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Full Length Research Paper

Application of damping torque analysis index for coordinated tuning of stabilizers in the large power grid

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This paper considers the coordinated tuning of stabilizers attached to the primary control loops of a Synchronous Generator (SG), Doubly Fed Induction Generator (DFIG) and Energy Storage System (ESS) in a large power grid. The indices obtained from a Damping Torque Analysis (DTA) method are used to evaluate the impact of different stabilizers subject to a range of low-frequency oscillations. According to the DTA Indices, a coordinated stabilizer-tuning strategy is proposed. Selected stabilizers are tuned effectively to dampen target oscillations without causing 'eigenvalue drift'. The damping ratios of the interarea oscillation modes and local modes in large power grids can be increased beyond satisfied values, without time-intensive and redundant-stabilizer adjustment.

Keywords: stabilizer, coordinated tuning, DTA Index, low-frequency oscillation, damping ratio

INTRODUCTION

Low-frequency oscillations in this paper refer to the electromechanical oscillations occurring in power systems with oscillation frequency up to a couple of Hz. They are the consequence of development of inter-connected large-scale power system. Small disturbances, for example small-variations in loads and generations, a short-time three-phase short circuit or tripping of a transmission line, are able to trigger these oscillations. Once started, they will continue for a while and then disappear, or continuously grow to cause system collapse. In the future, the power system will be more widely interconnected and complicated with the Uncertainty output power generated from large-scale renewable energy sources. Due to the severe influences induced by the unstable or weak-damped oscillations, the small-signal stability of the future power system needs to attract serious attentions (Kundur, 1994; Du et al., 2009). There are two essential theoretical methods to analyze and expatiate on the power system low-frequency oscillation damping mechanism up to now. One is the model (or eigenvalue) analysis method by calculation (Rogers, 1996; Rogers, 2000), and the other is the damping torque analysis method by physical insight (Wang et al., 2003). The model analysis method can not give a direct and effective description in the physical mechanism essentially, while the damping torque analysis method cannot be applied easily in the multi-unit power systems. In (Wang, 1999; Wang, 1998; Swift and

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Wang, 1997) DTA has been extent for the application in general multi-machine power systems and demonstrated to be basically equivalent to modal analysis. DTA Index denotes to the impact from the reconstructed feedback signal of the stabilizer to the selected oscillation loop. It is the summary in two loops. Firstly the stabilizer supplies the damping torque to the electromechanical loop of every synchronous generator. Then the delivered damping torque is converted into the affect to the specified oscillation mode by multiplying the eigenvalue sensitivity of the corresponding generator. DTA Indices for Power System Stabilizer (PSS), Flexible AC Transmission System (FACTS)-based stabilizer, Static Synchronous Compensator (STATCOM)-based stabilizer and Energy Storage System (ESS)-based stabilizer are obtained in (Wang and Swift, 1998;Wang et al., 1998; Wang, 2000;Wang, 1999;Du et al., 2009;Li et al., 2011) according to Phillips-Heffron model. They can be used to choose the locations (Wang et al., 1997), evaluate the contributions (Wang, 1998), adjust the parameters (Wang et al., 1997) and set the feedback signals of the stabilizers (Wang, 1999). In large power system with n machines, there exists n-1 oscillation modes which the interarea oscillation modes and local modes are included (Kundur, 1994). In present system, several types of stabilizers can be added and adjusted to improve the damping of the system, such as PSS, HVDC stabilizer (Mao et al., 2006), FACTS-based stabilizer (Cai and Erlich, 2005) etc and even Doubly Fed Induction Generator (DFIG)-based stabilizer (Hughes et al., 2005). How to coordinately tune various types of stabilizers to effectively increase the damping ratios of oscillation modes, without eigenvalue drift to each other, will be discussed in this paper. The organization of this paper is as follows: in Section II, small-signal analysis of the large power grid is presented. DTA Indices about PSS, ESS-based stabilizer and DFIG-based stabilizer are briefly described and obtained in Section III. Based on DTA Indices, a hierarchical coordinated stabilizer-tuning strategy is put forward. In Section IV, the effectiveness of the proposed tuning strategy is verified by the simulations in the system. Finally, brief remarks on the studies are presented that: PSS prefers to improve the damping of oscillation modes in which the corresponding synchronous generator is strongly participated; ESS-based stabilizer is suitable to suppress the tie-line power oscillation where it connects; DFIG-based stabilizer is better to smooth the output power oscillation in its outlet line. With the proposed strategy, only some selected stabilizers need to be tuned and low-frequency oscillations can be restrained within acceptable time.

Small signal analysis of large power grid (*System modeling)*

The small-signal stability analysis environment, which is a Chinese provincial power grid under the peak load condition of Year 2012, is established. The simulated system is mainly composed by 1000-, 500- and 220-kV level alternating current (AC) network with hundreds SGs and thousands 1.5 MW DFIGs distributed in 13 wind farms. In order for analysis, the system has been simplified to 66 equivalent SGs, 604 buses and 13 equivalent DFIGs, holding predominant oscillation modes of the system unshifted (Ni et al., 2002). A detailed model is adopted for equivalent generators with consideration of the speed governors, automatic voltage regulators (AVR), as well as PSS installed in 15 equivalent SGs (Tang et al., 2007). Comparing 65,000 MW output active powers of SGs, those generated from DFIGs are around 1900MW which occupy 2.84% in the total generations. A novel control strategy for DFIG given in (Bu et al., 2011) is utilized. The schematic configuration diagram of the power grid is shown in Figure 1.

