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Stabilizing a Multimachine Power System via Decentralized Feedback Linearizing Excitation Control

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Abstract

A new controller for the generator excitation system is described that uses a combination of feedback linearization and the observation decoupled state space. This creates a controller that can be realistically implemented using only local measurements, and whose performance is consistent with respect to changes in network configuration, loading and power transfer conditions. The control differs in this respect from linear constant-gain controllers such as power system stabilisers, whose characteristics can vary significantly with changes in operating conditions. The design is well-suited to a multimachine setting, in that it is not based on an infinite-bus approximation. Simulations are performed on a 38-bus reduced model of the Northeast Power Coordinating Council system and benchmarked against simulations in which automatic voltage regulators with power system stabilizers are substituted in place of the nonlinear controls.

1 Introduction

Power Systems are increasingly called upon to operate transmission lines at high transmission levels due to economic or environmental constraints. In the Northeast Power Coordinating Council (NPCC) system, economic operation often requires heavy power transfers from the northern and western regions of the state to the metropolitan New York City area in the south. The ability to transfer power in this fashion is restricted by voltage stability limitations which occur as the bulk power circuits in the central region are loaded above the surge impedance. In this configuration, several modes of interarea oscillation have been identified that are of concern to system planners, in that they are poorly-damped, and show the potential for becoming unstable as future loads increase.

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Several potential approaches exist in dealing with this problem, representing roughly two categories. The first involves the addition of new equipment such as HVDC tie lines and static VAR compensators [1, 2], while the second category involves enhancing the performance of existing equipment, in particular the excitation system of generators [3, 4, 5, 6]. It has been recognized in the literature that the use of rotor acceleration information in control design could improve the transfer capability of the interconnected system [7, 8, 9], and theoretical developments on feedback linearizing control (FBLC) of generator excitation have given added importance to this concept [10, 11, 12, 13, 14, 15]. The FBLC design relies upon a state transformation whereby a nonlinear feedback law can be defined, in conjunction with state feedback, to arrive at a system whose closed-loop dynamics are linear [13]. One obstacle to the successful implementation of the FBLC design is the difficulty of measuring the rotor acceleration, which is one of the state variables in the transformed space [10]–[15]. Currently, the most promising technique for generating rotor acceleration information is through the use of a digital state observer, as developed in [16, 17, 18].

In this paper, we extend the work reported in [10]–[15], [19], adding two new contributions. First, we propose the combination of FBLC design with the observation decoupled state space (ODSS), originally introduced in [20, 21], as a means of moving toward a truly decentralized FBLC design, without resorting to assumptions that may not be satisfied under faulted or unusual conditions. Second, we have simulated the new control on a system of significant complexity, which preserves the most critical of the interarea oscillation modes experienced on the NPCC system. This is a thirty-eight bus equivalent model, including fourteen fully-modeled generators and fifteen simplified machines represented by swing models. The use of the observation decoupled state space (ODSS) with feedback linearization allows the use of the machine rotor angle as a viable controlled variable in a decentralized setting, enhancing the ability of the system to damp slow oscillations and prevent the slow separation of groups of generators that leads to "islanding" of the power system following a severe transient, such as the loss of a transmission line. In the fault simulations, with the FBLC/ODSS combination implemented on two key equivalent machines, the critical oscillation is effectively damped and system breakup is prevented, whereas the use of linear power system stabilisers (PSS) in place of the FBLC controllers results in loss of synchronism and islanding.

2 Feedback Linearization

The transformation used for feedback linearisation was developed in [10, 15, 22], and the details of the derivation will not be repeated here. The model used in the transformation is the third-order single-axis model, with the E_d' dynamics reduced to an algebraic constraint, *viz.*:

$$\dot{E}_q' = \frac{1}{T_{do}'}\left[-E_q' - (x_d - x_d')i_d + E_{fd}\right] \quad (1)$$

$$\dot{\delta} = \omega - \omega_o \quad (2)$$

$$\dot{\omega} = -\frac{\omega_o}{2H}\left[P_m - P_e - \frac{D}{\omega_o}(\omega - \omega_o)\right] \quad (3)$$

$$= -\frac{\omega_o}{2H}\left[T_m - E_q' i_q - E_d' i_d - \frac{D}{\omega_o}(\omega - \omega_o)\right] \quad (4)$$

$$E_d' = (x_q - x_q')i_q \quad (5)$$

A new state space is then defined as

$$s = T(x) \quad (6)$$

where, for a system with N generators,

$$\mathbf{x} = [E_{q_1}' \quad \delta_1 \quad \omega_1 \quad \dots \quad E_{q_N}' \quad \delta_N \quad \omega_N]^T \quad (7)$$

$$\mathbf{s} = [\delta_1 \quad \omega_1 \quad \dot{\omega}_1 \quad \dots \quad \delta_N \quad \omega_N \quad \dot{\omega}_N]^T \quad (8)$$

