Inter-Area Oscillation Damping with Power System Stabilizers and Synchronized Phasor Measurements

Aaron F. Snyder[£,&], Nouredine Hadjsaïd[£], Didier Georges[#], Lamine Mili[&],
Arun G. Phadke[&], Olivier Faucon[@], Sylvain Vitet[@]

[£]Laboratoire
d'Electrotechnique de
Grenoble
ENSIEG/INPG
Grenoble, France

[#]Laboratoire
d'Automatique de
Grenoble
ENSIEG/INPG
Grenoble, France

[&]The Bradley Department
of Electrical and Computer
Engineering
VPI & SU
Blacksburg, Virginia USA

[@]Electricité de France
Direction des Etudes et
Recherches
Clamart, France

Abstract: Low-frequency oscillations are detrimental to the goals of maximum power transfer and optimal power system security. A contemporary solution to this problem is the addition of power system stabilizers to the automatic voltage regulators on the generators in the power system. The damping provided by this additional stabilizer provides the means to reduce the inhibiting effects of the oscillations. A novel modification of this controller is the inclusion in the feedback loop of information from a remote source. In this manner, the controller acts on the changes from the local source and the remote source. As will be demonstrated, this yields a controller capable of more rapidly diminishing the oscillations in a test power system.

Keywords: Inter-Area Oscillations, Power System Stabilizers, Synchronized Phasor Measurements.

I. INTRODUCTION

Low-frequency oscillations, related to the small-signal stability of a power system, are detrimental to the goals of maximum power transfer and power system security. Automatic voltage regulators (AVRs) help to improve the steady-state stability of power systems, but are not as useful for maintaining stability during transient conditions. The addition of power system stabilizers (PSSs) in the AVR control loop provides the means to damp these oscillations [1,2].

The added AVRs and PSSs are designed to act upon local measurements such as bus voltage, generator shaft speed, or the rotor angle of the associated machine. This type of feedback control is useful for *local* and *control* mode oscillations, but may be unsatisfactory for *inter-area* oscillations.

Synchronized phasor measurements (SPMs) have been proven useful for many control applications in power systems, including state estimation, transient stability, and FACTS device control [3,4]. SPMs provide important information about the power system in real-time, an aspect that traditional measurements lack. This paper addresses the analysis of the inclusion of synchronized measurements into the generator control loop in the form of inputs to a PSS installed in a two-area, four-machine test system. This test system contains a poorly damped inter-area oscillation. The test system was analyzed using conventional small-signal analysis tools through the use of Eurostag [5] and Matlab.

The system was first analyzed to discover the optimal site for the PSS. After this determination, an optimally tuned PSS [6] was inserted. Finally, a remote feedback controller (RFC), that is, a PSS with local *and* remote input signals, was designed using an adapted tuning methodology [7] and placed at the same optimal site to provide a comparison with the typical local feedback PSS.

Section Two discusses the small-signal analysis tools used in this study. Section Three describes the continuation power flow method and its results as applied to the test power system. Section Four presents the design and analysis of the remote feedback controller and Section Five provides a time-domain comparison of the controller structures.

II. SMALL-SIGNAL ANALYSIS

A four-machine test power system (Fig. 1) was used in this study. With a resemblance to the system in [8], this system contains two machines on each side of a transmission network. The two loads on Buses 3 and 13 are modeled as constant impedances. The generators were modeled following the two-axis method from [5,8] and the governor, turbine and constant gain excitation systems were modeled in detail [9].

Once these models were constructed, a non-reduced Jacobian formulation is finalized in order to complete the system representation. The linearized form of the differential equations can then be given in matrix form [10]:

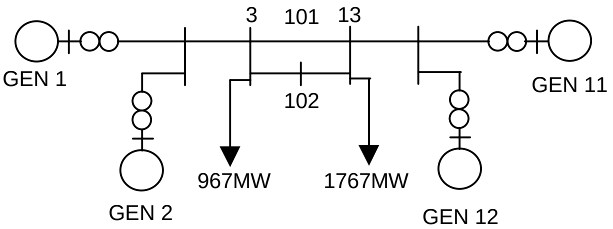

Fig. 1: Test System

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$$\Delta X = M\Delta X + N\Delta Z \qquad (1)$$

$$0 = P\Delta X + Q\Delta Z + B_{NR}\Delta U \qquad (2)$$

$$\Delta Y = C_{NR}\Delta Z \qquad (3)$$

ΔX : state vector

ΔU : input vector

ΔY : output vector

ΔZ : algebraic variable vector

B_{NR} : non-reduced input matrix

C_{NR} : non-reduced output matrix

$\begin{bmatrix} M & N \\ P & Q \end{bmatrix}$: non-reduced Jacobian matrix

Once the algebraic variables have been eliminated, the following state-space representation is obtained:

$$\Delta X = A\Delta X + B\Delta U \qquad (4)$$

$$\Delta Y = C\Delta X + D\Delta U \qquad (5)$$

where A is the state matrix and B, C and D are the input, output and feedforward matrices, respectively.

