

- CHAPTER 5 -

VALIDATION OF NEW POLE-SLIP ALGORITHM

“Keep on going and the chances are you will stumble on something, perhaps when you are least expecting it. I have never heard of anyone stumbling on something sitting down”

Charles F. Kettering

5.1 INTRODUCTION

PSCAD/EMTDC is an industry standard simulation tool for studying the transient behavior of electrical networks [50]. Its graphical user interface enables all aspects of the simulation to be conducted within a single integrated environment including circuit assembly, run-time control, analysis of results, and reporting. This chapter presents various simulations on different power systems and generators to test the operation of the new pole-slip algorithm by using PSCAD.

The key factors that would determine the accuracy of the new pole-slip algorithm are the following:

- Calculation of pre-fault transfer angle
- Accurate detection of fault-occurrence and fault-clearance
- Calculation of “during-fault” generator- and step-up transformer power angles
- Prediction of “post-fault” voltage magnitudes on generator and transformer terminals
- Prediction of average post-fault quadrature axis reactance $X_{q_{avg}}$ for round rotor generators
- Accuracy of pole-slip function with generators operating in parallel
- Accuracy of pole-slip function when operating with shunt loads

The new pole-slip algorithm is evaluated against conventional impedance pole-slip protection schemes. The new pole-slip algorithm is also evaluated against simulated results in PSCAD. Throughout this chapter a *simulated value* is compared to a *calculated value*. The *simulated value* is obtained from a PSCAD simulation measurement and is regarded as the correct/benchmark value. The *calculated value* is obtained from the new pole-slip algorithm that can be programmed into a protection relay.

5.2 EVALUATION CRITERIA

The following criteria are used to evaluate the effectiveness of the new pole-slip protection function:

- Tripping before a pole-slip occurs
- No spurious tripping where stability could be maintained after a fault
- Accuracy with generators in parallel
- Accuracy with shunt loads
- Dependence on network switching configurations
- Simplicity for engineers to set the function
- Simplicity for commissioning engineers to test the function

5.3 SIMULATION – POWER SYSTEM LAYOUT

Figure 5.1 shows the power system layout for all the simulations performed in this chapter. The PSCAD model with the newly developed pole-slip protection function is given in Appendix B. Generator 1 is the generator under consideration, which must be protected by the pole-slip function. Section 3.6 discussed the effect of shunt loads and the extra requirements for summation CTs as shown in Figure 5.1.

The aim is to identify the possibility of using the nearest power stations to Generator 1 and 2 as the infinite bus. The impedance of transmission lines T_{line1} and T_{line2} is therefore regarded as the effective impedance between the power station under consideration (Generators 1 and 2) and the “infinite bus”. For this assumption to be valid, the impedance of T_{line3} and T_{line4} must be small compared to the impedance of T_{line1} and T_{line2} .

The impedance of transmission lines T_{line3} and T_{line4} is expected to be small, since it represents all the transmission lines between Generators 3 and 4 and “the rest of the network”. Transmission line loads are considered as loads that connects the power station under consideration to another power station. Shunt loads are considered as loads (like cities, or large industries etc.) that are not connected to other power stations. A clear distinction has to be made between transmission line feeders and shunt load feeders in order to set up the new pole-slip protection function.

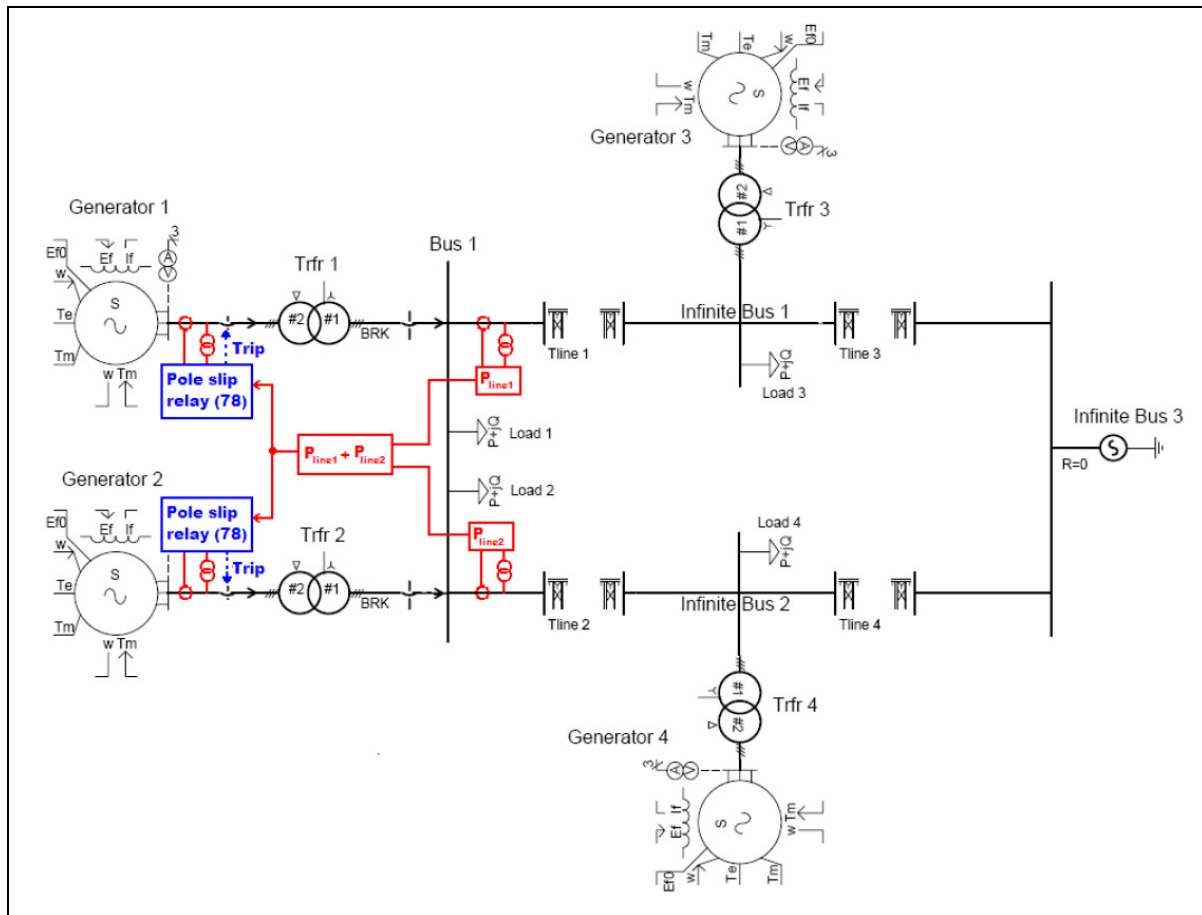


Figure 5.1: Power System Layout with shunt loads

5.4 GENERATORS TESTED

The pole-slip algorithm logics were built in PSCAD just as it can be built in a protection relay (refer to Appendix B for PSCAD logics). Table 5.1 shows a list of synchronous generators with their parameters that were used to test the new pole-slip function with PSCAD.

Table 5.1: Generators tested to determine accuracy of new pole-slip function

Round Rotor - Turbo generators															
Gen	MVA	kV	X_d	X'_d	X''_d	X_q	X'_q	X''_q	X_l	R_a	T'_{do}	T''_{do}	T'_{qo}	T''_{qo}	H
A	75	13.8	1.050	0.185	0.130	0.980	0.360	0.130	0.070	0.003	6.100	0.038	0.300	0.099	6.640
B	233	20	1.569	0.324	0.249	1.548	0.918	0.248	0.204	0.002	5.140	0.044	1.500	0.141	4.122
C	590	22	2.110	0.280	0.215	2.020	0.490	0.215	0.155	0.005	4.200	0.032	0.565	0.062	2.319
Salient Rotor - Hydro generators															
D	100	13.8	1.014	0.314	0.280	0.770	-	0.375	0.163	0.005	6.550	0.039	-	0.071	3.120
E	158	13.8	0.920	0.300	0.220	0.510	-	0.290	0.130	0.002	5.200	0.029	-	0.034	3.177
F	231	13.8	0.930	0.302	0.245	0.690	-	0.270	0.210	0.002	8.000	0.030	-	0.060	3.403

A Potier reactance X_p instead of X_l can be used in simulation software to provide for some effects of saturation. Round rotor machines have Potier reactances of typically $1.3 \times X_l$, while salient pole machines have Potier reactances of up to $3 \times X_l$ [13:385].

The Potier reactance X_p used in the PSCAD simulations are assumed to be as follows for all the tested generators:

Round Rotor Machines: $X_p = 1.3 \times X_l$ or $X_p = (X_d'' - 0.01)$ if $(1.3 \times X_l) > X_d''$

Salient Pole Machines: $X_p = 2 \times X_l$ or $X_p = (X_d'' - 0.01)$ if $(2 \times X_l) > X_d''$

An air gap factor of 1.0 was used for all generators in the simulations.

The PSCAD synchronous machine model includes saturation on the d-axis, but the effect of saturation is neglected on the q-axis [21], [51]. Kaberere et al performed simulations (on a basic power system) with different power system simulation packages that include saturation on the q-axis and compared it to stability study results obtained with the PSCAD synchronous machine model. It was concluded that the stability performance of PSCAD was similar to the other simulation packages [51]. However, the real test would be to compare all the simulation packages with real measurements from the field. Due to the practical constraints in attempting to measure pole-slip data from a real power system, the verification of the pole-slip protection algorithm in this study will rely on PSCAD simulated data.

The effect of saturation tends to make a synchronous generator less stable [48], [52]. The possible shortcomings in accounting for saturation means that a real generator could be less stable than the PSCAD simulated generators. Since the new pole-slip function is designed (and “tuned” with correction factors) to perform according to PSCAD simulated data, the new pole-slip function will rather refrain from tripping an unstable generator, than tripping a generator when it could have remained stable after the network disturbance.

All the generator types and sizes were tested successfully, but only the results (and plots) for generator no. C (590 MVA round rotor) in Table 5.1 are presented in this chapter. The reason for detailing the results of generator C in this chapter is due to the fact that Eskom steam generators (600 MVA, round rotor) is the closest in size to generator C. The simulation results of the other generators are provided in Appendix C.

The network parameters for the tested generators are as per the following table:

Table 5.2: Network impedances for new pole-slip function simulations

Generator	Transformer (pu)	Transmission lines (pu) (post-fault impedance)	Infinite bus (pu) (paralleled impedance)
A	0.1	$0.016 + j0.020$	$j0.001$
B	0.1	$0.014 + j0.049$	$j0.002$
C	0.15	$0.014 + j0.071$	$j0.003$
D	0.1	$0.034 + j0.043$	$j0.002$
E	0.1	$0.013 + j0.067$	$j0.003$
F	0.15	$0.005 + j0.028$	$j0.001$

The post-fault transmission line impedance in Table 5.2 is the impedance without the faulted transmission line included. The pre-fault paralleled impedance will be 50% of the post-fault impedance, since only two lines were operated in parallel in all the simulations. The infinite bus impedance is less than 5% of the post-fault transmission line impedance. That is a requirement for the pole-slip function to predict stability as will be discussed in section 5.5.

The step-up transformer tap-changer in all the simulations was set at 100%. When the tap-changer is set to increase the HV voltage, the transmission line base voltage must be adjusted accordingly. An impedance base must be calculated for every tap-changer setting, which must be used to calculate the transmission line per-unit impedance. When the HV side voltage of the transformer is increased, the power system will be more stable. This is compensated for in the transmission line per-unit impedance, which will reduce with an increased transformer HV-side voltage.

The pole-slip function is suitable for transmission line lengths of up to 200 km, since series capacitors are typically not installed on lines shorter than 200 km [57]. The pole-slip protection function only needs to determine the behaviour of transmission lines between the generator and the closest other power station. As discussed earlier, the stabilizing effect of the transmission line shunt admittance is already taken care of in the transfer angle calculation in equation (3.24), since the voltage and current measured at the sending end of the transmission line includes the compensating effect of the shunt admittance. There is no need to include additional shunt admittances in the pole-slip algorithm (similar to shunt loads), and therefore the transmission line shunt admittances are not shown in Table 5.2.

