CHAPTER 6

TEST RESULTS

The developed algorithm is applied with two test systems. The first one is the popular Western System Coordinating Council (WSCC) 3-machine, 9-bus system shown in Fig. 6.1. This system is used to validate the developed program. In literature [14] there are some discussions about this system. They calculate the operating condition from the nominal loading, initial condition of all variables, eigenvalues and participation factor of the system. Those calculation will be compared with the calculation from developed program so that we sure that the developed program is correct.

The next test system will be the system in the south part of Thailand, shown in Fig. 6.2. We want to get the state space model of the system and analyze the result. Beside the analysis that discussed in literature [14], we will do other analysis which is also important. From the developed program, we can calculate frequency and damping ratio of oscillation for each mode. Thus we can classify the problems into two types : local oscillation problem or global oscillation problem. In addition, we also calculate the controllability and observability of the system.

6.1 Program Validation Using WSCC Test System
This system appears in literature [3,14,15] and is widely used in some literatures.
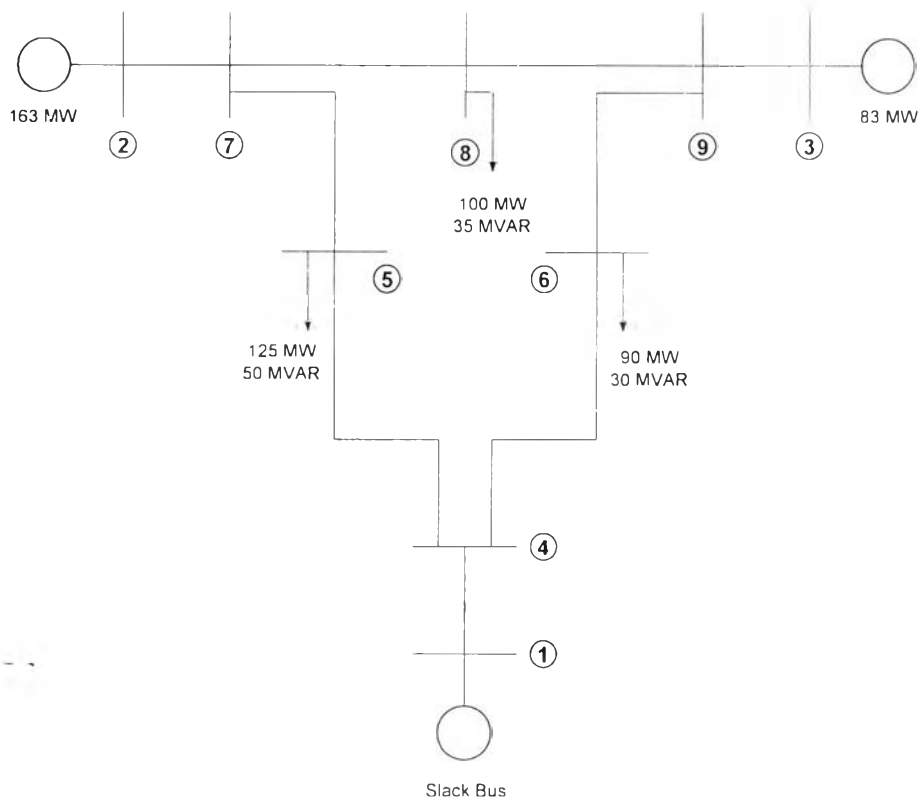

Figure 6.1 A single line diagram of the Western System Coordinating Council (WSCC) [14].

This system consists of three generators and nine buses. Generator no 1 is a slack/swing bus, no 2 and 3 are a PV bus. The rest of buses are load buses. The input data needed to run the program are : network data, parameter data of generator and exciter, parameter data of HVDC. Network data is consists of bus data, generator data, HVDC data, branch data. Table 6.1-6.3 showed the network data of the system. Generator and exciter parameters are shown in Table 6.4-6.5.

Table 6.1 Bus data of the WSCC

Bus	Type	Pd	Qd	Gs	Bs	Area	Vm	Va	baseKV	Zone	Vmax	Vmin	HVDC
1	3	0	0	0	0	1	1	0	345	1	1.1	0.9	0
2	2	0	0	0	0	1	1	0	345	1	1.1	0.9	0
3	2	0	0	0	0	1	1	0	345	1	1.1	0.9	0
4	1	0	0	0	0	1	1	0	345	1	1.1	0.9	0
5	1	125	50	0	0	1	1	0	345	1	1.1	0.9	0
6	1	90	30	0	0	1	1	0	345	1	1.1	0.9	0
7	1	0	0	0	0	1	1	0	345	1	1.1	0.9	0
8	1	100	35	0	0	1	1	0	345	1	1.1	0.9	0
9	1	0	0	0	0	1	1	0	345	1	1.1	0.9	0

Table 6.2 Generator data of the WSCC

Bus	Pg	Qg	Qmax	Qmin	Vg	MBase	Sta	Pmax	Pmin
1	0	0	300	-300	1.04	100	1	250	10
2	163	0	300	-300	1.025	100	1	300	10
3	85	0	300	-300	1.025	100	1	270	10

Table 6.3 Branch data of the WSCC

fbus	Tbus	R	X	B	rateA	rateB	rateC	Ratio	angle	status
1	4	0	0.0576	0	250	250	250	0	0	1
4	6	0.017	0.092	0.158	250	250	250	0	0	1
6	9	0.039	0.17	0.358	150	150	150	0	0	1
3	9	0	0.0586	0	300	300	300	0	0	1
9	8	0.0119	0.1008	0.209	150	150	150	0	0	1
8	7	0.0085	0.072	0.149	250	250	250	0	0	1
7	2	0	0.0625	0	250	250	250	0	0	1
7	5	0.032	0.161	0.306	250	250	250	0	0	1
5	4	0.01	0.085	0.176	250	250	250	0	0	1

The following data is parameter data of generator and exciter. In this system, there is no HVDC, so we did not fill the parameter data of HVDC.

Table 6.4 Generator parameters of the WSCC

Parameters	Gen 1	Gen 2	Gen 3
H	23.64	6.4	3.01
X_d	0.146	0.8958	1.3125
X'_d	0.0608	0.1198	0.1813
X_q	0.0969	0.8645	1.2578
X'_q	0.0969	0.1969	0.25
τ'_{d0}	8.96	6.0	5.89
τ'_{q0}	0.31	0.535	0.6
D	0	0	0

Table 6.5 Exciter parameters (IEEE type I) of the WSCC

Parameters	Exc 1	Exc 2	Exc 3
K_A	20	20	20
τ_A	0.2	0.2	0.2
K_E	1.0	1.0	1.0
τ_E	0.314	0.314	0.314
K_F	0.063	0.063	0.063
τ_F	0.35	0.35	0.35
A	0.0039	0.0039	0.0039
B	1.555	1.555	1.555

6.1.1 Steady State Operating Conditions

With the data above we can calculate operating condition of the network by running load flow program. We can see the results in Table 6.7. Also, we need to compute Y_{bus} , the bus admittance matrix which is needed to be input for the developed program.

Table 6.6 Load flow solutions of the WSCC

Bus	Type of bus	Voltage Magnitude (pu)	Voltage Angle (angle)	PG (pu)	QG (pu)	-PL	-QL
1	(swing)	1.04	0.000	0.716	0.271	-	-
2	(PV)	1.025	9.280	1.63	0.067	-	-
3	(PV)	1.025	4.665	0.85	-0.109	-	-
4	(PQ)	1.026	-2.217	-	-	-	-
5	(PQ)	0.996	-3.989	-	-	1.25	0.5
6	(PQ)	1.013	-3.687	-	-	0.9	0.3
7	(PQ)	1.026	3.720	-	-	-	-
8	(PQ)	1.016	0.728	-	-	1.00	0.35
9	(PQ)	1.032	1.967	-	-	-	-

6.1.2 Initial Conditions

This step will calculate initial variables in the system. We can calculate after we get operating point from running load flow program. The computed initial conditions are given in Table 6.7.

Table 6.7 Computed initial conditions

Variables	Gen 1	Gen 2	Gen 3
δ	3.586^0	61.098^0	54.137^0
I_d	0.303	1.290	0.561
I_q	0.671	0.932	0.619
V_d	0.065	0.806	0.779
V_q	1.038	0.634	0.666
E_d'	0	0.622	0.624
E_q'	1.056	0.788	0.768
E_{fd}	1.082	1.789	1.403
R_f	0.195	0.322	0.253
V_R	1.105	1.902	1.451
V_{ref}	1.095	1.120	1.098
T_M	0.716	1.630	0.850

6.1.3 Eigenvalue Comparison

In this system we have three generators and each generator has 7 states. Its mean, we will have 21 states. After we get operating point of network and initial condition of all variables, we can compute eigenvalues. Loads are assumed as constant power type. Table 6.8 lists the comparioson of eigenvalues obtained from developed program and literature [14] for the WSCC system.

