Use of Normal Forms Technique In Control Design
Part II: Numerical Results

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Abstract: This is Part II of a two part paper dealing with control design in power systems using the method of normal forms. The companion paper (part I) [1] describes the general theory and control procedure. This paper depicts numeral results to show the validation of the proposed method and to observe the effects of controller setting changes.

1. Introduction

In [1], we have provided the analytical developed of a procedure which uses the method of normal forms [2-4] to include the effect of nonlinear terms in tuning control parameters. Specifically, we have developed a procedure to tune settings for excitation control. A systematic technique to identify the critical modes, and a control tuning procedure have been developed in [1]. The critical mode identification is based on the determination of a nonlinear interaction index I1 developed in [2]. This index I1 provides a measure of the most important modes in terms of the magnitude of the nonlinear interaction. The tuning procedure utilizes the concepts of linear eigenvalue sensitivity, linear participation factors, sensitivity of the normal forms coefficients, and second order participation factors to improve stability and reduce the nonlinear interaction. In order to measure the reduction in the nonlinearity we utilize another index I2.

In the paper we conduct a testing of the proposed gain tuning procedure on the 50-generator IEEE test system [5]. The results obtained demonstrate the efficiency of the procedure.

2. Numerical Results

The proposed procedure was applied to the 50-generator IEEE test system [5], a portion of this system is shown in Figure 1, below. We consider a three phase stub fault at Bus #7 with clearing time t_{cl} = 0.05 sec. Generators at Buses #93 and #110 are producing 900MW each under constant loading conditions.

For the following discussion it is important to keep in mind that the linear analysis (eigenvalues, eigenvector matrix, and linear participation factors) and the nonlinear analysis are performed at the post-fault SEP. Both systems exhibit the same (global) stability behavior at the SEP.

As a base Case I, the gains of the exciters at Buses #104 and #111 are set to Ka=200, and those at Buses #105 and #106 are set to Ka=50. Changing the control setting (in our case gains on the exciters) changes the post-disturbance equilibrium point, so SEP's are different for different cases.

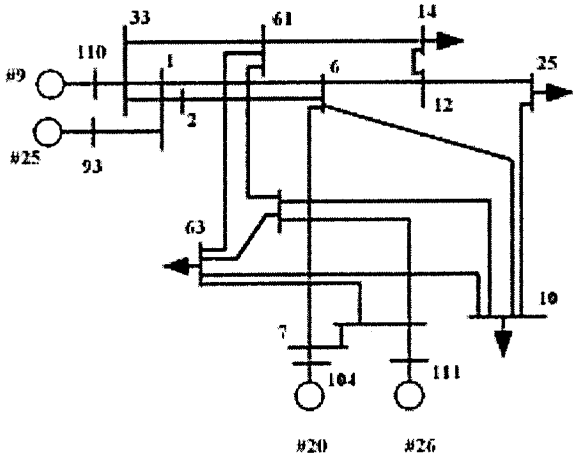

Figure 1: 50-generator System

Linear analysis identifies two low frequency inertial modes, namely modes 95 and 97. The eigenvalues of these modes are given in Table 1. We will concentrate on these modes and their interaction with control modes throughout this section. Table 2 shows the states participating in the important modes. These are modes 95 and 97, and the control modes corresponding to the exciters at Bus#104&111 and at Bus#105&106, because we will use the gain settings of these exciters for our analysis.

Table 1: Eigenvalues of low frequency modes

Mode	Eigenvalues
95	-0.00329 ± j2.05431
97	-0.00251 ± j1.89205

Table 2: Participating States

Mode	Participating States
95	X50,x44,x43,x42,x48,x36,x38,x40,x5,x1
97	X43,x50,x44,x42,x36
101	Xe3,x3,xe4,x4
103	Xe2,x2,xe6,x6,xe1
116	X5,x1,x3,xe5,xe1,x4,xe2

From Table 2 we see that mode 95/96 is an inter-area mode, mode 101/102 is the control mode dominated by the Bus#105&106 exciters, and mode 103/104 is dominated by the Bus#104&111 exciters. The control mode 116 shows participating states from both exciters. It is important to notice that modes 95 and 97 show no substantial participation of exciter states, and that modes 101,103,116 have no participation of the inertial modes 95 and 97. Therefore, on this level of linear analysis it is not possible to predict the influence of the control settings on the important inertial modes.

