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FORCE GENERATOR TRIPPING SCHEME USING TRANSIENT STABILITY INDEX, ACCELERATING POWER, AND SIPS

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ABSTRACT
Upon the occurrence of out-of-step (OOS) phenomena due to severe fault in the system, it is advisable to initiate force generator tripping as soon as possible within a few cycles while maintaining system stability. Due to this requirement, a fast OOS detection method is the most critical criterion. This paper analyses system behavior at selected study area in 790 Bus Test System Network using PSSE software to justify that TSI COI Speed can serve as an indicator to detect OOS at early stage in order to initiate Force Generator Tripping Scheme (FGTS). In this paper, TSI COI Speed and Accelerating Power are used as a new technique to be implemented in FGTS; a complete algorithm is developed that can detect OOS, initiate FGTS, calculate the amount of MW quantum to force trip generator, determine which generator and the most suitable location to force trip generator, evaluate on the effectiveness of FGTS, and initiate contingency action to take if OOS still exists in the system.

KEYWORDS: Out-of-Step detection, Force Generator Tripping Scheme, System Integration Protection Schemes, Area-Based Transient Stability Indexes: COI Angle and COI Speed, Accelerating Power.

I. INTRODUCTION
The existence of dynamic loads in the system will affect rotor angle and speed of generators during steady state and abnormal conditions [1]-[3]. It is important to look into various possible ways to preserve system stability by taking early precaution before the system plunges out of its limiting condition and runs out of synchronism. Anticipating the correct amount of mechanical power when the system is at steady state and when it is subjected to disturbances would minimize supply interruption and hence maintain system stability [4]. Generator can be transiently unstable when there is a large variation of input power either due to sudden increase in the input power to generator or system fault, especially when the system is subjected to severe system fault [5]-[9]. The response of a power system to a disturbance depends on the initial operating state of the system, the severity of the disturbance, the actions of protective relays and other power system controls. Severe fault on power system followed by its isolation from the system will cause variations in its critical parameters such as large separation of generator rotor angles, large swings of power flows, large fluctuations of voltages and currents, and finally loss of synchronism between groups of generators or between connected neighboring utility systems [10]. This unstable power swing can be classified based on the three characteristics of the separation interface tie-lines [11]: first, the active power on these lines crosses zero and oscillates periodically; second, the existence of out-of-step center point on the separation interface, whose voltage fluctuation amplitude is significantly larger than that of other points; last, the reactive power flows into the interior from both sides of the separation interface.

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II. MATERIAL AND METHODS

Power System Stability Analysis

Some of the methods used for power swing detection are measuring critical parameters using the synchrophasor measurement technique [7]; estimating the swing center voltage and its rate of change [8]; using probabilistic system index of transient stability [12]; measuring the rate change of resistance or impedance [13]; monitoring the unbalance power [14]; applying system integrity protection schemes (SIPS) [15], and monitoring Area-Based COI-Referred Transient Stability Index [16]. Power swing tripping must be set using data obtained from general stability studies by varying the system condition, creating the boundary equivalents, and determining the suitable place to apply the scheme and separating the system [17]. Reference [18] detects OOS based on direct correlation of power angle and modelable voltage in the point of minimal voltage (PMV), which is the projection voltage vector at the point of OOS protection. When a generator pole slips, it is desirable to disconnect it from the utility supply as quickly as possible, thus preventing possible damage to the generator, disturbance to the local power system, and system instability.

Force Generator Tripping Scheme

Reference [5] introduced transient stability emergency control based power switching using energy balance concept with respect to rotor angle and speed but not using synchrophasor measurement. A new multi-agent power system stability enhancement scheme is proposed by [12] based on the on-line measurements of generators' rotor angles and electrical powers of a multi-machine power system. The unstable units are predicted using the prediction agent applying the control agent to the most disturbed unit, which is identified by the power mismatch technique to establish the stability of the system. The prediction agent requires no prior knowledge of the system parameters except for the on line generators' rotor angles measurements. The stability behavior of the system is studied before, during and after initiation of the control agent. However, this method is not fully matured yet since more research work is needed to develop a multi-agent technique that will operate fast enough to maintain synchronism of all generators in the system. Reference [14] compares the original and controlled system as emergency control based on power switching using synchrophasor measurement. This transient stability emergency control based power switching uses energy balance concept with respect to rotor angle and speed. Referring to its findings, certain fault has delayed generator tripping due to the time consumed by the iteration of the algorithm. In some cases the tripping times in reference [14] are higher than the recommended time given by reference [15].

Force generator tripping scheme is introduced in reference [15] using SIPS; however, since the scheme is implemented on 2 area system with only 2 generators so there is no issue of which generator to force trip. Another method is proposed by [19] to prepare for a look-up table for generator trip arming using off-line time domain analysis through tracking and screening simulated rotor angles and electric power. Rotor angles are monitored to determine system stability condition; electric power of each generator before and after disturbance is compared to determine the most appropriate generator to trip. Out-of-step tripping schemes are designed to protect the power system during unstable conditions, isolating unstable generators or larger power system areas from each other with the formation of system islands, in order to maintain stability within each island by balancing the generation resources with the area load. OOS tripping systems must be applied at preselected network locations, typically near the network electrical center, and network separation must take place at such points to preserve a close balance between load and generation [9].

This research work analyzes OOS detection based on PSS®E simulation results on 790 Bus Test System Network and its simplified equivalent network on selected area as a test system. The objective of the analysis is to find the most sensitive technique to detect OOS phenomena that can be incorporated with synchrophasor technology and force trip the most suitable and effective generator to bring the system back to steady state condition. This paper introduces a new algorithm for FGTS that continuously monitors the health of the selected area of a system, detects OOS and force trips generator, determines the most suitable generator and location to force trip, and verifies the effectiveness of the FGTS using TSI COI Speed, Accelerating Power and SIPS methods.

System Integrity Protection Scheme (SIPS)

Reference [15] introduces an improvement to SIPS using synchrophasor measurements. This method is good for two-area power systems to allocate the electrical center, which is equivalent to half of the total impedance between two sources. The electrical center of the system can be at a transmission line or at any other part of the system that corresponds to half of the total impedance. SIPS requires that the location of system electrical center must be between the relays that acquire the synchrophasor measurements. The out of step protection scheme uses the positive sequence voltage synchrophasors that relays acquired at two power system busbars to calculate the angle difference between these voltages. In assessing power system stability using SIPS, the angle difference δ_k, slip frequency S_{fk}, and slip frequency acceleration A_{fk} are calculated; thus, predicting power angle of unstable conditions. A modal analysis based SIPS is then used to identify the undamped oscillations and take action before the system collapses [15].

$$\delta_k = V_{1\_Ang_k}^{Relay\ 1} - V_{1\_Ang_k}^{Relay\ 2} \qquad (1)$$

$$S_{fk} = \frac{(\delta_k - \delta_{k-1})}{360} MRATE \qquad (2)$$

$$A_{fk} = \left(S_{fk} - S_{fk-1}\right) * \ MRATE \qquad (3)$$

Where

$V_{1\_Ang_k}^{Relay\ 1}$ is the positive-sequence voltage angle of Relay 1 at the k processing interval

$V_{1\_Ang_k}^{Relay\ 2}$ is the positive-sequence voltage angle of Relay 2 at the k processing interval

S_{fk} is the slip frequency at the k processing interval

A_{fk} is the acceleration at the k processing interval

Area-Based TSI: COI Angle and COI Speed

When power system is subjected to disturbances, the synchronism assessment among generators can be made by analyzing the angular velocity in addition to checking the variation of rotor angle [2], [7], [14], [19]. The system is not stable if the rotor angle of a generator increases with respect to the rest of the system. Similarly, the angular velocity can be translated to system frequency. For a multi-machine system, Area-Based COI is a common transformation used in transient stability analysis [1], [2], [7], [14], [16]. The Area-based TSI: COI Angle and COI Speed are derived based on the swing equation [6].

$$M\frac{d^2\delta}{dt^2} = P_m - P_e = P_{acc} \qquad (4)$$

Where M is the moment of inertia of the machine, δ is the electrical power angle, P_m is the mechanical power, P_e is the electrical power, and P_{acc} is the Accelerating Power. The indexes shown in equation (5) and equation (9) relate to the rotor angle and angular speed of a particular area in a power grid and are based on an equivalent inertia representing the total inertia of the generators located in that area. The indexes are derived from the classical machine model by assuming that the dynamic behavior of generators in the system [7], [8], [14], [16]. If the indexes calculated show an out of step condition after the fault is cleared, the system is considered to be in an unstable condition. In addition, if the referred multi-machine system is in synchronism with all the machines turning at a constant speed [2], [7], [14], the system frequency is equal to the dynamic frequency (possibly above or below the steady state speed, ω_s). The COI reference transformation defines the COI Angle and COI Speed instead of referring to the angle of a specific machine [7]. The COI reference transformation defines the COI Angle as:

$$\delta_j^{coi} = \bar{\delta}_J - \bar{\delta}_{COI} \qquad (5)$$

$$\bar{\delta}_J = \frac{1}{N}\sum_{i=1}^{N} \delta_i \qquad (6)$$

$$\bar{\delta}_{COI}(t) = \frac{1}{M_T}\sum_{j=1}^{r} M_j\bar{\delta}_j \qquad (7)$$

$$M_T = \sum_{i=1}^{r} M_i \qquad (8)$$

Where δ_j^{coi} is the TSI COI Angle, N is the number of generator, M_T is the total system inertia, δ_i is the individual rotor angle, $\bar{\delta}_J$ is the area equivalent rotor angle of each area, $\bar{\delta}_{COI}$ is the COI Angle of the system, while r is total number of areas in a power system. The COI reference transformation defines the COI Speed as:

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$$\omega_j^{coi} = \overline{\omega}_J - \overline{\omega}_{COI} \tag{9}$$

$$\overline{\omega}_J = \frac{1}{N}\sum_{i=1}^{N} \omega_i \tag{10}$$

$$\overline{\omega}_{COI}(t) = \frac{1}{M_T} \sum_{j=1}^{r} M_j \overline{\omega}_j \tag{11}$$

Where ω_j^{coi} is the TSI COI Speed, ω_i is the individual rotor speed, $\overline{\omega}_J$ is the area equivalent rotor speed and $\overline{\omega}_{COI}$ is the COI Speed of the system.

