Supporting Document for:

Test Models for Stability/Security Studies of AC-DC Hybrid Power Systems with High Penetration of Renewables

Proposed by:

China Electric Power Research Institute (CEPRI)
Chinese Society for Electrical Engineering (CSEE)

Contributing Authors:

Huadong Sun, Bing Zhao, Shiyun Xu, Tiankai Lan, Zonghan Li and Wu Ping

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1. Test Model for Voltage Stability (CSEE-VS)

1.1 Common Parameters

This section gives basic parameters of CSEE-VS. Both scenarios of CSEE-VS share the parameters in this section.

In the test system, all terminal nodes of generators, renewables, and HVDCs are named after the related equipment, which are generally below 35kV. All the other AC nodes are named by numbers.

Table 1-1 Line parameters

No.	From Bus	To Bus	Resistance (p.u.)	Reactance (p.u.)	Susceptance (p.u.)	Base Voltage (kV)	Number of Branches in Parallel
1	02	01	0.00042	0.00912	0.00615	525	1
2	03	02	0.00052	0.00448	0.00210	525	1
3	04	03	0.00089	0.00103	0.00129	525	1
4	04	07	0.00076	0.00910	0.00400	525	1
5	04	02	0.00097	0.00602	0.00578	525	1
6	04	01	0.00037	0.00422	0.00327	525	1
7	05	08	0.00028	0.00356	0.00140	525	1
8	05	03	0.00050	0.00730	0.00450	525	2
9	06	05	0.00027	0.00377	0.00210	525	1
10	07	10	0.00081	0.00850	0.00321	525	1
11	08	11	0.00040	0.00760	0.00450	525	1
12	08	09	0.00019	0.00270	0.00170	525	1
13	08	06	0.00019	0.00267	0.00190	525	1
14	09	06	0.00040	0.00610	0.00840	525	1
15	12	10	0.00090	0.00107	0.00157	525	1
16	12	11	0.00090	0.00634	0.00351	525	1
17	13	05	0.00010	/	/	525	1
18	14	06	0.00012	0.00163	0.00306	525	1
19	15	07	0.00009	0.00134	0.00251	525	1
20	16	09	0.00012	0.00163	0.00306	525	1
21	17	12	0.00010	0.00020	0.00010	525	1
22	18	06	0.00030	0.00380	0.01840	525	1
23	19	11	0.00070	0.00980	0.01840	525	1
24	22	23	0.00186	0.01307	0.02412	230	4
25	24	25	0.00186	0.01307	0.02412	230	4
26	26	27	0.00186	0.01307	0.02412	230	4

Table 1-2 Two winding transformer parameters

No.	From Bus	To Bus	Rated MVA	Leakage Reactance (p.u.)	Tap Voltage (kV)	Number of Transformers in Parallel
1	21	DP-01	3000	0.006	525.0/210.4	1
2	21	DN-01	3000	0.006	525.0/199.4	1
3	13	DP-02	3000	0.006	525.0/210.4	1
4	13	DN-02	3000	0.006	525.0/199.4	1
5	WT19-01	32	450	0.01389	0.69/38.5	1
6	WT19-02	32	450	0.01389	0.69/38.5	1
7	WT19-03	32	450	0.01389	0.69/38.5	1
8	24	32	300	0.035	230.0/38.5	4
9	WT20-01	33	450	0.01389	0.69/38.5	1
10	WT20-02	33	450	0.01389	0.69/38.5	1
11	WT20-03	33	450	0.01389	0.69/38.5	1
12	26	33	300	0.035	230.0/38.5	4
13	PV18-01	31	300	0.02167	0.4/38.5	2
14	PV18-02	31	300	0.02167	0.4/38.5	2
15	PV18-03	31	300	0.02167	0.4/38.5	2
16	22	31	300	0.035	230.0/38.5	4
17	TP14-01	14	750	0.02671	20.0/525.0	1
18	TP15-01	15	750	0.02671	20.0/525.0	1
19	TP16-01	16	750	0.03331	20.0/525.0	1
20	TP17-01	17	750	0.03331	20.0/525.0	1

Table 1-3 Three winding transformer parameters

No.	Terminal Bus	Winding 1 Reactance (p.u.)	Winding 2 Reactance (p.u.)	Winding 3 Reactance (p.u.)	Rated MVA	Tap Voltage (p.u.)
1	18/23/28	0.01637	-0.00190	0.01922	1500/1500/450	500/230/66
2	19/25/29	0.01637	-0.00190	0.01922	1500/1500/450	500/230/66
3	01/27/30	0.01637	-0.00190	0.01922	1500/1500/450	500/230/66
4	01/34/35	0.01570	-0.00158	0.02668	1000/1000/360	525/230/37
5	02/36/37	0.01570	-0.00158	0.02668	1000/1000/360	525/230/37
6	03/38/39	0.01570	-0.00158	0.02668	1000/1000/360	525/230/37
7	04/40/41	0.01570	-0.00158	0.02668	1000/1000/360	525/230/37
8	05/42/43	0.01570	-0.00158	0.02668	1000/1000/360	525/230/37
9	06/44/45	0.01570	-0.00158	0.02668	1000/1000/360	525/230/37
10	07/46/47	0.01570	-0.00158	0.02668	1000/1000/360	525/230/37
11	08/48/49	0.01570	-0.00158	0.02668	1000/1000/360	525/230/37
12	09/50/51	0.01570	-0.00158	0.02668	1000/1000/360	525/230/37

13	10/52/53	0.01570	-0.00158	0.02668	1000/1000/360	525/230/37
14	11/54/55	0.01570	-0.00158	0.02668	1000/1000/360	525/230/37
15	12/56/57	0.01570	-0.00158	0.02668	1000/1000/360	525/230/37

Table 1-4 Generator parameters

Generator No.	Terminal Bus	Bus Type	Maximum Active Power (MW)	Maximum Reactive Power (Mvar)	Specified Voltage (p.u.)	Related Plant No.
1	TP14-01	Slack	660	300	1.0	G1
2	TP15-01	PV	660	300	1.0	G2
3	TP16-01	PV	660	300	1.0	G3
4	TP17-01	PV	660	300	1.0	G4

Table 1-5 Renewable parameters

No.	Terminal Bus	Related Plant No.	Rated MVA
1	PV18-01	PV1	400
2	PV18-02	PV1	400
3	PV18-03	PV1	400
4	WT19-01	W1	400
5	WT19-02	W1	400
6	WT19-03	W1	400
7	WT20-01	W2	400
8	WT20-02	W2	400
9	WT20-03	W2	400

Table 1-6 Loads and static compensations

No.	Connected Bus in Main Grid	Active Load (MW)	Reactive Load (Mvar)	Static Compensation (Mvar)
1	01	356	123	160
2	02	408	149	160
3	03	339	122	160
4	04	452	165	160
5	05	506	162	160
6	06	475	154	150
7	07	457	157	180
8	08	470	160	180
9	09	399	115	150
10	10	509	166	180
11	11	427	142	160
12	12	107	32	60

*All the loads are connected at the 220kV side of three winding transformers, and compensations are connected at the 35kV side of transformers.

*Static compensations for renewable plants and HVDC are specified according to their power level, and are not listed in the table.

1.2 Specific Parameters of Different Scenarios

Parameters of both scenarios in CSEE-VS are generally the same, and are given in the former section. In the continuous low voltage scenario, two additional synchronous condensers are equipped near the infeed bus of HVDC. This is listed in Table 1-7.

Table 1-7 Synchronous condenser parameters

Condenser No.	Terminal Bus	Connected Bus in Main Grid	Maximum Reactive Power (Mvar)	Minimum Reactive Power (Mvar)	Specified Voltage (p.u.)
1	SC05-01	05	300	-150	1.0
2	SC05-02	05	300	-150	1.0

1.3 Further Test of the Model

This section gives further test of the voltage response with varied operating conditions.

In the main body of the paper, the tests have already been conducted in different HVDC power level and varied renewable power level. In this section, response of voltage collapse scenario is further tested with different synchronous condenser configuration, and response of continuous low voltage scenario is further tested with varied load conditions.

In the voltage collapse scenario, as the capacity of synchronous generators are relatively small, most reactive power are provided by shunt capacitors. This deteriorates voltage stability of the system. Two additional scenario (Scenario S1, and S2) is therefore established, with enhanced dynamic reactive power support. In scenario S1, a synchronous condenser is installed at bus_05. The bus is approximate to the HVDC-infeed node of the system. Scenario S2 connects one more condenser to bus_05 on the basis of scenario S1. The Scenario S2 is in essence the continuous low voltage scenario. Figure 1-1 gives voltage response of bus_05 in all the three scenarios. Synchronous condensers effectively help to enhance voltage stability.

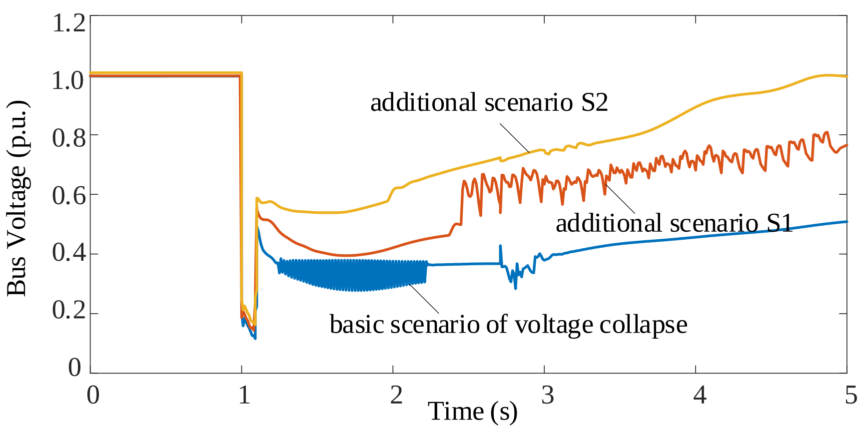

Figure 1-1 Post-fault active power of critical boundary

In the continuous low voltage scenario, the post-fault system can be roughly divided into a sending area and a receiving area. The receiving area is relatively weak, which includes bus_01, bus_02, bus_03, bus_04, and bus_07. Distribution of power loads in the system highly affect its voltage stability. Therefore, two additional scenarios are established to observe voltage characteristics (additional scenario S3, and S4). The newly established scenarios decrease power load in the receiving area, and equally increases the load in the rest of the system, keeping overall power load unchanged. Configurating of loads in the receiving area is listed in Table 1-7. Related voltage response is given in Fig. 1-2 for bus_01, and given in Fig. 1-3 for bus_05. The results have revealed that a decreased load in the receiving area enhances voltage stability, and voltage of different bus of the system can recover in very different way.