5.5 PRE-FAULT TRANSFER ANGLE CALCULATION

This section discusses the accuracy of the pre-fault transfer angle prediction function in the new pole-slip algorithm. Table 5.3 shows a list of pre-fault scenarios for the power system as shown in Figure 5.1. The pre-fault network impedance value ($\bar{Z}_{network}$) must be used to determine the pre-fault transfer angle:

$$\bar{Z}_{network} = \frac{\bar{Z}_{Tline1} \cdot \bar{Z}_{Tline2}}{\bar{Z}_{Tline1} + \bar{Z}_{Tline2}} + jX_{Tx1} \quad (5.1)$$

where $\bar{Z}_{Tline1}$, $\bar{Z}_{Tline2}$ is the transmission line impedances shown in Figure 5.1

The value of the infinite bus impedance $\bar{Z}_{inf}$ is determined as follows:

$$\bar{Z}_{inf} = \frac{\bar{Z}_{Tline3} \cdot \bar{Z}_{Tline4}}{\bar{Z}_{Tline3} + \bar{Z}_{Tline4}} \quad (5.2)$$

where $\bar{Z}_{Tline3}$, $\bar{Z}_{Tline4}$ is the transmission line impedances shown in Figure 5.1

$\delta_{transfer}$ in Table 5.3 refers to the transfer angle between the EMF of Generator 1 and the infinite bus 1&2. Depending on the impedance of $\bar{Z}_{inf}$, infinite busses 1&2 can have a different voltage angle, but the angle difference between these two busses should be small.

Table 5.3: Pre-fault Scenarios with Power Angle Calculations

Pre-fault conditions	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
P_{GEN1} (pu)	1	1	1	0.5	0.6
P_{GEN2} (pu)	1	0.5	0.25	1	0.5
P_{SHUNT} (pu)	0.1	0.1	0.5	0.1	0.5
Q_{SHUNT} (pu)	0.1	0.1	0.2	0.1	0.1
P_{GEN3} (pu)	0.5	0.5	0.5	0.5	0.5
P_{GEN4} (pu)	0.5	0.5	0.5	0.5	0.5
Simulated δ_{gen} (deg)	61.3	61.8	59.3	61.8	44.3
Calculated δ_{gen} (deg)	61.3	61.8	59.4	61.9	44.7
Simulated δ_{tx} (deg)	8.7	8.6	8.7	8.6	4.3
Calculated δ_{tx} (deg)	8.7	8.7	8.8	8.7	4.3
Simulated δ_{line} (deg)	8.0	5.3	2.5	5.9	2.6
Calculated δ_{line} (deg)	8.0	5.3	2.5	5.9	2.6
Simulated $\delta_{transfer}$ (deg)	78.0	75.7	70.5	76.3	51.2
Calculated $\delta_{transfer}$ (deg)	78.0	75.8	70.7	76.5	51.6

It can be seen from Table 5.3 that $\delta_{transfer}$ is calculated with good accuracy (less than 0.5 degrees error) compared to the PSCAD simulated $\delta_{transfer}$. It was found from repeated simulations that the ratio of $Z_{inf} / Z_{network}$ must be less than 0.05 for the new pole-slip function to predict instability accurately. For values of $Z_{inf} / Z_{network} > 0.05$, the pole-slip function could refrain from tripping in events that stability is lost after the fault. Spurious tripping will however not occur. A requirement of $Z_{inf} / Z_{network} < 0.05$ in practice is easily achievable for real power systems.

The choice of network scenarios in Table 5.3 was done to specifically test various loads on the generator under consideration as well as the generator in parallel. The shunt loads were also varied to confirm that the pole-slip function will work accurately for different shunt loads. In Scenario 4, the parallel generator (generator 2) is loaded higher than generator 1. The scenario 4 loads were chosen to simulate a scenario where generator 2 will pole-slip, but generator 1 will remain stable, in which case the relay on Generator 1 must refrain from tripping.

5.6 CHECK 2 – PREDICTION OF POST-FAULT VOLTAGES

This section presents the plots for the *post-fault* voltage prediction on the generator and transformer secondary terminals. The post-fault generator and transformer voltages will decrease as the transfer angle increases after the fault is cleared. Figure 5.2 shows the post-fault region on the voltages and rotor speed deviation graphs. Refer to section 4.8.3 for a detailed explanation of post-fault voltage prediction.

These post-fault voltages are required to calculate *Area 2* in the equal area criteria for accurate stability prediction after the fault is cleared. As discussed previously, the reason for the sagging in voltage after the fault is cleared is due to the rotor inertia that keeps the rotor above synchronous speed after the fault is cleared. This causes the transfer angle to increase after the fault is cleared, which consequently increases the generator current and decrease terminal voltage. Figure 5.2 to Figure 5.6 shows the results for the different scenarios in Table 5.3.

If the generator under consideration (Generator 1 in Table 5.3) operates at a higher pre-fault active power than Generator 2, the post-fault voltage prediction must be accurate. It was found in the simulations that the pole-slip function is most accurate when the *predicted* post-fault voltage $V_{gen_post-fault}$ has a magnitude smaller or equal to the average value of actual post-fault voltage. The predicted post-fault voltage must also be larger or equal to the minimum value of the actual post-fault voltage during the power swing to avoid spurious trips.

The variable “ $V_{gen_post-fault}$ ” and “ $V_{tx_sec_post-fault}$ ” in Figure 5.2 represents the predicted post-fault values for the generator and transformer respectively. The predicted post-fault voltages are indicated in **bold** in the figures to follow. The speed deviation curves of the generators are also provided to indicate the power

swing. Only the period after the fault is cleared until the generator speed crossed the 0 rad/s axis is relevant for the pole-slip protection algorithm. The variable “Speed Deviation” refers to Generator 1 and “Speed Deviation2” refers to Generator 2.

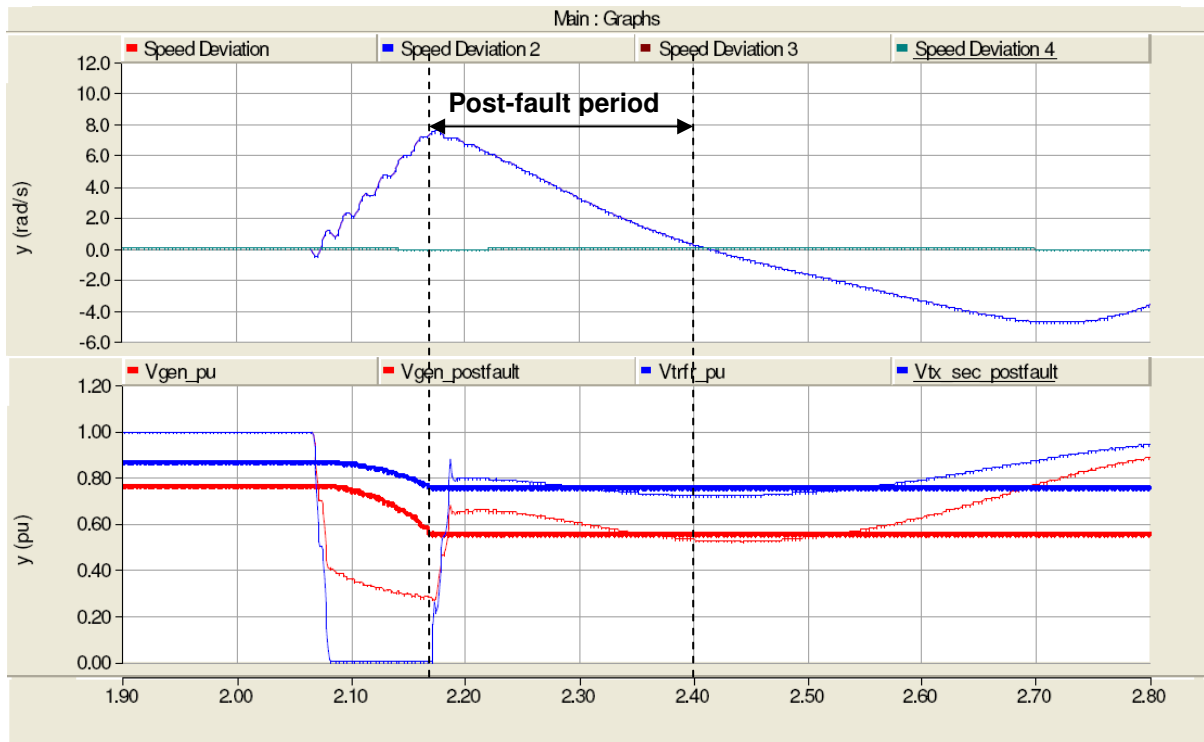


Figure 5.2: Scenario 1 – Post-fault voltage prediction on Generator 1 and Transformer 1 terminals

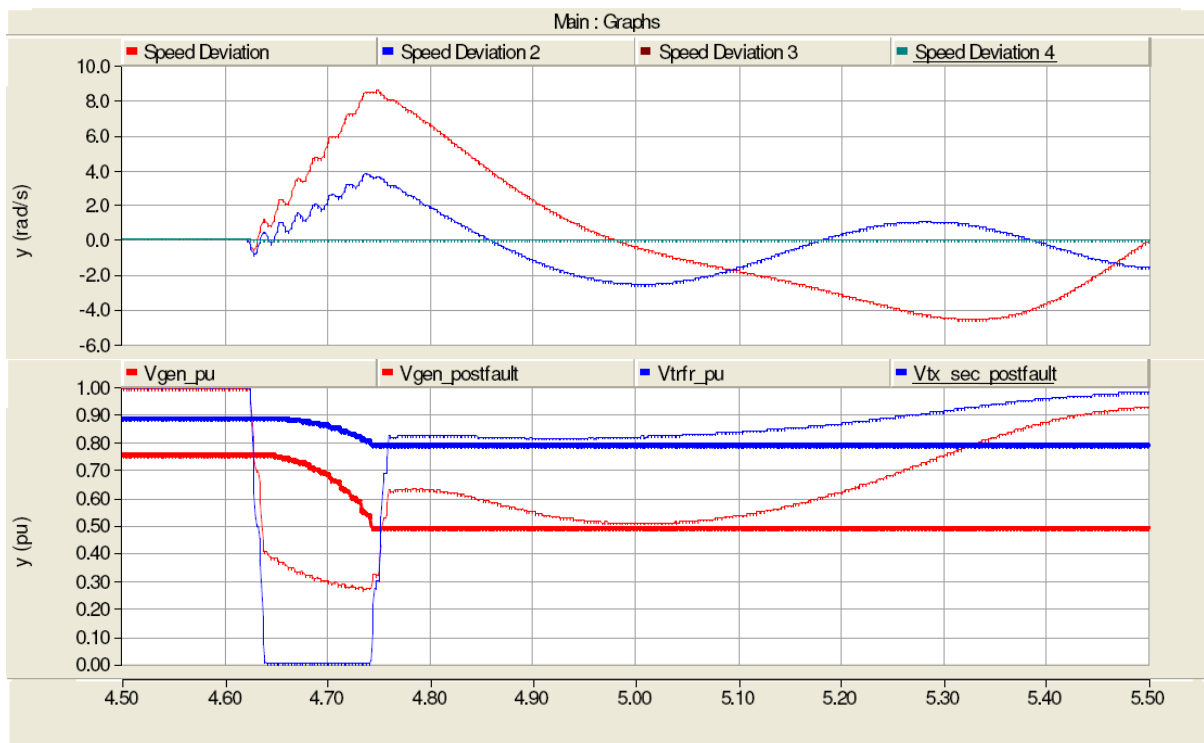


Figure 5.3: Scenario 2 – Post-fault voltage prediction on Generator 1 and Transformer 1 terminals

