Impact of power system controls on damping wind induced inter-area oscillations

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ABSTRACT. This paper assesses the performances of standard power system controllers in damping inter-area oscillations induced by wind power. System basic controllers considered are: Power System Stabilizer (PSS), Static Var Compensator (SVC) with Power Oscillation Damper (POD), High Voltage AC/DC (HVDC) transmission. Combined two controls are considered: PSS-HVDC, PSS-SVC POD. Wind turbines are based on: squirrel cage induction generator (SCIG), Doubly Fed Induction Generator (DFIG) and Direct Drive Synchronous Generator (DDSG). The study is applied on a four-machine two-areas power system integrating wind turbines of different technologies. Damping ratios are computed by the linear modal analysis technique. The wind induced inter-area frequency and its damping depend both on the turbine technology and the existing controls. The results demonstrate that power system stabilizer (PSS) helped increase inter-area oscillations damping better than SVC-POD and AC/DC link. A coordinated tuning of the combined two-controllers strategy must be performed to achieve optimum damping.

RÉSUMÉ : Cet article évalue les performances des régulateurs standards du réseau électrique dans l'amortissement des oscillations interzones induites par l'intégration éolienne. Les régulateurs étudiés sont : les stabilisateurs de réseau (PSS), compensateurs statiques (SVC) menus d'amortisseurs d'oscillation de puissance (POD), lignes à courant continu haute tension AC/DC (HVDC). Deux types de contrôles sont combinés : PSS-HVDC, et PSS-SVC POD. Les aérogénérateurs sont de technologies : générateur à induction à cage d'écureuil (SCIG), générateur à induction à double alimentation (DFIG), et générateur synchrone à entraînement direct (DDSG). L'étude est appliquée à un réseau à deux zones, comportant quatre générateurs et intégrant des éoliennes de différentes technologies. Les taux d'amortissement sont déterminés par une analyse modale. Les modes interzones induite par le vent et leurs amortissements dépendent à la fois de la technologie de la turbine et des commandes déployées. Les résultats montrent que le stabilisateur de réseau (PSS) a permis d'améliorer l'amortissement des oscillations interzones mieux que le control par SVC-POD et les liaisons AC/DC. Un réglage coordonné de la stratégie à deux régulateurs doit être déployés pour atteindre un amortissement optimal.

KEYWORDS: wind turbine, inter-area oscillations, damping, Static Vac Compensator (SVC), Power System Stabilizer (PSS), Power oscillation Damper (POD).

MOTS-CLÉS : éolienne, oscillations interzones, amortissement, compensateur statique (SVC), stabilisateur de réseau (PSS), amortisseur d'oscillation de puissance (POD).

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1. Introduction

Wind power generation has extensively been integrated in power systems. In 2017, global wind power capacity has reached 539.123 GW with an increase rate of 21.24% (Global wind report, 2017). Such large scale wind power integration affects the power system voltage regulation and dynamic stability issues, such as inter-area oscillations. Oscillations are a characteristic of power systems, initiated by normal small changes in the operating parameters such the system load or wind power variations. Indeed, wind power generation may be viewed as a continuous negative load variation that calls for speed governors to act continuously to set the generation-demand balance. Hence, power oscillations can be sustained due to the governors natural characteristics. Although the oscillations are not expected to increase in time, the sustained variations can become a problem.

Inter-area oscillations with frequency ranges from 0.1 to 0.7Hz (Klein *et al.,* 1991), limit the transmission capability of the power grid and may lead to system instabilities. Power System Stabilizers (PSS) are specially designed to damp these oscillations (Larsen et Swann, 1981). Nonetheless, the increasing demand for reliability makes the automatic voltage controllers used to prevent the generators from loosing synchronism following a system fault, very fast. This fast action tends to reduce the damping of the system oscillations.

