Chapter 4

Factors affecting Power system Transfer Capability

Transmission systems are complex networks connecting between generation units and lower voltage buses through substations. As mentioned in the previous chapter, transmission systems are developed to deliver reliable energy to lower voltage system such as distribution system to ensure service continuity and promote commercial activities. Under deregulated market, there are many incidents indicate that transmission networks seem to be a vulnerable point in the systems and cause the insecure operation. Therefore, transmission system is a significant part has to be carefully studied, designed and operated in order to accomplish its mission. Generally, the security problems are escalated by the limitation of transmission capability compare to the amount of power flow owning to power transactions. Construction of new transmission lines is a method which can alleviate or solve the problem since it eliminates the bottlenecks that are the sources of the problem. However, this construction takes long time and requires lot of investment costs that relatively unacceptable in some cases. From these reasons, an attempt to understand the factors that affect the ability of transmission system appears to be the best method to maintain system's security under competitive market as will be explained in this chapter.

It is hard to measure security level of power system directly under operating time frame since power system are dynamics, unpredictable and highly nonlinear. However, amount of power flow in transmission lines and voltage level at buses are two primary indicators that can be used to initially notify system's status. Generally, these two quantities can be utilized to prevent power system from insecure operation caused by unexpected severe incidents. Whenever power system are operated too close or exceed the security criteria, timely and appropriate remedial actions must be applied to secure the systems.

It is seen from many technical reports that major outages in power system can be prevented or reduced severity if system were monitored continuously. Abnormal incidents should be sensed and appropriate actions should be taken immediately to secure the system at the right moment. The DOE team found out that outages and depressed voltages in Long Island on July 3-8, 1999, Outages in Delmarva Peninsula on July 6, 1999 and Rotating outages in South-Central States on July, 23, 2000 [42] could have been avoided by the implementation of suitable emergency actions at the appropriate time. This is the proof that well understanding of the system, sufficient pre-studied and suitable remedial actions are important to maintain power system security.

According to the above motivation, an arising question about the method to establish criteria to achieve the reliably transactions as well as promote the market viable. In addition to thermal limits and voltage limits that are currently used in by power industry around the world, Contingency Studies, Transient Stability Studies, and Voltage Stability Studies should also be used to set-up the system security criteria

This chapter explains the basic ideas of power system security and control. Structure of deregulated power market; systems conditions and security limits are recognized as significant factors affecting power transfer in power system since they directly affect in transmission capability of power system. The purpose of this chapter is to provide practical information to evaluate security level of deregulated power market under real time operation. The term "Total Transfer Capability" in Real-time ATC formula is directly developed from these concepts.

4.1 Control of Power Flow in Transmission Systems

Generally, power system is large, complex encompassing vast geographical area. Direction and amount of electricity in the power system at a specific time are two imperative quantities that are difficult to forecast and control since they require lot of efforts and investment to accomplish the goal. Traditionally, utilities employ mechanical devices and control actions such as changing transformer tap and/or phase shift of transformers to control amount of power flow in the system. These efforts to control power flow in the systems are acceptable in the steady state but inadequate in emergency situation. Theoretically, an implementation of special equipment such as Flexible AC Transmission Systems (FACTS) devices to some appropriate locations is a favorable alternative in controlling the power flow. Although FACTS devices are not the main topic of this dissertation, it is worthwhile to mention in this dissertation because it introduce the future concept of power system control and operation. Examples of devices that are commonly used in power system for real and reactive flow control are shown as the following.

4.1.1 Static VAR compensators (SVCs):

The main function of SVCs is to balance reactive power requirements at their installed location (it is usually attached at bus) by absorbing or delivering reactive power. SVCs are easily figured as equipment composed of capacitor and reactor connected in parallel controlled by controller.

4.1.2 Thyristor-controlled series capacitors (TCSC):

This application of FACTS technology is designed to control the impedance of a transmission line. TCSC is the combination of series capacitor and thyristor-controlled unit which directly determine electrical distance seen over transmission lines. However, this device may cause problem on impedance relay zoning protection.

4.1.3 Unified power flow controller (UPFC):

UPFC is a new innovation of GTO-Thyristor (Gate Turn-off Thyristor) that voltage magnitude and angle are fully controlled. Therefore, UPFC in an ideal FACTs device that amount and direction of power can be regulated and directed as required once it is installed in the appropriate locations.

In addition to FACTS devices shown in 4.1.1 – 4.1.3, Interphase Power Controller (IPC), Thyristor Controlled Voltage Limiter (TCVL), Thyristor Controlled Phase-Angle Regulator (TCPAR), Super-Conducting Current Limiter (SCCL) and Hingorani Damper (NGH) [FACT] are also examples of FACTs devices currently applied to power system control and operation. However, FACT devices in 4.1.1 – 4.1.3 are explicitly explained since they are commonly used equipment.

Though they have been a lot of progress in developing and manufacturing of FACTs devices in laboratory, the application of FACTs devices in practical power system is still in the early stage. This concept of FACTs application works well with the power system which transmission networks are not complicate such as radial system since direction and amount of power flow are easy to control and only a few locations are required to install FACTs devices. In practical power system, transmission systems are far more complicated than radial system due to mesh or loop connections. Installation of FACTs devices with the purpose to control power flow in the system will result in tremendous investment as well as changing in dynamics characteristics of power system that may cause additional stability problem. From this reason, it is reasonable to conclude that "there is still no practical way to provide a specific, unique transmission path from a particular electricity supplier to a particular customer unless a explicit radial (not a part of the network) transmission line is built for that purpose [43].

4.2 Structure of Power Market

Structure of power system affects the transfer capability since it implies the hierarchy and geographical connection of the systems. Generally, when power system is considering to be deregulated, the structure of power market is partially influenced by topography of power system.

Generally speaking, bilateral contract market is suitable for power system which transmission lines are mostly radial connection. Pool or pool-based model is an appropriate market structure of a power system which transmission lines are mostly connected in loop or mesh. In this chapter, effects of power market structure both in bilateral contract and pool-based model [2,4-6,8,44] (include or exclude bilateral contract) will be explained and discussed.

4.2.1 Bilateral Contract Power Market

Calculation of transmission capability under the Bilateral Contract Power Structure is relatively straightforward and easy to understand since most of the transmission system is radial. Bilateral contract structure in this section is different from bilateral transactions in pool market. The bilateral contract structure is dealing the power system with the radial transmission system that encompasses large service areas. Unique characteristics of bilateral contract power market are the distance between suppliers and customers are relatively far. Most of electricity transactions are based on long-term contract that buyers and sellers agree upon a transaction.

Therefore, transactions in this structure are relatively consistent on both amount of power flow and direction.

Under bilateral contract power market, majority of power flow in transmission lines are resulted from load demand and transmission losses. Parallel path flow in each line is not a significant quantity to affect amount of power flow since the nature of radial transmission lines are not sensitive to parallel path flow. Therefore, according to the above information, maximum power transfer due to transactions in the bilateral contract power market is easily determined by increasing load at customer buses and generation at buyer buses simultaneously (start from any initial conditions for real-time analysis). In order to satisfy security criteria, thermal limits, voltage limits and stability limits must be considered as limiting conditions of the system. Example 1 gives the simulation result of effects of transaction in a typical radial system (region 3 of Thailand power system). One can see that parallel path flow does not change the amount of power flow in transmission lines significantly.

Example 1. Investigation of power flow in radial system.
Test System: Thailand Power System, region 3 as shown in figure 4-1*. (230kV)

Simulation Framework: Simulate different of transactions between sinks and sources and then investigate the amount of power flow in transmission lines in order to observe the amount of parallel path flow.

Simulation Results:

Four scenarios are simulated in this example. The first scenario is the result of power flow in the systems in the interested area under normal operating conditions (peak load - only 230 kV buses are presented).

Table 4-1. Power flow in the typical power system under normal conditions

From Bus	To Bus	CCT#	Power Flow	
			P (MW)	Q (MVAR)
RPB	SRT	1	-75.79	-17.45
	SRT	2	-75.79	-17.45
SRT	KN	1	-79.30	-28.37
	KN	2	-79.30	-28.37
SRT	BSP	1	-43.26	-4.90
	BSP	2	-43.26	-4.90
KN	NT	1	217.20	-7.82
	NT	2	217.20	-7.82
NT	PU	1	147.48	-19.03
	SRT	2	147.48	-19.03
PU	HY2	1	117.51	-21.70
	HY2	2	117.51	-21.70

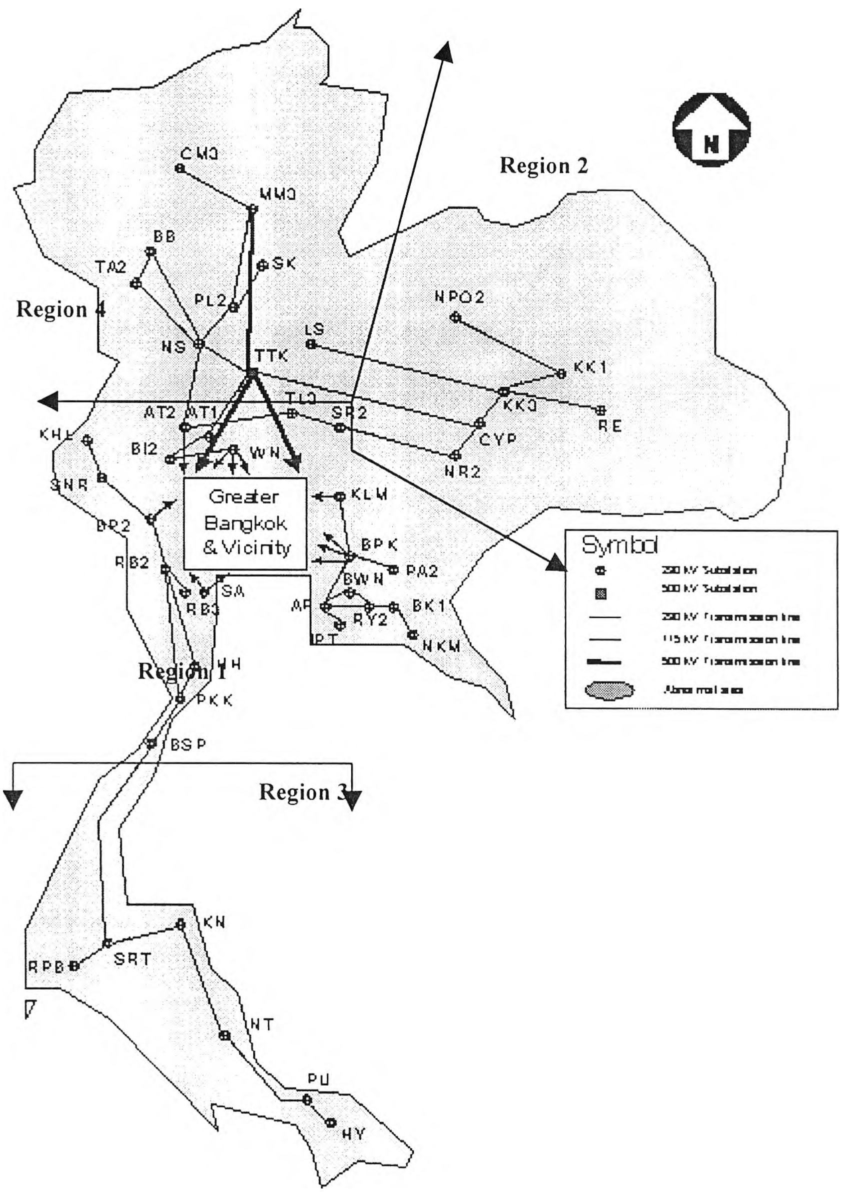


Figure 4-1 Thailand Power system

The second case is the simulation of the first case which has shown in table 4-1 with additional transaction between seller and customer buses in region 3 (100 MW transaction between bus 3703 (Surat Thani - SRT) and 3706 (Ranong - RN)). Results of this simulated case are shown in table 4-2.

Table 4-2. Power flow in the typical power system with transaction in area 3

From Bus	To Bus	CCT #	Power Flow		Change* (%)
			P(MW)	Q(MW)	
RPB	SRT	1	-100.86	-35.97	33.08
	SRT	2	-100.86	-35.97	33.08
SRT	KN	1	-75.32	-49.52	5.02
	KN	2	-75.32	-49.52	5.02
SRT	BSP	1	-44.87	-10.19	3.72
	BSP	2	-44.87	-10.19	3.72
KN	NT	1	221.17	-5.85	1.83
	NT	2	221.17	-5.85	1.83
NT	PU	1	149.39	-19.19	1.30
	PU	2	149.39	-19.19	1.30
PU	HY2	1	117.92	-22.72	0.35
	HY2	2	117.92	-22.72	0.35

The third case is the simulation of the transaction between seller in region 4 and customer in region 2 (100 MW transaction between bus 4808 (Mae Moh - MM) and 2703 (Nakhon Rat Chasima - NR)). Results of this case are shown in table 4-3.

Table 4-3. Power flow in the typical power system with transaction between area 4 and area 2

From Bus	To Bus	CCT #	Power Flow		Change* (%)
			P(MW)	Q(MW)	
RPB	SRT	1	-75.79	-17.45	0
	SRT	2	-75.79	-17.45	0
SRT	KN	1	-79.30	-28.37	0
	KN	2	-79.30	-28.37	0
SRT	BSP	1	-43.26	-4.90	0
	BSP	2	-43.26	-4.90	0
KN	NT	1	217.20	-7.82	0
	NT	2	217.20	-7.82	0
NT	PU	1	147.48	-19.03	0
	PU	2	147.48	-19.03	0
PU	HY2	1	117.51	-21.70	0
	HY2	2	117.51	-21.70	0

The last case is the situation when seller and buyer are in region 1 (100 MW transaction between bus 1705 (South Bangkok – SB) and 6724 (Khlong mai – KLM)). Results of this case shown in table 4-4.

Table 4-4. Power flow in the typical power system with transaction between area 1 and area 6

From Bus	To Bus	CCT #	Power Flow		Change* (%)
			P(MW)	Q(MW)	
RPB	SRT	1	-75.79	-17.45	0
	SRT	2	-75.79	-17.45	0
SRT	KN	1	-79.30	-28.37	0
	KN	2	-79.30	-28.37	0
SRT	BSP	1	-43.26	-4.90	0
	BSP	2	-43.26	-4.90	0
KN	NT	1	217.20	-7.82	0
	NT	2	217.20	-7.82	0
NT	PU	1	147.48	-19.03	0
	PU	2	147.48	-19.03	0
PU	HY2	1	117.51	-21.70	0
	HY2	2	117.51	-21.70	0

* Percent change of power flow compared to base case

Results from table 4-1 to table 4-4 give good examples that parallel path flow is relatively insignificant for a bilateral structure power market for a radial transmission system. Power flow in the systems is relatively predictable and straightforward. The results will be compared with the pool-based market structure in the next section.

4.2.2 Pool-Based Market

Pool-based power market structure affects the transmission capability in a different manner from bilateral contract power market since hierarchy and geographical connection of transmission lines under the this structure market are normally based on mesh or loop connection.

Normally, most of transmission network in loop or mesh connection are suitable for pool-based model since they are designed to serve the high-density load area. Therefore, there are many routes to deliver electricity from one location to the destination in the system. This property implies that effect of parallel path flow is dominant in pool-based power market structure which increase the complication of the calculation.

Additionally, deregulated power market based on pool model usually relies on scheduling processes which bids and offers are matched by prices mechanisms. This process makes the transactions in pool-based market more dynamics and complicated compare to the bilateral contract because sellers in the market are subjected to changed that will change the pattern of amount and direction of power flow in transmission systems. In addition, Parallel path flow plays an important role in pool-based market since it produces unpredicted power flow in transmission lines in the power system. A simple example of parallel path flow in loop network is shown in example 2. This example simulates the cases when different levels of transaction are dispatched in mesh power system (region 1 of Thailand power system). It is seen that variation of power flow in transmission lines are unpredictable and parallel path flow is a factor that cannot be overlooked.

Example 2. Investigation of power flow in meshed power system.
Test System: Thailand Power System Region 1 (Bangkok and vicinity areas) as shown in figure 4-2*. (230 kV buses)

Simulation Framework: Simulates variety of transactions between sinks and sources and then investigate the amount of power flow in transmission lines in order to observe the amount of parallel path flow.

* Source: Electricity Generation Authority of Thailand

Simulation Results:

Four scenarios are simulated in the example 2. First scenario is the result of power flow in the systems in the interested area under normal operating conditions (peak load - only 230 kV buses are presented).