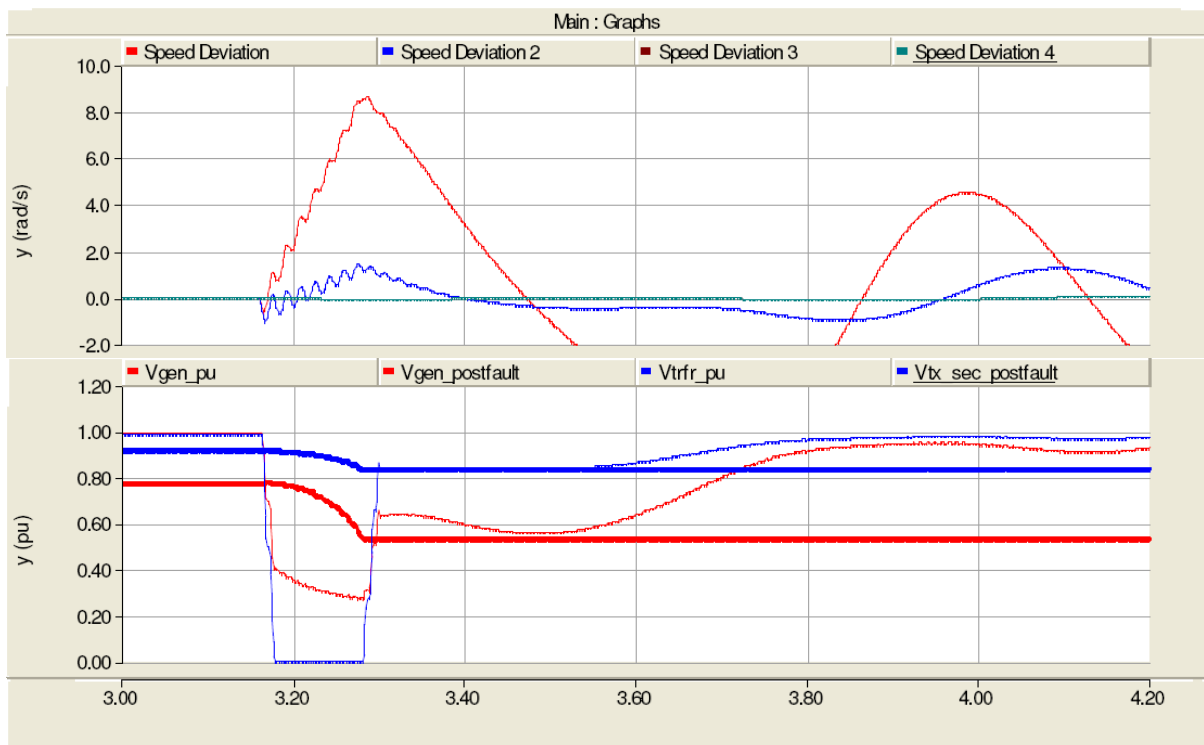


Figure 5.4: Scenario 3 – Post-fault voltage prediction on Generator 1 and Transformer 1 terminals

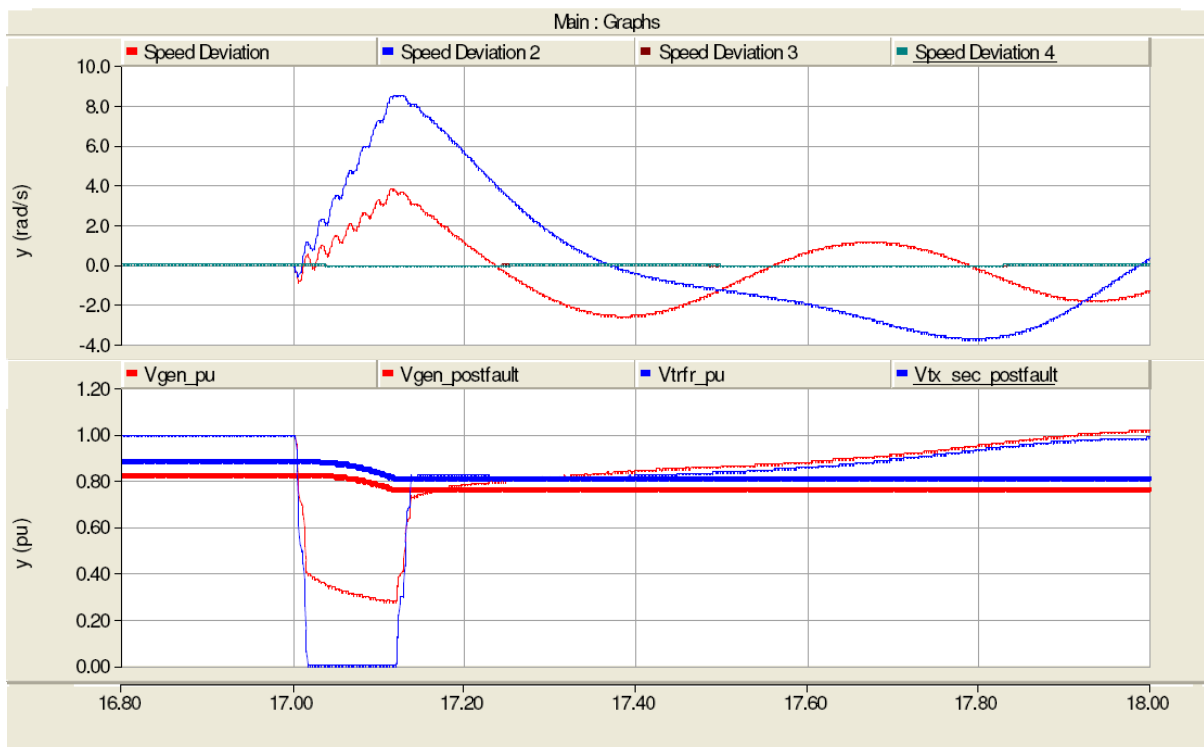


Figure 5.5: Scenario 4 – Post-fault voltage prediction on Generator 1 and Transformer 1 terminals

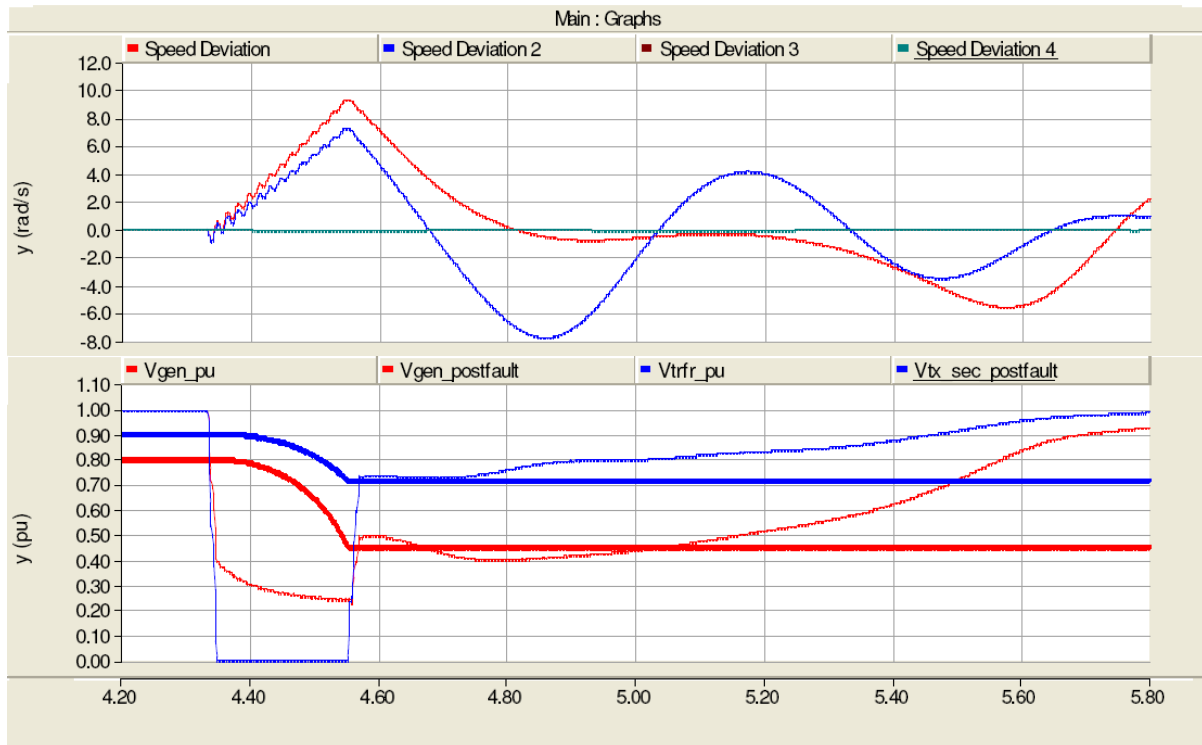


Figure 5.6: Scenario 5 – Post-fault voltage prediction on Generator 1 and Transformer 1 terminals

It can be seen that the post-fault voltages are predicted with good accuracy in all the figures above. As mentioned earlier, it was found in the simulations that the pole-slip function is most accurate when the *predicted* post-fault voltage $V_{gen_post-fault}$ has a magnitude smaller or equal to the average value of actual post-fault voltage, and larger or equal to the minimum value of the actual post-fault voltage during the power swing.

5.7 GENERATOR AND TRANSFORMER TRANSIENT POWER ANGLES CALCULATIONS

An important part of the equal area criteria is to determine the generator and transformer transient power angles in real time during the fault. An iterative solution was developed as was discussed in section 4.8.9. The results are presented in Figure 5.7 to Figure 5.12 for the different scenarios in Table 5.3. The “Calculated Power angles” are the transient values as calculated by the pole-slip algorithm, where the “Simulated Power angles” are the PSCAD simulated measurements. During the fault, the generator power angle reduces as was explained in section 3.2

The aim is to predict the value of the generator power angle continuously during the fault to see what the power angle would be at the instant when the fault is cleared. This prediction in power angle during the fault is used in the equal area criteria to determine stability. It is important to note that only the value of the power angles during the fault, and more specifically, at the instant when the fault is cleared, is of importance. The power angles after the fault is cleared are of no importance, since it is not used in the equal area criteria. Figure 5.7 shows the instant of importance for the angle calculations. Figure 5.8 shows the same information as Figure 5.7, but it is focussed on the moment when the fault is cleared.

The pre-fault calculated and simulated power angles differ considerably, since the generator *transient* reactance X_d' was used in an iterative algorithm as was explained in section 4.8.9. The iterative power angle calculation is therefore only valid for transient conditions. The calculated power angle is represented by the variable “delta_gen_i5” and “delta_tx_i5” for the generator and transformer respectively and is the **bold** graphs in the figures below. It was found that the iterative solution method calculates the transient power angles sufficiently accurate (less than 0.5 degrees error) for stability study purposes.

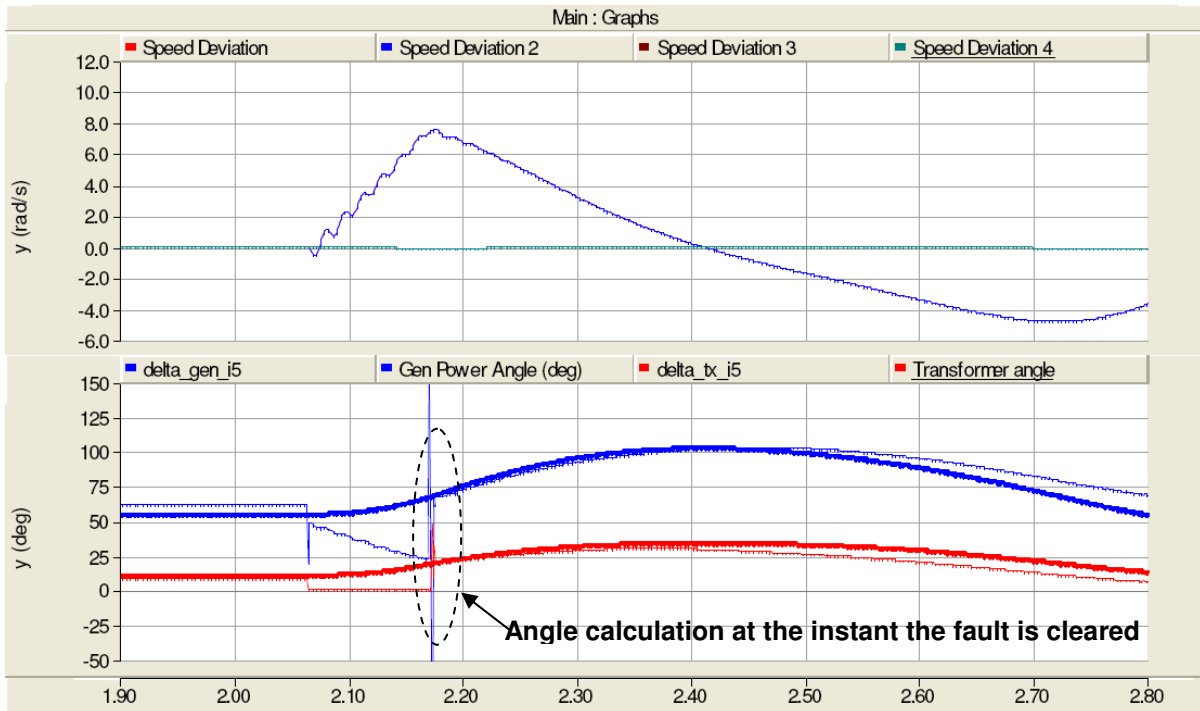


Figure 5.7: Scenario 1 – Transient Power angle calculation of Generator 1 and Transformer 1

