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A NOVEL APPROACH FOR TUNING OF MINIMUM PERFORMANCE ROBUST PSS USING GENETIC ALGORITHM

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ABSTRACT

This paper presents a novel approach for designing a fixed gain robust power system stabilizer (PSS) with particular emphasis on achieving a minimum closed loop performance, over a wide range of operating and system condition. The minimum performance requirements of the controller has been decided apriori and obtained by using a genetic algorithm (GA) based power system stabilizer. The proposed PSS is robust to changes in the plant parameters brought about due to changes in system and operating condition, guaranteeing a minimum performance. The efficacy of the proposed method has been tested on a multimachine system. The proposed method of tuning the PSS is an attractive alternative to conventional fixed gain stabilizer design, as it retains the simplicity of the conventional PSS and still guarantees a robust acceptable performance over a wider range of operating and system condition.

KEY WORDS

Power system stability, Power system stabilizer, Robust control, GA based controllers

1 Introduction

Various disturbances like sudden change in loads, changes in transmission line parameters, fluctuations in output of turbine and faults etc., result in low frequency oscillations which are associated with the electromechanical modes of the system. The use of fast acting high gain AVRs and evolution of large interconnected power systems with transfer of bulk power across weak transmission links have further aggravated the problem of low frequency oscillations. Damping of these oscillations is necessary as they limit the power transfer capability of the network. The application of power system stabilizer can help in damping out these oscillations and improve the system stability[1]. The traditional and till date, the most popular solution to this problem is application of conventional power system stabilizer (CPSS)[2]. However, continual changes in the operating condition and network parameters result in corresponding change in system dynamics. This constantly changing nature of power system makes the design of CPSS a difficult task.

Adaptive control methods have been applied to overcome this problem with some degree of success[4]. However, the complications involved in implementing such controllers restrict their practical use.

In recent years there has been a growing interest in robust stabilization and disturbance attenuation problem[5]. H_∞ control theory provides a powerful tool to deal with robust stabilization and disturbance attenuation problem[6]. However, with the standard H_∞ control theory, it is often difficult to obtain a desired degree of performance as well as a minimum performance guarantee over the entire expected range of operation of the power system.

This paper provides an alternative method of designing a fixed parameter controller to ensure robustness under model uncertainties. Minimum performance required of the PSS is expressed in terms of the placement of the closed loop poles of the system on the s-plane for the entire range of operation. This is achieved by first formulating objective functions based on system eigen values of a linearized model of the multimachine system and then optimizing these objective functions using Genetic Algorithmic techniques to attain the desired level of performance for the system.

Recently, genetic algorithms are being widely used for PSS design. Abdel-Magid [8], and Taranto[9] have applied parameter optimization using GA. The basic operating principles of GAs[10] are based on the principles of natural evolution. There are many variations of the genetic algorithms with the basic form being the simple genetic algorithm (SGA). This algorithm works with a set of population of candidate solution represented as strings. The initial population consists of randomly generated individuals. At every iteration of the algorithm, fitness of each individual in current population is computed. The population is then transformed in stages to yield a new current population for next iteration. The transformation is usually done in three stages by simply applying the following genetic operators: (1) Selection, (2) crossover, and (3) mutation. In the first stage selection operator is applied as many times as there are individuals in the populations. In this stage every individual is replicated with a probability proportional to its relative fitness in the population. In the next stage, the crossover operator is applied. Two individuals (Parents) are chosen and combined to produce two new individuals. The combination is done by choosing at random a cutting point at which each of parents is divided into two parts, these are exchanged to form the two offspring which replace their parents in the population. In the final stage, the mutation operator changes the values in a randomly chosen location on an individual. The algorithm terminates after a fixed number iterations and the best individual generated during the run is taken as the solution.

