Design of Passivity-Based Output Feedback Controllers for Power System Stabilization

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Abstract

This paper develops a method for designing passivity-based output feedback controllers for complex nonlinear systems that are not inherently passive. Using this methodology, three power system stabilizers are designed; two of these are output feedback sliding mode controllers and the third is designed using basic passivity principles. The controllers are examined to see how well they handle model uncertainty, disturbances and measurement noise. The results are compared to a previous study performed on the same benchmark power system model using six standard controllers. It was found that two of the new controllers designed in this paper outperformed the best of the controllers in the previous study.

I. Introduction

Historically, sliding mode controllers were implemented either with full state feedback or with estimated state feedback. However, the guaranteed robustness and disturbance rejection properties achievable with sliding mode control are lost when implemented with an observer, even a "robust observer." The robustness properties of sliding mode can be maintained if a static output feedback controller is used, yet most work in output feedback sliding mode has been limited to linear systems, see for example [1-3].

A method to design a robust output feedback sliding mode controller for passive nonlinear systems was developed in [4]. These results can be extended to nonpassive systems if a method was available to passify systems using only output measurements, but very little work has been done in this area. One recent exception was reported in [5], but the restrictions on the systems to which this method can be applied are severe.

This paper extends the results of [4] and [6] by showing how passivity can be used to design output feedback controllers for a complex system, especially one that is not inherently passive. Three new passivity-based controllers are designed in this paper for a power system model; two of these are sliding mode controllers and the third is based on principles of passivity. The model used in this paper, a single-machine infinite bus power system, was studied in detail in [6] where the performance of six standard output feedback controllers were compared as they reacted to model uncertainty, noisy measurements and disturbances. The controllers considered in [6] were a fuzzy logic control, sliding mode control (with an observer), two linear compensators, model-reference adaptive control, and nonlinear robust control (with an observer). The sliding mode controller performed poorly in this study [6] due primarily to the need for an observer in the implementation. That poor performance, along with sliding mode's reputation as a robust controller, motivated the work in [4] as well as the current work. This paper shows how to design an output feedback sliding mode controller for a complex nonlinear system that recaptures the robustness properties inherent with state feedback sliding mode control.

The next section gives an overview of the generic design methodology. Section III discusses how this methodology and the sliding mode design method given in [4] can be used to design three passivity-based power system stabilizers. Simulation results are shown in Section IV that investigate the performance of the new controllers with respect to model uncertainty, noisy measurements and disturbances. The results in this paper are compared to the behavior of the fuzzy logic controller, which performed best among the controllers reported in [6]. It is seen that two of the new passivity-based controllers perform significantly better than the fuzzy logic controller. Section V presents some discussion and conclusions.

II. Design Methodology

Consider a generic single-input, single output nonlinear system:

$$\begin{aligned} \dot{x} &= f(x) + g(x)u \\ y &= h(x) \end{aligned} \tag{1}$$

where $x \in \Re^n$, $y \in \Re$, and $u \in \Re$. The system (1) is passive from the input u to the output y if there is a storage function $\phi(x)$ such that the inequality

$$\phi(\Phi(t, x_0, u)) - \phi(x_0) \leq \int_0^t y(\tau)u(\tau)d\tau \tag{2}$$

is satisfied for all possible inputs and initial conditions. Strict passivity, a more demanding condition, requires the satisfaction of

$$\phi(\Phi(t, x_0, u)) - \phi(x_0) + \int_0^t S(\Phi(\tau, x_0, u))d\tau \leq \int_0^t y(\tau)u(\tau)d\tau \tag{3}$$

where $S(\cdot)$ is a positive definite matrix.

For nonlinear systems, there is no general way to form a storage function $\phi(x)$, hence, passivity can be difficult to prove in practical, complex systems. Some general methods have been considered in [7] and [8], but no systematic approach exists. There are conditions, however, when local passivity of a nonlinear system can be inferred from the passivity of the linearization of the system. The passivity of a linear system, usually referred to as positive realness, is a more studied area with many numerical results. This approach will be pursued in this paper since the role of a power system stabilizer is to control small oscillations about the operating point.