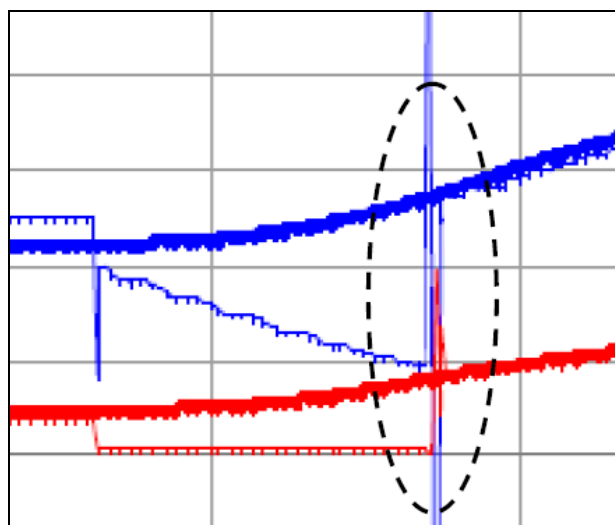


Figure 5.8: Scenario 1 – Transient Power angle calculation – Focussed on Instant of Fault Clearance

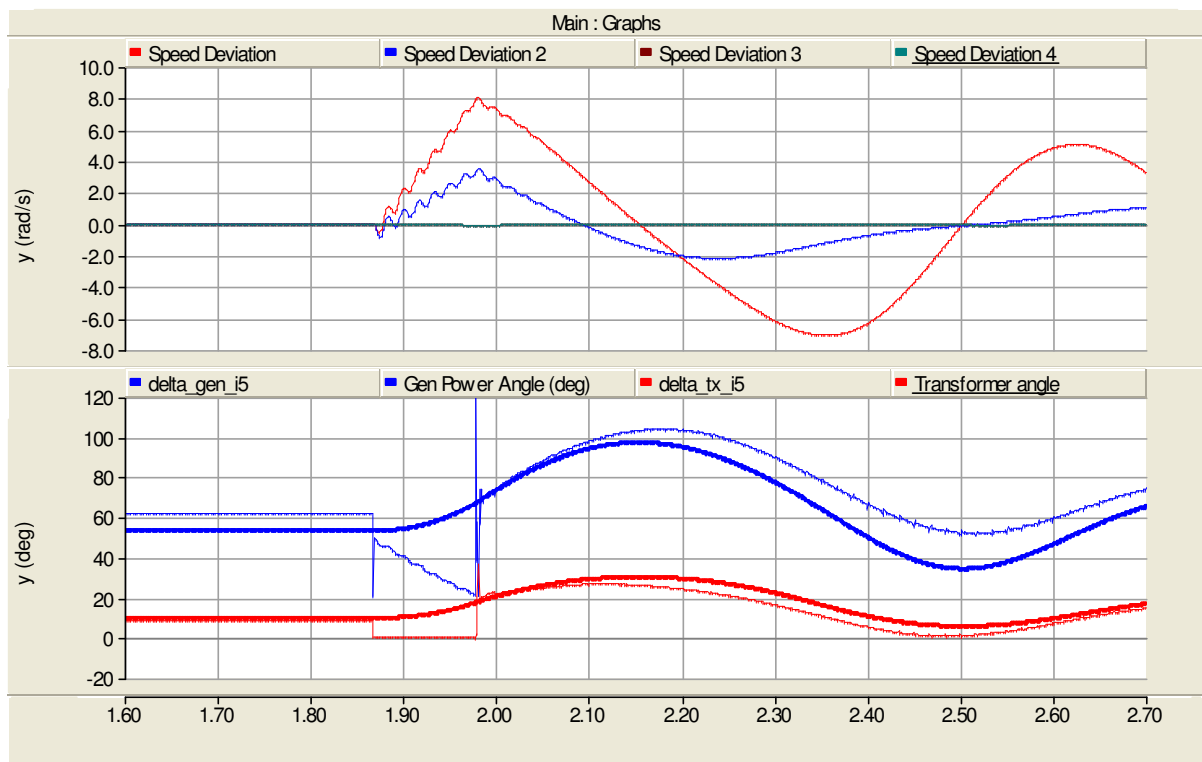


Figure 5.9: Scenario 2 – Transient Power angle calculation of Generator 1 and Transformer 1

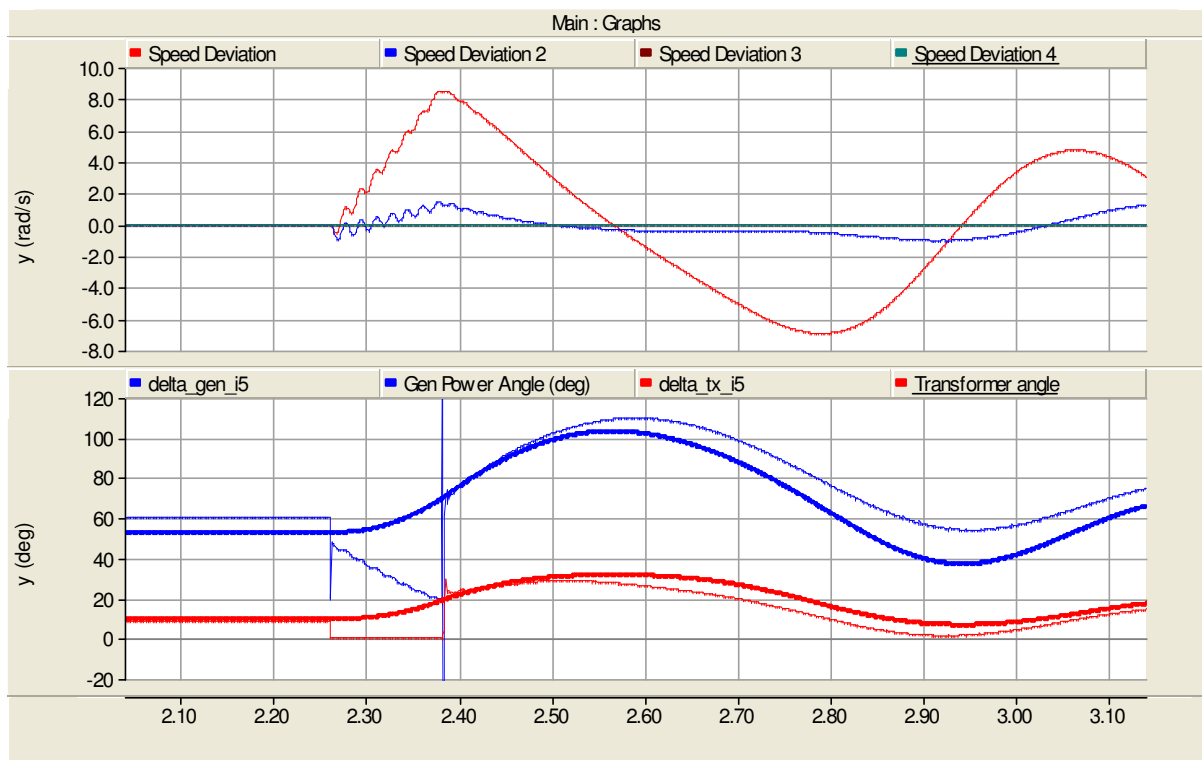


Figure 5.10: Scenario 3 – Transient Power angle calculation of Generator 1 and Transformer 1

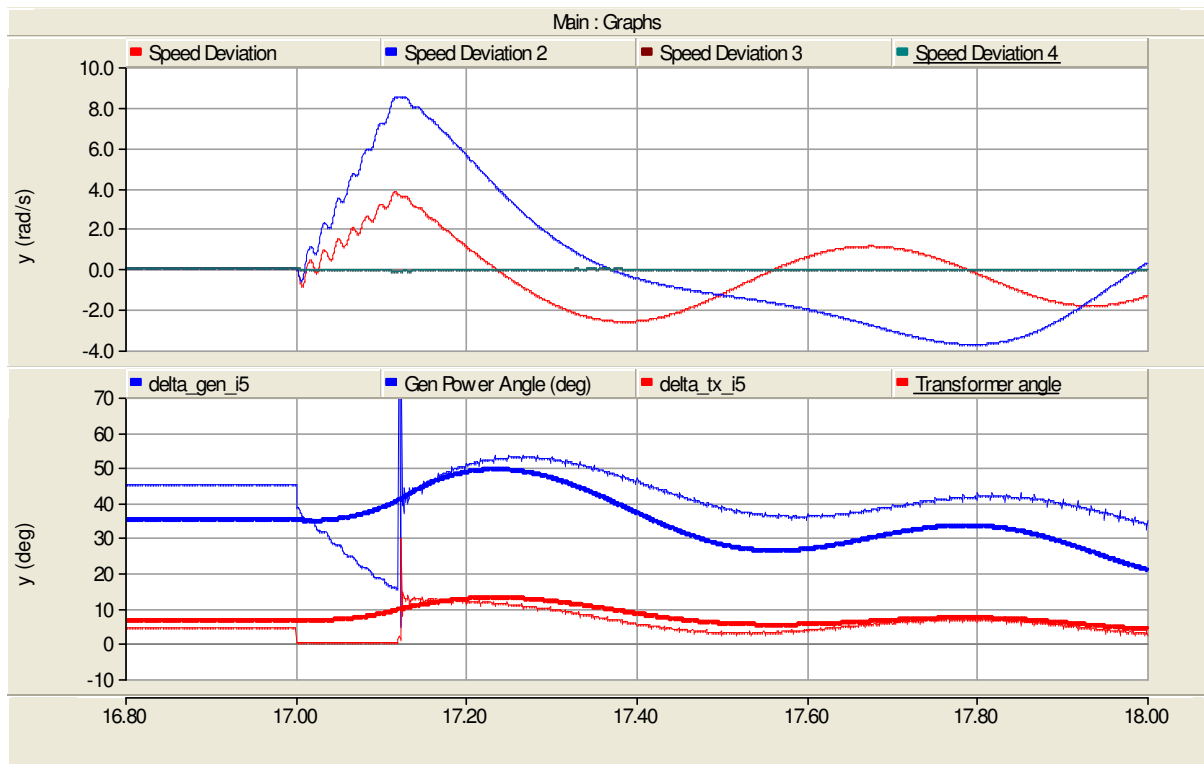


Figure 5.11: Scenario 4 – Transient Power angle calculation of Generator 1 and Transformer 1

