Coordinated Design and Application of Robust Damping Controllers for Shunt FACTS Devices to Enhance Small-signal Stability of Large-scale Power Systems

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***Abstract*—This paper presents a robust and coordinated supplementary damping controller design of multiple reactive FACTS controllers and their application in a large-scale power system. Reactive FACTS devices, such as static synchronous compensators (STATCOM) and static VAR compensators (SVC), are considered and assessed for their damping controller design. Control objectives, including regional pole placement and norm bounded mix sensitivities, are used to solve the bilinear matrix inequality (BMI) problems in each linearized model via a two-step method. Multiple damping controllers are sequentially designed to avoid coupling effect among the input signals and increase the reliability of the proposed design. A 5-area 16-machine 68-bus power system is used for the implementation of the damping controllers. Numerical linear analysis and real-time simulations in a test platform based on Real-time digital simulators (RTDS) are adopted to test the feasibility and robustness of the coordinated damping controllers.**

***Index Terms*—BMI, coordinated design, multi-model, multi-objective, robust control, RTDS, sequential design, small-signal stability, STATCOM, SVC, TCSC.**

I. INTRODUCTION

THE increasing demand of load centers and integration of renewable energy to the main grid lead to stretch operating capability limits of the existing system infrastructures [1]. AC systems have already been reported to be very much strained by many investigations and practical operational data [2]. Along with the opportunities brought by the development of novel electrical and electronic technologies, challenges arise in such circumstances, especially stability problems in large interconnected power systems. As one of the key issues imposed on the expanding power networks, small-signal stability should be addressed and properly improved in systems which lack damping where low frequency oscillation can be observed and can be categorized into local modes and inter-area modes. Inter-area oscillation is often aroused by the loss of synchronism of synchronous machines in different areas [3]. Compared to the local modes, inter-area modes are better tackled with the modulation of bus voltage, active power and reactive power on properly selected busbars and transmission lines [4]–[6]. In the light of the scenarios presented above, supplementary damping control for the enhancement of small-signal stability utilizing a wide range of fast-switching and controllable devices has been proven to be effective in many literatures [7]–[9].

FACTS devices have long been employed in modern power systems for infrastructure reinforcement. Despite the fact that supplementary damping functions are often considered as secondary; an increasing number of applications have incorporated the small-signal enhancement as an essential feature in the initial design stage. Reference [10] carried out the planning and pre-specification study to increase the system transfer capacity and stability limit in stressed areas. The planned implementation of a convertible static compensator in [11] was investigated for the optimal configuration with other FACTS devices for voltage, small-signal, and transient stability. A robust POD design for the TCSC mentioned in [12] was compared with its original approach to adapt to new challenges [13]. The non-smooth optimization technique was more capable to adopt various controller structures and disturbances. The incorporating of multiple operating points helped to built up the robustness of the proposed approach. Reference [14] employed TCSC for transmission capacity increment and oscillatory stability enhancement in the transmission corridor between the northern sea and Taiwan power grid, which was restricted by thermal limits on these transmission lines. In addition, a supplementary damping controller was designed for the TCSC to damp out the inter-area oscillations [15]. The WAM technology with PMUs offers new solutions to improve system stability [16], [17] with the expansion of feedback signal candidates. Without restricting the choice of local signals, remote signals with higher controllability and observability can be utilized in the damping control design. In [18]–[21], a MISO controller with a wide-area signal for TCSC enhanced system small-signal stability was used and it targeted inter-area oscillations. However, it's been difficult for

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a single device to cover all the under-damped oscillatory modes especially in a bulk power system with multiple inter-area modes that are an area for improvement. Therefore, the coordinated robust control of two or more devices is investigated. The coordinated control approaches in [22]–[26] with decentralized structures were tested effectively without adverse effects, but there still existed the cross-coupling effect among the controllers. The sequential approach in [27] provided higher reliability and independence in improving the system's damping characteristics.

In this paper, FACTS devices with reactive power control are considered for their flexibility of providing supplementary damping functions to the power system as well as the operability of the devices. Candidates, including STATCOM and SVC, are assessed and evaluated in respect of engineering practicality. The proposed control methodology is based on a multi-model system, simultaneously considering multiple operating conditions and introducing multiple control objectives. Regional pole placement, control effort optimization and disturbance rejection contribute to the robustness of the supplementary controllers. The BMI synthesis optimization problem is solved systematically via a two-step approach to find a common controller for all system models with different operating points. The resulted controller is subsequently tested with numerical linear analysis and real-time simulations in RTDS.

II. SMALL-SIGNAL MODELS OF POWER SYSTEMS

The small-signal models for electrical components used in this paper are illustrated in the following sections. Both algebraic and differential equations represent the statics and dynamics of power systems.

A. STATCOM

A static synchronous compensator (STATCOM) can be seen as a controllable source of reactive power compensation by altering the waveforms of the voltage and current of the VSC to either generate or absorb reactive power [28]. It is shunt connected to the busbar in the locations of the power system for voltage regulations.