The system defined in (1) is linearized about an operating point.

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned} \tag{4}$$

Lemma 2 [9]: The linear system in (4) is passive (strictly passive) if and only if there exists a symmetric, positive semi-definite matrix P (and matrix Q) such that

$$A^T P + PA \le 0 \quad (< -Q^T Q)$$
$$B^T P = C$$

The definitions of passivity and strict passivity for a linear system are identical to the definitions for positive real (PR) and strictly positive real (SPR), respectively. While it is hard to find a storage function $\phi(x)$ for nonlinear systems, much work has been done in determining if linear systems are SPR and in designing controllers to render systems SPR

There are two assumptions that must be satisfied by the systems in (1) and (4) for the main passivity result in this section, given in Theorem 1, to be valid. This theorem is a simplified version of a similar theorem given in [9].

A1. rank B = rank C = m
A2. rank $L_g h(x)$ is constant in a neighborhood of 0, where $L_g h(x)$ is the Lie derivative of $h(x)$ along $g(x)$, i.e., $L_g h(x) = \frac{\partial h(x)}{\partial x} g(x)$.

Theorem 1:
1. If system (1) is passive, then system (4) is passive.
2. If system (4) is strictly passive (i.e., SPR) and assumptions A1 and A2 are met, then there exists $B_0 \in \Re^n$ such that (3) holds for all $x_0 \in B_0$, for all u such that $\Phi(t,x_0,u)$ remains in B_0 for all t.

If Theorem 1 is satisfied, then the system in (1) is locally passive about an operating point and a passive controller can be designed to maintain local stability. Suppose that the linearized system in (4) is not SPR. The property of SPR is so powerful for the design of output feedback systems, that methods have been developed to make a system SPR using an augmented output feedback control. One such method, commonly used in adaptive control, adds a parallel filter to the plant as depicted in Figure 1 [10]. The parallel filter is designed so that the augmented system is SPR from the input u to the combined output $y_A = y + y_f$. The filter also should have the property that the contribution from the filter output is small when compared to the output of the plant (that is, $y_A \approx y$). Thus, designing an SPR-based (or passivity-based) controller for the augmented plant should result in a behavior of the original plant that is close to the behavior of the augmented plant. When applied to the nonlinear plant, the controller acts as a local controller meant to keep the plant near its desired operating point.

The discussion above leads to a methodology of designing an output feedback passivity-based controller for a nonlinear system. The systems to which this can be applied are quite general and include that of a power system comprised of a single machine connected to an infinite bus.

The methodology can be summarized in the following steps:

1) If the system is passive, use standard techniques to design a passivity-based controller. A method employing output feedback sliding mode controller can be used in order to achieve added robustness [4].
2) If you cannot prove that the system is passive, then linearize it about a desired operating point. If the conditions in Theorem 1 are satisfied, then the nonlinear system is (at least) locally passive. A passivity-based controller that operates locally can be designed.
3) If the linearized system is not SPR, then under certain conditions, it can be made SPR by designing an SPR filter to be used in parallel with the original plant such that it renders the augmented system SPR and results in a small perturbation to the plant output. A passivity-based controller for the augmented plant can be designed.

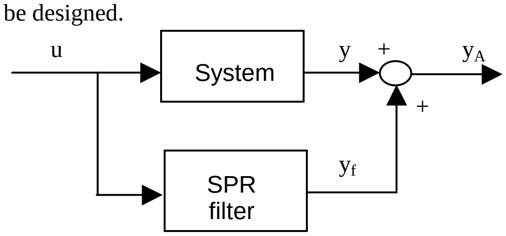

Figure 1: Augmented system.