Small signal analysis of the power grid

Inside the power grid, SGs are mainly centralized in the northern part as well as the DFIGs. But the electricity consumption centers are concentrated in the southern part. 11,210MW active powers are transferred from the northern part to the southern part via five 500-kV level and one 1000-kV level double-loop AC transmission lines across Yangtze River. Because of the heavy load burdens and long transmission distances, the suppression of power oscillations in these transmission lines is preferential and critical for the dynamic stability maintain in the system.

Besides the oscillations in the transmission lines between northern part and southern part, other oscillations exist in the tie-lines between the cities. The interarea electromechanical oscillation modes with frequency in the range of 0.1-1.0Hz and damping ratio less than 5% are picked out and listed in Table I. The weak-damped oscillations in the connected lines will lead to the disconnection of the subsystems.

Mode 1 is related to the oscillations between northern part and southern part. The equivalent SXZ_G, SPC3G, SKS_G (in Xz), STW_G, SXH1G (in Lyg) and SCJ_G (in Yc) oscillate against SLE_G, SWE_G (in Wx), SHS1G, SHS2G, SSE_G, SWR_G, SHB1G (in Sz), SQR3G (in Cz), and SJK_G (in Zj). Nearly all the cities in northern and southern parts are involved. The listed equivalent SGs are the 15 ones with PSSs installed.

Mode 2 is related to the oscillations between Xz and Lyg. The equivalent SXZ_G (in Xz) oscillates against STW_G, SXH1G and SXH2G (in Lyg).

Mode 3 is related to the oscillations between Sz and Wx, Cz. The equivalent SHS1G, SHS2G and SHB2G (in Sz) oscillate against SQR3G (in Cz) and SLE_G (in Wx).

All the listed equivalent SGs are participated in the corresponding oscillation modes with the participation

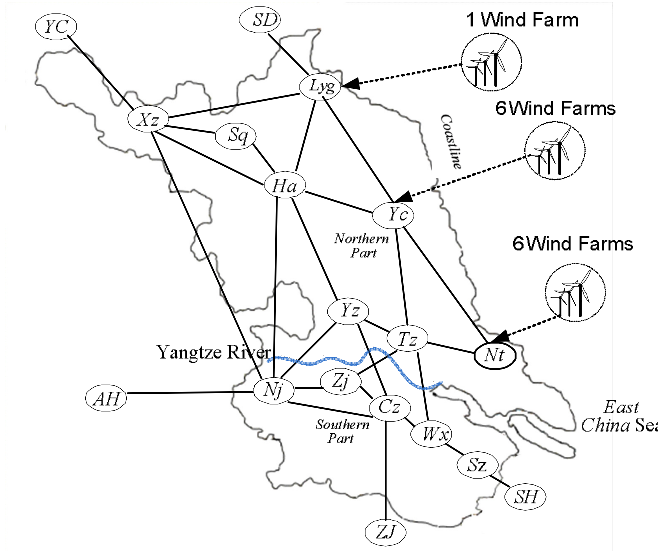

Figure 1. Schematic configuration diagram of large power system.

Table 1. Information on weak-damped interarea modes

Interarea Mode	Frequency (Hz)	Damping ratio
Mode 1	0.8035	2.62%
Mode 2	0.9994	3.47%
Mode 3	0.8646	3.93%

factors bigger than 0.1.

In the next section, a hierarchical coordinated stabilizer-tuning strategy based on DTA Index is proposed to increase the damping ratios of these listed modes beyond 5%, with the least adjustment.

Cordinated stabilizer-tuning strategy

DTA IndexTheoretically DTA Index investigates the forward-path information from the reconstructed feedback signal of the stabilizer to the oscillation mode via the electromechanical oscillation loops of the generators on the basis of the Phillips-Heffron (P-H) model [17].

$$\Delta\lambda_i = \sum_{j=1}^{N} S_{ij}\left[F_j(\lambda_i) r_j(\lambda_i)\right]\cdot\Delta G_{pss}(\lambda_i) = DI(\lambda_i)\cdot\Delta G_{pss}(\lambda_i) \quad (1)$$

where

N is the total number of equivalent SGs in the system.

λ_i is the concerned i^{th} oscillation mode.

S_{ij} denotes the sensitivity of the oscillation mode λ_i to the coefficient of the electric torque on the j^{th} generator.

$r_j(\lambda_i)$ is the reconstruction function of the feedback signal (input signal) y_{pss} by the rotor speed ω of the j^{th} generator.

$G_{pss}(\lambda_i)$ is the transfer function of the stabilizer.

$F_j(\lambda_i)$ relates to the forward transfer path from the control signal (output signal) u_{pss} of the stabilizer to the j^{th} generator electromechanical oscillation loop.

