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Stability Issues of Smart Grid Transmission Line Switching

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Abstract: This paper investigates the stability issues that might arise when incorporating transmission line switching into smart grid planning and operation. To demonstrate the feasibility of line switching, we use scenarios and dynamic simulations to demonstrate system security margin and online stability issues. Results show that proper line switching can resolve system emergency and boost system security margin, even though less transmission lines are used. Also it reveals that small signal instability can be triggered by line switching. It is necessary to apply sophisticated voltage controls and power system stabilizers (PSS) to avoid triggering rotor angle and voltage small signal instability for full benefits of line switching.

Keywords: Line switching, small signal stability, smart grid, PID control, PSS.

1. INTRODUCTION

Recently, multiple national and worldwide directives are called for the development of a smarter electrical grid. This includes, but is not limited to, the development of advanced transmission technologies as well as optimizing the use of transmission [1]. Benefits of treating transmission lines as controllable assets and incorporating transmission switching into power system operations are manifold. It has been shown in [2] that by dispatching transmission lines together with generation, a 25% saving in dispatch cost can be achieved. In [3] it is pointed out that corrective transmission switching can be used to improve the reliability of the grid as well as the operational efficiency. Moreover, paper [4] shows that transmission switching is effective for load shedding recovery under emergency and contingency situations.

The above studies that established the merits of transmission line switching are based on steady state and optimization study. However, frequent transmission line switching introduces disturbances to large power systems that may cause stability problems [5-7]. The potential stability issues can be classified into two categories. The first category is on the security margin of the switched systems: since the switched lines reduces transmission resources, does it result in a system with less stability margin? And the other category is on the online stability issue: will line switching actions itself cause system instability; and can conventional power system controls stabilize the system during online switching?

To give insights on the first issue, we built up a 9-bus three area system to show that in an emergency scenario, one proper line switching can relieve line overflows and bring the system back into normal state. In addition, the switching also boosts the transient stability margin of the system. This demonstrates that switching off transmission lines can improve system stability margin if done properly.

To investigate the second issue, we took a set of nine transmission switching actions proposed on the IEEE 118 bus system [8] and simulate the system dynamic response while switching off the lines one by one. Results show that with improper voltage controls, poorly damped rotor angle and voltage oscillations can be triggered by line switching, and system can become small signal unstable after switching off several lines when the load is heavy. Results also show the effectiveness of using PID controller in the voltage regulator together with Power System Stabilizer (PSS) to damp down the oscillations and keep the system small signal stable for various loadings. This reveals the importance of proper controls to better accommodate transmission switching.

This paper is organized as follows. In section 2, the 9-bus system is introduced and the stability margin is compared between the pre-switched and the switched system. In section 3, line switching simulation based on IEEE 118 bus system is presented. Impact of line switching on system online stability is shown. In section 4, use of sophisticated voltage controls to better accommodate line switching is investigated.

2. STABILITY MARGIN ASSESSMENT OF THE SWITCHED SYSTEM

2.1 System model description

Topology of the 9-bus 3-area system which resembles the interconnected power system in the western U.S. and Canada, designated as the Western Systems Coordinating Council (WSCC) can be seen from Fig. 1. The areas are denoted as top area, left area and right area. Line data, generation data and load data for the 9-bus system are shown in Appendix A, together with generator parameters and the exciter model. We assume the generators share the same per unit parameters with different MVA bases and the same excitation system with the same control parameters was applied to each generator. Governor was not applied in the simulation since no generation re-dispatch was involved.

2.2 Scenario description and power flow solution

In an emergency situation, due to unexpected loss of wind generation in the right area, overflows occurred on the tie lines between the left and right area. This is shown in Fig. 1. With no other control options, the load at bus Right2 must be shed by 13% to reduce the tie line flows to their limit. However, we demonstrate that by switching off the tie line between bus Top5 and Right1, line overflows can be relieved without any load shedding. The system power flow solution after switching off the tie line is shown in Fig. 2. Also, the real power loss is reduced for all the three areas (shown in table 1) because of reduced wheeling effect by switching off the tie line. The tie line real power losses are divided evenly into nearby areas when we calculate area real power losses.