III. Passivity-Based Power System Stabilizers

The methodology described above was used to design three passivity-based controllers for a power system. A single generator-infinite bus power system can be modeled as a sixth order system with a fifth order generator and a first order exciter [11]. The states of the system are the currents i_d, i_f, i_q, the rotor speed ω, the rotor angle δ, and the field voltage E_{FD}. The input to the system, u, is an additional voltage in the exciter which adds additional damping, and the output is the rotor speed, ω. The system equations are given in [6]. Parameter values used in simulations are given in Table 1. The state vector is defined as $x = [i_d \;\; i_f \;\; i_q \;\; \omega \;\; \delta \;\; E_{FD}]^T$. These values represent per-unitized values of parameters taken from an actual machine [11]. The model was simplified by holding the mechanical torque, T_m, constant. It is assumed that only ω is available for measurement.

Proving that this system is globally passive from the input u to the output $y = \omega$ has proven difficult. Therefore, the system is linearized about an operating point of $x = x_0$ =[-1.9253 2.9794 0.6673 1.000 1.1693 2.6662]^T. This operating point results in a desired shaft speed of $\omega = 1$ in the per-unit values. The resulting linear system is not relative degree one, therefore it is not SPR. It should be mentioned that there have been some papers that consider passivity of power systems, see for example [12] and [13], but these papers examine different models,

System	Parameter	Value		System	Parameter	Value
Nominal	R	0.001096		Transmission Line	R_e	0.02
	L_d	1.7			L_e	0.4
	L_f	1.651		Simple Exciter	K_A	40
	H	2.37			T_A	28.275
	V_∞	0.8284		Full Exciter	K_R	1
	R_f	0.00074			T_R	3.77
	L_q	1.64			K_F	0.04
	kM_f	1.55			T_F	269.55
	T_m	1.0015			K_E	-0.05
	V_{ref}	1.0667			T_E	188.5

Table 1: Nonlinear system variables.

including different inputs and outputs than used here. The model shown in [6] is chosen for this work because it is a well-known documented model that includes a representation of a standard/typical power system stabilizer.

The next step is to find a way to augment the system as shown in Figure 1 to change its relative degree. A strictly positive real filter is placed in parallel with the plant so that the resulting system from input u to output y_A has a relative degree one. It is this augmented system that will be used to show the passivity of the linear system. If designed correctly, the output of the filter, y_f, is small compared to the output of the power system, ω. A simple filter, which can be used for augmentation, is

$$R_f(s) = \frac{D_f}{\tau_f s + 1} \qquad (5)$$

This filter is used along with the linearized system (given by the triple {A,B,C}) to form an augmented system:

$$\begin{aligned} \dot{x}_A &= A_A x_A + B_A u \\ y_A &= C_A x_A \end{aligned} \qquad (6)$$

where

$$\begin{aligned} x_A &= [i_{d\Delta}\ i_{f\Delta}\ i_{q\Delta}\ \omega_\Delta\ \delta_\Delta\ E_{fd\Delta}\ y_f]^T \\ A_A &= \begin{bmatrix} A & 0 \\ 0 & -1/\tau_f \end{bmatrix} \\ B_A &= \begin{bmatrix} B^T & D_f/\tau_f \end{bmatrix}^T \\ C_A &= [C \quad 1] \end{aligned}$$

It is easy to show this augmented system still satisfies assumptions A1 and A2. The MATLAB m-file provided by the authors of [14] was used to verify that the linear augmented system in (6) is SPR. Many values of D_f and τ_f will make the augmented system SPR; values of D_f = 3.33 and τ_f = 1/30 were chosen because they resulted in good performance in the simulation results.

Since the system in (6) is SPR and assumptions A1 and A2 are met, then the nonlinear system (1) augmented with the filter in (5) satisfies the passivity inequality in (3) for some region B_0 around the steady state operating point. The nonlinear augmented system is given by

$$\begin{aligned} \dot{x}_A &= f(x_A) + gu \\ y_A &= [0 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 1] x_A \end{aligned} \qquad (7)$$

where $x_A = [i_d \quad i_f \quad i_q \quad \omega \quad \delta \quad E_{FD} \quad y_f]^T$,

$g = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & \frac{\omega_b K_A}{T_A} & \frac{D_f}{\tau_f} \end{bmatrix}^T$, and where $f(x_A)$ can be found from the nonlinear system equations given in [6].