Test System

In this research work, the analysis on the behavior of power system during abnormal condition is carried out on 790 Bus Test System Network but focusing on a selected area; its equivalent network is shown in Figure 1. The analysis is focusing on the system behavior for faults that may occur on the Six Circuit that comprises of 4 lines between Bus1001 – Bus1007 and 2 lines between Bus1001 – Bus1006. Severe fault in these lines such as 6 Line Fault (6LF) may lead to unstable power swing to the two transmission lines between Bus1004 – Bus1005. Referring to Figure 1, Bus 1001, Bus1002 and Bus1003 are connected to thermal power power plants and supplying power to meet power demand in this area and also to support the demand to the rest of the grid system while Bus1004 is connected to a hydro power plant. Majority of the generated power from this area is exported to the load center of the grid system through previously mentioned Six Circuit; conversely, another two lines from Bus 1001 and Bus 1004 are leading to mostly domestic customers. The Six Circuit is considered as the main arteries connecting from the generation center to the load centers in the network, which are mostly commercials and industrials while the area beyond Bus 1004, the lines are normally carrying light load.

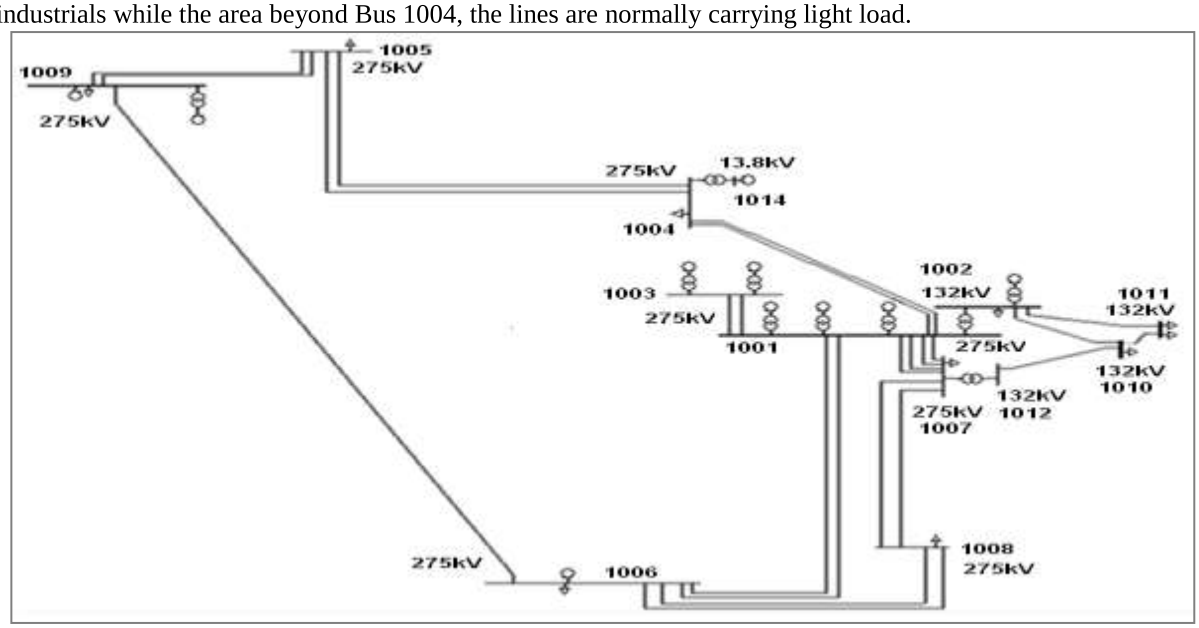

Figure 1: 790 Bus Test System Simplified Equivalent Network

Generators that are connected to Bus1001, Bus1002 and Bus1003 consist of either gas turbine (GT) or steam turbine (ST). The input power to steam turbine of each block at Bus1001 and Bus1002 very much depends on the flue gas from the other two gas turbines. Hence, reducing power generation from gas turbine will affect power generated by the steam turbine of the respective block. However, at Bus1003 due to the design of the connected plant, generator that powered by the steam turbine of each block has to shutdown if any of the gas turbine is down on outage. Bus1004 is a hydro power plant that consists of 4 generators with each generator has a maximum power generation of 100MW. Scheduling of power from these generators depends on the nature and construction of each plant. Taking into consideration on the constraint and limitation of each type of power plant, different combinations

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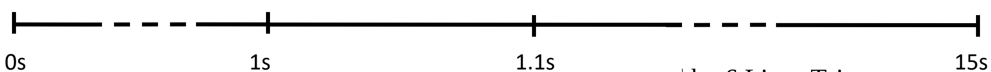
of generation scheduling were simulated to create different scenarios in order to justify the selected method of OOS detection.

III. RESULTS AND DISCUSSION

Numerous simulations were carried out on 790 Bus Test System Network for different network topologies at steady state and fault(s) conditions including different locations of fault within these significant buses: 1LF - Single line trip (Bus1001 – Bus1007); 1LF - Single line trip (Bus1001 – Bus1006); 2LF - Two parallel lines trip (Bus1001 – Bus1007); 3LF - Three parallel lines trip (Bus1001 – Bus1007); 4LF - Four parallel lines trip (Bus1001 – Bus1007); 5LF - Five lines trip (4 lines Bus1001 – Bus1007and 1 line Bus1001 – Bus1006); and 6LF - Six lines trip (4 parallel lines Bus1001 – Bus1007and 2 parallel lines Bus1001 – Bus1006) respectively. The system behaviors and response to bus fault were monitored in order to find the boundaries and segregate between stable and unstable conditions. Figure 2 shows the time line events of these faults: applying bus fault at Bus1001 at 1.0s and followed by tripping line(s) at a time delay of 100ms.



... by 6 Lines Tri

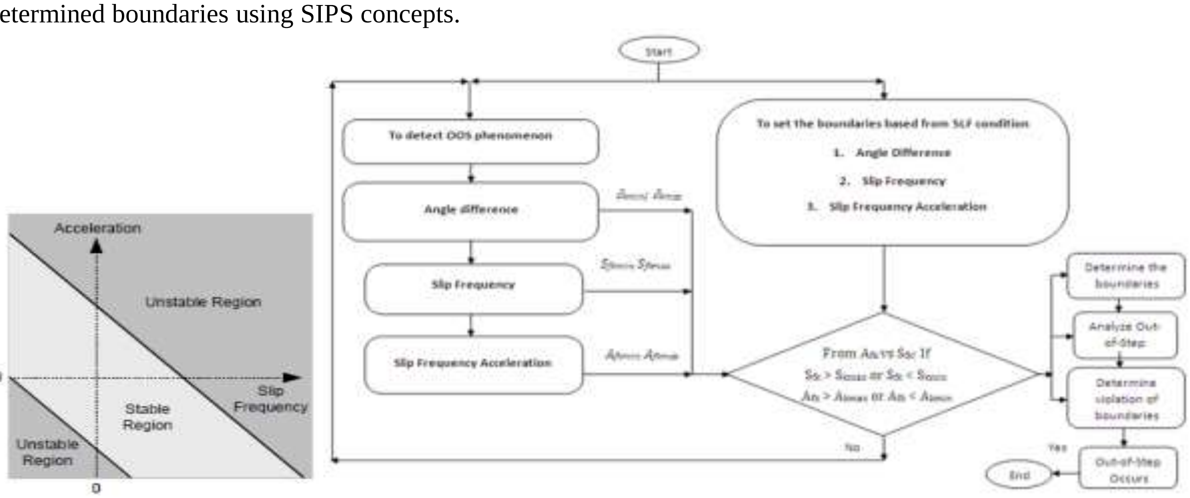
The objective of this system behavior study is to determine the most suitable boundaries to detect OOS using SIPS concept and the most suitable value of TSI COI Speed to serve as an OOS indicator that will distinguish between OOS and non OOS conditions. Out of all these seven scenarios, only 6LF will end up with an OOS condition while 5LF is declared as the boundary for the system stability.