Table 6.8 Comparioson of eigenvalues obtained from developed program
and from literature [14] for the WSCC system

No	Eigenvalues obtained from developed program	Eigenvalues obtained from literature [14]
1	-0.7201+12.7455i	-0.7209+12.7486i
2	-0.7201-12.7455i	-0.7209-12.7486i
3	-0.1907+8.3658i	-0.1908+8.3672i
4	-0.1907-8.3658i	-0.1908-8.3672i
5	-5.4875+7.9487i	-5.4875+7.9487i
6	-5.4875-7.9487i	-5.4875-7.9487i
7	-5.3235+7.9220i	-5.3236+7.9220i
8	-5.3235-7.9220i	-5.3236-7.9220i
9	-5.2218+7.8160i	-5.2218+7.8161i
10	-5.2218-7.8160i	-5.2218-7.8161i
11	-5.1778+0.0000i	-5.1761+0.0000i
12	-3.3997+0.0000i	-3.3995+0.0000i
13	-0.4444+1.2106i	-0.4445+1.2104i
14	-0.4444-1.2106i	-0.4445-1.2104i
15	-0.4394+0.7392i	-0.4394+0.7392i
16	-0.4394-0.7392i	-0.4394+0.7392i
17	-0.4258+0.4959i	-0.4260+0.4960i
18	-0.4258-0.4959i	-0.4260-0.4960i
19	0.0000+0.0000i	-0.0000+0.0000i
20	-0.0000+0.0000i	-0.0000+0.0000i
21	-3.2258+0.0000i	-3.2258+0.0000i

The zero eigenvalues, however may not be computed exactly because of mismatches in the power flow solution and the limited accuracy of eigenvalue calculation routines. They may therefore appear as small eigenvalues. This fact agrees with Kundur [2].

From eigenvalues above we see that all of real parts of eigenvalues are negative. It means that system is stable at this operating point.

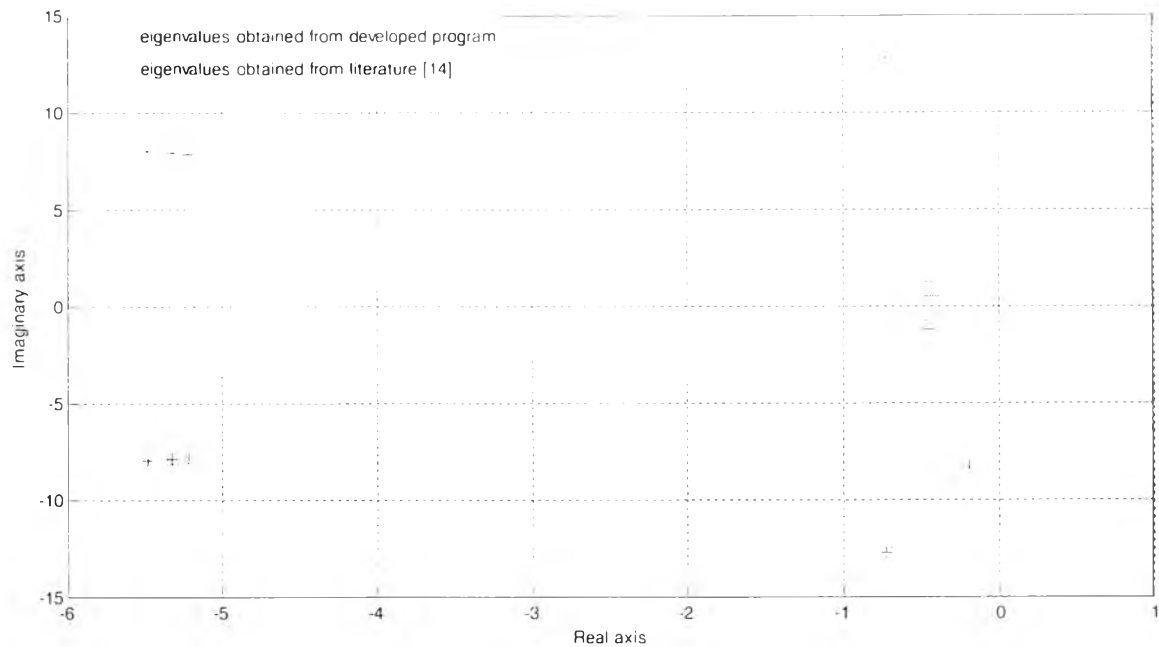Fig. 6.2 shows the comparison of eigenvalues obtained from developed program and literature.

Figure 6.2 Comparison of eigenvalues obtained from the developed program and from literature [14]

From figure above, we can see that the developed program gets almost the same result as in literature [14]. We can say that the generation algorithm to get state space model from developed program is valid.

6.1.4 Participation Factor Analysis

Due to large size of the power system, it is often necessary to construct reduced-order models for dynamic stability studies by retaining only a few modes. The appropriate definition and determination as to which state variables significantly participate in the selected modes become very important. This requires a tool for identifying the state variables that have significant participation in a selected mode.

This calculation identifies how each dynamic variable affects a given mode or eigenvalue. We can check participation of states from all machines to each mode.

Table 6.9 Participation factors for the WSCC (mode 1-11)

Eigenvalue State	G	1	2	3	4	5	6	7	8	9	10	11
δ	1	0.012077	0.012077	0.41915	0.41915	0.000537	0.000537	0.000538	0.000538	0.00043	0.00043	4.90E-05
ω	1	0.012077	0.012077	0.41915	0.41915	0.000537	0.000537	0.000538	0.000538	0.00043	0.00043	4.90E-05
E'_q	1	2.30E-05	2.30E-05	0.000118	0.000118	0.000567	0.000567	0.003139	0.003139	0.050991	0.050991	5.69E-06
E'_d	1	0	0	0	0	0	0	0	0	0	0	0
E_{fd}	1	1.52E-05	1.52E-05	0.000106	0.000106	0.016878	0.016878	0.17896	0.17896	0.97329	0.97329	8.76E-08
V_R	1	1.48E-05	1.48E-05	9.82E-05	9.82E-05	0.017438	0.017438	0.1842	0.1842	1	1	8.94E-07
R_F	1	1.11E-06	1.11E-06	2.33E-05	2.33E-05	0.004952	0.004952	0.0537	0.0537	0.30573	0.30573	1.50E-05
δ	2	0.22394	0.22394	1	1	0.002605	0.002605	0.000123	0.000123	0.000408	0.000408	0.013933
ω	2	0.22394	0.22394	1	1	0.002605	0.002605	0.000123	0.000123	0.000408	0.000408	0.013933
E'_q	2	0.01285	0.01285	0.042875	0.042875	0.035023	0.035023	0.004633	0.004633	0.006454	0.006454	0.015974
E'_d	2	0.013862	0.013862	0.019714	0.019714	0.004372	0.004372	0.001584	0.001584	0.003313	0.003313	1
E_{fd}	2	0.000434	0.000434	0.003849	0.003849	0.9835	0.9835	0.063088	0.063088	0.058253	0.058253	5.27E-05
V_R	2	0.000424	0.000424	0.003658	0.003658	1	1	0.063984	0.063984	0.059003	0.059003	0.000366
R_F	2	3.16E-05	3.16E-05	0.000847	0.000847	0.28855	0.28855	0.018931	0.018931	0.018299	0.018299	0.009019
δ	3	1	1	0.15921	0.15921	0.000755	0.000755	0.003355	0.003355	0.000921	0.000921	0.021408
ω	3	1	1	0.15921	0.15921	0.000755	0.000755	0.003355	0.003355	0.000921	0.000921	0.021408
E'_q	3	0.031014	0.031014	0.005812	0.005812	0.001848	0.001848	0.031142	0.031142	0.010844	0.010844	0.030766
E'_d	3	0.080829	0.080829	0.001141	0.001141	0.001313	0.001313	0.007865	0.007865	0.001295	0.001295	0.91959
E_{fd}	3	0.001609	0.001609	0.00106	0.00106	0.091795	0.091795	0.97626	0.97626	0.15878	0.15878	6.08E-05
V_R	3	0.001562	0.001562	0.00099	0.00099	0.094347	0.094347	1	1	0.16237	0.16237	0.000562
R_F	3	0.000117	0.000117	0.000233	0.000233	0.026931	0.026931	0.29295	0.29295	0.049877	0.049877	0.010403