The goal of the control design is to design controllers using only the output, y_A, to asymptotically stabilize the system; that is, remove oscillations so that the rotor maintains the synchronous speed. The controllers designed below will all use the fact that the system in (7) is passive about the operating point. Alternatively, the system in (7) can be translated to the origin using a transformation $z = x_A - [x_0{}^T \ \ 0]^T$ resulting in a system of the form

$$\begin{aligned} \dot{z} &= f_1(z) + gu \\ \hat{y} &= [0 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 1] z \end{aligned} \qquad (8)$$

where the new output is $\hat{y} = y_A - 1$.

3.1 Linear passive sliding mode controller

The first controller to be designed uses the method in [4] for output feedback sliding mode control. There are several assumptions that must be met by the system; the control is then straightforward. In this section, a simple switching surface will be chosen and all pertinent assumptions verified. For the sliding mode controller in this section, the switching surface, σ is chosen to be

$$\sigma = y_A - 1 \qquad (9)$$

Since the switching surface is a linear function of the output, the controller will be referred to as the "linear passive controller". Given (7), the control signal is

$$u = -\gamma\sigma - v_\sigma \qquad (10)$$

where

$$v_\sigma = \begin{cases} \dfrac{\sigma}{\|\sigma\| + \varepsilon} & if\ \sigma \neq 0 \\ 0 & otherwise \end{cases}$$

The small parameter ε >0 is used in order to smooth out the discontinuities in the control. The following assumptions from [4] give sufficient conditions for a generic system of the form given in (1) under which a sliding mode control law will drive the state trajectories to the switching surface and asymptotically stabilize the system to the origin.

A3. The matrix $N(x) = \dfrac{\partial \sigma}{\partial x} g(x)$ is positive definite.

A4. The sliding mode dynamics are asymptotically stable.

A5. The system is passive.

For the power system, these conditions must be checked on the translated system given in (8). Assumption A5 has already been shown (at least locally); the other assumptions can also be shown with relative ease.

3.2 Cubic passive sliding mode controller

The next controller to be designed will also use the method described in [4] for output feedback sliding mode control for passive systems. The controller designed in the previous section used a simple linear switching surface, that is σ=y_A - 1. This section considers instead a switching surface of

$$\sigma = (y_A - 1)^3 \qquad (11)$$

Since the switching surface is a cubic function of the output, the controller will be referred to as the "cubic passive controller". Given this choice, the control signal is

$$u = -\gamma\sigma^3 - v_\sigma \qquad (12)$$

$$v_\sigma = \begin{cases} \alpha \dfrac{\sigma}{\|\sigma\| + \varepsilon} & if\ \sigma \neq 0 \\ 0 & otherwise \end{cases}$$

Again, the small, positive parameter ε is used to smooth out the control signal. As in the case with the linear passive control, a new translated system must be defined in order to use the method in [4] to guarantee that the reaching condition is satisfied and that the system is asymptotically stable. The difference between the system defined for the linear passive control case and the system needed for the cubic control case is that the output of the translated system here is defined to be the switching surface, $\tilde{y} = \sigma = (y_A - 1)^3$, which differs from the switching surface selected in the previous case. It is found that the assumptions A3-A5 listed in the previous section were satisfied by the translated system. Thus, the cubic passive sliding mode controller satisfies the reaching condition and has asymptotic stability.

3.3 ZSD passivity-based controller

The controllers designed in the previous two sections were based on the sliding mode control developed in [4]. The possibilities of passivity-based controllers for the power system, however, are not limited to sliding mode. The control in this section uses Lemma 3, which was adopted from a more general form in [15], as its basis.

Lemma 3: Suppose system (8) is passive with positive definite storage function, $\phi(z)$, and is zero state detectable. Let $\eta(\hat{y})$ be any smooth function such that $\eta(0) = 0$ and $\hat{y}^T \eta(\hat{y}) > 0$. Then the control law $u = -\eta(\hat{y})$ asymptotically stabilizes the equilibrium $z = 0$.