The internal d-q control of the STATCOM is illustrated in Fig. 1 with damping control signal. d-q transformation and space vector control techniques are utilized to decouple d-axis and q-axis components. The d-axis component maintains DC voltage, while the q-axis component controls the AC voltage or reactive power.

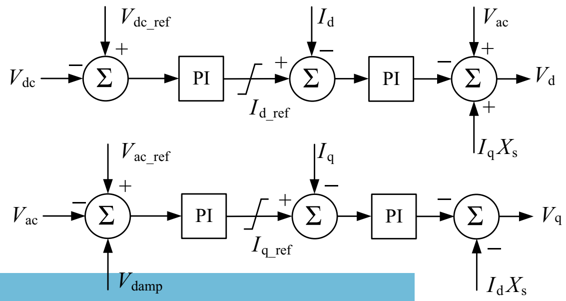

Fig. 1. d-q control of the STATCOM with damping signal.

The dynamics of the STATCOM consists of DC link capacitor dynamics, internal control dynamics and transformer algebraic equations, forming the state space model of the STATCOM [29].

B. SVC

As one of the most widely applied FACTS controllers, SVC is a shunt connected device that can absorb and generate reactive power for voltage regulation at the grid connection point. SVC is composed of a thyristor controlled reactor, thyristor switched capacitor, harmonic filter, mechanically switched capacitor and reactor. SVC can be continuously controlled to modify the reactive power injection to maintain bus voltage; its small-signal dynamics is depicted in the following block diagram, Fig. 2.

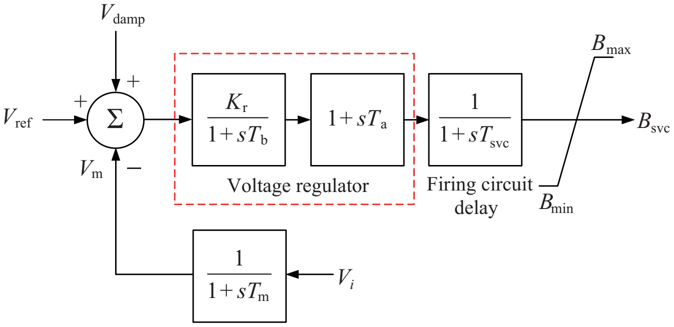

Fig. 2. Dynamic models of the SVC.

The differential equations representing SVC dynamics are given by:

$$\dot{B}_{\mathrm{svc}} = \frac{1}{T_{\mathrm{svc}}}\left(-B_{\mathrm{svc}} + \left(1-\frac{T_{\mathrm{a}}}{T_{\mathrm{b}}}\right)V_1 - \left(\frac{K_{\mathrm{r}}T_{\mathrm{a}}}{T_{\mathrm{b}}}\right)V_{\mathrm{m}}\right) + \frac{K_{\mathrm{r}}T_{\mathrm{a}}}{T_{\mathrm{svc}}T_{\mathrm{b}}}\left(V_{\mathrm{damp}}+V_{\mathrm{ref}}\right) \tag{1}$$

$$\dot{V}_1 = \frac{1}{T_{\mathrm{b}}}\left(-V_1 - K_{\mathrm{r}}V_{\mathrm{m}} + K_{\mathrm{r}}V_{\mathrm{ref}} + K_{\mathrm{r}}V_{\mathrm{damp}}\right) \tag{2}$$

$$\dot{V}_{\mathrm{m}} = \frac{1}{T_{\mathrm{m}}}\left(V_i - V_{\mathrm{m}}\right) \tag{3}$$

where B_{svc} is actual susceptance of SVC, V_1 is intermediate modelling signal, V_{m} is measured voltage, V_{ref} is voltage reference, and V_i is instantaneous bus voltage.

The power injection model of the SVC is given by:

$$Q_k = V_i^2 B_{\mathrm{svc}} \tag{4}$$

where Q_k is reactive power injection at Bus k.

C. Multi-Model System

In small signal stability studies, the power system is required to be linearized around a certain operating point and reorganized as a set of differential and algebraic equations (DAE). State-space representation is shown in the following equation:

$$\Delta\dot{x} = A\Delta x + B\Delta u. \tag{5}$$

Different from a single mode system where the power system is linearized around one operation point; a multi-model system allows the system to be linearized around several operating points which greatly increases the robustness of the damping controller, making it more effective under different system operating conditions. A series of linearized system models are integrated together to form the multi-model system.

A series of linearized system models are integrated together to form the multi-model system:

$$\begin{aligned} \Delta\dot{x} &= A_i\Delta x + B_i\Delta u \\ \Delta y &= C_i\Delta x + D_i\Delta u \\ i &= 1, 2, \ldots, L \end{aligned} \tag{6}$$

where i represents operating point number, L is the total number of operating points and Δy is the selected system output used as the controller feedback signal.