Table 1-7 Loads in Receiving-Area of Continuous Low Voltage Scenarios

	Active Load (MW)				
	Bus_01	Bus_02	Bus_03	Bus_04	Bus_07
Basic Scenario of Continuous Low Voltage	356	408	339	452	457
Additional Scenario S3	356	308	339	352	357
Additional Scenario S4	256	208	239	252	357

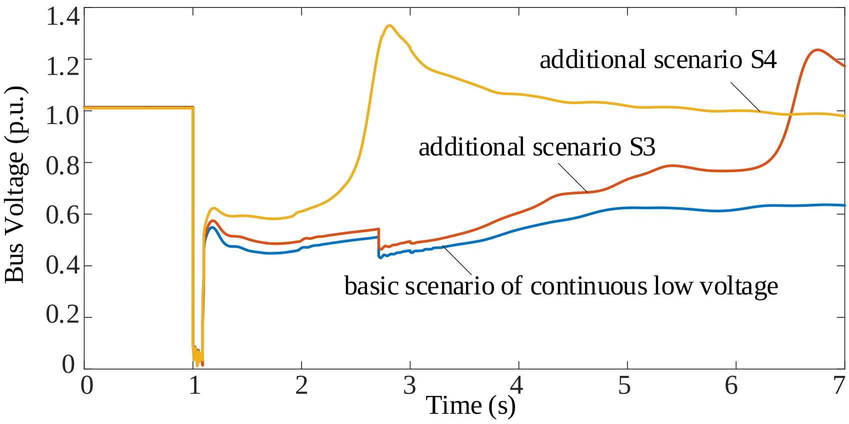

Figure 1-2 Post-fault voltage response of bus_01

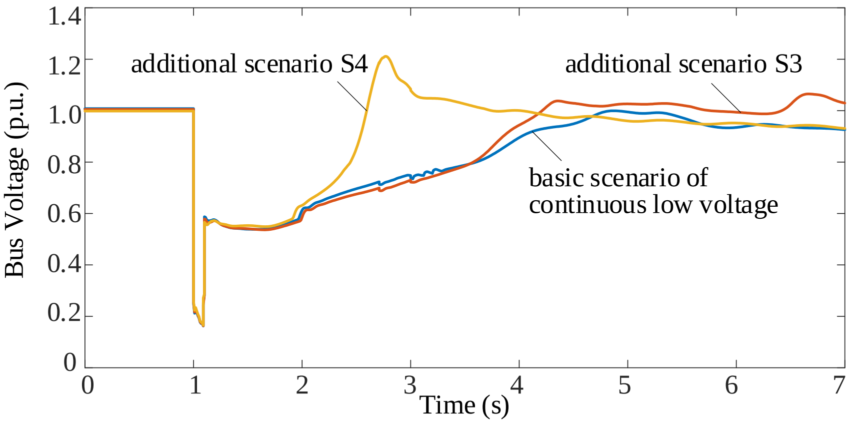

Figure 1-3 Post-fault voltage response of bus_05

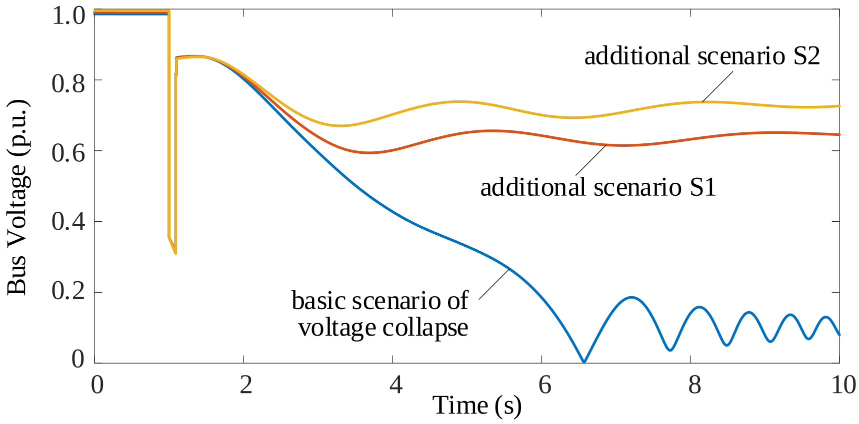

Figure 1-2 Post-fault bus voltage in varied scenarios

For the basic continuous low voltage scenario, two additional scenarios are established as well (scenario 3 and 4). Details of load modifications are the same as that in Table 1-9 (but with different generations, as given in Section 1.2). The post-fault active power of the line between bus_04 and bus_07 is given in Figure 1-3. The post-fault voltage of bus_01 is given in Figure 1-4. A lower transmitted power through critical boundary results in an enhanced voltage stability.

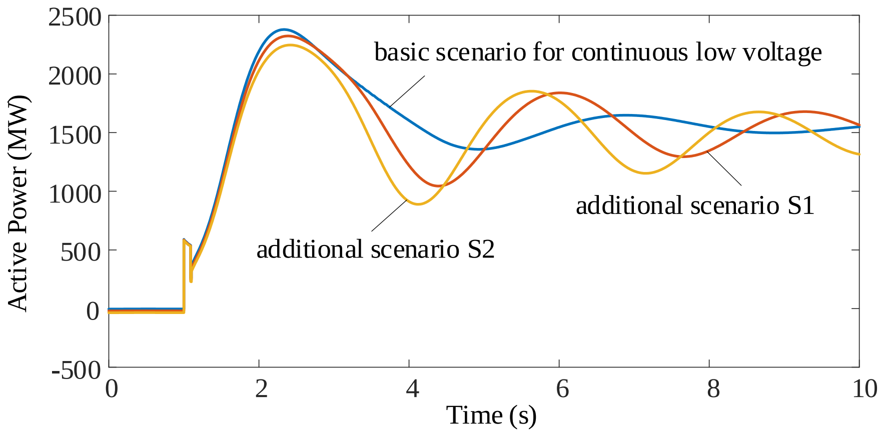

Figure 1-3 Post-fault active power of critical boundary

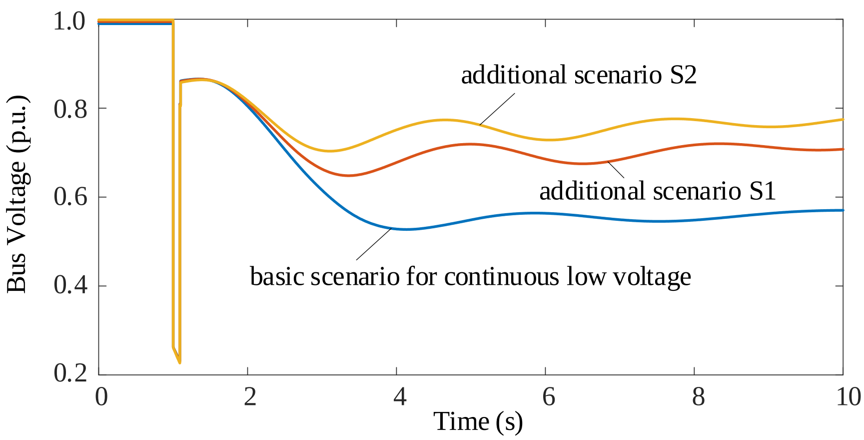

Figure 1-4 Post-fault bus voltage in varied scenarios

2. Test Model for Rotor Angle Stability (CSEE-RAS)

2.1 Common Parameters

This section gives basic parameters of CSEE-RAS. Both scenarios of CSEE-RAS share the parameters in this section.

In the test system, all terminal nodes of generators, renewables, and HVDCs are named after the related equipment, which are generally below 35kV. All the other AC nodes are named by numbers.

Table 2-1 Line parameters

No.	From Bus	To Bus	Resistance (p.u.)	Reactance (p.u.)	Susceptance (p.u.)	Base Voltage (kV)	Number of Branches in Parallel
1	02	01	0.0002	0.0067	0.3926	525	2
2	03	01	/	0.0004	/	525	1
3	04	02	/	0.0001	/	525	1
4	05	07	0.00089	0.02012	1.164	525	2
5	06	07	0.00023	0.0043	0.262	525	2
6	07	02	0.00013	0.00252	0.1643	525	3
7	08	09	0.00014	0.00197	0.10984	525	2
8	09	10	0.00014	0.00197	0.30984	525	2
9	11	10	0.00025	0.00921	0.5379	525	2
10	11	01	0.00045	0.0166	0.9682	525	2
11	14	15	0.00186	0.1307	0.2412	230	2
12	14	16	0.00186	0.1307	0.2412	230	2
13	14	17	0.00186	0.1307	0.2412	230	2
14	18	19	0.00186	0.1307	0.2412	230	2
15	18	20	0.00186	0.1307	0.2412	230	2
16	21	22	0.00186	0.1307	0.2412	230	2
17	21	23	0.00186	0.1307	0.2412	230	2
18	21	24	0.00186	0.1307	0.2412	230	2
19	25	26	0.00186	0.1307	0.2412	230	2
20	25	27	0.00186	0.1307	0.2412	230	2
21	30	31	0.00186	0.1307	0.2412	230	2
22	30	32	0.00186	0.1307	0.2412	230	2
23	34	35	0.00186	0.1307	0.2412	230	2
24	34	36	0.00186	0.1307	0.2412	230	2

Table 2-2 Two winding transformer parameters

No.	From Bus	To Bus	Rated MVA	Leakage Reactance (p.u.)	Tap Voltage (kV)	Number of Transformers in Parallel
1	07	DP01	0.006	3000	525/210	1
2	07	DN01	0.006	3000	525/210	1
3	08	DP02	0.006	3000	525/199	1
4	08	DN02	0.006	3000	525/199	1
5	08	SC08-1	0.023	360	525/20	1
6	08	SC08-2	0.023	360	525/20	1
7	08	SC08-3	0.023	360	525/20	1
8	15	39	0.035	300	230/37	1
9	15	40	0.035	300	230/37	1
10	16	41	0.035	300	230/37	1
11	16	42	0.035	300	230/37	1
12	17	43	0.035	300	230/37	1
13	17	44	0.035	300	230/37	1
14	19	46	0.035	300	230/37	1
15	19	47	0.035	300	230/37	1
16	20	48	0.035	300	230/37	1
17	20	49	0.035	300	230/37	1
18	22	51	0.035	300	230/37	1
19	22	52	0.035	300	230/37	1
20	23	53	0.035	300	230/37	1
21	23	54	0.035	300	230/37	1
22	24	55	0.035	300	230/37	1
23	24	56	0.035	300	230/37	1
24	26	58	0.035	300	230/37	1
25	26	59	0.035	300	230/37	1
26	27	60	0.035	300	230/37	1
27	27	61	0.035	300	230/37	1
28	31	64	0.035	300	230/37	1
29	31	65	0.035	300	230/37	1
30	32	66	0.035	300	230/37	1
31	32	67	0.035	300	230/37	1
32	35	70	0.035	300	230/37	1
33	35	71	0.035	300	230/37	1
34	36	72	0.035	300	230/37	1
35	36	73	0.035	300	230/37	1

36	WT03-1	39	0.022	300	0.69/37	1
37	WT03-2	40	0.022	300	0.69/37	1
38	WT03-3	41	0.022	300	0.69/37	1
39	WT03-4	42	0.018	300	0.4/37	1
40	PV03-1	43	0.018	360	0.4/37	1
41	PV03-2	44	0.018	360	0.4/37	1
42	WT04-1	46	0.022	300	0.69/37	1
43	WT04-2	47	0.022	300	0.69/37	1
44	WT04-3	48	0.022	300	0.69/37	1
45	WT04-4	49	0.022	300	0.69/37	1
46	WT05-1	51	0.022	300	0.69/37	1
47	WT05-2	52	0.022	300	0.69/37	1
48	WT05-3	53	0.022	300	0.69/37	1
49	WT05-4	54	0.022	300	0.69/37	1
50	PV05-1	54	0.018	360	0.4/37	1
51	PV05-2	55	0.018	360	0.4/37	1
52	PV06-1	58	0.018	360	0.4/37	1
53	PV06-2	59	0.018	360	0.4/37	1
54	PV06-3	60	0.018	360	0.4/37	1
55	PV06-4	61	0.018	360	0.4/37	1
56	PV10-1	64	0.018	360	0.4/37	1
57	PV10-2	65	0.018	360	0.4/37	1
58	PV10-3	66	0.018	360	0.4/37	1
59	PV10-4	67	0.018	360	0.4/37	1
60	PV11-1	70	0.018	360	0.4/37	1
61	PV11-2	71	0.018	360	0.4/37	1
62	PV11-3	72	0.018	360	0.4/37	1
63	PV11-4	73	0.018	360	0.4/37	1
64	TP03-1	03	0.023	780	20/525	1
65	TP03-2	03	0.023	780	20/525	1
66	TP04-1	04	0.023	780	20/525	1
67	TP05-1	05	0.023	780	20/525	1
68	TP05-2	05	0.023	780	20/525	1
69	TP05-3	05	0.023	780	20/525	1
70	TP06-1	06	0.023	780	20/525	1
71	TP09-1	09	0.023	780	20/525	1
72	TP09-2	09	0.023	780	20/525	1
73	TP09-3	09	0.023	780	20/525	1
74	TP10-1	10	0.023	780	20/525	1
75	TP10-2	10	0.023	780	20/525	1