Development of Out-of-Step Detection Algorithm Using SIPS

SIPS method is selected as a comparison to detect OOS condition when the system is subjected to fault. Based on reference [15], boundaries in the form of two straight line equations of Slip Frequency Acceleration versus Slip Frequency characteristics are set up to categorize between stable and unstable power swing as shown in Figure 3a. Referring to the simulation results for different network topologies on 790 Bus Test System Network, the most suitable boundaries to detect OOS are found to be:

- The upper boundary: Afk1 = 3.125Sfk + 15
- The lower boundary: Afk2 = 3.125Sfk – 15

Using the algorithm in Figure 3b, a MatLab program was developed to detect OOS with respect to the determined boundaries using SIPS concepts.



3a) 3b)

Figure 3: OOS boundaries [15] and the flow chart of OOS detection using SIPS based on the determined boundaries.

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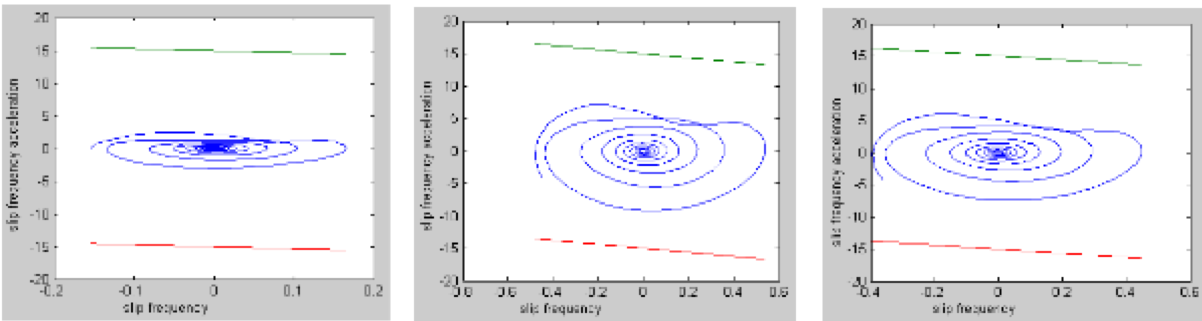
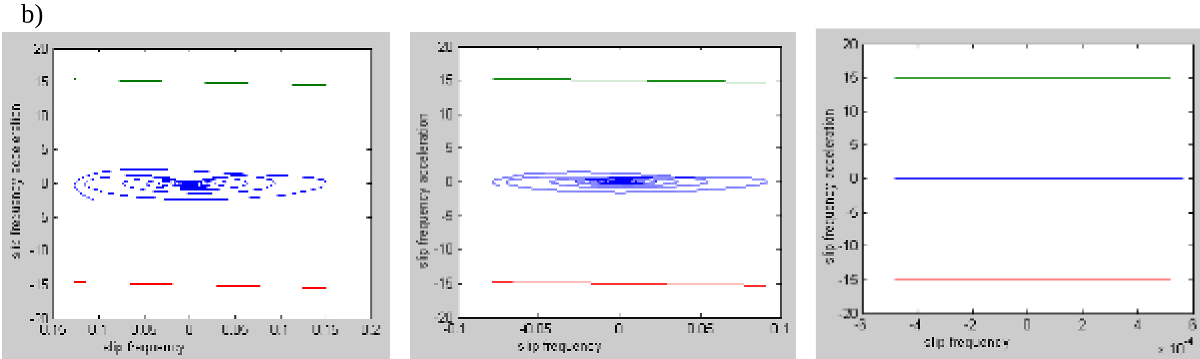
Stable conditions - Analysis using SIPS

Figure 4 shows the slip frequency acceleration versus slip frequency graphs for a fault that the system can still maintain its stability. The graphs oscillate with small radius and within the boundaries at all monitored locations.



a) Between Bus1004 – Bus1005
b) Between Bus1001 – Bus1006
c) Between Bus1001 – Bus1007
b)



d) Between Bus1001 – Bus1002
e) Between Bus1001 – Bus1004
f) Between Bus1001 – Bus1003

Figure 4: Slip Frequency Acceleration versus Slip Frequency Characteristics at Monitored Locations for a Scenario without OOS

Stable conditions: Analysis using TSI COI Angle, TSI COI Speed, and Accelerating Power

The oscillations in TSI COI Angle, TSI COI Speed and Accelerating Power are low and approaching stability for 5LF at all the monitored buses as shown in Figure 5. Among the 4 monitored buses, Bus1001 has the least oscillation followed by Bus 1003 and Bus1002 while Bus 1004 oscillates the most. When fault occurs, the faulted lines will be completely isolated from the system, which is as good as removal of load from the generator; as a result, there will be an unbalance between power generated and demand that will yield to accelerating power. If the fault is not severe, the generators manage to continue operating in synchronism though some of them may not settle at their respective initial operating angle during the post fault condition. It is found that the magnitude of TSI COI Angle, TSI COI Speed and Accelerating Power (P_m – P_e) depend on the severity of the fault.

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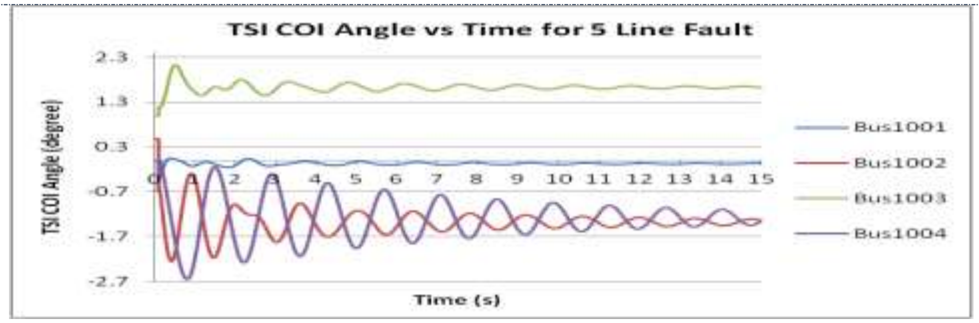
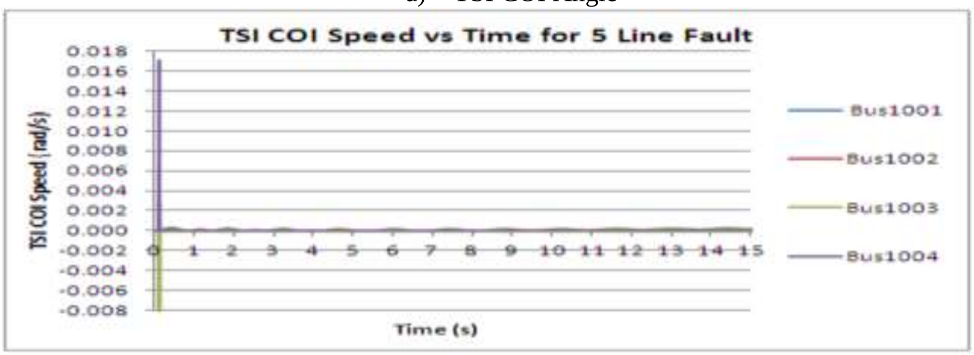
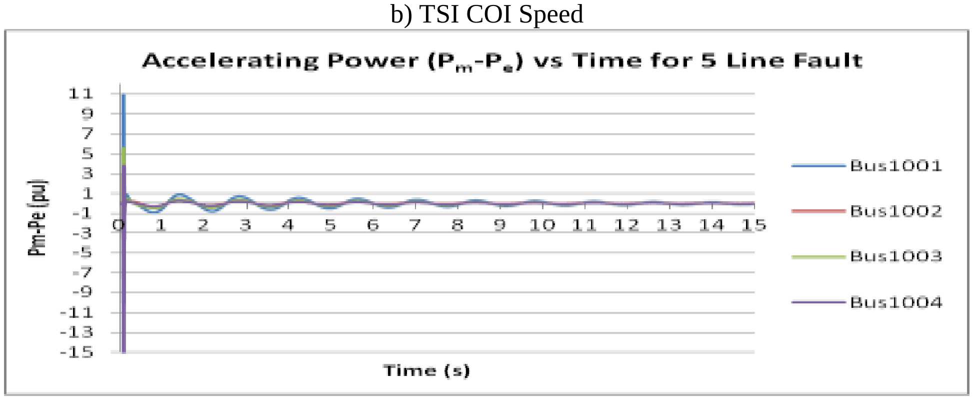


a) TSI COI Angle



b) TSI COI Speed



c) Accelerating Power (Pm – Pe)

Figure 5: System Behavior at Monitored Buses due to 5 Line Fault (5LF); trip line(s) at 0.1s

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Unstable Condition – Analysis using PSSE simulation results

When 6LF occurs in the system, all the six lines connecting from Bus1001 to Bus1007 and Bus 1006 respectively are completely isolated from the system. Generated power from this area will swing to Bus1004 and force to flow through the two remainder 275kV transmission lines that feeding the light load area. Another

lternative route would be to Bus1011, which leads to Bus1010 connecting to moderate loads but important customers and other 132kV loads within that area as shown in Figure 1 and Figure 6 respectively.

