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Design and Performance Analysis of a Robust Power System Stabilizer for Single Machine Infinite Bus using ADRC Approach

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Abstract: ***Due to the rapid growing demand for electricity, power systems nowadays have become operating under continually changing in loads and operating conditions which is a major cause of instabilities and could potentially result in serious consequences. This paper presents a novel design approach by employing a robust damping control of power systems based on 'Active Disturbance Rejection Control' (ADRC) algorithm in order to improve system stability. The advantage of this algorithm is that it requires little information from the plant model since the relative order of open loop transfer function information is quite sufficient to design a robust controller. This makes the power system more robust against a wide range of disturbances that are commonly encountered in such systems. Here, the proposed ADRC control algorithm is developed for a synchronous machine connected to infinite bus (SMIB) through external reactance under small-disturbance condition. The effectiveness of the proposed algorithm has been verified by comparing it with an optimally tuned Conventional Power System Stabilizer (CPSS) under various loading conditions. The comparison shows that the proposed approach guarantees system stability and exhibits higher performance than CPSS which lacks robustness at some severe operating points despite being optimally tuned.***

Index Terms: Active Disturbance Rejection Control (ADRC); Dynamic Analysis; Small Signal Stability; Power system stabilizer (PSS); Single Machine Infinite Bus (SMIB).

I. INTRODUCTION

The continuous increasing demand for electricity leads modern power systems to be large, complex, and nonlinear systems. As a result, these systems become highly influenced by any kind of disturbances such as continual load change or sudden change in mechanical power given by the prime mover. Generally, the disturbances are classified into two types (small and large). Disturbances which result in a sudden drop in the line voltages are classified as large disturbances while the random changes in the load or generation are classified as small disturbances [1]. Small disturbance is related to the system steady-state stability which is defined as the ability of the power system to maintain synchronism under small disturbances such as variations in loads or generations. Furthermore, a small signal analysis is one for which the system dynamics can be analysed using linearized model of the system [2].

With different powerful techniques and long history of successful implementations, Conventional Power System Stabilizer CPSS as well as PID controller have been used as well-established ways in order to enhance the stability of power systems [3]-[4]. However, the conventional PSSs still rather feeble versus the constantly changes in operating conditions of the system and therefore, a conventionally designed PSS may not guarantee the robustness over all possible operating points. To resolving this problem, many researches had been published explaining different intelligent techniques of optimally tuning the parameters of power system stabilizers [5]-[9]. Nevertheless, the robustness of these stabilizers is still in doubt, especially at serious conditions such as heavy loads. This paper presents a novel design of robust damping control of power system. Though the proposed controller can be applied to any complex power system model, a Single Machine Infinite Bus (SNIB) model is chosen here because the main purpose of the study is to demonstrate the superiority of the proposed control algorithm. The power system under study consists of a synchronous machine connected to infinite bus via a transmission line having equivalent reactance X_e as shown in Fig1.

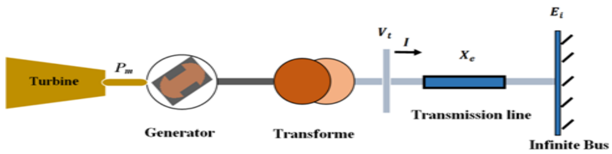

Fig 1. Single Machine Infinite Bus System

The proposed control approach is based on Active Disturbance Rejection Control (ADRC) which is not requiring accurate model information [10]. In this approach, the total disturbance including system uncertainty and external disturbance is estimated directly and then rejected in effective way, resulting in a stabilizer that is inseparably robust against structural uncertainties typically found in power systems. In addition, from a specific point of view, the ADRC has only two tuning parameters, making it simple to implement in practice compared to other modern controllers. By using MATLAB Simulation Toolbox, the performance of proposed controller is evaluated in the presence of system parameter uncertainties compared to an optimally tuned conventional power system stabilizer. The rest of the paper is organized as follows. In Section II, the dynamic modelling of the considered power system is presented. Section III describes the general structure of the conventional power system stabilizer. In Section IV, the design of ADRC is introduced.