III. MULTI-MODEL MULTI-OBJECTIVE SYSTEM APPROACH

Designing supplementary damping controllers requires careful assessment of control objectives regarding disturbance rejection, control effort optimization and regional pole placement and then these objectives are described with matrix inequalities forming a BMI-based synthetic optimization problem.

A. Regional Pole Placement

Regional pole placement in Fig. 3 is to move the poorly damped eigenvalues into the conic area of the desired damping ratio boundary, given by the equation $\zeta = \cos^{-1}\theta$.

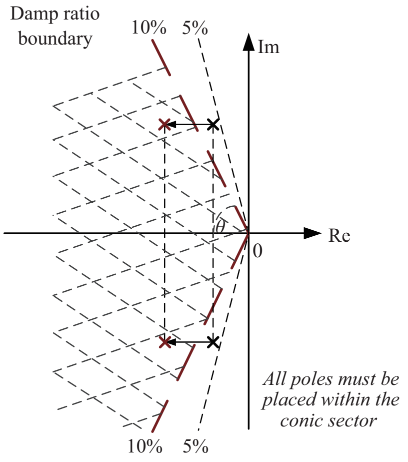

Fig. 3. Regional pole placement.

B. System Uncertainty Formulation

Disturbances such as load variation, line outage and excitation system disturbance can often cause low frequency oscillation in the system. Thus the primary objective of the damping controllers is to diminish the impact of the disturbances and meanwhile control effort in the design process should be optimized in accordance with the actual ratings of the actuators to avoid over-design.

The mixed H_2/H_∞ synthesis output feedback control is adopted to quantify these two objectives: disturbance rejection and control effort optimization. Fig. 4 shows the mixed-sensitivity system formulation where the system plant is the open-loop model and feedback controller K is to be designed. The sensitivity between disturbance $w(s)$ and system output $y(s)$ is defined by the transfer function $G_{wy}(s)$ and sensitivity between disturbance $w(s)$ and controller output $u(s)$ is defined as $G_{wu}(s)$. Weights w_y and w_u are carefully selected as a low pass filter and a high pass filter respectively.

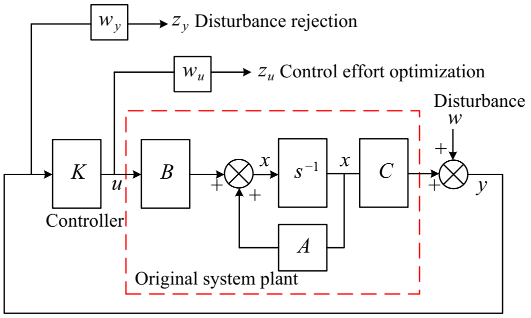

Fig. 4. System uncertainty formulation.

C. BMI Optimization Problem Formulation

The robust damping control problem for a multi-model system is expressed as:

$$\begin{aligned} &\min\,[\alpha_1 Trace(Q) + \alpha_2\gamma] \\ &\text{s.t.} \\ &\alpha \otimes P + \beta \otimes (PA_{\text{cl},i}) + \beta^{\text{T}} \otimes (A_{\text{cl},i}^{\text{T}} P) < 0 \\ &\begin{bmatrix} PA_{\text{cl},i} + A_{\text{cl},i}^{\text{T}} P & PB_{\text{cl},i} & C_{\text{cl1},i}^{\text{T}} \\ * & -\gamma I & D_{\text{cl1},i}^{\text{T}} \\ * & * & -\gamma I \end{bmatrix} < 0 \\ &\begin{bmatrix} Q & C_{\text{cl2},i} \\ * & P \end{bmatrix} > 0,\ Trace(Q) < \nu \\ &i = 1, 2, \ldots, L \end{aligned} \tag{7}$$

where α_1 and α_2 are weights of H_2 and H_∞ performance, and "$*$" is the transpose of its symmetry element in the matrix.

It's important to mention that the above different optimization specifications should be solved simultaneously for one Lyapunov matrix J as a joint convex optimization problem.

IV. SEQUENTIAL DESIGN APPROACH

When designing supplementary damping controllers for multiple devices, it is required that no adverse interactions between these controllers should occur.

A series of decentralized damping controllers for each device is designed sequentially to minimize the coupling effect and preventing adverse interactions among the controllers. The damping controller for the first device is designed and the first loop is closed, then the close-loop system is treated as the new open-loop system for the damping controller design for the second device.

In Fig. 5, the system state-space representation is depicted as A, B, C, D, and supplementary damping controllers $i = 1, \ldots, n$ are represented by $A_{Ki}, B_{Ki}, C_{Ki}, D_{Ki}$. Each controller is designed based on the mixed-sensitivity multi-objective BMI optimization technique and its feedback signal is carefully selected considering participation factor analysis and modal residue analysis. With each loop closure, the new close-loop system order increases with the addition of the feedback controller and system order reduction is carried out in each loop.

