BNL-72459-2004-CP

# *Multiple Oscillation Stabilizing Control*

**M. Yue, R. Schlueter, M.A. Azarm, R.A. Bari**

*To be Presented at the Power System Conference and Exposition*
*New York City, NY*
*October 10-13, 2004*

July 2004

**Energy Sciences and Technology Department**

**Brookhaven National Laboratory**
P.O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

*Managed by*
Brookhaven Science Associates, LLC
for the United States Department of Energy under
Contract No. DE-AC02-98CH10886

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

# DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

**FOR UNCLASSIFIED, UNLIMITED STI PRODUCTS**

Available electronically at:

**OSTI:**

http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy and its contractors, in paper from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831
Phone: (865) 576-8401
Facsimile: (865) 576-5728
E-mail: reports@adonis.osti.gov

**National Technical Information Service (NTIS):**

Available for sale to the public from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22131
Phone: (800) 553-6847
Facsimile: (703) 605-6900
Online ordering: http://www.ntis.gov/ordering.htm

Printed on recycled paper

# Multiple Oscillation Stabilizing Control

Meng Yue, *Member, IEEE*, Robert Schlueter, *Fellow, IEEE*, Mohamad A. Azarm, and Robert Bari

***Abstract*— This paper presents a strategy that may be used to guide stabilizing control design for multiple oscillations, which are difficult to control using conventional control design procedures. A multiple oscillation phenomena is observed in an example power system. A local bifurcation and an interarea bifurcation develop in an example power system due to multiple bifurcation parameter variations. The dynamic behaviors of the bifurcating system are complex due to the overlapping of the two different bifurcation subsystems and are shown to be difficult to control. The double bifurcations are studied in this paper and in order to stabilize them, three kind of $\mu$-synthesis robust controls are designed, (a) $\mu$-synthesis power system stabilizer (MPSS); (b) $\mu$-synthesis SVC control (MSVC); and (c) a mixed MPSS/MSVC control. Based on the bifurcation subsystem analysis, the measurement signals and locations of the controls are selected. The control performances of three kind of controls are evaluated and compared. The conclusions are given according to the analysis and time simulation results.**

***Index Terms*—Multiple bifurcations, local oscillation, interarea oscillation, overlapping bifurcation subsystem, $\mu$-synthesis control design**

## I. Introduction

With the complexity and stress increased on current power systems, multiple bifurcations are more likely to develop. In WECC system it has been verified that there could exist up to 6 interarea oscillations at the same time and these interarea oscillations are very difficult to control since they are strongly coupled to each other. Typically, a conventional power system control that stabilizes one oscillation destabilizes others [1]. Using the conventional control design procedure, the coordination of different controllers is a significant difficulty.

A multiple bifurcation phenomena is observed and the stabilization of the multiple bifurcations is studied for a two area power system in this paper. Usually multiple bifurcations are produced by more than one bifurcation parameter variation. More complex system behaviors are expected when more than one bifurcation develop simultaneously and the corresponding bifurcation subsystems overlap. This makes it more difficult to stabilize the system under this situation.

Robust control has been applied to power system interarea oscillation and/or voltage support [2] - [9] for a single bifurcation. Multiple bifurcation stabilization has not been studied extensively, although it is the most frequently encountered in a real power system. In [8] [9], a single measurement and a single control output $\mu$-synthesis based robust power system stabilizer (MPSS) and $\mu$-synthesis based robust SVC (MSVC) were shown to be very effective for a single bifurcation. As a very important step for multiple bifurcation stabilizations, a robust control design methodology was developed based the bifurcation subsystem method in [8]. The extension of this design methodology will enable designs of MPSS, MSVC, and mixed MPSS and MSVC control with different measurements and control outputs for stabilization of the multiple bifurcations in this paper.

This paper is aimed at investigation of possible coordinated controls to provide generic guideline for multiple oscillation stabilization, using the bifurcation subsystem based robust control design methodology [8] and different control devices including power system stabilizer and SVC. This involves in (1) the identification of the bifurcation subsystem and the understanding of the bifurcation nature; (2) the structured uncertainty modeling by using a bifurcation parameter or multiple bifurcation parameters as uncertainty parameter(s); (3) the selection of performance index, weighting transfer function matrix, the measurements, and siting of the control to be designed using the bifurcation subsystem analysis; (4) the relative gain array ($RGA$) analysis [10] of the open loop and closed-loop system. In this paper, all these properties except the $RGA$ analysis will be used to guide the robust control designs. Three MPSSs, two MSVCs, and a mixed MPSS/MSVC control are designed according to the nature of the multiple bifurcations. Time simulation results are given to evaluate and compare the individual robust control designs. A general conclusion is drawn to provide information and insight to the multiple bifurcation stabilizing control design.