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Then simulation results are shown in Section V. Finally, the concluding remarks are made in Section VI.

II. MATHEMATICAL MODEL OF THE SYSTEM

As described earlier, the examined system is a single machine connected to an infinite bus through a transmission line. Fig.2 shows the well-known Heffron-Phillips linearized model of Single Machine Infinite Bus system SMIB. More details about modelling along with linearizing of this system can be found in [11].

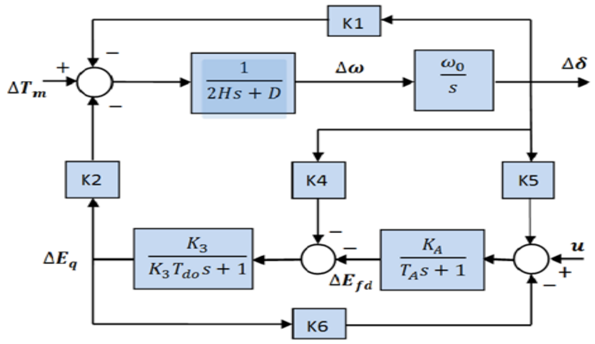

Fig 2. Single Machine Infinite Bus Heffron Phillips Model.

In this model, δ, ω are the rotor angle and rotor speed of the generator respectively, E_q is the quadrature-axis transient voltage, E_{fd} is the field voltage, T_m is the input mechanical torque, H is the inertia constant, D is the damping constant, T_{do} is the direct-axis open-circuit transient time constant of the generator, K_A is the gain of the exciter amplifier, T_A is the exciter time constant and the rest constants K_1 to K_6 are known as Heffron Phillips constants which are determine the relation between rotor speed and voltage control within the machine [2]. Calculation of these constants will be discussed later in Section 5.

III. CONVENTIONAL POWER SYSTEM STABILIZE

Fig.3 shows the basic structure of conventional power system stabilizer CPSS which is composed of three blocks. First one is phase compensator block that used to compensate the phase lag between exciter input and generator electrical torque. The phase compensator block is connected in series with washout block that serves as high pass filter in order to restrain the controller influence at steady state conditions. The third block is the stabilizer gain Kpss which is an important factor for the damping provided by the PSS [11].

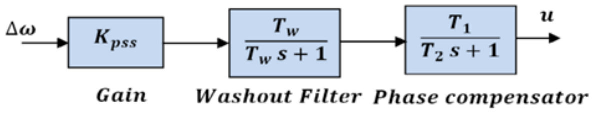

Fig. 3. The Basic Structure of CPSS

The input signal of CPSS is the rotor speed deviation of the machine and the output signal (control signal) is the supplementary stabilizing signal fed to the generator excitation system.

IV. DESIGN OF (ADRC) CONTROLLER

Based on the Extended State Observer (ESO), ADRC offers a new and inherently robust controller block which has the ability to actively estimate and then reject any disturbance influences the system in real time. The theoretical background of the time-domain ADRC can be found in [10].

Any system with input U(s) and output Y(s) together with disturbance can be represented by (1).

$$Y(s) = P_n(s)\,U(s) + D(s) \tag{1}$$

Where $D(s)$, is the total disturbance contains internal uncertain dynamics and external disturbances [12], $P_n(s)$ is the transfer function of the nominal plant (without disturbance) which is described by Eq. (2).

$$P_n(s) = \frac{Y(s)}{U(s)} = \frac{b_m s^m + b_{m-1} s^{m-1} + \cdots + b_1 s + b_0}{a_n s^n + a_{n-1} s^{n-1} + \cdots + a_1 s + a_0}\ ,\ n \geq m \tag{2}$$

Dividing both sides of (1) by $P_n(s)$, we get

$$\frac{1}{P_n(s)}\,Y(s) = U(s) + D^*(s) \tag{3}$$

Where $D^*(s) = \frac{D(s)}{P_n(s)}$,

$$\frac{1}{P_n(s)} = \frac{a_n s^n + a_{n-1} s^{n-1} + \cdots + a_1 s + a_0}{b_m s^m + b_{m-1} s^{m-1} + \cdots + b_1 s + b_0}$$

$$= c_{n-m} s^{n-m} + c_{n-m-1} s^{n-m-1} + \cdots + c_1 s + c_0 + G_r(s),\quad n \geq m \tag{4}$$