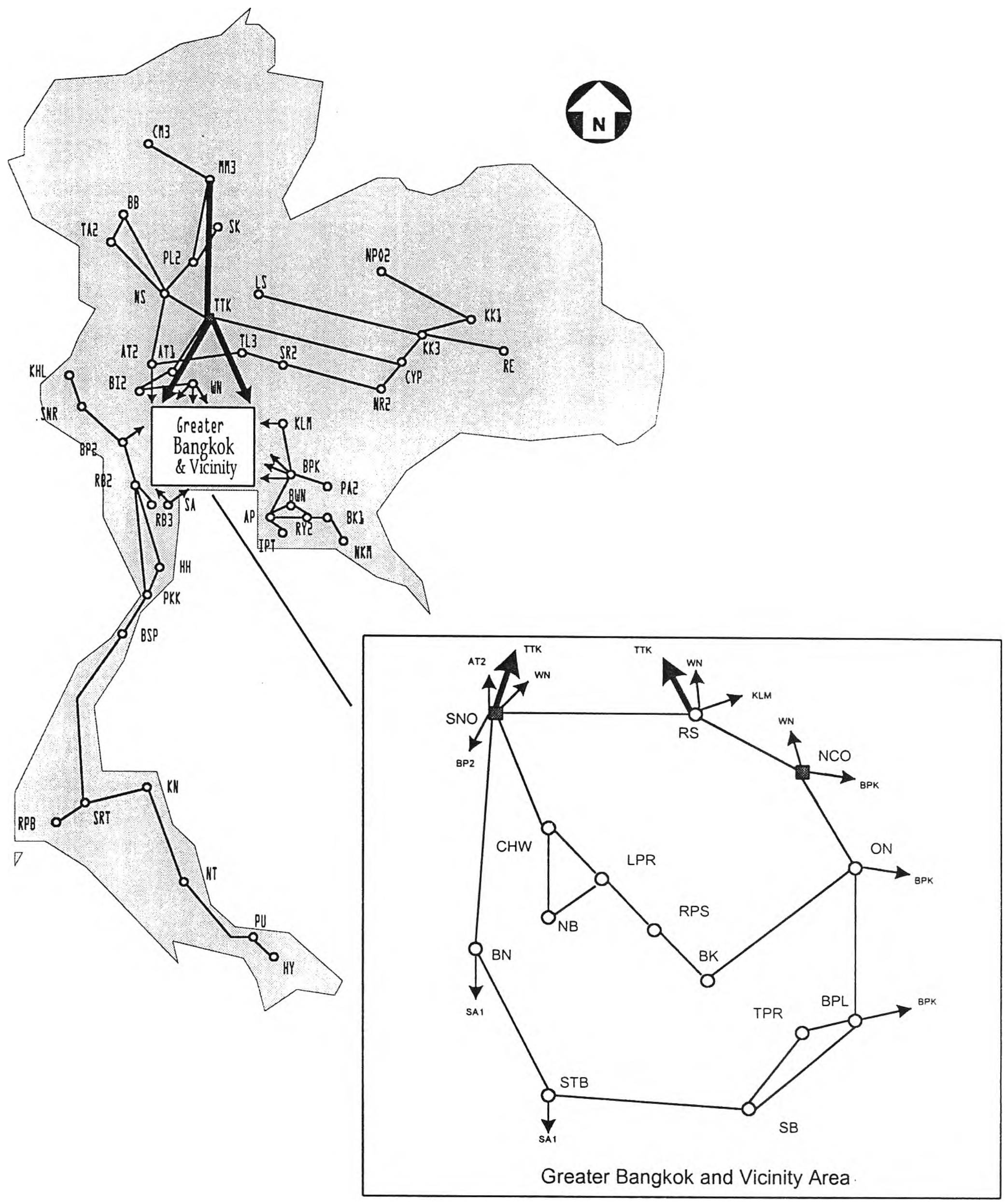


Figure 4-2. Region 1 of Thailand Power System

Table 4-5. Power flow in the sample power system under normal conditions

From Bus	To Bus	CCT#	Power Flow	
			P (MW)	Q (MVAR)
NB	NB	1	-146.55	-138.44
	NB	1	-238.44	56.52
LPR	NB	1	238.40	-57.02
	BK	1	-487.00	-37.33
	RPS	1	-416.04	1.35
	CWN	1	16.60	-237.51
BK	ON	1	-433.77	-101.08
	ON	2	-433.77	-101.08
	ONN	1	-430.75	-101.83
	ONN	2	-430.75	-101.83
	RPS	1	535.05	63.74
BPL	ON	1	-688.41	191.65
	ONN	1	-692.04	190.61
	TPR	1	-284.98	-157.81
	TPR	2	-284.98	-157.81
	BPK	1	850.71	-420.23
	BPK	2	850.71	-420.23
SB	STB	1	262.02	202.59
	STB	2	279.96	213.74
	STB	3	262.02	202.59
	TPR	1	570.00	315.91
STB	BN	1	87.36	129.45
	BN	2	87.36	129.45
	SA	1	158.23	65.52
BN	SNO	1	-439.99	-13.41
	SA	1	183.74	22.69
SNO	AT	1	-68.12	7.02
	AT	2	-68.12	7.02
	BP	1	81.31	-0.18
	BP	2	81.31	-0.18
RS	CWN	1	129.98	374.19
	WN	1	-379.40	-38.50
	WN	2	-379.40	-38.50
	WN	3	-379.34	-32.72
	WN	4	-379.40	-38.50

Table 4-5. Power flow in the sample power system under normal conditions (cont)

From Bus	To Bus	CCT#	Power Flow	
			P (MW)	Q (MVAR)
	KLM	1	487.27	-203.51
	KLM	2	487.27	-203.51
NCO	ONN	1	773.96	-30.62
	NCO	1	-68.99	-67.44
	BPK	1	-704.97	-74.06
ONN	BPK	1	-779.67	-44.58
NCO	ON	1	775.40	-33.45
	NCO	1	-69.70	-69.06
	BPK	1	-705.67	-75.73

The second case is the simulation of the base case with additional transaction between seller and customer buses in area 3 (100 MW transaction between bus 3703 and 3706). Result of this case is shown in table 4-6.

Table 4-6. Power flow in the sample power system with transaction in area 3

From Bus	To Bus	CCT #	Power Flow		MW* Change(%)
			P(MW)	Q(MW)	
NB	NB	1	-146.56	-138.44	0.0068
	NB	1	-238.43	56.51	0.0042
LPR	NB	1	238.39	-57.02	0.0042
	BK	1	-486.98	-37.33	0.0041
	RPS	1	-416.02	1.35	0.0048
	CWN	1	16.58	-237.51	0.1205
BK	ON	1	-433.76	-101.08	0.0023
	ON	2	-433.76	-101.08	0.0023
	ONN	1	-430.74	-101.83	0.0023
	ONN	2	-430.74	-101.83	0.0023
	RPS	1	535.03	63.75	0.0037
BPL	ON	1	-688.38	191.65	0.0044
	ONN	1	-692.00	190.61	0.0058
	TPR	1	-284.84	-157.83	0.0491
	TPR	2	-284.84	-157.83	0.0491
	BPK	1	850.54	-420.21	0.0200
	BPK	2	850.54	-420.21	0.0200
SB	STB	1	262.11	202.65	0.0343
	STB	2	280.06	213.80	0.0357
	STB	3	262.11	202.65	0.0343

Table 4-6. Power flow in the sample power system with transaction in area 3 (cont)

From Bus	To Bus	CCT #	Power Flow		MW* Change(%)
	TPR	1	569.72	315.94	0.0491
STB	BN	1	87.46	129.64	0.1145
	BN	2	87.46	129.64	0.1145
	SA	1	158.33	65.64	0.0632
BN	SNO	1	-439.88	-13.34	0.0250
	SA	1	183.82	22.78	0.0435
SNO	AT	1	-68.15	7.00	0.0440
	AT	2	-68.15	7.00	0.0440
	BP	1	81.49	-0.06	0.2214
	BP	2	81.49	-0.06	0.2214
RS	CWN	1	130.01	374.18	0.0231
	WN	1	-379.36	-38.51	0.0105
	WN	2	-379.36	-38.51	0.0105
	WN	3	-379.31	-32.72	0.0079
	WN	4	-379.36	-38.51	0.0105
	KLM	1	487.18	-203.50	0.0185
	KLM	2	487.18	-203.50	0.0185
NCO	ONN	1	773.92	-30.62	0.0052
	NCO	1	-68.99	-67.43	0.0000
	BPK	1	-704.98	-74.06	0.0014
ONN	BPK	1	-779.67	-44.58	0.0000
NCO	ON	1	775.36	-33.45	0.0052
	NCO	1	-69.70	-69.06	0.0000
	BPK	1	-705.68	-75.73	0.0014

The third case is the simulation of the transaction between seller in area 4 and customer in area 2 (100 MW transaction between bus 4808 and 2703). Result of this case is shown in table 4-7.

Table 4-7. Power flow in the sample power system with transaction between area 4 and area 2

From Bus	To Bus	CCT #	Power Flow		MW* Change(%)
			P(MW)	Q(MW)	
NB	NB	1	-146.73	-138.05	0.1228
	NB	1	-238.24	56.30	0.0839
LPR	NB	1	238.22	-56.56	0.0755
	BK	1	-486.70	-37.98	0.0616
	RPS	1	-415.75	0.55	0.0697
	CWN	1	16.17	-236.75	2.5904

Table 4-7. Power flow in the sample power system with transaction between area 4 and area 2 (cont)

From Bus	To Bus	CCT #	Power Flow		MW* Change(%)
BK	ON	1	-433.61	-101.98	0.0369
	ON	2	-433.61	-101.98	0.0369
	ONN	1	-430.60	-101.60	0.0348
	ONN	2	-430.60	-101.60	0.0348
	RPS	1	534.74	64.30	0.0579
BPL	ON	1	-704.78	196.39	2.3779
	ONN	1	-708.38	196.00	2.3611
	TPR	1	-295.61	-154.34	3.7301
	TPR	2	-295.61	-154.34	3.7301
	BPK	1	877.70	-419.81	3.1726
	BPK	2	877.70	-419.81	3.1726
SB	STB	1	255.07	203.76	2.6525
	STB	2	272.58	215.03	2.6361
	STB	3	255.07	203.76	2.6525
	TPR	1	591.28	309.10	3.7333
STB	BN	1	78.34	130.99	10.3251
	BN	2	78.34	130.99	10.3251
	SA	1	155.00	66.02	2.0413
BN	SNO	1	-458.49	-10.12	4.2046
	SA	1	184.19	22.46	0.2449
SNO	AT	1	-73.39	9.28	7.7363
	AT	2	-73.39	9.28	7.7363
	BP	1	82.70	-0.68	1.7095
	BP	2	82.70	-0.68	1.7095
RS	CWN	1	130.58	372.90	0.4616
	WN	1	-388.54	-37.72	2.4091
	WN	2	-388.54	-37.72	2.4091
	WN	3	-388.46	-31.80	2.4042
	WN	4	-388.54	-37.72	2.4091
	KLM	1	505.25	-204.55	3.6899
	KLM	2	505.25	-204.55	3.6899
NCO	ONN	1	787.49	-36.05	1.7482
	NCO	1	-85.23	-66.34	23.5396
	BPK	1	-702.44	-75.77	0.3589
ONN	BPK	1	-782.20	-44.08	0.3245
NCO	ON	1	778.91	-35.88	1.7423
	NCO	1	-85.65	-66.44	22.8838
	BPK	1	-703.15	-75.89	0.3571

The last case is the situation when seller in area 1 tries to deliver power to customer in area 6 (100 MW transaction between bus SB and 6724). Result of this case is shown in table 4-8.

Table 4-8. Power flow in the sample power system with transaction between area 1 and area 6

From Bus	To Bus	CCT #	Power Flow		MW* Change(%)
			P(MW)	Q(MW)	
NB	NB	1	-141.39	-139.63	3.5210
	NB	1	-243.62	57.55	2.1725
LPR	NB	1	243.59	-57.85	2.1770
	BK	1	-495.44	-35.53	1.7331
	RPS	1	-424.48	3.14	2.0287
	CWN	1	28.30	-240.10	70.4819
BK	ON	1	-438.00	-100.83	0.9752
	ON	2	-438.00	-100.83	0.9752
	ONN	1	-434.97	-100.48	0.9797
	ONN	2	-434.97	-100.48	0.9797
	RPS	1	543.49	61.96	1.5774
BPL	ON	1	-681.83	186.92	0.9558
	ONN	1	-685.47	186.54	0.9494
	TPR	1	-324.57	-159.73	13.8922
	TPR	2	-324.57	-159.73	13.8922
	BPK	1	883.73	-422.84	3.8815
	BPK	2	883.73	-422.84	3.8815
SB	STB	1	268.82	201.93	2.5952
	STB	2	287.19	213.00	2.5825
	STB	3	268.82	201.93	2.5952
	TPR	1	649.17	319.68	13.8895
STB	BN	1	96.20	128.74	10.1190
	BN	2	96.20	128.74	10.1190
	SA	1	161.40	65.22	2.0034
BN	SNO	1	-421.90	-15.16	4.1115
	SA	1	183.30	22.74	0.2395
SNO	AT	1	-65.52	6.64	3.8168
	AT	2	-65.52	6.64	3.8168
	BP	1	79.94	-0.07	1.6849
	BP	2	79.94	-0.07	1.6849
RS	CWN	1	113.09	377.76	12.9943
	WN	1	-383.67	-39.44	1.1255
	WN	2	-383.67	-39.44	1.1255

Table 4-8. Power flow in the sample power system with transaction between area 1 and area 6 (cont)

From Bus	To Bus	CCT #	Power Flow		MW Change(%)
	WN	3	-383.63	-33.58	1.1309
	WN	4	-383.67	-39.44	1.1255
	KLM	1	504.27	-203.50	3.4888
	KLM	2	504.27	-203.50	3.4888
NCO	ONN	1	775.53	-31.56	0.2029
	NCO	1	-70.94	-69.43	2.8265
	BPK	1	-704.67	-77.17	0.0426
ONN	BPK	1	-779.96	-46.60	0.0372
NCO	ON	1	776.95	-31.45	0.1999
	NCO	1	-71.78	-69.57	2.9842
	BPK	1	-705.39	-77.32	0.0397

* Percent change of power flow compared to base case

It is seen from results given in table 4-8 that mesh and loop connections of transmission systems result in the increasing of parallel path flow. This is a unique characteristic of pool-based power market. In some cases, parallel path flow may result in unexpected power flow in transmission lines outside the transaction areas. This may cause security problem in power system if this problems are not realized before the real operation of the system.

4.3 Thermal Limits

Thermal limit is the primary concern of the utilities with the purpose to indicate security level of power system. Generally, thermal limits are determined from ratings of facility in the network that can be divided into two sub-categories depend on the duration of operation. Normal rating is the long-term rating of while emergency rating is the ability of facility to tolerate an amount of power flow in a short period of time.

There are several severe situations that are directly resulted from thermal limits violation in transmission systems. Physical damages and increasing possibility to fault are good example of thermal limits violation. When the transmission lines are overloaded, the heat produced by current flowing in the transmission lines may cause followings unfavorable results in transmission systems.

a) The heat declines strength of high voltage transmission lines that usually made from aluminum. Transmission lines under this circumstance are easily to be damaged when they are subjected to forces or tension. This outcome of thermal limit directly results in physical damages of transmission systems.

b) Overload in transmission lines increases sag and decreases clearance between transmission lines and ground. These situations increase more opportunity to fault in the system since it is easier to have a fault when distance between transmission lines and ground decrease.

Basically, thermal limit rating of equipment such as transmission lines depend on type of material, structure of conductor, ambient temperature, wind velocity etc. Therefore, thermal limit of a facility is not constant all the time and it is varied by seasons and location of transmission lines. Examples of Extra High Voltage (EHV) transmission lines parameters are shown in table 4-9 [11].

Table 4-9. Typical overhead transmission line parameters

Nominal Voltage	R (Ω/km)	X(Ω/km)	Charging (MVA/km)	SIL (MW)
230 kV	0.0500	0.4880	0.18	140
345 kV	0.0370	0.3670	0.54	420
500 kV	0.0280	0.3250	1.30	1000
765 kV	0.0120	0.3290	2.92	2280
1,100 kV	0.0050	0.2920	6.71	5260

Generally, thermal limit violations can be easily identified by using power flow program to study the system under a particular condition. Thermal limit violation can be reported when total MVA flow in a transmission line exceeds its limit (normal or emergency operation rating). Most of power flow programs are able to report thermal limit violations automatically. Therefore, thermal limit is usually not a problem from analytical point of view since it is easy to detect by normal power flow program.

4.4 Voltage Limit

Voltage profile is an important index in power system to determine the security of the entire system. Deviations of voltage from the desired values can be accounted as a proximity to abnormal conditions since it indicates the situation of inappropriate amount of reactive power at that location.

A good example of effect of voltage level to power system is the relationship between amounts of reactive power supplied by shunt equipment such as capacitor banks and voltage level at that location. Generally, amount of reactive power delivered by this compensation shunt element are designed when power system are operated at rated voltage. However, actual amounts of reactive power depend on square of voltage level. Therefore, at high voltage this equipment delivers excessive reactive power to the system that may cause over voltage problem. On the contrary, during low voltage, insufficient reactive power is injected into the system provide less voltage support than expected.