Table 6.10 Participation factors for the WSCC (mode 12-21)

Eigenvalue State	G	12	13	14	15	16	17	18	19	20	21
δ	1	0.001217	0.000884	0.000884	0.001012	0.001012	3.01E-06	3.01E-06	1	1	0
ω	1	0.001217	0.000884	0.000884	0.001012	0.001012	3.01E-06	3.01E-06	1	1	0
E'_q	1	0.003037	1	1	1	1	0.00822	0.00822	2.12E-10	2.12E-10	0
E'_d	1	0	0	0	0	0	0	0	0	0	1
E_{fd}	1	7.34E-05	0.15518	0.15518	0.1401	0.1401	0.001126	0.001126	4.18E-11	4.18E-11	0
V_R	1	1.64E-06	0.10405	0.10405	0.091477	0.091477	0.000729	0.000729	7.47E-13	7.47E-13	0
R_F	1	0.025508	0.73996	0.73996	0.77701	0.77701	0.00651	0.00651	7.45E-11	7.45E-11	0
δ	2	0.001953	0.002853	0.002853	0.002876	0.002876	0.001697	0.001697	0.25761	0.25761	0
ω	2	0.001953	0.002853	0.002853	0.002876	0.002876	0.001697	0.001697	0.25761	0.25761	0
E'_q	2	0.001733	0.67086	0.67086	0.77789	0.77789	0.42542	0.42542	3.19E-10	3.19E-10	0
E'_d	2	0.89458	0.046364	0.046364	0.038942	0.038942	0.02802	0.02802	3.15E-13	3.15E-13	0
E_{fd}	2	5.08E-05	0.10175	0.10175	0.10838	0.10838	0.057586	0.057586	4.91E-12	4.91E-12	0
V_R	2	1.73E-05	0.079927	0.079927	0.084018	0.084018	0.044466	0.044466	1.25E-10	1.25E-10	0
R_F	2	0.017652	0.48516	0.48516	0.60108	0.60108	0.33293	0.33293	2.74E-11	2.74E-11	0
δ	3	0.009039	0.001701	0.001701	0.000743	0.000743	0.003754	0.003754	0.12233	0.12233	0
ω	3	0.009039	0.001701	0.001701	0.000743	0.000743	0.003754	0.003754	0.12233	0.12233	0
E'_q	3	0.006602	0.38428	0.38428	0.22343	0.22343	1	1	8.30E-11	8.30E-11	0
E'_d	3	1	0.026088	0.026088	0.021011	0.021011	0.11337	0.11337	6.53E-13	6.53E-13	0
E_{fd}	3	5.75E-05	0.059269	0.059269	0.032313	0.032313	0.144	0.144	4.13E-11	4.13E-11	0
V_R	3	4.86E-06	0.041734	0.041734	0.022258	0.022258	0.098534	0.098534	4.67E-11	4.67E-11	0
R_F	3	0.019988	0.28262	0.28262	0.1792	0.1792	0.83249	0.83249	1.49E-10	1.49E-10	0

From Table 6.9 and Table 6.10 we can check participation of state to each mode. For example. if we are interest in eigenvalue/ mode 19 and 20 (these two modes are near to instability. check Table 6.8). we can see the column 19 and 20 of eigenvalues (check Table 6.10). and find '1'. Wee can see that there are two number of 1 at column 19 and two number of 1 at column 20. These two numbers are in the same row with δ and ω of generator 1. It means that modes go unstable are due to the electromechanical variables δ and ω of generator 1. If we want to make system more stable due to these modes so we have to concern at those states. From a practical point of view, this information is very useful.

6.1.5 Controllability and Observability Analysis

From the developed program, we can get controllability matrix (CM).The result show that rank of CM is 11. It means that there are 10 modes cancellation, such that those modes cannot be controlled/affected by any input.

We also calculate observability matrix (OM), we get that rank of OM is 11. It means that, there are 10 modes cancellation, such that those modes cannot be observed in the output.

6.2 Test Result of the Southern Thailand Generation and Transmission Systems

In Fig, 6.3 we can see single line diagram of the system interest. Also we give graphical structure of the Southern Thailand transmission network which is depicted in Fig. 6.4. The system is from middle to south of Thailand.
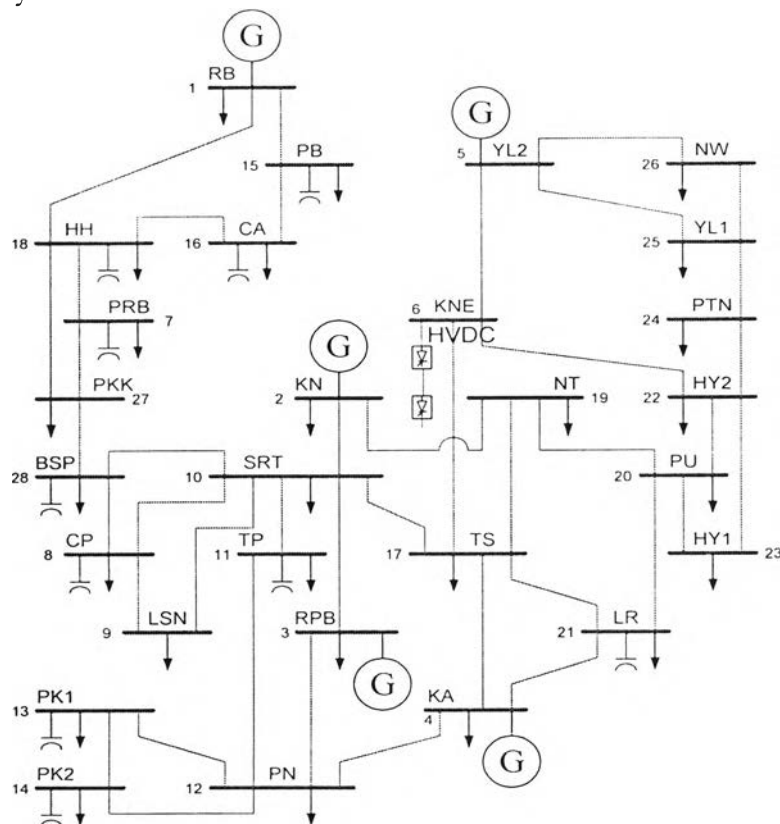

Figure 6.3 A single line diagram of the Southern Thailand generation and transmission systems (Reduced model) [21].

Table 6.11 List of buses name

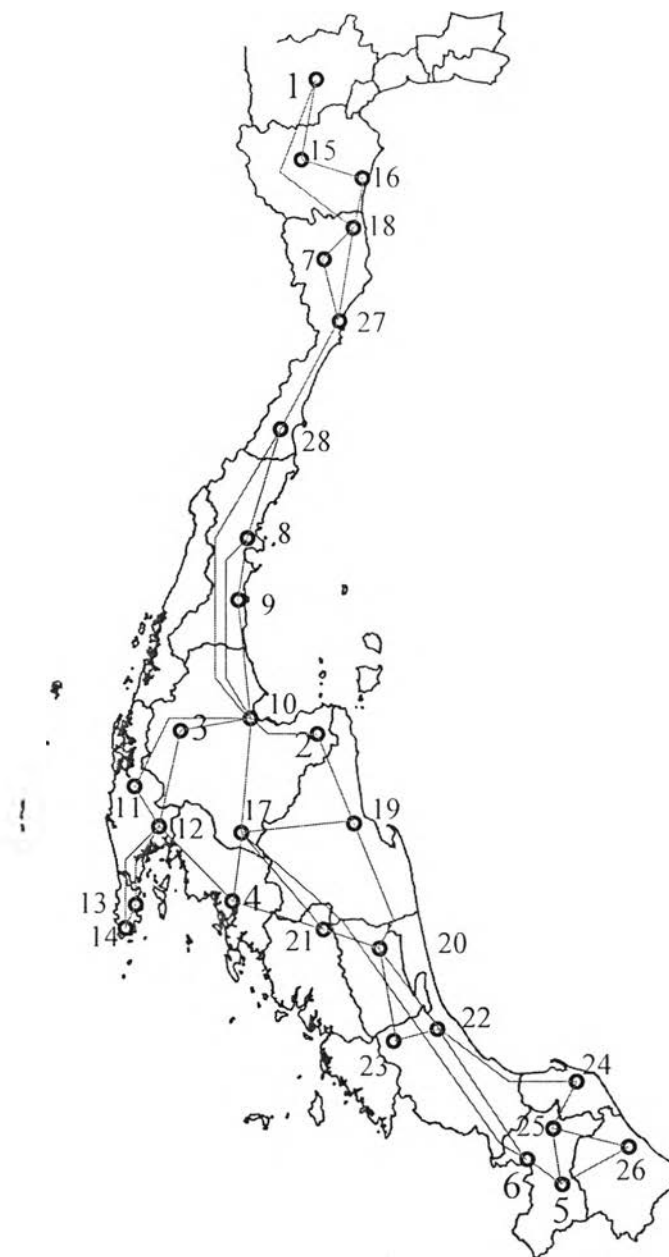| Bus	Code	Details	Bus	Code	Details
1	RB	Ratchaburi	15	PB	Phetchaburi
2	KN	Khanom	16	CA	Cha-Am
3	RPB	Rajjaprabha	17	TS	Thung-Song
4	KA	Krabi	18	HH	Hua-Hin
5	YL2	Yala 2	19	NT	Nakhon-Si-Thammarat
6	KNE	Khlong-Ngae	20	PU	Phatthalung
7	PRB	Pran-Buri	21	LR	Lam-Poo-Ra
8	CP- ·	Chumphon	22	HY2	Hat-Yai 2
9	LSN	Lang-Suan	23	HY1	Hat-Yai 1
10	SRT	Surat-Thani	24	PTN	Pattani
11	TP	Takua-Pa	25	YL1	Yala 1
12	PN	Phang-Nga	26	NW	Narathiwat
13	PK1	Phuket 1	27	PKK	Prachuap-Khiri-Khan
14	PK2	Phuket 2	28	BSP	Bang-Saphan