Moreover, after switching off the tie line, the system came back to normal state directly from the emergency state (if the requirement to keep the same system topology is no longer a part of normal state definition, which needs to be modified for smart grids with topology controls) with N-1 criterion satisfied, which means the system can withstand the loss of one more line or generator without violating any constraints.

2.3 Stability margin comparison between the two systems

Dynamic simulation using PSS/E was performed to check whether the system can settle down after the tie line switching. Representative results of relative rotor angles and bus voltages are shown in Fig. 3 and 4. It can be seen that the system settles down nicely after the tie line switching without causing any stability issues. Thus it is feasible to switch off the tie line to resolve the system emergency.

To compare the stability margin of the system after tie line switching with that of the emergency system, a three phase solid fault was simulated on one tie line between Top2 and Left1 and very close to Top2. The fault was applied at t=2s and the tie line was taken out at different times to simulate system dynamic behaviour with different fault clearing time.

Critical fault clearing time (CCT), which is defined as the maximum fault clearing time allowed without losing synchronism between synchronous machines, was obtained for both cases based on the simulation results shown in Fig. 5 and 6. The CCT for the emergency system is between 0.28s and 0.29s while between 0.29s and 0.3s for the switched system. This indicates that after line switching, the system's transient stability margin is marginally improved.

Concluded from this scenario, switching lines alone, if done properly, can resolve system emergency and bring the system back into normal operating state with N-1 criterion satisfied. Also, system stability margin after switching off lines can be improved from the original system. Less transmission resources does not imply less security margin.

Table 1. Real power loss comparison

	Area Real Power Losses		
	Top	Left	Right
All tie lines on	9.19	1.89	2.95
Tie line Top-Right off	8.55	0.25	1.13
Loss reduction %	7.0	86.8	61.7

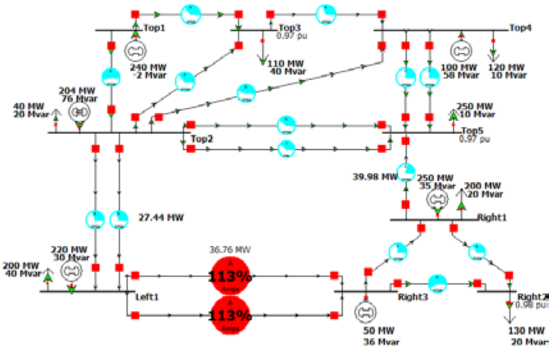

Fig. 1. Tie line overflows due to loss of wind generation.

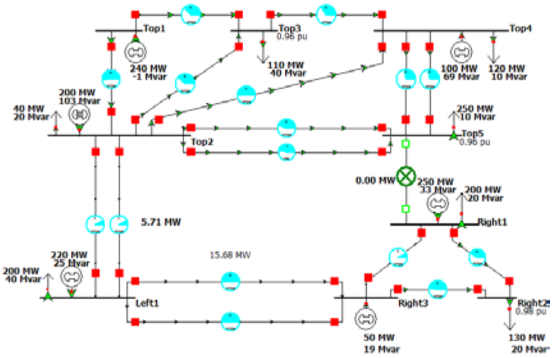

Fig. 2. Tie line overflows relieved by line switching.

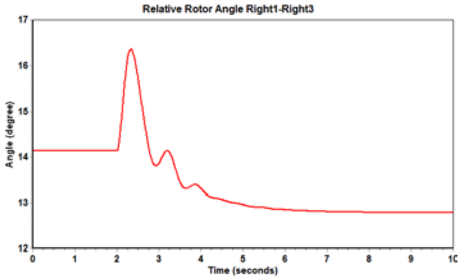

Fig 3. Relative rotor angle plot following line switching.

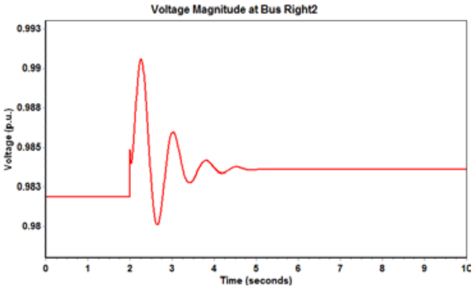

Fig 4. Bus voltage plot following line switching.