Here $c_i\ (i = 0,1,\ldots,n-m)$, are coefficients of the polynomial $\frac{1}{P_n(s)}$, and the remainder $G_r(s)$ is $G_r(s) = \frac{d_{m-1} s^{m-1} + d_{m-2} s^{m-2} + \cdots + d_1 s + d_0}{b_m s^m + b_{m-1} s^{m-1} + \cdots + b_1 s + b_0}$ (5)

Where $d_i\ (i = 0,1,\ldots,m-1)$, are remainder nominator's coefficients

Substituting Eq. (4) into Eq. (3), we get

$$c_{n-m} s^{n-m}\,Y(s) = U(s) - [c_{n-m-1} s^{n-m-1} + \cdots + c_1 s + c_0 + G_r(s)]\,Y(s) + D^*(s) \tag{6}$$

Diving both sides of Eq. (6) by c_{n-m} , we get

$$s^{n-m}\,Y(s) = b\,U(s) + F(s) \tag{7}$$

Where F(s) is the modified total disturbance given by

$$F(s) = -\frac{1}{c_{n-m}}\,[\,c_{n-m-1} s^{n-m-1} + \cdots + c_1 s + c_0 + G_r(s)]\,Y(s) + \frac{1}{c_{n-m}}\,D^*(s) \tag{8}$$

$$\text{And}\quad b = \frac{1}{c_{n-m}} = \frac{b_m}{a_n}\ ,\ n \geq m \tag{9}$$

The proposed controller will be designed based on the system model given by (7). Hence, the accurate estimation of F(s) plays a vital role for the effectiveness of the ADRC controller so, an Extended State Observer (ESO) is needed to estimate the F(s) in real time.

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Consequently the state variables of the system described by (7) should be augmented to include F(s) as follows:

Let $x_1 = y$, $x_2 = y^{(1)}, \ldots, x_{n-m+1} = y^{(n-m)}$

The system model represented by (7) can be rewritten as

$$\dot{x} = A\,x + B\,u + E\,f^{(1)}, \quad y = C\,x \tag{10}$$

Where $x = [x_1 \quad x_2 \quad \cdots \quad x_{n-m} \quad x_{n-m+1}]^T$,

$$A_{(n-m+1)\times(n-m+1)} = \begin{bmatrix} 0 & 1 & & \\ & 0 & & \\ & & \cdots & 1 \\ & & & 0 \end{bmatrix},$$

$$B_{(n-m+1)\times(1)} = [0 \quad 0 \quad \ldots \quad b \quad 0]^T,$$

$$E_{(n-m+1)\times(1)} = [0 \quad 0 \quad \ldots \quad 1]^T,$$

$$C_{(1)\times(n-m+1)} = [1 \quad 0 \quad \ldots \quad 0],$$

And $f^{(1)}$, is the first derivative of the total disturbance which is assumed bounded within domain of interests [13]. From [12], the ESO dynamics can be represented as

$$\dot{z} = A\,z + B\,u + L\,(y - \hat{y}), \qquad \hat{y} = C\,z \tag{11}$$

Where

$z = [z_1 \quad \cdots \quad z_{n-m} \quad z_{n-m+1}]^T$, is the estimated state vector of x.

$\hat{y}$, is the estimated output vector of y.

And $L = [\beta_1 \quad \cdots \quad \beta_{n-m} \quad \beta_{n-m+1}]^T$, is the observer gain vector which is designed in order to locate all the eigenvalues of the ESO at a desired location $(-\omega_0)$.