Various other techniques are used to improve damping of inter-area oscillations. In (Li *et al.,* 2012), a supplementary controller is attached to the rectifiers of a line commutated current-source converter high voltage direct current (LCC-HVDC) system to damp inter-area oscillations. In (Li, 2014), the DFIG rotor voltage control for system dynamic performance enhancement is proposed. The POD equipped with the DFIG based on a phase lead compensation is able to improve the network damping. In (Surinkaew et Ngamroo, 2014), a coordinated control of DFIG POD and local PSSs is assessed to damp inter-area oscillations in power system integrated wind farm. In (Li *et al.*, 2016), an optimization-based sequential design strategy is proposed to coordinate multiple local PSSs and one wide-area high voltage direct current (HVDC) stabilizer. The overall system stability is greatly enhanced. In (Zhengchao *et al*., 2016) a supplementary SVC control for damping inter-area oscillation is implemented. It consists of an amplification block, a low-pass filter, a washout filter and compensation block. It was demonstrated that the proper control of SVC installed in the two area power system can largely improve the inter-area oscillatory stability. In (Mohamed, 2016), a PSS for wind turbine employing a DFIG is used for network damping enhancement. In (Agus et Haryanto, 2017), a power oscillation damper (POD) is added to the STATCOM control to damp inter-area oscillations.

For power systems operating with large scale wind power integration, performances of the existing standard controls need further investigations. In the above works, single controllers are proposed, with no indication to the control method best suited since they are not applied on a benchmark system. The interactions between the wind power and the various oscillation dampers during normal operation needs further investigations.

The purpose of this paper is to assess the performances of standard power system controllers in damping inter-area oscillations induced by wind power: power system stabilizers static var compensator with power oscillation damper high voltage AC/DC transmission. Combined controls are considered: PSS-HVDC, PSS-SVC POD. Wind turbines are based on: squirrel cage induction generator, doubly fed induction generator and direct drive synchronous generator. The study is applied on a four-machine two area power system integrating wind turbines of different technologies. The proposed control strategies are compared based on their modal analysis frequency information.

2. Modeling of damping controllers

2.1. Model of Power System Stabilizer (PSS)

A power system stabilizer is one of the traditional forms of controls of power oscillations. This device is added to an automatic voltage regulator (AVR) loop to improve damping during power swings. It provides a component of the electrical torque in the synchronous machine rotor which is proportional to the deviation of the actual speed from the synchronous speed (Snyder *et al.*, 1999). The main purpose of PSS is to increase damping torque and suppress oscillations between synchronous machines through modulating the input voltage of the excitation system (Larsen and Swann, 1981). Figure 1 shows a PSS added to an AVR, where $\mathrm{E_{fd}}$ and V_{ref} are the output voltage and the reference voltage of AVR, *v* is the principal input signal of the excitation system, U_{pss} is the output stabilizing signal of PSS , K_A and T_A are the exciter gain and the time constant.

The dynamic model of the PSS is described as follows:

$$U_{pss} = K_{pss}\frac{sT_w}{1+sT_w}\left(\frac{1+sT_{1pss}}{1+sT_{2pss}}\right)\left(\frac{1+sT_{3pss}}{1+T_{4pss}}\right)\Delta\omega \qquad (1)$$

Where K_{pss}, T_{1pss}, T_{2pss}, T_{3pss}, T_{4pss} and T_w are the PSS gain, lead-lag time constants and the washout time constant respectively.

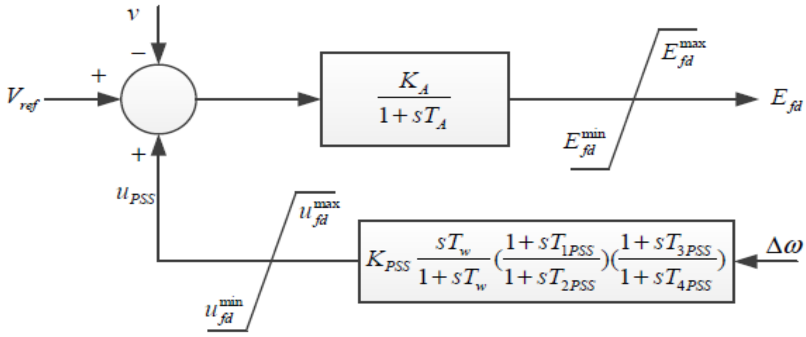

Figure 1. An automatic voltage regulator (AVR) with power system stabilizer (PSS)