Figure 6.4 Graphical structure of the Southern Thailand transmission network [21].

We model southern part of Thailand system which consists of 5 generators and 1 HVDC link. Total of buses is 28. Slack generator at bus no 1 RB (Ratchaburi) and others generators are assign as PV buses. HVDC link is already installed which connects bus 6 at KNE (Khlong-Ngae) to Gurun (Malaysia). This HVDC link is rated at 300 MW. Normally, Thailand system imports power from Malaysia system through this link. We also can export power to Malaysia when there is surplus in Thailand system. It allows bi-directional control of power interchange.

6.2.1 Input Data

The network data used for the study is given in the Appendix A.

From the network data, we can see that there are 5 generators. Table 6.12 gives the detailed capacity and type of them. Also the parameters of the generator are given in Table 6.13.

Table 6.12 Generator capacity data

Bus	Code	Location	Capacity (MW)	Type of gen	Type of bus
1	RB	Ratchaburi	1635	combine cycle	slack
2	KN	Khanom	824	combine cycle	PQ
3	RPB	Rajjaprabha	240	hydro	PQ
4	KA	Krabi	300	thermo	PQ
5	YL2	Yala 2	72	thermo	PQ

Table 6.13 Parameters of the generators

Parameter	G 1	G 2	G 3	G 4	G 5
Bus	1	2	3	4	5
H	3.8853	3.08738	3.11688	3.0061	4.9850
X_d	1.693	2.02	1.675	1.950	1.180
X'_d	0.346	0.358	0.311	0.317	0.220
X_q	1.6636	1.860	1.648	1.920	1.050
X'_q	0.991	0.565	0.979	1.120	0.380
τ'_{d0}	6.580	9.1	5.4	6	5.9
τ'_{q0}	1.5	0.46	1.5	1.5	0.3
D	2	2	2	2	2
r_s	0.0021	0.0019	0.0043	-	0.0035

Table 6.14 Parameters of the generator excitation systems

Parameter	G 1	G 2	G 3	G 4	G 5
Bus	1	2	3	4	5
K_A	400	50	245	400	25
τ_A	0.02	0.02	0.05	0.05	0.2
K_E	1	-0.0244	-0.17	-0.17	-0.0582
τ_E	0.015	0.1455	1.37	0.950	0.654
K_F	0.04	0.0233	0.04	0.04	0.105
τ_F	0.05	0.7750	1	1	0.350
A	0.1296	0.0015	0.0027	0.0027	0.0015
B	0.3814	1.5833	1.639	0.3857	1.5833

Due to unavailability of the actual data of HVDC installed in the Southern Thailand. here it is assumed that HVDC link of interest has its parameters as given in reference [9], and shown here in Table 6.15.

Table 6.15 Parameters of the HVDC link

Parameter	HVDC 1
Bus	6
R_{dc}	0.14
L_{dr}	0.25
L_{di}	0.25
X_r	0.01
X_i	0.01
K_r	-1
T_r	0.02
K_i	1
T_i	0.05

6.2.2 Case Studies

The dynamic stability of the power systems including HVDC link can be investigated using an eigenvalues analysis of the linearized state space model for the following case of study :

1. Without HVDC link in the system
   In this case there are 5 generators and 28 buses in the system. All of generators model as two axis. All of exciter model as IEEE type 1.

2. With HVDC link in the system
   In this case, type of all generators is same as case 1. Scheme control for HVDC is constant current at rectifier and constant extinction angle at inverter. This kind of scheme, describes at Fig. 2.6. In this configuration we can study some cases.

   a. There is no import or export power through HVDC link
      - Interface bus in the southern part of Thailand as a rectifier
        In this case we set $I_{dc} = 0$ so that the power flows in the AC lines are unaltered even after the inclusion of the HVDC link. Its mean the operating point will same with the case 1, when there is no HVDC in the system.
      - Interface bus in the southern part of Thailand as an inverter
        Similar previous case, we set $I_{dc} = 0$ so that the power flows in the AC lines are unaltered even after the inclusion of the HVDC link.

   b. There is 300 MW import power from Malaysia to Thailand
      This case reflects the real condition of system. With the developed program, we can analyze more detail in this configuration.

6.2.2.1 Test Results without HVDC

After running load flow. we get the operating condition of the network for nominal loading.

Table 6.16 Load flow solutions of the Southern Thailand system without HVDC

Bus	Voltage		Generator		Load	
#	magnitude	angle	P (MW)	Q (MVAR)	P (MW)	Q (MVAR)
1	1.02	-7.9	893.82	93.164	305.9	72.1
2	1.03	-30.726	800	74.886	77.9	18.7
3	1.03	-36.493	240	64.071	8.7	3.4
4	1.03	-36.754	300	76.11	52.9	26.5
5	1.01	-49.069	60.2	86.445	0	0
6	0.99466	-47.482			0	0
7	0.99198	-21.543			26.6	13.7
8	1.0024	-33.704			55.7	13
9	1.0153	-35.999			23.8	9.2
10	1.0163	-36.011			169.6	89.8
11	0.97799	-40.605			51.5	4.3
12	0.99035	-37.305			40.8	17.2
13	0.96403	-43.446			45.1	19.5
14	0.96098	-44.862			139	75.8
15	1.0053	-11.961			52	25.2
16	0.99002	-16.504			36.8	17.9
17	1.0109	-39.692			119.9	52.9
18	1.0015	-18.945			101	8
19	0.99837	-39.089			123.2	46.6
20	0.98894	-44.303			41	14.4
21	0.97481	-43.718			88.3	44.8
22	0.9836	-48.206			298.7	108.1
23	0.97952	-48.394			52.8	10.6
24	0.96573	-50.598			56.6	30.9
25	1.0082	-49.228			59.3	25.7
26	0.98334	-52.047			56.1	8.7
27	1.0054	-25.328			29.6	8.3
28	1.0105	-28.779			103	6.7

We see that at bus 6 there is no supply power. Load is zero, its mean there is no power import or export through HVDC link. We also see that most of voltage angles in this case are high.

The program will automatically calculate initial condition of all variables, after that the program will do multiple calculation to get the state space representation and finally calculate eigenvalues of the system. We can see eigenvalues, frequency and also damping ratio in Table 6.17.