Generally, acceptable voltage level in transmission systems is $\pm 5\%$ from nominal voltage (0.95 PU to 1.05 PU) in normal conditions and ranging between $\pm 5\%$ to $\pm 10\%$ in postfault conditions. Independent System Operator has responsibility to maintain voltage level within this range in order to maintain system's security. However, voltage fluctuation such as voltage dip may occur during the transient period. Similar to steady state period, reliability standard must be established to define the allowable amount and period of these fluctuations which may be different in quantity and contents in each systems. Example of transient voltage criteria of Western Systems Coordinating Councils (WSCC) is shown in Table 4-10 [45]

Table 4-10. WSCC voltage criteria

Performance Level	**Disturbances initialed by:** No Fault 3 phases fault Single Line to Ground fault DC Disturbances	**Transient Voltage Dip**	**Post Transient Voltage Deviation**
A	Generator One Circuit One Transformer	Max V Dip 25% Max Duration of V Dip Exceeding 20% - 20 cycles	5%
B	Bus Section	Max V Dip 30% Max Duration of V Dip Exceeding 20% - 20 cycles	5%
C	Two Generators Two Circuit	Max V Dip 30% Max Duration of V Dip Exceeding 20% - 40 cycles	10%
D	Three or more circuits on ROW Entire Substation Entire Plant including Switchyard	Max V Dip 30% Max Duration of V Dip Exceeding 20% - 60 cycles	10%

4.5 Stability Limit

Power system stability plays very an important role in determining maximum transmission capability in transmission system since it demonstrates the ability of a power system to remain in a state of operating equilibrium under normal operating conditions and to recover an acceptable state of equilibrium after a disturbance. Basic concepts, classification and evaluation of stability problems particularly stability criteria used in real-time ATC calculation are discussed in the later part of this chapter.

4.5.1 Basic Stability Concepts

The stability problem has been developed for a long time since the development of power industry. Traditionally, stability study focuses on the ability of synchronous generator to maintain synchronous operation among generators since synchronous generator is the major source of electricity generation. A stable system should satisfy necessary conditions that all generators, coherent machines [46], in the system remain in synchronism in any circumstances.

In modern power system operation, instability may be encountered when machines remain in synchronism [11]. Combined characteristics of load with high proportion of motor may result in difficulties in control of voltage if reactive power requirement is insufficient. This situation may cause stability problem by substantially reduce in voltage magnitude while synchronism of synchronous machines are maintained. Therefore, in this case, stability is not influenced by generators synchronism but ability to supply reactive power to load.

As seen from the above example, evaluation of stability problems requires the study of power system responds when it subjects to disturbances. Disturbances may be small or large, intermittence or continuously which ranging from gradually load changes to severe is necessary to classify stability into various categories and apply suitable technique to resolve the problem.

Generally, time-domain analysis employing various numerical techniques [11, 46-48] is sufficient to obtain simulation results of every stability categories. This method reveals information of system at each step of snap shot calculation. Nonlinearities of parameters and system have been included by this technique. However, accuracy is also depends on quality of input information and models of the system.

On the other hand, frequency domain analysis is an alternative for stability analysis. Since frequency domain analysis focuses on the natural frequency of the system response at the vicinity of the operating point, this technique is proper to parts of categories of power system stability such as small-signal stability as will be explained again later.

This section starts with the basic concept of stability phenomena including significant terms affecting stability of the system then continues with the classification of power system stability study exploited in this dissertation.

4.5.1.1 Rotor Angle Stability: The Stability Phenomena

Basically, operating point of power system is the equilibrium between two opposing forces [11], a force tend to decelerate one or more synchronous generators that caused by load and the counter force produced by synchronous generators. When conditions in power system changed, system will try to self-adjust itself to a new operating equilibrium. However, this capability of power system is applicable within a specific range depend on generation and transmission capacity. If load increased, a generator or group of generators tend to respond and increase angular separation. If this situation continues, it may lead to loss of synchronism of generators or "fall out of step" that will trigger protection system to isolate these generator from the system. This abnormal condition may present in either loss of synchronism of a single generator or the separation of a group of generators and the system. Generally, protection scheme will determine this generation isolation.

In electric power system, the change in electrical torque in synchronous generator is resulted from two components, torque change due to rotor angle perturbation $\Delta\delta$ and rotor speed perturbation $\Delta\omega$ as the following

$$\Delta T_e = T_S \Delta\delta + T_D \Delta\omega$$

Where

$T_S\Delta\delta$ = Torque change due to rotor angle perturbation

$T_D\Delta\omega$ = Torque change due to rotor speed perturbation

$\Delta\delta$ = Rotor angle perturbation

$\Delta\omega$ = Rotor speed perturbation

T_S = Synchronizing torque coefficient

T_D = Damping torque coefficient

Since the first component in electrical torque perturbation is related to rotor angle separation that determining synchronism of generators in the system, this term is also known as "Synchronizing Torque". Similarly, the second term is also called "Damping toque" since it results from the change in rotor speed compared to the synchronous speed that can be controlled by damping coefficient of generators.

According to the above explanations, power system will encounter a progress in aperiodic drift in rotor angle if it contains insufficient synchronizing torque. Vice versa, oscillations, fluctuating generator speeds, are result from damping torque deficiency. These two significant terms will be referred throughout this chapter since they explain rotor angle instability phenomena in power system.

Classification of rotor-angle stability [11]

Rotor-angle stability problem can be categorized by the disturbances subject to the generator as follows:

4.5.1.1.1 Small-signal stability:

This topic concentrates on the respond of power system when disturbances are small and continuously such as slightly change in load demand or generation dispatch. Under this situation, power system may experience unstable operating condition if it is lacking of synchronizing torque or damping torque as seen by instability through non-oscillatory mode, increasing in rotor angle, or rotor oscillation respectively. Basically, non-oscillatory instability can be alleviated or eliminated by the operation of automatic voltage regulator (AVR) since this equipment maintains suitable voltage magnitude at generators terminal for delivering sufficient power to supply load. As soon as load demand is satisfied, generator's rotor angle is controllable. Since AVR is the basic equipment in generator control loop, non-oscillatory instability problem is not a significant stability problem in modern power system.

On the contrary, oscillatory instability due to insufficient damping torque is the most frequently seen of the small signal stability in power system. This problem, ranging from oscillation to instability, may be categorized in several modes depend on the characteristics of instability as the followings.

a) Local modes: This mode of rotor-angle stability represents the swinging of generators inside a generation unit or a part of the system while the rest of the system is operating under normal conditions.

b) Interarea modes: Interarea oscillation occurs when at least two groups of generation units are swinging against each otehr. This situation is normally taken place with at least two groups of machine are interconnected by weak transmission system.

c) Control modes: This category of rotor-angle stability associates with the installation of poor setting control equipment such as exciters, speed governors, HVDC converters or Static Var Sstems (SVS).

d) Torsional modes: This mode of stability is closely related to the interaction between mechanical component of the system, shaft of generator, and other control or compensation equipment such as excitation controls, speed governors or series-capacitor-compensated lines.

4.5.1.1.2 Transient stability:

Transient stability phenomenon is the respond of power system when it subjects to severe disturbances. Generally, large disturbances cover several abnormal conditions that may occur in the system such faults, switching etc. but three-phase to ground fault is accepted as the standard simulation condition for general transient stability study since it is the most severe case of system disturbance. These disturbances result in large electromechanical transient in the system that may exceed the withstand ability of generators. Many factors, such as initial conditions, generators parameters, strength of transmission lines, and protection scheme determine the stability of power system under this circumstances.

Transient stability study focuses on the moment 3 to 5 seconds [11,46-50] following the disturbances. Instability may occur within the first swing of transient stability period that rotor generator rotor angle increase progressively until loss of synchronism or the system is stable during the first swing but contains the oscillations further develop to instability incident in the extended time scale that related to small long-term dynamics. However, first swing instability is relatively rare in practical system, association between oscillations during the first swing and the extended time period or sometime superposition of several oscillations are regularly recognized as the common transient instability in practical power system.

Properties of rotor angle stability are summarized as tabulated below.

Table 4-11 Summary of rotor angle stability in power system

	Transient stability	Small signal stability
Time frame	3-5 seconds (not exceed 10s)	> 10 seconds
Disturbances	Large, intermittence disturbances such as three-phase fault	Small, continuous disturbances
Analytical method(s)	Time domain analysis	Time domain analysis or Frequency domain analysis
Causes of instability	Loss of synchronism due to rotor angle separation	Loss of synchronism due to rotor angle separation or Uncontrollable rotor speed
Modes	First swing instability or extended time instability	Local, interarea, control and torsional modes

4.5.1.2 Voltage stability

Since instability of modern power system is not strictly caused by rotor angle stability, voltage stability, the ability of a power system to remain in acceptable operating condition is a significant factor to be considered in power system stability study. In fact, voltage stability problem causes many major power interruptions in the past two decades. Voltage stability is differentiated from rotor-angle stability by its characteristics, factors and measurements. In rotor-angle stability, power angle and speed of generators are two indicators indicating stability of power system. On the contrary, voltage magnitude is the key indicator of voltage stability since this severe upset is recognized by significant plunge in voltage magnitude of bus or group of buses that afterward expand to the other parts of system. If the protection scheme and remedial actions fail to limit this voltage decay it may result in major power outage due to the operation of protecting equipment. This phenomenon is also known as voltage collapse.

Reactive power insufficiency is the major cause of voltage instability since bus voltage magnitude is directly coupled with reactive power supplied at that area [11]. This also explains why voltage stability is classified as local stability or load side stability Basically, relationship between bus voltage magnitude and real power transferred at that bus, PV-curves, and relationship between bus voltage magnitude and its reactive power transferred, QV-curves, are two significant tools to study voltage stability during steady state operating conditions. These two series of curves provide information of security margin from the present operating point to instability region and sufficiency of reactive power at each bus respectively.

Strength of transmission system, base case power-transferred, load characteristics, generation reactive power capability, protecting scheme, characteristics of disturbances, reactive power compensator devices limit and characteristics are majors facilities influencing voltage respond of power system. It is foreseeable that voltage stability is a complicate problem dealing with many factors. However, for the purpose of analysis, it is useful to classify voltage stability problem associated with disturbances as the following [11].

a) Large-disturbance voltage stability: This mode of voltage stability study involves with the ability of power system to maintain acceptable voltage magnitude following a major disturbance such as faults. Due to large disturbance, the study of this mode must include responds from both system components and protection equipment. However, based on the survey of voltage collapse or nearly collapse incidents occurred around the world, large-disturbance voltage stability only shares small portion of entire voltage collapse incidents, this dissertation will not include large-disturbance voltage stability in ATC framework due to the above limitations.

b) Small-disturbance voltage stability: Similarly to rotor-angle stability in the classification of the problem, small-disturbance voltage stability concentrates on the ability of power system to maintain acceptable voltage magnitude when the system subject small disturbance such as gradually and continuous load changes. Since changing in system load demand is recognized as the most common cause of voltage instability, it will be included in the ATC calculation. Generally, small-disturbance voltage stability study can be done through static approaches such as PV-curves or QV-curves analysis. Responds of system and several control equipment such as On load Tap Changing Transformer (OLTC) to small disturbances are the key points to be investigated during this mode of voltage stability study.

4.5.2 Voltage Stability Limit

Voltage stability is a major concern of power system under the deregulated environment since it normally occurs in power system that is heavily loaded or lacking of reactive power. This phenomenon represents the situation when voltage levels in power system bus sharply decrease from the existing voltage without any precaution or proximity detected. Voltage instability problem usually occurs at one bus and then the abnormal conditions spread to surrounding buses in the systems. This situation may result in a major outage of power system or blackout. When protection devices are triggered to disconnect other facilities from the system owning to overload that makes the situation worse.

Based on voltage instability incidents in the past, these severe situations may occur in different time frame that correspond to the respond of different equipment [11,20]. Time frames of voltage stability and equipment associate with each time frame are summarized below.

a) Electromechanical transients: In this time frame, transient time scale, voltage collapse incidents may occur in the time range of seconds. Fast dynamics equipment e.g. generators, regulators, induction machines and power electronics devices directly influence the responds of power system. This dissertation includes this phenomenon in the transient stability analysis.

b) Discrete switching devices: With the longer time frame than the electromechanical transients, the time interval of discrete switching devices is at the range of minutes. The occurrence of voltage stability may associate with the responds of discrete switching devices such as load tap-changers and excitation limiters. This time frame of voltage stability study is classified as "Long-term Dynamics" that usually cause voltage collapse incidents around the world.

c) Load recovery processes: Load recovering processes span the interval of several minutes. Characteristics of nonlinear load e.g. induction motors during load recovering process may cause voltage stability problem due to high reactive power requirements at stating period.

Among three time frames of voltage stability mechanisms mentioned above, most voltage instability incidents around the world are recorded to be taken place in several minutes or greater that situate in the time scale of discrete switching devices respond or load recovering processes. Therefore, in order to satisfy security criteria, slow dynamic voltage stability should be taken into account in real-time ATC calculation. Classification of voltage stability problem divided by time-frame is shown in figure 4-3.

In addition to time frame and respond of equipment in each time frame that affect voltage stability, occurrence of voltage instability is also closely associated with other factors such as protection scheme. In some case, the operation of protective devices to isolate overloaded transmission lines may aggravate the situation or accelerate voltage instability incident since an amount of electricity is transferred to the rest transmission system that currently operated in stress conditions.

Since voltage stability is currently a major concern that threatens security of deregulated power system around the world. Therefore, it is necessary to incorporate Voltage Stability analysis is real time ATC framework. This section will dedicate to voltage stability study by starting with survey of voltage instability and nearly-voltage instability incidents happened in power industries, then theoretical and practical concepts and approaches used to study voltage stability are covered. Finally, this section ends with a practical method to determine voltage stability region during real-time ATC calculation since voltage level is insufficient to ensure that power system is secured to voltage instability.

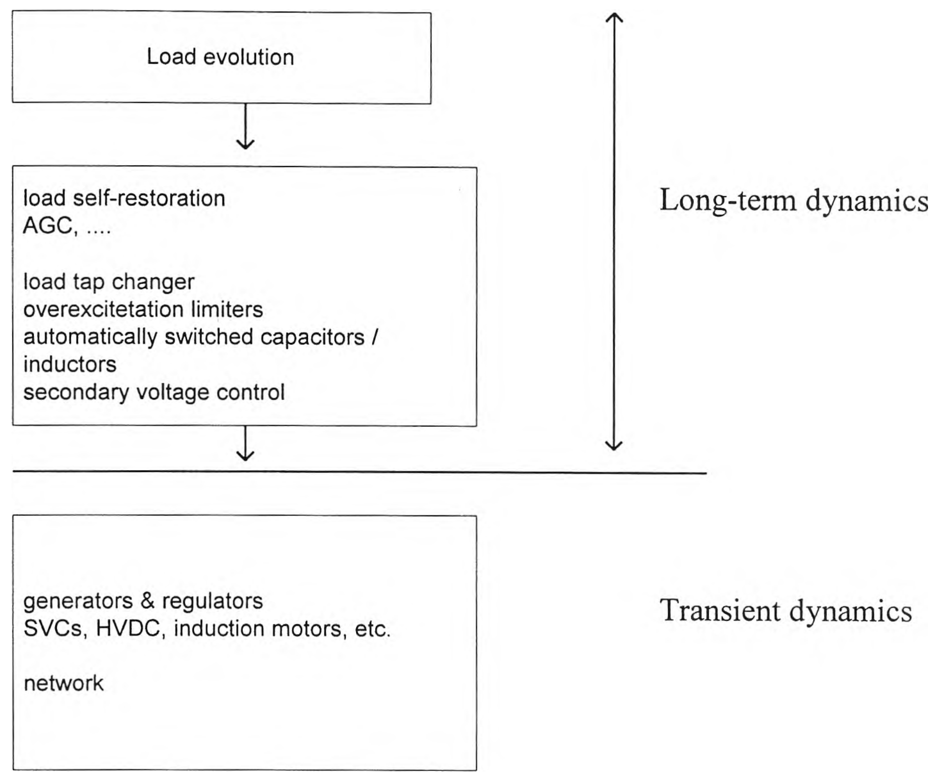


Figure 4-3 Classification of voltage stability problem by time frame [11]

4.5.2.1 Voltage instability incidents

In the past two decades, there are many blackouts or major outages around the world that voltage instability were identified to be the mechanisms behind these severe upsets. Generally, voltage instability could be triggered by one of many possible factors but shares several common characteristics. For instance, voltage stability problem is a cascading problem might be initiated by a simple abnormal condition such as loss of facility or load increasing. When power system are operated closed to voltage instability region, voltage at the weak bus will start to decrease significantly due to the nonlinear phenomena of dynamics system caused by insufficient reactive power. If appropriate remedial actions are not applied or the operating point of power system is still pursued in this direction, this problem may develop to severe situation such as blackout since this abnormal conditions may span to the vicinity area and it is more difficult to secure the previous state if the systems are operated too far from stable region. Basically, load shedding is the last efficient action to recover power system whether the system is operated too close to voltage instability region and other remedial actions fail to secure the system. Nonetheless, load-shedding scheme will result in poor power quality and customer satisfactory that are two significant issues in deregulated power system operation and control that the customers may reclaim for appropriate reasons or compensation due to the outage cost. Examples of voltage instability or nearly-voltage collapse incidents around the world in the last two decades are summarized below [25,50].

a) Florida system disturbance of December 28,1982

b) French system disturbances of December 19,1978 and January 12,1987

c) Northern Belgium system disturbance of August 4,1982

d) Swedish system disturbance of December 27,1983

e) Japanese system disturbance of July 23,1987

f) Sri Lanka system disturbance of May 2,1995

As mentioned above that voltage instability incident may take place in two time frames depend on nature of disturbances and responds of the system which ranging from seconds to hours. Transient (Short-term) voltage instability positions in electromechanical transient period, the moment suddenly after the disturbances such as fault or major switching. Mechanisms of voltage instability in this time frame are determined by respond from network and fast-respond components in power system such as generators, regulators, induction machines and power electronics devices. In contrary, long-term voltage instability associated with dynamics of slow-respond equipment such as On Load Tap Changing Transformer (OLTC), Excitation limits or gradually increased of system's load. Examples of voltage collapse and voltage instability without collapse (nearly-collapse) incidents and classification of voltage stability problem divided by time frames and disturbances are presented in table 4-12 and table 4-13 below.