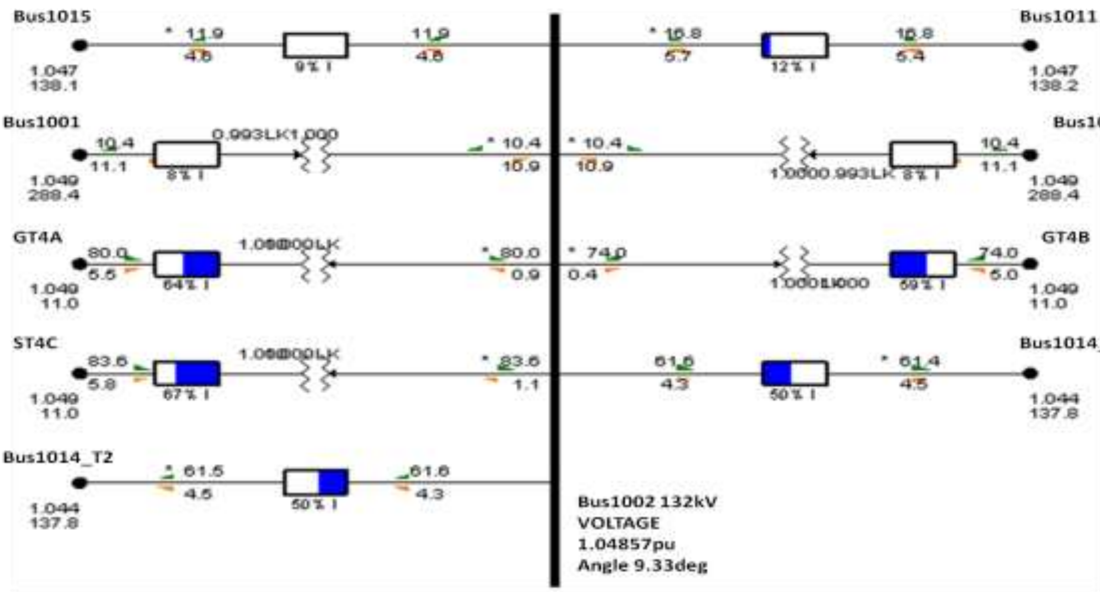


Figure 6: Power Flow to Bus1002

PSSE simulation report in Table 1 shows that the 132kV lines will sense the OOS phenomena first followed by the 275kV lines with a time lag of about 75ms as displayed in the table. If no action is taken to limit the disturbances at early stage, these phenomena will grow and spread to other weak buses and lead to cascading tripping and eventually would result to wide area interruption of power supply.

Table 1: PSSE Simulation Report

OUT OF STEP CONDITION AT TIME = 1.700s:

X------- F R O M -------X   X--------- T O ---------X

BUS#	X-- NAME --X	BASKV	BUS#	X-- NAME --X	BASKV	CKT	MW	MVAR	VOLTAGE
1010	132	132.00	1012	132	132.00	1	121.0	134.6	0.3350
1012	132	132.00	1010	132	132.00	1	-73.4	69.7	0.1874

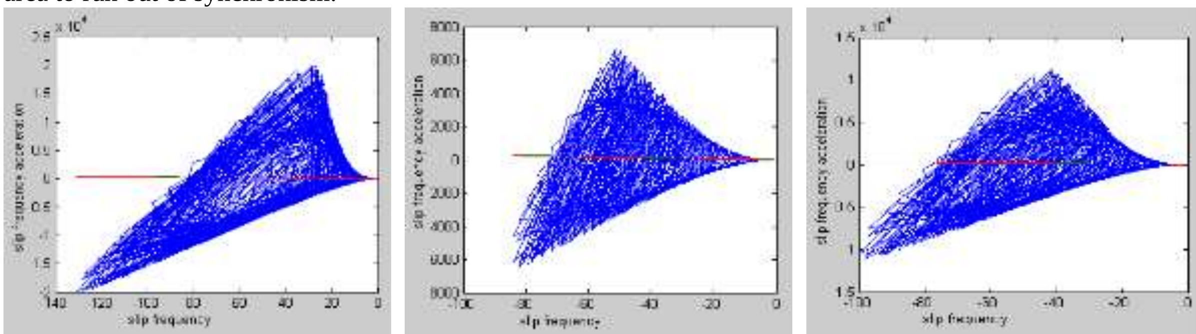
OUT OF STEP CONDITION AT TIME = 1.775s:

X------- F R O M -------X   X--------- T O ---------X

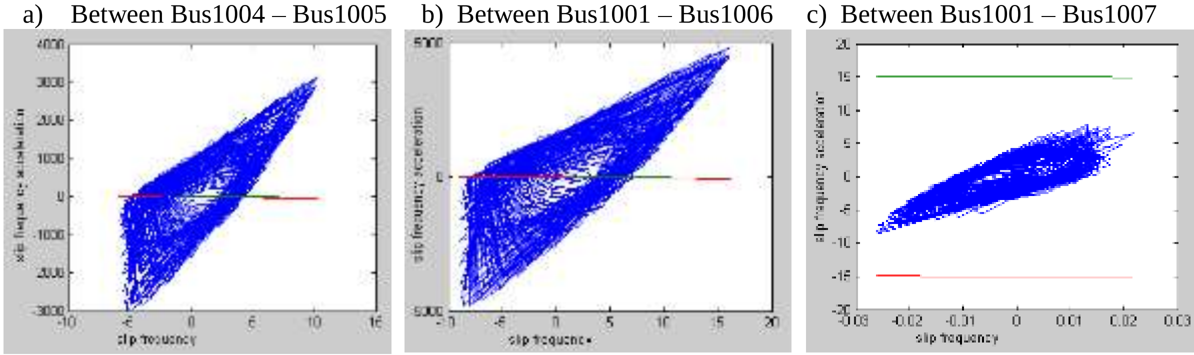
BUS#	X-- NAME --X	BASKV	BUS#	X-- NAME --X	BASKV	CKT	MW	MVAR	VOLTAGE
1010	132	132.00	1013	132	132.00	1	26.0	153.2	0.2810
1013	132	132.00	1010	132	132.00	1	8.7	35.2	0.0722
1010	132	132.00	1012	132	132.00	1	23.8	147.4	0.2810
1012	132	132.00	1010	132	132.00	1	22.2	47.5	0.0987
1005	275	275.00	1004	275	275.00	1	-277.1	201.2	0.2902

Unstable Condition - Analysis using SIPS

Comparing 6LF to 5LF as shown in the previous scenarios, the differences in system behavior are so obvious. The graphical illustrations in Figure 7 have proven that 6LF forces the system to run in out-of-step phenomena; the characteristics exceed beyond the boundaries. The fault is so severe that causes most of the generators in that area to run out of synchronism.



a) Between Bus1004 – Bus1005 b) Between Bus1001 – Bus1006 c) Between Bus1001 – Bus1007

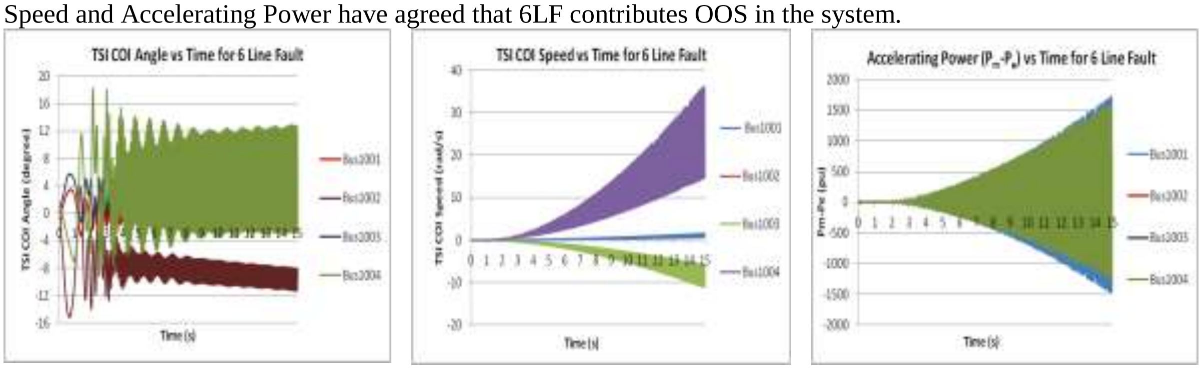


d) Between Bus1001 – Bus1002 e) Between Bus1001 – Bus1004 f) Between Bus1001 – Bus1003

Figure 7: Slip Frequency Acceleration versus Slip Frequency at Monitored Locations with OOS

Unstable conditions - Analysis using TSI COI Angle, TSI COI Speed, and Accelerating Power

Figure 8 shows system behavior based on TSI COI Angle, TSI COI Speed and Accelerating Power when 6LF occurs in the system. All the three graphical illustrations complement each other showing that the system is experiencing OOS condition: TSI COI Angle oscillates vigorously with TSI COI Speed and Accelerating Power infinitely increases at all the monitored locations. Results of all the methods used: SIPS, TSI COI Angle, TSI COI Speed and Accelerating Power have agreed that 6LF contributes OOS in the system.