After some manipulation, the state equations can be written in affine form:

$$\dot{\delta}_i = \omega_i \quad (9)$$

$$\dot{\omega}_i = \dot{\omega}_i \quad (10)$$

$$\ddot{\omega}_i = f_i(\mathbf{x}) + b_i(\mathbf{x})E_{fd_i} \quad (11)$$

where $f_i(x)$ and $b_i(x)$ are defined as follows:

$$f(\mathbf{x}) = -\frac{\omega_o}{2H}\left\{[(x_q - x_q')i_d + E_q']\dot{i}_q + E_d'\dot{i}_d + \frac{D}{\omega_o}\dot{\omega}\right.$$
$$\left. -[(x_q - x_q')i_d + E_q']\frac{\partial i_q}{\partial E_q'}\dot{E}_q' - E_d'\frac{\partial i_d}{\partial E_q'}\dot{E}_q'\right\} \quad (12)$$
$$+\frac{\omega_o}{2HT_{do}'}\left\{[(x_q - x_q')i_d + E_q']\frac{\partial i_q}{\partial E_q'}\right.$$
$$\left. +E_d'\frac{\partial i_d}{\partial E_q'} + i_q\right\}[E_q' + (x_d - x_d')i_d]$$

and

$$b(\mathbf{x}) = -\frac{\omega_o}{2HT_{do}'}\left\{[(x_q - x_q')i_d + E_q']\frac{\partial i_q}{\partial E_q'}\right.$$
$$\left. +E_d'\frac{\partial i_d}{\partial E_q'} + i_q\right\}[E_q' + (x_d - x_d')i_d] \quad (13)$$

We now define:

$$E_{fd_i} = 1/b(\mathbf{x})(v(\mathbf{s}) - f(\mathbf{x})) \quad (14)$$

$$v(\mathbf{s}) = a_o(\delta - \delta_o) + a_1(\omega - \omega_o) + a_2\dot{\omega} \quad (15)$$

resulting in a linear system with a block-diagonal form:

$$\dot{\mathbf{x}} = diag(A_1 \dots A_n)\mathbf{x} \quad (16)$$

$$A_i = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ a_{0_i} & a_{1_i} & a_{2_i} \end{bmatrix} \quad (17)$$

Of course, if all generators are not feedback linearised, the overall system will not have the block-diagonal form, but since the FBLC effectively decouples the machine dynamics from the dynamics of the system as a whole, the benefits of the nonlinear control can be realised by any subsystem without requiring that every generator be converted, and indeed, as the simulations show, the conversion of one machine can result in greatly improved behavior in machines coupled to it by the network.

From (15) it can be seen that the equilibrium point is well-defined for ω and $\dot{\omega}$ (respectively, 120π and 0), but the reference angle δ_o can be determined only by a full-scale load flow. This problem would normally place severe limits on the operation of the FBLC, since any change in the system (e.g. line outage) demands that the steady-state rotor angle change in order for the machine to reach an equilibrium that satisfies other system constraints, such as terminal voltage setpoints. Because E_{fd} is used as the feedback linearising input, the apparent decoupling of each machine subsystem is achieved at the expense of a sensitivity in E_{fd} to system changes, and it can be seen that no reference is provided to the controller for the terminal voltage. The effect of this is twofold: First, the control action initiates small voltage swings during transient behavior. This is not a major concern, provided that voltage deviations do not become too large, and can certainly be expected of PSS-equipped machines as well. The second effect is that the voltage at equilibrium is a by-product of the particular equilibrium point that is specified, *i.e.* it is determined by the value of δ_o that is supplied to the controller. Assuming for the moment that the proper angle reference can be found, the FBLC allows for arbitrary pole placement via the choice of the 'a' coefficients in (15), and the resulting subsystem is decoupled and insensitive to disturbances. It can be expected to operate predictably over a wide range of operating conditions, provided that an equilibrium exists within the operating constraints of the machine and the excitation system.

The problem of finding the "correct" value of δ_o could be solved, provided that enough information were available, by supplying the desired P_i and V_i for the generator to a load flow program, which would require up-to-the second information on configuration, loading and voltage for the entire system. If, on the other hand, the FBLC were supplied with some constant δ_e based on projected loads, it would operate at a constant rotor angle (within the capability of the machine), while the terminal voltage (and reactive power output) would become a function of the system operating conditions. This problem is addressed in Section 3.

3 The Observation Decoupled State Space

The ODSS concept was first developed in [21] in the context of a Lyapunov-based control scheme that relied on fast real-power modulation. For the purposes of implementing FBLC, the main interest in the ODSS is in its ability to provide a dynamic rotor angle reference that converges to a desired post-transient value, allowing the FBLC to achieve an acceptable equilibrium without requiring a load flow calculation. The version of the ODSS used here is called Space #2 in [21]. In the present context, the transform must be modified somewhat to allow for the interaction between the FBLC action and the ODSS calculation. Proof of the validity of the ODSS transform (smoothness and invertibility) can be found in [21], and the extension of the proof to the modified transform used with the FBLC is straightforward and will not be presented here. In order to define the ODSS transform clearly and with a minimum of clutter, consider a system in which we take the machine transient voltage E'_q to be directly connected to a transmission network. If transient saliency is neglected, this is the mathematical equivalent of including the transient impedance x'_d in the network admittance matrix and then eliminating the generator terminal busses by network reduction, while preserving load busses. This allows E'_q and the rotor angle δ to appear directly in the following definitions. We allow $V_i\angle\delta_i$ to represent the complex voltage at the i^{th} bus, and note that for the machine busses, V and θ coincide with E'_q and δ, respectively.