2 Problem Formulation

2.1 Performance Requirements of Power System Stabilizers

Practical considerations merely require that the troublesome low frequency oscillations, when excited, die down within a reasonable amount of time. No advantage is gained by having excessive damping for these system modes. In fact, it has been noted[2] that aggressive damping of oscillations can have detrimental effects on the system. Hence, rather than maximizing the damping at some particular operating condition, it seems more appropriate to decide upon the minimum amount of damping or minimum performance required of the closed loop and attempt to achieve this over the entire range of operating conditions which the system experiences. This set of operating conditions, which any given power system might experience, is always known a priori in terms of maximum and minimum values of power generations, transmissions and loads and all possible values of the network impedances. It is therefore possible to model this bounded variation in the system as an uncertainty and attempt to synthesize a PSS delivering the required performance over this entire range of variations.

The following points have been taken into considerations for deciding the performance requirements of a power system stabilizer.

- The frequency of oscillation is related to synchronizing torque and hence the imaginary part of the rotor mode eigen value should not change appreciably due to feed back.

- If any new modes arise as a result of closing the controller loop (e.g. exciter mode), these should also be well damped i.e. they should satisfy the same constraints on the real part and damping factor as the rotor modes.

- Real poles close to the origin can result in a sluggish response and persistent deviations of the system variables from their steady state values and hence should be avoided.

If all the closed loop system poles are located to the left of the contour shown in Fig.1, then the constraints on the damping factor and the real part of rotor mode eigen values are satisfied and a well damped small disturbance response is guaranteed. This contour is referred as the D-contour[7]. A system is said to be D-stable if all its pole lie on the left of this contour. This property is referred to as generalized stability in control literature.

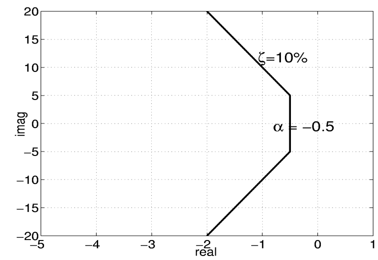


Figure 1. The D-contour on s-plane

2.2 How Much Damping do We Need?

In power system, a damping factor ζ, of at least 10% would be acceptable to most utilities and can be adopted as the minimum requirement. Further, having the real part of rotor mode eigen value restricted to be less than a value, say α, guarantees a minimum decay rate α. A value α = - 0.5 is considered to be adequate for an acceptable settling time. The closed loop rotor mode location should simultaneously satisfy these two constraints for an acceptable small disturbance response of the controlled system.

2.3 System Representation

In the study, both linear and nonlinear models of the multimachine system have been considered. Each machine is represented by IEEE model 1.1[3] and the differential equations representing the dynamics of system are given in ref[11].

Linearized 1.1 machine model for the i_{th} machine can be expressed as

$$\dot{x}_{mi} = [A_{mi}]x_{mi} + [B_{m1i}]\Delta i_{mi} + [B_{m2i}]\Delta E_{fdi} + [B_{m3i}]\Delta T_{mi} \quad (1)$$

where, $\Delta i^t_{mi} = [\Delta i_{di}\ \Delta i_{qi}]$, $x^t_{mi} = [\Delta\delta_i\ \Delta S_{mi}\ \Delta E^{'}_{qi}\ \Delta E^{'}_{di}]$, $[A_{mi}]$ is state matrix and depends upon operating conditions, $[B_{m1i}]$ is related to flux linkage with d-axis and q-axis, $[B_{m2i}]$ and $[B_{m3i}]$ are coefficient matrixes, ΔE_{fdi} is change in output of AVR and ΔT_{mi} is the change in mechanical torque. Description of the various terms and network model is given in ref[11].

The excitation system, represented by a first order model adequately describes a thyristor excitation system. Fig.2 shows the block diagram of excitation system. In the block diagram, K_a and T_a are the AVR gain and its time constant respectively, V_t is terminal voltage of the generator, V_s is the output of PSS and V_{ref} is reference input voltage. Windup limiter, with upper and lower limits E_{fdmax}

and E_{fdmin} respectively, has been considered to limit the output of the AVR.