a) TSI COI Angle b) TSI COI Speed c) Accelerating Power ($P_m – P_e$)

Figure 8: System Behavior at Monitored Buses due to 6LF; trip lines at 0.1s – Based on TSI COI Angle, TSI COI Speed and ($P_m – P_e$)

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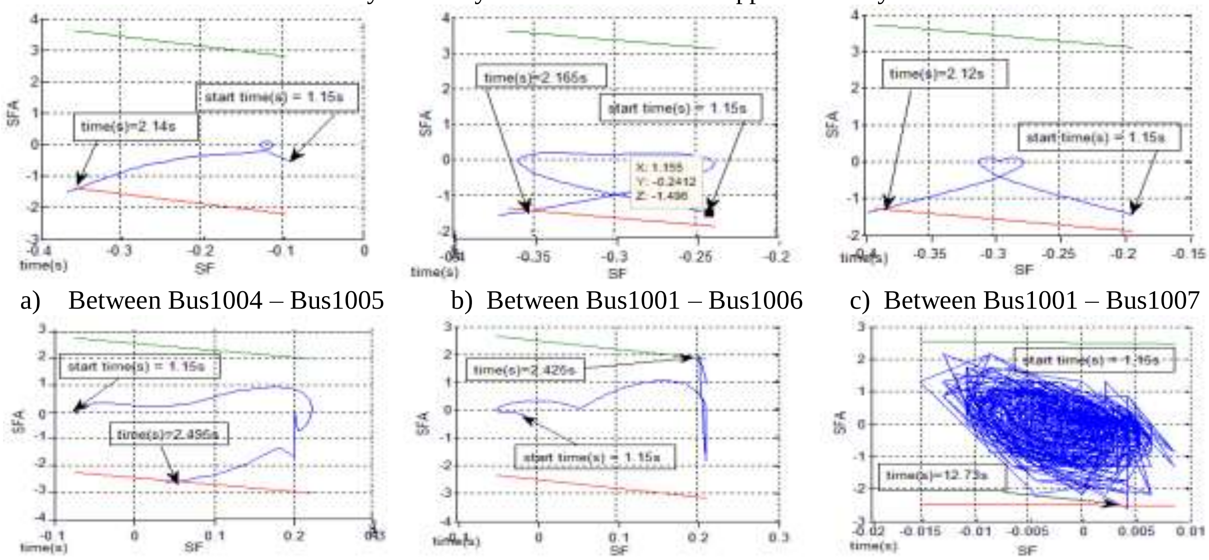
SIPS Sensitivity

Figure 9 illustrates the behavior of the Slip Frequency Acceleration versus Slip Frequency characteristic based on SIPS using the developed program to detect OOS. The figures show the time that the characteristic at each monitored location hits the stability boundary either at the lower or upper boundary.



a) Between Bus1004 – Bus1005 b) Between Bus1001 – Bus1006 c) Between Bus1001 – Bus1007

d) Between Bus1001 – Bus1002 e) Between Bus1001 – Bus1004 f) Between Bus1001 – Bus1003

Figure 9: Graphical Illustration on OOS Detection using SIPS for GSN7_100MW

Table 2 summarizes the time that the slip frequency hits the boundary and moves out from the stable region for different generation scheduling. To elaborate the table in detail; as an example, at GSN7_100MW: for Bus1004-Bus1005 the upper boundary is hit after 2.46s while the lower boundary is hit after 2.15s; for Bus1001-Bus1006 the hit time are after 3.39s and 2.18s; for Bus1001-Bus1007 after 3.00s and 2.13s; for Bus1001-Bus1002 after 2.87s and 2.50s; for Bus1001-Bus1004 after 2.43s and 2.57s and; for Bus1001-Bus1003 after 12.93s and 12.73s respectively. As a summary, it takes more than 1s after the 6LF is cleared for the OOS phenomena to be detected if SIPs were to be used, which is more than 50 cycles. Hence, it would delay the process of eliminating the OOS phenomena from the system and lead to wide area interruption.

Table 2: SIPS Results for Random Generation Scheduling GSN7_70MW – GSN7_100MW

FILENAME	OOS Status	Bus1004 - Bus1005		Bus1001 - Bus1006		Bus1001 - Bus1007		Bus1001 - Bus1002		Bus1001 - Bus1004		Bus1001 - Bus1003	
		Time above A_{fn1} (s)	Time below A_{fn2} (s)	Time above A_{fn1} (s)	Time below A_{fn2} (s)	Time above A_{fn1} (s)	Time below A_{fn2} (s)	Time above A_{fn1} (s)	Time below A_{fn2} (s)	Time above A_{fn1} (s)	Time below A_{fn2} (s)	Time above A_{fn1} (s)	Time below A_{fn2} (s)
GSN7_100MW	1	2.46	2.15	3.39	2.18	3	2.13	2.87	2.5	2.43	2.57	12.93	12.73
GSN7_90MW	1	2.73	2.43	3.67	2.45	3.28	2.39	3.15	2.78	2.7	2.82	13.62	12.32
GSN7_84MW	1	3.06	2.76	4.01	2.8	3.62	2.75	3.49	3.12	3.5	3.18	13.25	13.33
GSN7_83MW	1	3.24	2.95	4.2	2.98	3.8	2.92	3.67	3.31	3.69	3.37	13.99	13.27
GSN7_82.5M	1	3.48	3.2	4.44	3.24	4.05	3.18	3.92	3.55	3.93	3.61	14.43	13.23
GSN7_82.3MW	1	3.78	3.48	4.74	3.52	4.35	3.47	4.22	3.85	4.23	3.9	14.81	13.77
GSN7_82.2MW	0	0	0	0	0	0	0	0	0	0	0	0	0
GSN7_82.1MW	0	0	0	0	0	0	0	0	0	0	0	0	0
GSN7_82MW	0	0	0	0	0	0	0	0	0	0	0	0	0
GSN7_80MW	0	0	0	0	0	0	0	0	0	0	0	0	0
GSN7_78MW	0	0	0	0	0	0	0	0	0	0	0	0	0
GSN7_76MW	0	0	0	0	0	0	0	0	0	0	0	0	0
GSN7_74MW	0	0	0	0	0	0	0	0	0	0	0	0	0
GSN7_72MW	0	0	0	0	0	0	0	0	0	0	0	0	0
GSN7_70MW	0	0	0	0	0	0	0	0	0	0	0	0	0

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TSI COI Speed Sensitivity

The magnitude of TSI COIS Speed and Pm – Pe are monitored for scenarios with and without OOS conditions. Table 3 and Table 4 are referred; there is consistency in the behavior of TSI COI Speed magnitude especially at Bus1002: it increases as the fault gets severe. There is a significant difference between 5LF and 6LF; and it defers considerably for 6LF fault with and without OOS phenomena.

Table 3: TSI COI Speed and Accelerating Power for GSN7_70MW, Bus Fault - without OOS

a) Monitoring at Bus1001 and Bus1002

FILENAME	Bus1001						Bus1002					
GSN7_70MW	TSI COI Speed Before line fault (t=0.5s)	TSI COI Speed After line trip (t=1.19s)	TSI COI Speed (t=1.25s)	Pm - Pe Before line fault (t=0.5s)	Pm - Pe After line trip (t=1.19s)	Pm - Pe (t=1.25s)	TSI COI Speed Before line fault (t=0.5s)	TSI COI Speed After line trip (t=1.19s)	TSI COI Speed (t=1.25s)	Pm - Pe Before line fault (t=0.5s)	Pm - Pe After line trip (t=1.19s)	Pm - Pe (t=1.25s)
1LF_Bus1001-Bus1006	5.68E-14	-0.0129	-0.0263	0	-0.0981	-0.5029	5.68E-14	0.0296	0.0909	5.68E-14	0.1146	-0.3848
1LF_Bus1001-Bus1007	5.68E-14	-0.0140	-0.0271	0	-0.1665	-0.5573	5.68E-14	0.0264	0.0857	5.68E-14	0.0415	-0.4501
2LF	5.68E-14	-0.0128	-0.0261	0	-0.1548	-0.5483	5.68E-14	0.0220	0.0821	5.68E-14	0.0525	-0.4345
3LF	5.68E-14	-0.0098	-0.0234	0	-0.1308	-0.5285	5.68E-14	0.0098	0.0717	5.68E-14	0.0753	-0.4009
4LF	5.68E-14	0.0150	0.0021	0	0.0324	-0.4042	5.68E-14	-0.0919	-0.0324	5.68E-14	0.1945	-0.2303
5LF	5.68E-14	0.0379	0.0297	0	0.2515	-0.1894	5.68E-14	-0.1710	-0.1292	5.68E-14	0.3582	-0.0342
6LF	5.68E-14	0.0886	0.0936	0	0.7141	0.3429	5.68E-14	-0.3505	-0.3565	5.68E-14	0.6802	0.3920