76	TP11-1	11	0.023	780	20/525	1

Table 2-3 Three winding transformer parameters

No.	Terminal Bus	Winding 1 Reactance (p.u.)	Winding 2 Reactance (p.u.)	Winding 3 Reactance (p.u.)	Rated MVA	Tap Voltage (p.u.)
1	T3-01	0.0214	-0.00210	0.04093	1000/1000/300	525/230/37
2	T3-02	0.0214	-0.00210	0.04093	1000/1000/300	525/230/37
3	T3-03	0.0157	-0.00158	0.02668	1000/1000/360	525/230/37
4	T3-04	0.0157	-0.00158	0.02668	1000/1000/360	525/230/37
5	T3-05	0.0157	-0.00158	0.02668	1000/1000/360	525/230/37
6	T3-06	0.0157	-0.00158	0.02668	1000/1000/360	525/230/37
7	T3-07	0.0157	-0.00158	0.02668	1000/1000/360	525/230/37
8	T3-08	0.0157	-0.00158	0.02668	1000/1000/360	525/230/37
9	T3-09	0.0157	-0.00158	0.02668	1000/1000/360	525/230/37
10	T3-10	0.0157	-0.00158	0.02668	1000/1000/360	525/230/37
11	T3-11	0.0214	-0.00210	0.04093	1000/1000/300	525/230/37
12	T3-12	0.0214	-0.00210	0.04093	1000/1000/300	525/230/37
13	T3-13	0.0214	-0.00210	0.04093	1000/1000/300	525/230/37
14	T3-14	0.0214	-0.00210	0.04093	1000/1000/300	525/230/37
15	T3-15	0.0214	-0.00210	0.04093	1000/1000/300	525/230/37
16	T3-16	0.0214	-0.00210	0.04093	1000/1000/300	525/230/37
17	T3-17	0.0214	-0.00210	0.04093	1000/1000/300	525/230/37
18	T3-18	0.0214	-0.00210	0.04093	1000/1000/300	525/230/37
19	T3-19	0.0214	-0.00210	0.04093	1000/1000/300	525/230/37
20	T3-20	0.0157	-0.00158	0.02668	1000/1000/360	525/230/37
21	T3-21	0.0157	-0.00158	0.02668	1000/1000/360	525/230/37
22	T3-22	0.0214	-0.00210	0.04093	1000/1000/300	525/230/37
23	T3-23	0.0214	-0.00210	0.04093	1000/1000/300	525/230/37
24	T3-24	0.0157	-0.00158	0.02668	1000/1000/360	525/230/37
25	T3-25	0.0157	-0.00158	0.02668	1000/1000/360	525/230/37

Table 2-4 Generator parameters

Generator No.	Terminal Bus	Bus Type	Maximum Active Power (MW)	Maximum Reactive Power (Mvar)	Specified Voltage (p.u.)	Related Plant No.
1	TP03-1	PV	600	300	1.0	G1
2	TP03-2	PV	600	300	1.0	G1
3	TP04-1	PV	600	300	1.0	G2
4	TP05-1	PV	600	300	1.0	G3
5	TP05-2	PV	600	300	1.0	G3

6	TP05-3	PV	600	300	1.0	G3
7	TP06-1	Slack	600	300	1.0	G4
8	TP09-1	PV	600	300	1.0	G5
9	TP10-1	PV	600	300	1.0	G6
10	TP10-2	PV	600	300	1.0	G6
11	TP11-1	PV	600	300	1.0	G7
12	TP11-2	PV	600	300	1.0	G7
13	TP11-3	PV	600	300	1.0	G7

Table 2-5 Synchronous condenser parameters

Condenser No.	Terminal Bus	Connected Bus in Main Grid	Maximum Reactive Power (Mvar)	Minimum Reactive Power (Mvar)	Specified Voltage (p.u.)
1	SC08-1	08	300	-150	1.0
2	SC08-2	08	300	-150	1.0
3	SC08-3	08	300	-150	1.0

Table 2-6 Renewable parameters

No.	Terminal Bus	Rated MVA	Related Plant No.
1	WT03-1	320	W1
2	WT03-2	320	W1
3	WT03-3	320	W1
4	WT03-4	320	W1
5	WT04-1	320	W2
6	WT04-2	320	W2
7	WT04-3	320	W2
8	WT04-4	320	W2
9	WT05-1	320	W3
10	WT05-2	320	W3
11	WT05-3	320	W3
12	WT05-4	320	W3
13	PV03-1	315	PV1
14	PV03-2	315	PV1
15	PV05-1	315	PV2
16	PV05-2	315	PV2
17	PV06-1	315	PV3
18	PV06-2	315	PV3
19	PV06-3	315	PV3
20	PV06-4	315	PV3

21	PV10-1	315	PV4
22	PV10-2	315	PV4
23	PV10-3	315	PV4
24	PV10-4	315	PV4
25	PV11-1	315	PV5
26	PV11-2	315	PV5
27	PV11-3	315	PV5
28	PV11-4	315	PV5

2.2 Specific Parameters of Different Scenarios

This section gives specific parameters of the two scenarios in CSEE-RAS.

Table 2-7 Loads and static compensations of dynamic rotor angle stability scenario

No.	Connected Bus in Main Grid	Active Load (MW)	Reactive Load (Mvar)	Static Compensation (Mvar)
1	09	3084	200	680
2	10	1400	50	395

*All the loads are connected at the 220kV side of three winding transformers, and compensations are connected at the 35kV side of transformers.
*Static compensations for renewable plants and HVDC are specified according to their power level, and are not listed in the table.

Table 2-8 Loads and static compensations of transient rotor angle stability scenario

No.	Connected Bus in Main Grid	Active Load (MW)	Reactive Load (Mvar)	Static Compensation (Mvar)
1	01	450	50	125
2	02	450	50	105
3	09	4347	150	535
4	10	3590	200	505
5	11	1700	100	315

*All the loads are connected at the 220kV side of three winding transformers, and compensations are connected at the 35kV side of transformers.
*Static compensations for renewable plants and HVDC are specified according to their power level, and are not listed in the table.

Table 2-9 Generations and HVDC power level of the scenarios

Dynamic (Periodic) RAS Scenario			Transient (Aperiodic) RAS Scenario		
Type	Plant No.	Power Level (MW)	Type	Plant No.	Power Level (MW)
Thermal	G1	400	Thermal	G1	1200
	G2	400		G2	500
	G3	0		G3	1200
	G4	396		G4	375
	G5	480		G5	900

	G6	300		G6	900
	G7	300		G7	300
Wind Farm	W1	0	Wind Farm	W1	750
	W2	500		W2	800
	W3	500		W3	960
Photovoltaic	PV1	500	Photovoltaic (MW)	PV1	480
	PV2	300		PV2	0
	PV3	500		PV3	900
	PV4	0		PV4	600
	PV5	0		PV5	900
HVDC	/	800	HVDC	/	3000

2.3 Further Test of the Model

This section gives further test of CSEE-RAS with varied renewable generation and thermal power arrangement. Tests of other aspects have already been incorporated in main body of the paper.

In addition to the basic scenario of transient (aperiodic) RAS, three additional scenarios are established. Details of generations of the scenarios are given in Table 2-10. Overview of sending area, receiving area, and CCT of all the scenarios are given in Table 2-11. The results have revealed that transient RAS is closely related to renewable generation and thermal power arrangement.

In addition to the basic scenario of dynamic (periodic) RAS, two more scenarios are established with increased and decreased renewables, respectively. Configurations and calculated damping ratios of the scenarios are given in Table 2-12. Dynamics of rotor angle oscillations of the three scenarios are given in Figure 2-1.

Table 2-10 Generations of the additional scenarios

Connected Bus No. in Main Grid	Additional Scenario S5		Additional Scenario S6		Additional Scenario S7	
	Thermal (MW)	Renewable (MW)	Thermal (MW)	Renewable (MW)	Thermal (MW)	Renewable (MW)
03	1200	750	600	1500	1600	610
04	1095	400	200	1490	1600	400
05	1800	645	600	1200	1800	480
06	368	900	377	1200	391	300
09	450	0	1800	/	/	1200
10	300	1495	1495	/	/	1200
11	155	1200	1200	/	/	1200

Table 2-11 Overview of additional scenarios S5-S7

	Sending Area		Receiving Area		CCT
	Thermal	Renewable	Thermal	Renewable	
Basic Scenario	3275	3890	2100	1500	0.156
Additional Scenario S5	4463	2695	905	2695	0.100
Additional Scenario S6	1777	5390	3600	/	0.400
Additional Scenario S7	5391	1790	/	3600	0.002

Table 2-12 Scenarios with varied renewable penetration for dynamic (periodic) RAS

	Thermal Power (MW)	Renewable Power (MW)	Renewable Penetration	Damping Ratio
Basic Scenario	2276	2300	50.26%	0.0039
Additional Scenario S8	2078	2500	54.61%	0.0273
Additional Scenario S9	2475	2100	45.90%	0.0014

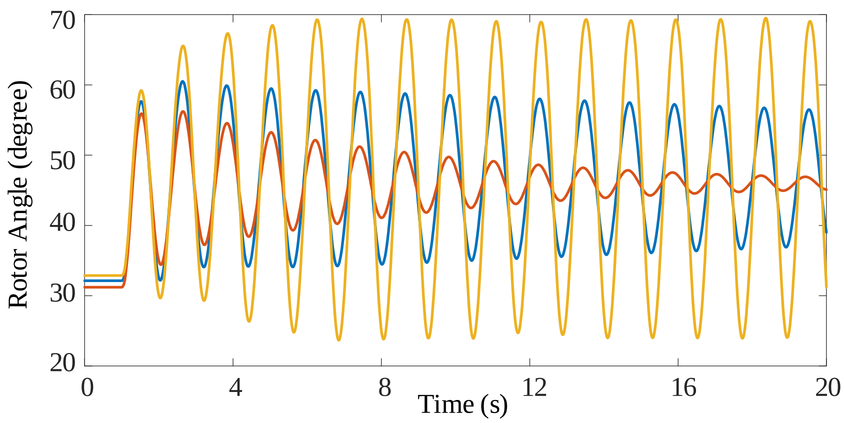

Figure 2-1 Dynamics of rotor angle oscillations of the three scenarios in Table 2-12.

3. Test Model for Frequency Stability (CSEE-FS)

3.1 Common Parameters

This section gives basic parameters of CSEE-FS. All the three scenarios of CSEE-FS share the parameters in this section.

In the test system, all terminal nodes of generators, renewables, and HVDCs are named after the related equipment, which are generally below 35kV. All the other AC nodes are named by numbers.

Table 3-1 Line parameters

No.	From Bus	To Bus	Resistance (p.u.)	Reactance (p.u.)	Susceptance (p.u.)	Base Voltage (kV)	Number of Branches in Parallel
1	01	02	0.00005	0.00068	0.37880	525	1
2	01	03	0.00025	0.00358	0.19970	525	1
3	01	04	0.00070	0.00920	0.10159	525	1
4	02	04	0.00057	0.00799	0.44622	525	1
5	02	07	0.00025	0.00358	0.19970	525	1
6	02	08	/	0.00010	/	525	1
7	03	05	0.00007	0.00095	0.00179	525	1
8	04	06	0.00011	0.00153	0.00287	525	2
9	05	06	0.00005	0.00066	0.00125	525	1
10	05	20	/	0.00010	/	525	1
11	06	07	0.00040	0.00550	0.01020	525	2
12	07	12	/	0.00010	/	525	1
13	09	DP02	/	0.00010	/	525	1
14	11	DP04	/	0.00010	/	525	1
15	13	DP06	/	0.00010	/	525	1
16	34	44	0.00186	0.01307	0.02412	230	2
17	35	45	0.00186	0.01307	0.02412	230	2
18	36	46	0.00186	0.01307	0.02412	230	2
19	37	44	0.00186	0.01307	0.02412	230	2
20	38	45	0.00186	0.01307	0.02412	230	2
21	39	46	0.00186	0.01307	0.02412	230	2
22	40	44	0.00186	0.01307	0.02412	230	2
23	41	45	0.00186	0.01307	0.02412	230	2
24	42	46	0.00186	0.01307	0.02412	230	2
25	43	45	0.00186	0.01307	0.02412	230	2