2.2. Model of SVC with POD

Static Var Compensator (SVC) is a type of FACTS devices installed over transmission lines to control power flow, improve voltage level, compensate reactive power and enhance stability. It composed of fixed capacitors and controllable reactance (Zhang and Rehtanz, 2012). The regulator structure of SVC is depicted in Figure 2. The dynamic model can be described as follows (Milano, 2011):

$$\dot{b}_{svc} = \frac{K_r(v_0^{ref} - v) - b_{SVC}}{T_r} \quad (2)$$

where $\boldsymbol{v_0}^{\boldsymbol{ref}}$, v and $\boldsymbol{b_{SVC}}$ are initial reference voltage , system bus voltage and the reactance of SVC. $\boldsymbol{K_r}$ and $\boldsymbol{T_r}$ are the gain and time constant of SVC regulator.

An SVC is installed over transmission lines to enhance voltage stability. As the inter-area oscillations are associated with heavy power transfer in interconnected power systems, small signal stability can be improved when a supplementary control loop which is Power Oscillation Damper (POD) in this study, is added to the SVC. control. The POD output modulating signal is input to the voltage control loop of SVC to provide additional damping torque effect for power oscillations. The structure of a POD is almost the same as a PSS. Indeed, it is composed of a stabilizer gain $\boldsymbol{K_{Stab}}$, a washout stage $\boldsymbol{T_w}$ and a 2nd lead-lag stage with time constants $\boldsymbol{T_{1POD}}$, $\boldsymbol{T_{2POD}}$, $\boldsymbol{T_{3POD}}$ and $\boldsymbol{T_{4POD}}$. The input feedback signal of POD is the line active power. The output signal $\boldsymbol{v_s}^{\boldsymbol{POD}}$ is used to adjust SVC reactive power injection. Figure 3 depicts the structure of a power oscillation damper.

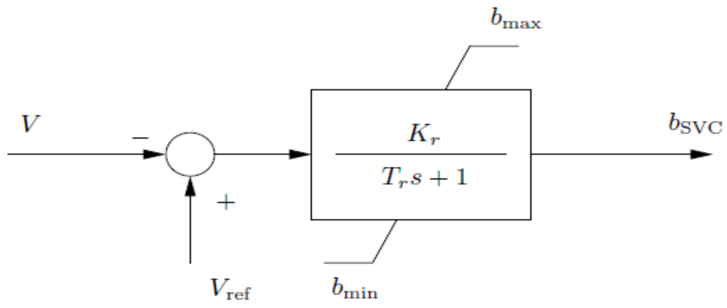

Figure 1. The structure of an SVC regulator

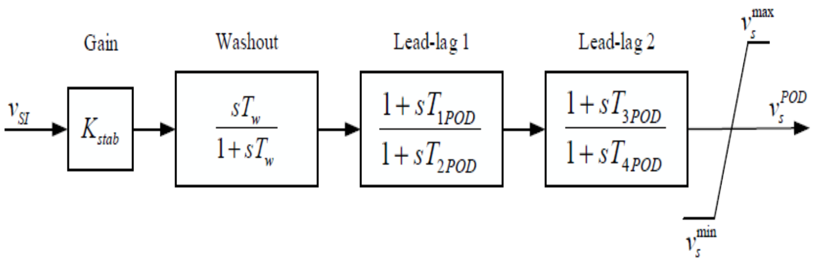

Figure 2. The structure of a power oscillation damper (POD)