The unmodified transform will be presented first, followed by the modified form. First, for a network of K busses, define

$$G_i(V_1,\ldots,V_K,\theta_1,\ldots,\theta_K) = P_{m_i} - P_{e_i} \qquad (18)$$

This is simply the difference between the input power and the output power, where the power output is defined by the load flow equation:

$$P_{e_i} = V_i \sum_{j=1}^{K} C_{ij} V_j \left[G_{ij}\cos(\theta_i-\theta_j) - B_{ij}\sin(\theta_i-\theta_j)\right] \qquad (19)$$

where $C_{ij} = 1$ if busses i,j are connected directly, 0 otherwise. δ_{ri} is then defined implicitly by the relationship

$$G_i(V_1,\ldots,V_K,\theta_1,\ldots,\delta_{ri},\ldots,\theta_K) = 0 \qquad (20)$$

The solution for this case is extremely simple. For the i^{th} generator,

$$\delta_r = \cos^{-1}\left(\frac{G_{ii}V_i^2 - P_m}{[\alpha^2+\beta^2]^{1/2}}\right) + \arg(\alpha + j\beta) \qquad (21)$$

where, allowing G_{Li} to represent the local load impedance (local constant power loads may be simply subtracted from the mechanical power term P_m) and representing line admittance as $Y_{ij} = G_{ij} + jB_{ij}$,

$$\alpha = V_i \sum_{j=1}^{k} C_{ij}V_j[G_{ij}\cos(\theta_j) + B_{jk}\sin(\theta_j)] \qquad (22)$$

$$\beta = V_i \sum_{j=1}^{k} C_{ij}V_j[G_{ij}\sin(\theta_j) - B_{jk}\cos(\theta_j)] \qquad (23)$$

$$G_{ii} = \sum_{j=1}^{k} G_{ij} + G_{Li} \qquad (24)$$

Finally, the new state-space for the N-machine system is defined as:

$$\bar{\delta}_i = \delta_i - \delta_{ri} \qquad (25)$$

$$\bar{x} = [\bar{\delta}_1 \;\; \omega_1 \;\; \dot{\omega}_1 \;\; \ldots \;\; \bar{\delta}_1 \;\; \omega_N \;\; \dot{\omega}_N]^T \qquad (26)$$

From (20), (18) and (3) it can be seen that δ_{ri} represents a sort of instantaneous equilibrium for the i^{th} machine, *i.e.* a point at which $\dot{\omega} = 0$ if all other values remain constant. Further, it may be seen that the vector 0 represents a systemwide equilibrium. The calculation can be repeated continuously, or triggered by the violation of a maximum or minimum allowable voltage on an FBLC-equipped generator. If repeated continuously, the iteration will converge to a true equilibrium, however the domain over which convergence will occur in this application is a question that has not yet been resolved. No problems in convergence have been observed in simulation, as long as the transient is not so severe that (20) has no solution. In this case the viability of the system is questionable under any circumstances.

Inspection of (19) reveals that δ_{ri} may be calculated using *only local information*, since only the voltages and angles of busses directly connected to the local bus affect the calculation ($C_{ij} = 0$ otherwise). These may either be measured or calculated from measurements of tie line real and reactive power flows, local bus voltage and prior knowledge of the locally connected transmission line impedances. Further, angles may be calculated with respect to *any convenient reference*. The reference need not be the same from one machine to the next, since only the angle differences from the rotor of the local machine to the directly connected busses are relevant to the local state variables, hence the name observation decoupled state space; In the ODSS, all the relevant state variables of a local subsystem are accessible based only on local information.

Unfortunately, the equilibrium defined above is unique only if the terminal voltages are separately controlled. It can be seen that there will be a continuous range of solutions (barring singularity points) to (20) if the value of the local voltage V_i is allowed to vary, and that for the ODSS as defined above, the point $\bar{x} = 0$ is uniquely determined (given some assumptions about the operating point [21]) only if constrained by the voltage setpoints of the generator AVR systems. Because the voltage of an FBLC generator is not regulated in the conventional sense, the simple substitution of $\bar{\delta}$ for $(\delta - \delta_o)$ in (15) results in a system that does not have a unique equilibrium. However, if the relationship (20) is redefined as:

$$G_i(V_1, \ldots, V_{ref_i}, \ldots, V_K, \theta_1, \ldots, \delta_{ri}, \ldots, \theta_K) = 0 \quad (27)$$

that is, if the *desired* terminal voltage of the local machine is substituted into the δ_r calculation in place of the actual value, then the zero equilibrium is unique within the assumptions referenced earlier, and it is the same as would be achieved using linear AVR's whose setpoints coincided with the assumed V_{ref} values.

In this case, because the terminal voltage is assumed constant, the terminal bus must be preserved in the admittance matrix. The calculation must therefore be separated into two very similar parts, the first of which determines an angle θ_r for the terminal voltage and a second calculation that determines an offset angle to be added to θ_r to arrive at δ_r. The second operation is identical to the first, except that it uses only V_{ref}, E' and the machine impedance as a single "line". If saliency is considered, the second part of the calculation cannot be solved using (21), but is easily solved by Taylor approximation or by iteration. With the calculation performed in this manner, we can then redefine (15) as

$$v_i(\bar{x}) = a_o(\bar{\delta}_i) + a_1(\omega_i - \omega_o) + a_2\dot{\omega}_i \quad (28)$$

to arrive at the FBLC/ODSS combination. It must be noted that $\bar{\delta}$ is a nonlinear function of the full state, and therefore its use in (28) re-introduces nonlinearity into the system, however the performance of the system is not severely degraded. In addition, the original proof of stability for the real power modulation scheme is not applicable to the present case, and this is a point of research, but the system has shown no stability problems in simulations done to date.