Following small-signal theory [8], participation factors for machine speed and rotor angle are used in conjunction with the right eigenvectors (mode shape) to identify and classify the oscillatory modes in the test system. Table 1 provides a view of the three most weakly damped modes for the nominal power flow solution of the system (Fig. 1). It can be seen that the third mode is clearly an inter-area mode, with generators 1 and 2 swinging against generators 11 and 12. The system can now be divided into two areas: the sending end machines (1 & 2) and the receiving end machines (11 and 12).

The participation factor magnitudes are now used to classify the optimal site for the PSS and RFC. Table 2 summarizes the magnitudes of the participation factors for the four machines. It can be seen that the composite participation of machine 11 is the greatest, thereby indicating the optimum site for the PSS and RFC. Methods based on the sensitivities of the eigenvalues [11] or those using the inertia of the machines [12] may also be used; however, in this small, symmetrical system with nearly equal machine inertias, these methods do not provide any additional insight into the site selection.

III. CONTINUATION METHOD ANALYSIS

Once the modes of the system have been identified and classified, and the controller sites determined, the power system may be analyzed using the continuation power flow method [13]. This method consists of increasing the power flow in the system until a conjugate pair of eigenvalues transversely crosses the imaginary axis, signifying an angular instability. This is called a Hopf Bifurcation Point [14].

TABLE 1: TEST SYSTEM OSCILLATION PROFILE

Mode	Frequency Hz	Damping Ratio	Mode Shape
-0.5977 ± j 7.0365	1.1199	0.0849	1 vs 2
-0.6060 ± j 7.2470	1.1534	0.0833	11 vs 12
0.0296 ± j 4.1784	0.665	-0.0071	1,2 vs 12,11

TABLE 2: PARTICIPATION FACTOR MAGNITUDES

Generator	ω	θ
1	0.2351	0.3064
2	0.1307	0.1885
12	0.2930	0.2294
11	0.3556	0.2839

3.1 Nominal System (no additional controllers)

With this analysis in mind, several tie-line power flow simulations were performed, with the goal to determine the limit of stability of the system. Fig. 2 shows the trace of the lightly-damped, inter-area mode for power flows of 0, 50, 100, 158MW.

Recalling the eigenvalues of Table 1, the system is clearly unstable at the nominal operating point. However, there are certain operating points (weaker power flows) for which the system remains stable. This is not a surprising result; in fact, automatic voltage regulators are capable of maintaining the stability of the power system for a limited range of operating conditions. However, the oscillatory modes remain very lightly damped and tend to instability after severe events in the power system, such as short circuits.

3.2 Addition of a PSS

For these tests, a PSS (Fig. A.1) was tuned [12] and added to the generator at the previously identified optimal site. The PSS parameters are given in Table A.1. The addition of a PSS resulted in the ability of the system to attain maximum power transfer without instability. The PSS is also robust over both the same range of operating points previously examined and over a wider range of tie-

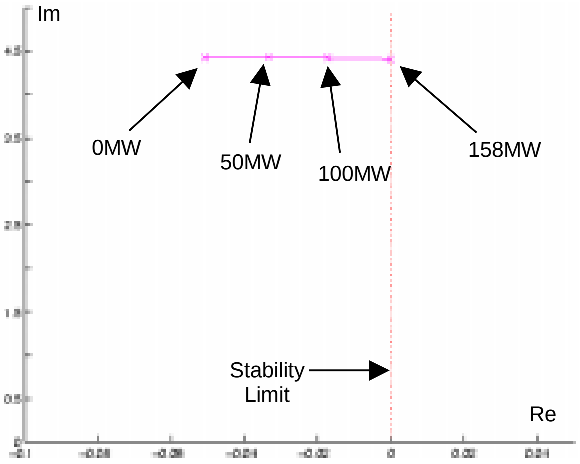

Fig. 2: Eigenvalue Trace for the Nominal System

line power flows. In fact, the Hopf Bifurcation Point conditions could not be met due to the voltage collapse limit.

