Analysis of Damping Characteristics of Distributed Synchronous Condenser with Different Configuration

Chengxiang Huo[1], Rui Song[2], Dengfeng Li[3], Pengcheng Guo[4], Yuchen Feng[4] and Ancheng Xue[4,*]
[1]*China Electric Power Research Institute Co., Ltd., China*
[2]*Electric Power Research Institute State Grid Qinghai Electric Power Co.,Ltd.Qinghai Province, China*
[3]*Electric Power Research Institute State Grid Chongqing Electric Power Co., Ltd.Chongqing Province, China*
[4]*State Key Laboratory of Alternate Electrical Power System with Renewable Energy Source, North China Electric Power University, Changping, Beijing, BJ 10, China*

Keywords: Distributed Synchronous Condenser, Excitation, PSS, Eigenvalue Analysis, Damping.

Abstract: The distributed synchronous condenser (DSC) can not only improve the voltage stability of the power system interconnected with wind power and photovoltaic, but also improve the damping characteristics of the system. However, the DSC has many types, and the damping of different types of DSC are unknown. This paper analyzes the damping characteristics of DSCs with different configurations, based on the eigenvalue analysis method. Specifically, firstly, the mathematical models of DSCs with different types of rotors, excitation systems and power system stabilizers (PSS) are established. Secondly, combined with the single machine infinite bus (SMIB) system, the damping characteristics of different types of DSCs are analyzed and compared. Finally, combined with the four-machine two-area (4M2A) system, the damping characteristics of different types of DSC are analyzed and compared. The above work can provide reference for the configuration of distributed synchronous condenser in power system.

1 INTRODUCTION

In order to deal with the depletion of fossil energy, climate change and environmental crisis, different countries vigorously develop the new energy. The installed capacity of new energy sources such as wind power and photovoltaic power plant growth rapidly (Zhenya, 2016; Xioxin et al., 2014; Wanxing et al., 2019). However, the new energy sources such as wind power and photovoltaic, are usually concentrated at the remote sending end of the power grid, which is far away from the load center and short of reactive power support. Furthermore, to the new energy sources, its voltage regulation ability, high and low voltage ride-through ability and inertia of the superimposed new energy units, are far less than those of the conventional units, resulting in the instability problem of sending end power system interconnected with the new energy, even induce large-scale cascading off grid accidents (Jingzhe et al., 2015; Song and Frade, 2016; Gu et al., 2018), and the distortion of stability of the sending end system, in the case of fault occurs(Jingzhe et al., 2015).

To solve the above problems, the installation of the synchronous condenser is a more effective method. The synchronous condenser is a synchronous motor under special operating conditions, which can be regarded as a synchronous generator without active load or a synchronous motor without mechanical load. The synchronous condenser can continuously adjust the reactive power by adjusting the excitation voltage to achieve reactive power support, while providing inertia and improving stability (Zhenya et al., 2015; Yating et al., 2017; Jin et al., 2018; Zhengpai et al., 2015).

There are two kinds of synchronous condensers: centralized synchronous condenser (CSC) and distributed synchronous condenser (DSC). For the wind or the photovoltaic power stations, the DSCs are currently recommended (Suo et al., 2019; Li et al., 2021; Xi et al., 2022; Bingchen, 2021).

Currently, the research about synchronous condensers, mainly focused on its voltage support level location and configuration scheme. For example. Ref. (Suo et al., 2019) compared the configuration schemes for centralized and decentralized access of synchronous condensers to different voltage levels, The results show that the distributed synchronous condenser can solve the transient overvoltage problem

* Corresponding author

Huo, C., Song, R., Li, D., Guo, P., Feng, Y. and Xue, A.
Analysis of Damping Characteristics of Distributed Synchronous Condenser with Different Configuration.
DOI: 10.5220/0012004300003612
In *Proceedings of the 3rd International Symposium on Automation, Information and Computing (ISAIC 2022)*, pages 627-632
ISBN: 978-989-758-622-4; ISSN: 2975-9463

of the sending end system. Ref. (Li et al., 2021) shows that the scheme of connecting the distributed condenser to the 35kV bus of the new energy station has better reactive power compensation effect. Ref. (Wang et al., 2022) shows that the installation of the condenser can effectively increase the generalized short circuit ratio of the system, and puts forward the location scheme of the reasonable configuration of the condenser. Ref. (Li et al., 2017) proposed a distributed / centralized hybrid optimal configuration scheme based on the short circuit ratio of multiple new energy stations, which can improve the voltage support strength of the grid after the access of new energy with the minimum total capacity. In addition, ref. (Yingkunet al., 2022) systematically analyzes the influence of various electrical parameters on the transient and sub-transient characteristics of the condenser, extracts the key technical parameters and measures for the dynamic performance optimization of the condenser, and gives suggestions for the specific optimization design scheme of the condenser.