Table 6.17 The obtained eigenvalues of the Southern Thailand system without HVDC

No	Eigenvalues	Frequency (Hz)	Damping Ratio
1	-2.26E+10	0	1
2	-18170	0	1
3	-124.55	0	1
4	-121.94	0	1
5	-119.39	0	1
6	-120.63	0	1
7	-98.267	0	1
8	-73.928	0	1
9	-50	0	1
10	-21.491+ 12.213i	1.9437	0.86942
11	-21.491 - 12.213i	1.9437	0.86942
12	-10.624 +15.702i	2.499	0.5604
13	-10.624 - 15.702i	2.499	0.5604
14	-3.9665 +7.4739i	1.1895	0.46879
15	-3.9665 - 7.4739i	1.1895	0.46879
16	-9.2955	0	1
17	-8.3055	0	1
18	-7.0292	0	1
19	3.107	0	-1
20	-2.5396	0	1
21	-2.2387	0	1
22	**0.25088+0.4018i**	**0.063949**	**-0.52963**
23	**0.25088 -0.4018i**	**0.063949**	**-0.52963**
24	1.01E-13	0	-1
25	-0.28386+0.38283i	0.060929	0.59561
26	-0.28386-0.38283i	0.060929	0.59561
27	-0.34636	0	1
28	-1.4271	0	1
29	-0.57931	0	1
30	-0.73248	0	1
31	-0.89149	0	1
32	-1.1018	0	1
33	-1.1144	0	1
34	-1.1321	0	1
35	-1.2903	0	1

From table above we see that there are 2 eigenvalues (mode 22 and 23) which have positive real part. From Fig. 6.5, we can observe that those two eigenvalues are located at right side of complex plane and indicate instability in the system We can check which mode responsible for those modes by check participation factor. It shows that state R_f of generator 4 gives the biggest participation for those modes.
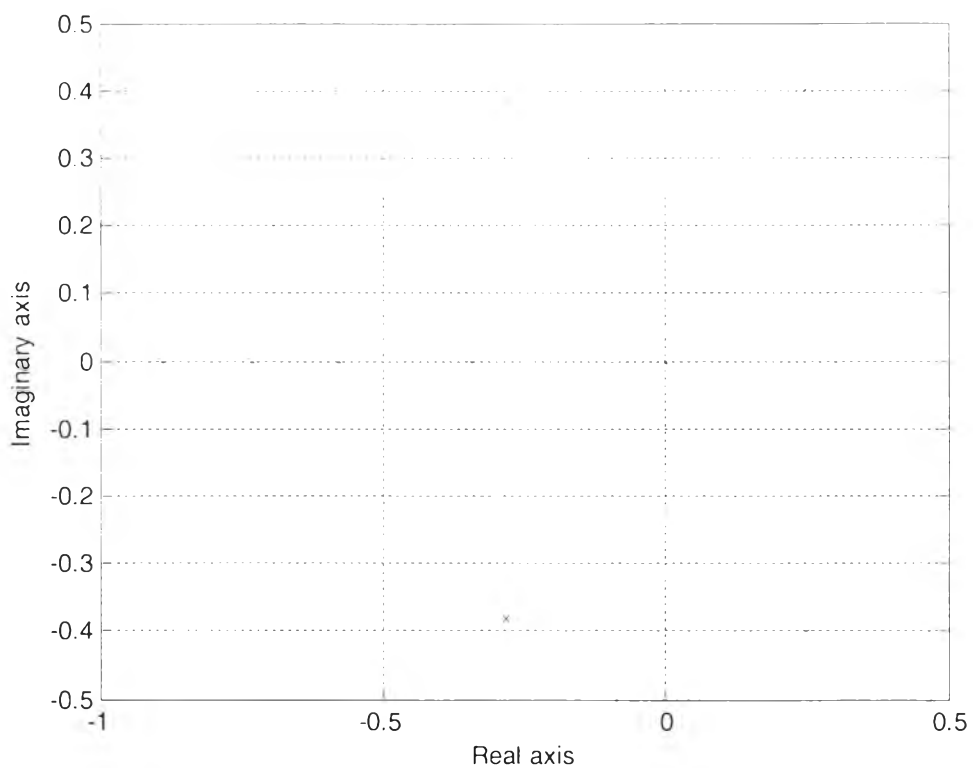
Figure 6.5 Plot of eigenvalues of the Southern Thailand system without HVDC.

The developed program also classify the problem into two kinds : local oscillation modes problem in the range 1 Hz-3 Hz and global oscillation modes problem in the range (0.1 Hz-0.99Hz). Result shows that there are 6 local modes contribute to global problems and there is no global mode in this case. Table 6.20 lists of local problems.

Table 6.18 Local oscillation problem of the system without HVDC

No	Mode	Frequency (Hz)
1	10	1.9437
2	11	1.9437
3	12	2.4990
4	13	2.4990
5	14	1.1895
6	15	1.1895

6.2.2.2 Test Results with HVDC

Firstly, we will calculate eigenvalues of the system when there is no import or export power through HVDC link. Also we will investigate when the interface bus in the southern part of Thailand acts as a rectifier and acts as an inverter. For those cases we set current in HVDC link to be zero ($I_{dc} = 0$). With this setting, the power flows in the AC lines are unaltered even after the inclusion of the HVDC link. Its mean the operating point will same with the case 1, when there is no HVDC in the system. We will compare the results with case 1 to see the stability before and after there is HVDC in the system.

After that we will calculate eigenvalues of the system when there is 300 MW import power from Malaysia through HVDC link.
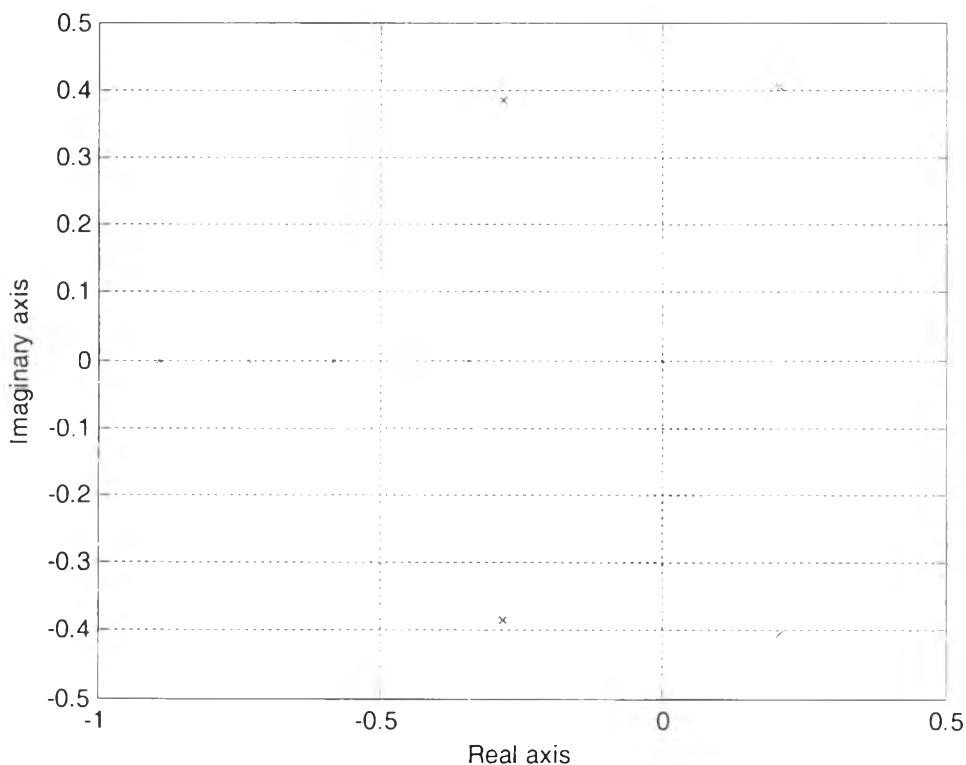
Figure 6.6 Plot of eigenvalues of the Southern Thailand system with no power flow in HVDC link whereby the Klong Ngae bus operating as rectifier.