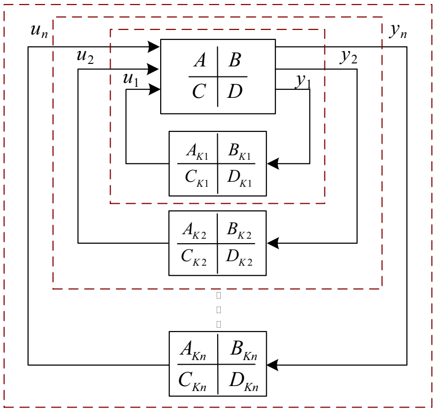

Fig. 5. Sequential design approach.

V. CONTROLLER DESIGNS

A. Test System

The controller designs are implemented on the test system presented in Fig. 6. It is the reduced equivalence of the interconnected New York Power System and New England Transmission System (NYPS-NETS) which is also widely recognized as the benchmark system for interarea oscillation studies [PA Anderson]. The system consists of 16 generators, 68 buses and is geographically mapped into 5 different areas: the NYPS mapped in Area 1 is connected to the NETS mapped in Area 2 via three transmission circuits; and the NETS is also connected to three remote areas (Area 3–5) represented by generators.

By running the eigenvalue analysis, the damping characteristics of the system can be assessed. The plot in Fig. 7 illustrates the poles of the system from which it is easy to conclude that there are 4 dominant weakly damped oscillatory modes which sit outside the conic sector restricted by the 10% damping ratio line. The robustness approach proposed in this paper utilizes multiple system models, hence the eigenvalue analysis is also repeated with variations in the power flow between the two major interconnected systems. This can be easily achieved by manipulating the generation and demand across different areas and the operating points are introduced as per Table I for the following studies. Table II shows the oscillatory frequency and damping ratio for these poorly damped modes. It is easy to find that the four oscillatory modes identified are inter-area oscillatory modes as their frequencies are all below 1 Hz which usually indicates involvement of multiple generator groups across different regions with larger total inertia.

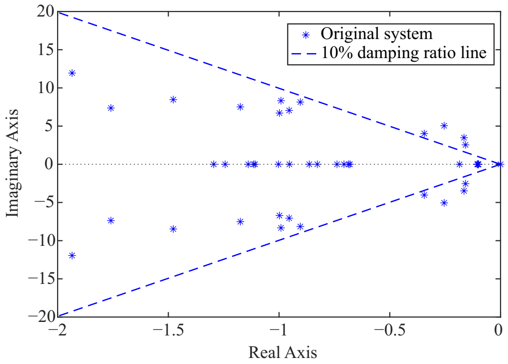

Fig. 7. Eigen-plot of the test system.

TABLE I
MULTI-MODEL SYSTEM OPERATING POINTS

Operating Points	Active Power Transfer $A_1 \rightarrow A_2$ (MW)
1	400 (Nominal model)
2	550 (Off-nominal Model 1)
3	700 (Off-nominal Model 2)

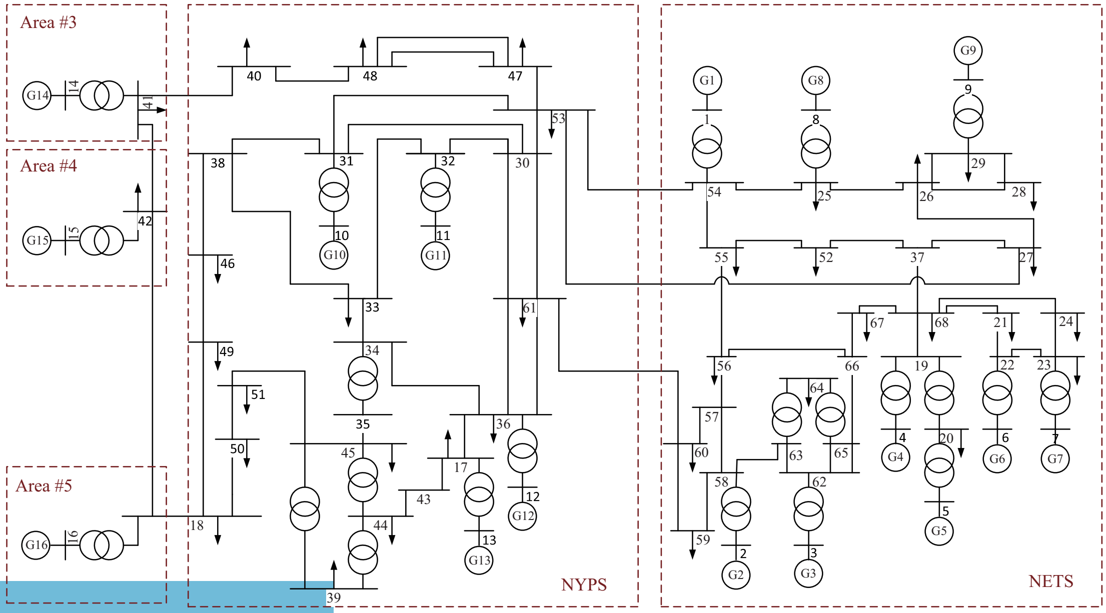

Fig. 6. Five-area test system.