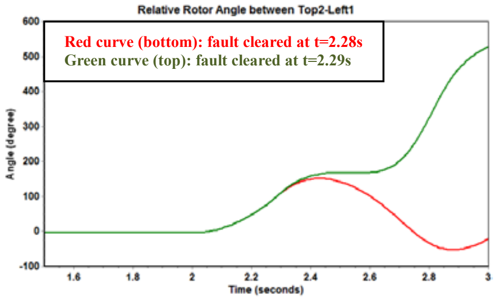

Fig 5. Relative rotor angle plot for the emergency system.

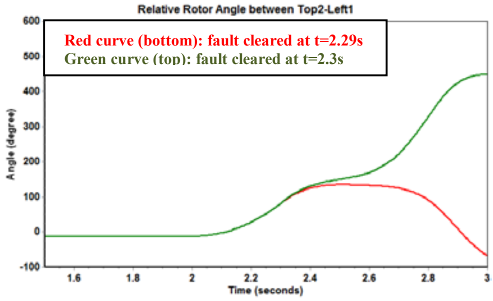

Fig 6. Relative rotor angle plot for the switched system.

3. ONLINE STABILITY ISSUES OF LINE SWITCHING

In the planning phase, generation dispatch together with system topology can be optimized to minimize generation cost with a certain load profile, as is proposed in [2]. Since the optimized topology and generation dispatch plan may be different for different load profiles, when the forecasted load profile changes, system will transit from one planned optimal state to another by means of line switching and generation re-dispatch. The question to be investigated here is whether the system can survive the transition phase and settle down to the new optimal state within a certain time period. If the system can settle down without causing stability issues, then system can benefit from considering topology change in planning.

3.1 System model

The IEEE 118-bus test case was used in the study. Data of the test system was downloaded from reference [8], with some modifications as described in [2]. The system consists of 118 buses, 186 transmission lines, 19 committed generators with a total capacity of 5,859 MW, 35 synchronous condensers, and 99 load buses with a total demand of 4,519 MW.

3.2 Line Switching scenario

Assume the system was initially working at the state where all lines were in service and only generation dispatch was optimized with a total cost of $2,054/h [2]. Then 9 lines were switched off one by one and the generation was re-dispatched at last to reach the state where generation cost was reduced by 22.3%. Generation cost in both cases was calculated in the DC optimization framework without considering power loss.

The set of line switching solution (shown in Appendix B) was obtained with a slight modification of the algorithm presented in [4]; specifically, the objective function was changed to the cost minimization function (as opposed to a load shed recovery function) proposed in [2]. The advantage of using the algorithm in [4] is that it provides a specific schedule to make the line switches one at a time; while the approach in [2] gives only a set of lines to switch without providing a switching sequence. Based on the switching sequence, lines were switched off one by one with 10 seconds in between till the optimal topology was reached (10 seconds is chosen to allow enough time for the breaker to operate and transients to damp down), then the generation was re-dispatched at last to optimize the total generation cost. The initial and final generation dispatches are shown in Appendix B.

3.3 Impact of line switching and associated generation re-dispatch on system stability with fundamental controls

Dynamic behaviour of the system can be quite different with the same set of line switching and generation re-dispatch when system loading is different and when different types of controls are applied in the system. To begin with, we limit our study using fundamental excitation control and simulate system dynamic behaviour with different loading levels. To simplify our presentation and analysis, we assume that the same excitation control system with the same control parameters was applied to each synchronous machine and the generators were equipped with the same type of governors with different real power output limit. Also, the synchronous machines share the same per unit parameters with different MVA bases. Synchronous machine parameters and control models and parameters are shown in Appendix B.

The switching and dispatch solution described in section 3.2 was derived from the base case with a total of 4519 MW real power load, which is defined as 100% loading case. Higher loading situations (110% through 150% loading) were achieved by increasing load at each bus proportionally. The real power generation limit of each generator and line transmission limits were also increased proportionally. As a result, for each loading situation, the same set of line switching solution was proposed and the proposed generation dispatch amount for each generator was increased from the base case with the same percentage as the increase of the load. This is due to the linear nature of DC optimization.

For each loading situation, PSS/E was used to simulate system dynamic response following each line switching and the final generation re-dispatch. Constant impedance load was used in the simulation. And the generation re-dispatch was carried out at once without considering generator ramp constraint, which served as the worst case study and speeded up the computation.