2.3. Model of HVDC

The High Voltage Direct Current line (HVDC) is modeled by a rectifier station and an inverter station connected by a single DC line which is modeled as an RL circuit. The firing angle α and the extinction angle γ are controlled by PI regulators, as shown in Figure 4. The control system regulates the current flow in the DC line. The model of the HVDC is described by (Milano, 2011):

$$\dot{I_{dc}} = (V_{Rdc} - V_{Idc} - R_{dc}I_{dc})/L_{dc} \tag{3}$$

$$\dot{x_R} = K_I(I_{R0} - I_{dc}) \tag{4}$$

$$\dot{x_I} = K_I(I_{dc} - I_{I0}) \tag{5}$$

$$P_{km} = \frac{V_{n_{dc}} I_{n_{dc}}}{S_n} V_{Rdc} I_{dc} \tag{6}$$

$$Q_{km} = \sqrt{{S_R}^2 - (\frac{V_{n_{dc}} I_{n_{dc}}}{S_n} V_{Rdc} I_{dc})^2} \tag{7}$$

$$P_{mk} = \frac{V_{n_{dc}} I_{n_{dc}}}{S_n} V_{Idc} I_{dc} \tag{8}$$

$$Q_{mk} = \sqrt{{S_I}^2 - (\frac{V_{n_{dc}} I_{n_{dc}}}{S_n} V_{Idc} I_{dc})^2} \tag{9}$$

$$\cos\alpha = x_R + K_p(I_{R0} - I_{dc}) \tag{10}$$

$$V_{Rdc} = \frac{3\sqrt{2}}{\pi} V_k \cos\alpha - \frac{3}{\pi} X_{tr} I_{dc} \tag{11}$$

$$S_R = \frac{3\sqrt{2}}{\pi} \frac{V_{ndc} I_{ndc}}{S_n} V_k I_{dc} \tag{12}$$

$$I_{R0} = \frac{V_k}{m_R} \tag{13}$$

$$\cos(\pi - \gamma) = x_I + K_p(I_{dc} - I_{I0}) \tag{14}$$

$$V_{Idc} = \frac{3\sqrt{2}}{\pi} V_m \cos(\pi - \gamma) - \frac{3}{\pi} X_{tI} I_{dc} \tag{15}$$

$$S_I = \frac{3\sqrt{2}}{\pi} \frac{V_{ndc} I_{ndc}}{S_n} V_m I_{dc} \tag{16}$$

$$I_{I0} = \frac{V_m}{m_I} \tag{17}$$

where $V_{ndc}, I_{ndc}, V_{Rdc}$ and V_{Idc} are the DC voltage rating, the DC current rating, the rectifier DC voltage and the inverter DC voltage respectively. I_{R0}, I_{I0}, X_{tr}, X_{tI} are the reference current of the rectifier , the reference current of the inverter , the transformer reactance of the rectifier and the transformer reactance of the inverter respectively. m_R and m_I are tap ratios of the rectifier and the inverter. $K_I$and K_p are the integral gain and Proportional gain. P_{km}, Q_{km} , P_{mk}, Q_{mk} are the active and reactive power output at the rectifier and inverter stations respectively.

3. Study cases

The study is applied on a four-machine two-areas power system. It consists of two symmetrical areas linked by two 230 kV lines of 220km length. It was specifically designed in (Kundur, 1994) to study small signal stability and damping control design in large interconnected power systems. Each area comprises two identical round rotor generators rated 20kV/900 MVA. The synchronous generators are presented by a six-order model with magnetic saturation neglected and voltage regulators and they have identical parameters. There are 2800MW installed generation capacity in this system (1400MW in each area), and 400MW of the total active power is transmitted from area 1 to area 2. The test system is depicted in Figure 4. The following scenarios are studied:

1) The test system without (PSS /SVC POD/ HVDC)
2) The test system with PSS
3) The test system with SVC POD
4) The test system with DC link in parallel with AC transmission line
5) The test system with PSS and SVC POD
6) The test system with PSS and DC/AC link
7) Case (1, 2, 3, 4, 5 and 6) with the integration of DFIG wind farm (140 MW)
8) Case (1, 2, 3 ,4, 5 and 6) with the integration of DDSG wind farm (140 MW)
9) Case (1, 2, 3, 4, 5and 6) with the integration of SCIG wind farm (140 MW)

Simulation results were carried out using a Power System Analysis Toolbox (PSAT) (Milano, 2011), which is a MATLAB-based toolbox for power system studies.