TABLE II
DOMINANT INTER-AREA OSCILLATION MODES FOR OPEN-LOOP SYSTEM

Operating	Mode 1		Mode 2		Mode 3		Mode 4	
Points	ζ (%)	ω (Hz)	ζ (%)	ω (Hz)	ζ (%)	ω (Hz)	ζ (%)	ω (Hz)
1	6.21	0.40	4.73	0.55	8.56	0.64	5.06	0.80
2	6.24	0.40	4.67	0.55	8.51	0.64	5.07	0.80
2	6.23	0.40	4.58	0.55	8.53	0.64	5.07	0.80

B. Locations for Shunt FACTS Devices and Feedback Signals for Controller Designs

Shunt FACTS devices are installed to the test system to provide reactive compensation as their primary function. It is usually a good practice to optimize the observability and controllability prior to the start of the designs by selecting suitable input and output signals. The installation location of the shunt device will decide the controllability of the controller as the location also determines the bus bar voltage the device will regulate; while the observability is usually determined by the feedback signal (input signal) selected for the controller and a good candidate signal should contain invaluable information of the target oscillatory mode(s), such as voltage, current and flows. In this study case, SVC is installed on Bus 18 and STATCOM on Bus 51.

The feedback damping control signal candidates should be scrupulously evaluated to ensure decent controllability and observability to the oscillatory modes. To this end, participation factor analysis of the contribution of generator states to certain modes and modal residue analysis of the sensitivity of system output to a particular oscillatory mode are executed regarding the damping characteristics of the original open-loop system.

Fig. 8 exhibits the normalized participation factor bar diagram of 16 rotor speed states representing 16 generators in respect to 4 weakly damped modes. This indicates the degree of involvement of each machine to each mode. It can be observed that all the generators including area equivalent generators 14–16 contributes to the inter-area oscillatory Mode 1; Mode 2 can be seen as the oscillation between generator 14 and generator 16; Mode 3 is between NYPS and NETS; finally, Mode 4 involves Generators 14, 15 and 16.

Modal residue analysis is considered here to assess the controllability and observability of the controllers to be designed. When installation locations are fixed based on the needs for the primary function of the shunt FACT devices, the assessment is purely carried out to find the most suitable feedback signals for the controllers. In Fig. 9 and Fig. 10, modal residue results are illustrated in absolute values for each oscillatory mode with respect to different current signals.

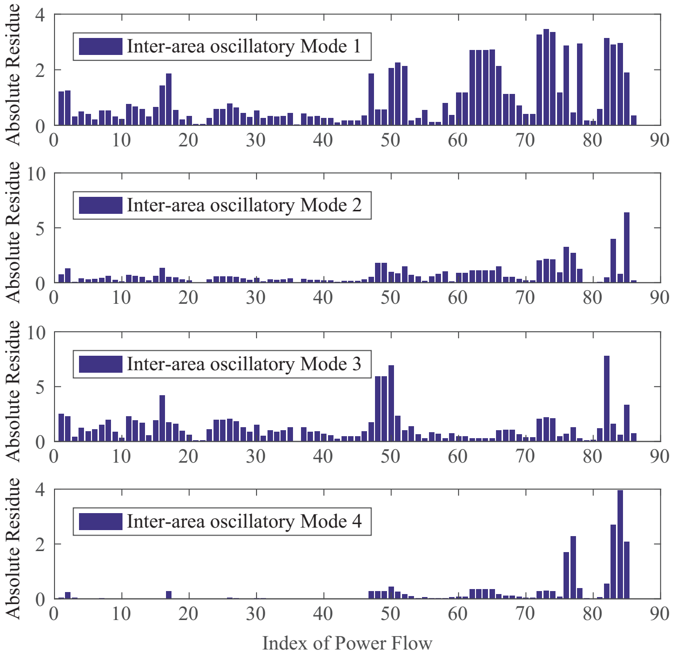

Fig. 9. Modal residue of all line currents for STACOM.

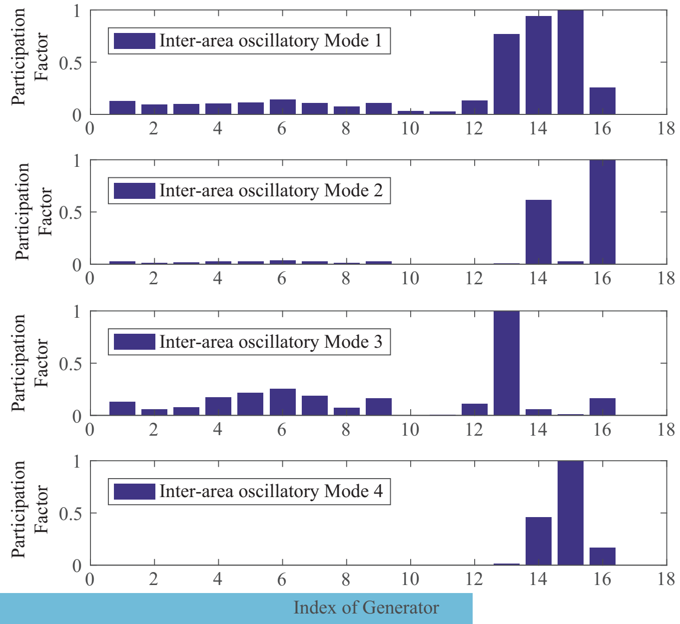

Fig. 8. Participation factor analysis.