$DI(\lambda_i) = \dfrac{\Delta\lambda_i}{\Delta G_{pss}(\lambda_i)}$ measures the effectiveness of the stabilizer in providing damping to the i^{th} oscillation mode in the system.

The stabilizers can be tuned according to DTA Index. If the stabilizer has been installed already, its control gain is adjusted to move the concerned oscillation eigenvalue left-forward; if the stabilizer is recommended to install, its detailed parameters can be set in order to improve the damping of the concerned oscillation mode. While the analysis about DTA Index is done with the stabilizer open-looped, the guidance to left-shift the eigenvalue can be given. The precise pole assignment of the eigenvalue can not be obtained.

Feedback Signal Chosen for PSSs

With the development of Phasor Measurement Unit (PMU), not only the rotor-speed of the PSS-installed generator, but also the one from the remote generator can be used as the feedback signal of PSS. DTA Index

Table 2. DTA Index of PSSs with different Feedback Signals related to Mode 2

Generator *	SXZ_G#	STW_G#	SXH1G#
SXZ_G	0.0358	0.0012	0.0010
STW_G	0.0017	0.0102	0.0021
SXH1G	0.0011	0.0013	0.0064

(* The generator listed in row denotes that PSS is installed in it; the generator listed in column implies that its rotor-speed is utilized as the feedback signal of PSS.
DTA Index listed here is the absolute value of its real part which relates to the damping ratio of the mode.)

of PSS can be obtained by Equation (1) in (Wang, 1998; Swift and Wang, 1997). The reconstruction functions are diverse with different feedback signals for PSS.

Table II lists the DTA Indices of the 3 example PSSs, in which rotor-speeds of different generators are chosen as their feedback signals. According to DTA Index, the optimal feedback signal for each PSS can be chosen.

From Table II, it can be seen that, according to DTA Indices obtained in the 3 example PSSs with different feedback signals, it is more economic and effective to use the rotor-speed signal of the PSS-installed generator as the feedback signal. In this paper, the feedback signals used for all PSSs are the rotor-speeds in PSS-installed generators.

DTA indices of PSSs related to the interarea oscillation modes

Table III lists DTA indices of PSSs related to the 3 listed interarea oscillation modes. From Table III, it can be seen that: for Mode 1, around 15 generators are involved. DTA Index of every single PSS is small. Adjusting the control gains of few PSSs can not significantly increase the damping ratio. While Mode 1 is the key interarea mode in the system, the parameters of all PSSs need to be coordinately tuned.

Mode 2, DTA Indices of PSSs installed in STW_G and SXH1G are high, and all the other PSSs have ignored impacts to this oscillation mode. That means adjusting the control gains of PSSs installed in STW_G and SXH1G can sufficiently increase the damping ratio.

Mode 3, DTA Indices of PSS installed in SLE_G, SHS1G and SHS2G are attractive, and all the other PSSs have neglected impacts to this oscillation mode. Adjusting the control gains of PSSs installed in SLE_G, SHS1G and SHS2G can increase the damping ratio beyond the satisfied value.

DTA indices of ESS-based stabilizers related to the interarea oscillation modes

With the advancement in the field of higher power electronics technology, large-scale applications of ESS become practical. In principle, applications of ESS-based stabilizers in the power system can effectively provide extra damping to power system oscillations, while damping function based on ESS can be achieved through the active power modulation with the exchange of active power directly between the ESS and the connected line (Du et al., 2009).

In this paper, ESS-based stabilizers are installed in the candidate buses of the river-crossed transmission lines. Active power deviations of the ESS-connected lines are chosen as the feedback signals. DTA Indices are obtained and listed in Table IV (Du et al., 2009; Li et al., 2011).

From Table IV, it can be seen that, ESS-based stabilizers installed in the terminal buses of the river-crossed transmission lines have great effectiveness to damp the tie-line power oscillations related to Mode 1. Their impacts to the other oscillation modes can be neglected.

DTA indices of DFIG-based stabilizers related to the interarea oscillation modes

A DFIG is not only capable of providing a network with better voltage recovery and fault ride-through characteristics, but it can also considerably enhance network damping via an auxiliary power system stabilizer loop (Hughes et al., 2006). The detailed process to obtain DTA Index of DFIG-based stabilizer is described in Appendix. The active power deviations of the outlet lines are picked out as the feedback signals of DFIG-based stabilizers. DTA Indices are listed in Table V.

From Table V, it can be seen that, the DFIG-based stabilizers can not contribute extra damping to the three interarea oscillation modes, because of their low participation factors and penetration levels. It can be used to suppress the power oscillations in the outlet lines (Knueppel et al., 2012).