Table 6.19 Eigenvalues of the Southern Thailand system with no power flow in HVDC link whereby the Klong Ngae bus operating as rectifier

No	Eigenvalues	Frequency (Hz)	Damping Ratio
1	-2.26E+10	0	1
2	-18170	0	1
3	-124.55	0	1
4	-121.94	0	1
5	-119.39	0	1
6	-120.63	0	1
7	-98.26	0	1
8	-73.928	0	1
9	-50	0	1
10	-49.342	0	1
11	-21.492 + 12.213i	1.9438	0.86943
12	-21.492 -12.213i	1.9438	0.86943
13	-10.625 +15.701i	2.4988	0.56047
14	-10.625 -15.701i	2.4988	0.56047
15	-19.012	0	1
16	-3.9662 + 7.474i	1.1895	0.46876
17	-3.9662 - 7.474i	1.1895	0.46876
18	3.2397	0	-1
19	-9.2968	0	1
20	-8.3064	0	1
21	-7.0299	0	1
22	-2.5792	0	1
23	-2.2492	0	1
24	**0.20847+0.40635i**	0.064673	-0.45647
25	**0.20847- 0.40635i**	0.064673	-0.45647
26	-4.33E-13	0	1
27	-0.28246 +0.384i	0.061116	0.59253
28	-0.28246 -0.384i	0.061116	0.59253
29	-0.34462	0	1
30	-1.5253	0	1
31	-0.58483	0	1
32	-0.73292	0	1
33	-0.88941	0	1
34	-1.1016	0	1
35	-1.1154	0	1
36	-1.1332		1
37	-1.2971		1
38	-1.2903		1

Table 6.20 Eigenvalues of the Southern Thailand system with no power flow in HVDC
link whereby the Klong Ngae bus operating as inverter

| No	Eigenvalues	Frequency (Hz)	Damping Ratio
1	-2.26E+10	0	1
2	-18170	0	1
3	-124.55	0	1
4	-121.94	0	1
5	-119.39	0	1
6	-120.63	0	1
7	-98.274	0	1
8	-73.928	0	1
9	-50	0	1
10	-49.361	0	1
11	-21.49 + 12.212i	1.9436	0.86942
12	-21.49 - 12.212i	1.9436	0.86942
13	-10.623 + 15.703i	2.4992	0.56034
14	-10.623 - 15.703i	2.4992	0.56034
15	-19.048	0	1
16	-3.9668 + 7.4739i	1.1895	0.46881
17	-3.9668 - 7.4739i	1.1895	0.46881
18	-9.2929	0	1
19	-8.3046	0	1
20	-7.0286	0	1
21	2.9471	0	-1
22	0.3017 + 0.39159i	0.062324	-0.61031
23	0.3017 - 0.39159i	0.062324	-0.61031
24	-2.5063	0	1
25	-2.2261	0	1
26	-4.85E-13	0	1
27	-0.28577 + 0.38101i	0.060639	0.60002
28	-0.28577 - 0.38101i	0.060639	0.60002
29	-0.34819	0	1
30	-0.57369	0	1
31	-0.73202	0	1
32	-1.3536 + 0.088156i	0.014031	0.99789
33	-1.3536 - 0.088156i	0.014031	0.99789
34	-0.89667	0	1
35	-1.1024	0	1
36	-1.1133	0	1
37	-1.1314	0	1
38	-1.2903	0	1
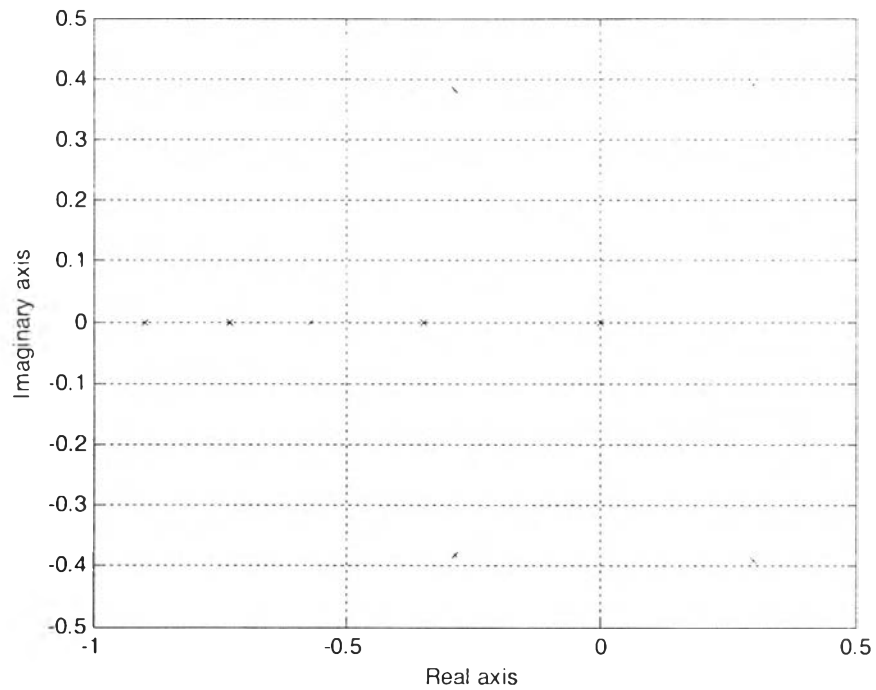
Figure 6.7 Plot of eigenvalues of the Southern Thailand system with no power flow in HVDC link whereby the Klong Ngae bus operating as inverter.
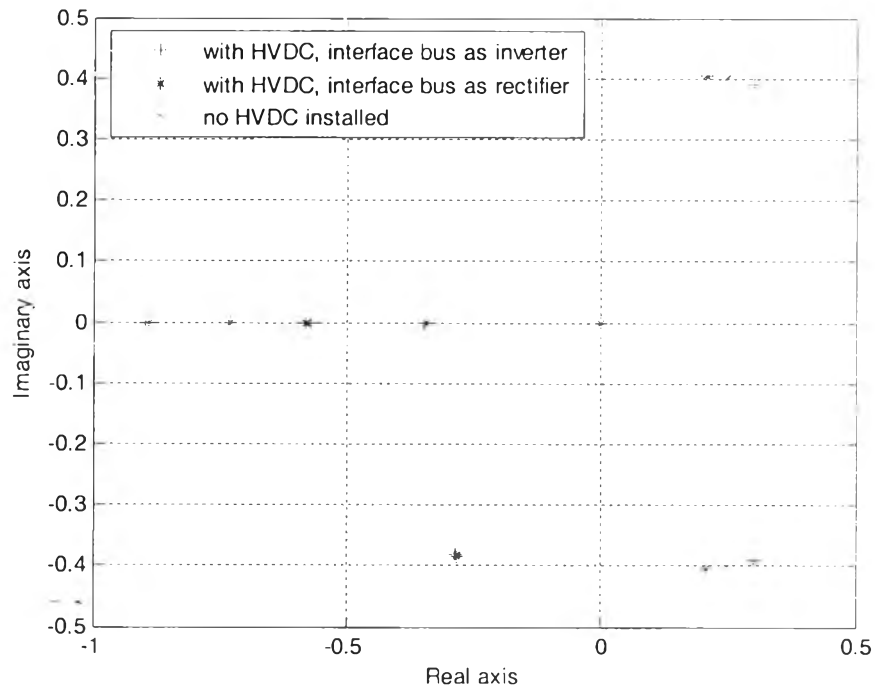

Figure 6.8 Comparison of plot of eigenvalues obtained in the cases before and after HVDC is installed in the system with no power flow through HVDC.

From Fig. 6.8 we see that the best case is when the interface at southern part of Thailand system acts as rectifier. When it acts as inverter, it gives the worst result. From this case we can say that in terms of setting gain and time constant the best one is when HVDC export power or interface bus is acts as rectifier.

Now we will investigate when there is 300 MW import power from Malaysia through HVDC link. We can see the operating condition of the network after we run load flow. Table 6.21 gives the results of load flow.

Table 6.21 Load flow solutions of the Southern Thailand system with 300 MW import from Malaysia through HVDC link

| Bus | Voltage | | Generator | | Load | |
#	magnitude	angle	Real power	Reactive power	Real power	Reactive power
1	1.02	-7.9	560.36	24.064	305.9	72.1
2	1.03	-1.0544	800	41.112	77.9	18.7
3	1.03	-8.2961	240	37.905	8.7	3.4
4	1.03	-5.5365	300	59.851	52.9	26.5
5	1.01	-12.227	60.2	116.98	0	0
6	0.98601	-10.516			-299.19	127.2
7	1.0207	-13.02			26.6	13.7
8	1.0189	-11.63			55.7	13
9	1.0215	-8.1349			23.8	9.2
10	1.0223	-7.9987			169.6	89.8
11	0.98095	-12.378			51.5	4.3
12	0.99188	-9.0178			40.8	17.2
13	0.96587	-15.14			45.1	19.5
14	0.96288	-16.552			139	75.8
15	1.0109	-10.4			52	25.2
16	1.0086	-12.126			36.8	17.9
17	1.014	-8.3716			119.9	52.9
18	1.028	-12.091			101	8
19	1.0027	-7.2694			123.2	46.6
20	0.99035	-10.198			41	14.4
21	0.97624	-11.585			88.3	44.8
22	0.97773	-11.8			298.7	108.1
23	0.97426	-12.086			52.8	10.6
24	0.96296	-13.966			56.6	30.9
25	1.0081	-12.391			59.3	25.7
26	0.98332	-15.208			56.1	8.7
27	1.0335	-12.854			29.6	8.3
28	1.0351	-12.925			103	6.7

From result above we see that the network data is updated. In the first time there is no load at bus 6 (see Appendix, Table A.1). After we run load flow, we see that there are loads at bus 6 : -299.19 MW of real power and 127.2 MVAR of reactive power. These loads are come from HVDC. Negative sign in real power indicate that the load

gives power to the system. It means there is import power to the system. Sign of reactive power is positive, it because of operation of HVDC needs reactive power from AC system. Table 6.22 shows eigenvalues of the system after we import power from Malaysia.