b) Monitoring at Bus1003 and Bus1004

FILENAME	Bus1003						Bus1004					
GSN7_70MW	TSI COI Speed Before line fault (t=0.5s)	TSI COI Speed After line trip (t=1.19s)	TSI COI Speed (t=1.25s)	Pm - Pe Before line fault (t=0.5s)	Pm - Pe After line trip (t=1.19s)	Pm - Pe (t=1.25s)	TSI COI Speed Before line fault (t=0.5s)	TSI COI Speed After line trip (t=1.19s)	TSI COI Speed (t=1.25s)	Pm - Pe Before line fault (t=0.5s)	Pm - Pe After line trip (t=1.19s)	Pm - Pe (t=1.25s)
1LF_Bus1001-Bus1006	5.68E-14	-0.0124	-0.0260	0	-0.0769	-0.3949	5.68E-14	0.0377	0.0359	0	-0.0137	-0.0878
1LF_Bus1001-Bus1007	5.68E-14	-0.0135	-0.0270	0	-0.1308	-0.4377	5.68E-14	0.0492	0.0483	0	-0.0260	-0.0985
2LF	5.68E-14	-0.0123	-0.0259	0	-0.1215	-0.4302	5.68E-14	0.0481	0.0471	0	-0.0239	-0.0965
3LF	5.68E-14	-0.0093	-0.0232	0	-0.1026	-0.4144	5.68E-14	0.0462	0.0448	0	-0.0202	-0.0926
4LF	5.68E-14	0.0158	0.0027	0	0.0251	-0.3174	5.68E-14	0.0340	0.0314	0	0.0087	-0.0686
5LF	5.68E-14	0.0388	0.0306	0	0.1973	-0.1485	5.68E-14	0.0021	-0.0059	0	0.0433	-0.0312
6LF	5.68E-14	0.0895	0.0946	0	0.5606	0.2680	5.68E-14	-0.0620	-0.0848	0	0.1150	0.0564

Table 4: TSI COI Speed and Accelerating Power for GSN7_82.3MW, Bus Fault - with OOS

a) Monitoring at Bus1001 and Bus1002

FILENAME	Bus1001						Bus1002					
GSN7_82.3MW	TSI COI Speed Before line fault (t=0.5s)	TSI COI Speed After line trip (t=1.19s)	TSI COI Speed (t=1.25s)	Pm - Pe Before line fault (t=0.5s)	Pm - Pe After line trip (t=1.19s)	Pm - Pe (t=1.25s)	TSI COI Speed Before line fault (t=0.5s)	TSI COI Speed After line trip (t=1.19s)	TSI COI Speed (t=1.25s)	Pm - Pe Before line fault (t=0.5s)	Pm - Pe After line trip (t=1.19s)	Pm - Pe (t=1.25s)
1LF_Bus1001-Bus1006	5.68E-14	-0.0135	-0.0266	0	-0.0973	-0.5047	5.68E-14	0.0288	0.0908	0	0.1171	-0.3858
1LF_Bus1001-Bus1007	5.68E-14	-0.0146	-0.0273	0	-0.1675	-0.5609	5.68E-14	0.0257	0.0858	0	0.0417	-0.4530
2LF	5.68E-14	-0.0134	-0.0263	0	-0.1553	-0.5508	5.68E-14	0.0211	0.0820	0	0.0529	-0.4364
3LF	5.68E-14	-0.0103	-0.0236	0	-0.1308	-0.5316	5.68E-14	0.0087	0.0714	0	0.0758	-0.4028
4LF	5.68E-14	0.0147	0.0022	0	0.0336	-0.4059	5.68E-14	-0.0943	-0.0343	0	0.1961	-0.2308
5LF	5.68E-14	0.0378	0.0300	0	0.2552	-0.1877	5.68E-14	-0.1742	-0.1322	0	0.3617	-0.0328
6LF	5.68E-14	0.0887	0.0942	0	0.7237	0.3483	5.68E-14	-0.3551	-0.3617	0	0.6865	0.3980

b) Monitoring at Bus1003 and Bus1004

FILENAME	Bus1003						Bus1004					
GSN7_82.3MW	TSI COI Speed Before line fault (t=0.5s)	TSI COI Speed After line trip (t=1.19s)	TSI COI Speed (t=1.25s)	Pm - Pe Before line fault (t=0.5s)	Pm - Pe After line trip (t=1.19s)	Pm - Pe (t=1.25s)	TSI COI Speed Before line fault (t=0.5s)	TSI COI Speed After line trip (t=1.19s)	TSI COI Speed (t=1.25s)	Pm - Pe Before line fault (t=0.5s)	Pm - Pe After line trip (t=1.19s)	Pm - Pe (t=1.25s)
1LF_Bus1001-Bus1006	5.68E-14	-0.0129	-0.0263	0	-0.0763	-0.3966	5.68E-14	0.0424	0.0373	0	-0.0144	-0.0902
1LF_Bus1001-Bus1007	5.68E-14	-0.0141	-0.0272	0	-0.1313	-0.4404	5.68E-14	0.0538	0.0495	0	-0.0272	-0.1010
2LF	5.68E-14	-0.0129	-0.0261	0	-0.1220	-0.4324	5.68E-14	0.0528	0.0484	0	-0.0251	-0.0990
3LF	5.68E-14	-0.0098	-0.0233	0	-0.1026	-0.4174	5.68E-14	0.0509	0.0462	0	-0.0213	-0.0949
4LF	5.68E-14	0.0155	0.0028	0	0.0259	-0.3189	5.68E-14	0.0390	0.0334	0	0.0079	-0.0706
5LF	5.68E-14	0.0387	0.0309	0	0.2005	-0.1472	5.68E-14	0.0073	-0.0035	0	0.0431	-0.0326
6LF	5.68E-14	0.0897	0.0953	0	0.5671	0.2725	5.68E-14	-0.0567	-0.0817	0	0.1158	0.0560

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Considering 5LF as the boundary for the system to remain stable, TSI COI Speed is set to a suitable value that will differentiate between stable and unstable condition. Referring to Table 5, |0.2400|rad/s is chosen as an OOS indicator; the analysis shows that the TSI COI Speed specifies that no OOS phenomenon is found for 1LF until 5LF faults indicated by '0' readings for TSI COI Speed and Time at all the monitored locations. OOS occurs only at 6LF, which is being identified as early as 1.2050s at Bus1002 with TSI COI Speed of |0.4335| rad/s and at Bus1004 with TSI COI Speed of |0.2412| rad/s at 1.5399s. Bus1002 seems to be the most sensitive and effective location to detect an OOS condition.

Table 5: Using TSI COI Speed=0.2400rad/s for OOS Detection

FILENAME	Bus1001		Bus1002		Bus1003		Bus1004	
	TSI COI SPEED	Time(s)	TSI COI SPEED	Time(s)	TSI COI SPEED	Time(s)	TSI COI SPEED	Time(s)
1LF_Bus1001 - Bus1006	0	0	0	0	0	0	0	0
1LF_Bus1001 - Bus1007	0	0	0	0	0	0	0	0
2LF	0	0	0	0	0	0	0	0
3LF	0	0	0	0	0	0	0	0
4LF	0	0	0	0	0	0	0	0
5LF	0	0	0	0	0	0	0	0
6LF	0	0	-0.4335	1.2050	0	0	-0.2412	1.5399

Table 6 shows that OOS is detected using TSI COI Speed at 1.205s consistently for all 33 different generation scheduling scenarios with Bus1002 being the most sensitive location to detect an OOS condition.

Table 6: Using TSI COI Speed = 0.2500rad/s as an indicator for OOS Detection

Scenarios (6LF)	Bus1001		Bus1002		Bus1003		Bus1004	
	TSI COI SPEED	Time(s)	TSI COI SPEED	Time(s)	TSI COI SPEED	Time(s)	TSI COI SPEED	Time(s)
GSN1	0	0	-0.3859	1.205	0	0	0	0
GSN2	0	0	-0.3859	1.205	0	0	0	0
GSN3	0	0	-0.3859	1.205	0	0	0	0
GSN4	0	0	-0.3859	1.205	0	0	0	0
GSN5	0	0	-0.3859	1.205	0	0	0	0
GSN6	0	0	-0.3859	1.205	0	0	0	0
GSN7	0	0	-0.3859	1.205	0	0	0	0
GSN8	0	0	-0.3859	1.205	0	0	0	0
GSN9	0	0	-0.3859	1.205	0	0	0	0
GSN10	0	0	-0.3859	1.205	0	0	0	0
GSN11	0	0	-0.3859	1.205	0	0	0	0
GSN12	0	0	-0.3859	1.205	0	0	0	0
GSN13	0	0	-0.3859	1.205	0	0	0	0
GSN14	0	0	-0.3859	1.205	0	0	0	0
GSN15	0	0	-0.3859	1.205	0	0	0	0
GSN16	0	0	-0.3859	1.205	0	0	0	0
GSN17	0	0	-0.3859	1.205	0	0	0	0
GSN18	0	0	-0.3859	1.205	0	0	0	0
GSN19	0	0	-0.3859	1.205	0	0	0	0
GSN20	0	0	-0.3859	1.205	0	0	-0.2597	1.210
GSN21	0	0	-0.3859	1.205	0	0	0	0
GSN22	0	0	-0.3859	1.205	0	0	-0.2963	1.210
GSN23	0	0	-0.3859	1.205	0	0	0	0
GSN24	0	0	-0.3859	1.205	0	0	0	0
GSN25	0	0	-0.3859	1.205	0	0	0	0
GSN26	0	0	-0.3859	1.205	0	0	0	0
GSN27	0	0	-0.3859	1.205	0	0	-0.2511	1.590
GSN28	0	0	-0.3859	1.205	0	0	-0.2502	1.605
GSN29	0	0	-0.3859	1.205	0	0	0	0
GSN30	0	0	-0.3859	1.205	0	0	0	0
GSN31	0	0	-0.3859	1.205	0	0	-0.2509	1.575
GSN32	0	0	-0.3859	1.205	0	0	0	0
GSN33	0	0	-0.3859	1.205	0	0	0	0