## II. Multiple Bifurcations and $\mu$-Synthesis Stabilizing Control Design

A two-area power system [1] shown in Fig 1 is studied. Two generation and load areas are interconnected by two parallel transmission lines. There are two generators in each area. The generators and their controls are almost identical except that generator 3 (G3) has a conventional power system stabilizer (CPSS) attached. Bus 101 has a conventional SVC (CSVC) control device.

This two-area system is vulnerable to the interarea oscillations caused by various bifurcation parameters and to saddle-node bifurcation under certain situations [11] - [14]. The CPSS and the CSVC are not able to maintain the system stability for relatively large change of different bifurcation parameters [8] [9].

A constant power load model is used in this paper. A double-bifurcation is produced by increasing the active power load and line susceptance connecting load bus 20 to generator bus 2 simultaneously. The bifurcation subsystems of the two bifurcations can be obtained and analyzed via bifurcation subsystem

M. Yue, M. A. Azarm, and R. Bari are with Energy Science and Technology Department, Brookhaven National Laboratory, Upton, NY 11973, USA (email: yuemeng, azarm, bari@bnl.gov)

R. Schlueter is with the Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824, USA (email: schluete@egr.msu.edu)

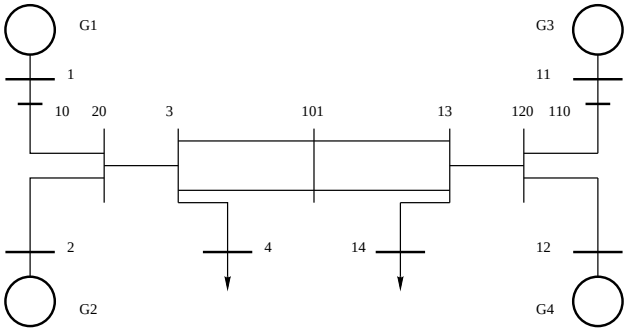


Fig. 1. Diagram of Two-area Example System

method [12] [13]. Two Hopf bifurcations, a local Hopf bifurcation (frequency of oscillation around 1 Hz) and an interarea Hopf bifurcation (frequency of oscillation less than 0.5 Hz) are observed in this study.

The generator angle vector diagrams of the interarea and the local Hopf bifurcation at the bifurcation point are shown in Fig 2 and 3, respectively. It is expected that the dynamic behaviors of the system with multiple bifurcations are more complicated because of the interaction between the interarea and local oscillations.

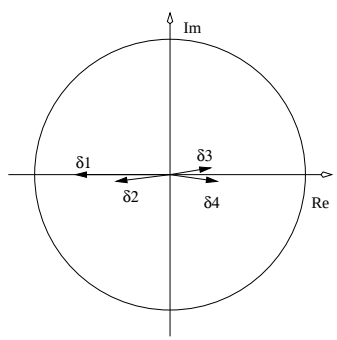


Fig. 2. Generator Angle Vector Diagram of Interarea Oscillation

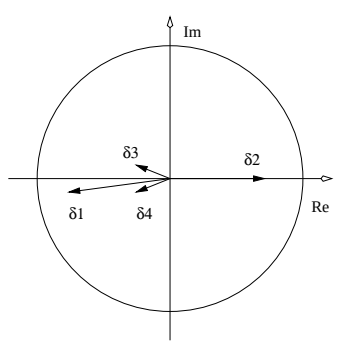


Fig. 3. Generator Angle Vector Diagram of Local Oscillation

Fig 2 verifies that an interarea Hopf bifurcation develops since the two generation areas $\{\delta_1, \delta_2\}$ and $\{\delta_3, \delta_4\}$ oscillate against each other. Fig 3 shows that the Hopf bifurcation is a local oscillation between generator 2 and the other generators in the system. Two bifurcation subsystems were obtained using the bifurcation subsystem identification algorithm [15].

The study of the bifurcation subsystems of the double bifurcations, which is not shown here due to the limit of the space, suggests that the two bifurcation subsystems overlap each other and the overlapping states of the two bifurcation subsystems are mainly involved in all the inertial dynamics and excitation systems states at generators 2 and 4. According to the bifurcation subsystem method, this implies that control improvements at generator 2 and 4 are most likely needed.