With 100% loading, following each line switching and the generation re-dispatch, the low frequency oscillations in rotor angles and in voltages were damped down properly and the system reached the optimal state fairly easily. Representative rotor angle and voltage plots are shown in Fig. 7 and 8. Note that the first line was switched off at t=2s.

When the system loading went higher, magnitudes of the oscillations became higher and damping of the oscillations became worse. Oscillations with increasing magnitude in rotor angles and voltages began to appear when system loading was increased to 140%, which implies small signal instability of the system after switching off the second line. In Fig. 9 and 10, simulation results following the first three line switching are shown and compared between 130% loading and 140% loading situation. In Fig. 10, the green curve was shifted up by three degrees for a better view.

From the simulation results, it can be concluded that with rudimentary excitation control, when system loading is high, small signal instability can be triggered by line switching, which will make the switching plan unsuccessful and thus prevent the system from reaching the planned optimal state, even though the power flow solution exists.

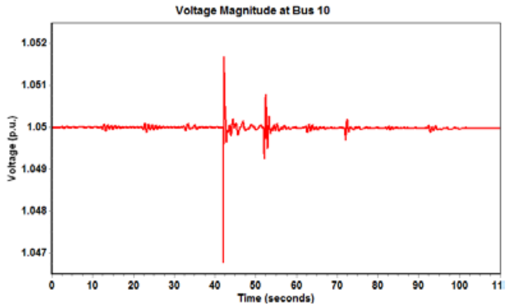

Fig 7. Bus voltage plot with 100% loading.

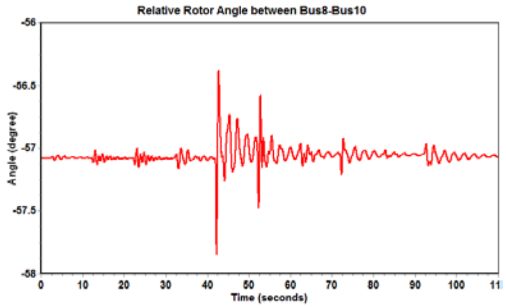

Fig 8. Relative rotor angle plot with 100% loading.

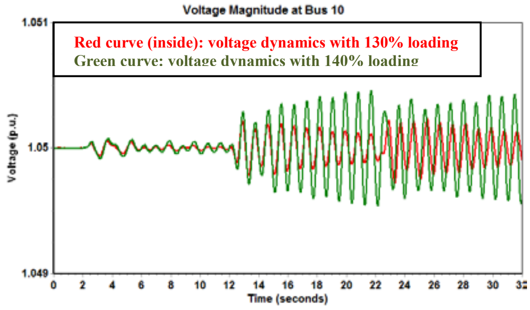

Fig 9. Bus voltage plot after the first three switching.

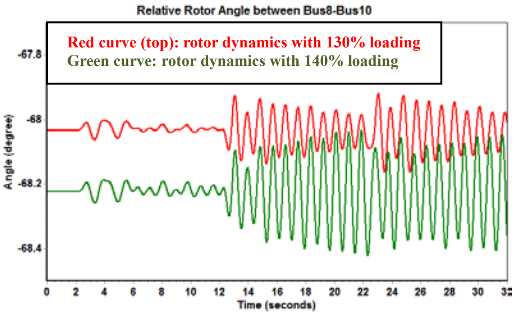

Fig 10. Relative rotor angle plot after the first three switching.

4. SOPHISTICATED VOLTAGE CONTROLS

Since poorly damped rotor angle and voltage oscillations can be triggered by line switching and generation re-dispatch, and system can become small signal unstable after the change of system topology, in this section, we investigate the influence of sophisticated voltage controls on system dynamic behavior and explore the possibility of applying sophisticated voltage controls to better accommodate line switching into planning and operation. Control models and parameters used in this section are shown in Appendix B.

4.1 Impact of low-pass filter in voltage regulator

Fig. 11 and 12 show representative voltage and relative rotor angle plots with 140% loading when a low-pass filter (LPF) is added to each voltage regulator. It can be seen that the system remain small signal stable after each switching and generation re-dispatch with 140% loading. However, the oscillations are still poorly damped. Moreover, with loading increased to 150%, system become small signal unstable after switching off the 9th line, as can be concluded from Fig. 13.