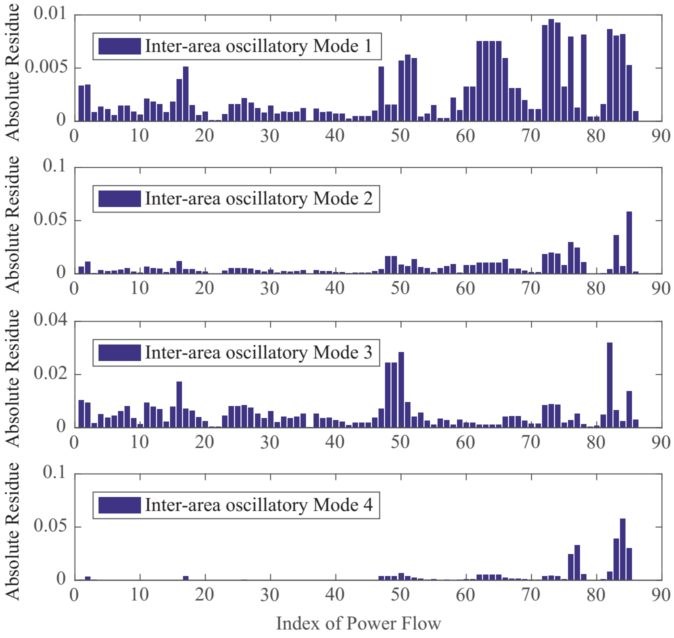

Fig. 10. Modal residue of all line currents for SVC.

In addition to the modal residue analysis, the locations of the signals play an important part in the evaluation process. Remote signals can greatly expand the range of feedback signal candidates and it allows signals with high modal residues to be considered whereas local signals are more reliable as they do not require additional wide area measurement units.

C. System Order Reduction

Typically, in a bulk system, the system order can go up to hundreds of states. Therefore, simplification of the system model is a necessary step for the ease of controller design and computational effort and avoiding the complexity of the desired controller. It is required that the equivalent system retains the information within the frequency range for inter-area oscillations i.e. 0.1–1 Hz for inter-area oscillation mode and 1–2 Hz for local mode so that it's a good approximation of the full-order original open-loop system.

Balanced modal truncation system reduction is carried out to reduce the system order to 7. Frequency response of the original system and reduced system in Fig. 11 and Fig. 12 clearly shows the system reduction to be valid since the bode diagram of the reduced and original systems are almost identical with few disparities.

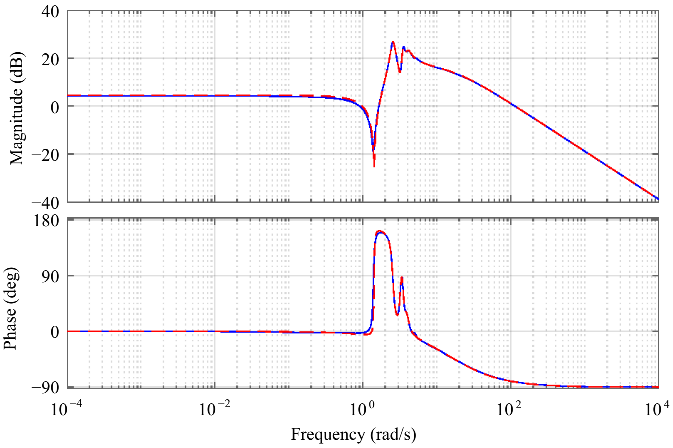

Fig. 11. Bode diagram of reduced system for STATCOM.

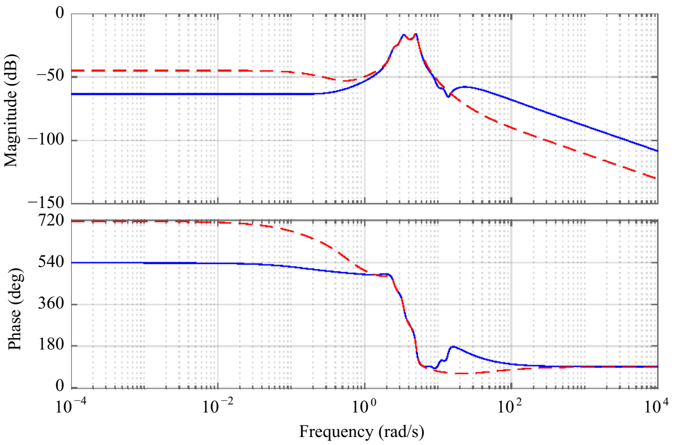

Fig. 12. Bode diagram of reduced system for SVC.