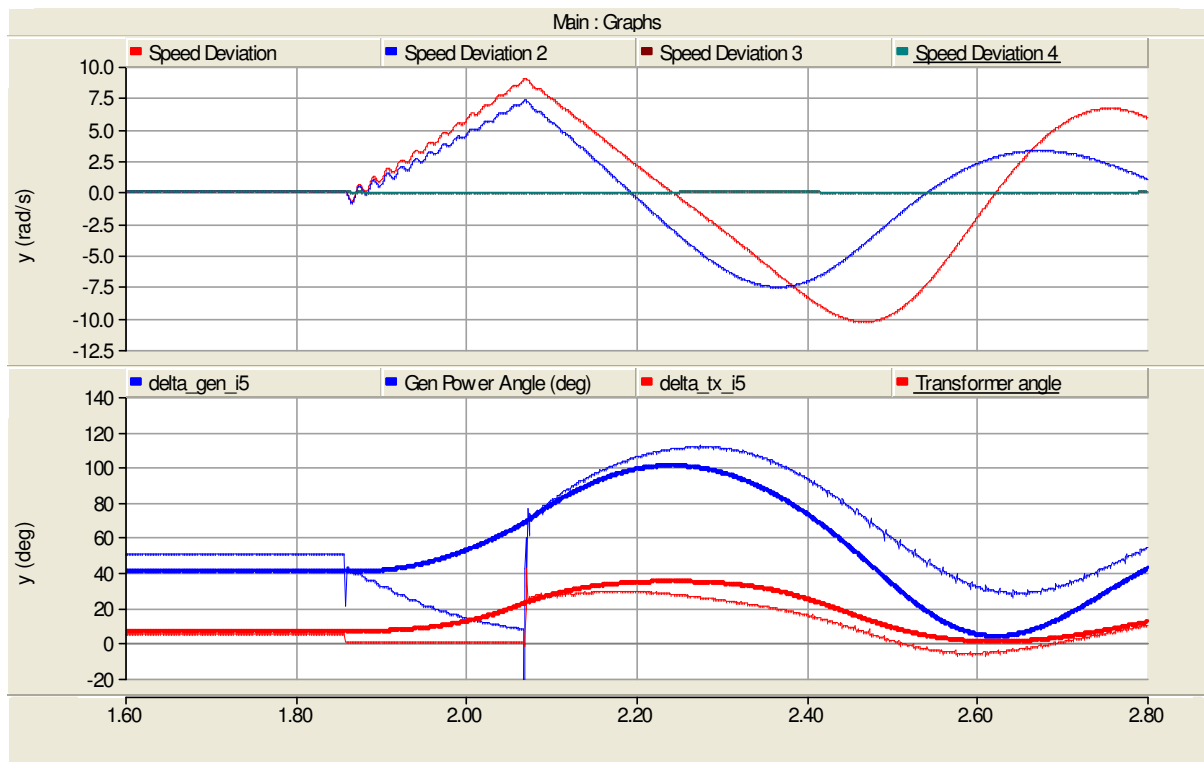


Figure 5.12: Scenario 5 – Transient Power angle calculation of Generator 1 and Transformer 1

5.8 CHOICE OF FAULT DURATIONS FOR DIFFERENT SIMULATED SCENARIOS

Two fault durations were chosen for each scenario discussed in section 5.9 (refer to Table 5.3). One of the fault durations is chosen such that the generator remains marginally stable. The other fault duration is increased to such an extent that the generator becomes unstable and to the point where the pole-slip function issues a trip. It must be noted that the second fault duration is not where the generator is marginally unstable. This fault duration is increased beyond the point where the generator is marginally unstable until the pole-slip function issues a trip.

It will be shown in section 5.8 that the pole-slip function will rather refrain from tripping an unstable machine, than to trip a machine that could have remained stable after the fault was cleared. This error margin of the pole-slip function is described in more detail in section 5.9.

5.9 TRIPPING BEFORE A POLE-SLIP OCCURS

Table 5.4 provides the “error margin” fault times for the different power system scenarios as defined in Table 5.3. The “error margin” is the margin of detection between a marginally stable fault duration and a marginally unstable fault duration. For example, a 200 ms fault duration might be a stable fault, but a 201 ms second fault will cause the generator to become unstable. The pole-slip algorithm might only predict that a 210 ms fault will cause instability. The error margin will then be $210\text{ ms} - 201\text{ ms} = 9\text{ ms}$. The pole-slip algorithm is designed not to cause spurious trips due to inaccuracies. The error margin will rather cause the pole-slip function not to trip even if the generator will become unstable. Incorrect operation (no tripping) will only occur in the unlikely event that the fault duration falls within the 9 ms error margin time.

Generator circuit breakers can have opening times of typically 50 ms to 100 ms. If 100 ms is taken as worst case scenario, the pole-slip protection function might issue a trip when instability is detected, but the breaker will only open 100 ms later. That means if the fault is cleared within the period that the circuit breaker is opening, the generator might still be exposed to some degree of mechanical stress. It will however be less than the stress the generator would experience if a protection trip was not issued before the fault was cleared.

Different fault types were simulated namely bolted three-phase faults and single-phase-to-phase (two-phase) faults. The equal area criteria was used to determine when a generator would become unstable after the fault. It was found that the protection function predicted all the pole-slip scenarios with an error margin of less than 10 ms.

Table 5.4: Simulated and Calculated stability times t_{stab} for different scenarios

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Tripped correctly	Yes	Yes	Yes	N/A	Yes
Error margin	< 10 ms	< 10 ms	< 10 ms	N/A	< 10 ms

Figure 5.13 to Figure 5.22 show the results for the operating scenarios presented in Table 5.3. The fault detection and fault clearance signals are shown in the figures together with *Area 1* and *Area 2*. As the fault progresses, *Area 1* becomes larger and *Area 2* becomes smaller. At the instant where *Area 1* crosses *Area 2*, the pole-slip function issues a trip.

Scenario 4 in Figure 5.20 was intentionally tested to confirm that Generator 2 will become unstable, but Generator 1 (the generator under consideration) will not become unstable after the fault. The pole-slip algorithm that protects Generator 1 must therefore not trip Generator 1 even if Generator 2 becomes unstable. The pole-slip relay of Generator 2 would have tripped Generator 2, which means Generator 1 can remain online and ensure maximum network stability after the fault.