On the other hand, the synchronous condenser has inertia, and will also impact the damping characteristics of the power system. However, there is few research in this area. In particular, the DSC has different types, what are the damping characteristics of different types of DSC, and which type of DSC has the best effect to improve the damping, has not been reported.

In reorganization the above, this paper analyze the influence of DSC with different types of rotors, excitation systems and PSS on the damping characteristic with the SMIB and 4M2A systems through eigenvalue analysis, and explore the guidance for the equipment selection of DSC.

The remainders of the paper are organized as follows. Section 1 introduces different types of DSC models, including different types of rotors, excitation systems and PSS. Section 2 analyzes and compares the damping characteristics of different types of DSC in a SMIB system. Section 3 analyzes and compares the damping characteristics of different types of DSC in the 4M2A system. Finally, Section 4 gives the conclusion.

2 MODELS FOR DISTRIBUTED CONDENSER

2.1 DSC Body Model

According to the difference of the distributed synchronous condenser body, excitation system and PSS, the distributed synchronous condenser has different Configuration.

The body of the DSC can be divided into two categories: hidden pole and salient pole. Hidden pole condenser is usually horizontal, its advantages are small size, easy installation of infrastructure, small starting system capacity, relatively simple rotor structure, easy maintenance; and its disadvantage is that the phase depth is poor, generally about half of the rated capacity. Salient pole condenser is usually vertical, the volume of salient pole condenser increases exponentially with the increase of pole pair, so its infrastructure cost is high, the starting system capacity is large; rotor structure is relatively complex, body maintenance is slightly larger, but its advantage is that the leading phase capacity is equivalent to the rated capacity, and the cooling system is relatively simple.

The mathematical model of hidden pole machine and salient pole machine can be written as:

$$\begin{cases} \dfrac{d\delta}{dt} = \omega_0 \cdot (\omega - 1) \\ \dfrac{d\omega}{dt} = \dfrac{1}{T_j} \cdot (-T_e - D(\omega - 1)) \\ T_{d0}^{''} \dfrac{dE_q^{''}}{dt} = E_q^{'} - E_q^{''} - (x_d^{'} - x_d^{''}) i_d \\ T_{q0}^{''} \dfrac{dE_d^{''}}{dt} = E_d^{'} - E_d^{''} + (x_q^{'} - x_q^{''}) i_q \\ T_{d0}^{'} \dfrac{dE_q^{'}}{dt} = E_f - E_q^{'} - \dfrac{x_d - x_d^{'}}{x_d^{'} - x_d^{''}} (E_q^{'} - E_q^{''}) \\ T_{q0}^{'} \dfrac{dE_d^{'}}{dt} = -E_d^{'} - \dfrac{x_q - x_q^{'}}{x_q^{'} - x_q^{''}} (E_d^{'} - E_d^{''}) \end{cases} \tag{1}$$

where δ is the power angle of the synchronous condenser; ω is the rotating speed of the synchronous condenser; ω_0 is the synchronous speed of the synchronous condenser; T_j is the inertia time constant, D is the damping coefficient, T_e is the electromagnetic torque of the synchronous condenser. $E_q^{'}$ ($E_d^{'}$) and $E_q^{''}$ ($E_d^{''}$) are respectively q(d)-axis transient electromotive force and sub-transient electromotive force, respectively. E_f is excitation electromotive force, x_q (x_d), $x_q^{'}$ ($x_d^{'}$) and $x_q^{''}$ ($x_d^{''}$) are q(d)-axis synchronous reactance, transient reactance and sub-transient reactance respectively. $T_{q0}^{'}$ ($T_{d0}^{'}$) and $T_{q0}^{''}$ ($T_{d0}^{''}$) are the q(d)-axis open-circuit transient time constant and sub-transient time constant, respectively. i_d and i_q i_q are the d-axis and q-axis components of the stator current, respectively.

For the hidden pole machine, there is $x_d = x_q$, $x_d'' = x_q''$; while for the salient pole machines, there is $x_d \neq x_q$, $x_d'' \neq x_q''$.

2.2 Excitation Model

There are two types of excitation models commonly used in DSCs, i.e., the FV type and FM type. The FV type belongs to the self-shunt static excitation system, as shown in Figure 1; the FM type is an AC exciter system, as shown in Figure2.