VI. LINEAR SYSTEM PERFORMANCE EVALUATION

The close-loop system performance is examined with eigenvalue analysis in Table III, Table IV and Table V. The system performance of the close-loop system with 3 forms of formulation are improved in different patterns.

First, the 7th order damping controller of the STATCOM is installed with the original open-loop system, forming a close-loop system. Its eigenvalue characteristic is presented in Table III, where improvements of the damping ratios of mode 1, 2 and 3 can be seen under all operating points and as mode 4 is not considered in the design stage, its damping ratio remains unchanged.

TABLE III
SYSTEM LINEAR PERFORMANCE WITH STATCOM DAMPING CONTROLLER

Operating	Mode 1		Mode 2		Mode 3		Mode 4	
Points	ζ (%)	ω (Hz)	ζ (%)	ω (Hz)	ζ (%)	ω (Hz)	ζ (%)	ω (Hz)
1	11.9	0.40	8.71	0.55	9.90	0.64	5.10	0.80
2	11.0	0.40	8.70	0.55	9.89	0.64	5.09	0.80
2	11.2	0.40	8.70	0.55	9.90	0.64	5.08	0.79

Secondly the 7th order damping controller of the SVC is implemented with the original open-loop system. This forms another close-loop system with dominant inter-area oscillatory modes and their damping ratios are shown in Table IV. Since the SVC damping controller is designed based on the close-loop system with a STATCOM controller, its control effort focuses on mode 4 alone and it shows great improvement from the previous under damped behavior.

TABLE IV
SYSTEM LINEAR PERFORMANCE WITH SVC DAMPING CONTROLLER

Operating	Mode 1		Mode 2		Mode 3		Mode 4	
Points	ζ (%)	ω (Hz)	ζ (%)	ω (Hz)	ζ (%)	ω (Hz)	ζ (%)	ω (Hz)
1	6.80	0.40	5.30	0.55	8.13	0.64	9.32	0.80
2	6.80	0.40	5.32	0.55	8.12	0.64	9.34	0.80
3	6.79	0.41	5.31	0.55	8.12	0.64	9.34	0.79

Finally, both controllers are sequentially put into practice with the original system. The synthesis control effort from both controllers has effectively meliorated the damping characteristics across all four modes. A minimum 9% damping ratio is guaranteed in all operating points, indicating a successful coordinated robust design, shown in Fig. 13.

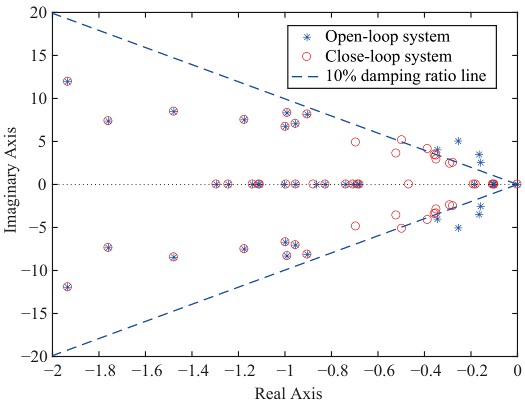

Fig. 13. Eigenvalue comparison of open-loop and close-loop systems.

TABLE V
SYSTEM LINEAR PERFORMANCE WITH STATCOM AND SVC DAMPING CONTROLLERS

Operating	Mode 1		Mode 2		Mode 3		Mode 4	
Points	ζ (%)	ω (Hz)	ζ (%)	ω (Hz)	ζ (%)	ω (Hz)	ζ (%)	ω (Hz)
1	10.9	0.40	10.3	0.55	9.80	0.64	9.64	0.80
2	10.9	0.40	10.2	0.55	9.81	0.64	9.65	0.80
3	10.8	0.41	10.2	0.55	9.80	0.64	9.66	0.79

VII. REAL-TIME SIMULATIONS

To fully examine the system performance, non-linear real-time digital simulations offer great insight in addition to the eigenvalue analysis. STATCOM and SVC damping controllers are installed in the test system and evaluated for the effectiveness and robustness under various disturbances and operating conditions.

A. Excitation System Disturbance

In the first case study, excitation system disturbance is caused by a step change of the excitation system reference voltage for small time duration. The reference voltage for generator 14 endures a step change of 0.02 p.u. for 500 ms and the system responses on the active power of Line 73 (Bus 18–50) are presented.

B. Load Variation

Unlike the small variation given to the voltage reference in the previous scenario, Load 41 experiences a permanent step down from 1000 MW to 800 MW, resulting in a power fluctuation of the active power on Line 78 (Bus 41 to 40).