Proposed coordinated tuning strategy for stabilizers

Using the optimization method to coordinately tune the parameters of all PSSs is the effective way to improve

Table 3. DTA Indices of PSSs related to Interarea Oscillation Modes

PSS-installed Generator	Oscillation Mode 1	Oscillation Mode 2	Oscillation Mode 3
SXZ_G	0.0010	0.0358	0.0000
SPC3G	0.0008	0.0000	0.0000
SKS_G	0.0012	0.0000	0.0000
STW_G	0.0033	0.0102	0.0000
SXH1G	0.0016	0.0064	0.0000
SCJ_G	0.0006	0.0000	0.0000
SLE_G	0.0018	0.0000	0.0104
SWE_G	0.0013	0.0000	0.0000
SHS1G	0.0016	0.0000	0.0157
SHS2G	0.0019	0.0000	0.0138
SSE_G	0.0007	0.0000	0.0000
SWR_G	0.0004	0.0000	0.0000
SHB1G	0.0010	0.0000	0.0000
SQR3G	0.0014	0.0000	0.0042
SJK_G	0.0005	0.0000	0.0000

Table 4. DTA Indices of ESS-based Stabilizers related to Interarea Oscillation Modes

ESS-installed Bus	Oscillation Mode 1	Oscillation Mode 2	Oscillation Mode 3
SSC (in Nj)	0.0351	0.0000	0.0000
SJD (in Yz)	0.0287	0.0000	0.0000
STX (in Tz)	0.0274	0.0000	0.0000

Table 5. DTA Indices of DFIG-based Stabilizers related to Interarea Oscillation Modes

DFIG	Oscillation Mode 1	Oscillation Mode 2	Oscillation Mode 3
DFW (in Yc)	0.0000	0.0000	0.0000
BHW (in Yc)	0.0001	0.0001	0.0001
SYW (in Yc)	0.0000	0.0000	0.0000
DTW (in Yc)	0.0000	0.0001	0.0000
GHW (in Yc)	0.0001	0.0000	0.0002
XSW (in Yc)	0.0000	0.0002	0.0000
GYW (in Lyg)	0.0002	0.0000	0.0000
LHW (in Nt)	0.0002	0.0002	0.0000
LLW (in Nt)	0.0000	0.0000	0.0000
LYW (in Nt)	0.0000	0.0000	0.0000
DYW (in Nt)	0.0001	0.0001	0.0002
RDW (in Nt)	0.0000	0.0000	0.0000
HQW (in Nt)	0.0001	0.0000	0.0000

the damping of the three critical oscillation modes simultaneously (Cai et al., 2011). But the optimal adjustment of PSSs for the interarea modes possibly deteriorates the local modes. For example, the damping ratio of the local mode in which SHS1G oscillates against SHS2G decreases from 6.2% to 4.7%. The more objectives are involved in the optimization function, the longer time the iteration processes will cost. So it is impractical to take all the local oscillation modes considered.

From the previous listed DTA Indices of PSSs, ESS-based stabilizers and DFIG-based stabilizers, the conclusion can be summarized that, every stabilizer has its effective-influenced oscillation mode. PSS prefers to improve the damping of oscillation modes in which the corresponding synchronous generator is strongly participated; ESS-based stabilizer is suitable to suppress the tie-line power oscillation where it connects; DFIG-based stabilizer has no impacts to the interarea oscillation mode and it can be used to smooth the power oscillation in its outlet line.

The coordinated tuning strategy for stabilizers is proposed based on the conclusion obtained from DTA Indices.

Step 1: The weak-damped or unstable interarea oscillation modes in which few synchronous generators are strongly participated are sorted out. The control gains of PSSs with high DTA Indices related to the corresponding interarea modes are tuned, also considering their dominantly-involved local modes. While the number of adjusted PSSs is limited, it is practical to take care of their close-relevant interarea and local modes. The adjusted PSSs have slightly impacts to the rest oscillation modes.

Step 2: After the adjustment of PSSs, ESS-based stabilizer is employed to improve the damping of the interarea oscillation modes, in which single PSS has small DTA Index and many PSSs need to be coordinately regulated. ESS-based stabilizer is connected to the corresponding tie-line and directly regulates the active power oscillation in the transmission line. While ESS-based stabilizer has ignored impacts to the other modes, it can be installed and adjusted for the target oscillation mode independently.

Step 3: After the previous 2 steps, the damping ratios of all interarea and local oscillation modes have been increased beyond the target value. DFIG-based stabilizer can be simply tuned to smooth its output power in light of its neglected impact to the interarea and local oscillation modes.

The proposed stabilizer-tuning strategy is demonstrated and verified by the simulations and eigenvalue calculations in the next section.

Simulations and eigenvaule calculations

Peak Load Condition of Year 2012

While the effectiveness of DTA Index has already been verified (Wang, 1999; Wang, 1998; Swift and Wang, 1997; Wang and Swift, 1998; Wang et al., 1998; Wang, 2000; Wang, 1999; Du et al., 2009; Li et al., 2011; Wang et al., 1997; Wang et al., 1997) in this section, simulations and eigenvalue calculations are employed to demonstrate and verify the effectiveness of the proposed stabilizer-tuning strategy. A three-phase short circuit disturbance happens in 500kV Bus SHF from 0.5s and lasts for 0.2s.