Table 3-2 Two winding transformer parameters

No.	From Bus	To Bus	Rated MVA	Leakage Reactance (p.u.)	Tap Voltage (kV)	Number of Transformers in Parallel
1	08	DP01-1	3000	0.006	525.0/210.4	1
2	08	DN01-1	3000	0.006	525.0/210.4	1
3	10	DP03-1	3000	0.006	525.0/210.4	1
4	10	DN03-1	3000	0.006	525.0/210.4	1
5	12	DP05-1	3000	0.006	525.0/210.4	1
6	12	DN05-1	3000	0.006	525.0/210.4	1
7	DP02	DP02-1	3000	0.006	525.0/199.4	1
8	DP02	DN02-1	3000	0.006	525.0/199.4	1
9	DP04	DP04-1	3000	0.006	525.0/199.4	1
10	DP04	DP04-1	3000	0.006	525.0/199.4	1
11	DP06	DP06-1	3000	0.006	525.0/199.4	1
12	DP06	DP06-1	3000	0.006	525.0/199.4	1
13	TP01	01	780	0.011	20.0/525.0	1
14	TP02	02	780	0.011	20.0/525.0	1
15	TP03	03	1400	0.011	20.0/525.0	1
16	TP04	04	780	0.011	20.0/525.0	1
17	HP05	05	1400	0.011	20.0/525.0	1
18	HP06	06	1400	0.011	20.0/525.0	1
19	TP07	07	780	0.011	20.0/525.0	1
20	WT01-1	14	350	0.018	0.69/38.5	1
21	WT01-2	17	350	0.018	0.69/38.5	1
22	WT01-3	20	350	0.018	0.69/38.5	1
23	WT02-1	15	350	0.018	0.69/38.5	1
24	WT02-2	18	350	0.018	0.69/38.5	1
25	WT02-3	21	350	0.018	0.69/38.5	1
26	WT03-1	16	350	0.018	0.69/38.5	1
27	WT03-2	19	350	0.018	0.69/38.5	1
28	WT03-3	22	350	0.018	0.69/38.5	1
29	PV01-1	23	350	0.022	0.4/38.5	1
30	PV01-2	26	350	0.022	0.4/38.5	1
31	PV01-3	29	350	0.022	0.4/38.5	1
32	PV02-1	24	350	0.022	0.4/38.5	1
33	PV02-2	27	350	0.022	0.4/38.5	1
34	PV02-3	30	350	0.022	0.4/38.5	1
35	PV02-4	32	350	0.022	0.4/38.5	1
36	PV02-5	33	350	0.022	0.4/38.5	1

37	PV03-1	25	350	0.022	0.4/38.5	1
38	PV03-2	28	350	0.022	0.4/38.5	1
39	PV03-3	31	350	0.022	0.4/38.5	1
40	14	34	350	0.035	38.5/230.0	1
41	15	35	350	0.035	38.5/230.0	1
42	16	36	350	0.035	38.5/230.0	1
43	17	34	350	0.035	38.5/230.0	1
44	18	35	350	0.035	38.5/230.0	1
45	19	36	350	0.035	38.5/230.0	1
46	20	37	350	0.035	38.5/230.0	1
47	21	38	350	0.035	38.5/230.0	1
48	22	39	350	0.035	38.5/230.0	1
49	23	37	350	0.035	38.5/230.0	1
50	24	38	350	0.035	38.5/230.0	1
51	25	39	350	0.035	38.5/230.0	1
52	26	40	350	0.035	38.5/230.0	1
53	27	41	350	0.035	38.5/230.0	1
54	28	42	350	0.035	38.5/230.0	1
55	29	40	350	0.035	38.5/230.0	1
56	30	41	350	0.035	38.5/230.0	1
57	31	42	350	0.035	38.5/230.0	1
58	32	43	350	0.035	38.5/230.0	1
59	33	43	350	0.035	38.5/230.0	1

Table 3-3 Three winding transformer parameters

No.	Terminal Bus	Winding 1 Reactance (p.u.)	Winding 2 Reactance (p.u.)	Winding 3 Reactance (p.u.)	Rated MVA	Tap Voltage (p.u.)
1	01/44/47	0.01570	-0.01580	0.02668	1000/1000/360	525/230/37
2	01/44/48	0.01570	-0.01580	0.02668	1000/1000/360	525/230/37
3	01/44/49	0.01570	-0.01580	0.02668	1000/1000/360	525/230/37
4	03/45/50	0.01570	-0.01580	0.02668	1000/1000/360	525/230/37
5	03/45/51	0.01570	-0.01580	0.02668	1000/1000/360	525/230/37
6	03/45/52	0.01570	-0.01580	0.02668	1000/1000/360	525/230/37
7	05/46/53	0.01570	-0.01580	0.02668	1000/1000/360	525/230/37
8	05/46/54	0.01570	-0.01580	0.02668	1000/1000/360	525/230/37
9	05/46/55	0.01570	-0.01580	0.02668	1000/1000/360	525/230/37
10	01/56/62	0.02143	-0.00210	0.04093	1000/1000/300	525/230/37
11	02/57/63	0.02143	-0.00210	0.04093	1000/1000/300	525/230/37
12	03/58/64	0.02143	-0.00210	0.04093	1000/1000/300	525/230/37

13	04/59/65	0.02143	-0.00210	0.04093	1000/1000/300	525/230/37
14	05/60/66	0.02143	-0.00210	0.04093	1000/1000/300	525/230/37
15	07/61/67	0.02143	-0.00210	0.04093	1000/1000/300	525/230/37

Table 3-4 Generator parameters

Generator No.	Terminal Bus	Bus Type	Maximum Active Power (MW)	Maximum Reactive Power (Mvar)	Specified Voltage (p.u.)	Related Plant No.
1	TP01	PV	600	300	1.0	G1
2	TP02	Slack	600	300	1.0	G2
3	TP03	PV	1000	600	1.0	G3
4	TP04	PV	600	300	1.0	G4
5	HP05	PV	1000	600	1.0	G5
6	HP06	PV	1000	500	1.0	G6
7	TP07	PV	600	250	1.0	G7

Table 3-5 PVs and wind farms parameters

No.	Terminal Bus	Related Plant No.	Rated MVA
1	WT01-1	W1	350
2	WT01-2	W1	350
3	WT01-3	W1	350
4	WT02-1	W2	350
5	WT02-2	W2	350
6	WT02-3	W2	350
7	WT03-1	W3	350
8	WT03-2	W3	350
9	WT03-3	W3	350
10	PV01-1	PV1	350
11	PV01-2	PV1	350
12	PV01-3	PV1	350
13	PV02-1	PV2	350
14	PV02-2	PV2	350
15	PV02-3	PV2	350
16	PV02-4	PV2	300
17	PV02-5	PV2	300
18	PV03-1	PV3	350
19	PV03-2	PV3	350
20	PV03-3	PV3	350

3.2 Specific Parameters of Different Scenarios

This section gives specific parameters of the three scenarios in CSEE-FS.

Table 3-6 Loads and static compensations for high/low frequency scenario

No.	Connected Bus in Main Grid	Active Load (MW)	Reactive Load (Mvar)	Static Compensation (Mvar)
1	01	1100	360	655
2	02	700	220	515
3	03	900	300	440
4	04	429	178	72
5	05	500	170	110
6	07	1223	400	351

*All the loads are connected at the 220kV side of three winding transformers, and compensations are connected at the 35kV side of transformers.
*Static compensations for renewable plants and HVDC are specified according to their power level, and are not listed in the table.

Table 3-7 Loads and static compensations for ultra-low frequency oscillation scenario

No.	Connected Bus in Main Grid	Active Load (MW)	Reactive Load (Mvar)	Static Compensation (Mvar)
1	01	300	140	90
2	02	300	100	105
3	03	300	110	75
4	04	329.1	78	20
5	05	300	70	20
6	07	323	79	20

*All the loads are connected at the 220kV side of three winding transformers, and compensations are connected at the 35kV side of transformers.
*Static compensations for renewable plants and HVDC are specified according to their power level, and are not listed in the table.

Table 3-8 Generations and HVDC power level of the scenarios

High/Low Frequency Scenarios			Ultra-Low Frequency Oscillation Scenario		
Type	Plant No.	Power Level (MW)	Type	Plant No.	Power Level (MW)
Thermal	G1	500	Hydro	G1	400
	G2	278		G2	411
	G3	600		G3	700
	G4	300		G4	500
	G7	400		G5	700
Hydro	G5	750		G6	700
	G6	650		G7	400
Wind Farm	W1	582	Wind Farm	W1	150
	W2	570		W2	150
	W3	570		W3	150

Photovoltaic	PV1	570	Photovoltaic	PV1	0
	PV2	950		PV2	0
	PV3	570		PV3	0
HVDC-1	/	794	HVDC-1	/	794
HVDC-2	/	794	HVDC-2	/	794
HVDC-3	/	794	HVDC-3	/	794

3.3 Further Test of the Model

This section gives further test of CSEE-FS with varied PV and wind farm penetration, and varied system fault.

Based on the high frequency scenario, two additional scenarios are designed to test system frequency response, with varied PV and wind farm penetration. Details of the scenarios are given in Table 3-9.

In all the three scenarios, system frequency is observed after HVDC-1-blocked-out. The dynamics are demonstrated in Figure 3-1. The dynamics are evaluated through the frequency stability indices in Table 3-10. The results have shown that frequency stability is deteriorated with the increasement of PVs and winds.

Table 3-9 Additional Scenarios for Post-Fault High Frequency with Varied PVs and Winds

	Capacity of Synchronous Generators (MVA)	Generation of Synchronous Generators (MW)	Capacity of PVs and Wind Farms (MVA)	Generation of PVs and Wind Farms (MW)	Inertial Time Constant (s)	Percentage of Solar and Wind Power
Basic Scenario	5850	3478	6950	3810	2.68	52.28%
Addition Scenario S10	4650	2700	9650	4600	2.25	63.02%
Addition Scenario S11	3500	2102	9650	5200	1.94	71.13%

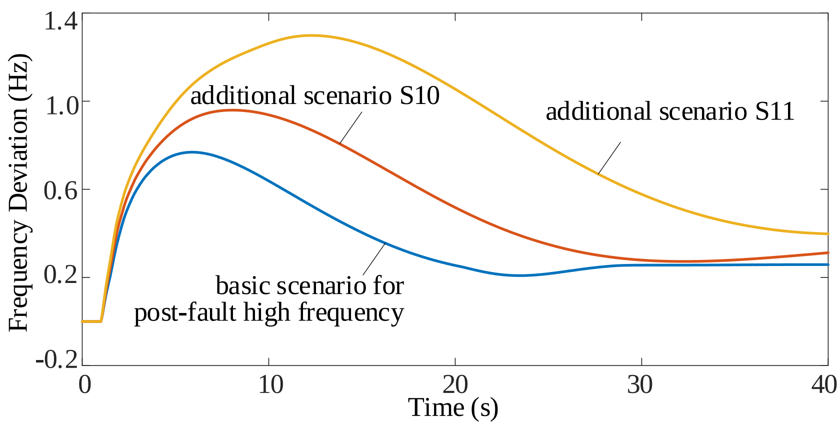

Figure 3-1 Frequency dynamics with varied PV and wind farm penetration

Table 3-10 Stability Evaluation for Post-Fault High Frequency with Varied PVs and Winds

	Frequency Zenith (Hz)	Time of Frequency Zenith (Hz)	Steady Frequency Deviation (Hz)
Basic Scenario	0.77	5.92	0.26
Addition Scenario 1	0.97	7.83	0.31
Addition Scenario 2	1.30	12.28	0.40

In frequency stability analysis, the type of lost generator significantly affects system dynamics. Generally, there are two types of lost generator: renewable generator and synchronous generator. The latter has a more severe impact on frequency stability.

When a generator is lost, active generation of the system is decreased, which means the frequency will drop. If the lost generator is a renewable generator, all the synchronous generators will participate in the frequency dynamics. The post-fault frequency nadir is mainly dependent on inertial of the generators, and steady frequency deviation is mainly dependent on frequency regulation capability of the generators. If the lost generator is a synchronous generator, system inertial will be decreased. Besides, frequency regulation capability of the overall system is decreased. This means the post-fault frequency nadir and steady frequency deviation is lower than the scenario in which a renewable generator is lost.

To address this issue, two types of generator lost are simulated in the basic scenario of post-fault low frequency case. Frequency response of the system is demonstrated in Figure 3-2. In this figure, the blue dashed line denotes frequency dynamics when 300MW wind generators are lost, and the red solid line denotes frequency dynamics when a 300MW thermal generator is lost.