In order to avoid the voltage collapse limit (loss of a load flow solution due to a singular Jacobian matrix), the impedance of the lines connecting the two halves of the test system was varied between 50 and 150% of the nominal value. However, while the hope of escaping the voltage collapse limit was unrealized under this range of impedance values, this test provided a view of the robustness of the controller for a variety of operating points. A trace of the eigenvalues for both the PSS and no-PSS tests at the nominal impedance is shown in Fig. 3.

IV. REMOTE FEEDBACK CONTROLLER

This section deals with the design and analysis of the remote feedback controller. Several preliminary assumptions were made, including that the input signals would be provided in a synchronized manner in real-time, without delay. This condition is not presumptuous if phasor measurement units [15] are installed at the desired positions in the system and connected with a dedicated communications link [16].

4.1 Controller Design

The Remote Feedback Controller (RFC) is a PSS with local *and* remote input signals. In this study, the accelerating power for machines 11 (the local machine) and 1 (the remote site) was selected as the input signal for the RFC. Machine 1 was selected based on the participation factor magnitude analysis previously discussed in Section Two.

To determine the RFC parameters (Table A.1), a method based on the residues of the critical mode eigenvalue was selected [15]. While originally developed for a two-loop feedback controller, the method is readily adapted to a single-loop RFC.

Quite simply, the amount of phase lead necessary, Φ_{ij}, is determined from the residue, R_{ij}, given by

$$\Phi_{ij} = 180° - \text{ang}(R_{ij}) \qquad (6)$$

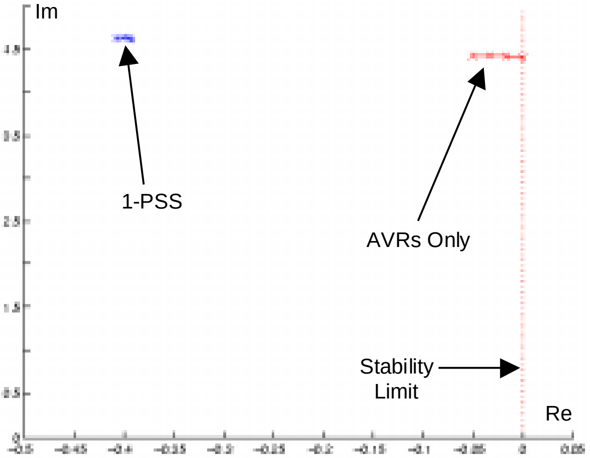

Fig. 3: Eigenvalue Trace for PSS and no-PSS Conditions

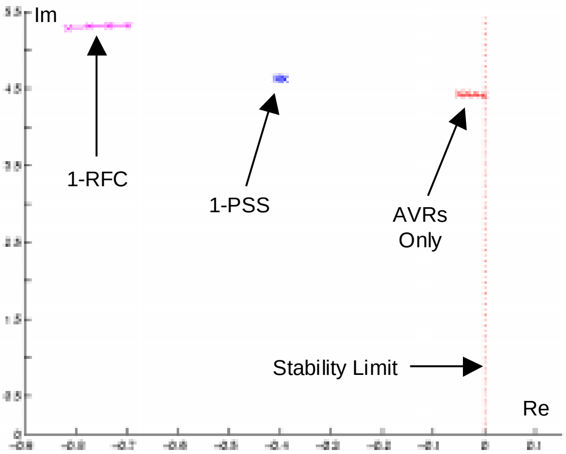

Fig. 4: Composite Eigenvalue Trace

where R_{ij} = Controllability $_{ij}$ * Observability $_{ij}$, j is the generator and i is the oscillatory mode. The controllability of the i-th mode from the j-th machine is given by

$$\text{Controllability}_{ij} = |lev_i B_j| \qquad (7)$$

The observatility of the i-th mode from the j-th machine is given by

$$\text{Observability}_{ij} = |C_j rev_i| \qquad (8)$$

where lev = left eigenvector, rev = right eigenvector and B and C are the system input and output matrices respectively. Once these values are calculated, the algorithm from [15] is applied to determine the necessary parameters, given the inputs and oscillatory mode of interest.

