A Study of Synchronized Sampling Based Fault Location Algorithm Performance under Power Swing and Out-of-step Conditions

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***Abstract*—Relay misoperations play an important role in cascading blackouts. Power swing and out-of-step conditions caused by large disturbances in the system may result in relay misoperations. This effect is analyzed and simulated in this paper. Synchronized sampling based fault location (SSFL) algorithm was proposed as part of an advanced fault analysis tool to give precise fault information and verify relay judgments. This paper further analyzes the algorithm under power swing and out-of-step conditions and tests it by both static and dynamic scenarios generated in ATP. The test results indicate that SSFL algorithm performs better than distance relay under power swing and out-of-step conditions and can be used as a robust fault analysis tool for practical use.**

***Keywords*—fault diagnosis, fault location, out-of-step, power swing, power system faults, power system protection, protective relaying, synchronized sampling.**

I. Introduction

Power systems are subjected to a variety of small or large disturbances during its operating conditions [1]. Changes in regulations and the opening of the power markets result in rapid changes in the way that the power grid is operated. The major blackouts in the US, such as Midwest and Northeast blackout on August 14, 2003 and Western blackouts on July 2 and August 10, 1996, are the results of heavy load and a number of multiple outages occur within a short period of time.

The variation in power flow which occurs when system generator rotor angles are advancing or retarding relative to each other is referred as power swing [2], which is often caused by fault, line switching, or loss of generation. In most cases, the power swings are stable if the generators do not slip poles and the system reaches a new state of equilibrium. On the other hand, if the system is transiently unstable and the power swing results in generator experiencing pole-slipping eventually leading to a loss of synchronism between groups of generators, it is called an out-of-step (OOS) condition.

Distance relays are proven to be influenced by power swing [2][3]. In some situation of power swing and out-of-step conditions, the distance relay can not distinguish the power swing from three-phase line fault. According to a report from the latest 2003 blackout [4], a lot of distance relays operated in zone 3 under the overload and power swing situation, which further stressed the system and caused the cascading blackout in the end.

Fault location is a very useful tool to actually locate the fault and verify the occurrence of the fault. Synchronized sampling based fault location algorithm has been developed earlier and its good performance was demonstrated [5]. In [6,7], an advanced real-time fault analysis tool, using Neural network based fault detection and classification (NNFDC) algorithm and synchronized sampling based fault location (SSFL) algorithm, is proposed to give more reliable and accurate fault detection, classification and location than conventional relays.

In this paper, we focus on evaluating the performance of SSFL algorithm especially under the power swing and OOS conditions. The paper describes a series of detailed simulation in ATP used to model the power swing and test the SSFL algorithm. If the test results can prove that SSFL algorithm is marginally affected by the power swing and OOS conditions, the SSFL algorithm will be more suitable as a relay operation confirmation tool to correct the relay misoperations.

This paper first introduces, in Section II, the fundamentals of the power swing and out-of-step characteristics. The analysis of the SSFL algorithm under the power swing and out-of-step condition is introduced in Section III. Section IV presents the test results and analysis for the performance evaluation of SSFL algorithm. Conclusions of this paper are given in Section V.

II. Power Swing and Its Influence on Distance Relay

The real power system is a dynamic system and the normal operation condition may be altered by certain disturbances caused by faults, load rejection, line switching, and loss of excitation. Power swing or even out-of-step may occur when mentioned disturbances happen [2].

Distance relay for transmission line protection is designed to isolate the faults that occurred within the desired zone only. It is not supposed to trip the line during the power swing caused by the disturbances outside the protected line. Even for the out-of-step conditions, the preferred operation is to separate the system with an out-of-step tripping (OST) protection at pre-selected network locations and blocking

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other distance relays by out-of-step blocking (OSB) protection [2].

Power swing, either stable or unstable, may have impacts on distance relay judgment. Such kind of relay misoperation may make the weakened system even worse. The reason is given below.

An example of two machine system is shown in Fig. 1. For steady state, assume the two sources have the terminal voltages as $E_{S0}\angle\delta_0$ and $E_{R0}\angle 0$ respectively, where the phase angle of the receiving end generator is always used as the angle reference. As for the two-machine system, the power swing appears to a relay as an oscillation of magnitudes and the angles of two generators. At certain time during the power swing, assume the voltages are $E_S\angle\delta$ and $E_R\angle 0$.