The following notations, which were adopted in [8], are still used here: $P_{R_i} = P_{m_i}$ and $P_{O_i} = P_{G_i}$,$i = 1, 2, \cdots, 4$, indicate the input power references and active power outputs on generator bus $1, 2, 11, 12$. $V_{R_i}$ and $V_{O_i}$, $i = 1, 2, \cdots, 5$, indicate the voltage references and measured voltage outputs on generator terminal bus $1,\ 2,\ 11,\ 12$, and SVC bus 101, respectively. $V_{O_i}, i = 6, \cdots, 13$, represent the voltage outputs on other buses $3, 4, 10, 13, 14, 20, 110, 120$. $\omega_i, i = 1, 2, \cdots, 4$, represent the frequency on generator bus $1, 2, 11, 12$.

The fundamental robust control design and $\mu$ analysis and synthesis theory, which can be found in [10], were summarized in [8]. The uncertainty is modeled using the second order matrix polynomial [8] [9] for the two bifurcation parameters: active power load at generator 2 and line susceptance between bus 2 and bus 20. The resultant uncertainty model is of higher order than for a single bifurcation parameter, but is simplified using the approach in [16]. The design procedure is the same as that shown in [8] and [9] using $\mu$-synthesis method [10] [17].

A performance index to be minimized is formulated according to the nature of the interarea and local bifurcations:

$$\begin{aligned} J &= \min[\Sigma_{i=1}^{4}|P_{R_i} - P_{O_i}| + \Sigma_{i=1}^{5}|V_{R_i} - V_{O_i}| \\ &+ \Sigma_{i=1}^{2}|\omega_i - \omega_3| + \Sigma_{i=1}^{2}|\omega_i - \omega_4|] \end{aligned} \quad (1)$$

This performance index reflects both the requirements of the interarea and local oscillation control and also avoids the conflicts between the control requirements of them. It is slightly modified from the performance index shown in [8] [9], where a single Hopf bifurcation developed. This performance index will be used through this paper. The terms $\Sigma_{i=1}^{4}|P_{R_i} - P_{O_i}|$ and $\Sigma_{i=1}^{5}|V_{R_i} - V_{O_i}|$ assure regulation of the output power and voltage of the four generators and the voltage of the SVC bus. The term $\Sigma_{i=1}^{2}|\omega_i - \omega_3|$ and $\Sigma_{i=1}^{2}|\omega_i - \omega_4|$ assure damping of the inter area oscillation between generators 1 and 2 and generators 3 and 4 as well as the oscillation of generator 2 against generators 3 and 4.

In [8], it was shown that the control configuration was flexible in terms of different control designs, measurement selections, and control sitings. The control configuration can be easily obtained for each control design considered in this paper by the slight modification of the diagram shown in Fig 6 in [8] and will not be presented individually. Following the design procedures of MPSS shown in [8] [9], the individual control can be obtained using $\mu$-synthesis toolbox provided in Matlab [17]. The order of the resultant controllers will be reduced using a Hankel norm and the bifurcation subsystem information [8] sicne otherwise the control dimension is near that of the full system model.

The $RGA$ matrix is proved to capture the bifurcation subsystem structure [18] such that the $RGA$ matrix is block diagonal where the diagonal blocks represent the bifurcation subsystem

and external subsystem structure. Due to the limit of space, $RGA$ analysis will not be presented in this paper.

## III. $\mu$-Synthesis Power System Stabilizer for Multiple Bifurcations

Because the multiple bifurcations develop in the different locations (generators) of the two area system, it is thus anticipated that more measurements or controls are either required or are able to improve the control of the system undergoing multiple bifurcations. Therefore, three increasingly more complex $\mu$-synthesis robust power system stabilizer designs are considered in this section that have:

(1) a single measurement and a single control on generator 2 considering that both interarea and local oscillations need to be controlled. Generator 2 speed is taken as the measurement. The voltage excitation control set point on generator 2 is the single control. This is a typical local controller but is sited to affect the interarea oscillation between generator 1 and 2 and generator 3 and 4 and for the local oscillation between generator 2 and generators 1, 3, and 4;

(2) two measurements and a single control on generator 2. Because a local oscillation develops at generator 2 in addition to the interarea oscillations, the measurement on generator 2 and 4 should provide information on both areas containing generators 1 and 2 and the other area containing generators 3 and 4 as well as the local oscillation of generator 2 against generators 1, 3, and 4. This controller is not local any more since a communication link will be needed for the measurement on generator 4 to wherever the controller is located on generator 2. The control is chosen to be on the excitation voltage setpoint on generator 2 since it should provide control over the interarea and local oscillation. This controller should perform better than the local controller since it has measurements that should capture both oscillations;

(3) two measurements and two controls on generator 2 and 4. The measurements of the speed on generator 2 and 4 are used as in the case above. This is expected to achieve better control performance than either of the above two designs since one has both sufficient information to detect and estimate the states associated with both oscillations and since there is also sufficient control to independently control both oscillations. Above designs are now addressed for $\mu$-synthesis power system stabilizer.