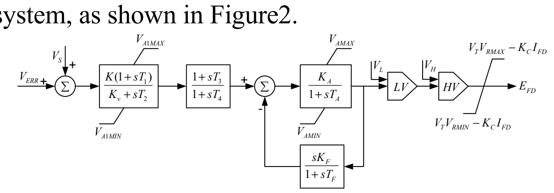

Figure 1: Model block diagram of FV excitation system

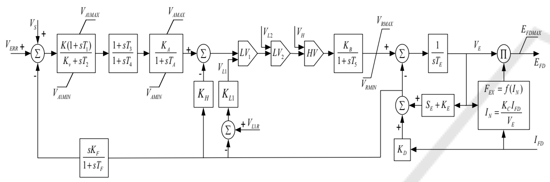

Figure 2: Model block diagram of FM excitation system.

2.3 PSS Model

There are two types of PSS models commonly used in distributed synchronous condensers, i.e., the SS type and SI type. The SS type is PSS1A type, as shown in Figure 3. The SI type belongs to PSS2B type, as shown in Fig.4.

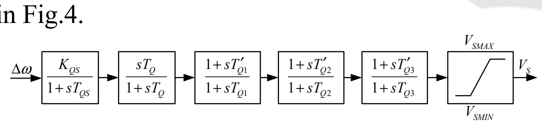

Figure 3: Model block diagram of SS-type PSS.

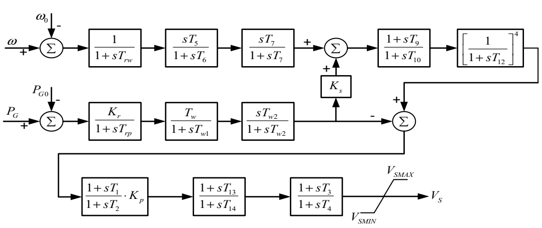

Figure 4: Model block diagram of SI PSS.

3 DAMPING PERFORMANCE IN THE SMIB SYSTEM

This section analyzes and compares the damping characteristics of different types of DSC in a SMIB system. Specifically, a DSC is added to a single machine infinite bus system, as shown in Figure 5. The eigenvalue method is used to compare the corresponding damping ratio.

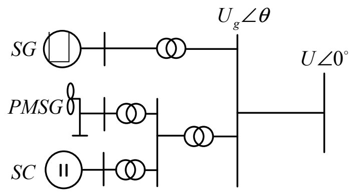

Figure 5: Single machine infinite bus system structure

3.1 Damping with Different Rotors

The eigenvalue and damping ratio of the system of following three cases: the system without a condenser, the system with a condenser and the rotor with hidden poles and salient poles, can be obtained, respectively, as shown in table 1.

Table 1: Eigenvalue and damping ratio of SMIB system with different types of rotors for condenser.

Rotor type	Real part	Imaginary part	Frequency	Damping ratio
-	-0.188	5.874	0.935	0.032
Hidden pole	-0.202	5.794	0.922	0.035
Salient pole	-0.229	5.786	0.921	0.039

Table 1 shows that the rotor with salient pole type has better effect on improving the system damping than the rotor with hidden pole type.

3.2 Damping with Different Excitation

The frequency and damping ratio of the system with FV-type and FM-type excitations can be obtained, respectively, as shown in table 2.

Table 2: Frequency and damping ratio of SMIB system with different excitation systems for condenser.

Rotor type	Type of excitation	Frequency	Damping ratio
-		0.935	0.032
Hidden pole	FV	0.925	0.033
	FM	0.922	0.035
Salient pole	FV	0.922	0.038
	FM	0.921	0.039

Table 2 shows that the FM type excitation system has a better effect on the system damping in both the hidden pole condenser and the salient pole condenser.

3.3 Damping with Different PSS

Considering the SS-type and SI-type for PSS, the frequency and damping ratios of the system can be obtained, as shown in Table 3 and Table 4.

Table 3: Frequency and damping ratio of SMIB with different types of PSS for hidden pole condenser.

Rotor type	Excitation	PSS	Frequency	Damping ratio
-			0.935	0.032
Hidden pole	FV	SS	0.920	0.038
		SI	0.923	0.037
	FM	SS	0.931	0.041
		SI	0.923	0.039

Table 3 shows that in the hidden pole condenser, whether the excitation system is FV type or FM type, the SS type PSS has a better effect on the system damping.

Table 4: Frequency and damping ratio of SMIB system with different types of PSS for salient pole condenser.