Then we have

$$\dot{I} = \frac{E_S\angle\delta - E_R\angle 0}{Z} \tag{1}$$

Where $Z = X_S + Z_L + X_R$. From Fig.1, we have

$$\dot{V}_m = E_S\angle\delta - jX_S\cdot\dot{I} \tag{2}$$

Therefore, the apparent impedance seen by the relay at bus *m* can be expressed as

$$Z_m = \frac{\dot{V}_m}{\dot{I}} = -jX_S + jZ\frac{E_S\angle\delta}{E_S\angle\delta - E_R} \tag{3}$$

The trajectory of Z_m with respect to E_S, E_R and δ can be found in [2,3]. When the angle difference δ becomes large enough, the trajectory of Z_m will float into the relay setting area and cause relay misoperation.

Now, let us extend the idea to regular multi-machine systems. Still look at Fig. 1. Consider the line in the middle as one of the transmission lines in the system with the terminal voltages of $V_m\angle\theta_m$ and $V_n\angle\theta_n$. The other parts outside the line represent the rest of the system.

If there is no fault on the line, the impedance seen by relay at bus *m* is,

$$Z_c = \frac{\dot{V}_m}{\dot{I}_m} = \frac{\dot{V}_m}{(\dot{V}_m - \dot{V}_n)/Z_L} = Z_L\left(\frac{1}{1-\left|\frac{V_n}{V_m}\right|\angle\theta_{nm}}\right) \tag{4}$$

According to (4), Z_c is only related to the magnitude ratio $(|V_n/V_m|)$ and angle difference $(\theta_{nm} = \theta_n - \theta_m)$ of the bus voltages at the two ends. When power swing occurs in the system, $V_m\angle\theta_m$ and $V_n\angle\theta_n$ will oscillate during that time. Assuming line impedance $Z_L = 1\angle 80^\circ$, we can draw the figure of Z_c trajectories in the R-X phase with respect to voltage magnitude ratios and angle differences, as shown in Fig. 2.

This is very similar to the figures drawn in [2,3]. The conclusion is also similar as in the two-machine system. If the power swing causes θ_{nm} large enough, the impedance seen by relay will reach the zone settings and relay will misoperate.

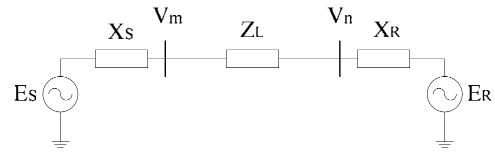


Fig. 1. A Two Machine System

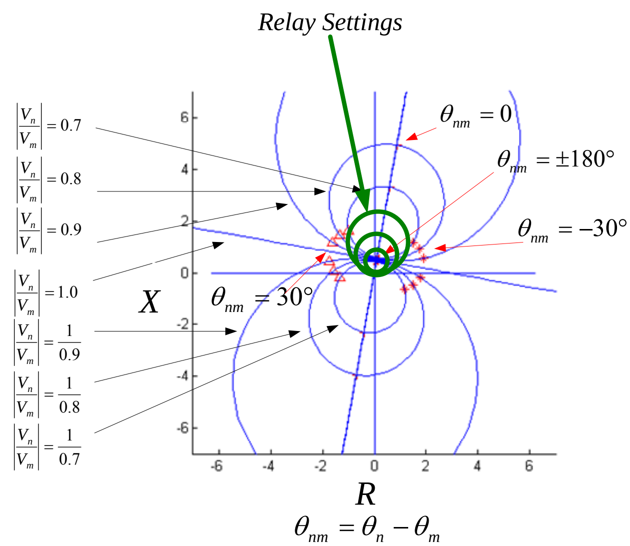


Fig.2. Z_c trajectory in the R-X phase

III. SSFL Algorithm Performance under Power Swing

Fault location techniques are used to precisely determine location of a fault on a transmission line. They are very important because the fault location can confirm whether a fault has indeed occurred on the line. If used online, it can also serve as a relay verification tool for a back-up fault detection algorithm. When the fault is precisely located, one should know which breakers are responsible to clear that fault, and unnecessary trips that could spread an outage should be avoided. Both the dependability and security of protection system operation will be improved by incorporating a precise fault location function.

Synchronized sampling based fault location algorithm uses raw samples of voltage and current data synchronously taken from two ends of the transmission line [8]. This can be achieved using Global Positioning Satellite (GPS) receivers, which generate the time reference for data acquisition equipment.