Table 4-12. Examples of voltage collapse incidents and associated time frame

Date	Location	Time Frame
11/30/86	SE Brazil, Paraguay	2 seconds
05/17/85	South Florida	4 seconds
08/22/87	Western Tennessee	10 seconds
12/27/83	Sweden	50 seconds
09/02/82	Florida	1-3 minutes
11/26/82	Florida	1-3 minutes
12/28/82	Florida	1-3 minutes
12/30/82	Florida	2 minutes
08/04/82	Belgium	4.5 minutes
01/12/87	Western France	4-6 minutes
07/23/87	Tokyo	20 minutes

Table 4-13. Examples of voltage instability without collapse incidents and time frame

Date	Location	Time Frame
05/21/83	Northern Carolina	2 minutes
05/20/86	England	5 minutes
09/22/70	New York State	Several hours
07/20/87	Illinois and Indiana	Hours
06/11/84	Northeast United States	Hours

Power system under deregulated environment usually contain large numbers of electricity transactions which cause the transmission systems to be operated under stress conditions since voltage instability incident is the result of reactive power inadequacy that caused by limitation of reactive power generation or transmission systems limit, it can be seen that power system with these characters have higher risk in encountering voltage collapse incident.

4.5.2.2 Reactive Power Transfer Capability limit

Since reactive power cannot be transmitted over the long transmission lines, this phenomenon classify reactive power as a "local power" that is different from real power which can be conveniently moved throughout the system [51-52]. The following reasons explain the above mentioned phenomenon.

a) Reactive power transfers depend on voltage gradients. Reactive power traverses from high voltage level buses to low voltage buses. As mentioned in the previous topic that voltage level criterion at every bus is usually not allowed to exceed 5% deviation from nominal voltage. Therefore, reactive power cannot be dispatched in the long distance since it requires large voltage gradient. Any attempt to deliver large amount of reactive power between two remote buses may causes voltage problem in the systems. This concept is different from real power dispatching since it can be dispatched in long transmission lines based on angle gradient.

b) Generally, high voltage transmission lines absorb reactive power due to high proportion of reactance to resistance (X/R ratio). This property is one of an obstacle to deliver reactive power from reactive power sources to the customers located far from generators.

c) In present time, electric utilities usually install shunt capacitors (capacitor bank) as a main reactive power compensator device to prevent undervoltage problem, it is foreseeable that responds of these shunt devices play important role in determining amount of reactive power and its corresponding to the voltage magnitude at each location. Unfortunately, reactive power obtained from shunt capacitors highly depends on square of voltage magnitude at its installed location. Transmission system has tendency to receive significantly low reactive power compensation during heavy load conditions because transmission system usually operated at lower voltage at that operating conditions.

d) Any attempt to transmitted large amount of reactive power from sources to sinks results in poor power factor and subsequences in increasing of power loss in the system.

4.5.2.3 Voltage Stability Study methods

There are many approaches to perform the voltage stability analysis of power system. This dissertation will explain the commonly used approaches that suitable for the deregulated power market in studying as the following.

a) Voltage stability study based on power flow method [11,20]: The maximum power transfer and collapsing point is determined by increasing loading level in AC power flow calculation. This 'snapshot' calculation is repeated until voltage collapse incident occurs in the systems. Voltage stability analysis based on AC power flow approach is the fundamental of several approaches and tools such as continuation power flow method, P-V curves or Q-V curves. The advantages of this method are reliability of results, acceptable computation time and completeness of results since it employs power flow program. Voltage instability point (point of maximum power transfer – PMPT or point of collapse - POC) can be determined when power flow fails to converge based on the processes described above. According to these benefits, this dissertation will choose this approach as the main method to determine voltage collapse point.

b) Continuation Power Flow method: Based on conventional AC power flow such as AC power flow, Continuation Power Flow (CPF) employs the predictor-corrector technique to speed up the calculation and avoid divergence problem at point of collapse (POC) [53-54]. In the process of predictor, the next predicted value of result is calculated by projecting in the direction of the slope of function (graphical approach of predictor-corrector method is shown in figure 4-4). Then, the forecasted error is corrected by corrector process that comparing predicted value with the actual result from the function at that position and compensate for error. From the above concept, CPF is an interesting method in voltage stability since it can reduce computation time by adjusting step in prediction process [51,55]. However, CPF contains several limitations compared to AC power flow. For example several system significant data such as reactive power limit disappear in CPF method. In addition, CPF bases on many assumptions and it is harder to modified CPF algorithm compared to AC power flow. Example of this difficulty is it is much harder in CPF to simulate the system when load in each area has different load growth and this is the main reason why CPF fails to be the main approach in voltage stability study in this dissertation.

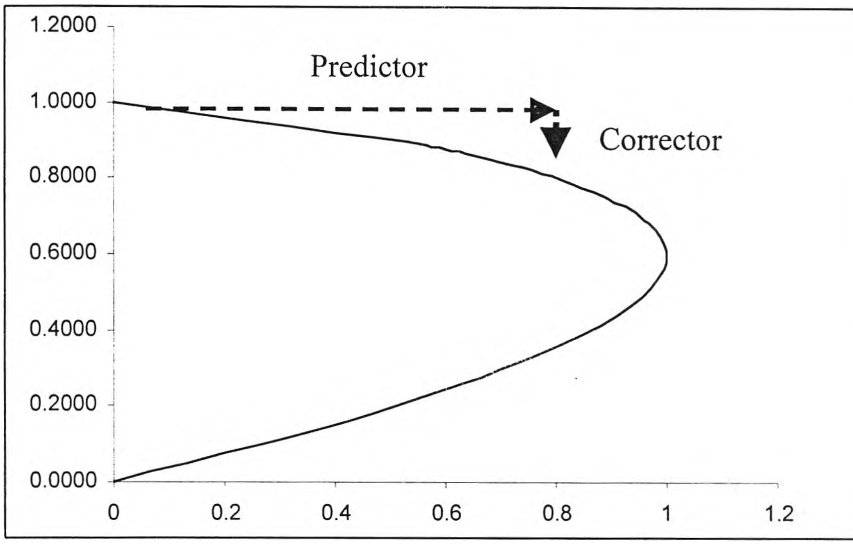


Figure 4-4 Predictor- Corrector in Continuation Power Flow method

c) Bifurcation Analysis: Bifurcation theory is a new theory which is applied to power system under the concept that power system is a highly nonlinear system [56-57]. Voltage instability incident is represented as the situation that equilibrium of power system is suddenly disappeared while parameters are gradually changing until they reach a right combination. This theory explains voltage collapse and oscillation in power system by trajectories and values of eigenvalue. However, uncertainties and error of information which is the inherently nature of power system are obstacles of this method to give the commercial-grade result. Further developments are required for this method to overcome the uncertainties and error problems.

4.5.2.4 Voltage Stability Evaluation Methods

Several methods are prevalently used to analyze static voltage stability problem. Two of them which based on capability curves are widely accepted in power industry as the main tools to evaluate static voltage stability. P-V curves and Q-V curves [11,58-59 are those two methods that determine maximum loadability limit of the system as well as proximity of voltage when load is subjected to change. P-V curves and Q-V curves can be generated from AC power flow-based program as plot of real power or reactive power with their corresponding voltage level as explained below.

4.5.2.4.1 P-V Curves

P-V curves provide information of relationship between power system loading and voltage magnitude at each bus. The maximum power transfer, loadability limit and proximity to voltage instability (given in term of voltage stability indices) are three basic results given from this curve. P-V curve is currently used in many utilities around the world as the main tool to identify potential voltage stability problem. Example 3 explains the voltage stability phenomena in a simple radial line. Constant PQ load is used in the whole simulation processes. System responds corresponding to each load level is measured and shown as shown in figure 4-5.

Example 3 PV curves of a typical power system with different loading level

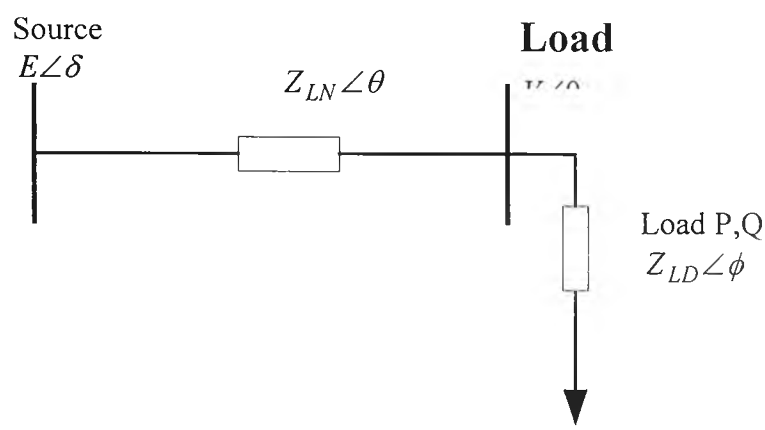


Figure 4-5. A single radial system for voltage stability study

In order to generate P-V curves, relationship between loading (P,Q) and voltage magnitude must be investigated. Generally, transfer power over transmission lines can be written as

$$I = \frac{E\angle\delta}{Z_{LN}\angle\theta + Z_{LD}\angle\phi}$$

Current magnitude

$$I = \frac{E}{\sqrt{(Z_{LN}\cos\theta + Z_{LD}\cos\phi)^2 + (Z_{LN}\sin\theta + Z_{LD}\sin\phi)^2}}$$

From identity: $\cos(A - B) = (\cos A \cos B) + (\sin A \sin B)$

$$I = \frac{E}{\sqrt{(Z_{LN}\cos\theta)^2 + (Z_{LD}\cos\phi)^2 + 2Z_{LN}Z_{LD}\cos\theta\cos\phi + (Z_{LN}\sin\theta)^2 + (Z_{LD}\sin\phi)^2 + 2Z_{LN}Z_{LD}\sin}}$$

$$I = \frac{E}{\sqrt{Z_{LN}^2(\cos\theta^2 + \sin\theta^2) + Z_{LD}^2(\cos\phi^2 + \sin\phi^2) + 2Z_{LN}Z_{LD}(\cos\theta\cos\phi + \sin\theta\sin\phi)}}$$

$$I = \frac{E}{\sqrt{Z_{LN}^2 + Z_{LD}^2 + 2Z_{LN}Z_{LD}(\cos(\theta-\phi))}}$$

$$I = \frac{E}{Z_{LN}\sqrt{1 + (\frac{Z_{LD}}{Z_{LN}})^2 + 2\frac{Z_{LD}}{Z_{LN}}(\cos(\theta-\phi))}}$$

$$I = \frac{E}{Z_{LN}\sqrt{F}} \tag{1}$$

Receiving end voltage magnitude

$$V_R = Z_{LD}I = \frac{1}{\sqrt{F}}\frac{Z_{LD}}{Z_{LN}}E \tag{2}$$

Power supplied to the load

$$P_R = V_R I\cos\phi$$

$$P_R = \frac{Z_{LD}}{F}\left(\frac{E}{Z_{LN}}\right)^2\cos\phi \tag{3}$$

where

P_R = Power supplied to the load (transmission system capacity)
E = Voltage magnitude at source bus
V = Voltage magnitude at source bus
δ = Angular displacement between sending end and receiving end bus voltage
Z_{LN} = Transmission line impedance
Z_{LD} = Load impedance (representation of load)

According to maximum power transfer theory, transmission lines will be operated and their maximum capacity if voltage drop in transmission line equal to voltage drop in load (Z_{LN} = Z_{LD}) or Z_{LN}/Z_{LD}=1. Since PV curves, plot between amounts of electricity received at the receiving end and bus voltage magnitude, are important tool to study voltage stability in large-scale power system. Examples of P-V plots between normalized real power and normalized voltage can be plotted as shown in figure 4-6.

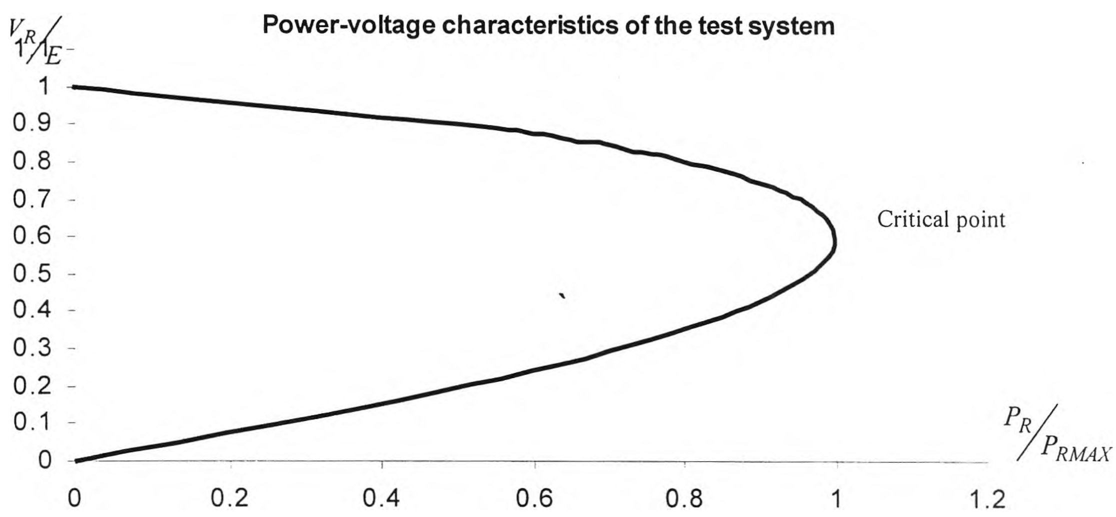


Figure 4-6. P-V curves of the typical power system

Assume:

E = 1.05 per unit
ϕ = 18.19 degree
θ = 25.83 degree
Z_{LN} = 0.10+0.20 j per unit

As mentioned earlier, P-V curve is a useful tool that can be applied for studying operational margin of power system. It gives the information responding the margin between the current operating point and voltage stability limit as well as proximity of voltage alteration at each loading level. In addition, P-V curve is the foundation of several voltage stability indices that are prevalently used in voltage stability evaluation such as Tangent Vector Index (TVI) or Voltage Instability Proximity Index (VIPI) [56]. During real-time operation of power system, pre-studied P-V curves are sufficient to ensure security due to voltage stability of the current and upcoming operating conditions as long as configuration and load/generation dispatch of the systems are not much different from the study case. However, it is possible to generate real-time PV curves of power system if real-time information is available (for example, real-time information from SCADA or EMS system). Secured transactions in deregulated power system must situate in the secure area referring to voltage stability.

A power system contains numerous possible P-V curves due to the changes of its operating conditions. Variation of load level, power factor, structure of the systems are the factors affecting the shape and voltage instability point (Point of Collapse – POC) of the systems. In order to ensure voltage stability during real-time operation, a set of P-V curves covering the most feasible situations that are important to security of power system must be studied as references for the future transactions. Examples of P-V curve at different power factor are shown in figure 4-7.

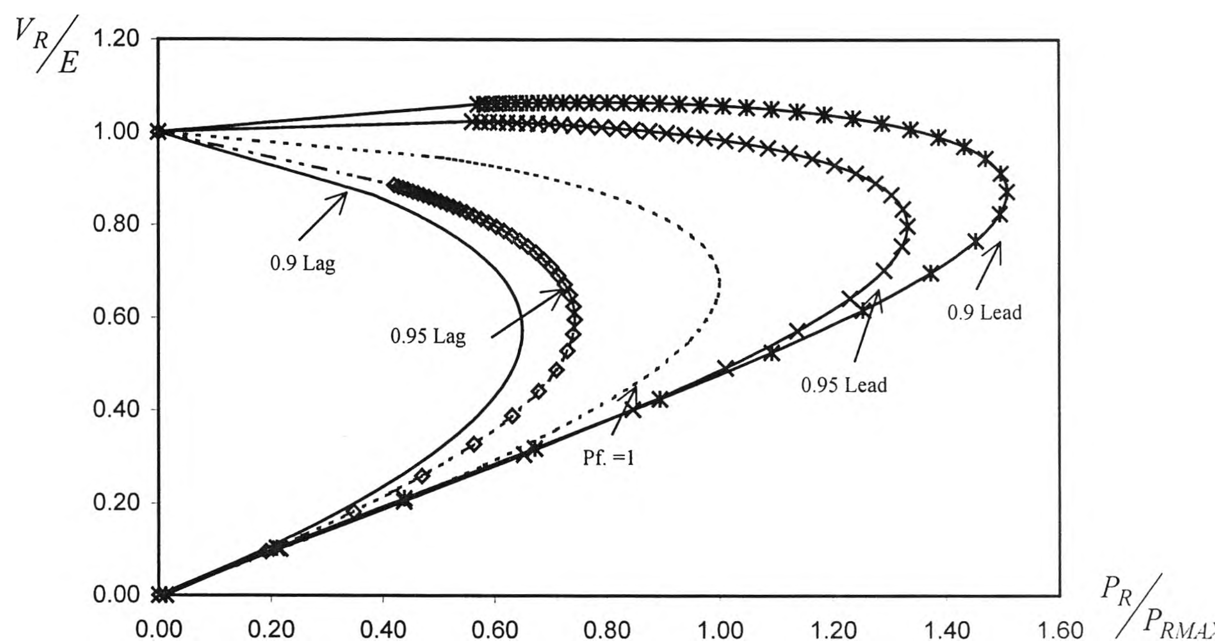


Figure 4-7. P-V curves of typical power system at different power factor

4.5.2.4.2 Q-V Curves

Formulation of Q-V curves is similar to PV curves since they are be obtained by quantities from power flow analysis. However, the Q-V curves are used to identify the vulnerable locations of power system as well as required reactive power to maintain system security. Generally, Q-V curves give information regarding the proficiency of reactive power at each bus at current operating condition. In addition, sensitivity of injected reactive power and voltage magnitude at each bus can be used to determine proximity to voltage instability of power system. Power system is secured to voltage stability if power injection in every buses in the system result in increasing of voltage magnitude at those buses.