4.2 Impact of PID control in voltage regulator

With both PID control and a low pass filter applied in each voltage regulator, the oscillations in voltages and rotor angles were damped down better, and the system was able to withstand the switching and dispatching disturbances with up to 150% loading, as is shown in Fig. 14. The impact of I controller is to maintain generation bus voltage at the scheduled value. Fig. 15 compares the voltage magnitude plot at bus 77 with and without I-controller (either PID control or PD control was applied). I-controller in this case boost the steady state bus voltage and keep it as scheduled.

4.3 Impact of Power System Stabilizer

In addition to low-pass filter and the PID control, Power System Stabilizer (PSS) is effective to damp down the oscillations in both voltages and rotor angles. After adding PSS to all the synchronous machines, oscillations caused by switching disturbances are damped down nicely, as can be seen in Fig. 16 and 17.

Concluded from section 4, PID control in voltage regulator together with a low-pass filter, if well-tuned, can help to mitigate the small signal stability issue as well as maintaining the scheduled voltage profile of the system. Also, results prove the effectiveness of applying PSS to further damp down the oscillations caused by line switching. With proper voltage controls present in the system, line switching can be carried out to gain full benefits such as reducing the generation costs without worries on small signal instability.

5. CONCLUSIONS

As a beneficial tool to be incorporated into power system planning and operation, transmission line switching may cause undesirable disturbances into the system. System stability is undoubtedly a big concern to carry out frequent transmission line switching. This paper reveals the potential small signal instability issue that can be caused by transmission line switching and proves the effectiveness of using conventional voltage controls to remedy the issue. This paper also gives insights on how security margin of the system can be improved instead of harmed by switching off transmission lines. Even though the conclusions are based on case studies and there are remaining open questions such as whether the existing controls need to be upgraded and whether the control parameters need to be tuned periodically to better accommodate line switching, this paper establishes the feasibility of transmission line switching from system stability perspective. Transmission line switching can be beneficial to the system without damaging system security margin or causing stability issues if it is done properly with enough needed controls well tuned in the system.

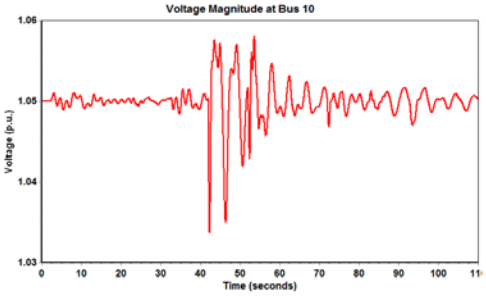

Fig 11. Bus voltage plot with 140% loading (LPF).

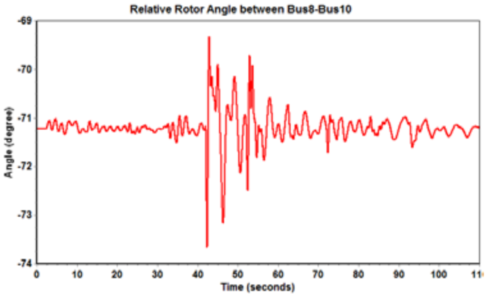

Fig 12. Relative rotor angle plot with 140% loading (LPF).

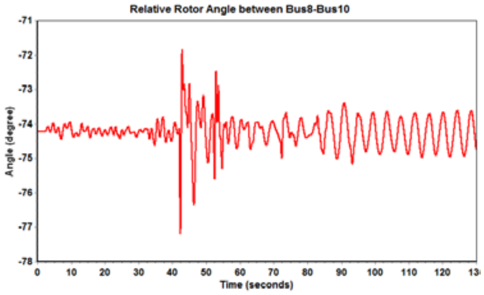

Fig 13. Relative rotor angle plot with 150% loading (LPF).

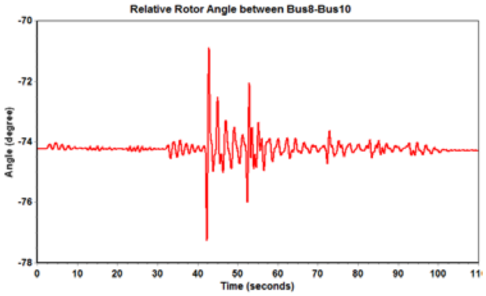

Fig 14. Relative rotor angle plot with 150% loading (PID).