A. Representation of SSFL Algorithm for Short Line and Long Line Models

The algorithm is derived by solving the classic transmission line differential equations [8,9]. Short line algorithm and long line algorithm are derived using lumped RL line parameters and distributed RLC line parameters respectively. The principle of this algorithm is shown in Fig.3. The voltage and current at the faulted point can be represented by both sending end data and receiving end data using linear relationship because the homogenous parameter line is separated by the fault point. If there is no fault on the line, the fault location

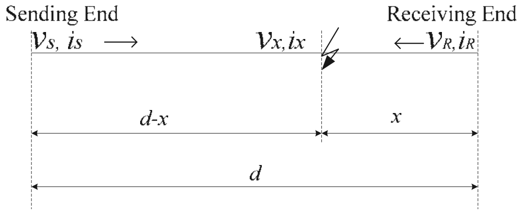


Fig. 3. A faulted transmission line

can not be found because there are multiple solutions in that case. Different algorithms use different techniques to find the fault point [8].

For short line, which is usually shorter than 50 miles, the fault location can be calculated directly using minimum square estimate method, as follows [8]:

$$x = \frac{-\sum_{m=a,b,c}\sum_{k=1}^{N} A_m(k)B_m(k)}{\sum_{m=a,b,c}\sum_{k=1}^{N} B_m^{\ 2}(k)} \tag{5}$$

Where

$$\begin{aligned} A_m(k) &= v_{ms}(k) - v_{mR}(k) \\ &-d\sum_{p=a,b,c}\left[\left(r_{mp}+\frac{l_{mp}}{\Delta t}\right)i_{pS}(k) - \frac{l_{mp}}{\Delta t}i_{pS}(k-1)\right] \qquad m=a,b,c \end{aligned} \tag{6}$$

$$\begin{aligned} B_m(k) = \sum_{p=a,b,c}\Bigg\{&\left(r_{mp}+\frac{l_{mp}}{\Delta t}\right)\left[i_{pS}(k)+i_{pR}(k)\right] \\ &-\frac{l_{mp}}{\Delta t}\left[i_{pS}(k-1)+i_{pR}(k-1)\right]\Bigg\} \qquad m=a,b,c \end{aligned} \tag{7}$$

where k is the sample point, Δt is sample period, subscription S, R stand for the values from sending end and receiving end of the line.

For long line, we can build the voltage and current profiles along the line based on Bergeron's equation [9]:

$$\begin{aligned} v_{j,k} &= \frac{1}{2}\left[v_{j-1,k-1}+v_{j-1,k+1}\right]+\frac{Z_c}{2}\left[i_{j-1,k-1}+i_{j-1,k+1}\right] \\ &+\frac{R\Delta x}{4}\left[i_{j-1,k-1}+i_{j-1,k+1}\right]-\frac{R\Delta x}{2}i_{j,k} \end{aligned} \tag{8}$$

$$\begin{aligned} i_{j,k} &= \frac{1}{2Z_c}\left[v_{j-1,k-1}-v_{j-1,k+1}\right]+\frac{1}{2}\left[i_{j-1,k-1}+i_{j-1,k+1}\right] \\ &+\frac{R\Delta x}{4Z_c}\left[i_{j-1,k+1}-i_{j-1,k-1}\right] \end{aligned} \tag{9}$$

where $\Delta x = \Delta t/\sqrt{lc}$ is the distance that the wave travels with a sampling period Δt; $Z_c = \sqrt{l/c}$ is the surge impedance. Subscription j is the position of the discretized point of the line and k is the sample point.

The final location is obtained by an indirect method [9], as shown in Fig.4.

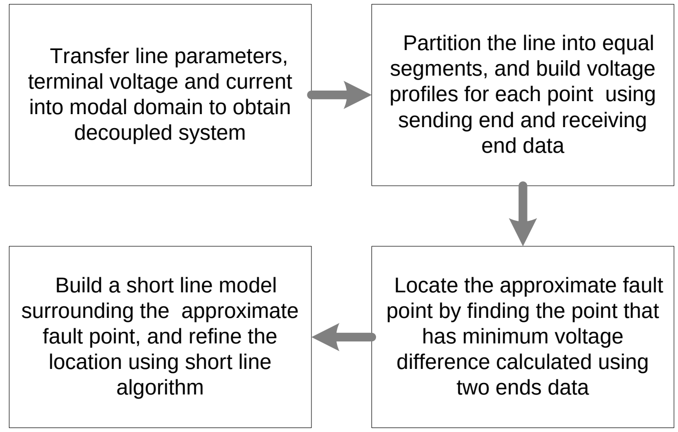


Fig. 4. Steps for long line fault location algorithm

The accuracy of both algorithms is dependent on accuracy of data synchronization, sampling rate and accuracy of line model. It is less affected by fault parameters and system conditions because there is no assumptions for those factors during the derivation.

B. SSFL Algorithm during Power Swing

The performance of SSFL algorithm during power swing relates to two situations. The theoretical analysis will be discussed here.