Therefore, QV-curve is a tool that sufficient and useful for providing information of security to voltage stability, optimum locations and appropriate amount of reactive power compensation as well as weakest bus in voltage stability point of view and optimal amount of reactive power required to satisfy static voltage stability requirements. Figure 4-8 shows an example of Q-V curves generated by the plot between normalized reactive power and normalized voltage given by power flow program at the different loading level of real power.

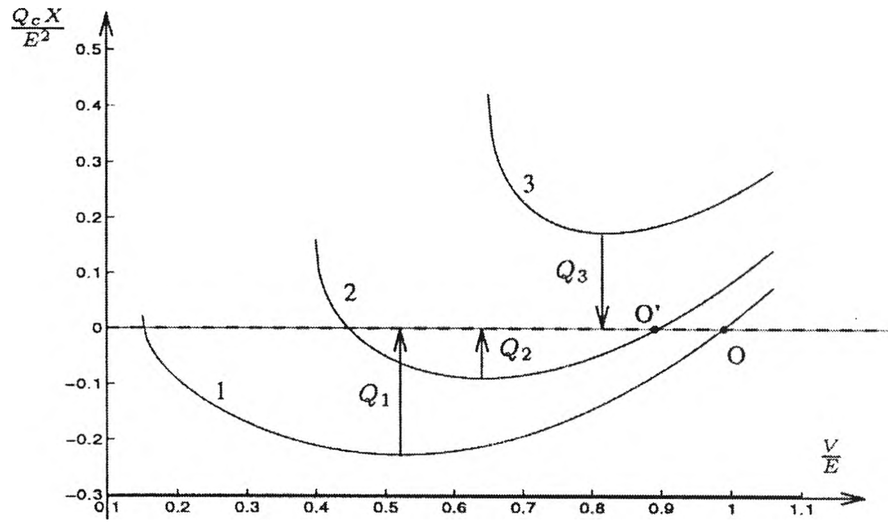


Figure 4-8. Q-V curves of the typical power system

Objective of voltage stability study is to obtain the maximum power transfer limit of power system that will be referred as references for further transaction in the deregulated market. Many approaches have been developed to identify voltage stability problem but power flow based method is proven to be the most reliable for practical power system by utilities around the world. Therefore, this dissertation will adopt power flow calculation method to calculate the P-V curves of power system when a sink and source of transaction are specified. Results of this calculation will be used to determine the insecure region of operation of deregulated power system.

4.5.3 Transient Stability Limit

Transient stability is the ability of power system to maintain synchronism after severe disturbances. Generally, severe disturbances in transient stability study represent the situation when power system loss a significant facility such as transmission line, generator or large load due to short circuit of equipment (faults). These interruptions result in electromechanical transient that may cause stability problem in the systems. Since transient stability study considers the system behavior right after the disturbances, only generator and network response are fast enough to react to this change and becoming two major factors to affect the ability of power system to remain stable conditions.

Disturbances of power system during transient period are represented by short-circuit which results in outage of transmission line or generator. Though more than

70% of transmission lines faults are single-line-to-ground-fault, the most severe fault, three phase to ground fault, is used to simulate the transient respond of the system. This dissertation will focus on the situation when transmission line or generator is disconnected from the system due to the fault. This concept based on the definition of n-1 contingency defined in ATC calculation framework.

Differ from voltage stability, transient stability is a rotor-angle stability problem that results in loss of synchronism of generator. A transient instability situation is observed by the uncontrollable increasing of rotor angles that finally trigger the protection system to disconnect generator from the system before it is damaged. Figure 4-9 [22] presents a comparison between power system under transient stability stable and transient stability unstable situations. It is seen that rotor angles among buses clearly explain the phenomena of transient stability.

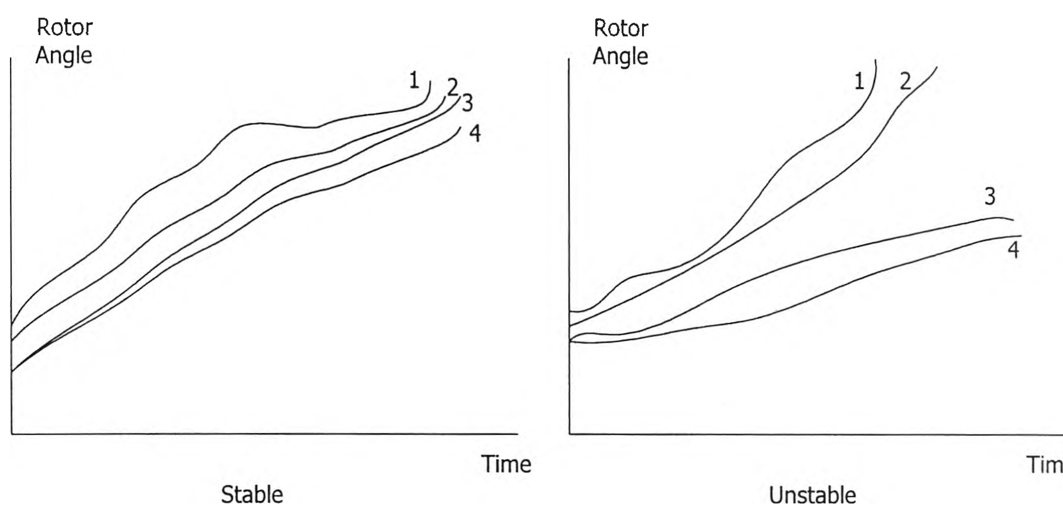


Figure 4-9. Rotor angles of stable and unstable of a 4-machines power system under transient period

4.5.3.1 Factors Influencing Power System Transient Stability

Ability of power system to survive under transient situation depends on many factors. Factors influencing transient stability of power system are summarized and explained below.

a) Loading conditions of power system: Power system with heavy load are weaker than power system under light load since loading condition determines amount of power flow in the system and generators. Fault occurs in power system during heavy loaded condition is more severe and power system have tendency to be unstable if corrective actions such as load shedding or remedy actions are reacted too slow.

b) The generator output during the fault: Generator output determines capability of a generator to supply power during fault condition. However, effect of existing loading conditions of a generator to transient stability also depends on location of fault. A generator with high output level may survive during transient period if fault location seen by this generator is relatively far. In contrast, a generator with light load may be unstable if a severe fault occurs close to it. Distance seen by generator in this topic represents the electrical distance which depend upon both the geographical location and the strength of transmission systems.

c) The fault-clearing time: Fault-clearing time is determined by protection scheme of power system. Longer fault-clearing time reduces the opportunity to disconnect facility of power system due to the occurrences of temporary fault but may result in lost of synchronism if the permanent fault is exist too long. On the other hand, short fault-clearing time may result in unnecessary interruption of service since temporary faults are interpreted as harmful faults. However, power system is safer to transient instability.

d) The postfault transmission system reactance: After faults are cleared, power system will be operated under a new system configuration. This factor directly affects the loading conditions and dispatching of generators.

e) The generator reactance: Reactance affects the initial rotor angle and peak power supply capability of generator. Since generator reactance is computed as a part of reactance between generator and load, power delivered from generator and initial rotor angle are directly affected by this quantity.

f) The generator inertia: Generator inertia is proportion to the sizes of generator. When fault occurs in power system, generator with larger inertia constant has tendency to be able to tolerate to fault more than small generator due to size of amount of energy stored in generator. In the other word, comparing to large generator, generator with smaller inertia constant is more sensitive to disturbance that may develop to unstable operation situation.

g) The generator internal voltage magnitude (E'): Internal voltage magnitude of a synchronous generator is created by field currents of that generator. Higher internal voltage results in higher voltage gradient between source and load that also determine severity of fault. Generally, field current supplied to synchronous generator is regulated by auxiliary devices such as automatic voltage regulator (AVR).

h) Power factor of the generation: Power factor of the generation determines fraction of real and reactive power generated by generators. However, since measurement of transactions in the deregulated power market are based on amount of real power only, many utilities try to maximize their profit by minimizing their reactive power generation. This generation behavior may result in serious security problem due to insufficient reactive power sources in the systems.

4.5.3.2 Transient Stability Study methods

There are many methods have been developed to analyze the characteristics and responses of power system during transient period. Equal-area criterion and direct method are two well-known approaches where responses of power system after the major disturbance are presented by graphical and numerical approaches respectively. Details of equal-criterion criteria and numerical approaches are explained separately below

4.5.3.2.1 Equal-area criterion

Equal-area criterion is the method to analyze transient of a generator by graphical method. Stability of a generator is determined by area of power-angle diagram prior to and after the disturbance. Since area of the power-angle diagram implies the energy in each period of the incident, a stable generator must contain more energy to inhibit the developing of power angle due to demand of energy during transient period. Example of power-angle diagram is shown in figure 4-10.

Formulation of problem and application of equal-area criterion to power system transient stability are explained below.
Based from equation of motion of a generator

$$\frac{2H}{\omega_0}\frac{d^2\delta}{dt^2} = P_m - P_e \tag{8}$$

Where

P_m = Mechanical Power input in per unit
P_e = Electrical Power input in per unit
H = Inertia constant of generator (MWs.MVA)
δ = Rotor angle in radian
ω_0 = Rated angular speed (radian/second)

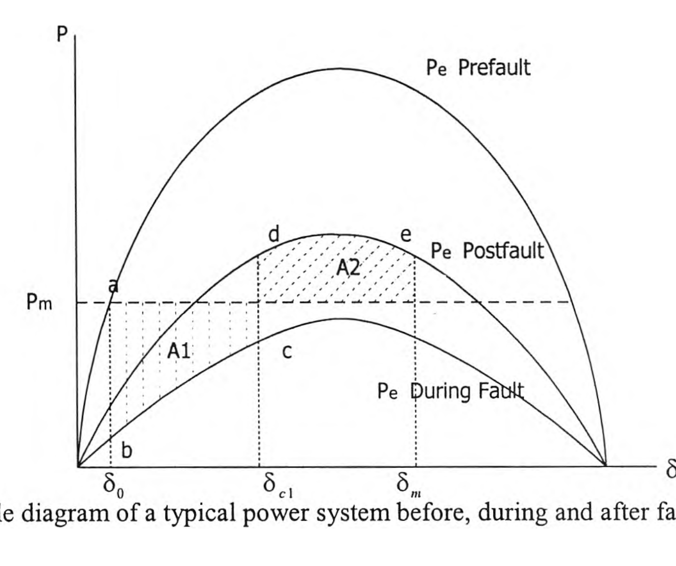


Figure 4-10. Power-angle diagram of a typical power system before, during and after fault

Rearrange equation (8) to obtain the relationship between rotor angle and power

$$\frac{d^2\delta}{dt^2} = \frac{\omega_0}{2H}(P_m - P_e) \tag{9}$$

Since the change of rotor speed, $\frac{d\delta^2}{dt^2}$, is the quantity to be investigated with different time frame, equation (9) has to be modified by multiplying $2\frac{d\delta}{dt}$ in both side of equation

$$2\frac{d\delta}{dt}\frac{d^2\delta}{dt^2} = \frac{\omega_0}{H}(P_m - P_e)\frac{d\delta}{dt} \tag{10}$$

Areas of power angle diagram are obtained by integrating equation (10) with different time period.

$$\left[\frac{d\delta}{dt}\right]^2 = \int \frac{\omega_{0(P_m - P_e)}}{H} d\delta \tag{11}$$

According equation 11), the sufficient constraint for stable operation of this system is generator must be able to supply power load demanded represented by mechanical power (P_m). Therefore, generator will be operated under stable condition if it satisfies the balance of power equation given in 12)

$$\int_{\delta_0}^{\delta_m} \frac{\omega_{0(P_m - P_e)}}{H} d\delta = 0 \tag{12}$$

Normally, speed of generator $d^2\delta / dt^2$ will be investigated in two intervals. The accelerating energy obtained in period of time from the fault occurred until the fault is cleared while the rotor speed is accelerating due to positive unbalancing between mechanical power and electrical power. Later on, decelerating energy from the interval since fault is cleared until the generator reaches the maximum rotor angle is obtained to determine stability of the generator. Derivation of these two areas are given in equation (13) and (14) respectively

$$\text{Accelerating energy} = \int_{\delta_0}^{\delta_1} \frac{\omega_{0(P_m - P_e)}}{H} d\delta \tag{13}$$

$$\text{Decelerating energy} = \int_{\delta_1}^{\delta_m} \frac{\omega_0 (P_m - P_e)}{H} d\delta \tag{14}$$

Where δ_1 = angle where fault is cleared

δ_m = maximum angle of generator

Stability of a generator can easily be justified by comparing area of accelerating energy to the area of decelerating energy. A generator will be transient stable if only the area of decelerating energy is equal or greater than accelerating energy.

However, the equal-area criterion is not suitable for calculation of large-scale power system due to difficulty in formulating of system components into consideration. Time domain simulation is the most practical method to study transient stability since response of power system due to major disturbances is dominant in very short period of time after the incidents as explained in the earlier of this section. Examples of useful techniques in time-domain analysis are given as follow.

4.5.3.2.2 Numerical method approach

Numerical approach is the most practical tools based on time-domain step-by-step integration to analyze power system transient stability. Since power system is highly nonlinear so accurate responds of power system can be obtained by time-domain analysis starting from its operating point that fault occur. From this approach, nonlinearlities of power system have been automatically included in the results.

There are several numerical techniques in time-domain analysis are suitable for transient stability study. Explicit methods such as Euler method, Modified Euler method and Runge-Kutta method are examples of well-known methods that result of the next step calculation (n+1) is based on the current solution (n). Besides, the implicit method is an alternative way to calculate the result by employing interpolation technique. In this section, the Runge-Kutta (R-K) methods and implicit integration methods will be explained as example of practical methods for Transient Stability study.

a) Runge-Kutta (R-K) Method :Development of the R-K method is based on Taylor series expansion. R-K method is divided into several methods depend on the order of solution. Second-order R-K method and Fourth-order R-K method will be mentioned in this dissertation as the foundation of transient stability study. Primary, before the calculation, changes in power system can be modeled by different functions

$$\frac{dx}{dt} = f(x,t) \tag{15}$$

where

X is the state vector (voltage, current, etc)

Equation (15) gives information of a function at the initial condition. In order to calculate the next movement of calculation (time domain), second-order R-K can be applied as shown below

$$x_1 = x_0 + \Delta x = x_0 + \frac{k_1 + k_2}{2} \tag{16}$$

where

$$k_1 = f(x_n, t_n)\Delta t$$
$$k_2 = f(x_0 + k_1, t_0 + \Delta t)\Delta t$$

It is seen that second-order R-K method employs second order derivative to calculate the next solution. Error given in this method is in the order 3 (x^3). For more accurate R-K method, an appropriate technique must me applied to this formula. The general formula of fourth-order R-K which rely on higher order of derivative and weighting technique is shown below

$$x_{n+1} = x_n + \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4) \tag{17}$$

where

$$k_1 = f(x_n, t_n)\Delta t = \text{Slope at the beginning}$$
$$k_2 = f(x_n + \frac{k_1}{2}, t_n + \frac{\Delta t}{2})\Delta t = \text{Slope at the midstep}$$
$$k_3 = f(x_n + \frac{k_2}{2}, t_n + \frac{\Delta t}{2})\Delta t = \text{Slope at the midstep}$$
$$k_4 = f(x_n + x_3, t_n + \Delta t)\Delta t = \text{Slope at the end}$$

b) Implicit Integration Methods: Implicit Integration Methods calculate the next solution of function by employing interpolation technique. The simplest approach of Implicit Integration Methods approximates the next solution by Trapezoidal rule [11, 61]. Integration of a function is calculated by area under the integral as shown in figure 4-11.