Table 6.22 Eigenvalues of the Southern Thailand system with 300 MW import from Malaysia through HVDC link

| No	Eigenvalues	Frequency (Hz)	Damping Ratio
1	-1.95E+10	0	1
2	-784.76 + 744.86i	118.55	0.72531
3	-784.76 - 744.86i	118.55	0.72531
4	-124.29	0	1
5	-121.31	0	1
6	-119.49	0	1
7	-97.122	0	1
8	-74.038	0	1
9	-50	0	1
10	-49.169	0	1
11	-18.268 + 12.119i	1.9287	0.83331
12	-18.268 - 12.119i	1.9287	0.83331
13	-10.542 + 15.7i	2.4987	0.55746
14	-10.542 - 15.7i	2.4987	0.55746
15	-19.283	0	1
16	-4.0328 + 7.5247i	1.1976	0.47237
17	-4.0328 - 7.5247i	1.1976	0.47237
18	-8.9286	0	1
19	-7.0972	0	1
20	0.26251 + 1.0941i	0.17414	-0.2333
21	0.26251 - 1.0941i	0.17414	-0.2333
22	-2.4214	0	1
23	-2.1065 + 0.080981i	0.012889	0.99926
24	-2.1065 - 0.080981i	0.012889	0.99926
25	0.20705 + 0.3399i	0.054097	-0.52023
26	0.20705 - 0.3399i	0.054097	-0.52023
27	-4.60E-15	0	1
28	-0.28405 + 0.41082i	0.065385	0.56871
29	-0.28405 - 0.41082i	0.065385	0.56871
30	-0.43493+0.027581i	0.00439	0.998
31	-0.43493 -0.027581i	0.00439	0.998
32	-0.82254	0	1
33	-1.3478 + 0.051841i	0.008251	0.99926
34	-1.3478 - 0.051841i	0.008251	0.99926
35	-1.1302	0	1
36	-1.086	0	1
37	-1.1048	0	1
38	-1.2903	0	1
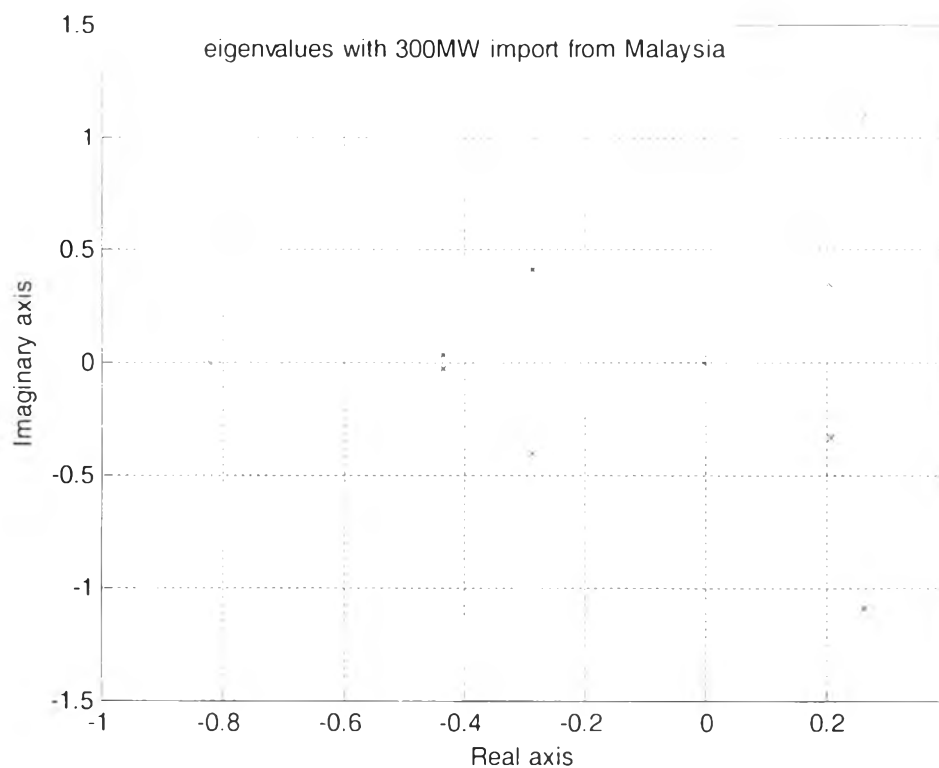
Figure 6.9 Plot of eigenvalues of the Southern Thailand system with 300MW power import from Malaysia through HVDC link.

From figure above we see that there are 4 modes cross the right plane. It shows instability in the system. These modes are number 20, 21, 25 and 26. When we check in the participation factor those modes are due to δ of generator 1 and 2.

From the eigenvalues we can calculate that there are 6 local modes contribute to global problems and there is 2 global mode in this case. Here list of local and global problems.

Table 6.23 Local oscillation problem of the system with HVDC

No	Mode	Frequency (Hz)
1	11	1.9287
2	12	1.9287
3	13	2.4986
4	14	2.4986
5	16	1.1973
6	17	1.1973

Table 6.24 Global oscillation problem of the system with HVDC

No	Mode	Frequency (Hz)
1	20	0.1799
2	21	0.1799

We plot the comparison of eigenvalues when there is HVDC which is import 300 MW power from Malaysia and when there is no HVDC in the system. We also plot the comparison of voltage profile for each bus and real power transmitted for each branch.
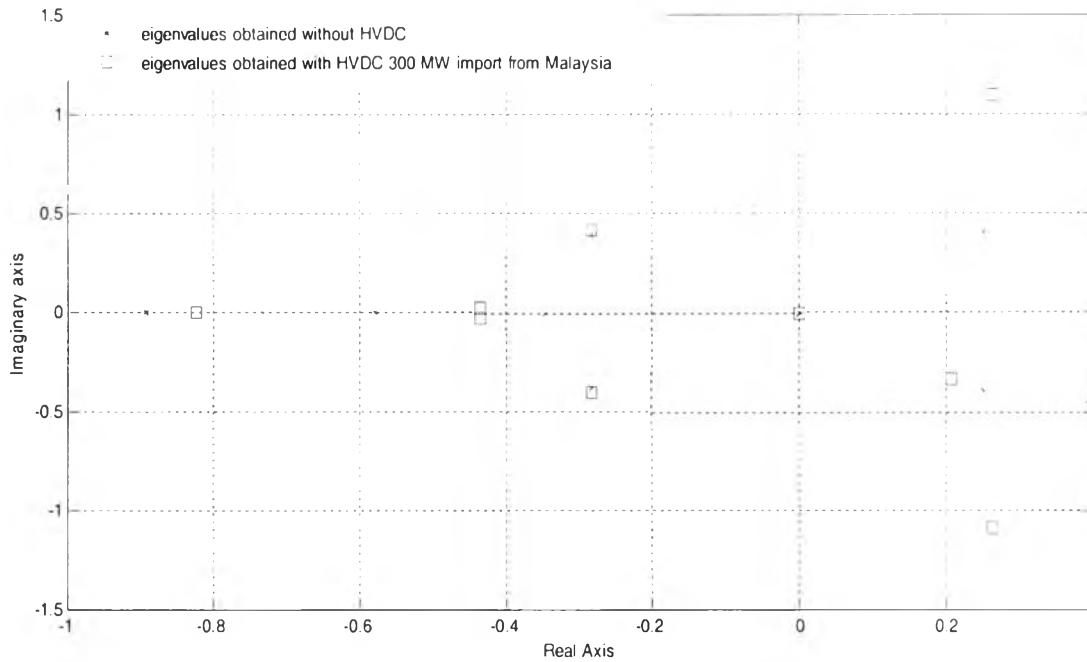