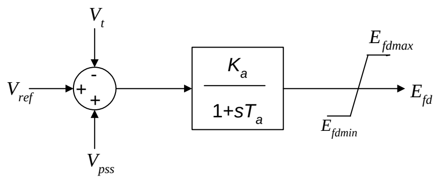


Figure 2. Excitation System

Two stage lead-lag PSS with following transfer function is considered.

$$V_{pss} = K_S \left(\frac{sT_w}{1+sT_w}\right)\left(\frac{1+sT_1}{1+sT_2}\right)^2 \Delta S_m \qquad (2)$$

where K_s is PSS gain, T_1 and T_2 are lead and lag time constants of PSS, T_w is the washout circuit time constant, ΔS_m is change in slip. Upper and lower limits of limiter are V_{smax} and V_{smin}.

2.4 Objective Function

As shown in Appendix I, the equation of D-contour shown in Fig.1 can be written as

$$f(z) = Re(z) - \min[-\zeta|Im(z)|,\ \alpha] = 0 \qquad (3)$$

where $z \in \mathcal{C}$, is a point on D-contour, $\mathcal{C}$ represents the complex plane.

Define *J* as

$$J = \max_{i}[Re(\lambda_i) - \min\{-\zeta|Im(\lambda_i)|,\ \alpha\}] \qquad i = 1,2,...,n \qquad (4)$$

where, n is the number of eigen values. λ_i is the i_{th} eigen value of the system at an operating point. A negative value of J implies that all the eigen values lie on the left of the D-contour. Similarly some or all eigen values will lie on the right of the D contour, if, J is positive. On the basis of these facts, objective function F is defined as

$$F = \begin{cases} J & if\ J \leq 0 \\ \beta & if\ J > 0 \end{cases} \qquad (5)$$

where, β is a large positive constant. Optimization problem can be stated as

Minimize *F*

Subjected to:

$$\begin{array}{l} K_{sj}^{min} \leq K_{sj} \leq K_{sj}^{max} \\ T_{1j}^{min} \leq T_{1j} \leq T_{1j}^{max} \\ T_{2j}^{min} \leq T_{2j} \leq T_{2j}^{max} \\ \qquad j = 1,2,...,m \end{array} \qquad (6)$$

where, m is the number of machines. K_{sj}, T_{1j} and T_{2j} are PSS parameters of j_{th} machine.

3 Proposed Method of Optimization

The proposed method can be explained in following steps:

$Step$ *1*. Start with an initial operating condition,preferably suggested by Larsen and Swann[2], i.e. for speed input PSS strong system with heavy loading.

$Step$ *2*. Solve the constrained optimization problem given by equation(6) using genetic algorithm and obtain the PSS parameters.

$Step$ *3*. Once PSS parameters are obtained check for robustness with these parameters. For this, generate a set of loading conditions.

$Step$ *4*. Run load flow for each loading condition, eliminate those loading conditions for which load flow does not converge.Obtain the operating conditions from load flow.

$Step$ *5*. For each operating, condition evaluate J, as given in equation(4).

$Step$ *6*. If $J \leq 0$ for all operating conditions then all the eigen values lie on the left of the D-contour, hence PSS parameters obtained in step 2 guarantee minimum performance of PSS with robustness.

$Step$ *7*. If $J > 0$ for some operating conditions then take the operating for which J is maximum positive as an initial condition. Go to step 2 and repeat the procedure till the criteria given in step 6 is satisfied for all operating conditions.

The flow chart for the above mentioned process is shown in Fig.3. It is clear from the flow chart that each set of PSS parameter undergoes the robustness screening. After screening of all the sets only that set is selected which satisfies the minimum performance criteria for the entire set of operating conditions.

4 Case Study

4.1 Multimachine System

The proposed method has been applied for PSS design in 3 machine 9 bus power system model. Single line diagram of the system is shown in Fig.4 and machine data are given in ref[12],[13]. Each machine is equipped with exciter having $K_a = 100$ and $T_a = 0.05$. Limits of the AVR outputs are taken as ± 7. PSS is employed on each of the three machines. T_w is taken as 10 and output of the PSS is limited to ± 0.15pu.