Calculation of the next solution

$$\frac{dx}{dt} = f(x,t) \tag{18}$$

The answer of power system in the next incremental time (Δt) is obtained by integration of equation (18)

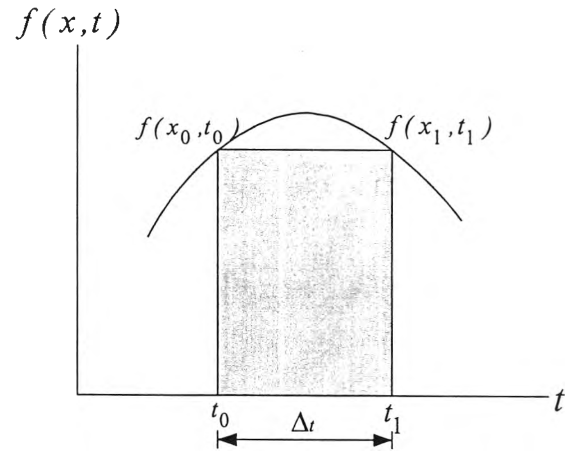


Figure 4-11. Implicit Integration Methods

$$x_1 = x_0 + \int_{t_0}^{t_1} f(x,\tau)d\tau \tag{19}$$

Applying Trapezoidal rule, the integral of equation (19) is equal to

$$x_1 = x_0 + \frac{\Delta t}{2}\left[f(x_0,t_0) + f(x_1,t_1)\right] \tag{20}$$

Since transient stability study by numerical method based on iterative calculation. The general form on the answer at time (t+1) compared to the answer at time t is given by

$$x_{n+1} = x_n + \frac{\Delta t}{2}\left[f(x_n,t_n) + f(x_{n+1},t_{n+1})\right] \tag{21}$$

Transient stability study by numerical method is shown in example 4 below

Example 4: Transient Stability Study
Test Power system: The test system is shown in figure 4-11 below.

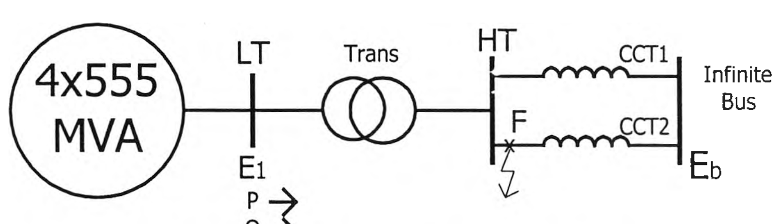


Figure 4-12. Typical Test System in example 4

System Data:

Generator: Four unit of 555MVA, 24 kV, 60 Hz

Classical model $X_d = X_d' = 0.3$ PU (2220 MVA, 24 kV Base),

H = 3.5 MW.s/MVA, $K_D = 0$

Transformer: $X_{tr} = 0.15j$ PU

Transmission lines: $X_{L1} = 0.5j$ PU, $X_{L2} = 0.93j$ PU.

Initial System Conditions: P=0.9 PU, Q=0.436 PU, $E_t = 1.0\angle 28.34^\circ$, $E_B = 0.90081\angle 0^\circ$

Solution: Single line diagram of the test system is shown in figure 4-13.

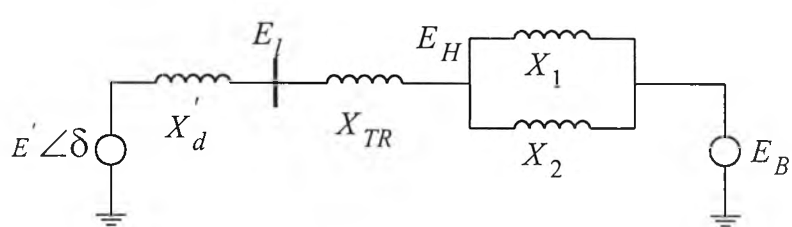


Figure 4-13. Single line diagram of transient stability test system

From the information given above, voltage behind transient E' is

$$E' = E_t + jX_d' I_t$$

$$= 1.0\angle 28.34^\circ + \frac{0.3j(0.9 - 0.436j)}{1.0\angle -28.34^\circ}$$

$$= 1.1626\angle 41.77^\circ$$

Single line diagrams of the system during prefault, during fault and postfault periods are shown in figure 4-14

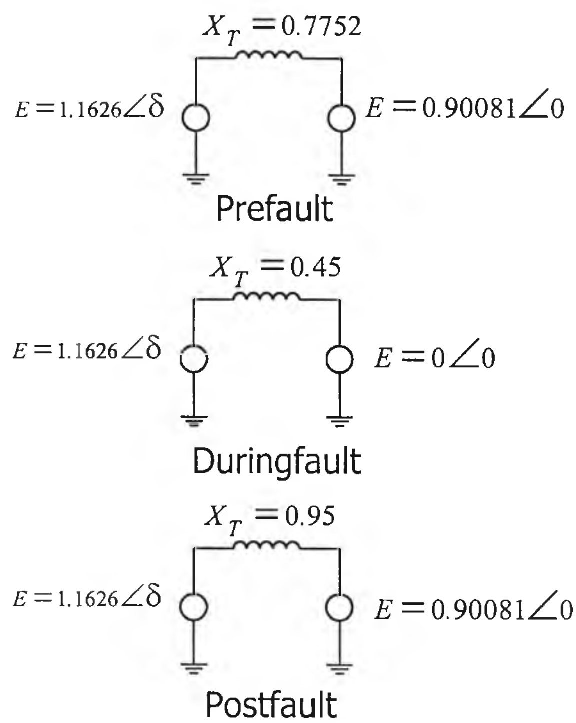


Figure 4-14. Single line diagram of the test system in prefault, during fault and postfault

Electrical power P_e in each condition

Prefault:
$$P_e = \frac{1.1626x0.90081}{0.7752}\sin\delta$$
$$= 1.351\sin\delta$$

During fault: $P_e = 0$

Postfault:
$$P_e = \frac{1.1626x0.90081}{0.95}\sin\delta$$
$$= 1.1024\sin\delta$$

It is seen that the ability to transfer power of transmission system in postfault condition is less than the prefault condition since protective devices disconnect one of transmission lines from the systems.

Numerical Integration

From swing equation

$$\frac{d^2\delta}{dt^2} = \frac{\omega_0}{2H}(P_m - P_e)$$

Rewrite equation in first-order differential equation format

Differential equation for speed

$$\frac{1}{\omega_0}\frac{d^2\delta}{dt^2} = \frac{1}{2H}(P_m - P_e)$$

$$p(\Delta\omega_r) = \frac{1}{2H}(P_m - P_e)$$

$$p(\Delta\omega_r) = \frac{1}{2H}(P_m - P_{\max}\sin\delta)$$

Differential equation for rotor angle

$$p(\delta) = \omega_0\Delta\omega_r$$
$$= 377\Delta\omega_r$$

Where

$$P_{\max} = \left(\begin{array}{ll} 1.351 & \text{Prefault} \\ 0 & \text{During Fault} \\ 1.1024 & \text{Postfault} \end{array}\right.$$

Then, any numerical technique can be used to solve the problem. By selecting second-order Runge-Kutta method, two necessary terms of each case can be calculated.

Two constant terms for speed

$$k_1^{'} = \left[0.1286 - \frac{P_{\max}}{7.0}\sin(\delta)_n\right]\Delta t$$

$$k_2^{'} = \left[0.1286 - \frac{P_{\max}}{7.0}\sin(\delta + k_1^{''})_n\right]\Delta t$$

Two constant terms for rotor angle

$$k_1^{''} = \left[377(\Delta\omega_r)_n\right]\Delta t$$

$$k_2^{''} = \left[377(\Delta\omega_r)_n + k_1^{'}\right]\Delta t$$

Figure 4-15 shows results of the calculation by the relationship between rotor angles versus time. Three situations are simulated with different fault clearing time.

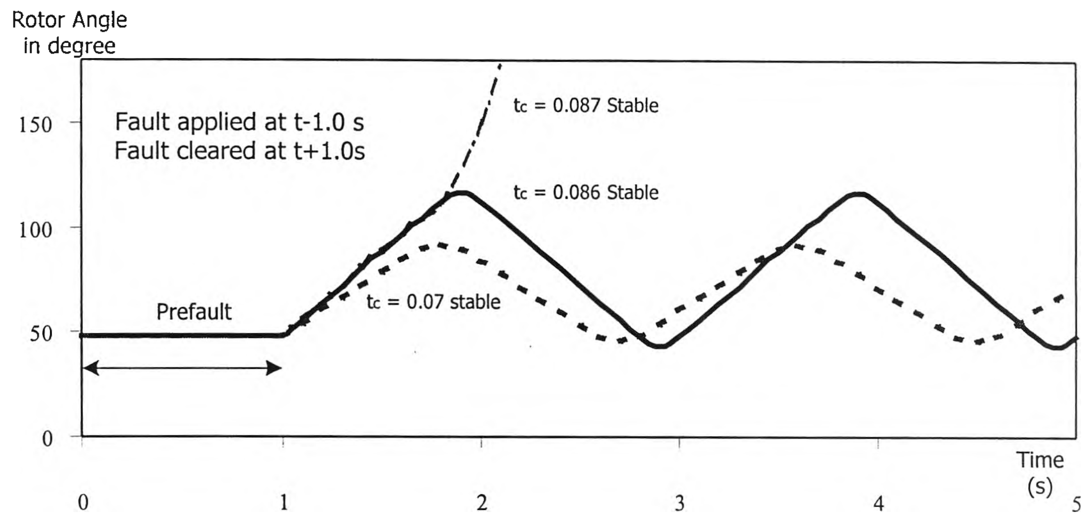


Figure 4-15. Rotor angle characteristics with different fault-clearing time

Normally, transient stability situations occur in the time period ranging between 1 to 3 seconds after the fault that faster than the respond time of compensation devices such as Automatic Generation Control (AGC), Automatic Voltage Regulator (AVR), On-load tap changing transformer (OLTC) or other facilities. Therefore, these slow-respond equipments are not necessary to be included in transient stability study. However, fast response devices such as high speed AVR, Governor control etc are installed in today's generation units

4.5.4 Long-term dynamics

Development and new innovation in power electronics have enhanced the ability of control equipment in power system to respond with the input signal in much faster time than the past. This result in the operation of some control equipment will be shifted to operate within the transient period instead of long-term period. Therefore, it is foreseeable that extended-time transient stability study in modern power system may be used to investigate system respond during dynamic period. This concept will be used in real-time ATC calculation in this dissertation since it saves the processing time and supplies information of the system in the extended time. However, in order to provide the basic concept of power system long-term dynamics limit [62], the basic concept of this topic will be review as shown below [62]

4.5.4.1 Basic Models for Power System Long-term Dynamic Studies

For any electric power system dynamic study, a proper and adequate mathematical model must be chosen to include all significant components relevant to the problem in the model, and to exclude insignificant components irrelevant to the problem from the model.

There are various kinds of power system dynamic problems such as high- or low-frequency oscillations with large or small disturbances. However, there are only a limited number of system components important to the dynamic study: the hydraulic and steam turbines, the synchronous generators, governors, the excitation systems, load characteristics, and so on. For each of them, several basic models are recommended by the professional societies, and can be adapted for the studies of specific problems.

The problems in simulation are the preparation of input data for detailed models. The data for existing machines often fail to cover the full set of parameters needed to characterize them in the detail needed for a more demanding studies, and all data must be assumed when the studies apply to proposed new equipments. Accordingly, proper use of a dynamic simulation program requires clear understanding of the effects represented in each machine model, and of their importance in relation to the type of system situation and disturbance being studied. Therefore, the preparation of data files has become a major task.

This chapter will present the basic models of generator, exciter and automatic voltage regulator, PSS, and turbine and governor, and assist the power system analyst in choosing appropriate models for power system studies.

4.5.5 Synchronous Machine Model

4.5.5.1 Model Classifications

The basic approach of a synchronous machine model [11, 63-65] has been to consider three stator windings with 120 electrical degrees apart, and a rotating structure with an excitation or field winding and one or more equivalent rotor body windings. The axis of the field winding is defined as the direct axis, and an orthogonal axis, called the quadrature axis, is located 90 electrical degrees ahead. The equivalent rotor windings reflect induced current paths in a round rotor iron body, or in damper bars that are also used in round rotor turbo-generators, as well as in salient pole hydro-generators. One group of equivalent circuits is aligned in the direct axis, and the other group is aligned in the quadrature axis.

R. H. Park[4] developed this concept further by mathematically transforming the three phase stator quantities into corresponding two-axis quantities. The effect of such transformation is to remove all the machine time-varying inductances coefficients from the machine flux linkage equations. Time varying three-phase stator voltages, currents, and flux linkages are also transformed into time invariant direct and quadrature axis quantities under steady state conditions.

The stator and rotor equation can be represented in terms of direct and quadrature axis equivalent circuits. In considering the equivalent circuits, the model structure for both axes is the basic form or configuration of the model, and its order can be directly observed, ranging usually from first order to third order. Order can be simply defined as the number of rotor circuits in either the direct or quadrature axis.

Model parameters values have usually been given in terms of reactances and time constants for the direct or quadrature axis. Alternatively, resistance and inductance values can be assigned to the elements of a direct or quadrature axis equivalent circuit.

Consider the matrix shown on Table 4-12, which can be conveniently chosen for describing model structures ranging from first order to third order in each axis, depending upon the number of inductance/resistance series combinations representing the field and direct(d) axis equivalent rotor circuits, or the number representing quadrature(q) axis equivalent circuits.

In this complete matrix there are 12 possible combinations of direct and quadrature axis representations, plus one "constant flux linkage" direct axis model. The most complex (Model 3.3) has a field winding and two equivalent d axis rotor iron (damper) circuits in the direct axis, and three quadrature axis equivalent (damper) windings. It appears there are seven model structures that could be serious candidates for inclusion in large system stability simulations. In Table 4-12, six(6) of these model structures are drawn, and the seventh (Model 0.0) is the constant rotor flux linkage (or alternatively constant voltage behind transient reactance) model.

4.5.5.2 Rationale for Suggesting or Selecting Models

If a detailed study is being made of the stability performance of such a generator with relatively complex damper assemblies in both axes, the most complex model, Model 3.3, is suggested for use, if parameters are available. Basically, the higher order the model, the better the results will be for special applications, provided those values for the parameters or elements of the advanced models can be obtained.

For most turbo-generators, particularly those without damper windings, Model 2.2 is likely to be more than adequate for studies involving either linear perturbations or for large disturbance type studies. A popular and widely used structure in many current programs can be described, based on Model 2.2, which considers two windings in each axis, including the direct axis field winding. Parameter values for this model structure have normally been supplied by manufacturers for synchronous machines, or have been, for the direct axis, obtained by tests described in IEEE Std 115-1983(R1991).

The q axis amortisseur (damper) effects may be approximated by considering only one q axis rotor circuit, as in Model 2.1. This model with a single q-axis equivalent damper circuit, has had extensive use for representing hydro-generators.

The classical model which is a variation of Model 0.0 assumes in essence a constant voltage behind transient reactance. It often offers a significant improvement in computational simplicity, particularly in a large system, where the voltage depressions during, and subsequent to, faults are small. It is frequently used along with the generator inertia constant, where the approximate response of an electrically remote machine is considered adequate. This is often the case where the electrical distance from the study area is greater than 0.5 to 1.0 pu reactance on the study MVA base. The user is not interested in the local oscillatory control modes of these remote machines, and their dominant effect on the stability problem being examined can be principally reflected in their inertia.

4.5.6 Exciter and Voltage Regulator Models

The function of the excitation system is to provide magnetizing current to the rotating generator field winding. In order to accomplish this, the excitation system must be designed so that control of the applied voltage is accurate and sensitive. The excitation system is varied depending upon manufacturers and their types. This gives the operator the means of controlling generator output voltage, power factor, and the associated control of reactive current between the generator and the rest of the system.

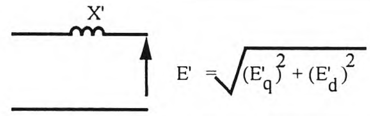
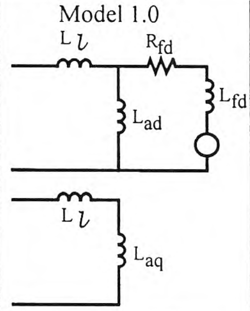
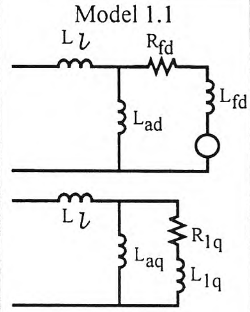
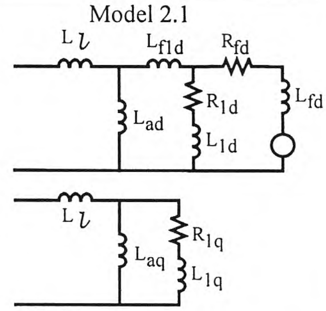
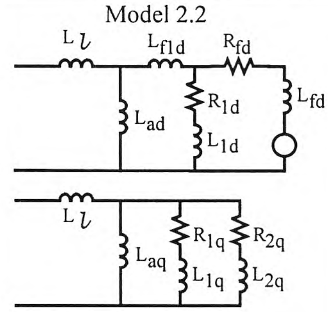
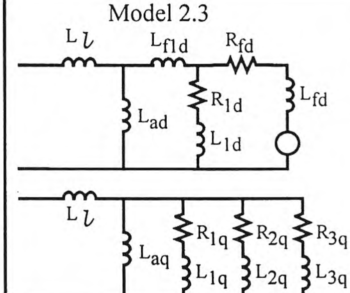
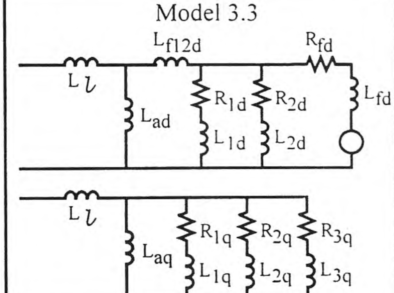
The general functional block diagram shown in Figure 4-16 indicates various synchronous machine excitation subsystems. These subsystems may include a terminal voltage transducer and load compensator, excitation control elements, an exciter, and, in many instances, a power system stabilizer.