With a well tuning of ESO we can get

$$Z_{n-m+1}(s) = \hat{F}(s) \approx F(s) \tag{12}$$

Where $\hat{F}(s)$, is the estimation of $F(s)$

If the control input is designed as

$$u = \frac{u_0 - z_{n-m+1}}{b} \tag{13}$$

The Eq. (7) will be reduced to

$$s^{n-m}\,Y(s) = b\left(\frac{U_0(s) - z_{n-m+1}(s)}{b}\right) + F(s) = U_0(s) - \hat{F}(s) + F(s) \approx U_0(s) \tag{14}$$

The control goal is to regulate the output y to zero. This can be achieved by using traditional PD controller. Therefore, the control law $U_0(s)$ is chosen as

$$U_0(s) = K_0\big(R(s) - Z_1(s)\big) - K_1 Z_2(s) - \ldots - K_{n-m-1} Z_{n-m}(s) \tag{15}$$

With the control law given by (15), Y(s) will be driven to the reference input R(s), which is zero for our case. In order to further simplify the tuning process, all the closed-loop poles of the PD controller are set to a certain location $(-\omega_c)$.

V. SIMULATION RESULTS

In this section, the effectiveness of ADRC is tested through single machine infinite bus power system. As shown in Fig. 4, the system output y is the deviation of the angular speed of the rotor $\Delta\omega$. The input signal u is the output of the controller which is fed to the generator exciter. The change in mechanical torque ΔT_m is considered as an external disturbance d.

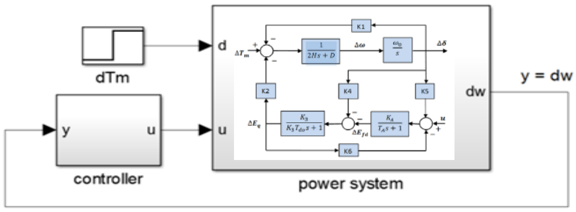

Fig. 4. Simulation Model Including Controller & External Disturbance Blocks.

The performance of the proposed controller is evaluated in terms of rejection the total disturbance which is consisting of sudden change in mechanical torque and unexpected change in operation conditions. The effectiveness of proposed ADRC controller is tested compared to an optimally tuned conventional power system stabilizer. The parameter values of the system under study as well as the data of applied conventional power system stabilizer are considered from the test system in [15] and are given in appendix A.

As mentioned in Section 2, the interaction between the speed and voltage control equations of the machine is often expressed in terms of six constants K_1 to K_6. The values of these constants depend upon the loading conditions, namely real power P and reactive power Q as well as the excitation level in the machine. These constants are modelled in [2] and the expressions that used to determine their values are illustrated in appendix B. Fig.5 shows the variation of K-constants for different operating conditions(P,Q).

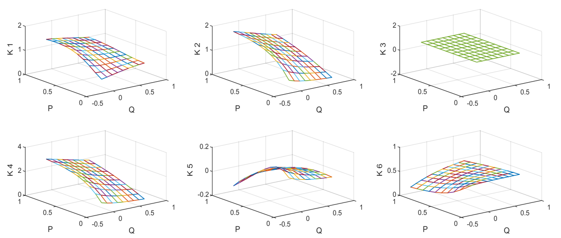

Fig.5. Variation of K-Constants for Different Operating Conditions.

The proposed ADRC controller can be designed according to the discussions in Section 4 as follows:

Substituting the parameter values of the system into (2) at operating point {light load $(P = 0.5, Q = 0)$ pu (per unit)}, we will have

$$P_n(s) = \frac{-145.1\,S}{S^4+50.49\,S^3+382.2\,S^2+2739\,S+13560} \quad (16)$$

From (16) we get: $n = 4$, $m = 1$, $b = \frac{b_m}{a_n} = -145.1$

Consequently the ESO dynamics is

$$\dot{z} = (A - L\,C)\,z + B\,u + L\,y \quad (17)$$

Where

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ b \\ 0 \end{bmatrix}, C = [1 \quad 0 \quad 0 \quad 0]$$

In order to locate all the eigenvalues of the ESO to specific location $(-\omega_0)$, the observer gain L is chosen as

$$L = [4\omega_0 \quad 6\omega_0^2 \quad 4\omega_0^3 \quad \omega_0^4]^T$$

And the control input can be represented by the following equations.