PSS parameters $(K_{si}, T_{1i}, T_{2i},\ i = 1,2,3)$ are optimized simultaneously using genetic algorithm. Population size, number of generations, crossover probability and probability of mutation were taken as 500, 400, 0.95 and 0.033 respectively. The optimal parameters, obtained using proposed algorithm, are shown in Table 1.

CPSS was designed using tuning guidelines given in ref [2]. Performance of the proposed PSS is compared with CPSS, employed on each machine with the following trans-

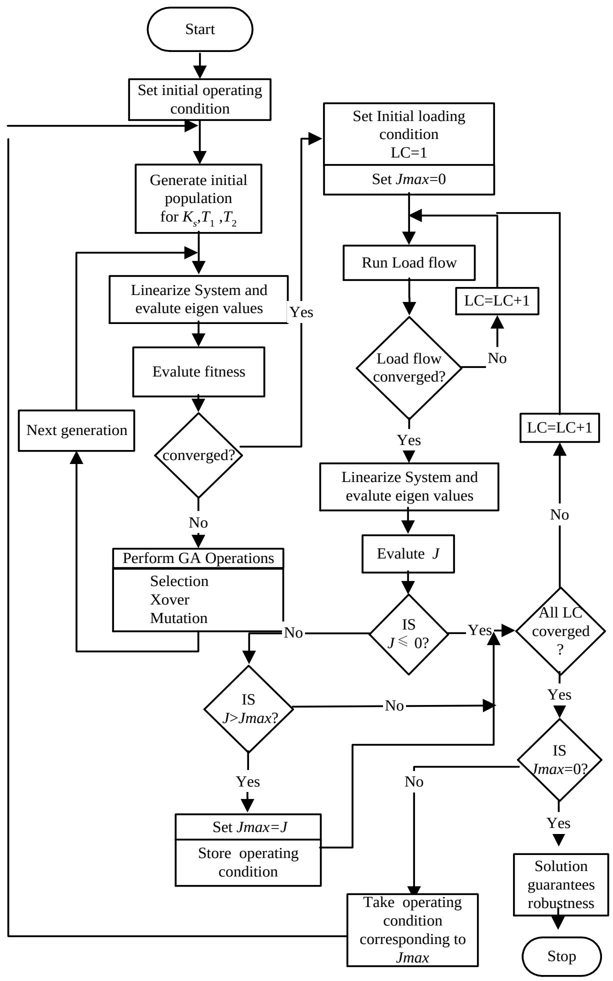


Figure 3. Flow chart for the proposed approach

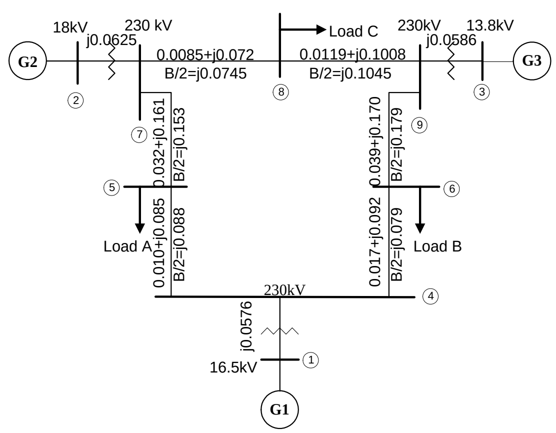


Figure 4. 3 machine 9 bus system

fer function

$$V_{pss} = 2.0 \left(\frac{10s}{1 + 10s} \right) \left(\frac{1 + 0.22178s}{1 + 0.05s} \right)^2 \Delta S_m \qquad (7)$$

Table 1. Optimal stabilizer parameters of proposed PSS

Generator	K_S	T_1(sec)	T_2(sec)
G_1	23.641	0.1245	0.0244
G_2	2.910	0.3215	0.0895
G_3	3.732	0.1704	0.0364

4.2 Eigen Value Plots

A range of operating conditions for this system was obtained by varying the system loads and generations from 35% to 250% of the base case. Table 2 shows the nominal (base case), minimum and maximum loading conditions of the system.