Proposed Force Generator Tripping Scheme

Figure 10 shows the algorithm used for FGTS that continuously monitors the health of the selected area of a system using System Integration Protection Schemes [6] that detects OOS and force trips generator using TSI COI Speed, determines the most suitable generator and location to force trip using Accelerating Power, and verifies the effectiveness of the FGTS using TSI COI Speed. The effectiveness of the FGTS is tested on Scenario GSN7_2MW – GSN7_100MW of Case Study 6 and another 20 different topologies by scheduling steam turbine and generator turbine.

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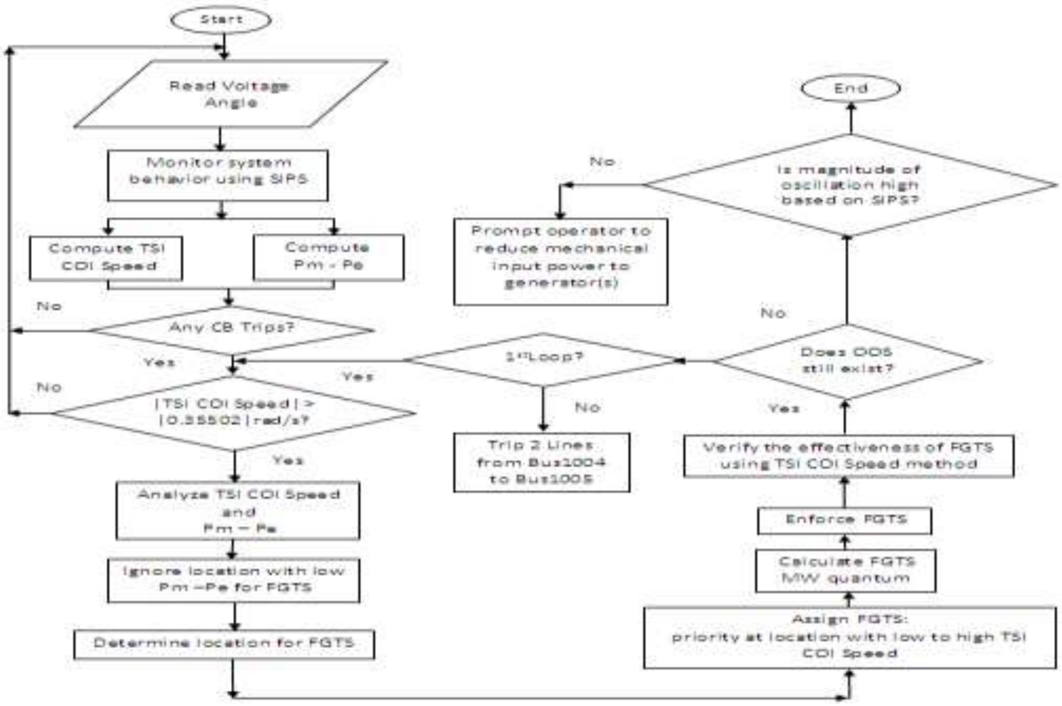

Figure 10: A New Algorithm for Monitoring the Health of Power System and Force Generator Tripping Scheme Using Wide Area Protection

Table 7 displays samples of the results of SIPS analysis on OOS status upon the occurrence of 6LF but before force generator tripping to verify that all possible scenarios experience OOS due to the impact of severe fault in the system. Using TSI COI Speed to detect OOS with an indicator of |0.35502|rad/s, it can be seen that Bus 1002 is the most sensitive location for every scenario with a detection time of 1.195s as shown in Table 8. Other information that can be extracted from these tables is that as generation increases TSI COI Speed increases accordingly at the detection time. Based on the flow of the algorithm, FGTS is initiated to eliminate the OOS phenomenon from the system.

Table 9 shows samples of the results of force tripping action. Bus1004 has the lowest Accelerating Power; hence, its contribution towards eliminating OOS from the system is minimal. Therefore, it is advisable to exclude Bus1004 from the list of force tripping. The tables indicate that the effective contribution of FGTS would come from Bus1001 and Bus1003. The MW quantum tripped to bring the system back to stable condition is also displayed in these tables. As expected based on the concept of swing equation, the more generation the more will be the unbalanced power; thus, more MW quantum to force trip is required. When effective FGTS is applied to the system accordingly, OOS is being eliminated from the system as proven in Error! Reference source not found. and Error! Reference source not found. through SIPS analysis labeled as ‘0’ for OOS Status.

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Table 7: OOS Detection using SIPS for Scenarios GSN7_48MW to GSN7_100MW

Scenarios	OOS Status	BUS 1004 - BUS 1005		BUS 1001- BUS 1006		BUS 1001 - BUS 1007		BUS 1001 - BUS 1002		BUS 1001 - BUS 1004		BUS 1001 - BUS 1003	
		Above A_{fk2} [Hz/s]	Below A_{fk1} [Hz/s]	Above A_{fk2} [Hz/s]	Below A_{fk1} [Hz/s]	Above A_{fk2} [Hz/s]	Below A_{fk1} [Hz/s]	Above A_{fk2} [Hz/s]	Below A_{fk1} [Hz/s]	Above A_{fk2} [Hz/s]	Below A_{fk1} [Hz/s]	Above A_{fk2} [Hz/s]	Below A_{fk1} [Hz/s]
GSN7_48MW	1	4723	-8437	482	-1375	1603	-3251	1658	-635	2288	-1209	0	0
GSN7_50MW	1	1265	-8414	1072	-1312	1208	-3174	1645	-245	2250	-249	0	0
GSN7_52MW	1	58	-967	84	-787	1097	-1056	1595	-9	76	-27	0	0
GSN7_54MW	1	1045	-7234	951	-935	1027	-2523	1392	-78	1769	-22	0	0
GSN7_56MW	1	3658	-6558	1622	-811	2598	-2256	1262	-761	1545	-960	0	0
GSN7_58MW	1	723	-198	727	-175	730	-286	1102	-73	1279	-7	0	0
GSN7_60MW	1	8516	-3110	1385	-294	3688	-825	506	-1349	521	-1919	0	0
GSN7_62MW	1	433	-1272	457	-97	409	-226	209	-88	70	-71	0	0
GSN7_64MW	1	439	-2486	434	-1388	383	-2112	331	-46	481	-74	0	0
GSN7_66MW	1	3805	-8521	415	-1468	1446	-3379	1674	-569	2328	-1020	0	0
GSN7_68MW	1	1252	-8565	1062	-1332	1175	-3211	1644	-224	2269	-253	0	0
GSN7_70MW	1	53	-1024	1016	-840	1107	-1138	1617	-70	90	-26	0	0
GSN7_72MW	1	1075	-6860	963	-833	1032	-2256	1247	-71	1605	-23	0	0
GSN7_74MW	1	3526	-6417	1625	-759	2490	-2082	1160	-714	1464	-928	0	0
GSN7_76MW	1	646	-289	656	-279	637	-409	914	-65	1080	-103	0	0
GSN7_78MW	1	497	-8162	517	-1640	477	-3527	1643	-55	2304	-82	0	0
GSN7_80MW	1	7291	-8323	1650	-1610	3632	-3516	1665	-1244	2332	-1734	0	0
GSN7_82MW	1	186	-8576	209	-1534	135	-3463	1694	-76	2363	-39	0	0
GSN7_84MW	1	116	-4331	137	-1707	1249	-2883	785	-75	1121	-31	0	0
GSN7_86MW	1	8450	-7180	1079	-896	3267	-2387	1316	-1281	1705	-1945	0	0
GSN7_88MW	1	760	-6652	750	-804	749	-2176	1214	-131	1534	-126	0	0
GSN7_90MW	1	720	-1825	716	-1212	709	-1738	153	-65	276	-119	0	0
GSN7_92MW	1	643	-484	656	-33	637	-21	128	-65	2216	-117	0	0
GSN7_94MW	1	1840	-8035	1337	67	1638	-3582	1622	-369	2288	-424	0	0
GSN7_96MW	1	245	-774	276	-677	208	-906	1674	-33	54	-42	0	0
GSN7_98MW	1	201	-8380	233	-1200	161	-3010	1612	-25	2145	-36	0	0
GSN7_100MW	1	4539	-8208	1735	-1149	2954	-2916	1571	-905	2073	-1183	0	0