For system (8) to be zero state detectable, then $\hat{y} \equiv 0$ and $u \equiv 0$ imply that $z(t) \to 0$. This can be shown by examining (9) when $\hat{y} \equiv 0$, $\dot{\hat{y}} \equiv 0$, and $u \equiv 0$. For this application, the following was chosen for $\eta(\hat{y})$:

$$\eta(\hat{y}) = \beta \hat{y} \cos^2(\hat{y}) \qquad (13)$$

The function $\eta(\hat{y})$ was chosen arbitrarily, as it performed well in simulation. Other functions did not perform as well in simulations, for instance, a similar function $\eta(\hat{y}) = \beta \hat{y} \sin^2(\hat{y})$, took a much longer time to converge with similar size gain β.

IV. Simulation Results

The three passivity-based power system stabilizers, two based on the sliding mode control method from [4] and the third based on Lemma 3, are compared to a fuzzy logic controller from [6] on how well they perform on a power system model. In particular, their performance to a nominal power system subjected to a fault is considered. The controllers' ability to handle input disturbances, measurement noise, parameter variations and unmodeled dynamics is examined.

The simulations in this paper use the same system and perturbations described in the comparison paper [6]. These results, therefore, will be used not only to compare the responses of the three passivity controllers to each other but also to compare their responses to the controllers in [6].

A 5 cycle fault was applied to the nonlinear system in (5) with the three controllers designed in Section III and the results were compared under the additional constraint that the maximum allowable control magnitude is u=0.12 (in per-unit quantity). In particular, the behavior of the different controllers under various types of perturbations to the model were explored. The perturbations examined are unmodeled dynamics, parameter variations, measurement noise and input disturbances. Since part of the purpose of these simulations is to compare the responses to those of [6], the fuzzy controller response is included in all figures in this chapter. The fuzzy controller was chosen due to its good performance in the simulations in [6]. Most system parameters are given in Table 1. The parameters for the augmentation filter and the three controllers are given in Table 2.

Control	Expression	Parameter
Augmentation filter	$R_f(s) = \dfrac{D_f}{\tau_f s + 1}$	$D_f = 3.33$ $\tau = 1/30$
Linear Passive ($\sigma = y_A - 1$)	$u = -\gamma\sigma - \alpha \dfrac{\sigma}{\|\sigma\| + \varepsilon}$	$\alpha = 20$ $\gamma = 20$ $\varepsilon = 0.001$
Cubic Passive ($\sigma = (y_A - 1)^3/3$)	$u = -\gamma\sigma - \alpha \dfrac{\sigma}{\|\sigma\| + \varepsilon}$	$\alpha = 20$ $\gamma = 20$ $\varepsilon = 0.001$
ZSD Passive	$u = -\beta(y_A - 1)\cos^2(y_A - 1)$	$\beta = 1$

Table 2: Simulation parameter values.

To provide a quantitative measure of performance, a standard LQR cost function is used to compare the controllers' performance. That is,

$$J = \int_0^T \alpha(\omega - 1)^2 + \beta u^2 dt \qquad (14)$$

where ω is the speed of the rotor, u is the control signal and T is the length of the simulation for the particular perturbation. The weighting factors α and β indicate the importance of the control on the cost. Some of the controllers required much less control effort for some of the perturbations than the maximum allowed of u_{max} = 0.12. This fact is reflected in allowing part of the cost function to rely on the control signal size.

Tuning was performed on all of the controllers so that the corresponding response of the nominal nonlinear model to the 5 cycle fault was virtually identical. To verify this quantitatively, the LQR cost was calculated for the controllers with $\alpha = 1$, $\beta = 0$, that is, the cost due to just the response without considering the amount of control signal. These costs are shown in Table 3. Note they differ only by at most 0.3%.

Controller	J
Fuzzy	0.00013132145996
Linear Passive	0.00013141741650
Cubic Passive	0.00013136143659
ZSD Passive	0.00013171666756

Table 3: Nominal LQR cost with $\alpha = 1$, $\beta = 0$.

