From these tests one can conclude that, for damping of the interested modes, the performance of DOFC is Considerable. For same level of damping, robustness is improved with proposed DOFC POD strategy.

V. CONCLUSION

The problem of power oscillations damping control of a VSC-HVDC was addressed in the particular context where the link is inserted in a meshed AC grid. The only information of the residues of the modes to be damped is not sufficient in this case and a dynamic control model which captures not only

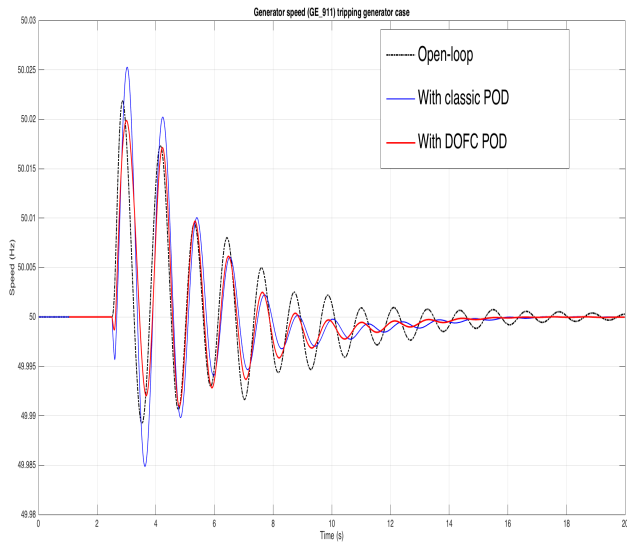


Fig. 7. Tripping generator case.

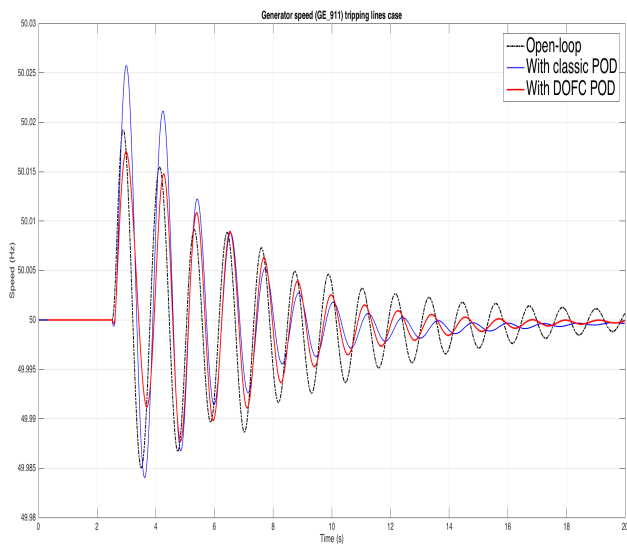


Fig. 8. Tripping lines case.

the modes to be damped but also the other dynamics which might be excited by the closed-loop is proposed. Moreover, information from this model was used in a *reference model*, in order to counteract the effects of non-minimum phase zeros. In addition, realistic situations of power grids motivated us to improve robustness against typical variations of the grid and un-modeled dynamics. This allowed us to provide better robustness, i.e., maintain the damping properties not only in the nominal case but also in case of disturbances (short-circuits) and usual grid variation (line /generator trips, modification of operation point, etc). The control was validated on a realistic

case in simulation with a professional grid dedicated software (Eurostag). The resulting control can be easily implemented in state-space in real-word of grid applications.

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