The models in this standard do not include underexcitation limiters (UEL). They do show how outputs, V_{UEL}, of such limiters would normally be connected to the various excitation system models. The outputs of the UEL may be received as an input to the excitation system at various locations, either as a summing input or as a gated input; but, for any one application of the model, only one of these inputs would be used.

Terminal voltage and terminal V/HZ limiters are not normally represented in excitation system models. Some models, however, do provide a gate through which the output of a terminal voltage limiter, V_{OEL}, could enter the regulator loop. A terminal voltage limiter function is also included with one of the supplementary discontinuous excitation control models.

Three distinctive types of excitation systems are identified on the basis of excitation power source:

Table 4.14 Selection of Generator Models
Table 2.1 Selection of Generator Models

D - Axis / Q - Axis	Field Circuit Only	Field Circuit & One Equiv. Damper Circuit	Field Circuit & Two Equiv. Damper Circuit
Constant Rotor Flux Linkages	Model 0.0 		
No Equiv. Damper Circuit	Model 1.0 	2.0	3.0
One Equiv. Damper Circuit	Model 1.1 	Model 2.1 	3.1
Two Equiv. Damper Circuit	1.2	Model 2.2 	3.2
Three Equiv. Damper Circuit	1.3	Model 2.3 	Model 3.3 

a) Type DC excitation systems, which utilize a direct current generator with a commutator as the source of excitation system power.

b) Type AC excitation systems, which use an alternator and either stationary or rotating rectifiers to produce the direct current needed for the synchronous machine field.

c) Type ST excitation systems, in which excitation power is supplied through transformers or auxiliary generator winding and rectifiers.

A block diagram of the terminal transducer and the load compensator is shown in Figure 4-16. For some systems, there may be separate and different time constants associated with the functions of voltage sensing and load compensation.

If the distinction can not be recognized in this model, one time constant, T_R is used for the combined voltage sensing and compensation signal. When load compensation is not employed ($R_C = X_C = 0$), the block diagram reduces to a simple sensing circuit. While the filtering associated with the voltage transducer may be complex, it can usually be reduced, for modeling purposes, to the single time constant, T_R, shown. For many systems, this time constant is very small, and provision should be made to set it zero.

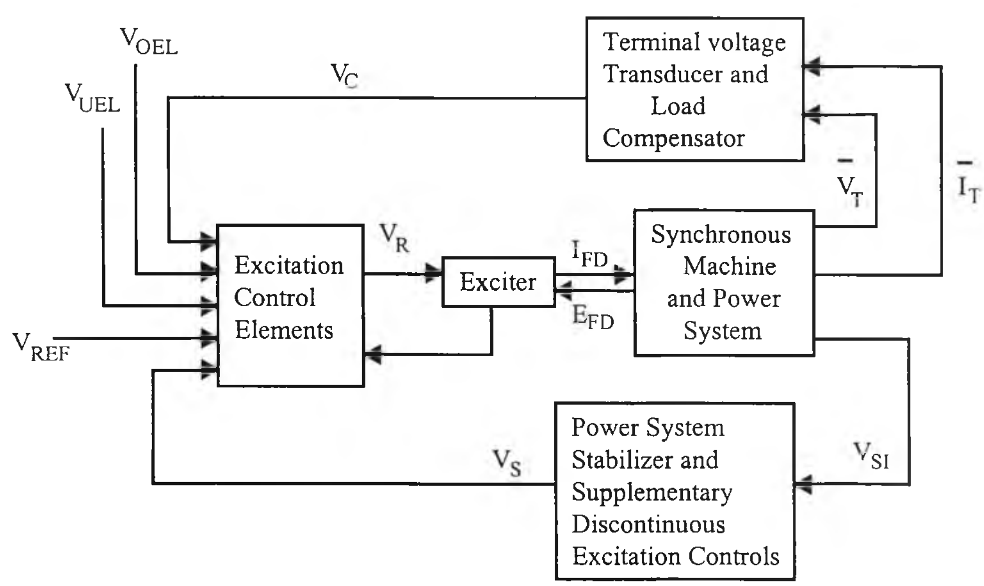


Figure 4-16. General Functional Block Diagram for Synchronous Machine Excitation Control System

The terminal voltage transducer output, V_C, is compared with a reference that represents the desired terminal voltage setting, as shown on each of the excitation system models. The equivalent voltage regulator reference signal, V_{REF}, is calculated to satisfy the initial operating conditions. Therefore, it will take on a value unique to the synchronous machine load condition being studied. Without load compensation, the excitation system, within its regulation characteristic, attempts to maintain a terminal voltage determined by the reference signal.

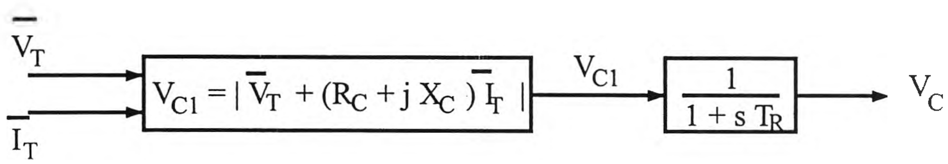


Figure 4-17. Terminal Voltage Transducer and Optional Load Compensation Elements

4.5.6.1. Type DC - Direct Current Commutator Exciters

Few type DC exciters are now being produced, having been superseded by type AC and ST systems. However, there are many such systems still in service. Table 4-13. is the example exciter of DC type excitation model.

4.5.6.2. Type DC1A Excitation System Model

Because this model has been widely implemented by the industry, it is sometimes used to represent other types of systems when detailed data of other types of excitation systems are not available or when a simplified model is required.

Table 4-15. Example Exciters of Type DC Excitation Model

Type	Company and Type	*	**
DC1A	Allis Chalmers -Regulex™ regulator General Electric - Amplidyne regulator GDA regulator Westinghouse - Mag-A-Stat™ regulator Rototrol™ regulator Silverstat™ regulator TRA™ regulator Brown Boveri - Type AB regulator Type KC™ regulator	Type 1	DC1
DC2A	Westinghouse - Type PRX-400™ General Electric - Type SCR	-	DC2
DC3A	General Electric - GFA4™ regulator Westinghouse - BJ30™ regulator	Type 4	DC3

The principal input to this model is the output, V_C, from the terminal voltage transducer and load compensator model described above. At the summing junction, terminal voltage transducer output, V_C, is subtracted from the set point reference, V_{REF}. The stabilizing feedback, V_F, is subtracted, and the power system stabilizing signal, V_S, is added to produce an error voltage. In the steady-state, these last two signals are zero, leaving only the terminal voltage error signal. The resulting signal is amplified in the regulator. The major time constant, T_A, and gain, K_A, associated with the voltage regulator are shown incorporating nonwindup limits typical of saturation or amplifier power supply limitations. A discussion of windup and nonwindup limits is provided in Appendix B. These voltage regulators utilize power sources that are essentially unaffected by brief transients on the synchronous machine or auxiliaries buses. The time constants, T_B and T_C, may be used to model equivalent time constants inherent in the voltage regulator; but these time constants are frequently small enough to be neglected, and provision should be made for zero input data.

When a self-excited shunt field is used, the value of K_E reflects the setting of the shunt field rheostat. In some instances, the resulting value of K_E can be negative, and allowance should be made for this.

Most of these exciters utilize self-excited shunt field with the voltage regulator operating in a mode commonly termed "buck-boost." The majority of station operators manually track the voltage regulator by periodically trimming the rheostat set point so as to zero the voltage regulator output. This may be simulated by selecting the value of K_E such that initial condition are satisfied with $V_R = 0$. In some programs, if K_E is not provided, it is automatically calculated by the program for self-excitation..

If a value for K_E is provided, the program should not recalculate K_E because a fixed rhoestat setting is implied. For such systems, the rheostat is frequently fixed at a value that would produce self-excitation near rated conditions. System with fixed field rheostat settings are in widespread use on units that are remotely controlled. A value of $K_E = 1$ is used to represent a separately excited exciter.

The term $S_E[E_{FD}]$ is a nonlinear function with a value defined at any chosen E_{FD}. The output of this saturation block, V_X, is the product of the input, E_{FD}, and the value of the nonlinear function, $S_E[E_{FD}]$, at this exciter voltage.

A signal derived from field voltage is normally used to provide excitation system stabilization, V_F, via the rate feedback with gain, K_F, and time constant, T_F.

4.5.6.3. Type DC2A Excitation System Model

The model shown in Figure 4-18 is used to represent field controlled dc commutator exciters with continuously acting voltage regulators having supplies obtained from the generator or auxiliaries bus. It differs from the type DC1A model only in the voltage regulator output limits, which are now proportional to terminal voltage V_T.

4.5.6.4. Type DC3A Excitation System Model

The type DC3A systems are the representative of the first generation of high gain, fast-acting excitation sources. This model is used to represent older systems, in particular those DC commutator exciters with noncontinuously acting regulators that were commonly used before the development of the continuously acting varieties.

These systems respond at basically two different rates, depending upon the magnitude of voltage error. For small errors, adjustment is made periodically with a signal to a motor-operated rheostat. Larger errors cause resistors to be quickly shorted or inserted and a strong forcing signal to be applied to the exciter. Continuous motion of the motor-operated rheostat occurs for these larger error signals, even though it is bypassed by contactor action. Figure 4-18 illustrates this control action.

The exciter representation is similar to that of the systems described previously. Note that no excitation system stabilizer is represented.

Depending upon the magnitude of voltage error, V_{REF} - V_C, different regulator modes come into play. If the voltage error is larger than the fast raise/lower contact setting, K_V (typically 5 %), V_{RMAX} or V_{RMIN} is applied to the exciter, depending upon the sign of the voltage error. For an absolute value of voltage error less than K_V, the exciter input equals the rheostat setting, V_{RH}. The rheostat setting is notched up or down, depending upon the sign of the error. The travel time representing continuous motion of the rheostat drive motor is T_{RH}. A nonwindup limit is shown around this block to represent the fact that, when the rheostat reaches either limit, it is ready to come off the limit immediately when the input signal reverses. Additional refinements, such as dead-band for small errors, have been considered, but were not deemed justified for the relatively few older machines using these voltage regulators.

The model assumes that the quick raise/lower limits are the same as the rheostat limits. It does not account for time constant changes in the exciter field as a result of changes in field resistance.

4.5.7 Type AC - Alternator Supplied Rectifier Excitation Systems

These excitation systems use an ac alternator and either stationary or rotating rectifiers to produce the direct current needed for the generator field. Loading effects on such exciters are significant, and the use of generator field current as an input to the models allows these effects to be represented accurately. Table 4-16. is the example exciter of AC type excitation model.

4.5.7.1 Type AC1A Excitation System Model

The model shown in Figure 4-18 represents the field controlled alternator-rectifier excitation systems designated as type AC1A. These excitation systems consist of an alternator main exciter with noncontrolled rectifiers. The exciter does not employ self-excitation, and the voltage regulator power is taken from a source that is not affected by external transients. The diode characteristic in the exciter output imposes a lower limit of zero on the exciter output voltage.

The demagnetizing effect of load current, I_{FD}, on the exciter alternator output voltage, V_E, is accounted for in the feedback path that includes the constant, K_D. This constant is a function of the exciter alternator synchronous and transient reactances.

Exciter output voltage drop due to rectifier regulation is simulated by inclusion of the constant, K_C, which is a function of commutating reactance and the rectifier regulation curve, F_{EX}.

Table 4-16. Example Exciters of Type AC Excitation Model

Type	Company and Type	*	**
AC1A	Westinghouse brushless excitation system	Type 2	AC1
AC2A	Westinghouse high initial response brushless excitation system		AC2
AC3A	General Electric - ALTERREX™		AC3
AC4A	General Electric - ALTHYREX™ Rotating thyristor excitation system		AC4
AC5A	Basler and Electric Machinery - small excitation system		
AC6A	C.A. Parsons - Stationary diode system		

In the model, a signal, V_{FE}, proportional to exciter field current is derived from the summation of signals from exciter output voltage, V_E, multiplied by $K_E + S_E[V_E]$ and I_{FD} multiplied by the demagnetization term, K_D. The exciter field current signal, V_{FE}, is used as the input to the excitation system stabilizing block with output, V_F.

4.5.7.2 Type AC2A Excitation System Model

The model shown in figure 4-18, designated as type AC2A, represents a high initial response field controlled alternator-rectifier excitation system. The alternator main exciter is used with noncontrolled rectifiers. The type AC2A model is similar to that of type AC1A except for the inclusion of exciter time constant compensation and exciter field current limiting elements.

The exciter time constant compensation consists essentially of a direct negative feedback, V_H, around the exciter field time constant, reducing its effective value and thereby increasing the small signal response bandwidth of the excitation system. The time constant is reduced by a factor proportional to the product of gains, K_B and K_H, of the compensation loop and is normally more than an order of magnitude lower than the time constant without compensation.

To obtain high initial response with this system, a very high forcing voltage, V_{RMAX}, is applied to the exciter field. A limiter sensing exciter field current serves to allow high forcing but limits the current. By limiting the exciter field current, exciter output voltage, V_E, is limited to a selected value that is usually determined by the specified excitation system nominal response. Although this limit is realized physically by a feedback loop, the time constants associated with the loop can be extremely small and can cause computational problems. For this reason, the limiter is shown in the model as a positive limit on exciter voltage back of commutating reactance, which is in turn a function of generator field current. For small limiter loop time constants, this has the same effect, but it circumvents the computational problem associated with the high gain, low time constant loop.

4.5.7.3 Type AC3A Excitation System Model

The model shown in figure 4-18 represents the field controlled alternator-rectifier excitation systems designated as type AC3A. These excitation systems include an alternator main exciter with noncontrolled rectifiers. This exciter employs self-excitation and the voltage regulator power is derived from the exciter output voltage. Therefore, this system has an additional nonlinearity, simulated by the use of a multiplier whose inputs are the voltage regulator command signal, V_A, and the exciter output voltage, E_{ED}, times K_R. The other exciter is same as AC1A.

The excitation system stabilizer has a nonlinear characteristic. The gain is K_f with exciter output voltage less than E_{FDN}. When exciter output exceeds E_{FDN}, the value of this gain becomes K_N. The limits on V_E are used to represent the effects of feedback limiter operation.

4.5.7.4 Type AC4A Excitation System Model

The type AC4A alternator supplied controlled rectifier excitation system illustrated in figure 4-18 is quite different from the other type AC systems. The high initial response excitation system utilizes a full thyrister bridge in the exciter.

The voltage regulator controls the firing of the thyrister bridges. The exciter alternator uses an independent voltage regulator to control its output voltage to a constant value. These effects are not modeled; however, transient loading effects on the exciter alternator are included. Loading effects can be accounted for by using the exciter load current and commutating reactance to modify excitation limits. The excitation system stabilization is frequently accomplished in thyristor systems by a series lead/lag network rather than through rate feedback. The time constants, T_B and T_C, allow simulation of this control function. The overall equivalent gain and the time constant associated with the regulator and /or firing of the thyristors are simulated by K_A and T_A, respectively.

4.5.7.5 Type AC5A Excitation System Model

The model shown in figure 4-18, designated as type AC5A is a simplified model for brushless excitation systems. The regulator is supplied from a source, such as a permanent magnet generator, that is not affected by system disturbances.

Note that, unlike other ac models, this model uses loaded rather than open circuit exciter saturation data in the same way as it is used for the dc models. Because the model has been widely implemented by the industry, it is sometimes used to represent other types of systems when either detailed data for them are not available or simplified models are required.

4.5.7.6 Type AC6A Excitation System Model

The model shows in figure 4-18 is used to represent field controlled alternator-rectifier excitation systems with system-supplied electronic voltage regulators. The maximum output of the regulator, V_R,is a function of terminal voltage, V_T and the model includes an exciter field current limiter.

4.5.8. Type ST - Static Excitation Systems

In these excitation systems, voltage(and also current in compounded systems) is transformed to an appropriate level. Rectifiers, either controlled or noncontrolled, provide the necessary direct current for the generator field.

For many of the static systems, exciter ceiling voltage is very high. For such systems, additional field current limiter circuits may be used to protect the exciter and the generator rotor. Table 4-17. is the example exciter of ST type excitation model.

4.5.8.1. Type ST1A Excitation System Model

The computer model of the type ST1A potential source controlled-rectifier exciter excitation system shown in figure 4-18 is intended to represent systems in which excitation power is supplied through a transformer from the generator terminals and is regulated by a controlled rectifier. The maximum exciter voltage available from such systems is directly related to the generator terminal voltage.

Table 4-17. Example Exciters of Type ST Excitation Model

Type	Company and Type	*	**
ST1A	-Canadian General Electric Silcomatic Excitation System -Westinghouse Canada solid State Thyristor Excitation System -Westinghouse Type PS Static Excitation System with Type WTA, WHS or WTA-300 regulators -ASEA Static Excitation System -Brown Boveri Static Excitation System -Rayrolle-Parsons Static Excitation System -GEC-Eliott Static Excitation System - Toshiba Static Excitation System - Mitsubishi Static Excitation System - General Electric Potential Source Static Excitation System - Hitachi Static Excitation System - Basler Model SSE Excitation System - ABB UNITROL Excitation system		ST1

Table 4-17. Example Exciters of Type ST Excitation Model (cont.)