### A. MPSS Design I

MPSS with a single measurement ($\omega_2$) and a single control on generator 2 (MPSS Design I) will be designed. In order to improve the control performance, the inverse dynamics [8] of the corresponding generators are included in the control design. The closed-loop system $\mu$ value with MPSS Design I is shown in Fig 4. In Fig 4, the maximum $\mu$ value appears at very low frequency (around $10^{-3}$ rad/sec) instead of bifurcation frequency for single bifurcation. Another fact is that the peak $\mu$ value of the closed-loop system is greater than one. However, we are not concerned with this because it occurs at very low frequency beyond the frequency range that is the most important to the system behaviors are of concern. Two local maximum points appear around 3 and 8 rad/sec that correspond to frequencies of the interarea and the local oscillation. This verifies that multiple bifurcations develop in the two area system.

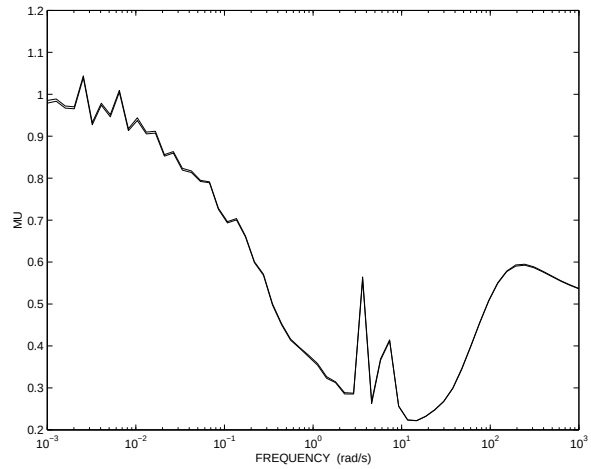


Fig. 4. Closed-loop $\mu$ Value: MPSS Design I

A $40\%$ increase in active power load and a $30\%$ increase in line susceptance above the nominal values are applied to generator bus 2 and the line between bus 2 and bus 20 to bring the system close to the point of the double bifurcations. This result will reflect the variation in the feasibility region in both bifurcation parameter directions. The time response of the closed-loop system with MPSS Design I is shown in Fig 5. Compared to the open loop time response of a single bifurcation [8] the wave form shown in Fig 5 is more complex. The magnitudes of the swings change alternatively and thus, indicate the occurrence of more than one bifurcation. This is because of the combination of the two bifurcations and the system response reflects the two oscillations.

From Fig 5, the open loop system can not maintain the stability while MPSS Design I is not able to achieve good control performance for multiple bifurcations. It is able to stabilize the perturbed system because the oscillations decay with time as shown in Fig 5. However, the transition time is too long. The oscillations are not completely damped out yet even after 100 seconds. Therefore, a single measurement and a single MPSS control is not a good choice when multiple bifurcations develop.

### B. MPSS Design II

A MPSS with two measurements ($\omega_2$ and $\omega_4$) and a single control on generator 2 (MPSS Design II) is designed now. This controller should perform better than the local controller since it has measurements that should capture both oscillation information.

The time response of the closed-loop system with MPSS Design II is shown in Fig 6. A $40\%$ increase in active load and a $20\%$ increase in the line susceptance above the nominal value are applied to generator 2. The increase in the bifurcation parameters brings MPSS Design I to the point of bifurcation. It can be seen that the damping of the oscillations has been increased dramatically compared to Fig 5 for MPSS Design I.

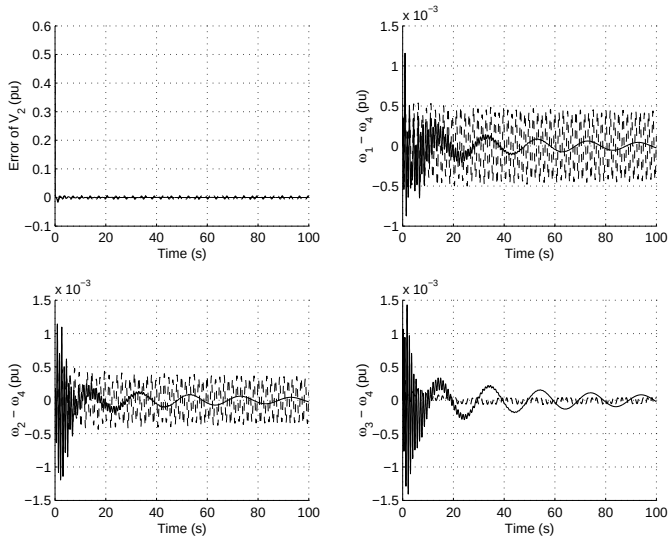


Fig. 5. MPSS Design I (-) and Open Loop System (- -)