The power system was subjected to several perturbations and the cost J was calculated for each controller for each perturbation and for the nominal case. Details of the perturbations are given next while the quantitative results for $\alpha = 0.9$, $\beta = 0.1$ and for $\alpha = 0.8$, $\beta = 0.2$ are summarized in Tables 4 and 5, respectively. The total cost for each controller is obtained by normalizing the value in each row by the maximum in the row, and then averaging the normalized values for each type of perturbation. Since the parameter variations are both the same type of perturbation, the average of the costs for parameter variations is used in determining the total of cost for each controller. The results are shown for the three passivity-based controllers as well as the fuzzy controller from [6]. The numbers for the fuzzy controller are slightly different than they were in [6] since the fuzzy controller was retuned to have a similar nominal response as the passivity-based controllers.

Unmodeled dynamics: To test the controllers' ability to deal with unmodeled dynamics, a Type 1 exciter [6] was included in the simulations (excluding the saturation and limiting effects), and the controller responses were compared. Parameter values for the full exciter are given in Table 1. All the controllers obtain approximately the same response from the system. The cubic passive uses less control energy than the others, while the linear passive again uses the most available control energy. The LQR cost computed in Tables 4 and 5 ranks the controllers, from best to worst, as cubic passive, ZSD passive, fuzzy and linear passive.

Parameter variations: The parameter values given in Table 1 are nominal values. It is possible that the parameter values could be incorrectly determined or that the parameter values could change with time. To see how the controllers react to such a possibility, the transmission line parameter values (L_e and R_e) were increased by 50% and system response explored. Note that this variation is an unmatched disturbance. The cubic passive controller and the ZSD passive seem to have slightly better response than the others with clearly the smaller control effort. This qualitative evaluation agrees with the results of Tables 4 and 5 which rank the controllers, from best to worst, as cubic passive, ZSD passive, fuzzy and linear passive.

To explore a different parameter variation, L_e was kept at its nominal value and all of the resistances (R,R_e,R_f) increased by 50% from their nominal values (again an unmatched disturbance). Considering control effort, performance and LQR cost, the cubic passive controller has the best response, followed closely by the ZSD passive. The linear passive controller and the fuzzy controller both have good performance, but the controllers again needed more control energy to achieve the results.

Measurement noise: The effect of measurement noise on the controllers was explored by adding a noise, n, to the output before it enters the controller. That is,

$$y_n = y_A + n = (y_f + \omega) + n$$

where y_f is the output of the augmentation filter, ω is the measured rotor speed, and y_n is the signal input to the controller. Many different sinusoidal noise signals of varying amplitudes and frequencies were tested. Sinusoidal noise was chosen because it can be more destructive than a random input since it may excite resonances. A representative sinusoid of n = 0.001sin600t was used for the results in Tables 4 and 5. For this noise signal, all controllers use full control energy. The ordering of the controllers, from best to worst, in Tables 4 and 5 is cubic passive, ZSD passive, fuzzy and linear passive.

As the amplitude of the noise signal is increased, the passive controllers are still able to stabilize the system. At an amplitude of 0.005, where the model reference adaptive controller from [2] failed to stabilize the system, all three passive controllers still stabilized, taking a much longer time than at 0.001. The linear passive did the quickest job of removing the oscillations. As the frequency was decreased to 500, while the amplitude was kept at 0.005, all three passive controllers stabilized the system, taking less time than at a frequency of 600. Overall, the passive controllers seem less affected by measurement noise than the controllers considered in [6].