Rotor	Excitation	PSS	Frequency	Damping ratio
-			0.935	0.032
Salient pole	FV	SS	0.921	0.042
		SI	0.918	0.041
	FM	SS	0.927	0.044
		SI	0.922	0.042

Table 4 shows that in the salient pole condenser, whether the excitation system is FV type or FM type, the SS type PSS has a better effect on the system damping.

4 RESULTS IN THE 4M2A

In this section, the damping characteristics of different types of DSC in a modified 4M2A system, are analyzed and compared.

Specifically, the DSCs is installed to the modified 4M2A system with wind power interconnection as shown in Figure 6. The eigenvalues and corresponding damping ratios of the system are calculated by eigenvalue method, and the damping variations of the system with different types of rotors, excitation systems and PSS are compared.

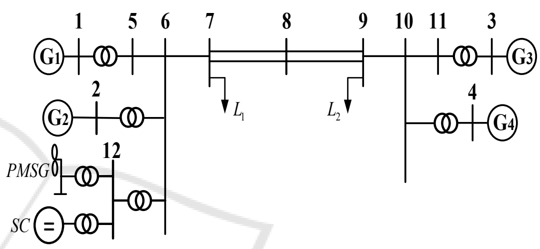

Figure 6: Four-machine two-area system structure diagram.

The oscillation modes of the 4M2A system without SDCs are shown in Table 5.

Table 5: Oscillation modes of a 4M2A system without a condenser.

Frequency	Damping ratio	Correlative unit
1.502	0.075	G1，G2
1.613	0.075	G3，G4
1.052	0.013	G1,G2，G3,G4

Furthermore, after adding the DSC, the damping ratio of the inter-area oscillation changed, and the damping ratio of the local oscillation almost unchanged. Therefore, the following analysis only focuses on the inter-area oscillation mode between regions.

4.1 Damping with Different Rotors

For the case with the DSC, considering the rotor adopting the hidden pole and the salient pole respectively, the frequency and damping of the system inter-area oscillation can be obtained as shown in Table 6.

Table 6: Eigenvalues and damping ratios of 4M2A system with different types of rotors for condenser.

Rotor type	Frequency	Damping ratio
-	1.052	0.013
Hidden pole	1.052	0.015
Salient pole	1.051	0.017

Table 6 shows that the rotor with salient pole type has better effect on improving the system damping than the rotor with hidden pole type.

4.2 Damping with Different Excitation

The frequency and damping ratios of the inter-area oscillation, considering the FV and FM type excitations, with used for the hidden-pole and salient-pole tuners, can be obtained, as shown in Table 7.

Table 7: Frequency and damping ratio of 4M2A system with different types of excitation systems for condenser.

Rotor type	Type of excitation	Frequenc y	Damping ratio
-		1.052	0.013
Hidden pole	FV	1.055	0.015
	FM	1.052	0.015
Salient pole	FV	1.054	0.017
	FM	1.051	0.017

Table 7 shows the influence of different types of excitation systems on system damping is not very obvious in either the hidden pole condenser or the salient pole condenser.

4.3 Damping Characteristics with Different Types of PSS

The frequency and damping ratios of the system inter-area oscillation can be obtained, as shown in Table 8 and Table 9, considering the SS-type and SI-type PSS for the hidden polar and salient polar condensers, respectively.

Table 8: Damping ratio of 4M2A system with different types of PSS for hidden polar condenser.

Rotor type	Type of excitation	Type of PSS	Freque ncy	Damping ratio
-			1.052	0.013
Hidd en pole	FV	SS	1.055	0.017
		SI	1.056	0.016
	FM	SS	1.054	0.017
		SI	1.054	0.016

Table 8 shows that in the hidden pole synchronous condenser, no matter the excitation system is FV type or FM type, SS type PSS has better effect on the system damping.

Table 9: Damping ratio of 4M2A system with different types of PSS for salient pole condenser.

Rotor type	Type of excitation	Type of PSS	Frequency	Damping ratio
-			1.052	0.013
Salie nt pole	FV	SS	1.054	0.019
		SI	1.054	0.017
	FM	SS	1.056	0.019
		SI	1.052	0.018

Table 9 shows that in the salient pole synchronous condenser, whether the excitation system is FV type or FM type, SS type PSS has a better effect on the system damping.

In summary, in the four-machine two-area system, the distributed condenser adopts the salient pole type rotor, and the SS PSS have the best effect on the system damping improvement.

5 CONCLUSION

In this paper, through the eigenvalue analysis method, combined with the SMIB and 4M2A systems, the damping characteristic of the system are analyzed when the distributed synchronous condenser(DSC) adopts different types of rotors, excitation systems and PSS. The results are as follows.

a) The DSC with salient pole type rotor has better performance on improving the system damping than that with hidden pole type rotor.