4.2 Controller Analysis

The continuation method was performed for the same variation in line impedance and power flow as for the AVR-only and 1-PSS cases. The RFC was robust over the same range of operating points as the PSS, while assuring the stability of the system. Fig. 4 shows the eigenvalue trace for all three type of controllers. An examination of the damping factors (Fig. 5) for each controller shows that for all tie-line power flows, the non-optimal RFC is able to provide better damping of the inter-area mode compared to

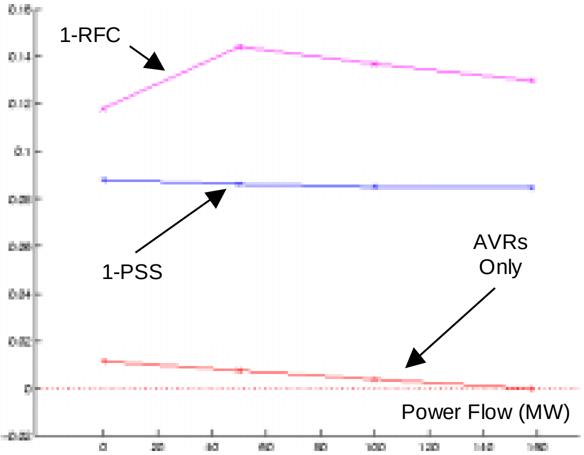

Fig. 5: Damping Factors For all Cases

the optimal PSS. This will be shown through time-domain analysis as well. The weak damping provided by the use of AVRs is also evident.

V. TIME-DOMAIN ANALYSIS

To validate the RFC under normal and extreme operating condition, time-domain simulations using Eurostag were performed. In the first example, a short circuit of 100ms is initiated and cleared on the line 3-102 (recall Fig. 1).

Fig. 6 shows that the system is clearly oscillatory and unstable at the critical power flow (158MW) with only the AVRs installed. Fig. 7 provides a comparison between the 1-PSS and 1-RFC cases. It is evident that there is a damping benefit provided by the RFC.

While it might be contended that the damping is sufficient with a single PSS installed in the system, the use of the RFC provides a benefit in electrical power swing and transfer capabilities. Figure 8 shows the difference in response for the two controllers.

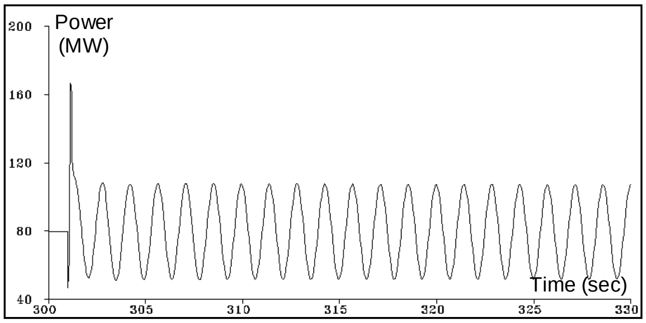

Fig. 6: Short-Circuit, AVR Only Case

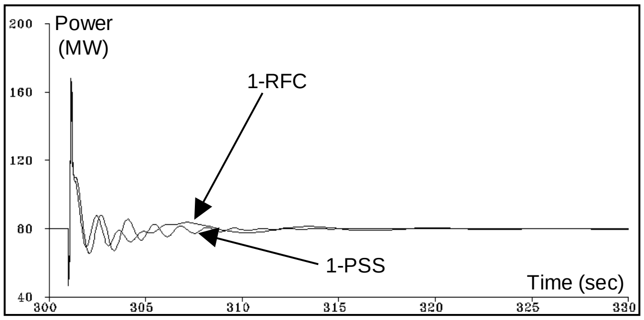

Fig. 7: Short-Circuit, 1-PSS and 1-RFC Cases

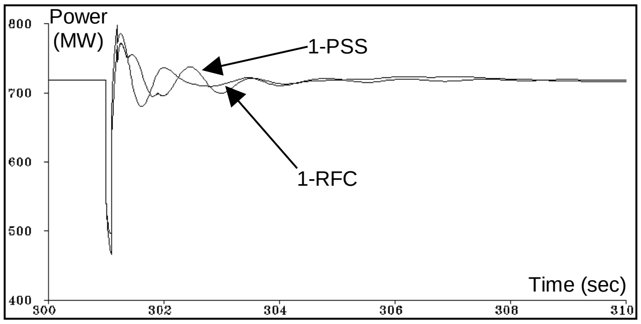

Fig. 8: Machine 11 Electrical Power

VI. CONCLUSIONS

In this paper, a remote feedback controller has been designed and placed in a four-machine test power system. The addition of synchronized measurements from optimally selected sites into the generator control loop has been shown to improve the damping of the low-frequency inter-area oscillation present in the test system. The benefit of this controller was shown through the ability to maintain voltage and electrical power support of the machine versus a single PSS on the same machine. A net increase in the tie-line power transfer in the system without loss of stability was also realized compared with a traditional automatic voltage regulator. Time domain simulations were used to verify the transient stability of the controller following a short-circuit.