Perturbation	**Linear Passive**	**Cubic Passive**	**ZSD Passive**	**Fuzzy**
Nominal	0.00496228	0.00280742	0.00249232	0.00325736
Unmodeled Dynamics	0.04816543	0.03195346	0.03276722	0.04504469
Parameter #1 (Transmission Line)	0.0073606	0.002332042	0.00234228	0.00439878
Parameter #2 (Resistance)	0.00794711	0.00176809	0.00186501	0.00510600
Measurement Noise	0.14406343	0.13623663	0.13704264	0.14346293
Input Disturbance	0.14275349	0.00377987	0.00822738	0.14028092
Total	1	0.494193	0.493581	0.83804

Table 4: Cost for each controller for each perturbation: α = 0.9, β = 0.1. Total cost is the average of the normalized costs for each type of perturbation.

Perturbation	**Linear Passive**	**Cubic Passive**	**ZSD Passive**	**Fuzzy**
Nominal	0.00979314	0.00548347	0.00485292	0.00638340
Unmodeled Dynamics	0.09592786	0.06348896	0.06511656	0.08968621
Parameter #1 (Transmission Line)	0.01462414	0.00456567	0.00458691	0.00870083
Parameter #2 (Resistance)	0.01579460	0.00343950	0.00363369	0.01011214
Measurement Noise	0.28793671	0.27230819	0.27395003	0.28675477
Input Disturbance	0.28531762	0.00739372	0.01626024	0.28033668
Total	1	0.491678	0.490924	0.836558

Table 5: Cost for each controller for each perturbation: α = 0.8, β = 0.2. Total cost is the average of the normalized costs for each type of perturbation

Input disturbance: Often, disturbances are introduced at the input that degrade performance. The controllers' ability to overcome this disturbance is examined by adding a disturbance, *d*, to the control input before it enters the system, that is $\tilde{u} = u + d$ where $\tilde{u}$ is the signal actually applied to the excitation system. Note that this is a matched disturbance. Many different sinusoidal disturbance signals were tested.

For a representative sinusoid of *d*=0.3sin 0.4t, the cubic passive controller seems to do the best job, followed by the ZSD passive controller, neither of which uses all available control energy for the entire time. The fuzzy and linear passive controllers also do a good job of removing the perturbation, but use more control energy than the cubic passive and ZSD passive controllers. These results agree with the ordering shown in Tables 4 and 5, that is, cubic passive, ZSD passive, fuzzy and linear passive. The results are relatively similar when the amplitude and frequency are decreased. There are some interesting results when the amplitude is decreased to 0.1 and the frequency increased to 10. The ZSD and cubic passive controllers still stabilized the system, but had very large sustained oscillations. The linear passive controller, on the other hand, had a much better response. Oscillations due to the input disturbance are still present, but are significantly smaller than the responses of the other two controllers.

V. Discussion and Summary

Examining Tables 4 and 5, it is evident that the passive controllers performed well. The cubic passive and ZSD passive controllers have the best overall ability to handle the perturbations introduced. The linear passive controller and the fuzzy controller both had very good responses, but the excessive control energy is the reason their numbers are worse than the other controllers listed in the tables. Overall, then, it appears the ZSD passive controller and the cubic passive had the best performance.

While the 5 cycle fault disturbance was a good test for the controllers (it was large enough to excite nonlinear behavior), other disturbances could also be used. To explore this further, the controllers' ability to handle a 10% change in reference voltage was examined (in place of the fault) and the perturbations discussed above were introduced. The responses were analyzed using the LQR cost function given in equation (14). The results were that the fuzzy controller had the lowest total cost, followed by the linear passive, the ZSD passive, and the cubic passive controllers. All of the controllers actually performed very well, with individual costs about a tenth of their values for the fault (in Tables 4 and 5). These rankings are different from those obtained with the fault disturbance; the reason is the relative size of the disturbances. The 10% change in reference voltage is a very mild disturbance to the system resulting in very low amplitudes of response. The cubic passive controller operates on the cube of the error, so it effectively has a low gain at low amplitudes and a high gain at high amplitudes. The linear passive controller operates on a linear function of the error, so that it has a higher gain at low amplitudes and a lower gain at high amplitudes than the cubic passive controller. A controller that uses the cube of the error (such as the cubic passive) would do better than a controller that uses the error directly (such as the linear passive) for large disturbances and worse for small disturbances. This suggests that a controller that uses a polynomial of the error consisting of a cubic term and a linear term might give better overall response for both large and small disturbances.