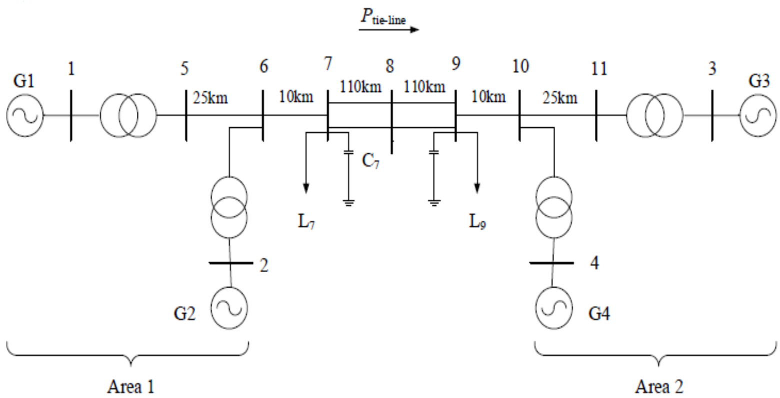

Figure 3. The test power system

4. Simulation results

4.1. Modal analysis without /with damping controllers

The purpose of this section is twofold: First, we evaluate the performances of each damping controllers which are PSS, SVC-POD and HVDC link on damping inter-area oscillations in interconnected power system without integration of wind energy. Second, two types of damping controllers are incorporating simultaneously in the power system to assess if they improve the damping of inter-area oscillations or they may have adverse effects.

The parameters of PSS and SVC-POD are tuned as in (Kundur, 1994). The parameters of HVDC link are modified from the CIGRE benchmark model (Faruque *et al.*, 2006). It's a monopolar 500kV, 230MVA, 0.46kA HVDC link modeled as a π equivalent circuit. Each converter has its own converting transformer. The HVDC transmission line is 220 km. Results of eigenvalue analysis are summarized in Table 1. The damping ratios of inter-area oscillations in all cases are represented by histograms in Figure 7.

SVC POD is connected to bus 8 of the test power system and HVDC transmission line is connected in parallel with the AC tie-line, as it's shown in Figures 5 and 6.

From Table 1, it can be seen that all controllers can improve the damping of inter-area oscillation which is (21.1%, 8.34% and 6.08%) in case of (PSS, SVC POD and HVDC) respectively. It's clear that the power system stabilizer (PSS) helped increase inter-area oscillation damping better than SVC POD and HVDC link. Indeed, PSSs are installed at the generators having a strong correlation with the swing mode. That's why the damping of inter-area oscillation is significant. The static var compensator (SVC) is generally installed over transmission lines to improve voltage stability, and as inter-area oscillations are associated with transfer power over transmission lines, the SVC can enhance the damping of inter-area oscillations if the power oscillation damper (POD) is integrated into the control of SVC. Thus, SVC-POD can improve inter-area oscillation damping as it's able to control the transfer power in tie – lines. However, the addition of HVDC link to the AC tie-line has a small effect on damping of the inter-area mode. On the other hand, when a PSS and SVC-POD are used simultaneously in the power system, damping of inter-area mode increases significantly, 26.72% approximately.