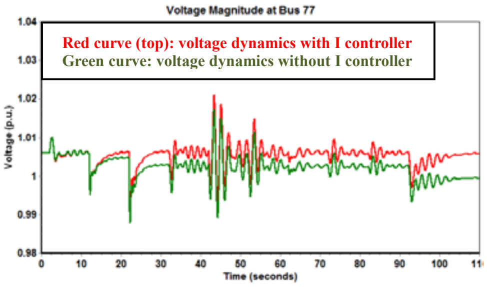

Fig 15. Voltage plot with 150% loading (PID/PD).

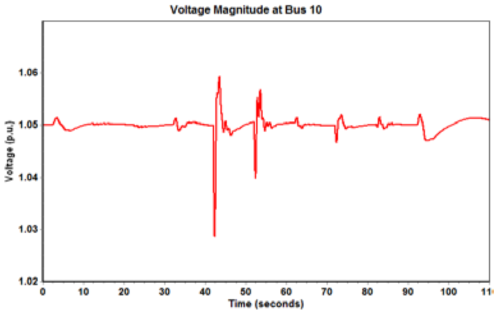

Fig 16. Voltage plot with 150% loading (PSS).

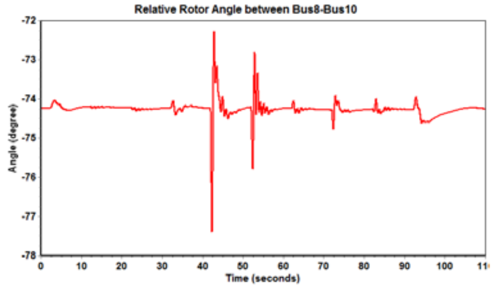

Fig 17. Relative rotor angle plot with 150% loading (PSS).

6. ACKNOWLEDGMENT

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Appendix A. POWER FLOW DATA AND DYNAMIC PARAMETERS USED IN THE 9-BUS SYSTEM

Generation data:

Bus Name	Top1	Top2	Top4	Left1	Right1	Right3
Set Voltage (p.u.)	1.0	1.0	1.0	1.0	1.0	1.0
P Dispatch (MW)	240	slack	100	220	250	50
MVA base	278	278	122	256	289	67

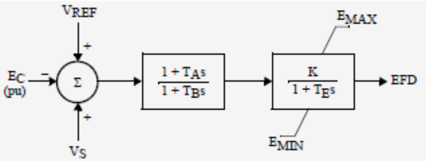
Load data:

Bus Name	Top1	Top2	Top3	Top4	Top5	Left 1	Right 1	Right 2	Right 3
P load (MW)	0	40	110	120	250	200	200	130	0
Q load (MVar)	0	20	40	10	10	40	20	20	0

Line data:

From Name	To Name	Circuit	R	X	B	LimA MVA
Top1	Top2	1	0.025	0.1	0.02	260
Top1	Top3	1	0.01	0.2	0.02	300
Top2	Top3	1	0.01	0.2	0.04	120
Top2	Top4	1	0.01	0.2	0.04	160
Top2	Top5	1	0.01	0.4	0.03	170
Top2	Top5	2	0.01	0.4	0.03	170
Top3	Top4	1	0.01	0.15	0.02	150
Top4	Top5	1	0.01	0.3	0.05	180
Top4	Top5	2	0.01	0.3	0.05	180
Top2	Left1	1	0.08	0.2	0.04	100
Top2	Left1	2	0.08	0.2	0.04	100
Top5	Right1	1	0.08	0.2	0.04	200
Right3	Left1	1	0.08	0.2	0.04	35
Right3	Left1	2	0.08	0.2	0.04	35
Right2	Right1	1	0.01	0.1	0.02	150
Right3	Right1	1	0.01	0.1	0.02	150
Right3	Right2	1	0.01	0.1	0.02	150

Exciter model:



Exciter parameters:

Parameter	T_a / T_b	T_b	K	T_E	E_{min}	E_{max}
Value	1	1	100	0.1	0	6

Generator dynamic parameters:

Parameter	T_{d0}'	T_{d0}''	T_{q0}'	T_{q0}''	H	D	X_d	X_q
Value	6	0.05	1	0.05	3	0	1.4	1.35
Parameter	X_d'	X_q'	$X_d''=X_q''$		X_l	$S(1.0)$	$S(1.2)$	
Value	0.3	0.6	0.2		0.1	0.03	0.4	

Appendix B. MODELS AND PARAMETERS USED IN ONLINE STABILITY STUDY

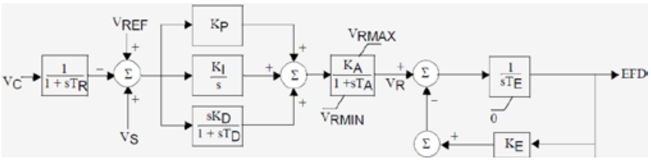
Proposed line switching sequence:

Sequence	1st	2nd	3rd	4th	5th
Line Switched off	89-91	77-80	79-80	94-95	38-65
Sequence	6th	7th	8th	9th	
Line Switched off	42-49	70-74	45-49	59-61	

Proposed generation dispatch:

Generation bus No.	Initial Generation (MW)	Final Generation (MW)	Generation Cost ($/MWh)
10	550	550	0.217
12	0	0	1.052
25	271.8075	320	0.434
26	414	414	0.308
31	0	0	5.882
46	0	0	3.448
49	304	304	0.467
54	0	0	1.724
59	0	0	0.606
61	0	45.03254	0.588
65	491	491	0.2493
66	492	492	0.2487
69	805.2	805.2	0.1897
80	577	577	0.205
87	70.71836	9.942184	7.142
92	0	0	10
100	352	352	0.381
103	140	140	2
111	51.21112	18.82527	2.173

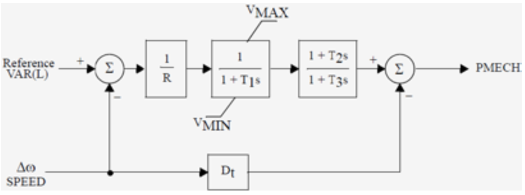
Exciter Model:



Exciter parameters:

Fundamental Control	Parameter	K_P	K_A	K_E	T_E	V_{min}	V_{max}
	Value	6	0.05	1	0.05	3	0
Low Pass Filter	Parameter	K_A			T_A		
	Value	1			10		
PID Control	Parameter	K_P		K_I		K_D	T_D
	Value	100		10		100	0

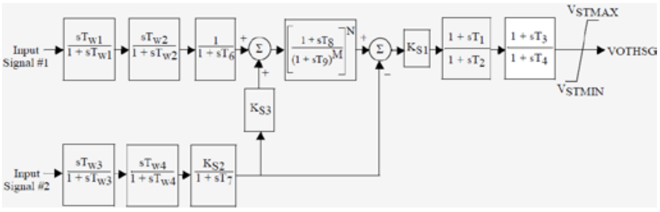
Turbine Governor Model:



Turbine Governor parameters:

Parameter	R	T_1	V_{MAX}	V_{MIN}	T_2	T_3	D_t
Value	0.05	0.049	0.833	0	1.5	5	0

PSS Model:



PSS parameters:

Input signal #1: Rotor speed deviation (p.u.)

Input signal #2: Generator electrical power (p.u.)

Parameter	T_{w1}	T_{w2}	T_6	T_{w3}	T_{w4}	T_7	K_{S2}	K_{S3}	T_8
Value	2	2	0	2	0	2	0.3065	1	0.5
Parameter	T_9	K_{S1}	T_1	T_2	T_3	T_4	V_{STMAX}	V_{STMIN}	
Value	0.1	10	0.15	0.25	0.15	0.03	0.1	-0.1	

Generator dynamic parameters:

Parameter	T_{d0}'	T_{d0}''	T_{q0}'	T_{q0}''	H	D	X_d	X_q
Value	4.621	0.034	0.367	0.07	3.263	0	1.936	1.876
Parameter	X_d'	X_q'	$X_d''=X_q''$		X_l	$S(1.0)$	$S(1.2)$	
Value	0.37	0.568	0.246		0.203	0.064	0.261	