C. Discussion

The non-linear simulation results in Fig. 14–17 clearly demonstrated the damping effort of the supplementary controllers of the STATCOM and SVC. The settling time of the system undergoing disturbances has been significantly shortened to less than 20 s. Moreover, the damping controllers exhibit great robustness against different types of disturbances. The multi-model approach enables the controllers to be adaptive when system operating conditions are changed and provide effective damping to the inter-area oscillation modes.

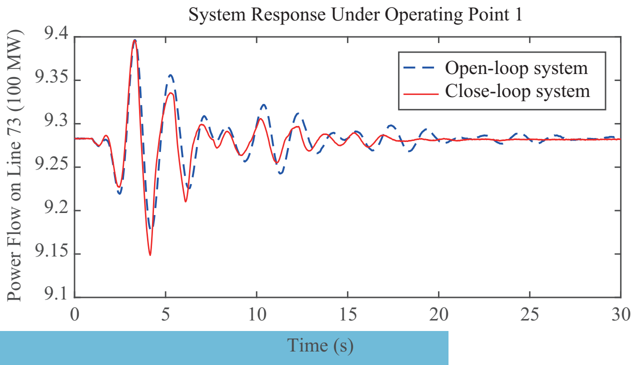

Fig. 14. Excitation system disturbance under operating Point 1.

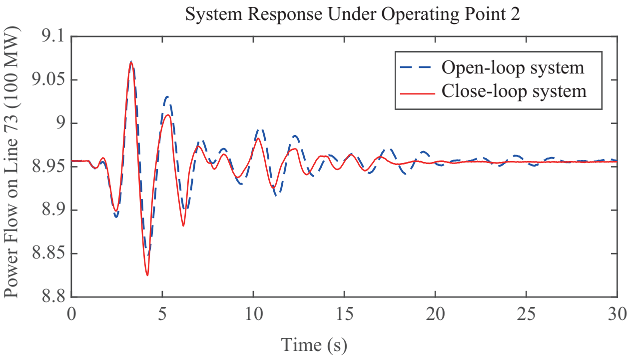

Fig. 15. Excitation system disturbance under operating Point 2.

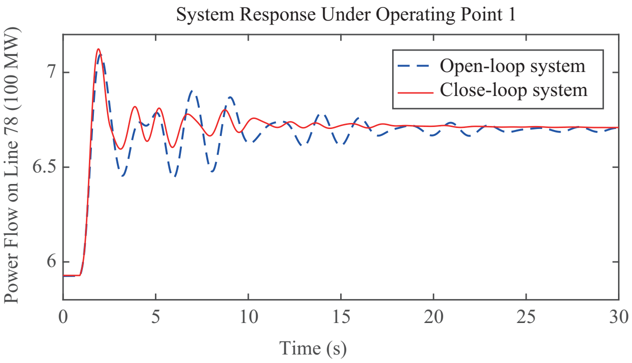

Fig. 16. Load variation under system operating Point 1.

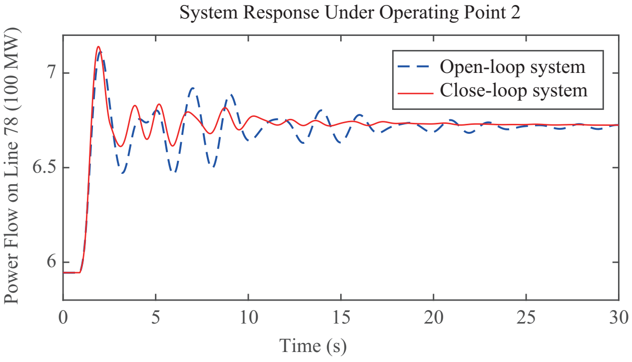

Fig. 17. Load variation under system operating Point 2.

VIII. CONCLUSION

This paper introduces damping control for two different devices: STATCOM and SVC. In a pragmatic and interconnected power system, multiple inter-area oscillatory modes with disparate mode shapes can be found especially in weakly connected transmission corridors. Under such circumstances, the capability of a single device to provide sufficient and effective damping towards all the oscillatory modes can be quite limited due to the installation location mainly decided by its primary functions. Therefore, the coordinated damping control of various types of devices should be considered to guarantee satisfactory control effort in accordance with practical ratings. In this study, the sequential design resulted in a series of SISO damping controllers for each device, instead of a centralized MIMO controller, to minimize the coupling effect and assure the robustness and potency of each controller. The supplementary damping controllers were formulated with a BMI-based multi-objective multi-model optimization problem which was solved via a two-step method. The validity of the controllers was checked with linear system performance analysis for eigenvalue characteristics under all operating points. It showed the controllers control effort for specified modes and the improvement of the damping ratios to a decent level. Furthermore, the real-time simulation in RTDS exhibited the system behavior when suffering from various types of disturbances. In addition, the controllers demonstrated great robustness regarding different operating conditions.

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