Artificial Fish Swarm Algorithm (AFSA), which is the modern control theory and widely used to solve the optimization function, is induced to coordinately adjust the parameters of PSSs. The simulations are compared by using proposed strategy and AFSA respectively to improve damping ratios of these three interarea oscillation modes.

Adjusted stabilizers: Using the proposed method, the control gains of PSSs installed in SXZ_G and SHS1G, SHS2G are adjusted to increase the damping of Mode 2 and Mode 3 respectively. An extra ESS with 100MW capacity is installed in SSC (in Nj). The stabilizer is designed and attached to ESS (Du et al., 2009; Li et al., 2011;Du et al., 2011). But according to AFSA, all the parameters of PSSs in the system need to be adjusted.

Time cost: Using the proposed method, time is mainly cost in DTA Index calculation. This work is done only once under certain load flow condition. With DTA Index, the solution to maintain power system dynamic stability can be proposed. But according to AFSA, eigenvalue calculation should be done in every iteration process. The construction of the linear matrix for such huge system is complicated and time-cost. Normally 15-20 iterations are needed to get the optimal parameters.

Economic cost: Using the proposed method, an extra ESS is needed. ESS could be large-scale battery storage, pump storage or super-capacitor. When the support is asked by the system operator, ESS can be grid-connected and suppress the oscillations via exchanging active power with the grid. Although no extra equipment is asked according to AFSA, the order sent by system operator may be rejected by the generation side, while PSS adjustment benefited to the interarea oscillation modes has the possibility to deteriorate the oscillations among the local generators.

Effects to the interarea oscillation modes: Table VI shows the comparisons of eigenvalues related to the three interarea oscillation modes by using the proposed tuning strategy and AFSA.

From Table VI, it can be seen that, using the proposed strategy, the same effect to Mode 1 can be achieved as with AFSA.

Because weight factors are utilized to classify the priorities of different optimization objectives in AFSA, the tuning of PSSs is mainly to increase the damping ratio of Mode 1 which is more critical to maintain power safety transmission between northern and southern parts. The damping ratios of Mode 2 and Mode 3 with less-priorities do not have such significant increments as in Mode 1.

With proposed tuning strategy, selected PSSs are adjusted for Mode 2 and Mode 3 respectively. No interactions are induced by this adjustment of specified PSSs between each other. ESS-based stabilizer is installed and designed to improve the damping ratio of Mode 1, without leading to the eigenvalue-drift to the other two modes. While the three oscillation modes can be regulated independently, their damping ratios can be increased to the same satisfied values.

The time-domain simulations of three interarea oscillation modes are compared with proposed strategy and AFSA respectively in Figure 2-4.

(Case A: with initial parameters of stabilizers; Case B: Only control gain of the stabilizer in STW_G adjusts to 15 times of the initial one. Case C: with the designed parameters of ESS-based stabilizer at Bus SSC based

Table 6. Comparisons of Eigenvalues

Oscillation Mode		Mode 1	Mode 2	Mode 3
	Frequency (Hz)	0.8035	0.9994	0.8646
Initial Condition	*Damping Ratio*	2.62%	3.47%	3.93%
	Frequency (Hz)	0.8257	1.0375	0.8871
ProposedStrategy	*Damping Ratio*	7.21%	7.13%	7.18%
	Frequency (Hz)	0.8112	1.0301	0.8799
AFSA	*Damping Ratio*	7.14%	6.02%	5.75%

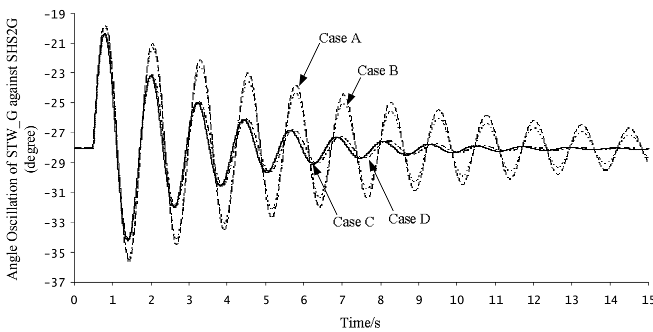

Figure 2. Comparison of the angle oscillation in Mode 1.

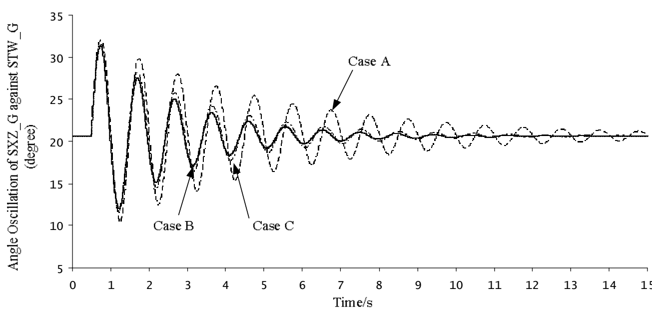

Figure 3. Comparison of the angle oscillation in Mode 2.