Future work will include the placement, design and analysis of a remote feedback controller for a larger test power system, as well as treatment of the delay of the input signals to the controller.

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APPENDIX A

The form of both the PSS and the RFC used in this study are shown in Fig. A.1, with their parameters given in Table A.1. The input signal of the PSS was taken to be the accelerating power (Pa = Pmechanical - Pelectric) of the machine where the controller was installed. For the RFC, the input signal was the difference between the accelerating powers of the two optimally selected machines; i.e., Pa_{local} - Pa_{remote}.

TABLE A.1: PSS TUNING

Parameter	PSS	RFC
K_S	11.3	7.6667
T_1	0.1432	0.2361
T_2	2.1511	0.2426
T_3	10.0	0.2334
T_4	10.0	0.2409
T_W	30.0	10.0
$VPSS_{max}$	0.055	0.055
$VPSS_{min}$	-0.055	-0.055

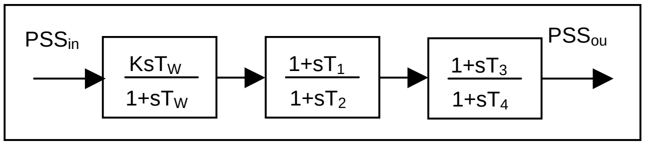

Fig. A.1: PSS and RFC Form

BIOGRAPHIES

Aaron F. Snyder (Stud. ’89) obtained his bachelor (1993) and master’s degrees (1997) in electrical engineering from Virginia Polytechnic Institute and State University, Blacksburg, Virginia. He is currently completing his Ph.D. at the Institut National Polytechnic de Grenoble in Grenoble, France.

Nouredine Hadjsaïd (M) received the “Doctorat de l’INPG” degrees from the Institut National Polytechnique de Grenoble (INPG) in 1992. From 1988 to 1992 he served as a research and teaching assistant at the Ecole National Supérieure d’Ingenieurs Electriciens de Grenoble (ENSIEG) and at the Laboratoire d’Electrotechnique de Grenoble (LEG). He is currently an associate professor at ENSIEG-LEG. His research interests are power system operation and security.

Didier Georges received the Dr. Eng. degree in Applied Mathematics and Automatic Control from the "Ecole des Mines" (Paris, France) in 1987. He also received his "Habilitation à Diriger des Recherches" degree from INPG in 1997. He is currrently an Assistant Professor at ESISAR and the "Laboratoire d'Automatique de Grenoble" (LAG/INPG/CNRS). His main field of interest is optimal and robust control theory with applications to power systems and open-channel hydraulic systems.

Lamine Mili (SM, 1991) received the B.S. degree from the Swiss Federal Institute of Technology, Lausanne, in 1976, the M.S. degree from the University of Tunis in 1983 and the Ph.D. degree from the University of Liege, Belgium, in 1987. He is currently an Assistant Professor of Electrical Engineering at Virginia Tech. His research interests include state estimation, transient stability, voltage collapse and power system control.

Arun G. Phadke (F, 1980) is the American Electric Power Professor of Electrical Engineering at Virginia Tech, Blacksburg, Virginia. Before joining Virginia Tech, Professor Phadke worked with the Allis-Chalmers Company, the University of Wisconsin and the AEP Service Corporation in NY. Professor Phadke has been a member and Chairman of several working groups of the Power System Relaying Committee and the SC 34 of CIGRE. He is currently a member of the National Academy of Engineers.

Olivier Faucon earned his Engineering degree in 1991 from the Ecole Supérieure d’Electricité in Paris, France. He joined the Electricité de France (EdF) Research Center in 1992. He is presently a member of the EdF Project Team in charge of the realization of the Future Defense Plan.

Sylvain Vitet (M) received his enginering degree in 1985 from the Ecole Nationale Supérieure des Mines de Saint-Etienne, France, and a degree in management from the Institut d'Administration des Enterprises in Paris, France, in 1989. Since 1986, he has been working at Electricité de France on a variety of projects, including pollution phenomena in power systems and serving as the manager on a 400kV alternative solution project. From 1996, he as been the Head of the Power System Dynamics, Protection and Control research group at the Electricité de France-Clamart research center. He is a member of the Society of Electrical and Electronics Engineering in France, IEEE and CIGRE.