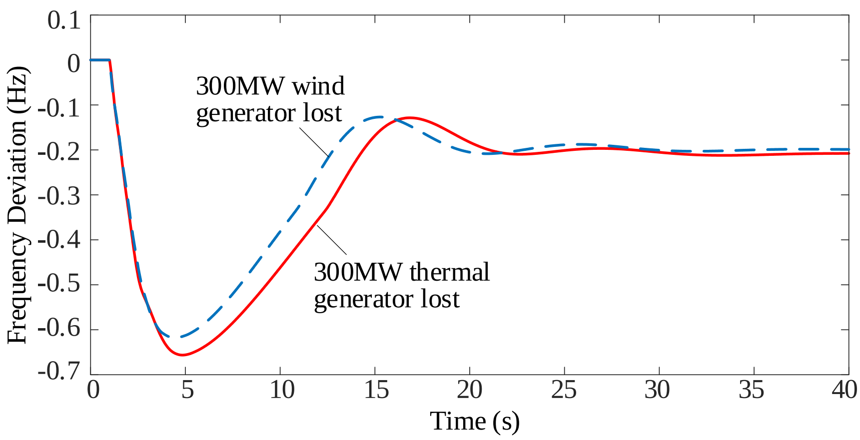

Figure 3-2 Comparison of impact different lost generator

Based on the ultra-low frequency oscillation scenario, impacts of three different disturbances are compared in Figure 3-3. The disturbances are successive CF of HVDC-1, 50MW load increasement at bus_01, and three-phase-to-ground fault followed by disconnection of transmission line between bus_03 and bus_05 (‘N-1’ fault). Related quantifying indices are given in Table 3-11. The results have shown that ultra-low frequency oscillation is not sensitive to the type of disturbance.

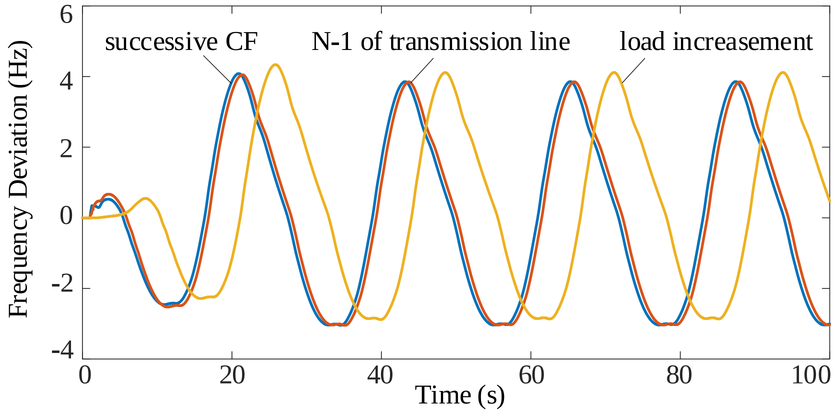

Figure 3-3 Ultra-low frequency oscillation stimulated by different disturbances

Table 3-11 Quantification of ultra-low frequency oscillation

	Frequency of Oscillation (Hz)	Amplitude of Oscillation
Successive CFs	0.045	6.88
N-1 Fault	0.045	6.82
Load Increasement	0.044	6.92

4. Test Model for Power Frequency Overvoltage (CSEE-PFO)

4.1 Common Parameters

This section gives basic parameters of CSEE-PFO. Both the scenarios of CSEE-PFO share the parameters in this section.

In the test system, all terminal nodes of generators, renewables, and HVDCs are named after the related equipment, which are generally below 35kV. All the other AC nodes are named by numbers.

Table 4-1 Line parameters

No.	From Bus	To Bus	Resistance (p.u.)	Reactance (p.u.)	Susceptance (p.u.)	Base Voltage (kV)	Number of Branches in Parallel
1	08	01	/	0.0001	/	525	1
2	01	02	0.00017	0.00279	0.94143	525	1
3	01	02	0.00014	0.00277	0.94111	525	1
4	01	03	0.00017	0.00279	0.94143	525	1
5	01	03	0.00014	0.00277	0.94111	525	1
6	01	04	0.00007	0.00106	0.37106	525	1
7	01	04	0.00007	0.00111	0.37669	525	1
8	01	05	0.00007	0.00101	0.34864	525	1
9	01	05	0.00007	0.00103	0.35739	525	1
10	01	06	0.00011	0.00199	0.13682	525	2
11	01	07	0.00011	0.00199	0.13682	525	2
12	RE-Bus	09	/	0.0001	/	525	1
13	10	17	0.00186	0.01307	0.02412	230	2
14	10	18	0.00186	0.01307	0.02412	230	2
15	10	19	0.00186	0.01307	0.02412	230	2
16	10	20	0.00186	0.01307	0.02412	230	2
17	11	25	0.00186	0.01307	0.02412	230	2
18	11	26	0.00186	0.01307	0.02412	230	2
19	11	27	0.00186	0.01307	0.02412	230	2

Table 4-2 Two winding transformer parameters

No.	From Bus	To Bus	Rated MVA	Leakage Reactance (p.u.)	Tap Voltage (kV)	Number of Transformers in Parallel
1	08	DP01	0.006	3000	525/210	1
2	09	DP02	0.006	3000	525/199	1

3	08	DN01	0.006	3000	525/210	1
4	09	DN02	0.006	3000	525/199	1
5	40	17	0.035	300	37/230	1
6	41	17	0.035	300	37/230	1
7	42	18	0.035	300	37/230	1
8	43	18	0.035	300	37/230	1
9	44	19	0.035	300	37/230	1
10	45	19	0.035	300	37/230	1
11	46	20	0.035	300	37/230	1
12	47	20	0.035	300	37/230	1
13	56	25	0.035	300	37/230	1
14	57	25	0.035	300	37/230	1
15	58	26	0.035	300	37/230	1
16	59	26	0.035	300	37/230	1
17	60	27	0.035	300	37/230	1
18	61	27	0.035	300	37/230	1
19	WT02-01	40	0.2708	240	0.69/37	1
20	WT02-02	41	0.2708	240	0.69/37	1
21	WT02-03	42	0.2708	240	0.69/37	1
22	WT02-04	43	0.2708	240	0.69/37	1
23	WT02-05	44	0.2708	240	0.69/37	1
24	WT02-06	45	0.2708	240	0.69/37	1
25	WT02-07	46	0.2708	240	0.69/37	1
26	WT02-08	47	0.2708	240	0.69/37	1
27	PV03-01	56	0.01806	360	0.4/37	1
28	PV03-02	57	0.01806	360	0.4/37	1
29	PV03-03	58	0.01806	360	0.4/37	1
30	PV03-04	59	0.01806	360	0.4/37	1
31	PV03-05	60	0.01806	360	0.4/37	1
32	PV03-06	61	0.01806	360	0.4/37	1
33	TP04-01	04	0.03331	750	20/525	1
34	TP04-02	04	0.03331	750	20/525	1
35	TP04-03	04	0.03331	750	20/525	1
36	TP05-04	05	0.03331	750	20/525	1
37	TP05-05	05	0.03331	750	20/525	1
38	TP05-06	05	0.03331	750	20/525	1
39	TP05-07	05	0.03331	750	20/525	1

Table 4-3　Three winding transformer parameters

No.	Terminal Bus	Winding 1 Reactance (p.u.)	Winding 2 Reactance (p.u.)	Winding 3 Reactance (p.u.)	Rated MVA	Tap Voltage (p.u.)
1	02/10/29	0.0157	-0.00158	0.02668	1000/1000/360	525/230/37
2	02/10/30	0.0157	-0.00158	0.02668	1000/1000/360	525/230/37
3	02/10/31	0.0157	-0.00158	0.02668	1000/1000/360	525/230/37
4	03/11/32	0.0157	-0.00158	0.02668	1000/1000/360	525/230/37
5	03/11/33	0.0157	-0.00158	0.02668	1000/1000/360	525/230/37
6	03/11/34	0.0157	-0.00158	0.02668	1000/1000/360	525/230/37
7	01/12/35	0.0157	-0.00158	0.02668	1000/1000/360	525/230/37
8	04/13/36	0.0157	-0.00158	0.02668	1000/1000/360	525/230/37
9	05/14/37	0.0157	-0.00158	0.02668	1000/1000/360	525/230/37
10	06/15/38	0.0157	-0.00158	0.02668	1000/1000/360	525/230/37
11	07/16/39	0.0157	-0.00158	0.02668	1000/1000/360	525/230/37

Table 4-4　Generator parameters

Generator No.	Terminal Bus	Bus Type	Maximum Active Power (MW)	Maximum Reactive Power (Mvar)	Specified Voltage (p.u.)	Related Plant No.
1	TP04-01	PV	660	522	1.0	G1
2	TP04-02	PV	660	522	1.0	G1
3	TP04-03	PV	660	510	1.0	G1
4	TP05-04	PV	660	510	1.0	G2
5	TP05-05	PV	660	300	1.0	G2
6	TP05-06	Slack	660	300	1.0	G2
7	TP05-07	PV	660	510	1.0	G2

Table 4-5　Renewable parameters

No.	Terminal Bus	Related Plant No.	Rated MVA
1	WT02-01	W1	200
2	WT02-02	W1	200
3	WT02-03	W1	200
4	WT02-04	W1	200
5	WT02-05	W2	200
6	WT02-06	W2	200
7	WT02-07	W2	200
8	WT02-08	W2	200
9	PV03-01	PV1	400
10	PV03-02	PV1	400
11	PV03-03	PV1	400
12	PV03-04	PV1	400

13	PV03-05	PV2	400
14	PV03-06	PV2	400

4.2 Specific Parameters of Different Scenarios

This section gives specific parameters of the scenarios in CSEE-PFO.

Table 4-6 Loads and static compensations for temporary PFO scenario

No.	Connected Bus in Main Grid	Active Load (MW)	Reactive Load (Mvar)	Static Compensation (Mvar)
1	10	260	70	/
2	11	260	70	/
3	12	50	32	/
4	13	230	30	/
5	14	230	30	/
6	15	400	70	/
7	16	400	70	/

*All the loads are connected at the 220kV side of three winding transformers, and compensations are connected at the 35kV side of transformers.
*Static compensations for renewable plants and HVDC are specified according to their power level, and are not listed in the table.

Table 4-7 Loads and static compensations for continuous PFO scenario

No.	Connected Bus in Main Grid	Active Load (MW)	Reactive Load (Mvar)	Static Compensation (Mvar)
1	10	260	70	/
2	11	260	70	/
3	12	50	32	/
4	13	230	30	/
5	14	230	30	/
6	15	400	70	/
7	16	400	70	/

*All the loads are connected at the 220kV side of three winding transformers, and compensations are connected at the 35kV side of transformers.
*Static compensations for renewable plants and HVDC are specified according to their power level, and are not listed in the table.

Table 4-8 Generations and HVDC power level of the scenarios

Temporary PFO			Continuous PFO		
Type	Plant No.	Power Level (MW)	Type	Plant No.	Power Level (MW)
Thermal	G1	1200	Thermal	G1	1320

	G2	1548		G2	1430
Wind Farm	W1	800	Wind Farm	W1	800
	W2	800		W2	800
	W3	/		W3	/
	W4	/		W4	/
Photovoltaic	PV1	800	Photovoltaic	PV1	800
	PV2	400		PV2	400
HVDC	/	3700	HVDC	/	3700

Table 4-9 Synchronous condenser parameters of temporary PFO scenario

Condenser No.	Terminal Bus	Connected Bus in Main Grid	Maximum Reactive Power (Mvar)	Minimum Reactive Power (Mvar)	Specified Voltage (p.u.)
1	SC02-01	02	300	-150	1.0

Table 4-10 Synchronous condenser parameters of continuous PFO scenario

Condenser No.	Terminal Bus	Connected Bus in Main Grid	Maximum Reactive Power (Mvar)	Minimum Reactive Power (Mvar)	Specified Voltage (p.u.)
1	SC02-01	02	300	-150	1.0
2	SC02-02	02	300	-150	1.0
3	SC02-03	03	300	-150	1.0
4	SC03-04	03	300	-150	1.0

4.3 Further Test of the Model

This section gives further test of CSEE-PFO of both scenarios.