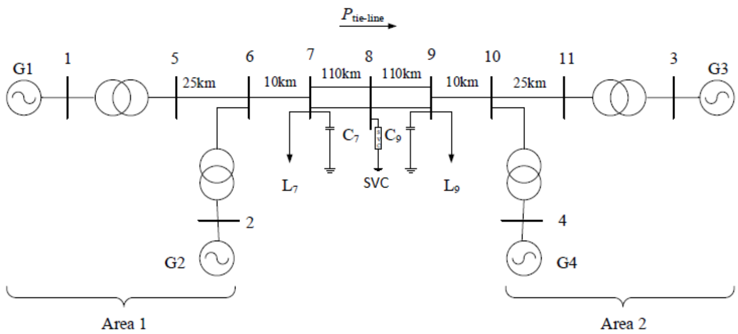

Figure 4. SVC connected to bus 8 of the power system

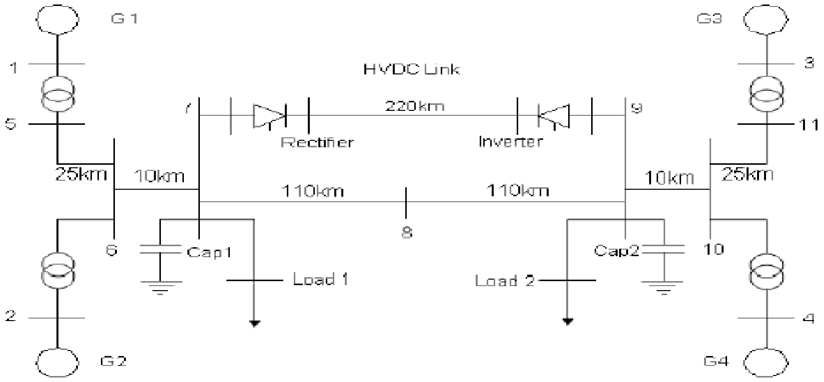

Figure 5. HVDC link in parallel with AC tie-line

Table 1. Oscillation modes of the test power system

Cases	Modes	Frequency f (Hz)	Damping ratio ζ(%)
Without controllers	Local mode 1	1.0348	14.85
	Local mode 2	1.0032	15.15
	Inter-area mode	**0.5637**	**5.65**
PSS	Local mode 1	1.3722	36.92
	Local mode 2	1.2949	37.76
	Inter-area mode	**0.56632**	**21.16**
HVDC	Local mode 1	10366	15.11
	Local mode 2	1.002	15.14
	Inter-area mode	**0.58821**	**6.08**
SVC-POD	Local mode 1	1.059	14.77
	Local mode 2	1.0074	15.22
	Inter-area mode	**0.63087**	**8.34**
PSS and HVDC	Local mode 1	1.3812	36.53
	Local mode 2	1.2936	37.66
	Inter-area mode	**0.59335**	**21.19**
PSS and SVC POD	Local mode 1	1.4631	33.65
	Local mode 2	1.3334	37.44
	Inter-area mode	**0.62633**	**26.72**

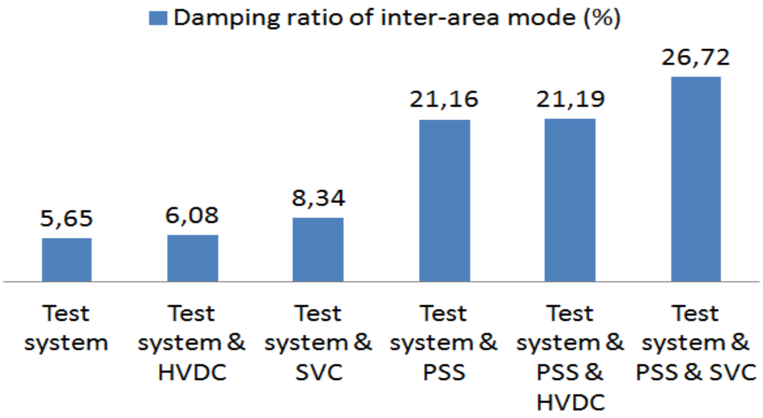

Figure 6. Damping ratios of inter-area oscillation mode in all cases

4.2. Linear modal analysis of wind power integration

A wind farm of 140 MW is connected to bus 6 of the test power system and scenarios of section 4.1 are restudied after the integration of this farm. An aggregate wind farm model is used. Three types of wind turbine technologies are tested which are doubly fed induction generator (DFIG), direct drive synchronous generator (DDSG) and squirrel cage induction generator (SCIG). Resulting oscillation modes of the modified two area power system are summarized in Tables 2, 3 and 4. We focus only on inter-area oscillations. The results are represented by the histograms in Figures 8, 9 and 10.