If there is no line fault occuring during the power swing, the power swing may cause the false judgment of distance relays because the relay will see a low voltage and a high current during the swing. SSFL algorithm will avoid this misjudgment by its inherent characteristics. During the power swing, although the bus voltage and line current at two ends of line will oscillate from time to time, we still have the relation between the line currents seen from two ends $[i_{pS}(k)+i_{pR}(k)] \approx 0$. The reason is that the line parameters are still homogeneous along the entire line as long as there is no fault on it. Then, from (7) we have $B_m(k) \approx 0$. In this case, a reasonable fault location can not be found using (5). Similarly, in the third step of the long line algorithm, as shown in Fig.4, if there is no fault on the line, the voltage difference computed using two ends data is almost the same along the entire line because the line parameters are homogenous. A prominent minimum point can not be found. In this sense, the power swing will not affect the long line algorithm either.

If there is indeed a fault occurring during the power swing, the accuracy of SSFL in locating the fault is evaluated. According to the algorithm derivation, there is no assumption about system conditions. Therefore, the influence of the power swing may be less than for other fault location algorithms.

IV. Performance Evaluation

A. Simulation of Power Swing

Any power system simulation tool that can model generator dynamics is capable for simulating power swing. In this paper, we use Alternative Transient Program (ATP) to implement the simulation [10].

Statically, we can use two-machine system to imitate a snapshot of power swing. From the local view, whatever the cause is, power swing and OOS will result in the oscillation of bus voltages at both ends of the transmission line. For two-machine system, as shown in Fig.1, we can fix the terminal voltage of receiving end as $E_R\angle 0$ and adjust the voltage magnitude and phase angle of the sending end to simulate the voltage oscillation caused by power swing and OOS condition. Because the frequency of power swing is usually much lower than 60Hz, for one cycle data usually used in fault diagnose algorithm, the terminal voltages will not change too much during the power swing.

To be close to the real situations, the power swing needs to be simulated in a dynamic system. The generator dynamic parameters should be known for the simulated system. In this paper, we setup a test model in ATP based on the WECC 9-bus system. The one-line diagram and its ATP model are shown in Fig.5 and Fig.6 respectively. In ATP model, "SM59" synchronous machine module is used for generator modeling. Transient bus voltage and branch current signals used by SSFL can be obtained by ATP measurement components.