In the temporary PFO scenario, system performances are tested under varied HVDC power and varied renewable penetration. Four additional scenarios are established, as listed in Table 4-11. The typical fault is still configured as an HVDC block-out following two successive CFs.

Table 4-11 Additional scenarios for temporary PFO test

	Renewable Generation (MW)	HVDC Power (MW)	Compensation for Renewable Plants (Mvar)	Compensation for HVDC Rectifier (Mvar)
Basic Scenario	2800	3700	80	1865
Additional Scenario S10	2520	3700	20	1865
Additional Scenario S11	2240	3700	0	1865

Additional Scenario S12	2800	3500	80	1625
Additional Scenario S13	2800	3300	80	1550

The post-fault voltage dynamics with varied renewable penetration are shown in Figure 4-1 and Figure 4-2, respectively for PCC of HVDC and renewables. The post-fault voltage dynamics with varied HVDC power are shown in Figure 4-3 and Figure 4-4. Voltage peaks in all the figures are zoomed-in for a better observation. Table 4-12 evaluates the temporary PFO level through fault-induced maximum voltage and transient voltage increase. It is revealed that a higher renewable penetration (or HVDC power level) results in a higher temporary PFO level.

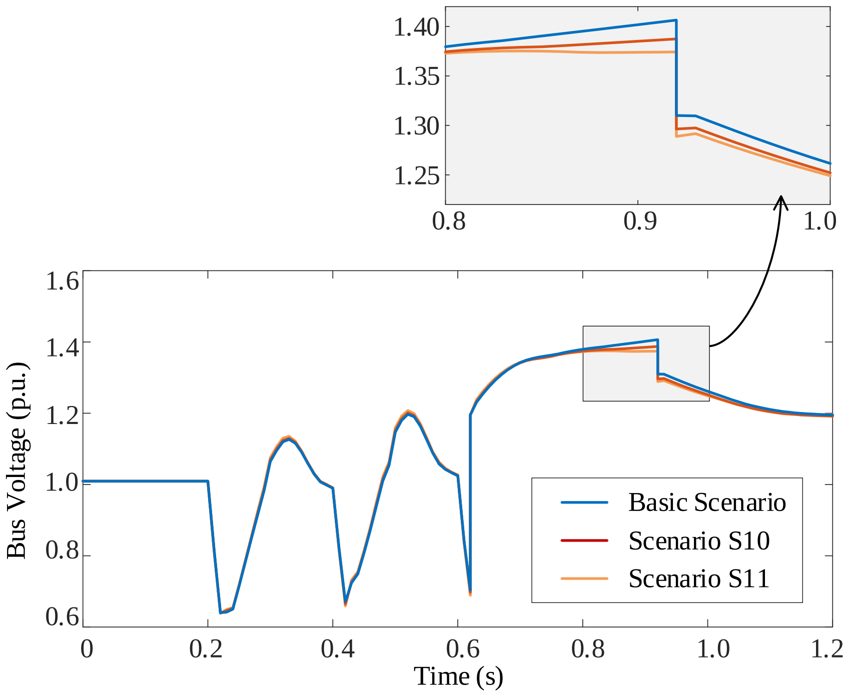

Figure 4-1 Post-fault voltage dynamics with varied renewable penetration for HVDC PCC.

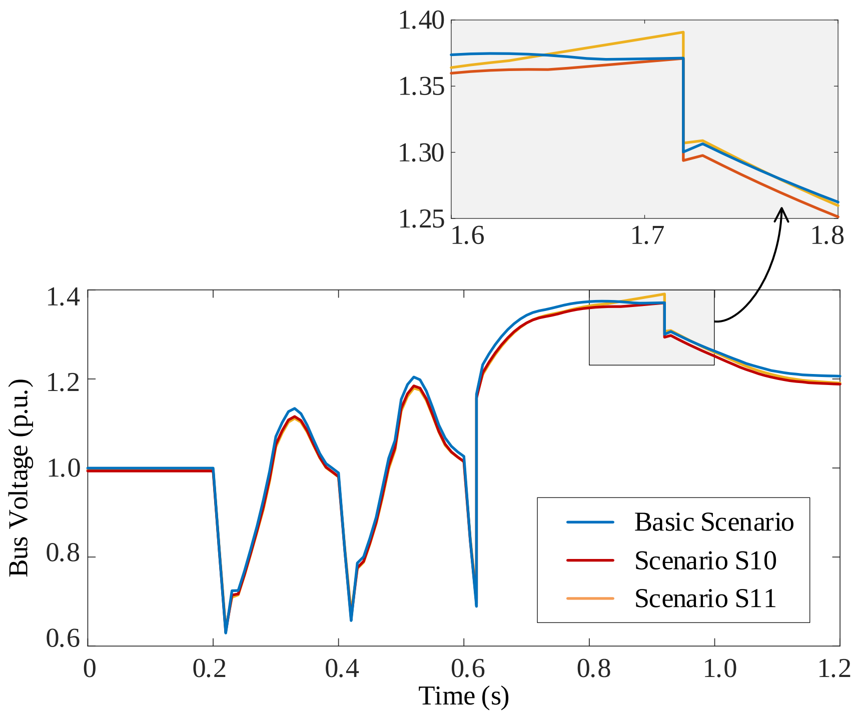

Figure 4-2 Post-fault renewable terminal voltage dynamics with varied renewable penetration.

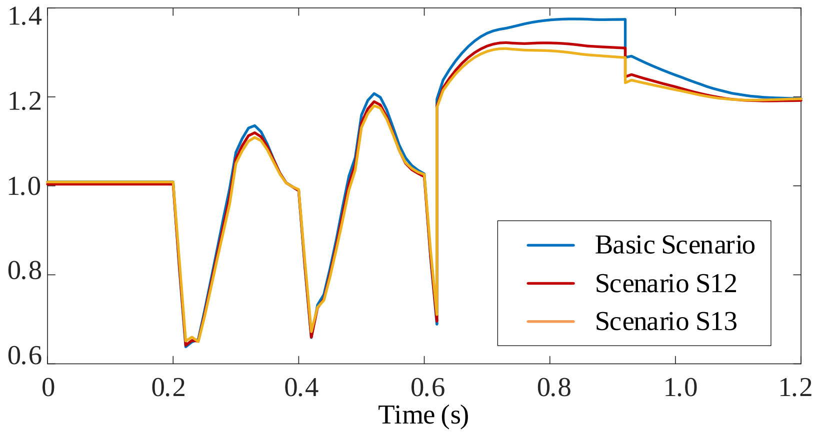

Figure 4-3 Post-fault HVDC PCC voltage dynamics with varied HVDC power.

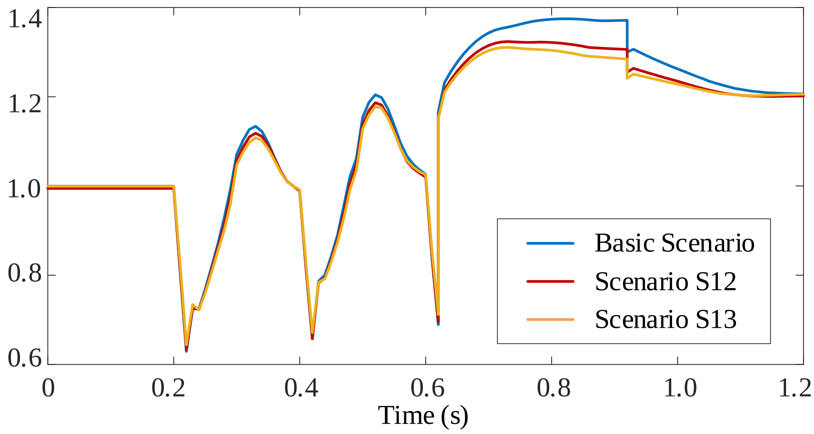

Figure 4-4 Post-fault renewable terminal voltage dynamics with varied renewable penetration.

Table 4-12 Evaluation of temporary PFO level of the scenarios

	Voltage of PCC of HVDC (p.u.)			Voltage of PCC of Wind Turbine WT02-01 (p.u.)		
	Pre-Fault Voltage	Maximum Voltage	Transient Voltage Increase	Pre-Fault Voltage	Maximum Voltage	Transient Voltage Increase
Basic Scenario	1.009	1.375	0.366	1.000	1.375	0.375
Additional Scenario S10	1.010	1.387	0.378	0.993	1.371	0.378
Additional Scenario S11	1.009	1.406	0.397	0.996	1.391	0.395
Additional Scenario S12	1.004	1.322	0.318	0.995	1.324	0.329
Additional Scenario S13	1.009	1.309	0.300	1.000	1.311	0.311

In the continuous PFO scenario, system performances are tested with varied configuration of rectifier station, varied HVDC power level, and varied contingency control after HVDC block-out.

In the test of varied rectifier station, two additional scenarios are established, with different inter-station compensation. Overall reactive consumption of the station is thus adjusted. Compensations in the rest of the system are adjusted as well, maintaining a constant pre-fault steady-state voltage. The compensations and simulation results of the scenarios are given in Table 4-13, with time-domain voltage dynamics demonstrated in Figure 4-5. It is revealed that a decreased inter-station compensation would in turn increase continuous PFO level.

Table 4-13 Test of continuous PFO level with varied HVDC station configuration

	HVDC Power (MW)	Reactive Consumption of Overall Rectifier Station (Mvar)	Pre-Fault Voltage (p.u.)	Post-Fault Voltage (p.u.)	Steady Voltage Increase (p.u.)

Basic Scenario	3700	131	1.006	1.054	0.048
Additional Scenario S14	3700	29	1.006	1.050	0.044
Additional Scenario S15	3700	307	1.005	1.062	0.057

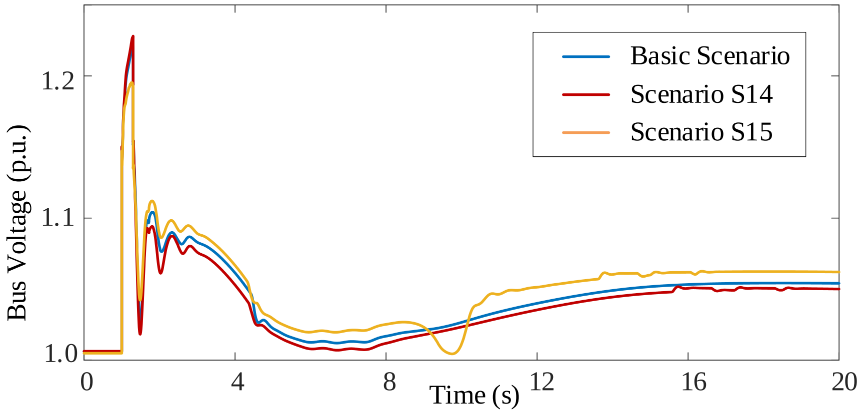

Figure 4-5 Voltage dynamics of HVDC PCC with varied station compensation.

In the test of varied HVDC power, one additional scenario is established as shown in Table 4-14. Related voltage dynamics are demonstrated in Figure 4-6. It is revealed that a decreased HVDC power would decrease continuous PFO level.

Table 4-14 Test of continuous PFO level with varied HVDC power

	HVDC Power (MW)	Reactive Consumption of Overall Rectifier Station (Mvar)	Pre-Fault Voltage (p.u.)	Post-Fault Voltage (p.u.)	Steady Voltage Increase (p.u.)
Basic Scenario	3700	131	1.006	1.054	0.048
Additional Scenario S16	3400	103	1.007	1.020	0.013

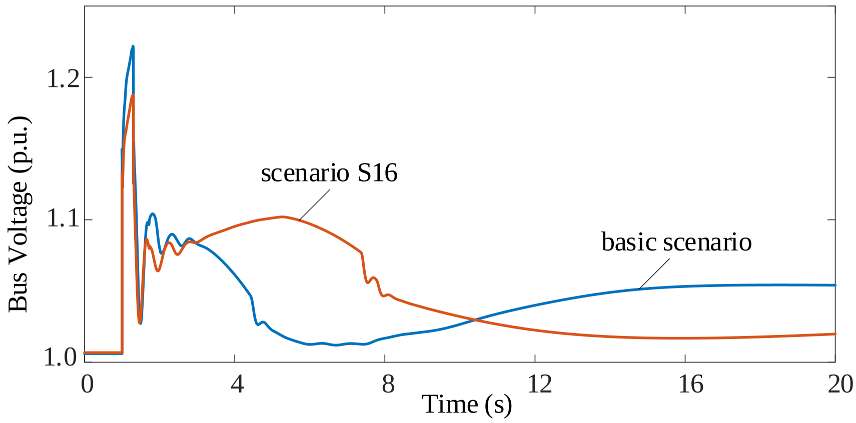

Figure 4-6 Voltage dynamics of HVDC PCC with varied HVDC power level.