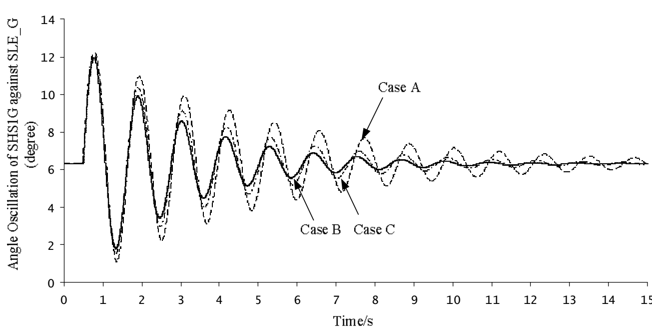

Figure 4. Comparison of the angle oscillation in Mode 3.

on proposed strategy. Case D: with the optimal parameters of PSSs obtained by AFSA.)

From Figure 2, it can be seen that, adjust the parameters of single PSS can not significantly increase the damping ratio of Mode 1. The proposed tuning strategy and AFSA are the effective methods to improve the damping in Mode 1.

(Case A: with initial parameters of stabilizers; Case B: Only control gain of the stabilizer in SXZ_G adjusts to 8 times of the initial one based on proposed strategy. Case C: with the optimal parameters of PSSs obtained by AFSA.)

(Case A: with initial parameters of stabilizers; Case B: Only control gain of the stabilizer in SHS1G and SHS2G adjusts to 11 times of the initial one based on proposed strategy. Case C: with the optimal parameters of

PSSs obtained by AFSA.)

From Figure 3 and 4, it can be seen that, the proposed tuning strategy can be more effectively to improve the damping in Mode 2 and 3, because it adjusts Mode 1 and the two oscillation modes independently.

From the analysis of DTA Indices of DFIG-based stabilizers, they have ignored impacts to the interarea oscillation modes. The transfer function of the stabilizer shown in [25] is utilized with the given parameters. The power oscillations in the DFIG-connected lines are simulated. In Figure 5, GYW is set as an example.

From Figure 5, it can be seen that, with the stabilizer attached to DFIG, the power oscillation in the outlet line can be effectively suppressed.

Compared with AFSA, the three oscillation modes can be regulated independently with less-stabilizer adjustment, less time-cost, acceptable economic cost for ESS assignment in proposed stabilizer-tuning strategy. In this system, only the control gains of PSSs installed in SXZ_G and SHS1G, SHS2G are adjusted for Mode 2 and Mode 3 respectively. Extra stabilizer is designed and attached to ESS in Bus SSC for Mode 1.

The effectiveness of the proposed strategy based on the obtained DTA Index is demonstrated and verified by the simulations and eigenvalue calculations. The damping ratios of three weak-damped interarea oscillation modes are all significant increased, without inducing eigenvalue-drift to the rest modes.

Peak load condition of year 2015

The planning system construction in 2015 mainly inherits that in 2012. Two more 1000kV-level double-loop AC transmission lines from Tz to Nj and Sz respectively are put into operation to connect the northern and southern parts of the system. The capacity of the electricity generation is increased, of which the penetration of wind farms also rises, to meet the growing demand of load consumptions. The system is simplified to with 56 equivalent SGs, of which 33 PSSs are installed, and 14 equivalent DFIGs. Although dynamic stability of the system is much improved with the help of the more connection lines and PSSs in service, there still exists some weak-damped interarea oscillation modes listed in Table VII. DTA Indices of the oscillation modes are obtained.

Mode 1 is related to the oscillations between northern and southern parts. The equivalent SXZ_G, SKS_G (IN XZ), STW_G, STS_G, SXH1G (IN LYG) AND SCJ_G (IN YC) oscillate against SLE_G (IN WX), SHS1G, SHS2G, SSC_G, SJC_G, SHX_G (IN SZ), SQR3G (IN CZ), AND SJK_G (IN ZJ). The listed equivalent sgs are all with psss installed. According to calculated results, DTA indices of participated generators are relatively small. The highest dta index of sxz_g is 0.0026. But DTA- indices of ess-based stabilizers
installed in BUS SSC, SJD and STX can be calculated AS 0.0298, 0.0265 AND 0.0135 respectively.

Mode 2 is related to the oscillations between Xz and Lyg. The equivalent SXZ_G (in Xz) oscillates against STW_G, SXH1G (in Lyg). DTA Indices of SXZ_G, STW_G and SXH1G can be got as 0.0425, 0.0301 and 0.0198 respectively.

The weak-damped oscillations between Sz and Wx, Cz have been suppressed with the support of new PSSs in service. The damping ratio has been increased to 6.78% and will not analysis in this section.

The damping of the weak-damped oscillation modes can be improved according to the proposed strategy. The control gain of PSS installed in SXZ_G magnifies to 8 times of its initial value and extra ESS-based stabilizer designed and installed in Bus SSC. The eigenvalues with the adjusted stabilizers are listed in Table VIII.

The simulations are done under the same three phase short circuit disturbance.

From Figure 6 and 7, it can be seen that, according to the proposed stabilizer-tuning strategy, only the control gain adjustment of single PSS and extra ESS-based stabilizer installed can effectively suppress the two interarea oscillations.