$$U_0(s) = K_0\big(R(s) - Z_1(s)\big) - K_1 Z_2(s) - K_2 Z_3(s) \quad (18)$$

$$U(s) = \frac{U_0(s) - Z_4(s)}{b} \quad (19)$$

For purpose of simplify the tuning process, all the closed-loop poles of the controller are set to $(-\omega_c)$. So, the controller gains in Eq. (18) are chosen as

$$K_0 = \omega_c^3, K_1 = 3\,\omega_c^2, K_2 = 3\,\omega_c.$$

The observer bandwidth (ω_0) is often chosen as three to five times of controller bandwidth (ω_c) [13]. As a result, there are only two tuning parameters for the ADRC design which are the controller gain (b) and the controller bandwidth (ω_c). Moreover, as we have good information about the system transfer function (i.e. (b) is known), the ADRC tuning parameters are reduced to only one[14]. After some trial and error (tuning), the controller parameters of the ADRC are chosen as

$$\omega_c = 5 \ , \quad \omega_0 = 3\,\omega_c \ , \quad b = -145.1$$

To test the effectiveness of the proposed controller, a wide range of loading conditions is studied. Namely, three different cases are considered as system structural uncertainties. During the simulation process, the mechanical torque reference ΔT_m is increased and the system operating point (load) is changed. The numerical values of the three cases that considered in the simulation are listed in Table 1.

The time domain response of the system is observed in the comparison of the rotor angle deviation and the rotor speed deviation of the machine with proposed ADRC control, with optimally tuned conventional power stabilizer, and without control taking into consideration that the parameter values of ADRC controller are designed at the light load operating point $(P = 0.5, Q = 0.0)$pu and then remain unchanged in the three considered cases whereas the parameter values of CPSS controller are fixed as designed in [15] which is used as a benchmark. The simulation results for all cases are demonstrated in Figures (6 to 11).

Table 1 The Numerical Values Used for Case Studies

Case	Load $(\mathbf{P}, \mathbf{Q})$ $\mathbf{p.u}$	$\Delta \mathbf{T_m}$
(1)	Light $(\mathbf{0.5}, \mathbf{0.0})$, $\mathbf{t} < 6\,s$ Normal $(\mathbf{0.9}, \mathbf{0.3})$, $\mathbf{t} \geq \mathbf{6\,s}$	$0\,\%$, $\mathbf{t} < 1\,s$ $\mathbf{100\,\%}$, $\mathbf{t \geq 1\,s}$
(2)	Light $(\mathbf{0.5}, \mathbf{0.0})$, $\mathbf{t} < 6\,s$ Heavy $(\mathbf{1.0}, \mathbf{0.8})$, $\mathbf{t} \geq \mathbf{6\,s}$	
(3)	Light $(\mathbf{0.5}, \mathbf{0.0})$, $\mathbf{t} < 6\,s$ Heavy leadPF$(\mathbf{1.1}, \mathbf{-0.8})$, $\mathbf{t} \geq \mathbf{6\,s}$	

In case1, a 1 (p.u) step external disturbance change is applied to the system at t=1s, whereas the operating point is changed from light load to normal load at t=6 s. The speed deviation and the angle deviation of the rotor, in this case, are depicted in Fig. 6 and Fig. 7 respectively.