4 Simulations

Simulations were performed on the 38-bus reduced-order model of the NPCC system, which includes equivalent machines in New York, New England and Ontario. The names used to describe the machines in the simulation are used for convenience to describe major facilities within each equivalenced group. The model used was a sixth-order generator model, coupled to exciter models of varying complexity, depending upon the machine being simulated. The sixth-order model was preserved for the subsystems fitted with FBLC/ODSS, in spite of the fact that the FBLC transform was derived only for third-order dynamics. This gives some indication of the behavior of the control in the presence of unmodeled dynamics. The fault scenario selected for simulation was a five-cycle three-phase fault at the Selkirk bus, followed by the tripping of an equivalent line carrying 1083 MW from Oswego to Selkirk. In the base case, this results in a poorly-damped oscillation at approximately 0.8 Hz involving several machines, with loss of synchronism of the Chateauguay generator in 3.5 seconds, followed by the loss of the Oswego equivalent machine. (see figure 1). A major interest in this project was to determine the extent to which the system behavior could be influenced by modification done to New York Power Pool machines. Accordingly, three equivalent plants were selected that represent NYPP machines that participate in the 0.8 Hz. oscillation, specifically, the Oswego equivalent, at approximately 2900 MW output, Sprainbrook at 7500 MW and Millstone at 3600 MW. For these simulations, the generators were configured with all poles at -5, a rather mild configuration that was selected to keep the system poles more than a decade slower than the dynamics associated with shaft torsion. The same fault was repeated in simulations with one, two and three of the selected plants fitted with FBLC/ODSS control. In order to compare results obtained with the nonlinear control to the results that might be obtained by the use of a PSS, simulations were also performed with PSS/static exciter combinations fitted to the same machines.

It must be recognized that the task of preparing an exhaustive comparison of different control configurations and tuning methods is daunting if not impossible. The comparison with the PSS-equipped machines is not intended to be taken as conclusive, but only to illustrate that the excellent damping exhibited by the PSS-equipped units is not sufficient in this case to maintain the integrity of the system, and to indicate the value of a systemwide approach to the evaluation of control methods.

We chose to use a PSS model consisting of two lead-type blocks followed by a washout block and a limiter, acting upon the frequency error signal. No effort was made to optimise the tuning of the PSS units for the particular case considered. Rather, they were tuned and tested to present roughly equivalent behavior to FBLC in infinite-bus simulations that duplicated the loading and effective line impedance of the larger model. Their performance was very close to the performance of the FBLC units in these tests. Space considerations preclude the presentation of these simulations, but we note that the performance of the PSS-equipped machines is such that demonstrating a clear advantage in FBLC without assigning unrealistic system poles is a delicate task in the infinite-bus models. Finally, we emphasize that the issue of an "optimal" pole placement for the FBLC has not been pursued in depth. The focus in this investigation has thus far been to resolve the difficulties presented by the decentralization constraint, to demonstrate the potential of FBLC, and to set the stage for further work in the areas of robustness and practicality of the design.

4.1 Simulations with FBLC's

4.1.1 Simulations With One FBLC Unit

In the first configuration, the FBLC on the Oswego unit decouples its rotor from the 0.8 Hz oscillation completely, and additionally, shifts the frequency of oscillation of Chateauguay from $\approx$ 0.8 Hz to $\approx$ 1.2 Hz, perhaps due to the loss of the oscillating mass of Oswego. The oscillation also becomes reasonably well-damped, but nonetheless, the average rotor angle of the Chateauguay unit increases slowly until finally it loses synchronism (See figure 2).

The terminal voltages are quite well-behaved in this scenario, which may indicate the possibility for improvement by increasing the interval between calculations of the reference angle and/or by changing the location of the system poles. In other words, more control action could be tolerated without violating voltage constraints. Figures 3, 4 and 5 illustrate the generator voltages, the field excitation of the modified machine, and the bus voltage of the critical load busses, respectively. In all cases, the spikes on the field voltage plots are caused by the fact that the angle recalculation was not done continuously in these simulations, and consequently each step in the evolution of the reference angle causes a small spike in the field voltage.

4.1.2 Simulations With Two FBLC Units

In the second configuration (see figures 6–9), FBLC was implemented on both Oswego and Sprainbrook. For the period of the simulation, the system remains viable, with no loss of synchronism. Furthermore, the machine terminal voltages remain at acceptable levels. The voltage plot of the Sprainbrook unit is somewhat misleading since it is measured on the line side of a step-up transformer. The load-side voltage is somewhat lower (in pu) because of the transformer impedance. The voltages at the Selkirk, Leeds and Fraser buses are greatly improved, experiencing only a slow decline of somewhat less than 0.1 pu from prefault values. The field voltages are also plotted for the two FBLC-equipped units (figure 8), showing that damping is achieved without excessive field voltages. The original field voltage limits (that is, the excitation limits from existing exciters that were replaced in simulations) were preserved in the FBLC exciters, with the exception that zero was always taken as the (more restrictive) lower limit in this and subsequent simulations. From figure 6, once the immediate transient response is stabilized, a second oscillatory mode becomes evident at $\approx$ 0.4 Hz. This oscillation was stabilized by the addition of a third FBLC unit on the Millstone unit.