DFIG-based stabilizer can be utilized to smooth the output power oscillation in its outlet line. In Figure 8, GYW is set as an example.

(Case A: with initial parameters of stabilizers; Case B: with the designed parameters of ESS-based stabilizer at Bus SSC based on proposed strategy.)

(Case A: with initial parameters of stabilizers; Case B: Only control gain of the stabilizer in SXZ_G adjusts to 8 times of the initial one based on proposed strategy.)

The dynamic stability of the system under the peak load condition in Year 2015 can be maintained according to the stabilizer-tuning proposed strategy.

CONCLUSIONS

In a large-scale multi-regional interconnected power grid with bulk power transmitted over long distances, interarea low-frequency oscillation is usually a problem. This paper describes a comprehensive small-signal analysis for a real Chinese provincial power grid in Year 2012 and explores the hierarchical control strategy for both PSS controls and ESS-based stabilizers by means of coordinated parameter adjustment based on DTA Index. The target is to restrain power grid interarea oscillations in Year 2012.

From the calculated DTA Index, the conclusion can be obtained: ESS-based stabilizer is suitable to suppress the tie-line power oscillation where it connects; PSS prefers to improve the damping of oscillation modes in which the corresponding synchronous generator is

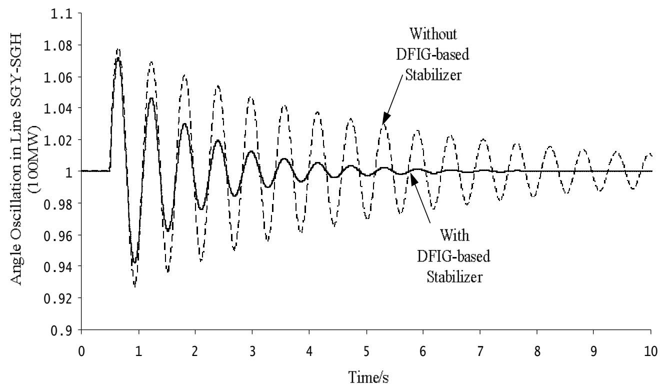

Figure 5. Comparison of the power oscillation in Line SGY-SGH.

Table 7. Information on weak-damped interarea modes

Interarea Mode	Frequency (Hz)	Damping ratio
Mode 1	0.8674	5.19%
Mode 2	1.0362	4.67%

Table 8. Comparisons of Eigenvalues

Oscillation Mode		Mode 1	Mode 2
	Frequency (Hz)	0.8674	1.0362
Initial Condition	*Damping Ratio*	5.22%	4.74%
	Frequency (Hz)	0.8712	1.0415
Proposed Strategy	*Damping Ratio*	8.74%	8.59%

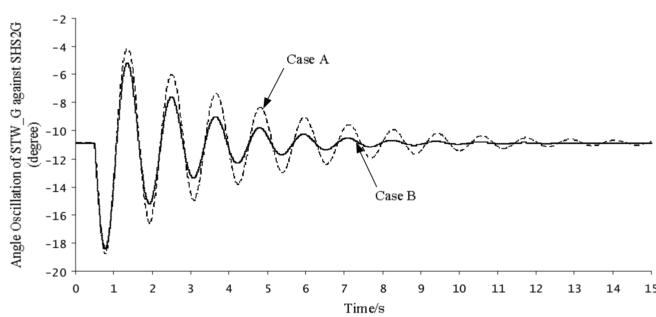

Figure 6. Comparison of the angle oscillation in Mode 1.

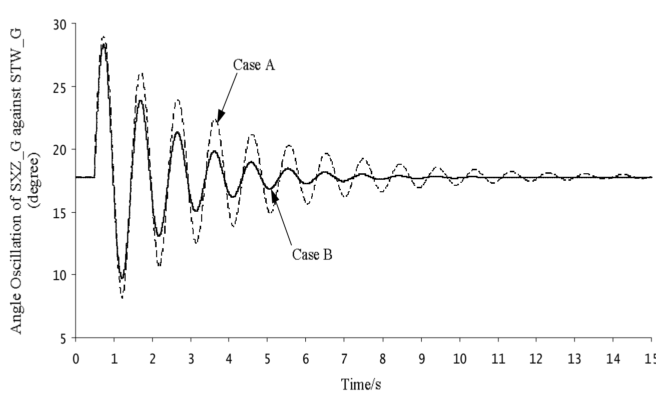

Figure 7. Comparison of the angle oscillation in Mode 2.

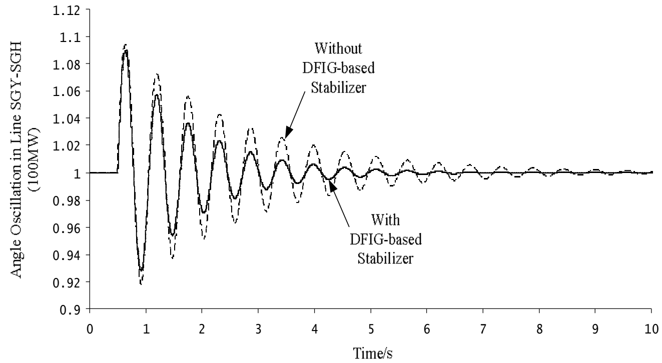

Figure 8. Comparison of the power oscillation in Line SGY-SGH.

strongly participated; DFIG-based stabilizer is better to smooth the output power oscillation in its outlet line. With the proposed strategy, only a few stabilizers need to be tuned and all interarea oscillations can be suppressed within acceptable time. The effectiveness of this method is demonstrated and verified by the simulations and eigenvalue calculations obtained in Year 2012 and utilized in Year 2015 power grid.