In summary, this paper has shown how to design three passivity-based power system stabilizers. The performances of three passivity-based power system stabilizers were examined in terms of their responses to various perturbations to a system that undergoes a three-phase fault. All three controllers had performance results comparable or superior to the fuzzy controller, which had some of the best responses from [6] for most of the perturbations. In fact, when an LQR cost function was calculated for each perturbation, the cubic passive controller and the ZSD passive controller had total costs that were significantly lower than any of the controllers from [6]. The linear passive controller had an overall cost that is worse than all but the two controllers from [6], which again resulted from the use of excessive control energy not inferior performance.

References:

[1] Yallapragada, S.V., Heck, B.S. and Finney, J.D., "Reaching Conditions for Variable Structure Control with Output Feedback," *AIAA Journal of Guidance, Control, and Dynamics*, vol. 19, no. 4, pp. 848-853, July-August 1996.

[2] Diong, B.M. and Medanic, J.V., "Simplex-type variable structure controllers for systems with non-matching disturbances and uncertainties," *International Journal of Control*, vol.68, no.3, Oct. 1997, p.625-56.

[3] Edwards, C. and Spurgeon, S.K., "Compensator based output feedback sliding mode controller design," *International Journal of Control*, vol.71, no.4, Nov. 1998, p.601-14.

[4] Falkner, C..M. and Heck, B.S., "Variable Structure Control with Output Feedback for Nonlinear Systems," *Proc.of the CDC, vol*, pp 3522-3524, Kobe, Japan, December 1996.

[5] Lee, J.S.; Shim, H.; Byun, J.; Seo, J.H., "Robust stabilization of a class of MIMO nonlinear systems: sliding mode control and passification approach," *Proc. of the ACC*, Philadelphia, PA, USA , pp. 24-26 June 1998.

[6] Falkner, C.M. and Heck, B.S., "Comparison of Robust Nonlinear Controllers on a Single Generator-Infinite Bus Power System," *Proc. of the ACCe*, pp. 1550-1555, Seattle, WA, June 1995; also accepted in the *Journal of Intelligent and Fuzzy Systems*.

[7] Hill, D. and Moylan, "The stability of nonlinear dissipative systems," *IEEE Transactions on Automatic Control*, vol. 21, 1976, p. 708-711.

[8] Willems, J., " Dissipative Dynamical Systems Part I: General Theory," *Arch. Rational Mechanics and Analysis*, vol. 45, 1972, p. 321-351.

[9] Nijmeijer, H., Ortega, R., Ruiz, A., and der Schaft, A.V., "On passive systems: from linearity to nonlinearity," *IFAC Nonlinear Control Design*, 1992, pp. 373-378.

[10] Kaufman, H., Bar-Kana, I., and Sobel, K., *Direct Adaptive Control Algorithms: Theory and Applications*, Springer-Verlag, 1994.

[11] Anderson, P. and Fouad, A., *Power System Control and Stability*, IEEE Press, 1994.

[12] Pogromsky, A., Fradkov, A., and Hill, D., " Passivity based damping of power system oscillations," *Proc. of the CDC*, Dec. 1996, p. 3876-3881.

[13] Espinosa-Perez, G., Alcantar, M.G., and Ramirez, G.G., "Passivity-based speed control of synchronous generators," *IEEE International Symposium on Industrial Electronics*, vol. 1, 1997, p. 101-106.

[14] Sadegh, N., Finney, J.D. and Heck, B.S., "An Explicit Method for Computing the Positive Real Lemma Matrices," *International Journal of Robust and Nonlinear Control*, vol. 7, no. 12, pp. 1057-1069, December 1997.

[15] Byrnes, C., Isidori, A., and Willems, J., "Passivity, Feedback Equivalence, and the Global Stabilization of Minimum Phase Nonlinear Systems," *IEEE Transactions on Automatic Control*, vol. 36, 1991, p. 1228-1240.