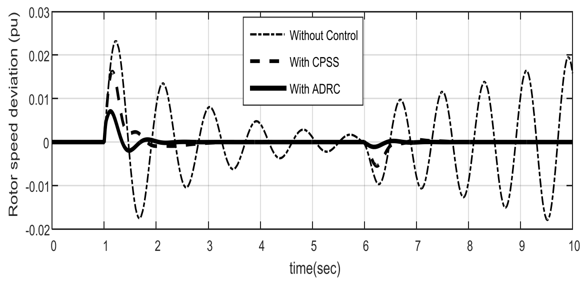

Fig. 6. Rotor Speed Deviation for Case Study No.1

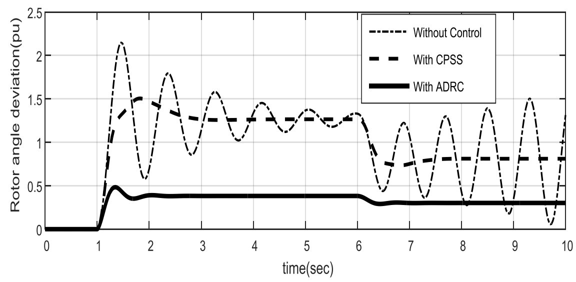

Fig. 7. Rotor Angle Deviation for Case Study No.1

On the other hand, the speed deviation and the angle deviation of the rotor in case 2 are shown in Fig. 8 and Fig. 9 respectively where a 1 (p.u) step external disturbance change is applied to the system at t=1s whereas the operating point is changed from light load to heavy load at t=6s.

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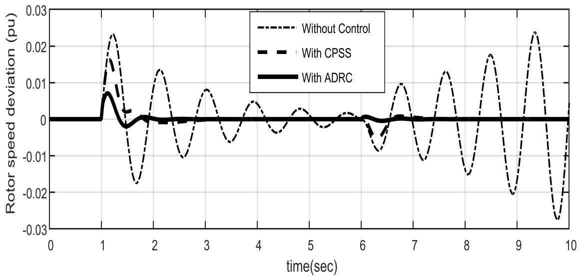

Fig. 8. Rotor Speed Deviation for Case Study No.2

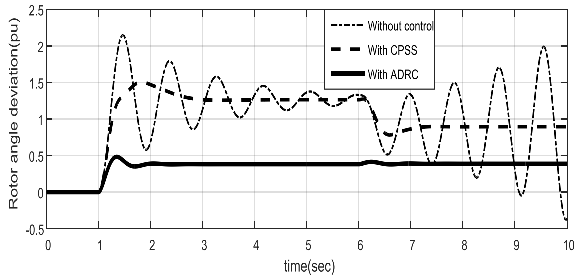

Fig. 9. Rotor Angle Deviation for Case study No. 2

Finally, Fig. 10 and Fig. 11 show the speed deviation and the angle deviation of the rotor in case 3 where a 1 (p.u) step external disturbance change is applied to the system at t=1s whereas the operating point is changed from light load to heavy-lead power factor- load at t=6 s.

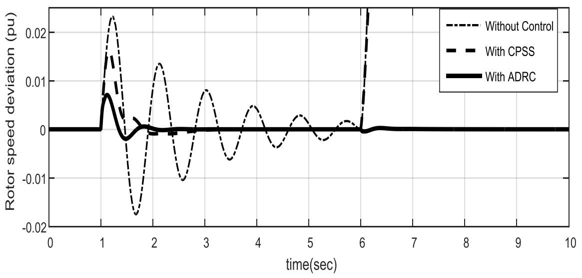

Fig. 10. Rotor Speed Deviation for Case Study No.3

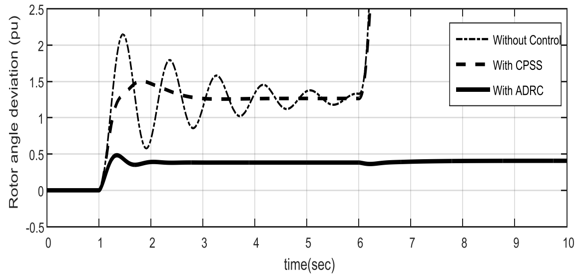

Fig.11. Rotor Angle Deviation for Case Study No.3

From the results obtained in case 1 and case 2, it is visible that the proposed ADRC method has a better dynamic performance regarding stability with the corresponding improvement in overshoots and undershoots than the CPSS. Moreover, the superiority of ADRC against system structural uncertainty is clearly demonstrated in the simulation results of case 3 where the ADRC maintained its robust performance at severe operating point while the conventional stabilizer failed at that point even though it has been optimally tuned.