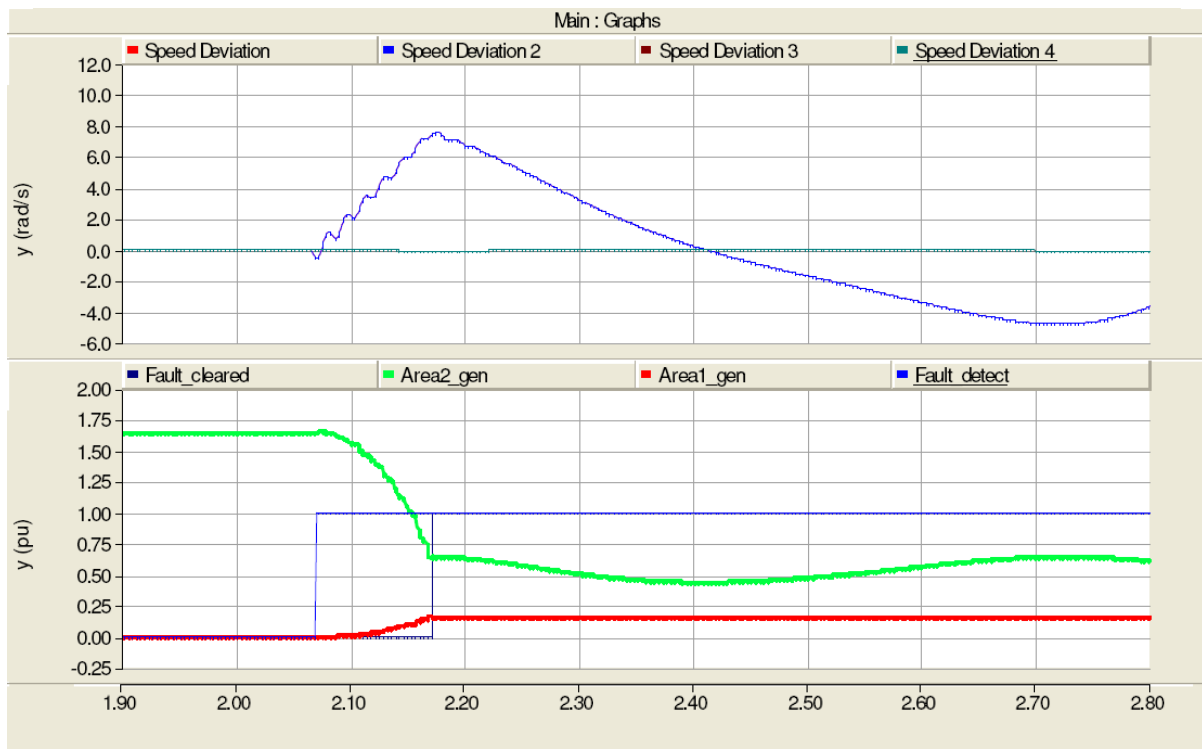


Figure 5.13: Scenario 1 – Stable 106 ms fault

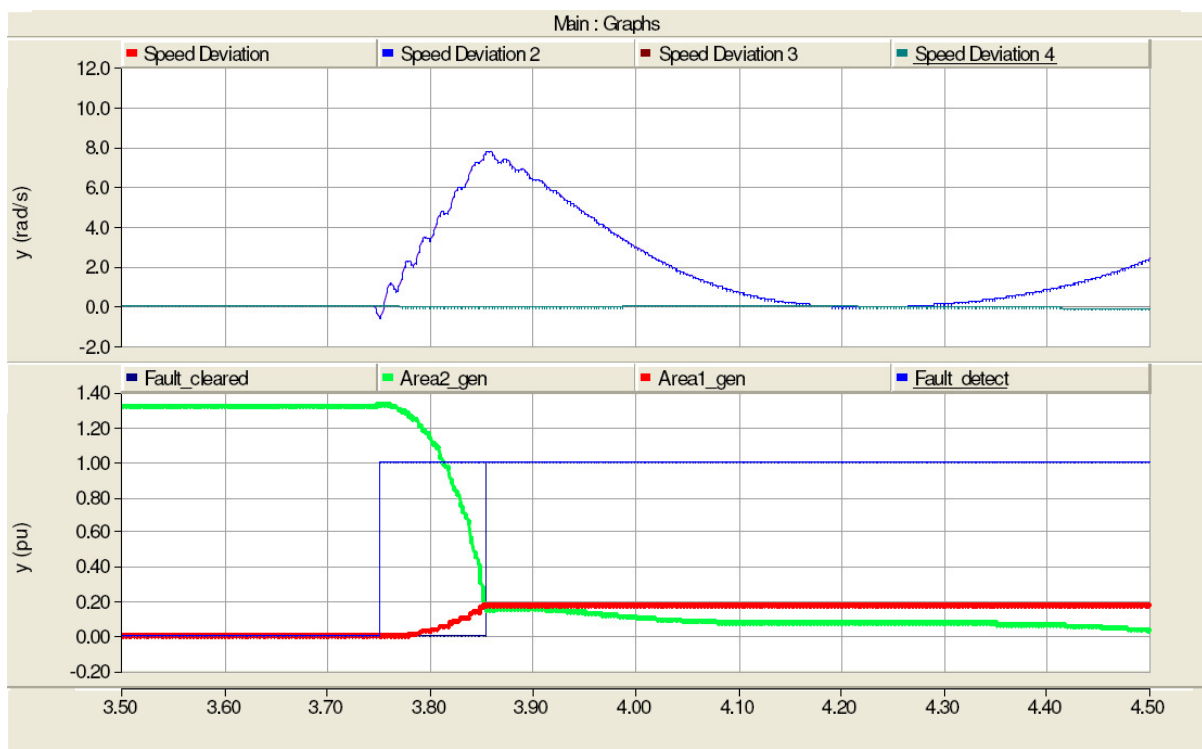


Figure 5.14: Scenario 1 – Unstable 116 ms fault

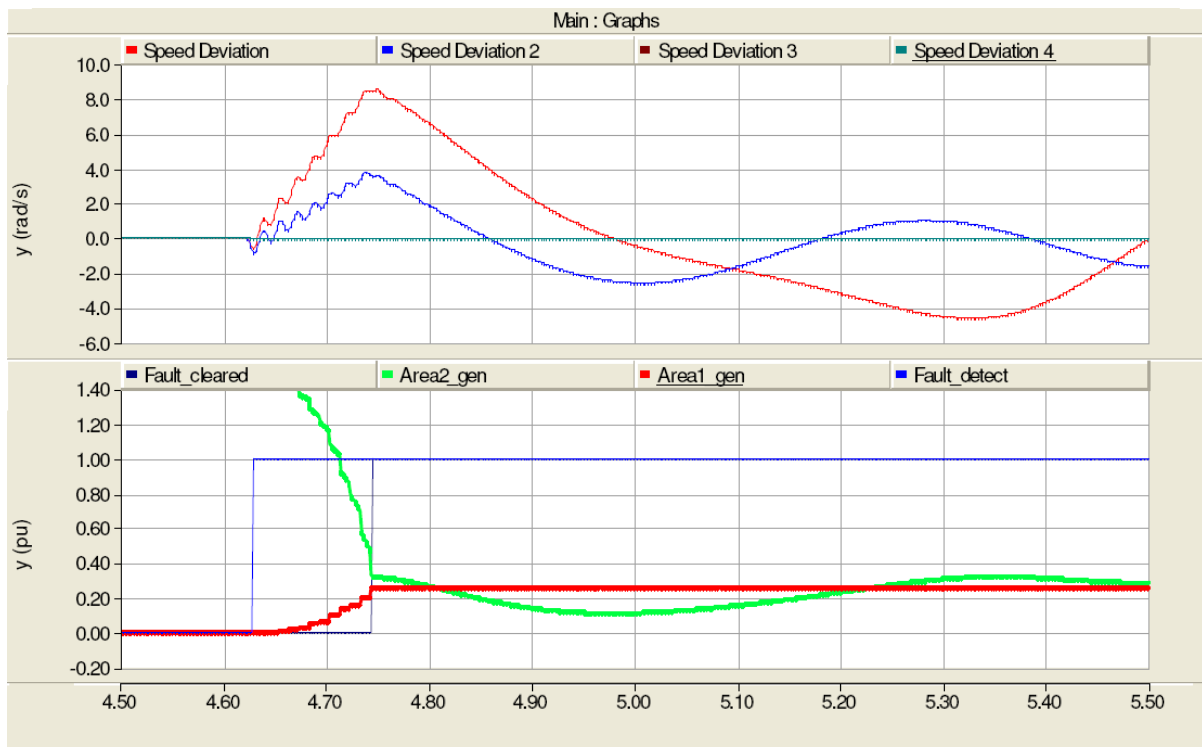


Figure 5.15: Scenario 2 – Stable 108 ms fault

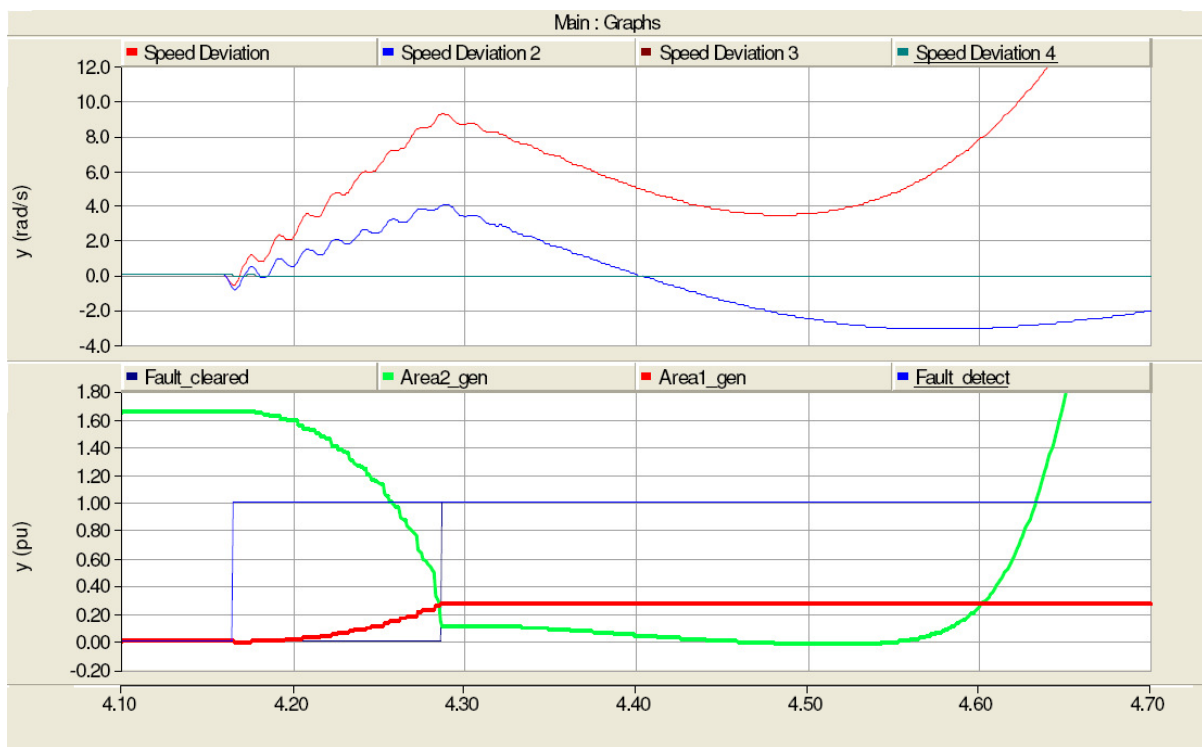


Figure 5.16: Scenario 2 – Unstable 114 ms fault

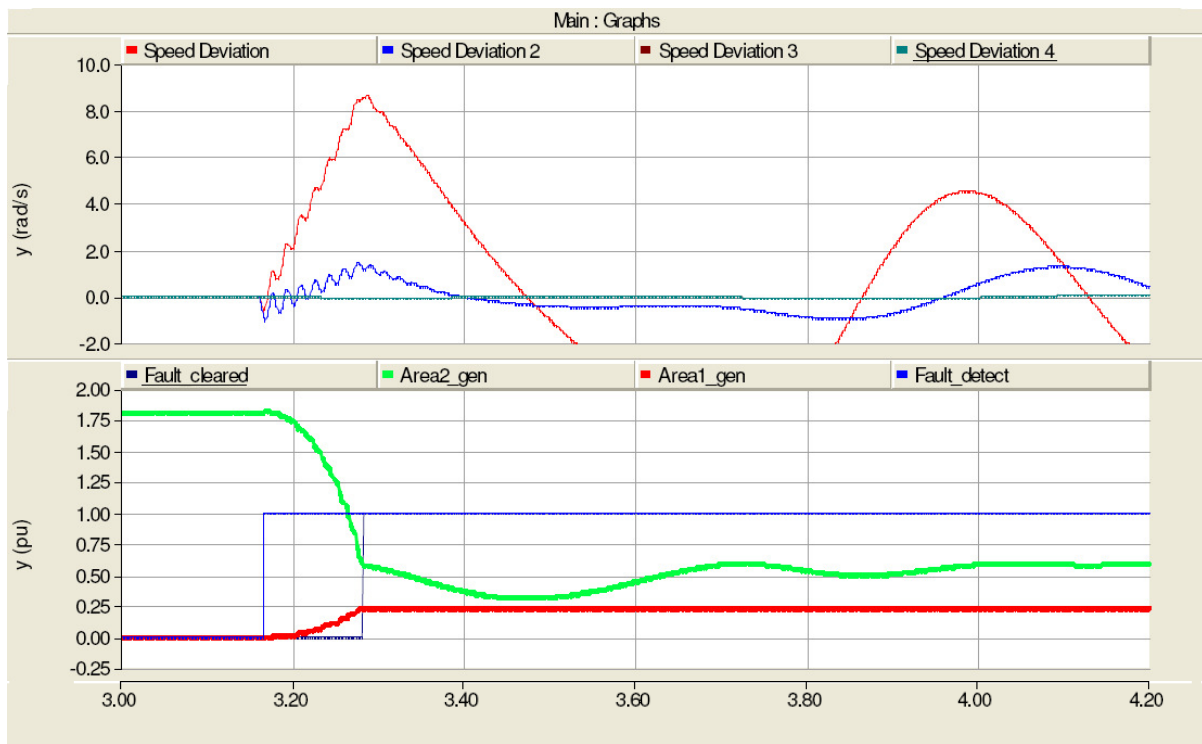


Figure 5.17: Scenario 3 – Stable 121 ms fault

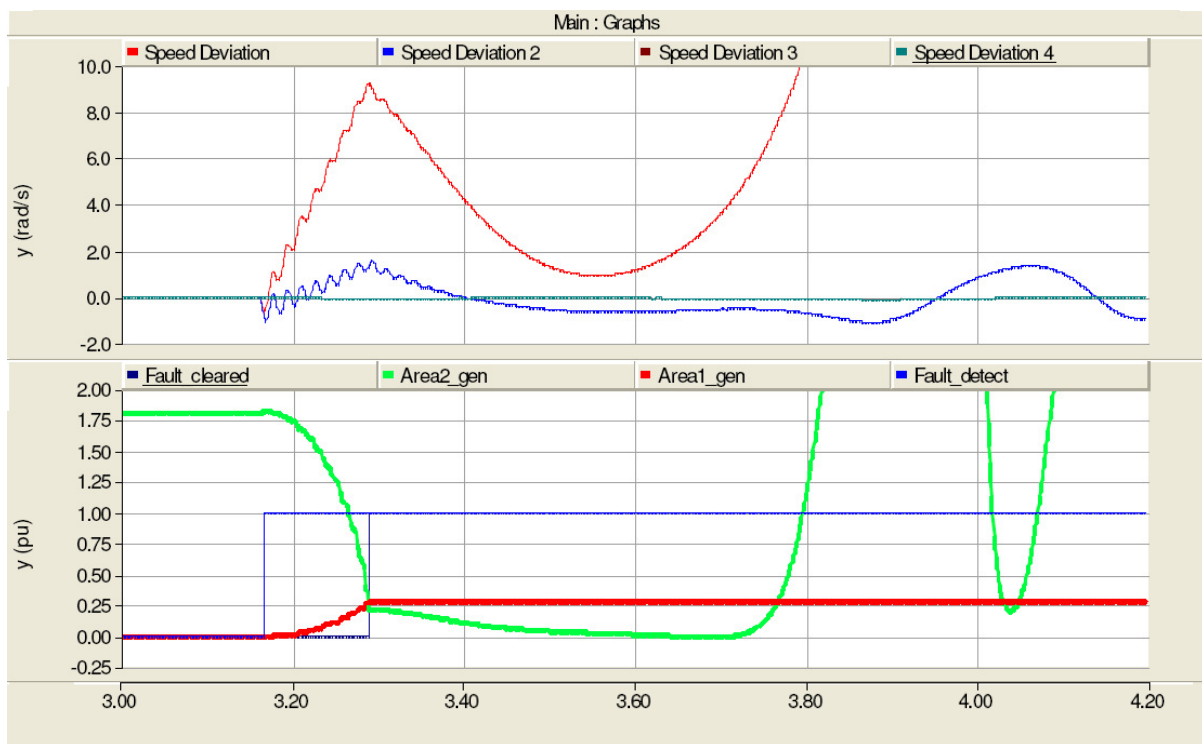


Figure 5.18: Scenario 3 – Unstable 126 ms fault

As discussed earlier, Generator 1 remains stable while Generator 2 becomes unstable in scenario 4. Generator 1 must therefore not be tripped as can be seen from the equal area curves in Figure 5.20.