4.1.3 Simulations With Three FBLC Units

For the simulation with three modified machines, the period of the simulation was extended to fifteen seconds, and the scale of the plots was enlarged somewhat. The addition of the third FBLC generator successfully damps the 0.4 Hz oscillation that is apparent in the two-machine case, and effectively stabilizes the system. The 0.4 Hz oscillation is not immediately apparent in the earlier simulations because the rapid disintegration of the system masks the effect. The terminal voltages remain within acceptable limits, and for the most part, they stabilize quickly. The voltages at Selkirk, Fraser and Leeds also show a slight improvement over the two-machine case, however, although the value is somewhat

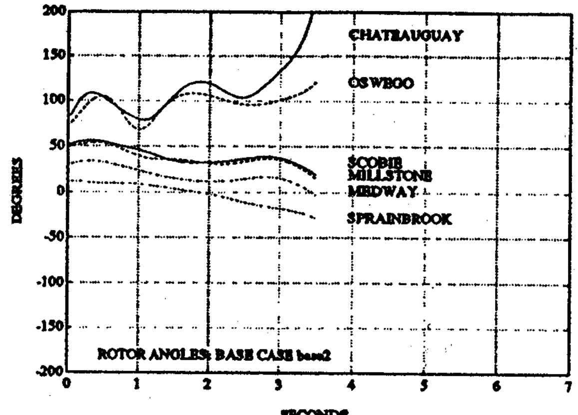

Figure 1: Unmodified System

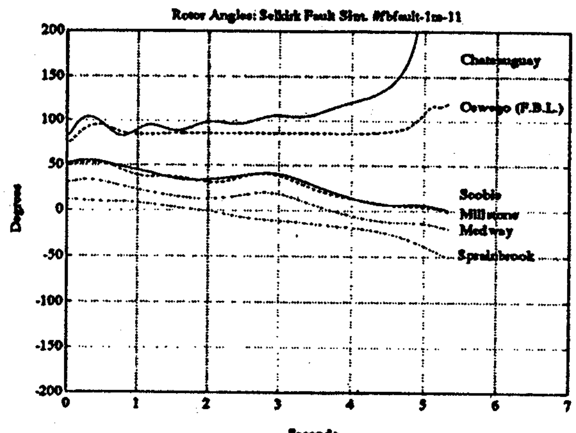

Figure 2: FBLC on Oswego Unit

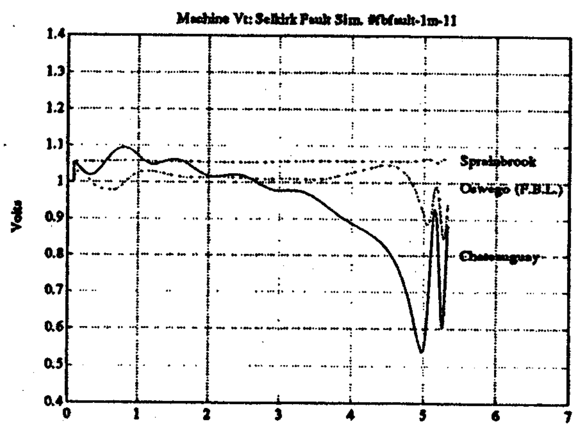

Figure 3: FBLC on Oswego Unit

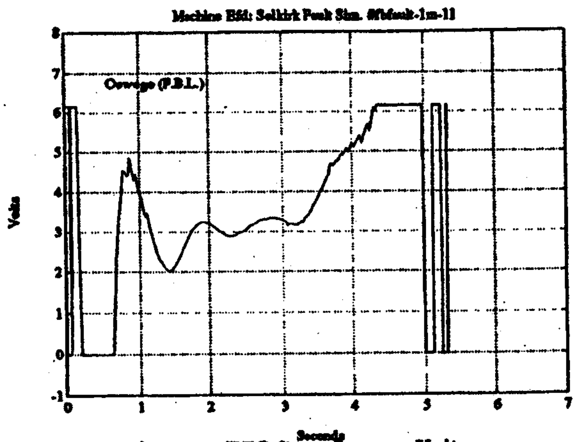