Table 2. Loading conditions of 3 machine, 9 bus system

Bus No.	Power injection(pu)					
	Minimum		Nominal		Maximum	
	P	Q	P	Q	P	Q
1*	-	-	-	-	-	-
2+	0.570	-	1.63	-	3.994	-
3+	0.296	-	0.85	-	2.083	-
4	0.000	0.000	0.00	0.00	0.000	0.000
5	-0.438	-0.175	-1.25	-0.50	-3.060	-1.225
6	-0.315	-0.105	-0.90	-0.30	-2.205	-0.735
7	0.000	0.000	0.00	0.00	0.000	0.000
8	-0.350	-0.123	-1.00	-0.35	-2.450	-0.858
9	0.000	0.000	0.00	0.00	0.000	0.000

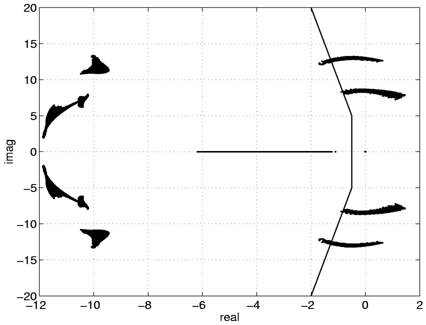
*slack bus, +PV bus.

From the loading conditions given in Table 2, approximately 60,000 operating conditions were generated to test the performance of the proposed PSS for a wide range of operating conditions. Eigen value plots for these operating conditions are shown in Fig.5.

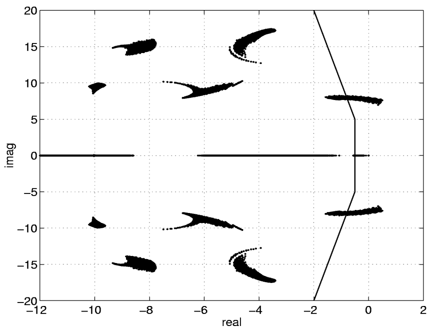
Fig.5(a) shows the open loop poles of the system for the range of load variation.The low frequency oscillatory modes are seen to be poorly damped or undamped for most of the operating conditions. Fig.5(b) shows that by using the CPSS these modes can be shifted in the left of the D-contour, up to some extent. Fig.5(c) shows the system poles with proposed PSS. As seen, The low frequency modes have been shifted into the acceptable region.

4.3 Simulation Results and Discussion

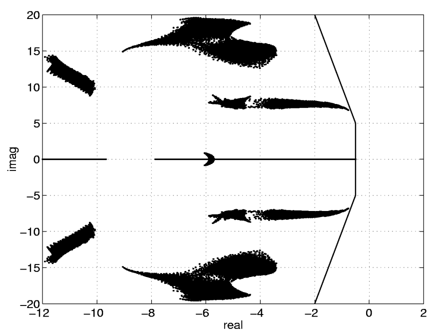
The system is simulated for 10 sec, for various operating conditions as shown in Table 3.The responses of the system with proposed stabilizer have been compared with system equipped with CPSS and system without PSS. Machine 1 has the highest inertia constant and this is taken as the reference. The responses of $S_{m21}(= S_{m2} - S_{m1})$ and $S_{m31}(= S_{m3} - S_{m1})$ have been plotted for each disturbance which is initiated at $t = 1.0$ sec. The following



(a) Open loop poles



(b) Closed loop poles with CPSS



(c) Closed loop poles with proposed PSS

Figure 5. Eigen value plots

Table 3. Operating points of generators on a 100 MVA base

	Heavy		Nominal		Light		other	
	P	Q	P	Q	P	Q	P	Q
G_1	2.21	1.09	0.71	0.28	0.36	0.17	1.85	0.73
G_2	1.92	0.57	1.63	0.07	0.80	-0.11	3.85	0.93
G_1	1.28	0.36	0.85	-0.11	0.45	-0.20	2.00	0.23