*b)*The FM excitation system has a better performance on the system damping.

c) In the SMIB and 4M2A system, the SS type for PSS has better performance on improving the damping.

Thus, from the viewpoint of damping characteristics, it is better to adopt salient pole system, FM type excitation system and SS type PSS.

This paper only analyzes the configuration of distributed condenser types from the viewpoint of damping characteristics. In the actual configuration, the voltage and reactive power characteristics, cost also need to be considered.

ACKNOWLEDGMENTS

This work is supported by project of “Research of adaptive optimization of distributed synchronous condensers and its applications in oscillation suppression in the power interconnected with high-proportion renewable energy” by the State Grid Corporation of China.

REFERENCES

Liu Zhenya., 2016.Research of Global Clean Energy Resource and Power Grid Interconnection. Proceedings of the CSEE, 36(19):5103-5110.

Zhou Xiaoxin, Lu Zongxiang, Liu Yingmei, et al.,2014.Development models and key technologies of future grid in China. Proceedings of the CSEE, 34(29):4999-5008.

Sheng Wanxing, Wu Ming, Ji Yu, et al.,2019. Key techniques and engineering practice of distributed renewable generation clusters integration. Proceedings of the CSEE, 39(8):2175-2186.

Tu Jingzhe, Zhang Jian, Liu Mingsong, et al.,2015 Study on wind turbine generators tripping caused by HVDC contingencies of wind-thermal-bundled HVDC transmission systems. Power System Technology,39(12):3333-3338.

Song Yipeng, Frade Blaabjerg.,2016. Overview of DFIG-based wind power system resonances under weak networks. IEEE Trans-actions on Power Electronics,32(6):4370.

H. Gu,R. Yan and T.K. Saha.,2018 Minimum Synchronous Inertia Requirement of Renewable Power Systems. IEEE Transactions on Power Systems,33(2):1533-1543.

Tu Jingzhe, Zhang Jian, Wang Jianming, et al.,2015. Mechanism analysis on the sending-side instability caused by the receiving-side contingencies of large-scale HVDC asynchronous interconnected power systems. Proceedings of the CSEE ,35(21):5492-5499.

Liu Zhenya, Zhang Qiping, Wang Yating, et al.,2015. Research on reactive compensation strategies for improving stability level of sending-end of 750 kV grid in Northwest China. Proceedings of the CSEE, 35(5):1015-1022.

Wang Yating, Zhang Yichi, Zhou Qinyong, Li Zhiqiang, et al.,2017. Study on Application on New Generation Large Capacity Synchronous Condenser on Power Grid. Power System Technology, 41(01):22-28.

JIN Yiding, YU Zhao, LI Mingiie, et al.,2018 Comparison of new generation synchronous condenser and power electronic reactive power compensation devices in application in UHVDC/AC grid. Power System Technology,42(7):2095.

Cui Zhengpai, Wang Haojing, Ma Suoming, et al.,2015. Operation situation analysis and improvement measure study for dynamic reactive compensation equipment applied in large-scale wind power systems. Power System Technology ,39(7):1873-1878.

SUO Zhiwen, LIU Jianqin, JIANG Weiyong, et al.,2019. Research on synchronous condenser configuration of large-scale renewable energy DC transmission system. Electric Power Automation Equipment,39(9):124-129.

LI Zhiqiang, HE Fengjun, GUO Qiang, et al.,2021. Comparative study on dynamic reactive power compensation scheme in the concentrated delivery area of new energy in southern Qinghai. Modern Electric Power,38(1):87-93.

Xi Gongwei, Zhao Bing, Zheng Shuaifei, et al.,2022. Transmission Capacity and Improvement Measures of New Energy Base via UHVAC Transmission System. Electric Power Construction, 43 (07): 131-138

Liu Bingchen.,2021. Research on dynamic reactive power compensation scheme of high proportion new energy transmission system. North China Electric Power University (Beijing).

WANG Kang, LI Ziheng, YANG Chaoran, et al.,2022. Siting method of synchronous condenser for small-signal stability improvement of large-scale renewable energy base. Automation of Electric Power Systems ,46(4):66-74.

Li Zhiqiang, Jiang Weiyong, Wang Yanbin, et al.,2017. Key technical parameters and optimal design of new types of large capacity synchronous condenser. Large Electric Machine and Hydraulic Turbine, 15-22.

Zhou Yingkun, Sun Huadong, Xu Shiyun, et al.,2022.Optimal Configuration Method of Adjusting Camera for Improving Power Grid Voltage Support Strength. Power System Technology:1-10.