Both interarea and local oscillations can be damped out in 30 seconds. The simulation result in [18] showed that the bifurcation parameters can be further increased before the double bifurcations would occur. This fact suggests that MPSS Design II would provide an even larger increase in the feasibility region in the direction of these two bifurcation parameters. However, the voltage control performance is not satisfactory because the transition time is long and the error magnitude is relatively large. This control design also needs to be improved.

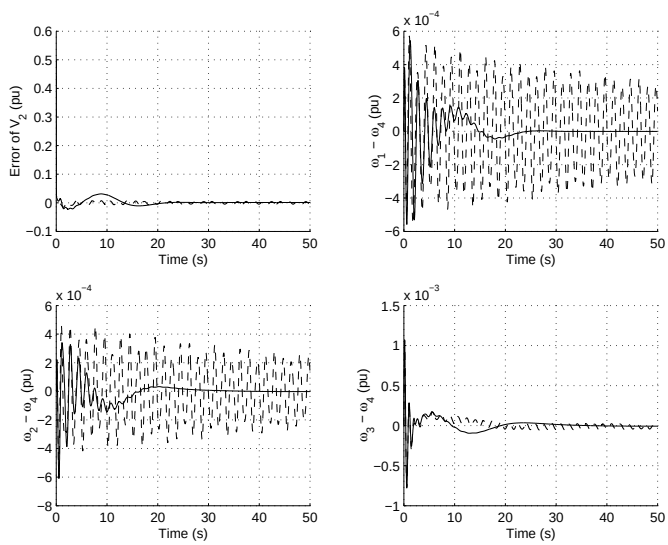


Fig. 6. MPSS Design II (-) and Open Loop System (- -)

### C. MPSS Design III

A MPSS with two measurements ($\omega_2$ and $\omega_4$) and two controls on generators 2 and 4 (MPSS Design III) is considered. The measurements of the speed on generator 2 and 4 are used as in the case above to provide both interarea and local oscillation information. The control actions will be taken on the excitation system voltage setpoint on generator 2 as well as generator 4. This is expected to achieve better control performance than above two designs since one has sufficient information to detect both oscillations and sufficient control to independently control both oscillations.

The time simulation of the closed-loop system with MPSS Design III is shown in Fig 7. Again, the robustness of the control design is stressed with a $40\%$ increase in the active load and a $20\%$ increase in the line susceptance above the nominal value. The robustness of the control design is observed in not only being able to increase the feasibility region in the bifurcation parameter directions by the above percentages but also to achieve a slightly better frequency control performance. The oscillations are damped more quickly and transient responses are more smooth compared to the time response shown in Fig 6 for $(\omega_1 - \omega_4)$ and $(\omega_2 - \omega_4)$. The magnitude of the oscillation on $(\omega_3 - \omega_4)$ is larger and is no longer at the local oscillation frequency ($\approx 1$ Hz) but now at the interarea frequency ($\approx 0.5$ Hz). This is because that the local bifurcation occurred on generator 2 is easier to control than the interarea oscillation, and thus, the improvement of the frequency control performance is not obvious.

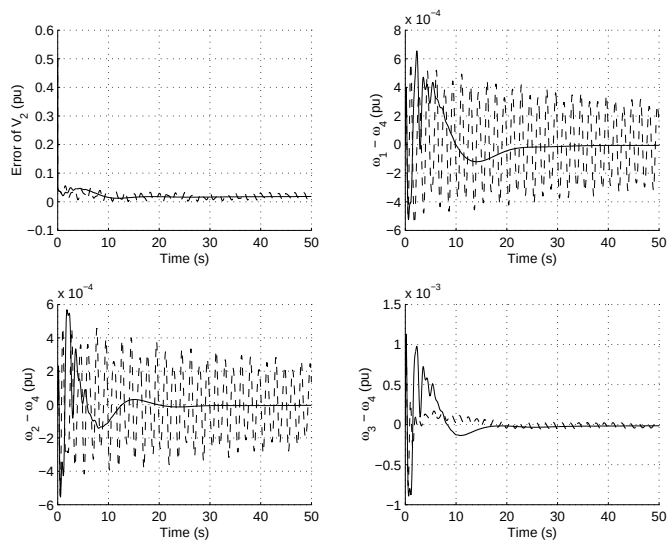


Fig. 7. MPSS Design III (-) and Open Loop System (- -)

The voltage control of the MPSS Design III is not improved at all and this is clear in Fig 7. The generator 2 speed measurement does not provide any voltage information and the power system stabilizer increases the damping effect by directly changing the generator terminal voltage setpoint. Conflicted objectives are difficult to obtain simultaneously for two power system stabilizers.