	Heavy	Nominal	Light	other
Y_{LA}	2.314-j0.925	1.261-j0.504	0.640-j0.542	3.383-j0.194
Y_{LB}	2.032-j0.677	0.878-j0.293	0.431-j0.335	2.004-j0.109
Y_{LC}	1.584-j0.634	0.969-j0.339	0.472-j0.236	2.503-j0.126

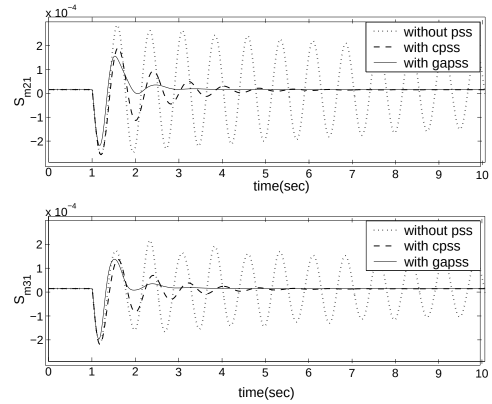


Figure 6. Step change in mechanical torque($\Delta T_m = 0.1$ pu) at generator 1 under heavy loading condition.

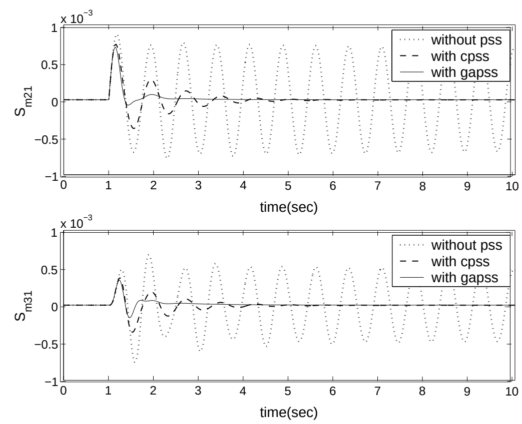


Figure 7. Step change in mechanical torque($\Delta T_m = 0.1$ pu) at generator 2 under normal loading condition.

cases have been considered.

(a) A step change of 0.1 pu in the input mechanical torque.

(b) A three-phase to ground fault for 100 ms between buses 6 and 9, and then removal of line between these buses.

Fig.6 to Fig.8 illustrate the simulation results under step changes in input mechanical torque. With proposed PSS settling time as well as peak overshoot is less than that could be achieved with CPSS. Fig.9 shows the case of an operating condition for which CPSS is unstable.

Fig.10 illustrates the situation when there is a three-phase to ground fault between buses 6 and 9 under heavily loaded operating condition. The system is unstable for this disturbance without stabilizer but it is stable with both stabilizers.With proposed stabilizer oscillations are damped within 2 sec.

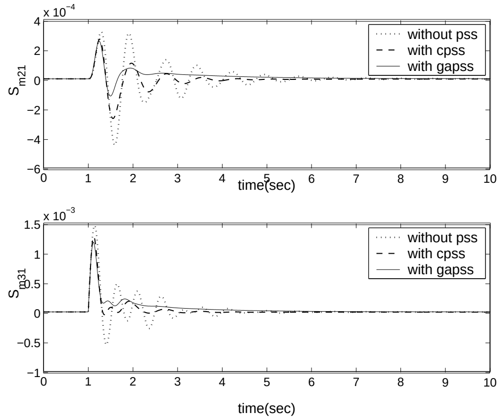


Figure 8. Step change in mechanical torque($\Delta T_m = 0.1$ pu) at generator 3 under light loading condition.