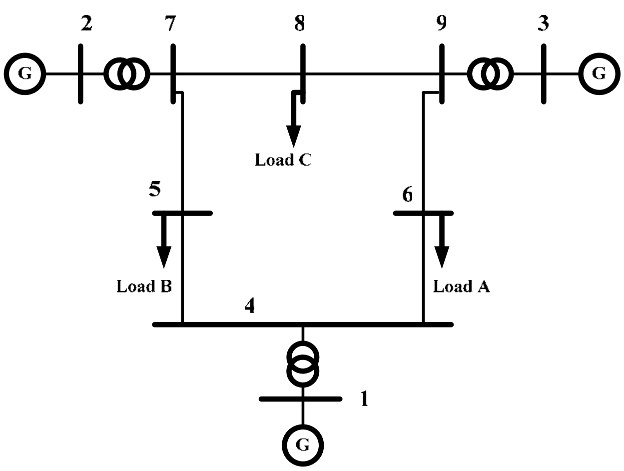


Fig.5. One line diagram of WECC 9-bus system

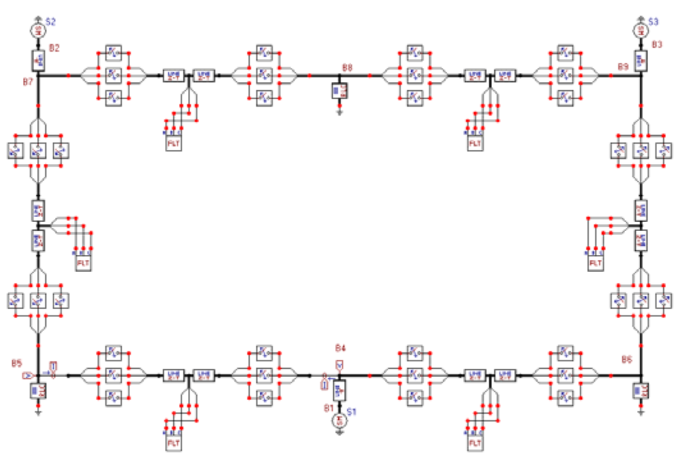


Fig.6. WECC 9-bus system modeled in ATP

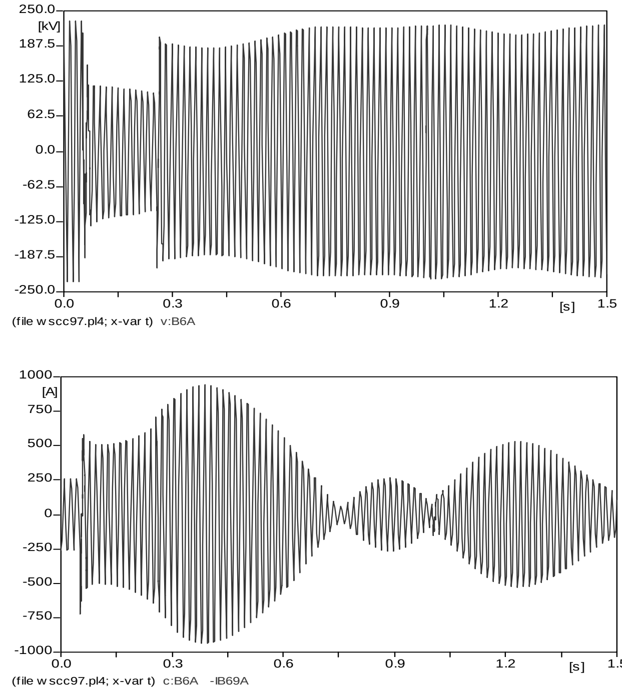


Fig.7. An example of voltage and current profiles during power swing

For this model, SSFL is set up to implement fault location for one of the six transmission lines. Power swing is generated by the disturbances such as line fault, load changing and line switching at locations elsewhere of the system.

Fig.7 is an example of voltage and current signals during a stable power swing in WECC 9-bus system. The voltage signal is taken at bus 6 and the current signal is taken at line 6-9. The power swing is caused by a three-phase fault at middle of the line 4-5. Fault started at 0.05s and is cleared at 0.25s. As can be seen, even for a stable swing, the oscillation is very big for the current.

B. Static Tests using Two-machine Model

The static tests for SSFL are implemented based on the two-machine system shown in Fig. 1. The system is modeled in ATP using short line and long line parameters respectively. The line parameters are obtained from real system models, and are given in the Appendix.

In the static test, we generate a series of normal and fault scenarios during power swing to evaluate the SSFL performance. In this test, fault resistance, incidence angle and sampling rate are fixed as 2Ω, 0° and 20KHz respectively. The test data are generated by the scenarios combining the following four types of parameter pools:

Fault and event types:
No fault, AG, BC, BCG, ABC
Fault locations:
10%, 50%, 90%
Sending end voltage magnitudes (p.u):
0.8, 0.9, 1.0, 1.1, 1.2
Sending end voltage phase angles:
±10° , ±30° , ±60° , ±90° , ±120° , 180°

Total of 55 normal cases and 660 fault cases are generated. For any scenario, the post-fault transient voltage and current signals from both ends are measured simultaneously for one cycle. Those measurements are fed to SSFL algorithm to implement the fault location computing. The performance of SSFL during power swing is evaluated in two aspects:

1. Dependability/Security. As by the similar definition for relays, SSFL should "find" the fault location when there is a fault and it should not "find" the fault location when there is no fault.
2. Accuracy. It is defined as the error of SSFL when locating the fault during the power swing:

$$Error(\%) = \frac{|Actual\ Location - Computed\ Location|}{Line\ Length} \times 100 \qquad (10)$$

The results of dependability/security tests are shown in Table I. As expected, SSFL algorithm did well in distinguishing the fault and normal state even during the power swing. Therefore, for the detection issue, the power swing will not cause the misjudgment of SSFL.

The results of the accuracy tests are shown in Fig.8 and Fig.9 for short line and long line model respectively. In each figure, the upper diagram indicates the average error for each fault type and the lower diagram shows the error distribution with respect to fault type and angle difference. The fault location and sending end voltage magnitude are fixed as 50 and 1.0 p.u respectively in those lower diagrams.

TABLE I
THE TEST RESULTS OF RELIABILITY TESTING

	Case 1	Case 2
Short line algorithm	0 of 55	0 of 660
Long line algorithm	0 of 55	0 of 660

Case1: Number of false cases that detect the fault in non-fault condition
Case2: Number of false cases that cannot locate the real fault