Figure 4: FBLC on Oswego Unit

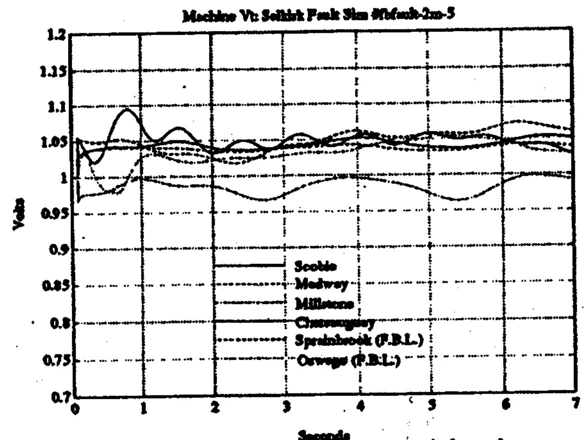

Figure 7: FBLC on Oswego, Sprainbrook

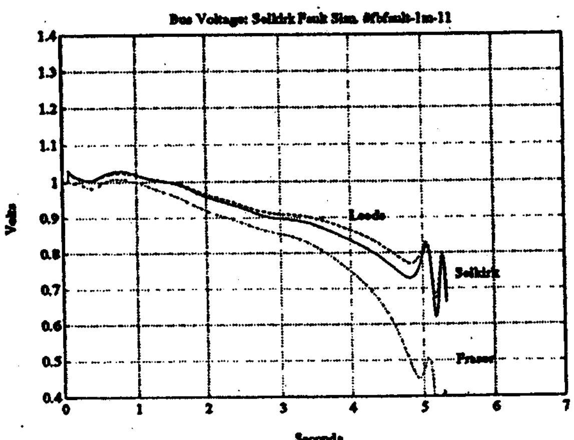

Figure 5: FBLC on Oswego Unit

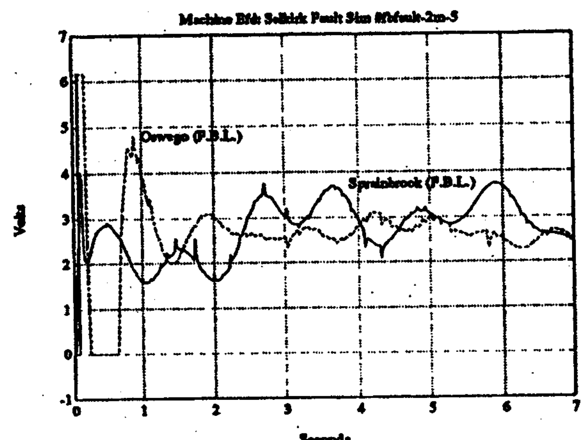

Figure 8: FBLC on Oswego, Sprainbrook

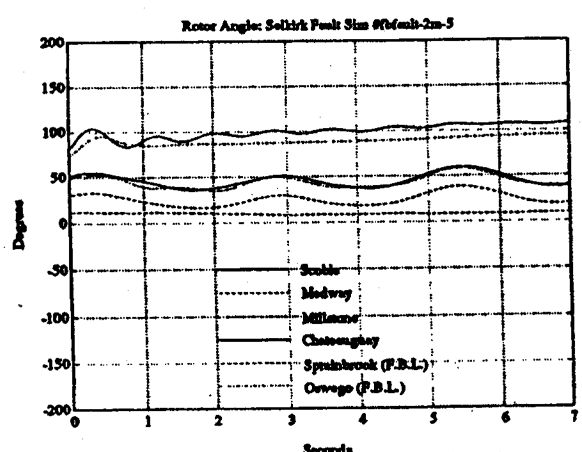

Figure 6: FBLC on Oswego, Sprainbrook

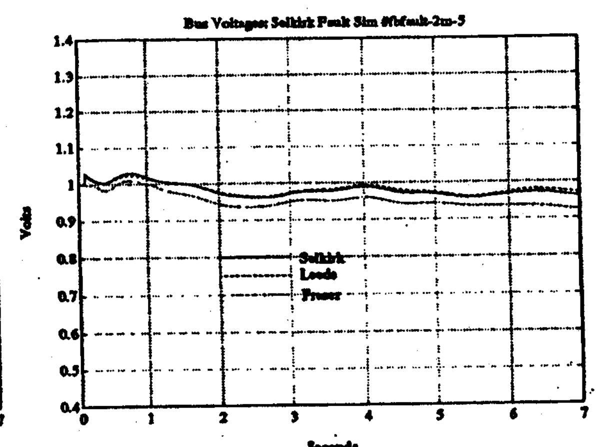

Figure 9: FBLC on Oswego, Sprainbrook

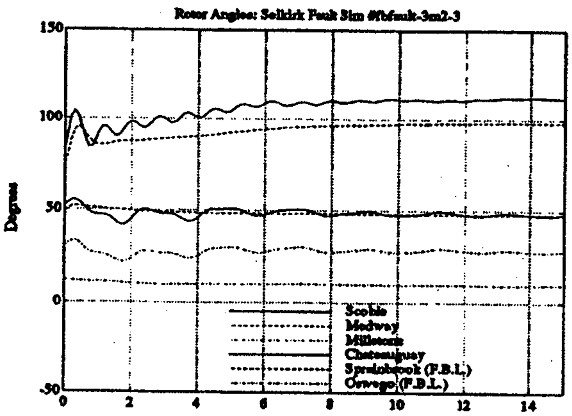

Figure 10: FBLC on Oswego, Sprainbrook, Millstone

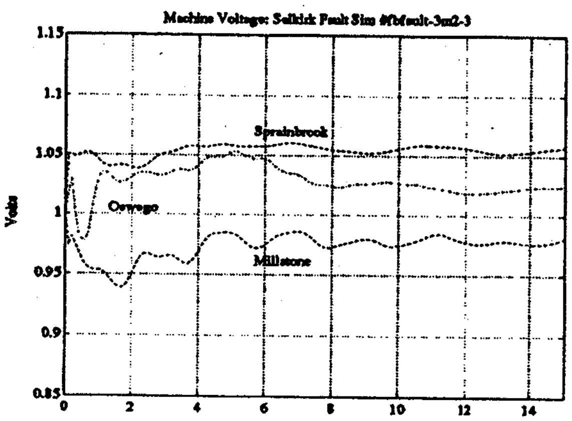

Figure 11: FBLC on Oswego, Sprainbrook, Millstone

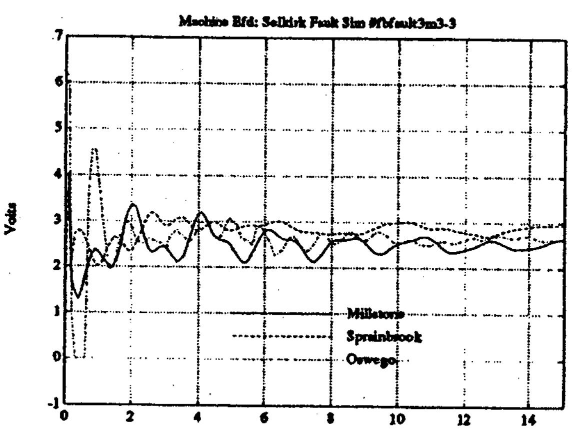

Figure 12: FBLC on Oswego, Sprainbrook, Millstone

higher at 7 seconds, the voltages continue to decline slowly (figures 10–13). This simulation was continued for fifteen seconds in order to allow a clear equilibrium to be reached for the rotor angles, however a longer simulation will be required to assess the long-term behavior of the voltages at the critical load busses.