In order to understand, how the exciter gains influence the eigenvalues of modes 95 and 97, we compute their eigenvalue sensitivity with respect to Ka (Bus#104&111) and Ka (Bus#105&106). The results are shown in Table 3. The linear sensitivity analysis indicates that the real part of mode #95 is affected more by the gain settings of the exciters at Bus #104&111 than Bus#105&106 as seen by the higher value of the eigenvalue sensitivity. Increasing the gain will push the eigenvalue into the right half plane.

Table 3: Eigenvalue sensitivity

Mode	Ka of #104&111	Ka of #105&106
95	0.966e-4+j0.728e-4	0.709e-4-j0.908e-4
97	0.295e-4+j0.279e-4	0.271e-4-j0.297e-4

We express the dependence of the eigenvalues on Ka (Bus#104&111) and Ka (Bus#105&106) as a linear function, using the values from Tables 1 and 3. This corresponds to the first order term in the Taylor expansion of the eigenvalues as functions of Ka. We obtain for the real part of mode 95 as a function of Ka (Bus#104&111):

$$\lambda_N = 0.0000966 * Ka - 0.02260$$

and as a function of Ka (Bus#105&106):

$$\lambda_P = 0.0000709 * Ka - 0.006836$$

Table 4 shows some values of these functions, and the true values obtained from the analysis of the nonlinear system with corresponding gain settings.

Table 4: Eigenvalue dependence of modes 95&97

Ka's		Linear sensitivity		Full system	
		Mode 95	Mode97	Mode95	Mode97
200	50	-.003289	-.002513	-.003289	-.002513
180	50	-.005221	-.003103	-.005344	-.003169
200	45	-.003646	-.002646	-.003636	-.002644
240	50	.000572	-.001334	.000046	-.001594
200	60	-.002582	-.002239	-.002545	-.002224

On the level of linear sensitivity of the real parts of the eigenvalue it can be seen that mode 95 is more sensitive to exciter gain changes than mode 97. The influence of both exciters is of similar magnitude in both modes. From these data it is not clear, via which mechanism the exciters influence the critical inertial modes, nor is it clear, which exciters have dominant influence. The following analysis based on second order normal forms will explain these phenomena.

Nonlinear analysis

The nonlinear interaction index I1 for the important inertial and control modes is given in Table 5. Modes 95 and 97 are identified as the critical low frequency modes (rank 1 and 2 among these modes), and modes 103 and 101 are the important control modes with participating states dominated by the respective exciters at Bus#104&111, and Bus#105&106.

Table 5: Nonlinear interaction index I1

Mode	Index I1	Rank
95	4.361	13(2)
97	4.410	11(1)
101	12.128	7
103	12.297	5

The second order interaction coefficients identify those modes that contribute most to the nonlinear (second order) solution of the critical modes. These solutions consist of two terms, the first shows the (nonlinear) dependence on the initial value z_0, the second term account for the nonlinear interaction h2 * z_0 * z_0. The corresponding values are presented in Table 6.

Table 6: z_{jo} and 2nd order interactions

Mode	z_{jo}	$h2^j_{kl} * z_{ko} * z_{lo}$
95	0.211∠-141.0	(116,116)3.68∠33.6 (101,102)2.83∠37.1 (101,116)1.64∠-45.6 (103,104)0.92∠-165.1
97	1.801∠101.9	(116,116)2.57∠-94.7 (101,102)1.97∠-91.9 (81,82)1.40∠34.9 (103,104)0.67∠68.7
101	11.812∠178.7	(103,104)4.98∠36.9 (101,115)3.09∠-77.9 (116,116)3.06∠27.2
103	7.205∠-57.6	(103,115)4.95∠-97.4 (97,104)3.03∠146.4 (103,104)2.04∠-126.3
116	7.788∠0.0	(103,104)7.36∠0.0 (115,116)0.62∠0.0 (116,116)0.60∠0.0

This Table 6 identifies the control mode 116 as the dominant interaction mode for both inertial modes, followed by the control modes 101 and 103. In order to assess the influence of the exciter gains on the behavior of the inertial modes 95 and 97, we look at the participation factors and at the sensitivity of the normal form transformation with respect to exciter gains. Linear participation analysis (Table 2) shows that mode 101/102 is dominated by the exciters at Bus#105 &106,

mode 103/104 by the exciters at Bus#104&111, and mode 116 shows participation from both inertial and control modes. The nonlinear second order participating states are given in Table 7.