VI. CONCLUSION

Since power system is frequently undergoing changes, conventional power system stabilizer can become inefficient in the case of serious operation conditions. In this paper, the ADRC controller has been employed as a satisfactory solution to damp low-frequency oscillations in a wide range of circumstances. The considered control approach has been compared, in this study, to an optimally tuned classical PSS controller. All conditions were chosen to be equal for both of the controllers to have a fair comparison. For the purpose of testing the robustness, both of the control methods were first designed for a certain operating point. Then, this point was changed several times in the presence of external disturbance, and simulations were repeated without any change in the controller parameters.

The simulation results were obtained under MATLAB environment, and the effectiveness of the proposed ADRC method has been evaluated through time–domain simulations. The results demonstrate that the Extended State Observer (ESO), being a main part of ADRC, effectively estimated the total disturbance, which includes the external disturbances, modelling imprecision, and other system perturbations. And therefore The ADRC exhibited magnificent performance in terms of making the power system more robust against high external disturbances as well as system uncertainty problems.

APPENDIX A

Generator parameters (p.u.):

$$\mathbf{X_d = 1.97\,, X_q = 1.9\,, X_d' = 0.3\,, T_{do} = 6.84\,, H = 3\,,}$$
$$\mathbf{D = 0\,, V_t = 1.01, F = 50\ Hz.}$$

Exciter parameters:

$$\mathbf{K_A = 100\,,\ \ T_A = .02\ s}$$

Transmission line parameters (p.u.):

$$\mathbf{R_e = 0\,,\ \ X_e = 0.4}$$

CPSS parameters:

$$\mathbf{T_1 = 0.2\ s\,, T_2 = 0.0895\ s\,, T_w = 0.5\ s\,,}$$
$$\mathbf{K_{pss} = 17.3618}$$

APPENDIX B

Calculation of Heffron-Phillips K-constants:

$$K_1 = \frac{(x_q - x_d')i_{q0}E_0\sin\delta_0}{x_e + x_d'} + \frac{E_{q0}E_0\cos\delta_0}{x_e + x_q}\ ;$$

$$K_2 = \frac{E_0\sin\delta_0}{x_e + x_q'}\ ;\quad K_3 = \frac{x_e + x_d'}{x_e + x_d}\ ;$$

$$K_4 = \frac{(x_d - x_d')E_0\sin\delta_0}{x_e + x_d'}\ ;$$

$$K_5 = \frac{x_q e_{d0}E_0\cos\delta_0}{(x_e + x_q)e_{t0}} + \frac{x_d' e_{q0}E_0\sin\delta_0}{(x_e + x_d')e_{t0}}\ ;$$

$$K_6 = \frac{x_e e_{q0}}{(x_e + x_d')e_{t0}}$$

The parameters $\mathbf{i_{q0}}$, $\mathbf{e_{d0}}$, $\mathbf{e_{q0}}$, $\mathbf{i_{d0}}$, $\mathbf{E_0}$, $\mathbf{E_{q0}}$ and $\boldsymbol{\delta_0}$ can be calculated for given operating point ($\mathbf{P_0, Q_0\,, e_{t0}}$) using the following equations:

$$i_{q0} = \frac{P_0 e_{t0}}{\sqrt{(P_0 x_q)^2 + (e_{t0}^2 + Q_0 x_q)^2}}\ ;$$

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$$\mathbf{e_{d0} = i_{q0} x_q} \quad ;$$

$$\mathbf{e_{q0} = \sqrt{e_{t0}^2 - e_{d0}^2}} \quad ; \quad \mathbf{i_{d0} = \frac{Q_0 + i_{q0}^2 x_q}{e_{q0}}} \quad ;$$

$$\mathbf{E_0 = \sqrt{(e_{d0} + i_{q0} x_e)^2 + (e_{q0} - i_{d0} x_e)^2}} \quad ;$$

$$\mathbf{E_{q0} = e_{q0} + i_{d0} x_q} \quad ; \quad \mathbf{\delta_0 = \tan^{-1}(\frac{e_{d0} + i_{q0} x_e}{e_{q0} - i_{d0} x_e})}$$

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