4.2 Simulation with Power System Stabilizers

For this work, the PSS/exciter combination, consisting of the IEEE standard PSS model coupled to an IEEE type ST1 static exciter, [3] was substituted in place of the exciters on the same units that had been modified previously. The fault scenario was identical.

The simulations with PSS-equipped machines were identical to the FBLC simulation with the exception that the modified units were equipped with power system stabilizers instead of FBLC's.

In the one-machine case (figure 14), the results of the two simulations are quite similar. The damping of Oswego is good, with only the settling time only slightly longer than for the FBLC. Synchronism is still lost at Chateauguay at about 4.5 seconds.

In the two-machine case (figure 15), the advantage of the FBLC's becomes clear. While the two-machine FBLC configuration successfully prevented the loss of Chateauguay, the two-machine PSS case is not significantly better than the one-machine case. In the three-machine simulation (figure 16), the 0.4 Hz oscillation of the Scobie/Millstone/Medway group is attenuated somewhat, but again, only slight improvement is realized over the previous case in the time before the loss of Chateauguay.

5 Controller Impact on Generator Reactive Power Output

In all simulations performed to date on both the NPCC equivalent and other systems, the reactive power output during transient stabilization of the FBLC-equipped machines is consistently lower than conventionally controlled generators. As noted earlier, heavy power transfers often result in depressed system voltages and susceptibility to voltage instability. In addition, instances of voltage instability are often reported to be initiated or exacerbated when generators reach their reactive power output limit. Examination of the voltages at the central New York busses (figure 5) leads to the conjecture that low voltage at those points may contribute to the poor damping of the interarea oscillations. The fact that the FBLC-equipped machines support the voltage at these busses while operating at a lower power factor during the transient interval suggests that, in situations where voltage stability is a concern, the FBLC generators are capable of enhancing voltage stability while also reducing the likelihood of violating reactive power limits.