## IV. $\mu$-Synthesis SVC for Multiple Bifurcations

For multiple bifurcations the control performance of MPSS was shown to be less than perfect since the voltage control of network buses degraded. In [9], it has been concluded that MSVC is more effective than MPSS for a single bifurcation due to the local property of power system stabilizer. Similar to MPSS designs considered in the previous section, the MSVC will be designed

(1) with a single measurement ($\omega_2$) and a single control (at SVC bus);

(2) with two measurements ($\omega_4$ and $\omega_2$) and a single control (at SVC bus). The inverse dynamics are again included in the MSVC design.

### A. MSVC Design I

A MSVC with a single measurement ($\omega_2$) and a single control at SVC bus 101 (MSVC Design I) is designed here. The closed-loop $\mu$ value with MSVC Design I is shown in Fig 8. The multiple bifurcation phenomena can be verified by inspecting the peak $\mu$ value around frequency 3 and 8 rad/sec in Fig 8.

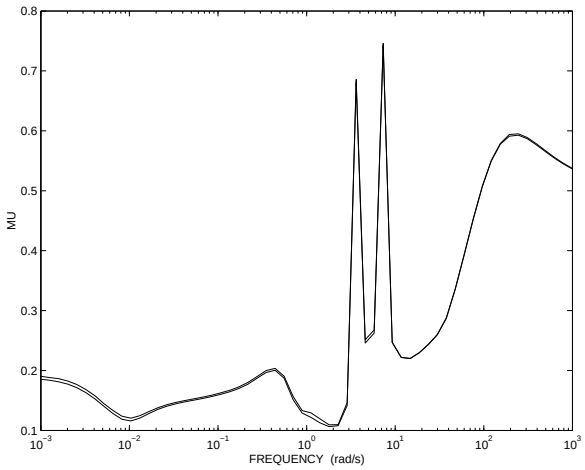


Fig. 8. Closed-loop $\mu$ Value: MSVC Design I

The time simulation of the open loop system and closed-loop system with MSVC Design I is shown in Fig 9. By applying $40\%$ more active power load than the bifurcation value for the interarea oscillation and $30\%$ more line susceptance than the bifurcation value for the local oscillation on generator bus 2, the closed-loop system interarea and local oscillations can be eliminated effectively by the MSVC Design I and the voltages are controlled well.

### B. MSVC Design II

A MSVC with two measurements ($\omega_2$ and $\omega_4$) and one control at SVC bus 101 (MSVC Design II) is designed.

It is expected that MSVC with more measurements improves the control performance. This is verified in Fig 10, where the MSVC Design II is applied to the system with the same disturbance as for MSVC Design I. Same active power load stress is applied to the original system. The control performance improvement can be seen in terms of smaller oscillation magnitude and shorter transition period compared to Fig 9.

## V. Mixed MPSS/MSVC Design

A mixed $\mu$-synthesis PSS/SVC control with two measurements ($\omega_2$ and $\omega_4$) is designed in this section. The MPSS is located on generator 2 that is involved in both interarea the local oscillation. This mixed MPSS/MSVC design will try to take

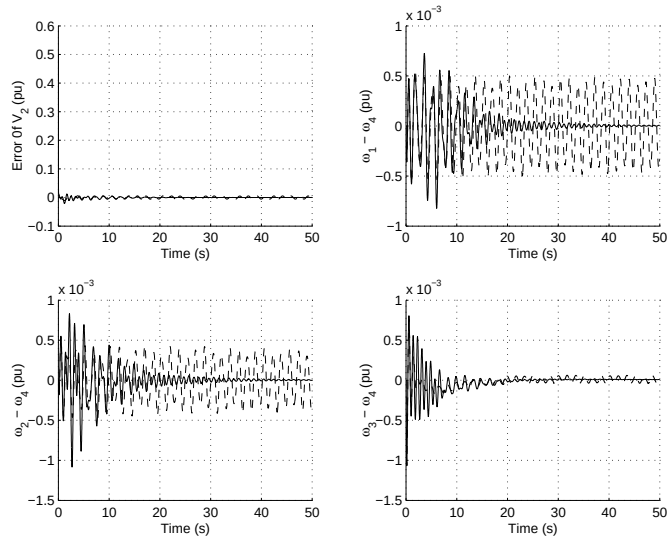


Fig. 9. MSVC Design I (-) and Open Loop System (- -)