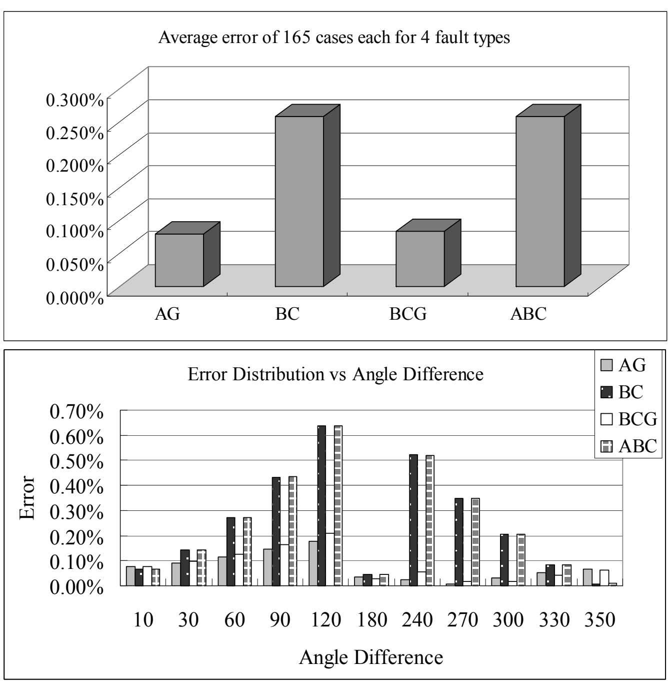


Fig.8. Test results for short line model

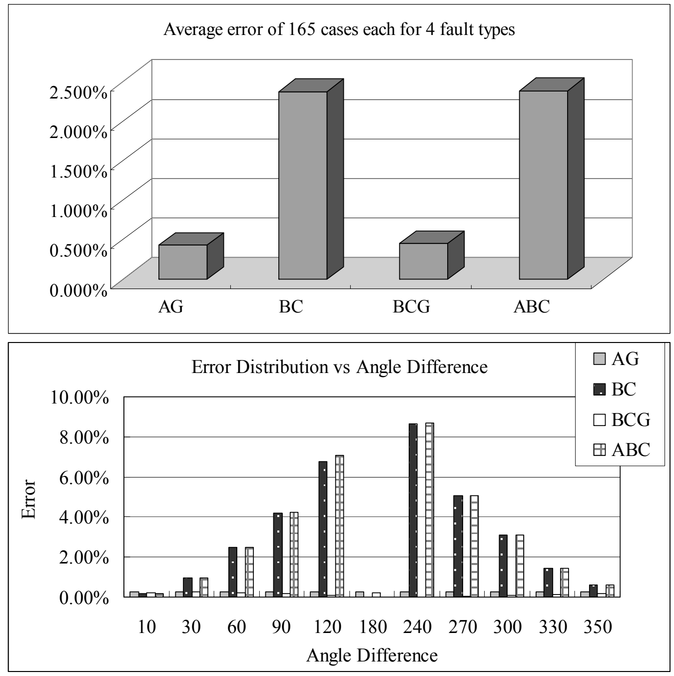


Fig.9. Test result for long line model

Following conclusions can be made by analyzing the test results:

- The accuracy of SSFL is indeed affected by power swing and OOS condition. The maximum error is up to 8.706% for long line model.
- Short line algorithm is less influenced by OOS than the long line algorithm. The maximum error is still under 1% for all scenarios.
- Both algorithms do very well in locating ground fault (AG, BCG) but not so well for the aerial fault (BC, ABC) during the power swing.
- The most determinative parameter for the algorithm accuracy is the terminal angle difference. Usually the larger the angle, the larger the error.
- Most of the cases have error lower than 2% when phase angle difference is lower than 60°, which is the usual situation for a stable power swing.

C. *Dynamic Tests using WECC 9-bus model*

The static tests can only indicate the performance of the SSFL in a theoretical way. The conclusion needs to be justified in the situation close to the real case. In this section, we implement the performance study of SSFL using the dynamic ATP model of WECC 9-bus system that is introduced in Fig. 6. According to the original lumped line parameters, Line 7-8, which has the smallest series impedance, is substituted by the short line RL model. Other lines are modeled as long lines using distributed RLC parameters. The system initial balanced condition is calculated by power flow program.