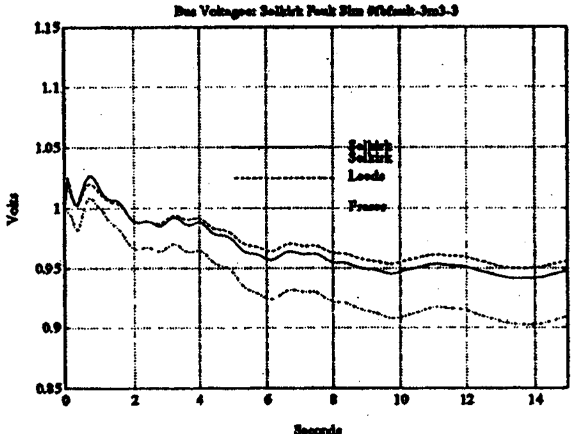

Figure 13: FBLC on Oswego, Sprainbrook, Millstone

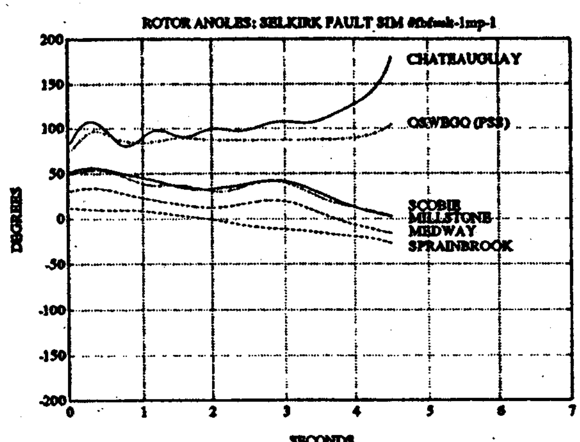

Figure 14: PSS on Oswego

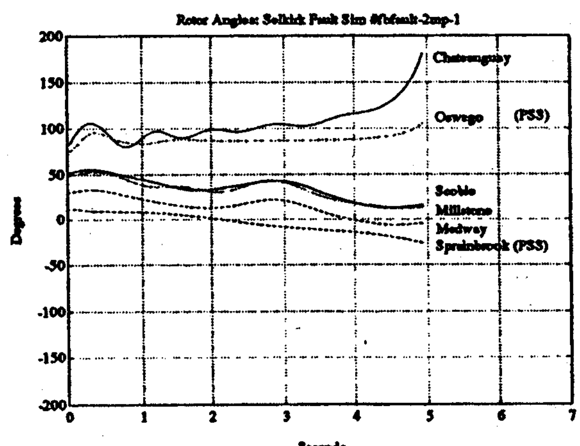

Figure 15: PSS on Oswego, Sprainbrook

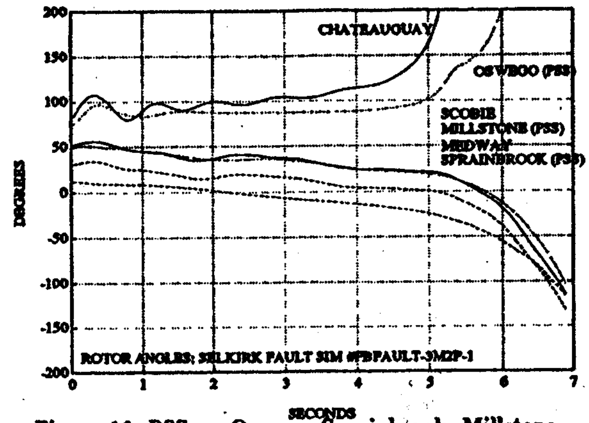

Figure 16: PSS on Oswego, Sprainbrook, Millstone

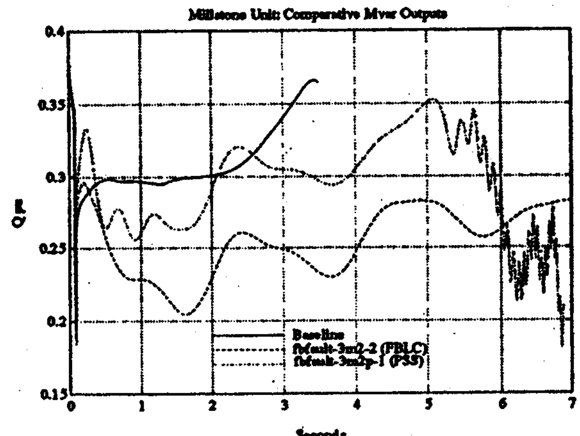

Figure 17: Generator Q Comparison

6 Conclusions

The FBLC/ODSS combination has been shown to perform well in simulations demonstrating a multimachine oscillation of concern to NPCC planners. It has been shown that at least in this particular case, the improvement in damping at a given machine, due to the installation of a PSS, is not sufficient to prevent the breakdown of the system. The FBLC controller has also been found to operate at a lower reactive power output during system transients.

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Discussion

G.J. Rogers and P. Kundur (Ontario Hydro): This paper presents an interesting new technique in power system excitation control. The idea of using nonlinear feedback to cancel the inherrent system non-linearities has the potential to enhance the range of control available from the excitation system.

It has long been realized that control through the excitation systems of generators is one of the most cost-effective ways in which to stabilize power systems. In Ontario Hydro, we have actively used exciter controls, such as power system stabilizers and our Transient System Excitation Control (TSEC)[A], to stabilize local and interarea oscillations, and area mode transient stability respectively. The non-linear TSEC works effectively, but requires exhaustive simulation to arrive at the control parameters. It seems that the control technique proposed may be able to combine the action of both power system stabilizers and TSEC, and allow a comparitively straightforward technique to be used for control parameter determination.

Of course, there are a number of difficulties to be overcome before the technique is ready to be evaluated on the system rather than on a simplified system model.

The loss of voltage control will be significant in practice. Generators which are capable of significant control of oscillations are likely to also contribute significantly to voltage support. But, surely the control could be modified so that it augments a conventional AVR rather than replacing it totally. We agree with the authors that with any stabilizing control which works through an exciter one must expect changes in the system voltage; indeed the mechanism of stabilization is through changes in the system loads caused changing voltage. In a practical system, the excitation limits will not always be sufficient to keep the generator voltage within safe limits. In our implementation of TSEC we had to design a fast acting terminal voltage limiter to ensure that the control did not force the generator voltage beyond the safe limit.

The system used by the authors, although based on a reduced model of the Northeastern interconnected system, may show their controls to be more effective than they would be in practice. Each of the system's generators is a large equivalent and the provision of a linearizing controller on any one has perhaps more effect than placing a similar control at each generator which has been aggregated into the equivalent. It would be particullarly interesting to study the effect of the control when placed on selected single generators.

The authors' choice of the final linear plant transfer function is very arbitary. As they say, more work has to be done in this area. Have they investigated the effect of faster linearized system response? Are there constraints, on the speed of response, imposed by practical excitation considerations? We assume that in a practical application the controlled generator response would be determined using small signal, linearized models of the other dynamic devices on the system.

Reference

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J.W. CHAPMAN, M.D ILIC, ET AL. The authors would like to thank the discussers for their comments.

The issue of voltage control is a trade-off between tight control of voltage and good control of other system dynamics. In the system described here, the ODSS does control the generator voltage over a time scale that is sufficiently long with respect to the rotor angle dynamics that it does not seriously degrade the function of the nonlinear control. The object of the ODSS is to allow a return to the voltage set point without impairing the short-term stability of the system. It is not unreasonable to suppose that an adequate voltage control could be achieved by adding a voltage feedback loop to the nonlinear control, and this was suggested and simulated in [22], but it is hoped that the ODSS will provide a more effective and flexible means of achieving the same end.

Of course the simulations on the thirty-eight bus system cannot duplicate the dynamics of the entire NPCC system, and our efforts have lately been directed toward simulating the new control on a much larger ($\approx$ 8000 bus) model. The use of the nonlinear control in groups of machines that participate in the inter-area oscillations is being investigated, again with respect to maximizing the control effectiveness while minimizing the number of machines to be modified.

We believe that the limiting factor in the assignment of the poles on the linearized generators will be unmodeled dynamics and/or the limitations of the machine excitation systems, in much the same way that higher-order dynamics have limited the design of power system stabilizers, to the extent of requiring elaborate input filtering or other measures to avoid exciting unmodeled oscillatory modes. Although further investigation of the systemwide effects of a given pole assignment on a particular machine is certainly in order, we feel that it is unrealistic in simulations of an equivalent system such as the one used here to assign poles much faster than -5. As was mentioned in the paper, it was felt that the controller poles should be about an order of magnitude slower than a nominal 10 Hz threshold that represents the range in which shaft torsional dynamics occur. For this reason, the opportunity to significantly affect the system behavior beyond what is shown here, through pole selection may be limited. As a practical matter, we would foresee a series of simulations of various transients and system configurations as a requisite for the development and commissioning of an FBLC exciter, in much the same fashion as is currently performed in PSS or SVC design.

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