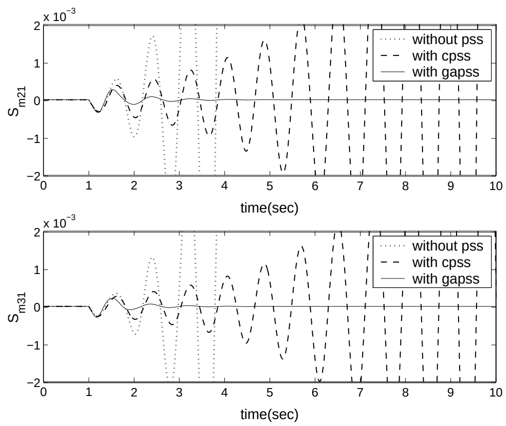


Figure 9. Step change in mechanical torque($\Delta T_m = 0.1$ pu) at generator 1 under other loading condition given in Table 3.

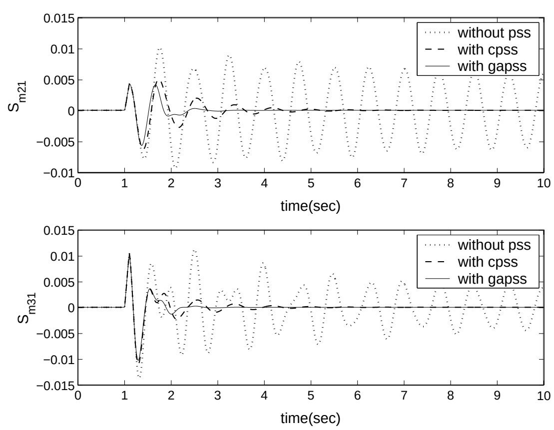


Figure 10. Three phase fault for 100 ms between buses 6 and 9.

5 Conclusion

Performance evaluation of proposed PSS on multimachine system shows that robust fixed parameter stabilizers are indeed a viable solution to the problem of low frequency oscillations. Eigen value analysis and extensive simulation studies show that the proposed method for PSS design provides the desired closed loop performance over the prespecified range of operating conditions. Furthermore, robust performance of the proposed PSS over a widely varying operating conditions shows its superiority over existing stabilizers. The attractive features of the proposed stabilizer are its simple structure and design procedure. Due to simple design procedure and robust performance the proposed stabilizer bears much potential for practical implementation.

Appendix Proof of the Equation 3

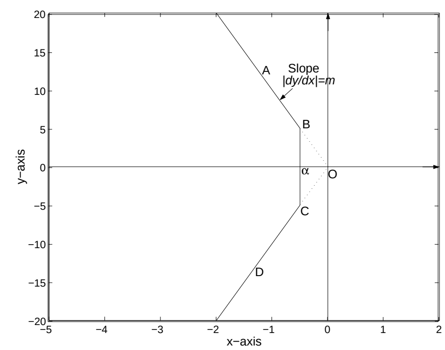


Figure 11. D-contour in $x - y$ plane

Consider the Fig.11. As shown, the equation of lines ABO and CDO in $x - y$ plane can be written as:

$$\begin{aligned} & |y| = -m.x \\ \Rightarrow \quad & x = -\frac{1}{m}|y| \\ \Rightarrow \quad & x + \frac{1}{m}|y| = 0 \end{aligned} \tag{8}$$

where m is the +ve slope of the line (i.e. $m = |\frac{dy}{dx}|$). Now equation of line BC can be written as:

$$\begin{aligned} & x = \alpha \\ \Rightarrow & \, x - \alpha = 0 \end{aligned} \tag{9}$$

Combining Equations 8 and 9, the equation of D-contour $ABCD$ can be written as

$$x - \min\{-\frac{1}{m}|y|, \alpha\} = 0 \tag{10}$$

Defining $\frac{1}{m} = \zeta$, and considering the case of complex plane, Equation 10 can be written as:

$$f(z) = Re(z) - \min[-\zeta|Im(z)|,\ \alpha] = 0 \tag{11}$$

where $z = x + iy$ (i.e. $x = Re(z)$ & $y = Im(z)$).

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