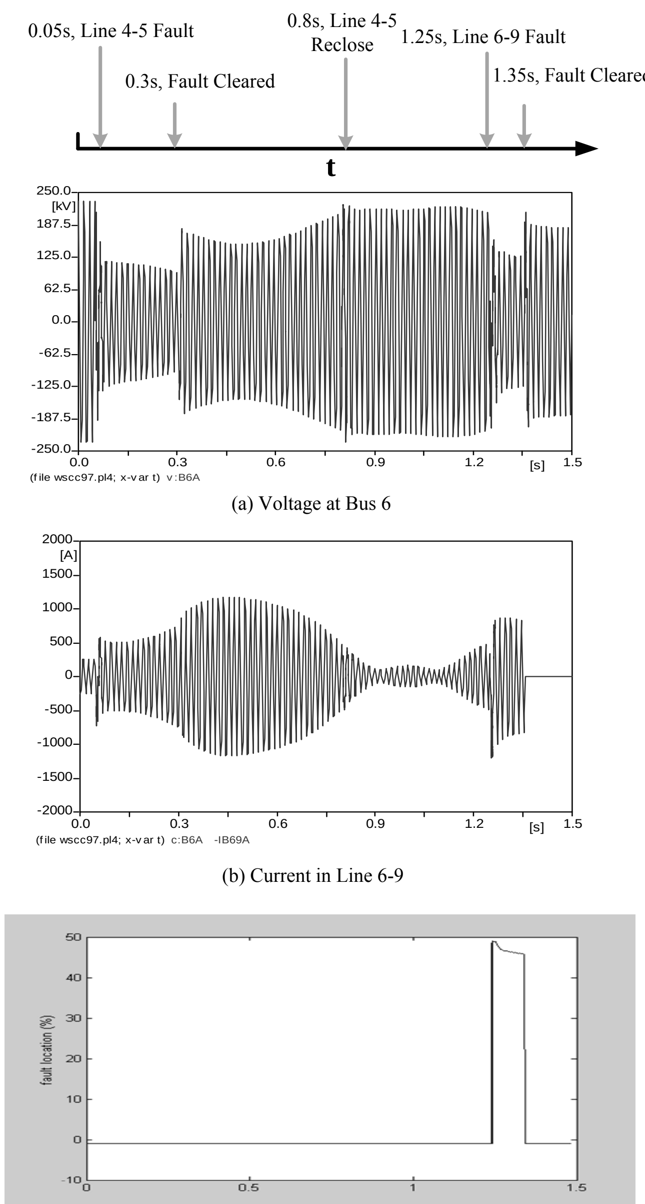
In this test, the SSFL is installed on **line 7-8** and **line 6-9** to study the short line algorithm and long line algorithm respectively. Since the power swing could be caused by many contingencies and may have indefinite appearances, we just create two typical ones to demonstrate two obvious stable swing and unstable swings. The sequence of triggering events for each type of power swing is stated below:

i) **Stable swing**: Three-phase fault in the middle of line 4-5, starting at 0.05s and clearing at 0.30s. Then line 4-5 is reclosed at 0.80s.

ii) **Ustable swing (OOS)**: Three-phase fault in the middle of line 4-5, starting at 0.05s and clearing at 0.35s. Then line 4-5 is reclosed at 0.80s.

The difference is whether the line 4-5 was cleared before the critical clearing time (CCT). During each type of swing, a second fault (with different fault type and fault location) was placed on the studied line (line 7-8 or line 6-9), starting at 1.25s and clearing at 1.35s.

An assumption is made that other relays in the system will not trip the lines either during a stable swing or during an unstable swing. The entire sequence of events may not be realistic, but it is good for studying the power swing issue.



(a) Voltage at Bus 6

(b) Current in Line 6-9

(c) Fault Location Result

Fig. 10. An example of fault location in WECC 9-bus system

In dynamic tests, we further evaluate SSFL algorithm's dependability/security and accuracy during the power swing. For the former test, SSFL is used for fault location calculation throughout the entire sequence of event. The input data for SSFL is a sliding window with one cycle moving forward from the starting time to the ending time.

An example result of long line algorithm for this test is shown in Fig.10. This scenario is for the case of a stable power swing. The event sequence is labeled on the top. The voltage and current profile of line 6-9 at bus 6 are given in the middle. From the diagram of fault location result, we can see that only the second fault on line 6-9 is "found" by its SSFL algorithm. The event on other lines as well as power swing process, have no influence on fault detection issue for SSFL. For other scenarios in the dependability/security tests, SSFL also performs well.

For accuracy tests, the errors of SSFL when locating the second fault on line 7-8 and line 6-9 during the power swing are measured. The two ends post-fault data of the second fault are measured together for SSFL to compute the final fault location. The definition of fault location error is same as (10).

The results of this test are shown in the Table III and Table IV in the Appendix. By observing the result, most of the conclusions are the same as in the static tests. The short line algorithm is even less influenced either during stable power swing or during unstable power swing.