The operating performances of PSS and ESS-based stabilizer can be used to improve the damping of target interarea oscillations. The proper coordination of ESS-based stabilizers and PSSs can maximize the damping of interarea oscillations in large-scale power grid independently. The output power oscillations of DFIGs can be maintained by DFIG-based stabilizers.

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APPENDIX

Linearized from the rotor-side converter control system model of the single DFIG proposed in (Bu et al., 2011) and combined the linear matrix of DFIGs into the whole system (Kundur, 1994; Wang et al., 2003;Ni et al., 2002):

$$\begin{bmatrix} \dot{\Delta\boldsymbol{\delta}} \\ \dot{\Delta\boldsymbol{\omega}} \\ \dot{\Delta\mathbf{Z}} \\ \dot{\Delta\mathbf{X}}_{\mathbf{DFIG}} \end{bmatrix} = \begin{bmatrix} \mathbf{0} & \boldsymbol{\omega}_0 & \mathbf{0} & \mathbf{0} \\ -\mathbf{M}^{-1}\mathbf{K}_1 & -\mathbf{M}^{-1}\mathbf{D} & -\mathbf{M}^{-1}\mathbf{K}_2 & -\mathbf{M}^{-1}\mathbf{K}_3 \\ \mathbf{A}_{31} & \mathbf{A}_{32} & \mathbf{A}_{33} & \mathbf{A}_{34} \\ \mathbf{A}_{41} & \mathbf{A}_{42} & \mathbf{A}_{43} & \mathbf{A}_{44} \end{bmatrix} \begin{bmatrix} \Delta\boldsymbol{\delta} \\ \Delta\boldsymbol{\omega} \\ \Delta\mathbf{Z} \\ \Delta\mathbf{X}_{\mathbf{DFIG}} \end{bmatrix} + \begin{bmatrix} \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{B}_{\mathbf{DFIGPSS}} \end{bmatrix} \Delta\mathbf{u}_{\mathbf{DFIGPSS}} \qquad (A.1)$$

where

$\Delta\boldsymbol{\delta}, \Delta\boldsymbol{\omega}, \Delta\mathbf{Z}$ are the state variable vectors denoting rotor angles, rotor speeds and other variables of SGs.

$\Delta\mathbf{X}_{\mathbf{DFIG}}$ is the vector describing the state variables of DFIGs.

$\mathbf{M}, \boldsymbol{\omega}_0, \mathbf{D}$ are the diagonal matrices describing inertia constants, reference rotor-speeds and natural damping coefficients of SGs.

$\mathbf{K}_1, \mathbf{K}_2, \mathbf{K}_3, \mathbf{A}_{31}, \mathbf{A}_{32}, \mathbf{A}_{33}, \mathbf{A}_{34}, \mathbf{A}_{41}, \mathbf{A}_{42}, \mathbf{A}_{43}, \mathbf{A}_{44}$ are the coefficient matrices determined by the system operating conditions.

$\mathbf{B}_{\mathbf{DFIGPSS}}, \mathbf{u}_{\mathbf{DFIGPSS}}$ are the control matrix and output signal vector of multi DFIG-based stabilisers.

The forward-transfer vector for multi DFIG-based stabilisers can be calculated:

$$\Delta\mathbf{F}_{\mathbf{DFIGPSS}}(s) = \left(\mathbf{K}_3 \frac{\dfrac{\mathbf{A}_{34}\mathbf{B}_{\mathbf{DFIGPSS}}}{s\mathbf{I} - \mathbf{A}_{44}}}{s\mathbf{I} - \left(\mathbf{A}_{33} + \dfrac{\mathbf{A}_{34}\mathbf{A}_{43}}{s\mathbf{I} - \mathbf{A}_{44}} \right)} + \mathbf{K}_4 \frac{\mathbf{B}_{\mathbf{DFIGPSS}}}{s\mathbf{I} - \mathbf{A}_{44}} \right) \mathbf{I}_{\mathbf{n}} \qquad (A.2)$$

where

$\mathbf{I}$ is the unit diagonal matrix.

s is the value of the concerned oscillation mode.

$\mathbf{I}_{\mathbf{n}} = [0 \;\; \ldots \;\; \underset{Lth}{1} \;\; \ldots \;\; 0]$ if a stabiliser is installed in the $L\text{th}$ DFIG.

The processes to obtain the sensitivity and reconstruction function are the same as for PSS and FACTS-based stabiliser represented in (Wang, 1998; Swift and Wang, 1997) The DTA Index of DFIG-based stabiliser can be obtained by Equation (1).