Type	Company and Type	*	**
ST2A	- General Electric - SCT-PPT and SCPT system	Type 3	ST2
ST3A	- General Electric - GENERREX		ST3

In this type system, the inherent exciter time constants are very small, and exciter stabilization may not be required. On the other hand, it may be desirable to reduce the transient gain of these systems for other reasons. The model shown is sufficiently versatile to represent transient gain reduction implemented either in the forward path via time constants, T_B and T_C (in which case K_F would normally be set to zero), or in the feedback path by suitable choice of rate feedback parameters, K_F and T_F. Voltage regulator gain and any inherent excitation system time constant are represented by K_A and T_A, respectively. The time constants, T_{C1} and T_{B1}, allow for the possibility of representing transient gain increase, with T_{C1} normally being greater than T_{B1}.

The way in which the firing angle for the bridge rectifiers is derived affects the input-output relationship, which is assumed to be linear in the model by choice of a sample gain, K_A.

As a result of the very high forcing capability of these systems, a field current limiter is sometimes employed to protect the generator rotor and exciter. The limit start setting is defined by I_{LR}, and the gain is represented by K_{LR}. To permit this limit to be ignored, provision should be made to allow K_{LR} to be set to zero.

While, for the majority of these excitation systems, a fully controlled bridge is employed, the model is also applicable to systems in which only half of the bridge is controlled, in which case the negative field voltage ceiling is set to zero ($V_{RMIN} = 0$).

4.5.8.2. Type ST2A Excitation System Model

Some static systems utilize both current and voltage sources to comprise the power source. These compound-source rectifier excitation systems are designated type ST2A and are modeled as shown in figure 4-18. It is necessary to form a model of the exciter power source utilizing a phasor combination of terminal voltage, V_T, and terminal current, I_T. Rectifier loading and commutation effects represents the limit on the exciter voltage due to saturation of the magnetic components. The regulator controls the exciter output through controlled saturation of the power transformer components. T_E is a time constant associated with the inductance of the control windings.

4.5.8.3. Type ST3A Excitation System Model

Some static systems utilize a field voltage control loop to linearize the exciter control characteristic as shown in figure 4-17. This also makes the output independent of supply source variations until supply limitations are reached.

These systems utilize a variety of controlled rectifier designs: full thyristor complements or hybrid bridges in either series or shunt configurations. The power source may consist of only a potential source, either fed from the machine terminals or from internal windings. Some designs may have compound power sources utilizing both machine potential and current. These power sources are represented as phasor combinations of machine terminal current and voltage and are accommodated by suitable parameters in the model shown.

The excitation system stabilizer for these systems is provided by a series lead/lag element in the voltage regulator, represented by the time constants, T_B and T_C. The inner loop field voltage regulator is comprised of the gains, K_M and K_G, and the time constant, T_M. This loop has a wide bandwidth compared with the upper limit of 3 Hz for the models described in the standard. The time constant, T_M, may be increased for study purposes, eliminating the need for excessively short computing increments while still retaining the required accuracy at 3 Hz. The V_{BMAX} limit is determined by the saturation level of power components.

4.5.9. Power System Stabilizers

Power system stabilizers are used to enhance damping of power system oscillations through excitation control. Commonly used inputs are shaft speed, terminal frequency, and power.

The stabilizer models provided below are generally consistent with the excitation models, within the range of frequency response outlined in the scope. They may not be applicable for investigation of control modes of instability that normally occur above 3 Hz.

Stabilizer parameters should be consistent with the type of input signal specified in the stabilizer model. Parameters for stabilizers with different input signals may look very different while providing similar damping characteristics.

Figure 4-18 shows the model of a power system stabilizer with a single input. Some common stabilizer input signals are speed, frequency, and power. Stabilizer gain is set by the term K, and signal washout is set by the time constant, T. The next two blocks allow two stages of lead/lag compensation, as set by constants T_1 to T_4. Stabilizer output can be limited in various ways, not all of which are shown in figure 4-18. This model shows only simple stabilizer output limits, H_{LIM} and L_{LIM}.

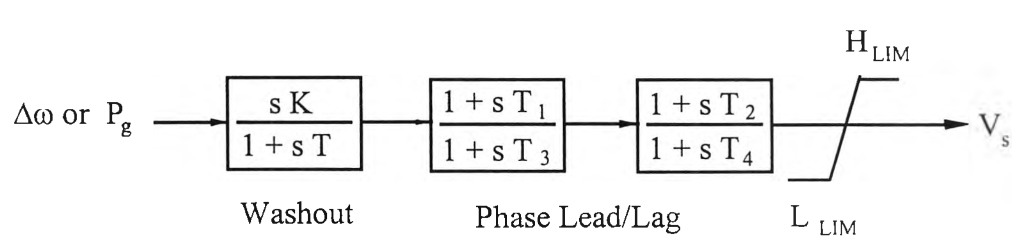


Figure 4-18. Power System Stabilizer Model

4.6 Turbine and Governor Models

The original function of a governor is to maintain a constant speed of the prime mover by controlling the energy input using speed deviation as the control feedback. The speed deviation is obtained by comparing the actual speed, ω, with a reference speed ω_{REF},

$$\Delta\omega = \omega_{REF} - \omega \tag{1}$$

which is a negative feedback. The governor is so designed that a speed drop of the prime mover below a reference level will bring about an energy increase, and a speed increase above the reference level will bring about an energy decrease.

The original governor function has also been expanded to include, for instance, the area power and frequency control, that is, maintenance of the electrical and mechanical energy balance at a constant frequency not only within an area of the system but also including the committed interchanges with neighboring areas. The power and frequency control present a very important power system dynamic problem.

The diagram of figure 4-19 includes functional blocks for the governor speed changer and for automatic generation control to show their relationship to the speed-governing system.

In this section, the mathematical models for speed-governing systems and turbines in power system stability studies are discussed.

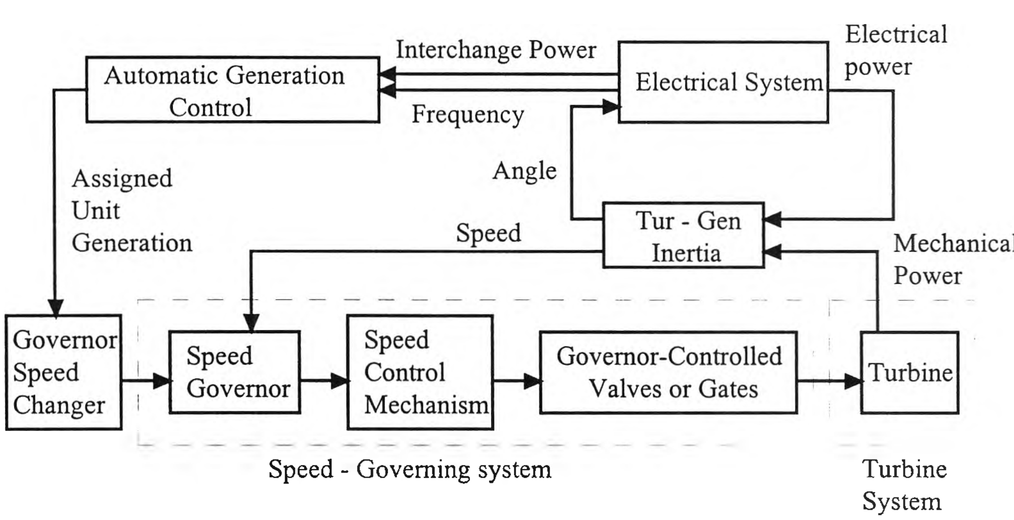


Figure 4-19. Functional Block Diagram of Governor and Turbine System

4.6.1. Speed - Governor System

The models for speed-governing systems are diverse depending upon the manufacturers. However, the speed-governing model of figure 4-20 for a steam turbine system may be used to represent either a mechanical-hydraulic system or an electro-hydraulic system be means of an appropriate selection of parameters. This model shows the load reference as an initial power P_0.

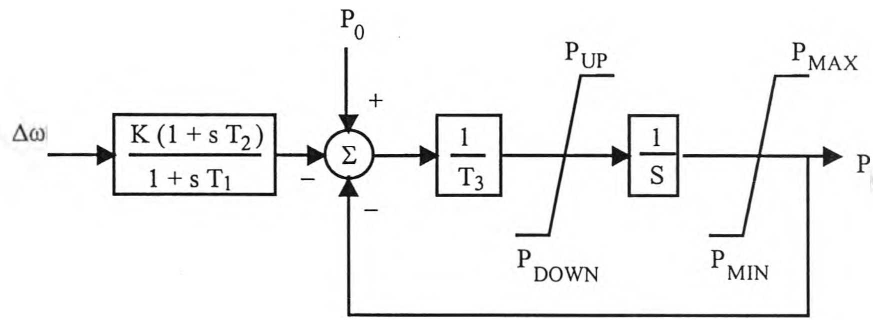


Figure 4-20. The Speed-Governing System for Steam Turbine

The block diagram of figure 4-21(A) is an approximate nonlinear model for a hydro turbine. The simplified model of figure 4-21(B) is the one most often utilized for hydro turbine speed governing systems in large system stability studies.

4.6.2. Turbine System

A general model that would accommodate all types of steam turbine is shown in figure 4-17. The models are convenient for computer program development and as a basis for data files.

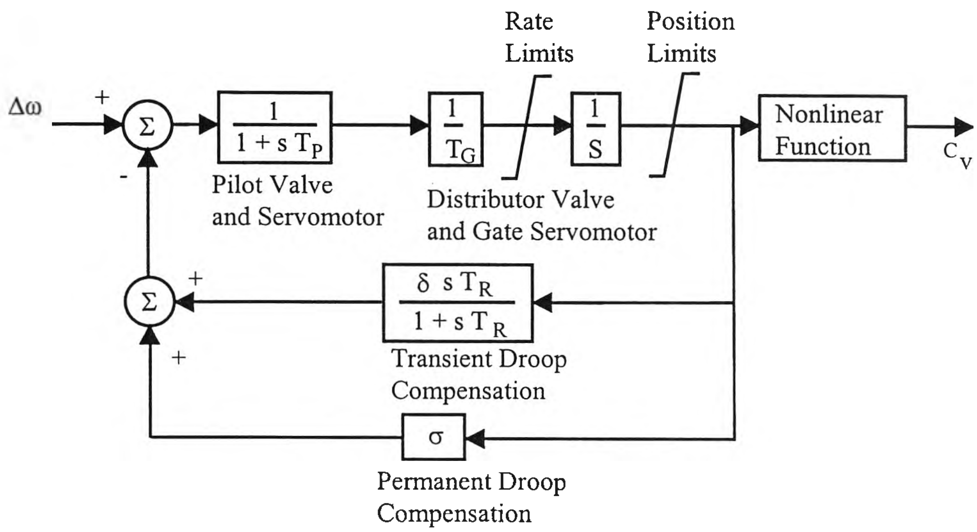
The coefficients K_1 to K_8 determine the contributions from various turbine sections. In most cases, the turbine response is adequately modeled by three time constants, the high pressure turbine bowl, T_4, the reheater, T_5, and the crossover, T_6. The additional time constant T_7 is needed in the case of double reheat units.

The block diagram of figure 4-21(A) contain the hydro turbine models most often used in system studies. In figure 4-21(A), the time constant T_w is called the water starting time or water time constant. For an ideal turbine, the coefficients of a_{11} to a_{23} are such that the model reduces to that shown in figure 4-21(B).

For small perturbations about a steady state condition the turbine may be represented by the following linearized equations:

$$q = a_{11}\, h + a_{12}\, n + a_{13}\, g \qquad (2)$$

$$m = a_{21}\, h + a_{22}\, n + a_{23}\, g \qquad (3)$$



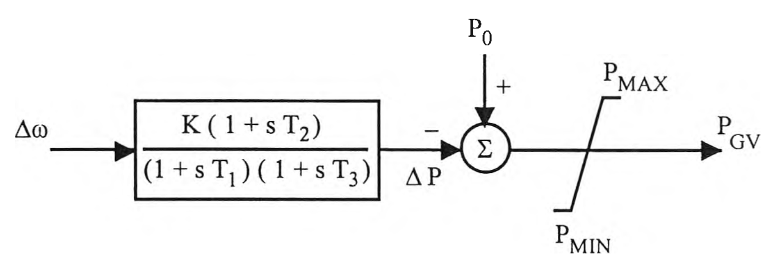


Figure 4-21. The Speed-Governing System for Hydro Turbine
(A) Approximate Nonlinear Model. (B) General Model

where q = p.u. deviation in flow
h = p.u. deviation in head
n = p.u. deviation in speed
g = p.u. deviation in gate position
m = p.u. deviation in torque

and $a_{11} = \partial q/ \partial h$, $a_{12} = \partial q/ \partial n$, $a_{13} = \partial q/ \partial g$
$a_{21} = \partial m/ \partial h$, $a_{22} = \partial m/ \partial n$, $a_{23} = \partial m/ \partial g$

For the ideal turbine at rated speed, head and
$a_{11} = 0.5$, $a_{12} = 0$ $a_{13} = 1$
$a_{21} = 1.5$ $a_{22} = -1$ $a_{23} = 1$

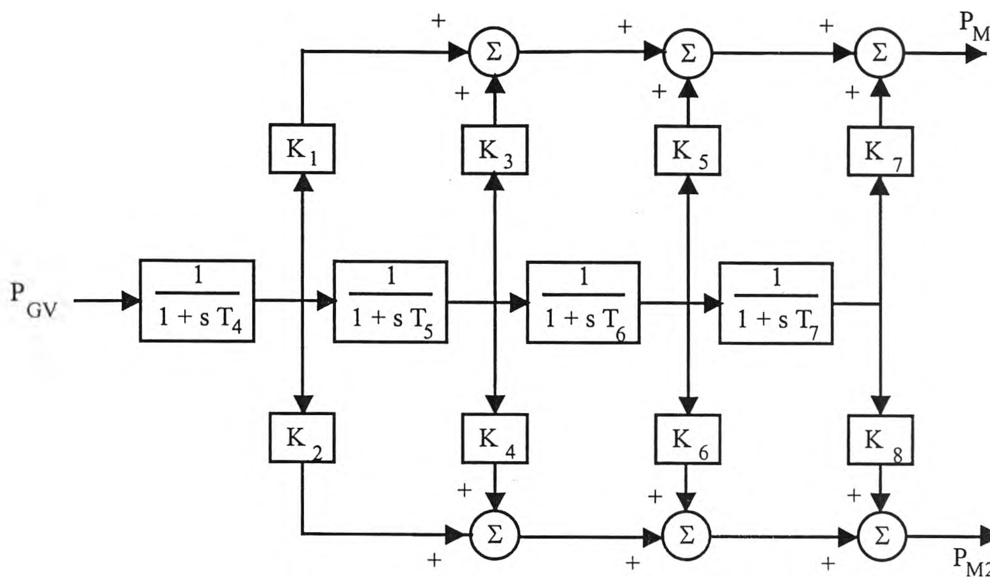


Figure 4-22. Steam Turbine Models

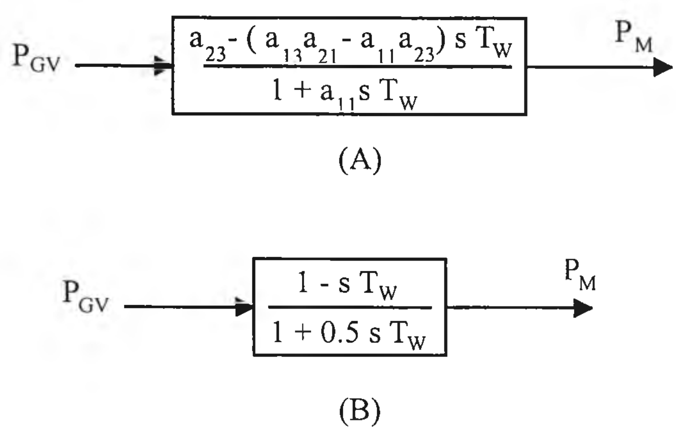


Figure 4-23. Hydro Turbine Model

4.7 Conclusions and Discussions

This chapter includes the factors affecting transfer capability of transmission system that is crucial to Available Transfer Capability calculation. Structure of power system, thermal limits, voltage limit and stability limits are major factors determining transfer capability since power system will be considered as an insecure system if it is operated beyond these limits. It is foreseeable that these limiting conditions must be included in ATC calculation to ensure system security.

Generally, thermal limits and voltage magnitude limits are the most common limits used by utilities and ISO around the world to measure security of the system since they are simple, straightforward and give acceptable result. However, the incidents of major blackouts around the world in the past two decades have proven that these two limits are insufficient to ensure system security. Due to the surprising increase in transactions result from deregulation process that increase the complexity of the system, stability limits play more important role in system security as seen from much more abnormal situations caused by stability limits violations. Consequently, this dissertation will include thermal limits, voltage limits, voltage stability limits and transient stability limits, in real-time ATC algorithm in order to ensure security of the system when ATC values are employed in the deregulated system.