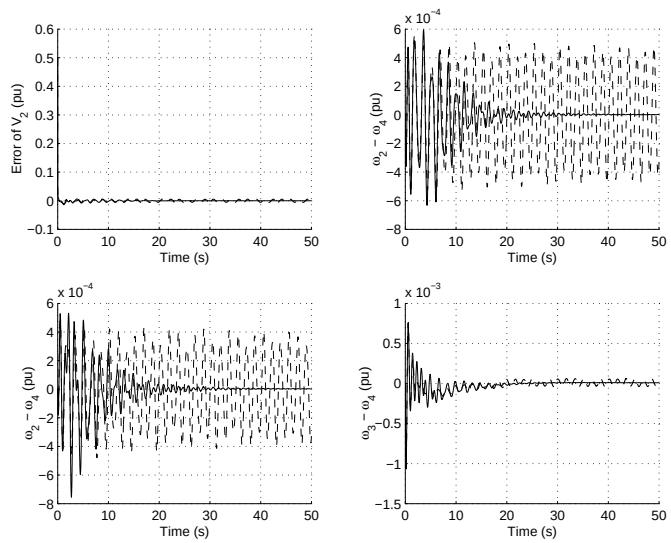


Fig. 10. MSVC Design II (-) and Open Loop System (- -)

the advantage of capability of voltage support of SVC and the damping of power system stabilizer at generator 2.

Fig 11 shows the time response of the closed-loop system with mixed MPSS/MSVC design. It can be seen that this design gives the best overall performance, although this time the increase of $40\%$ in active stress and $20\%$ increase in line susceptance above bifurcation values are applied. The competition for control of bus voltages at 6, 7, 8, and 11 is eliminated. Both voltage and oscillations are very well controlled. It demonstrates the advantages of both SVC control and power system stabilizer. The addition of the MPSS showed a significant improvement of the oscillation produced by the double bifurcations. The control of voltage $V_2$ is shown to degrade due to the MPSS but not seriously.

It is noted that the a single measurement and a single control MSVC (MSVC Design I) shown in section IV gives satisfactory performance and robustness. This does not mean that multiple measurements and multiple control designs are unnecessary be-

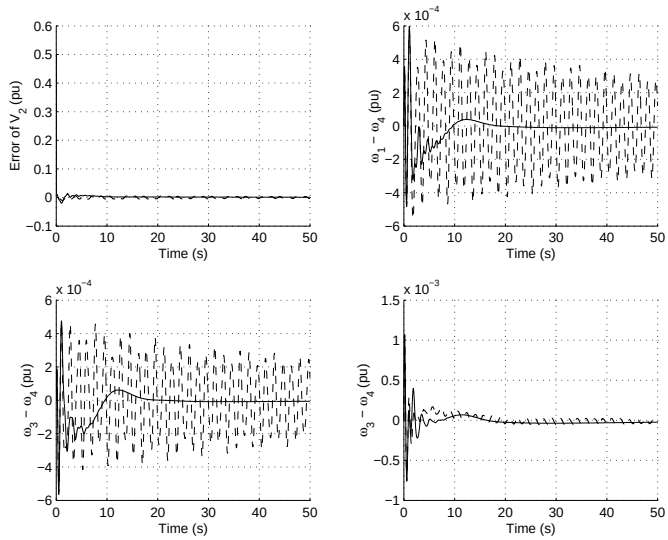


Fig. 11. Mixed MPSS/MSVC (-) and Open Loop System (- -)

cause of (a) the small size of this two area system makes it easy to control; (b) one of the two bifurcations is local bifurcation, which is easier to control than the interarea oscillation; and (c) adding more measurements and/or controls improves the control performance. For large power grids, the bifurcation behaviors are much more complex and thus, more measurement information and more control are important.

## VI. Conclusions

A multiple bifurcation phenomena observed in a two area power system is studied in this paper. The multiple bifurcations are more difficult to stabilize due to the overlapping and the strong coupling of the bifurcation subsystems of each bifurcation. Based on the study and the analysis of the double bifurcations using bifurcation subsystem method and a bifurcation subsystem based control design methodology, MPSS, MSVC, and, a mixed MPSS/MSVC control are designed. Time simulation results are compared.