In the test of varied contingency control, one other control is designed as shown in Table 4-15. After HVDC block-out, a part of power sources should be disconnected as a contingency control, in order to maintain frequency stability. It is revealed that disconnecting less thermal power helps to decrease continuous PFO level. Related voltage dynamics are shown in Figure 4-7.

Table 4-15 Test of continuous PFO level with varied Contingency Control

	Amount of Thermal Disconnection (MW)	Amount of Wind Disconnection (Mvar)	Pre-Fault Voltage (p.u.)	Post-Fault Voltage (p.u.)	Steady Voltage Increase (p.u.)
Contingency Control in Basic Scenario	1980	1800	1.006	1.054	0.048
Designed New Control for Comparison	1320	2400	1.006	1.047	0.041

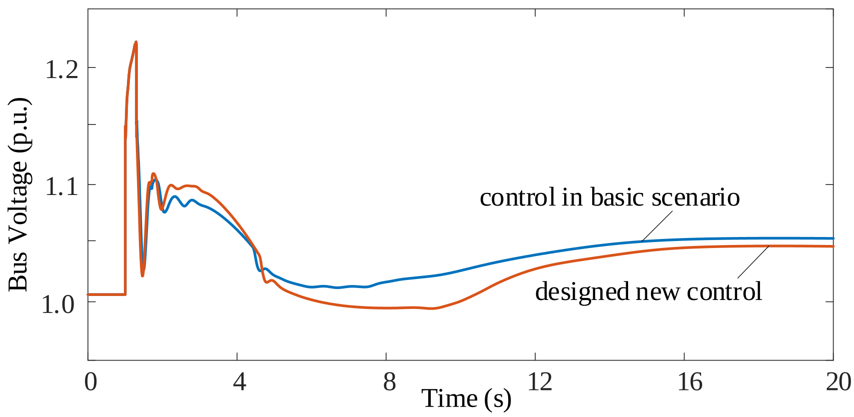

Figure 4-7 Voltage dynamics with varied contingency control.

5. Device-Level Dynamic Models and Parameters

This section describes device-level dynamic models and parameters of the test systems.

In the dynamic models of renewables, PV and type-IV wind have similar grid interface, which means their models are similar. A block diagram is drawn in Figure 4-1, which applies to both PV and type-IV wind in the test models. One can distinguish between PV and wind based on the generator model block in Fig. 5-1.

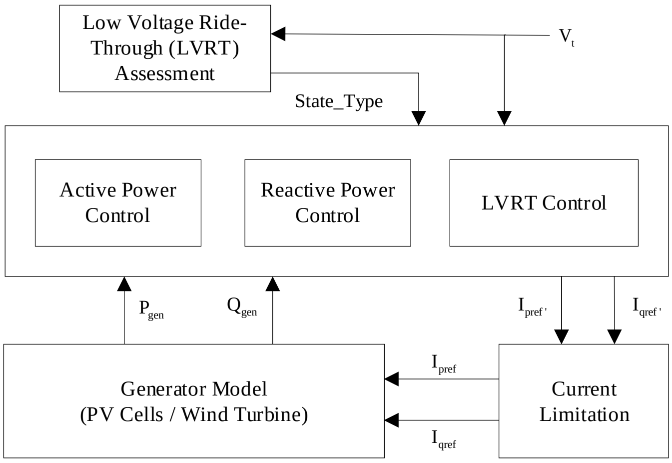

Figure 5-1. Overall block diagram of PV and type-IV wind.

In the block diagram of Figure 5-1, the active power control and reactive power control are very important in electromechanical simulations. Details of the controls are given in Figure 5-2 and 5-3, respectively. One can refer to BPA manuals to obtain more details of the models.

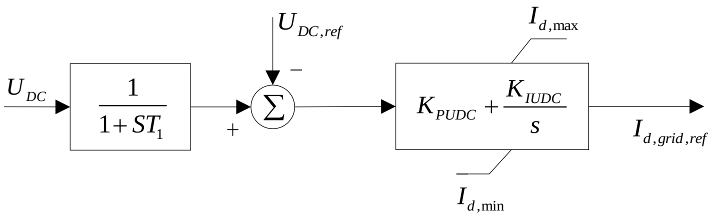

Figure 5-2. Active power control of PV and type-IV wind.

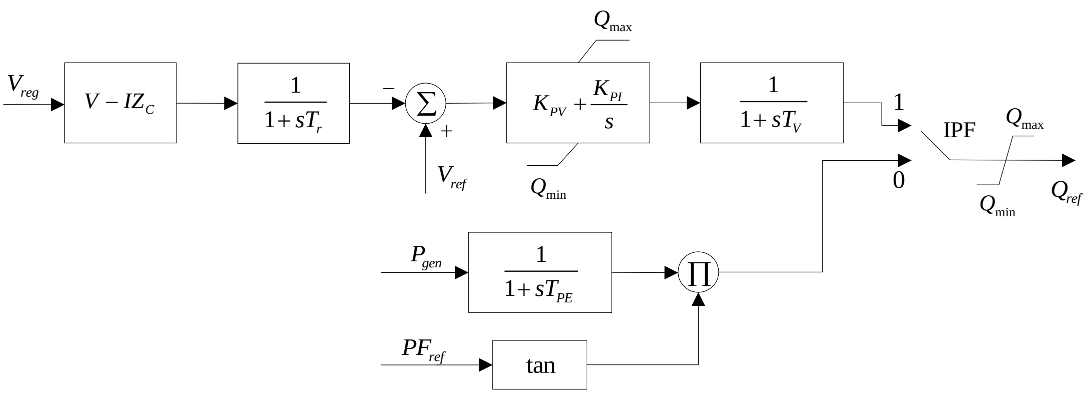

Figure 5-3. Reactive power control of PV and type-IV wind.

Model of type-III wind is much more complex, which is shown in Figure 5-4. In type-III wind, reactive power of the turbine is controlled as zero. Reactive power of the grid-side converter is the same as what is shown in Figure 5-3. Active power response of type-III wind is shown in Figure 5-5.

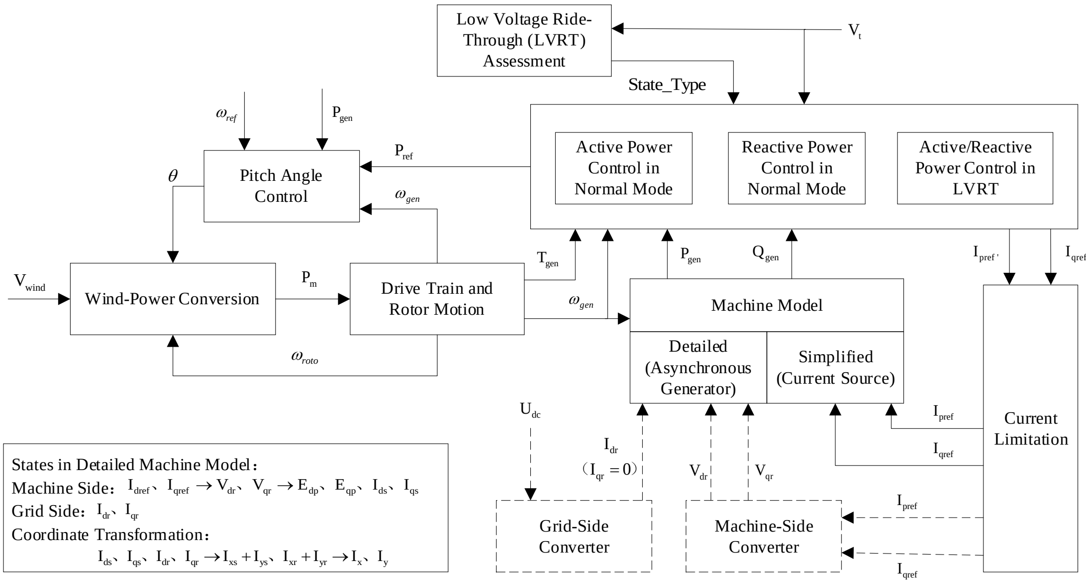

Figure 5-4. Overall dynamic model of type-III wind turbine generator

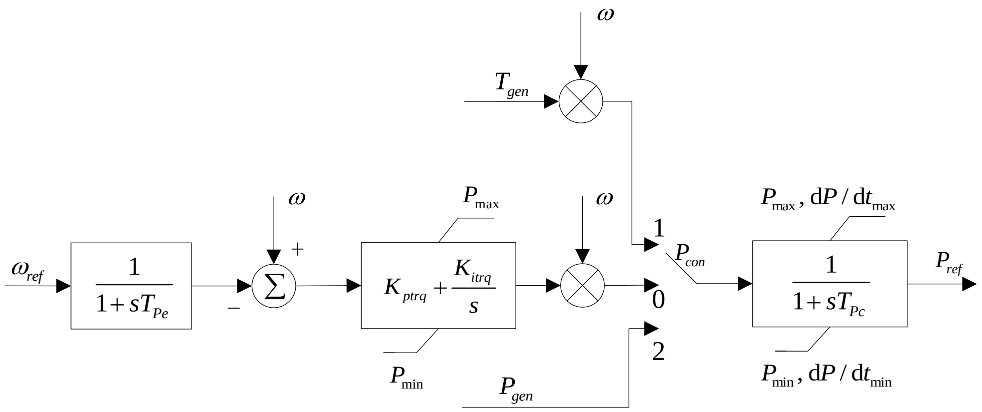

Figure 5-5. Block diagram of the active power control of type-III wind.

Generator models in the test system adopts the model in Power System Stability and Control, authored by Kundur. It which is a widely applied model. HVDC model in the test system is fairly complex, with consideration of several features HVDC in practical engineering. For detailed design of the model, it would be better to refer to the BPA manual.

Some major dynamic parameters in the test models are given in the followings. Meanings of most variables can be found in the above figures.

1) Dynamic parameters of CSEE-VS

In the test model of voltage stability, a set of generic dynamic parameters are applied, which are concluded from practical power systems. Notably, the parameter can be varied in different countries, and for different manufacturers. The given parameters can serve as a reference, while any users can specify their own parameters according to their demands.