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Table 8: OOS detection using TSI COI Speed for generator 2MW to 46MW

Scenarios	BUS 1001		BUS 1002		BUS 1003		BUS 1004	
	TSI COI SPEED	time (s)	TSI COI SPEED	time(s)	TSI COI SPEED	time(s)	TSI COI SPEED	time(s)
GSN7_2MW	0	0	-0.394	1.195	0	0	0	0
GSN7_4MW	0	0	-0.395	1.195	0	0	0	0
GSN7_6MW	0	0	-0.395	1.195	0	0	0	0
GSN7_8MW	0	0	-0.395	1.195	0	0	0	0
GSN7_10MW	0	0	-0.396	1.195	0	0	0	0
GSN7_12MW	0	0	-0.396	1.195	0	0	0	0
GSN7_14MW	0	0	-0.397	1.195	0	0	0	0
GSN7_16MW	0	0	-0.397	1.195	0	0	0	0
GSN7_18MW	0	0	-0.398	1.195	0	0	0	0
GSN7_20MW	0	0	-0.398	1.195	0	0	0	0
GSN7_22MW	0	0	-0.399	1.195	0	0	0	0
GSN7_24MW	0	0	-0.399	1.195	0	0	0	0
GSN7_26MW	0	0	-0.400	1.195	0	0	0	0
GSN7_28MW	0	0	-0.400	1.195	0	0	0	0
GSN7_30MW	0	0	-0.401	1.195	0	0	0	0
GSN7_32MW	0	0	-0.401	1.195	0	0	0	0
GSN7_34MW	0	0	-0.402	1.195	0	0	0	0
GSN7_36MW	0	0	-0.402	1.195	0	0	0	0
GSN7_38MW	0	0	-0.403	1.195	0	0	0	0
GSN7_40MW	0	0	-0.403	1.195	0	0	0	0
GSN7_42MW	0	0	-0.404	1.195	0	0	0	0
GSN7_44MW	0	0	-0.404	1.195	0	0	0	0
GSN7_46MW	0	0	-0.405	1.195	0	0	0	0

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Table 9: FGTS: TSI COI SPEED & Accelerating Power (Indicator |0.35502|rad/s; Monitoring Window between 1.190s to 1.200s) -1

Scenarios	Time of OOS Detection [s]	BUS 1001		BUS 1002		BUS 1003		BUS 1004		Force Trip [MW]	Location of Force Generator Tripping Priority			
		TSI COI SPEED [rad/s]	Pm-Pe [pu]	TSI COI SPEED [rad/s]	Pm-Pe [pu]	TSI COI SPEED [rad/s]	Pm-Pe [pu]	TSI COI SPEED [rad/s]	Pm-Pe [pu]					
GSN7_2MW_6LF	1.1950	0.10189	2.3611	0.39421	0.7356	0.10346	1.2356	0.08494	0.5166	446.71		BUS 1001	BUS 1003	BUS 1002
GSN7_4MW_6LF	1.1950	0.10188	2.3652	0.39461	0.7369	0.10347	1.2367	0.08439	0.5165	451.25		BUS 1001	BUS 1003	BUS 1002
GSN7_6MW_6LF	1.1950	0.10189	2.3652	0.39501	0.7372	0.10347	1.2377	0.08384	0.5163	455.79		BUS 1001	BUS 1003	BUS 1002
GSN7_8MW_6LF	1.1950	0.10188	2.3714	0.39542	0.7377	0.10349	1.2383	0.08327	0.5162	460.39		BUS 1001	BUS 1003	BUS 1002
GSN7_10MW_6LF	1.1950	0.10190	2.3714	0.39586	0.7386	0.10347	1.2404	0.08272	0.5165	465.34		BUS 1001	BUS 1003	BUS 1002
GSN7_12MW_6LF	1.1950	0.10190	2.3745	0.39629	0.7393	0.10348	1.2420	0.08211	0.5163	470.16		BUS 1001	BUS 1003	BUS 1002
GSN7_14MW_6LF	1.1950	0.10190	2.3765	0.39673	0.7399	0.10348	1.2425	0.08152	0.5166	475.01		BUS 1001	BUS 1003	BUS 1002
GSN7_16MW_6LF	1.1950	0.10190	2.3806	0.39719	0.7411	0.10350	1.2436	0.08089	0.5168	480.08		BUS 1001	BUS 1003	BUS 1002
GSN7_18MW_6LF	1.1950	0.10191	2.3806	0.39766	0.7416	0.10348	1.2447	0.08027	0.5168	485.28		BUS 1001	BUS 1003	BUS 1002
GSN7_20MW_6LF	1.1950	0.10191	2.3858	0.39811	0.7422	0.10348	1.2474	0.07962	0.5173	490.30		BUS 1001	BUS 1003	BUS 1002
GSN7_22MW_6LF	1.1950	0.10191	2.3888	0.39860	0.7434	0.10350	1.2490	0.07898	0.5177	495.63		BUS 1001	BUS 1003	BUS 1002
GSN7_24MW_6LF	1.1950	0.10192	2.3919	0.39908	0.7439	0.10349	1.2501	0.07831	0.5178	500.90		BUS 1001	BUS 1003	BUS 1002
GSN7_26MW_6LF	1.1950	0.10194	2.3919	0.39958	0.7453	0.10347	1.2533	0.07763	0.5184	506.43		BUS 1001	BUS 1003	BUS 1002
GSN7_28MW_6LF	1.1950	0.10192	2.3991	0.40008	0.7459	0.10350	1.2533	0.07692	0.5186	511.78		BUS 1001	BUS 1003	BUS 1002
GSN7_30MW_6LF	1.1950	0.10192	2.4022	0.40059	0.7471	0.10349	1.2560	0.07622	0.5193	517.32		BUS 1001	BUS 1003	BUS 1002
GSN7_32MW_6LF	1.1950	0.10192	2.4063	0.40110	0.7476	0.10349	1.2581	0.07550	0.5202	522.78		BUS 1001	BUS 1003	BUS 1002
GSN7_34MW_6LF	1.1950	0.10193	2.4073	0.40164	0.7487	0.10349	1.2586	0.07477	0.5203	528.58		BUS 1001	BUS 1003	BUS 1002
GSN7_36MW_6LF	1.1950	0.10193	2.4114	0.40217	0.7499	0.10349	1.2608	0.07402	0.5211	534.20		BUS 1001	BUS 1003	BUS 1002
GSN7_38MW_6LF	1.1950	0.10194	2.4155	0.40271	0.7510	0.10348	1.2635	0.07327	0.5218	539.92		BUS 1001	BUS 1003	BUS 1002
GSN7_40MW_6LF	1.1950	0.10192	2.4217	0.40324	0.7517	0.10350	1.2645	0.07249	0.5227	545.51		BUS 1001	BUS 1003	BUS 1002
GSN7_42MW_6LF	1.1950	0.10192	2.4248	0.40381	0.7529	0.10349	1.2678	0.07170	0.5232	551.44		BUS 1001	BUS 1003	BUS 1002
GSN7_44MW_6LF	1.1950	0.10192	2.4268	0.40437	0.7538	0.10348	1.2688	0.07089	0.5232	557.31		BUS 1001	BUS 1003	BUS 1002
GSN7_46MW_6LF	1.1950	0.10192	2.4340	0.40492	0.7550	0.10347	1.2726	0.07007	0.5239	563.05		BUS 1001	BUS 1003	BUS 1002

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IV. CONCLUSION

Research work has proven that SIPS and TSI COI Speed can be used to detect OOS condition. For SIPS method, the upper and lower boundaries are the most significant; they have to anticipate the behavior of the system in terms of Slip Frequency Acceleration versus Slip Frequency when the system is subjected to severe fault. These boundaries are meant to discriminate between the OOS and non OOS conditions. The width of the stable region must be carefully set to maintain the dependability and security of the system. Despite of noise may fall outside the boundaries for most of the events, the boundaries should be very accurate and able discriminate between the useful and deception data. Hence, it takes a longer time to sense an OOS condition.

TSI COI Speed is reliable to act as an indicator in detecting OOS phenomena at early stage. It is proven that whenever OOS occurs, the behavior of this indicator shows a drastic change in terms of amplitude and/or oscillation depending on the severity of fault and generator scheduling. TSI COI Speed and Accelerating Power have demonstrated consistent results for all case studies in this research work. It is proven that TSI COI Speed can single out the OOS event at an early stage. Monitoring at a single location does not reflect the behavior of a system as a whole with respect to OOS condition. Strategic location of installing synchrophasor to monitor the system behavior needs to be determined in order to obtain an accurate health condition of the system.

FGTS could help to eliminate OOS phenomenon from the system provided the OOS is detected at early stage and force generator tripping is implemented without delay with the correct MW quantum and at effective location(s). It is proven that the novel algorithm developed in this research works using: TSI COI Speed as an indicator to detect OOS; decrement of TSI COI Speed from its reference value to calculate the MW quantum to force trip generator; and the combination of TSI COI Speed and Accelerating power to determine the location to force trip, is applicable and effective in eliminating OOS condition from the system.

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