From Tables 2, 3 and 4, it can be noticed that with the integration of wind power, there is one more inter-area oscillation mode. Its frequency and its damping depend on the type of wind turbine generator. Furthermore, the integration of wind farm improves the damping of the existing inter-area mode. From a control point of view, both PSS and HVDC improve the damping of the two inter-area modes. The damping of the new inter-area oscillation is significantly improved by PSS in case of variable speed WTGs: from 27.24% to 62.65% in case of DFIG and from 39.48% to 83 % in case of DDSG. However, SVC-POD improves only the existent mode and decreases the damping of the new inter-area mode for all types of wind turbine technologies. Thus, parameters of SVC POD must be returned taking into account the presence of wind farm. On the other hand, the addition of PSS and HVDC simultaneously, has a positive impact on the new inter-area oscillation damping in case of DFIG and SCIG and has a negative impact in case of DDSG. Indeed, the damping of the new inter-area mode increases from 62.57% in case of PSS only to 66.53% in case of PSS and HVDC. But in case of DDSG, the damping ratio of the new inter-area mode decreases from 83% to 82.54%. Therefore, the following conclusions can be made:

– The SVC-POD must be retuned taking into account the integration of the wind farm and the type of the wind turbine generators. If not it can have negative impact.

– A coordination control of the PSS and the HVDC and of the PSS and the SVD-POD must be performed to avoid the interaction between controllers and to obtain maximum damping.

Table 2. Inter-area oscillation modes in case of DFIG wind turbine

Cases	Modes	Frequency f (Hz)	Damping ratio ζ(%)
Test system & DFIG	Inter-area mode 1	0.57117	6.5
	New inter-area mode	0.16258	27.24
PSS	Inter-area mode 1	0.57391	21.75
	New inter-area mode	0.16922	62.57
HVDC	Inter-area mode 1	0.58977	7
	New inter-area mode	0.14236	29.9
SVC POD	Inter-area mode 1	0.6294	9.39
	New inter-area mode	0.14786	27.18
PSS & HVDC	Inter-area mode 1	0.59689	21.84
	New inter-area mode	0.15808	66.53
PSS & SVC- POD	Inter-area mode 1	0.62656	27
	New inter-area mode	0.16125	57.7

Table 3. Inter-area oscillation modes in case of DDSG wind turbine

Cases	Modes	Frequency f (Hz)	Damping ratio ζ(%)
Test system & DDSG	Inter-area mode 1	0.56087	6.69
	New inter-area mode	0.10604	39.48
PSS	Inter-area mode 1	0.56433	22.12
	New inter-area mode	0.12232	83
HVDC	Inter-area mode 1	0.584	7.09
	New inter-area mode	0.10573	39.37
SVC POD	Inter-area mode 1	0.62403	9.58
	New inter-area mode	0.10464	39.32
PSS & HVDC	Inter-area mode 1	0.58857	21.94
	New inter-area mode	0.12148	82.54
PSS & SVC- POD	Inter-area mode 1	0.62114	27.65
	New inter-area mode	0.12114	75.96

Table 4. Inter-area oscillation modes in case of SCIG wind turbine

Cases	Modes	Frequency f (Hz)	Damping ratio ζ(%)
Test system & SCIG	Inter-area mode 1	0.55386	7.8
	New mode	0.6659	20.62
PSS	Inter-area mode 1	0.6721	22.61
	New mode	0.55205	21.96
HVDC	Inter-area mode 1	0.5761	8.18
	New mode	0.66542	20.55
SVC-POD	Inter-area mode 1	0.61703	10.9
	New mode	0.66536	20.13
PSS & HVDC	Inter-area mode 1	0.57384	21.5
	New mode	0.67193	22.11
PSS & SVC-POD	Inter-area mode 1	0.67031	24
	New mode	0.60811	27.28

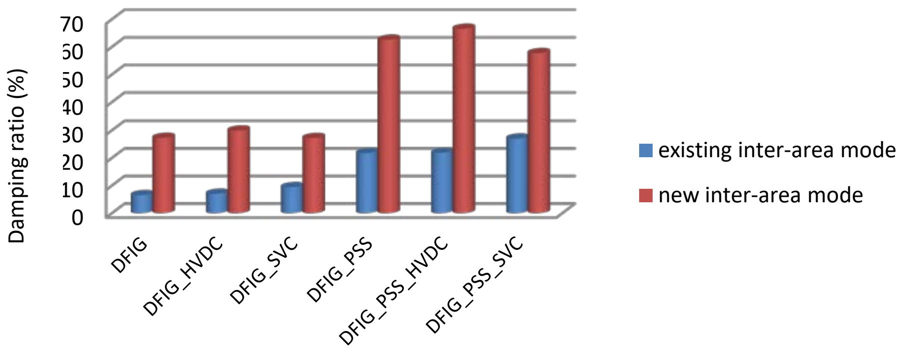

Figure 7. Damping ratios of inter-area oscillation modes in case of DFIG wind farm