Table 5-1 Parameters of active power control of PVs in CSEE-VS

T_1	K_{PUDC}	K_{IUDC}	$I_{d,max}$	$I_{d,min}$
0.02	2.0	0.1	1	-1

Table 5-2 Parameters of reactive power control of PVs in CSEE-VS

T_r	K_{PV}	K_{PI}	Q_{max}	Q_{min}	T_V	IPF
0.02	18	5	0.436	-0.436	0.15	1

Table 5-3 Parameters of active power control of type-IV winds in CSEE-VS

T_1	K_{PUDC}	K_{IUDC}	$I_{d,max}$	$I_{d,min}$
0.02	2.0	0.1	1	-1

Table 5-4 Parameters of reactive power control of type-IV winds in CSEE-VS

T_r	K_{PV}	K_{PI}	Q_{max}	Q_{min}	T_V	IPF
0.02	18	5	1.1	-1.1	0.02	1

Table 5-5 Parameters of active power control of type-III winds in CSEE-VS

T_{Pe}	K_{ptrq}	K_{itrq}	T_{Pc}	P_{max}	P_{min}	$\mathrm{d}P/\mathrm{d}t_{max}$	$\mathrm{d}P/\mathrm{d}t_{min}$	P_{con}
60	3.0	0.6	0.05	1.0	0.04	0.45	-0.45	2

Table 5-6 Parameters of reactive power control of type-III winds in CSEE-VS

T_r	K_{PV}	K_{PI}	Q_{max}	Q_{min}	T_V	IPF
0.02	18	5	1.1	-1.1	0.02	1

Table 5-7 Parameters of generators in CSEE-VS

S_{base}	X_d	X'_d	X''_d	$\mathrm{T}'_{\mathrm{d0}}$	$\mathrm{T}''_{\mathrm{d0}}$	X_q	X'_q	$\mathrm{X}''_{\mathrm{q}}$	$\mathrm{T}'_{\mathrm{q0}}$	$\mathrm{T}''_{\mathrm{q0}}$
733	2.38	0.336	0.251	8.61	0.045	2.32	0.485	0.247	0.96	0.066

Table 5-8 Basic parameters of HVDC in CSEE-VS

Parameter	Value
Rated DC current (A)	5000
DC resistance (Ω)	5
DC reactance (mH)	800

DC voltage (kV)	500
Ignition angle of rectifier (degree)	15
Extinction angle of inverter (degree)	17

Table 5-9 Parameters of HVDC control in CSEE-VS

G_{max}	T_{amax}	γ_{ref}	γ_{min}	K_{pvca}	T_{ivca}	K_{1ra}	K_{2ra}	C_{dl}	D_l	D_{ecr}	T_{ga}	T_{dret}	T_{hret}	T_{hres}
0.15	0.012	17	11.7	10	0.0004	0.85	0.7	30	30	0.37	0.065	164	0.15	0.034

Table 5-10 Parameters of synchronous condensers in CSEE-VS

S_{base}	X_d	X'_d	X''_d	T'_{d0}	T''_{d0}	X_q	X'_q	X''_q	T'_{q0}	T''_{q0}
300	1.535	0.165	0.111	8.96	0.05	1.394	0.317	0.11	0.83	0.096

2) Dynamic parameters of CSEE-RAS

In the test model of rotor angle stability, similar to the above CSEE-VS, a set of generic dynamic parameters are applied. The given parameters can serve as a reference, while any users can specify their own parameters according to their demands.

Table 5-11 Parameters of active power control of PVs in CSEE-RAS

T_1	K_{PUDC}	K_{IUDC}	$I_{d,max}$	$I_{d,min}$
0.02	2.0	0.1	1	-1

Table 5-12 Parameters of reactive power control of PVs in CSEE-RAS

T_r	K_{PV}	K_{PI}	Q_{max}	Q_{min}	T_V	IPF
0.02	18	5	0.436	-0.436	0.15	1

Table 5-13 Parameters of active power control of type-IV winds in CSEE-RAS

T_1	K_{PUDC}	K_{IUDC}	$I_{d,max}$	$I_{d,min}$
0.02	2.0	0.1	1	-1

Table 5-14 Parameters of reactive power control of type-IV winds in CSEE-RAS

T_r	K_{PV}	K_{PI}	Q_{max}	Q_{min}	T_V	IPF
0.02	18	5	1.1	-1.1	0.02	1

Table 5-15 Parameters of active power control of type-III winds in CSEE-RAS

T_{Pe}	K_{ptrq}	K_{itrq}	T_{Pc}	P_{max}	P_{min}	$\mathrm{d}P/\mathrm{d}t_{max}$	$\mathrm{d}P/\mathrm{d}t_{min}$	P_{con}
60	3.0	0.6	0.05	1.0	0.04	0.45	-0.45	2

Table 5-16 Parameters of reactive power control of type-III winds in CSEE-RAS

T_r	K_{PV}	K_{PI}	Q_{max}	Q_{min}	T_V	IPF
0.02	18	5	1.1	-1.1	0.02	1

Table 5-17 Parameters of generators in CSEE-RAS

S_{base}	X_d	X'_d	X''_d	T'_{d0}	T''_{d0}	X_q	X'_q	X''_q	T'_{q0}	T''_{q0}
667	1.918	0.284	0.218	7.88	0.046	1.867	0.4284	0.217	0.87	0.07

Table 5-18 Basic parameters of HVDC in CSEE-RAS

Parameter	Value
Rated DC current (A)	5000
DC resistance (Ω)	5
DC reactance (H)	800
DC voltage (kV)	500
Ignition angle of rectifier (degree)	15
Extinction angle of inverter (degree)	17

Table 5-19 Parameters of HVDC control in CSEE-RAS

G_{max}	T_{amax}	γ_{ref}	γ_{min}	K_{pvca}	T_{ivca}	K_{1ra}	K_{2ra}	C_{dl}	D_l	D_{ecr}	T_{ga}	T_{dret}	T_{hret}	T_{hres}
0.15	0.012	17	11.7	10	0.0004	0.85	0.7	30	30	0.37	0.065	164	0.15	0.034

Table 5-20 Parameters of synchronous condensers in CSEE-VS

S_{base}	X_d	X'_d	X''_d	T'_{d0}	T''_{d0}	X_q	X'_q	X''_q	T'_{q0}	T''_{q0}
300	1.535	0.165	0.111	8.96	0.05	1.394	0.317	0.11	0.83	0.096

3) Dynamic parameters of CSEE-FS

In the test model of frequency stability, the high/low frequency and ultra-low frequency oscillation has very different physical process. Consequently, although renewable parameters are the same in all scenarios, the synchronous generators are varied. Still, the given parameters are a set of generic ones as a reference, while any users can specify their own parameters according to their demands.

Table 5-21 Parameters of active power control of PV01-1 and PV03-1

T_1	K_{PUDC}	K_{IUDC}	$I_{d,max}$	$I_{d,min}$
0.02	2.0	0.1	2	-1

Table 5-22 Parameters of active power control of PVs except PV01-1 and PV03-1

T_1	K_{PUDC}	K_{IUDC}	$I_{d,max}$	$I_{d,min}$
0.02	3.0	0.1	2	-1

Table 5-23 Parameters of reactive power control of PVs

T_r	K_{PV}	K_{PI}	Q_{max}	Q_{min}	T_V	T_{PV}	IPF
0.02	18	5	0.436	-0.436	0.15	0.05	1

Table 5-24 Parameters of active power control of type-IV winds

T_1	K_{PUDC}	K_{IUDC}	$I_{d,max}$	$I_{d,min}$
0.02	2.0	0.1	1	-1

Table 5-25 Parameters of reactive power control of type-IV winds

T_r	K_{PV}	K_{PI}	Q_{max}	Q_{min}	T_V	IPF
0.02	18	5	1.1	-1.1	0.02	1

Table 5-26 Parameters of active power control of type-III winds

T_{Pe}	K_{ptrq}	K_{itrq}	T_{Pc}	P_{max}	P_{min}	$\mathrm{d}P/\mathrm{d}t_{max}$	$\mathrm{d}P/\mathrm{d}t_{min}$	P_{con}
60	3.0	0.6	0.05	1.0	0.04	0.45	-0.45	2

Table 5-27 Parameters of reactive power control of type-III winds

T_r	K_{PV}	K_{PI}	Q_{max}	Q_{min}	T_V	IPF
0.02	18	5	1.1	-1.1	0.02	1

Table 5-28 Basic parameters of positive poles of HVDCs

Parameter	Value
Rated DC current (A)	5000
DC resistance (Ω)	5
DC reactance (mH)	800
DC voltage (kV)	500
Ignition angle of rectifier (degree)	15
Extinction angle of inverter (degree)	17

Table 5-29 Basic parameters of negative poles of HVDCs

Parameter	Value
Rated DC current (A)	5000
DC resistance (Ω)	5
DC reactance (mH)	785.37
DC voltage (kV)	500
Ignition angle of rectifier (degree)	15

Extinction angle of inverter (degree)	17

Table 5-30 Parameters of HVDC control

G_{max}	T_{amax}	γ_{ref}	γ_{min}	K_{pvca}	T_{ivca}	K_{1ra}	K_{2ra}	C_{dl}	D_l	D_{ecr}	T_{ga}	T_{dret}	T_{hret}	T_{hres}
0.15	0.012	17	11.7	10	0.0004	0.85	0.7	30	30	0.37	0.065	164	0.15	0.034

a) Parameters generators in Post-Fault High/Low Frequency Scenarios

Table 5-31 Parameters of generators TP01, TP02, TP04 and TP07

S_{base}	X_d	X'_d	X''_d	T'_{d0}	T''_{d0}	X_q	X'_q	X''_q	T'_{q0}	T''_{q0}
667	1.918	0.284	0.218	7.88	0.046	1.867	0.4284	0.217	0.87	0.07

Table 5-32 Parameters of generator TP03

S_{base}	X_d	X'_d	X''_d	T'_{d0}	T''_{d0}	X_q	X'_q	X''_q	T'_{q0}	T''_{q0}
1150	1.918	0.284	0.218	7.88	0.046	1.867	0.4284	0.217	0.87	0.07

Table 5-33 Parameters of generators in HP05 and HP06

S_{base}	X_d	X'_d	X''_d	T'_{d0}	T''_{d0}	X''_q	T''_{q0}
1150	1.037	0.32	0.248	9.2	0.23	0.221	0.435

b) Parameters generators in Ultra-Low Frequency Oscillation Scenarios

Table 5-34 Parameters of generators HP01, HP02, HP04, and HP07

S_{base}	X_q	X_d	X'_d	X''_d	Td	T'_{d0}	T''_{d0}	X''_q	T''_{q0}
667	0.74	1.007	0.263	0.237	9.19	9.2	0.1	0.231	0.22

Table 5-35 Parameters of generators HP03, HP05, and HP06

S_{base}	X_q	X_d	X'_d	X''_d	Td	T'_{d0}	T''_{d0}	X''_q	T''_{q0}
1150	0.74	1.007	0.263	0.237	9.19	9.2	0.1	0.231	0.22

4) Dynamic parameters of CSEE-PFO

Table 5-36 Parameters of active power control of PVs in CSEE-PFO

T_1	K_{PUDC}	K_{IUDC}	$I_{d,max}$	$I_{d,min}$
0.02	2.0	0.1	1	-1

Table 5-37 Parameters of reactive power control of PVs in CSEE-PFO

T_r	K_{PV}	K_{PI}	Q_{max}	Q_{min}	T_V	IPF
0.02	18	5	0.436	-0.436	0.15	1

Table 5-38 Parameters of active power control of PV in CSEE-PFO

T_1	K_{PUDC}	K_{IUDC}	$I_{d,max}$	$I_{d,min}$
0.02	2.0	0.1	1	-1

Table 5-39 Parameters of active power control of type-III winds in CSEE-PFO

T_1	K_{PUDC}	K_{IUDC}	$I_{d,max}$	$I_{d,min}$
0.02	2.0	0.1	1	-1

Table 5-40 Parameters of reactive power control of type-III winds in CSEE-PFO

T_r	K_{PV}	K_{PI}	Q_{max}	Q_{min}	T_V	IPF
0.02	18	5	1.1	-1.1	0.02	1

Table 5-41 Parameters of generators in CSEE-PFO

S_{base}	X_d	X'_d	X''_d	T'_{d0}	T''_{d0}	X_q	X'_q	X''_q	T'_{q0}	T''_{q0}
733	2.38	0.336	0.251	8.61	0.6	2.32	0.485	0.247	0.96	0.066

Table 5-42 Basic parameters of HVDC in CSEE-PFO

Parameter	Value
Rated DC current (A)	5000
DC resistance (Ω)	5
DC reactance (H)	800
DC voltage (kV)	500
Ignition angle of rectifier (degree)	15
Extinction angle of inverter (degree)	17

Table 5-43 Parameters of HVDC control in CSEE-PFO

G_{max}	T_{amax}	γ_{ref}	γ_{min}	K_{pvca}	T_{ivca}	K_{1ra}	K_{2ra}	C_{dl}	D_l	D_{ecr}	T_{ga}	T_{dret}	T_{hret}	T_{hres}
0.15	0.012	17	11.7	10	0.0004	0.85	0.7	30	30	0.37	0.065	80	0.15	0.034

Table 5-44 Parameters of synchronous condensers in CSEE-PFO

S_{base}	X_d	X'_d	X''_d	T'_{d0}	T''_{d0}	X_q	X'_q	X''_q	T'_{q0}	T''_{q0}
300	1.535	0.165	0.111	8.96	0.05	1.394	0.317	0.11	0.83	0.096