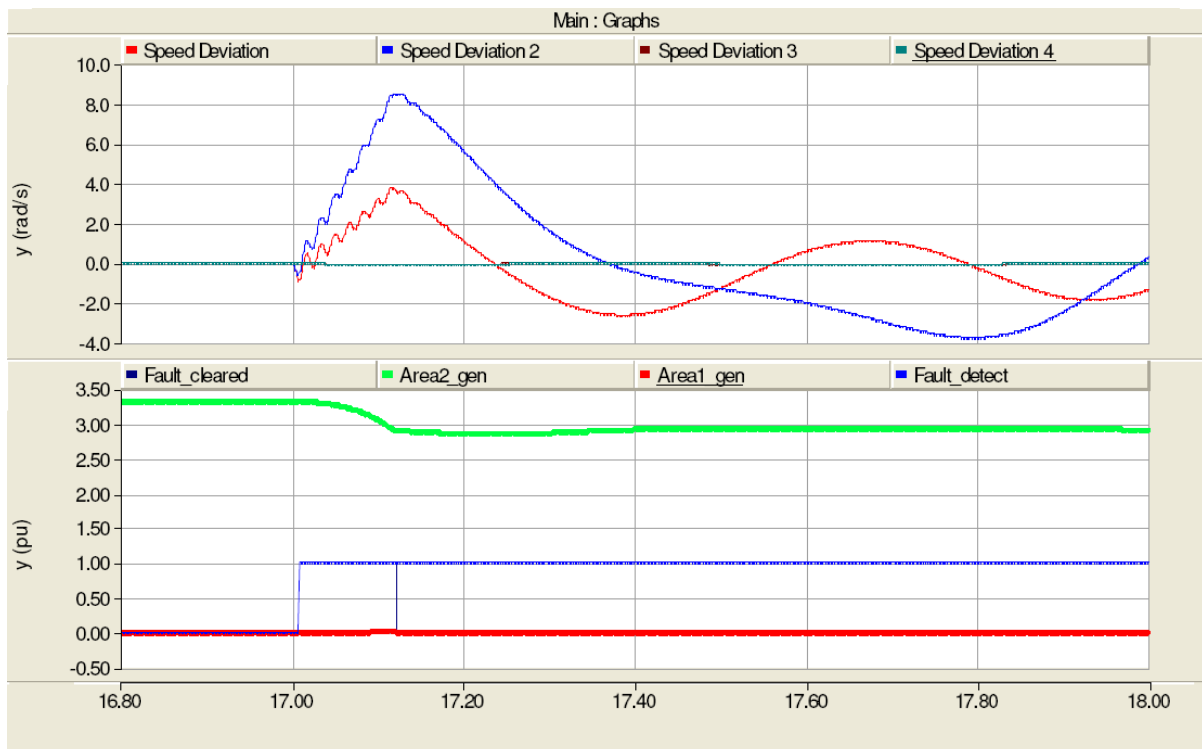


Figure 5.19: Scenario 4 – Stable 120 ms fault

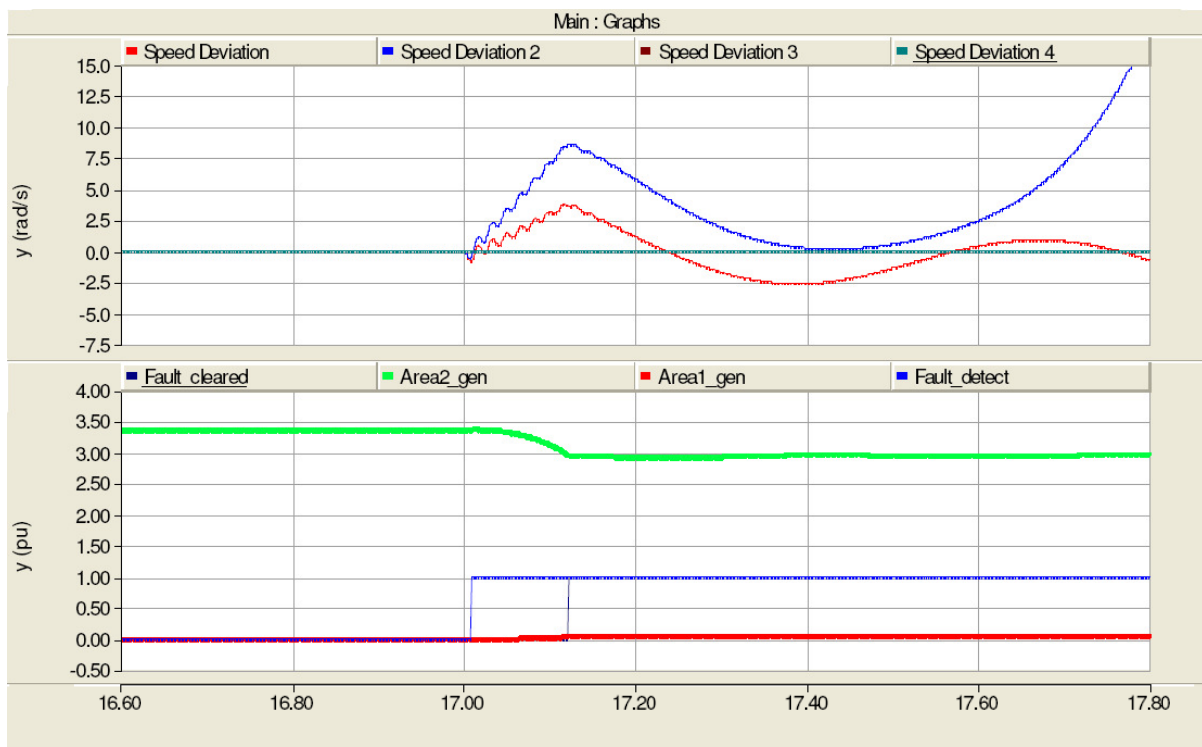


Figure 5.20: Scenario 4 – Generator 1 Stable 130 ms fault

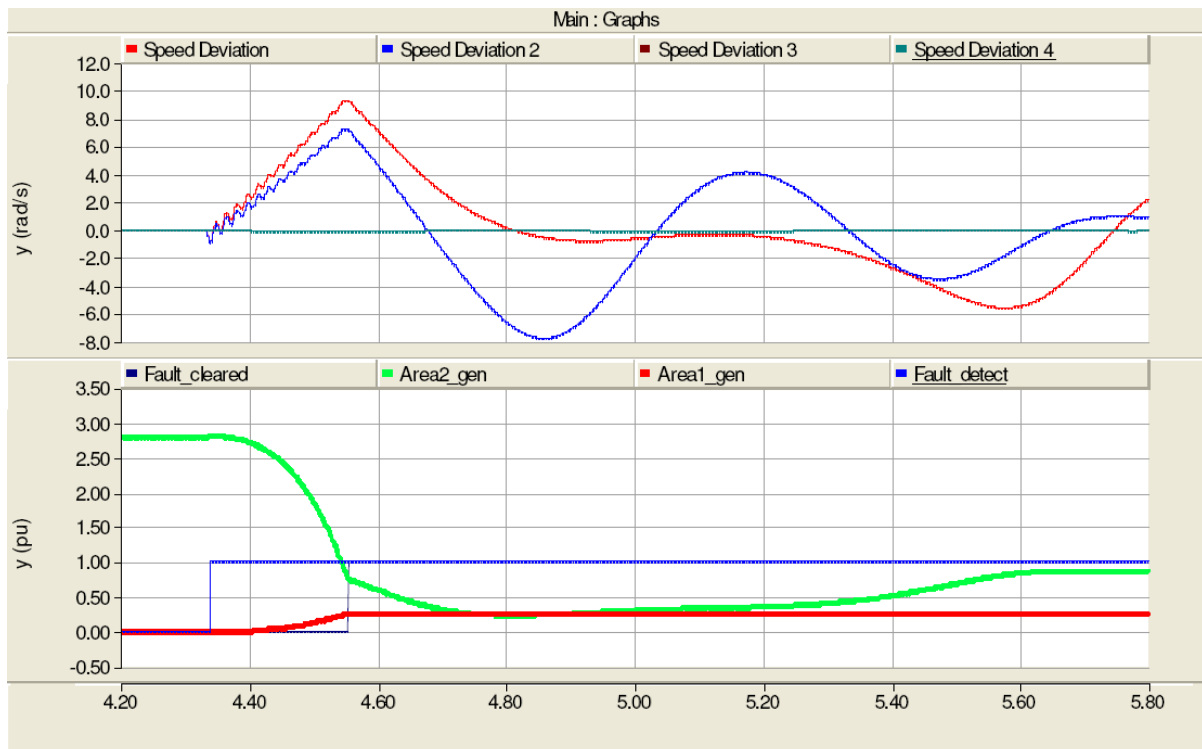


Figure 5.21: Scenario 5 – Stable 220 ms fault

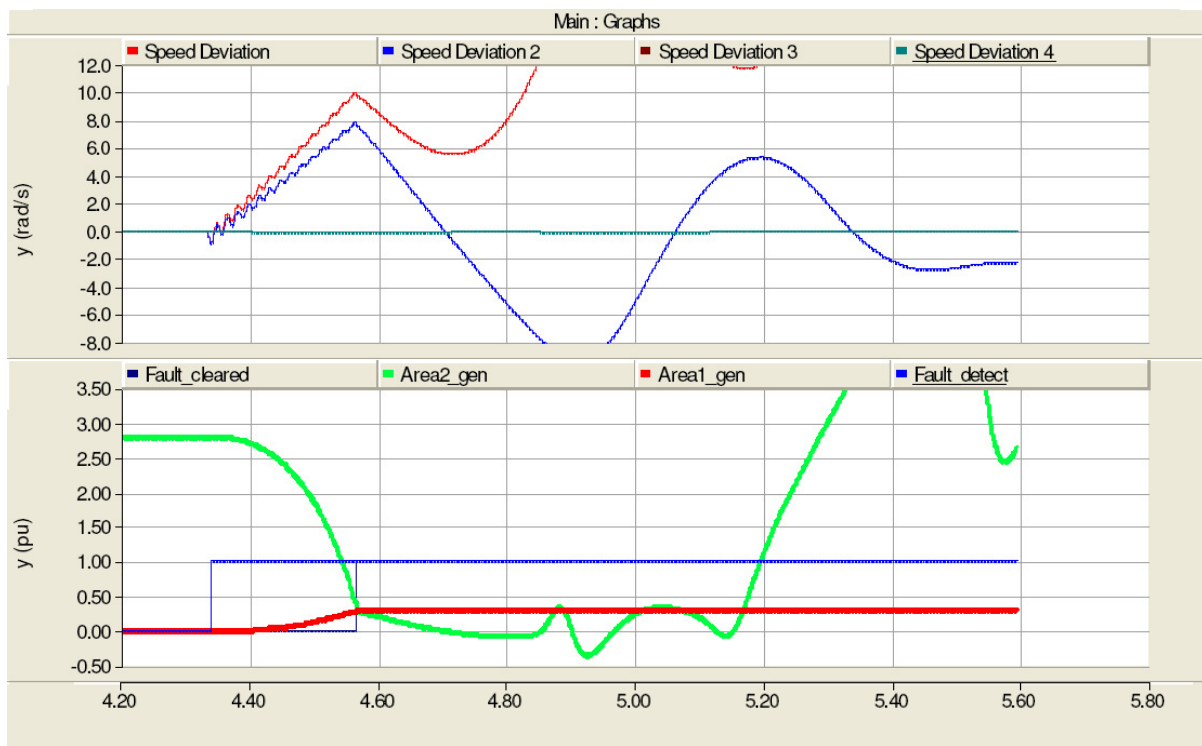


Figure 5.22: Scenario 5 – Unstable 230 ms fault

5.10 BLOCK TRIPPING FOR STABLE FAULT SCENARIO

The simulations done in section 5.8 indicated that the pole-slip function did not trip the generator during a fault after which stability was maintained. The margin of error is less than 10 ms for all scenarios. If the fault duration lies within the 10 ms error margin, the generator will rather refrain from tripping an unstable machine instead of tripping a generator that could have remained stable after the fault was cleared. If the generator would remain stable after a fault, the pole-slip function will not trip the machine regardless of how long the fault duration was.

As discussed in section 5.8, Generator 1 remains stable while Generator 2 becomes unstable in scenario 4. This is because Generator 2 was heavily loaded before the fault, while Generator 1 was lightly loaded. Generator 1 was not tripped even when Generator 2 became unstable. This ensures that Generator 1 can remain online and improve network stability after Generator 2 was tripped.

5.11 DEPENDENCE ON NETWORK SWITCHING CONFIGURATIONS

5.11.1 SHUNT LOADS

Both the impedance scheme function and the new pole-slip function is dependant on the network switching scenarios. However, the new pole-slip function measures in real time what the shunt load active and reactive power is and adjusts itself accordingly. The accuracy of the new pole-slip function is therefore not influenced by shunt loads, whereas shunt loads can cause the conventional impedance relays to malfunction.

5.11.2 TRANSMISSION LINES

The transmission line feeder power flow is monitored as is explained in section 3.6. With this power-flow information, it can be determined which transmission line feeders are in operation. When one of the transmission line feeders is isolated / opened, the relay will detect that no active power flows through that specific transmission line and will accordingly adjust the algorithm to exclude that transmission line impedance from the Thévenin equivalent circuits as was explained in section 4.8.6.

The accuracy of the new pole-slip function is therefore not influenced by switching of transmission lines at the power station, whereas different network configurations can cause the conventional impedance relays to malfunction.

5.11.3 SERIES CAPACITORS

Series capacitors are used in transmission lines longer than 200 km to compensate for the transmission line inductance [57]. Figure 5.23 shows a typical series capacitor bank used in a long transmission line. MOVs, in parallel to the capacitors, are typically used to protect the series capacitors from overvoltages during fault conditions on the transmission line [58]. The bypass breaker in parallel to the series capacitors will also close immediately when a fault occurs to direct the fault current away from the series capacitors [58]. The closed breaker and short-circuited MOV will cause the transmission line impedance to change.