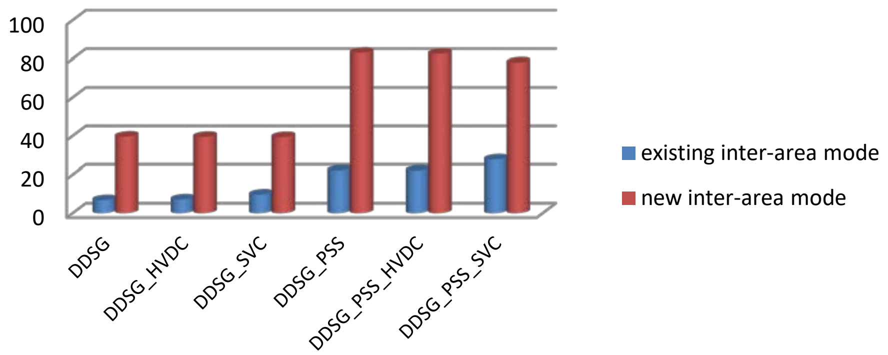

Figure 8. Damping ratios of inter-area oscillations in case of DDSG wind turbine

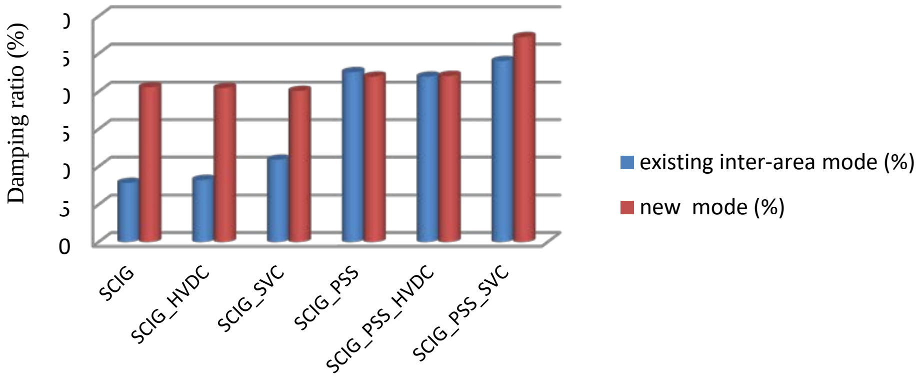

Figure 9. Damping ratios of inter-area oscillations in case of SCIG wind turbine

5. Conclusion

This paper has investigated the effect of power system controls on damping inter-area oscillations in power system integrating wind power. First, three control strategies oscillations were compared: Control by power system stabilizers installed in synchronous generators, control by static var compensator with power oscillation damper, and control by HVDC transmission. Second, two of these controllers were combined: PSS-HVDC and PSS-SVC POD in search for optimal damping performances. The study was applied on a four-machine two-areas power system integrating wind turbines of different technologies: the squirrel cage induction generator , the doubly fed induction generator, and the direct drive synchronous generator.

Eigenvalue analysis showed that in case of interconnected power system without the integration of wind energy, the power system stabilizer (PSS) helped increase the damping of inter-area oscillations better than the static var compensator equipped with power oscillations damper and the HVDC link. Furthermore, the incorporation of PSS and SVC-POD simultaneously improved the inter-area oscillation damping significantly.

On the other hand, the integration of a wind farm induced one more inter-area oscillation mode, which frequency and damping ratio depend on the wind turbine generator. From a control point of view, PSS improved the damping of the existing and the new inter-area mode. The SVC -POD must be retuned taking into account the integration of the wind farm and the type of the wind turbine generators. If not, it can have negative impact. A coordinated tuning of the combined two-controllers strategy must be performed to achieve optimum damping.

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