Figure 6.10 Comparison of plot of eigenvalues with 300 MW power import through HVDC link and without HVDC in the Southern Thailand system.
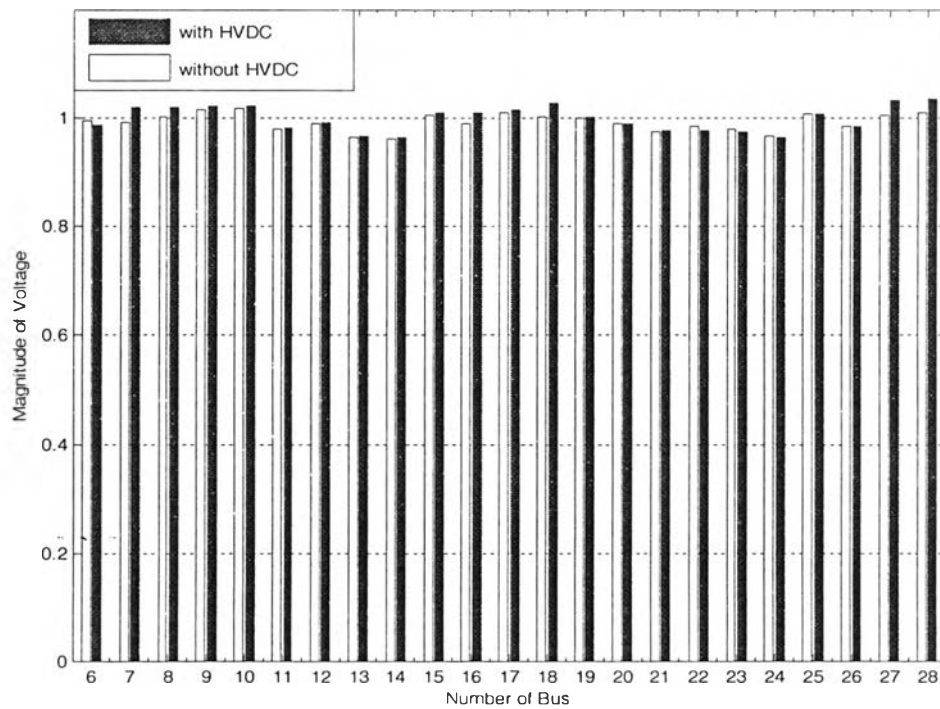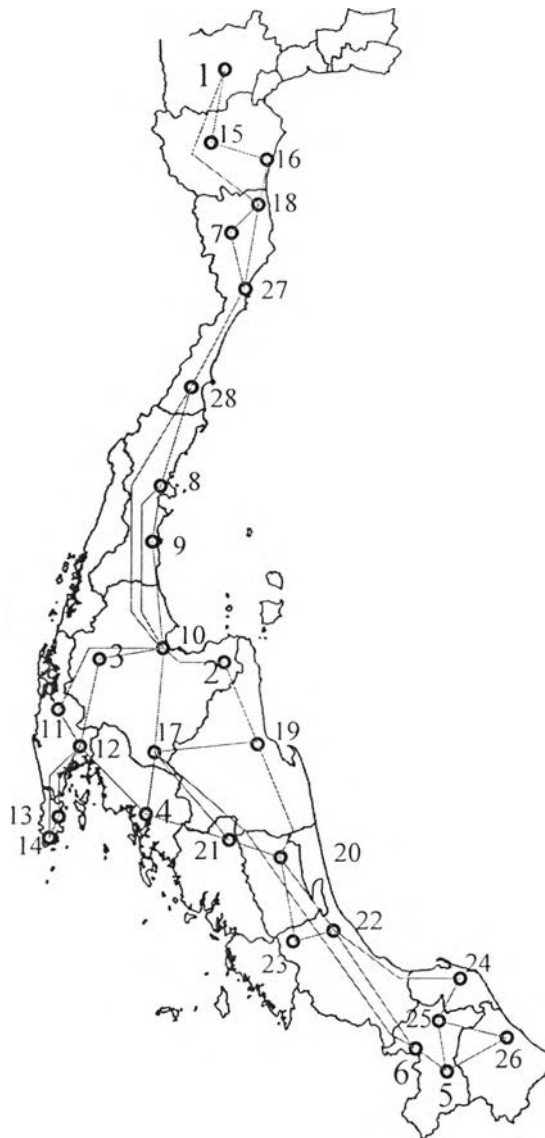

Figure 6.11 Comparison of voltage profile at each bus with 300 MW power import through HVDC link and without HVDC in the Southern Thailand system.

Table 6.25 Comparison of real power transmitted at each branch with 300 MW power import through HVDC link and without HVDC in the Southern Thailand systems

Branch	From bus	To bus	Real power Before HVDC installed	Real power With HVDC 300 MW
1	1	18	422.2	172.4
2	1	15	132.7	82.0
3	16	18	40.5	7.7
4	18	27	325.7	38.9
5	18	7	57.3	23.1
6	15	16	79.3	29.5
7	27	28	320.6	5.6
8	27	7	29.8	2.7
9	28	8	101.4	20.4
10	28	10	112.9	78.2
11	8	9	21.1	37.5
12	8	10	21.7	40.2
13	10	9	3.2	61.4
15	10	3	34.4	21.8
16	10	17	224.5	25.6
17	10	2	323.7	423.7
22	12	4	7.9	20.2
26	19	17	12.0	24.2
27	17	21	50.1	42.0
28	17	6	259.7	75.3
29	2	19	398.4	298.4
30	19	20	255.8	146.8
31	21	20	0.7	-11.5
32	20	22	191.1	81.7
33	20	23	21.4	11.6
34	22	23	32.3	41.5
35	22	24	29.0	25.8
36	6	22	171.0	285.3

We see that after we import power from Malaysia, most of the bus voltages are increased (see Fig. 6.11). There are 4 buses decrease their voltage, at bus number 6, 22, 23 and 24. It is because of the HVDC needs reactive power to do the conversion, and it draws from AC network, so that the magnitudes of voltage at some buses are decreased.

From Table 6.25 above, we can check the real power transmitted at each branch. The biggest decreasing is at branch number 1, this branch is connected bus number 1 and 18. When there is no HVDC, this branch transmits 455.2 MW and after import power from Malaysia, this branch transmits 172.43 MW. Note that not all branches list in Table 6.25, just branches which have significant different real power transmitted are listed. At

branch 31. we see that after there is 300 MW from Malaysia through HVDC. the sign of real power transmitted is negative. it means the transfer of power are reverse. In the first time, from bus 21 to 20. after that from bus 20 to 21.

From Fig. 6.10. we see that even though voltage profile is better, the system is worst than before. Compare to the system when there is no HVDC. just 2 eigenvalues go to unstable modes. In this case there are 4 eigenvalues which have positive real part. For those modes. we can see that the damping ratios are negative. its mean those modes go to unstable mode. From literature [22]. it observed that the current and power controller in the rectifier of HVDC can provide slightly negative electrical damping. Due to that fact, the result is reasonable. Also, probably it is because of certain parameter such as : K_r, K_i, T_r, and T_i are poorly tuned so that cause instability problem in the system.

Calculation of controllability matrix (CM) and observability matrix (OM) shows that there are some infinite elements in the CM and OM. Due to this reason, we cannot calculate rank of CM and OM. Thus we investigate using PBH (Popov-Belevich-Hautus) test [19]. There are two kind of test : PBH rank test for controllability and PBH rank test for observability. From PBH rank test for controllability, we found that there are 2 modes not full rank, it means those modes are not controllable. Those modes are eigenvalues number 1 and 38, and the biggest participation factor for those modes are state E_{fd} in generating unit number 2 and state R_f in generating unit number 2 . Because those two modes are uncontrollable, thus we cannot apply any controller in those states. From Table 6.24, we see that the real parts of those modes are negative. it means those modes are stable modes. Although we cannot apply controller to those state, no problem for the system, because those modes are stable already.

From PBH rank test for observability, we found that there are 5 modes not full rank, it means those modes are not observable. Those modes are eigenvalues number 1, 2, 3, 9 and 38.

Table 6.26 The uncontrollabe modes and their biggest participation factor

No	Mode	Eigenvalue	Biggest participaption factor	
			Generating Unit Number	State Variable
1	1	-1.95E+10	2	E_{fd}
2	2	-784.76 + 744.86i	1	E_{fd}
3	3	-784.76 -744.86i	1	E_{fd}
4	9	-50	2	V_R
5	38	-1.2903	2	R_f

From Table 6.26, we can see which state variable give the biggest participation factor to the uncontrollabe modes. Because those modes are uncontrollable, it means when we want to apply any observer-based controller to the system, we have to neglect those mode.