V. CONCLUSION

This paper analyzes the issue of power swing and OOS conditions and is focusing on evaluating synchronized sampling based fault location (SSFL) algorithm during power swing. Based on the theoretical analysis and ATP simulations, the following conclusions can be drawn:

- For power swing issue, it is a concern that it may cause distance relay to trip an unfaulted line. That is unacceptable for a stressed system and may cause cascading blackouts.
- The dependability/security of SSFL is very good even under power swing and out-of-step conditions. SSFL locates the internal fault no matter if the system is experiencing power swing. The application of SSFL in the real system can reduce the false operation in the protection system.
- If a line fault occurs during the power swing, the accuracy of SSFL may be influenced, but it is mostly still in the acceptable range. The short line algorithm is less influenced than the long line algorithm. Locating a ground fault is less influenced than locating aerial fault. From the historical experience, more than 90% of the transmission line faults are ground fault. Therefore, SSFL algorithm will still have good performance during the power swing in the practical applications.

VI. Appendix

TABLE II
PARAMETERS FOR TWO-MACHINE MODEL (SIMILAR AS FIG.1)

	Short line	Long line
E_S	345 kV	345 kV
E_R	345 kV	345 kV
Z_S	Z0 2.95+j3.29 Ω Z1 4.43+j31.72Ω	Z0 2.135+j41.223 Ω Z1 1.512+j37.132Ω
Z_R	Z0 25.84+j150.97Ω Z1 4.26+j62.63Ω	Z0 0.272+j15.284Ω Z1 0.345+j17.496Ω
Z_L	Z0 1.985+j10.279Ω/mile Z1 0.311+j2.886Ω/mile	Z0 0.4359+j2.0099Ω/mile Z1 0.0614+j0.5664Ω/mile Y0 j4.3725 mho/mile Y1 j7.6245 mho/mile
length	10.15 mile	167.44 mile

TABLE III
THE ERROR OF LOCATION FOR TESTING THE SHORT LINE (LINE7-8)

	Fault Location				
Type	10%	30%	50%	70%	90%
AG	0.13%	0.09%	0.08%	0.06%	0.00%
BC	0.12%	0.10%	0.09%	0.08%	0.01%
BCG	0.13%	0.10%	0.09%	0.08%	0.00%
ABC	0.15%	0.11%	0.10%	0.08%	0.00%

(a) During Stable Power Swing

	Fault Location				
Type	10%	30%	50%	70%	90%
AG	0.04%	0.03%	0.03%	0.03%	0.00%
BC	0.01%	0.03%	0.04%	0.05%	0.06%
BCG	0.02%	0.03%	0.04%	0.05%	0.05%
ABC	0.03%	0.04%	0.04%	0.05%	0.04%

(b) During Unstable Power Swing

TABLE IV
THE ERROR OF LOCATION FOR TESTING THE LONG LINE (LINE 6-9)

	Fault Location				
Type	10%	30%	50%	70%	90%
AG	1.30%	0.59%	0.19%	0.63%	1.88%
BC	2.77%	2.00%	1.72%	0.91%	0.28%
BCG	1.78%	0.77%	0.20%	0.06%	1.87%
ABC	3.12%	2.88%	2.34%	1.29%	0.06%

(a) During Stable Power Swing

	Fault Location				
Type	10%	30%	50%	70%	90%
AG	1.50%	0.43%	0.45%	0.84%	1.61%
BC	1.43%	2.03%	2.92%	3.58%	3.64%
BCG	1.35%	0.43%	0.45%	0.83%	1.68%
ABC	2.43%	3.57%	3.11%	3.58%	3.51%

(b) During Unstable Power Swing

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VIII. Biographies

Nan Zhang (S'04) received his B.S. and M.S. degrees from Tsinghua University, Beijing, China both in electrical engineering, in 1999 and 2002 respectively. Since Jun. 2002, he has been with Texas A&M University pursuing his Ph.D. degree. His research interests are power system analysis, power system protection, power system stability, system-wide disturbances, as well as signal processing and artificial intelligence applications in power systems.

Mladen Kezunovic (S'77, M'80, SM'85, F'99) received his Dipl. Ing. Degree from the University of Sarajevo, the M.S. and Ph.D. degrees from the University of Kansas, all in electrical engineering, in 1974, 1977 and 1980, respectively. Dr. Kezunovic's industrial experience is with Westinghouse Electric Corporation in the USA, and the Energoinvest Company in Sarajevo. He also worked at the University of Sarajevo. He was a Visiting Associate Professor at Washington State University in 1986-1987. He has been with Texas A&M University since 1987 where he is the Eugene E. Webb Professor and Director of Electric Power and Power Electronics Institute. His main research interests are digital simulators and simulation methods for equipment evaluation and testing as well as application of intelligent methods to control, protection and power quality monitoring. Dr. Kezunovic is a registered professional engineer in Texas, and a Fellow of the IEEE.