Table 7: Nonlinear participating states

Modes	Participating states
(116,116)	xe2,xe6
(102,102)	xe2,xe3,xe6,xe4
(103,104)	xe1,xe6,xe5,xe2

The interaction mode (116,116) is dominated by the exciters at Bus#104&111, and even the modes (101,102) and (103,104) show substantial influence of the same exciters. This indicates that gain variation at the exciters at Bus#104&111 will have the greatest influence on the systems nonlinear behavior. This agrees with the (linear) eigenvalue sensitivity reported in Table 3.

Sensitivity of the normal form coefficient indicates, how fast and in which direction the nonlinearity in the system changes depending on exciter gain variation. Table 8 contains the sensitivities of the second order coefficients of the inertial modes with respect to gain variation at Bus#104&111 (Ka2) and Bus#105&106 (Ka3).

Table 8: Sensitivity of the 2nd order normal form coefficients

j	(k,l)		Rectangular	Polar
95	(103,104)	Ka2	0.78e+0+j0.85e+0	0.12e+1 ∠ 47.4
		Ka3	-0.48e+0-j0.92e-1	0.49e+0 ∠ 190.9
	(104,118)	Ka2	-0.21e-2+j0.41e-1	0.41e-1 ∠ 92.9
		Ka3	-0.13e-1+j0.11e-2	0.13e-1 ∠ 175.1
	(103,118)	Ka2	-0.51e-1+j0.53e-1	0.73e-1 ∠ 133.9
		Ka3	0.58e-2+j0.22e-1	0.22e-1 ∠ 74.8
	(116,116)	Ka2	-0.17e-4+j0.22e-4	0.28e-4 ∠ 231.7
		Ka3	0.11e-4-j0.30e-4	0.32e-4 ∠ -69.5
	(101,102)	Ka2	-0.50e-4-j0.58e-4	0.77e-4 ∠ 229.2
		Ka3	0.21e-2-j0.28e-2	0.35e-2 ∠ -54.1
97	(103,104)	Ka2	0.48e+0+j0.92e+0	0.10e+1 ∠ 62.4
		Ka3	0.16e-1+j0.32e-1	0.36e-1 ∠ 63.9
	(103,118)	Ka2	-0.59e-1+j0.48e-1	0.75e-1 ∠ 140.8
		Ka3	0.83e-2+j0.25e-1	0.26e-1 ∠ 71.4
	(116,116)	Ka2	0.12e-5-j0.19e-4	0.19e-4 ∠ -86.6
		Ka3	0.18e-4-j0.34e-4	0.38e-4 ∠ -61.4
	(101,102)	Ka2	0.18e-4-j0.64e-4	0.66e-4 ∠ -74.7
		Ka3	0.25e-2-j0.37e-2	0.45e-2 ∠ -55.4
	(81,82)	Ka2	-0.36e-3-j0.56e-3	0.66e-3 ∠ 237.4
		Ka3	-0.59e-3+j0.66e-3	0.88e-3 ∠ 132.0

This Table 8 shows that both inertial modes are most sensitive to the variation of the exciter gain at Ka2(Bus#104&111). The interacting modes that are predominantly affected by the change of Ka2 all contain participating states of the exciters at Bus#104&111, hence increasing the gain Ka2 will lead to an increase in the nonlinear behavior of the system as shown by the results of Table 4, and 8. In addition we also note that the linear sensitivity analysis does not correctly capture the change in stability behavior for the change in exciter settings because of the nonlinearity caused by the change. As a result, these cases illustrate the importance of using the normal forms analysis to include the effects of the nonlinearity.

3. Conclusions and Discussions

Initial results on a sample test system, demonstrate the importance of including the effect of the second order nonlinear terms in the analysis. The results provided also indicate some of the shortcomings of the linear approach, and illustrate the nature of the added information provided by the higher order terms. The nonlinear interaction index I1 clearly identifies the control modes interacting with the inertial modes, and the use of the nonlinear participation factors provided information regarding the states participating in the interacting modes. The sensitivity of the nonlinear coefficients to the identified control parameters provides information on the changes to the settings to reduce nonlinearity and improve stability.

References

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