Figure 5.23: Series capacitors in all three phases of a transmission line [58]

In the case when a power station is isolated from other power stations via a long transmission line, the shorted series capacitors (during the fault) will cause the line impedance to increase. With higher line impedance than what the relay is programmed for, the pole-slip function will refrain from tripping even though the generator can become unstable. But with increased line impedance, the generator is likely not to be mechanically damaged after one pole-slip as is explained in section 2.12, and can therefore be tripped by conventional pole-slip protection after the first pole-slip.

The part of the grid, which is of importance for the new pole-slip function, is only the transmission lines between the power station under consideration and the closest other power station. It is recommended in section 7.4 that further fields of study should include the behaviour of the bypass breakers on series capacitors as well as the behaviour of MOVs that could be present in lines longer than 200km.

5.12 EASE OF SETTING THE POLE-SLIP RELAYS

5.12.1 IMPEDANCE POLE-SLIP FUNCTION

The impedance pole-slip protection function requires the settings as shown in Figure 5.24.

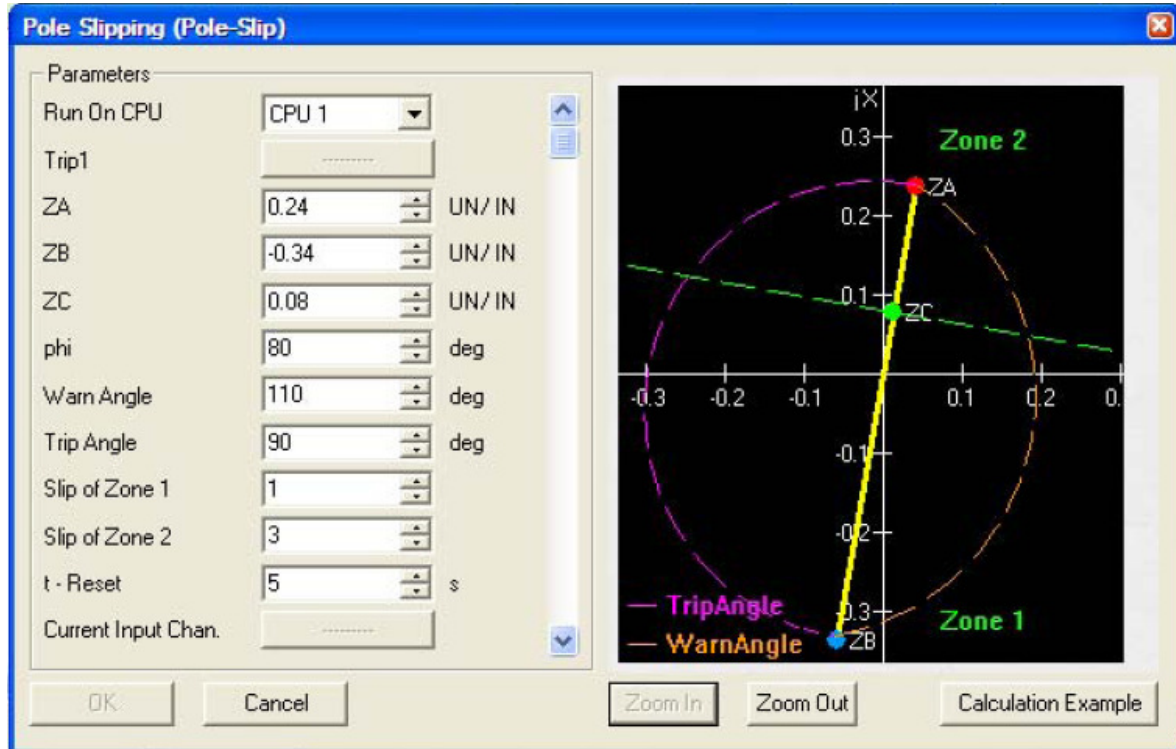


Figure 5.24: Typical Impedance scheme pole-slip protection user interface

The impedances required are interpreted as follows:

- Z_A Impedance of “the rest of the network” as measured from the generator terminals
- Z_B The generator direct-axis impedance (X_d')
- Z_C The margin between zone 1 and zone 2. Zone 1 typically represents the impedance of the generator and step-up transformer combination. Zone 2 represents the impedance of the rest of the network (excluding the step-up transformer).

The most difficult impedance to estimate is Z_A , since Z_A changes every time network switching is done. The impedance scheme protection can malfunction because of different switching scenarios and shunt loads as is explained in section 5.11.

5.12.2 NEW POLE-SLIP FUNCTION

The new pole-slip function requires the transmission line and transformer parameters as shown in Figure 5.1. It also requires the following generator parameters:

- X_d - direct-axis reactance

- X_d' – direct-axis transient reactance
- X_q – quadrature-axis reactance
- Power and Voltage rating
- H -factor for generator / prime-mover combination
- Generator Type – Salient Pole / Round Rotor

The generator parameters are relatively easy to obtain from manufacturers datasheets. The transmission line impedance needs careful consideration of where the closest power stations to the one under consideration are. An estimate of Z_{inf} must also be made. If Z_{inf} is difficult to calculate, it can typically be estimated as $0.05 \times Z_{line}$.

5.13 SIMPLICITY TO TEST THE FUNCTION

5.13.1 IMPEDANCE POLE-SLIP FUNCTION

The impedance pole-slip function can only be accurately tested by using a secondary injection set with a *COMTRADE* file [37]. The *COMTRADE* file can be created by using simulations from software like PSCAD. The *COMTRADE* file contains three-phase current and voltage values of a pole-slip scenario. These values can be reproduced by the secondary injection set in terms of physical current and voltage outputs.

A *COMTRADE* file needs to be developed for every size generator (or motor) to be tested. The *COMTRADE* simulation must incorporate the exact network impedance scenarios as well in order to accurately test the impedance pole-slip function. That means that a time-consuming, complex simulation needs to be done every time a new motor or generator pole-slip protection function is tested.

Commissioning engineers and technicians often do not have accurate simulated pole-slip current and voltage values in a *COMTRADE* file to properly test the pole-slip function. It is therefore very difficult to prove simple aspects like CT and VT polarity connections when an accurate *COMTRADE* file is not available.

5.13.2 NEW POLE-SLIP FUNCTION

5.13.2.1 Steady-state Testing

The typical communication setup that is required for the new pole-slip function was shown in Figure 4.35. A software or hardware link can be used to transfer the tie-breaker status to each relay. A software link is required for transmitting the E_q' , $\delta_{post-fault}$ and δ_{fault} for all the generators.

Each generator protection relay needs to know the status of the E_q' , $\delta_{post-fault}$ and δ_{fault} variables of all the other generators. However, only $\delta_{post-fault}$ and δ_{fault} is required during transient conditions. E_q' is regarded as constant during transient conditions. The pre-fault E_q' value for all the generators will be stored in each protection relay for use in transient conditions.

The testing procedure for the new pole-slip protection function is explained in Chapter 6. Since the new pole-slip logics are already tested to be working correctly, the most important aspect to test is the communications interface connections to the relay. The communication transfer of E_q' , $\delta_{post-fault}$ and δ_{fault} can be tested by forcing a value of E_q' , $\delta_{post-fault}$ and δ_{fault} in each protection relay. It must then be confirmed that the other protection relays display the forced value of E_q' , $\delta_{post-fault}$ and δ_{fault} on their mimics. The tie-breaker status must also be confirmed to correctly display on all the relays.

When the generator is in operation, the sign of the power angle (on the relay mimic) can be used to determine whether the CT and VT connections are correct. Table 5.5 gives the power angle ranges for correct CT and VT connections for motors and generators. Section 2.2 discusses synchronous machine conventions that is applicable to the new pole-slip protection function. The pole-slip function developed in this study does not include protection for motors, but the angles for motors are shown in the table below for clarity.

Table 5.5: Power Angle ranges of Synchronous Generators and Motors

	Power Angle δ
Motor	$\delta \leq 0$
Generator	$\delta \geq 0$

The power angle calculation can be tested by injecting any arbitrary currents and voltages into the relay. The power angle on the relay mimic must correspond to the equations in Table 2.1. Care must be taken on whether the injected currents and voltages simulate an over- or an underexcited machine. If the reactive power (Q) on the relay Mimic is negative or zero, the underexcited equation is used and when Q is positive, the overexcited equation is used.

The transfer angle over the step-up transformer is calculated by using the equation below (refer to section 4.7.1):

$$\delta_{Trfr} = \sin^{-1} \left(\frac{P \cdot X_{Tx}}{V_{pri} \cdot V_{sec}} \right) \quad (5.3)$$

The sign of the power angle must be positive for positive active power. The CT connections can be verified for positive active power to result in a positive power angle over the step-up transformer.

The transfer angle over the transmission line is calculated by the following equations (refer to section 3.7):

$$\phi_{corrected} = \tan^{-1} \left(\frac{Q_{Line_Total}}{P_{Line_Total}} \right) \quad (5.4)$$

$$|Z_{a_corrected}| = \frac{|V_{pu}|^2}{\sqrt{(P_{Line_Total})^2 - (Q_{Line_Total})^2}} \quad (5.5)$$

From Figure 3.14, the angle α :

$$X_{a_corrected} = |Z_{a_corrected}| \cdot \sin(\phi_{corrected}) \quad (5.6)$$

$$R_{a_corrected} = |Z_{a_corrected}| \cdot \cos(\phi_{corrected}) \quad (5.7)$$

$$\alpha = \tan^{-1} \left| \frac{X_{Tline} - X_{a_corrected}}{R_{a_corrected} - R_{Tline}} \right| \quad (5.8)$$

The power angle over the transmission line is calculated from Figure 3.14 as:

$$\delta_{Tline} = \alpha + \phi_{corrected} \quad (5.9)$$

The transmission line power angle can be verified by substituting injected power values into the above equations for different values of P_{line} and Q_{line} . The value of the transmission line angle on the relay mimic must correlate with the calculated values from above equations.

5.13.2.2 Transient Testing

In order to test the transient operation of the new pole-slip function, a *COMTRADE* file must be available with the applicable voltage and current values. The transient testing is therefore not any easier than the testing of the conventional impedance pole-slip relays. However, if the steady-state testing was done properly to prove correct CT and VT polarities, the transient testing is not required. This will obviously depend on whether the client wants to get the transient testing done.

It can be concluded that although the new pole-slip function is a more complex function than the conventional impedance pole-slip functions, it is easier to test the steady-state operation of the new

function. With the steady-state testing done, the transient operation will also work as is proven with the RTDS testing in chapter 6.

5.14 SUMMARY

The performance of the new pole-slip function was evaluated by building the new pole-slip algorithm logics in PSCAD. Since it is impractical to do stability tests on a real power system, PSCAD was used to simulate power system pole slip conditions. In parallel to this power system simulation, the new pole-slip protection logics were executed in PSCAD and tested by comparing the results with the PSCAD power system simulation measurements.

The different stages in the new pole-slip algorithm were checked. Some of the stages include post-fault voltage prediction and transient power angle calculations. The checks confirmed that the algorithm calculated the transient power angles with an error of less than 0.5 degrees. The post-fault voltage magnitudes were also calculated with sufficient accuracy.

The evaluation criteria included tripping before a pole-slip occurs, but to refrain from tripping if stability could be maintained after a fault is cleared. It was found that the new pole-slip function could predict stability within a 10 ms fault duration error margin. This means that the new pole-slip function will predict stability accurately for all fault durations, except for a 10 ms band. In the unlikely scenario that the fault duration lies within this 10 ms band, the pole-slip function will not trip the machine although it will become unstable after the fault. The pole-slip function was designed to be conservative towards not giving spurious trips. For inaccuracies, the new pole-slip function will rather refrain from tripping instead of tripping where stability could be maintained after the fault is cleared. For most network configurations, it was found that the error margin for the fault duration is less than 10 ms.

The ease of setting and commissioning the new pole-slip function was discussed. It was concluded that the steady-state testing of the new pole-slip function can easily be done with a secondary injection set. When the steady-state power angle and power factor signs are correct for the steady-state conditions, the transient portion of the pole-slip function will also work correctly. If the client insists on testing the transient portion of the pole-slip function, PSCAD simulation data must be used in the form of a *COMTRADE* file to inject currents and voltages with a secondary injection set. It was concluded that the transient portion of the new pole-slip function would require the same skill and effort to test as the conventional impedance pole-slip schemes.