The study in this paper indicates that multiple bifurcations can be stabilized via properly designed control. It is shown that (1) PSS, as a local control device, can only provide limited control to the system; (2) a properly designed MSVC is more effective than a MPSS design from the fact that a single measurement and a single MSVC control (MSVC Design I) is able to provide much better control performance than a single measurement and a single MPSS control (MPSS Design I); (3) more measurements and/or controls are necessary (for MPSS design) or help improve the robustness and control performance (for both MPSS and MSVC design); (4) the mixed design such as the mixed MPSS/MSVC, which exploits advantages of different devices, is more likely able to achieve better control performance; and (5) either measurements or controls should not be more than necessary. One fact that was not shown is that controllers with more measurements and/or control outputs than we used in this paper were tested and they did not show any obvious improvement in terms of time simulation.

It should be pointed out that the controls designed in this paper are formulated based on the full system model. For large power grids, it is impossible due to extremely high complexity and the resultant unaffordable computation efforts. Bifurcation subsystem method is shown to provide a much lower order model that can be used to design control that is able to successfully stabilize the full system for a single bifurcation [18] [19]. This effect is not studied in this paper but will be pursued for multiple bifurcation stabilization in the future.

## References


[1] G. Rogers, "Power System Oscillations," Norwell, MA: Kluwer, 1999

[2] S. Chen and O. P. Malik, "$H_\infty$ Optimization-based Power System Stabiliser Design," IEE Proc. Gener., Transmi. Distrib., Vol. 142, No. 2, March, 1995

[3] Q. Zhao and J. Jiang, "Robust SVC Controller Design for Improving Power System Damping," IEEE Transactions on Power System, Vol. 10, No. 4, Nov., 1995

[4] M. Djukanovic, M. Khammash, and V. Vittal, "Application of the Structured Singular Value Theory for Robust Stability and Control Analysis in Multimachine Power System," IEEE Transactions on Power System, Dec., 1997

[5] G. E. Boukarim, S. Wang, J. H. Chow, G. N. Taranto, and N. Martins, "A Comparison of Classical, Robust, and Decentralized Control Design for Multiple Power System Stabilizers," IEEE Transactions on Power Systems, Jan., 2000

[6] M. Klein, L. X. Le, G. J. Rogers, S. Farrokhpay, and N. J. Balu, "$H_\infty$ Damping Controller Design in Large Power Systems," IEEE Transactions on Power Systems, Vol. 10, No. 1, Feb., 1995

[7] X. Yu, M. Khammash, and V. Vittal, "Robust Design of a Damping Controller for Static Var Compensators in Power Systems," IEEE Transactions on Power Systems, Aug., 2001

[8] M. Yue and R. Schlueter, "$\mu$-synthesis Power System Stabilizer Design Using a Bifurcation Subsystem Based Methodology," IEEE Transactions on Power Systems, Vol. 18, No. 4, Nov., 2003

[9] M. Yue and R. Schlueter, "A $\mu$-synthesis Robust SVC Control Design," Proceedings of the IEEE PES Transmission and Distribution Conference, Dallas, Oct., 2003

[10] S. Skogestad and I. Postlethwaite, "Multivariable Feedback Control, Analysis and Design," John Wiley & Sons, 1997

[11] M. Klein, G. J. Rogers, and P. Kundur, "A Fundamental Study of Interarea Oscillations in Power Systems," IEEE Transactions on Power Systems, Vol. 6, No. 3, 1991

[12] M. Yue and R. Schlueter, "Bifurcation Subsystem for Hopf Bifurcation," Proceedins of the North American Power Symposium, Oct., 2001

[13] M. Yue and R. Schlueter, "Bifurcation Subsystem for Saddle-node Bifurcation," Proceedings of the North American Power Symposium, Oct., 2001

[14] M. Yue and R. Schlueter, "Bifurcation Subsystem Method Based Classification for Power System Stability Problems," accepted by Electric Power Components and Systems, to appear

[15] M. Yue and R. Schlueter, "Bifurcation Subsystem Identification," Proceedings of the IEEE PES Summer Meeting, July, 2002

[16] G. E. Boukarim and J. Chow, "Modeling of Nonlinear System Uncertainties using a Linear Fractional Transformation Approach," Proceedings of the American Control Conference, June, 1998

[17] "Mu Analysis and Synthesis Toolbox User's Guide," The Mathworks Inc.

[18] M. Yue, "Bifurcation Subsystem Method and Its Applications in Analysis and Control Design for Power Systems," Ph.D Dissertation, Michigan State University, 2002

[19] M. Yue and R. Schlueter, "A Model and Controller Reduction Method for Robust Control Design," Proceedings of the North American Power Symposium, Oct., 2003